CHAPTER 2. HEALTH EFFECTS

2.1 INTRODUCTION

The primary purpose of this chapter is to provide public health officials, physicians, toxicologists, and other interested individuals and groups with an overall perspective on the toxicology of mercury. It contains descriptions and evaluations of toxicological studies and epidemiological investigations and provides conclusions, where possible, on the relevance of toxicity and toxicokinetic data to public health.

A glossary and list of acronyms, abbreviations, and symbols can be found at the end of this profile.

To help public health professionals and others address the needs of persons living or working near hazardous waste sites, the information in this section is organized by health effect. These data are discussed in terms of route of exposure (inhalation, oral, and dermal) and three exposure periods: acute (≤14 days), intermediate (15–364 days), and chronic (≥365 days).

As discussed in Appendix B, a literature search was conducted to identify relevant studies examining health effect endpoints. The following figures provide overviews of the human and animal databases included in this chapter of elemental mercury (Figure 2-1), inorganic mercury (Figure 2-2), organic mercury (Figure 2-3), and for exposures where the predominant form mercury is unknown (general populations) (Figure 2-4). These studies evaluate the potential health effects associated with inhalation and oral exposure to mercury but are not inclusive of the entire body of literature.

Results of epidemiological studies are provided in each section of Chapter 2. Animal studies are presented as follows: inhaled elemental mercury, Table 2-1 and Figure 2-5; inhaled mercuric oxide, Table 2-2 and Figure 2-6; oral inorganic mercuric salts, Table 2-3 and Figure 2-7; and oral organic mercury, Table 2-4 and Figure 2-8. No quantitative dermal data were identified for mercury compounds.

Levels of significant exposure (LSEs) for each route and duration are presented in tables and illustrated in figures. Note that for all studies, exposure is expressed in terms of mercury (i.e., mg Hg/kg/day), and not in terms of specific mercury compounds, to allow comparison of doses across studies. The points in the figures showing no-observed-adverse-effect levels (NOAELs) or lowest-observed-adverse-effect levels (LOAELs) reflect the actual doses (levels of exposure) used in the studies. Effects have been classified into “less serious LOAELs” or “serious LOAELs (SLOAELs).” “Serious” effects are those that evoke

failure in a biological system and can lead to morbidity or mortality (e.g., acute respiratory distress or death). "Less serious" effects are those that are not expected to cause significant dysfunction or death, or those whose significance to the organism is not entirely clear. ATSDR acknowledges that a considerable amount of judgment may be required in establishing whether an endpoint should be classified as a NOAEL, "less serious" LOAEL, or "serious" LOAEL, and that in some cases, there will be insufficient data to decide whether the effect is indicative of significant dysfunction. However, the Agency has established guidelines and policies that are used to classify these endpoints. ATSDR believes that there is sufficient merit in this approach to warrant an attempt at distinguishing between "less serious" and "serious" effects. The distinction between "less serious" effects and "serious" effects is considered to be important because it helps the users of the profiles to identify levels of exposure at which major health effects start to appear. LOAELs or NOAELs should also help in determining whether or not the effects vary with dose and/or duration, and place into perspective the possible significance of these effects to human health. Levels of exposure associated with cancer (Cancer Effect Levels, CELs) of oral inorganic mercury are indicated in Table 2-3 and Figure 2-7; CELs for oral organic mercury are indicated in Table 2-4 and Figure 2-8.

A User's Guide has been provided at the end of this profile (Appendix C). This guide should aid in the interpretation of the tables and figures for LSEs and MRLs.

Mercury and mercury compounds have been used for industrial and medicinal purposes since ancient times and the toxicity of mercury compounds has long-been recognized (Clarkson 2006; Genchi et al. 2017). Environmental mercury exposures that could result in adverse health effects were only recognized in the early 1950s when residents of Minamata, Japan consumed methylmercury-contaminated fish and seafood (Ekino et al. 2007). Since the Minamata poisoning, an extensive database of epidemiological and animal studies has examined relationships between exposures to mercury and effects on health outcomes.

In this profile, mercury compounds are classified into three categories: (1) elemental mercury; (2) inorganic mercury compounds (primarily inorganic mercury salts); and (3) organic mercury compounds, with each mercury category exhibiting different properties. These properties play a significant role in defining the toxicokinetics and toxicity profiles for each mercury class. Mercury has no known physiological role in humans (Carocci et al. 2014). The focus of this profile is to summarize toxicological effects of the three mercury classes using epidemiological and animal studies that are relevant to the major sources of environmental exposure. Various consumer (e.g., skin lightening creams and soaps, herbal remedies, laxatives, tattooing dyes, fingerpaints, artists paints, and make-up paints) and

medicinal products (e.g., thimerosal, an ethylmercury-containing compound that was used as a preservative in vaccines) that contain mercury or mercury compounds can contribute to exposure to consumers (DeVito and Brooks 2013; McKelvey et al. 2011; Rastogi 1992; Wendroff 1990). Toxicities of consumer and medicinal products, other than mercury dental amalgams, are not specifically considered or evaluated in this profile, as these exposures are not classified as environmental exposures. However, any mercury released into air, water, or soil via consumer use or disposal of mercury-containing products would contribute to exposures detected in environmental media and/or biomarkers of exposure in epidemiological studies. The toxicology of mercuric cyanide is not discussed in this profile because the exposure-response relationship for mercuric cyanide will reflect contributions of inorganic mercuric mercury and cyanide. The toxicology of inorganic mercuric mercury is described in this the profile. The toxicology of cyanide is described in the ATSDR Toxicological Profile for Cyanide.

Since the development of the previous Toxicological Profile on Mercury in 1999, the database for epidemiological studies has grown considerably, with more extensive investigations of populations with high dietary exposure to mercury-contaminated fish and of general populations with lower levels of mercury exposures. Studies have also expanded investigations to focus on effects and endpoints other than neurological. In addition, more epidemiological studies have included biomarkers of exposure (e.g., mercury in blood, hair, or urine). The literature database for studies in laboratory animals has expanded with evaluations of effects in other organ systems, and more recent studies have evaluated lower exposure levels than those used in earlier studies.

Literature Search Strategy and Inclusion Criteria. The literature database on health effects of mercury is enormous, with a large number of epidemiological studies, including studies in children, and studies in laboratory animals. Due to the extent of the literature database, it is not practical or realistic to cite all, or even most, of the studies on health effects of mercury. Thus, this profile does not attempt to provide a comprehensive review of all literature; instead, the profile summarizes the major lines of evidence regarding health effects. Due to the extensive number of available epidemiological studies, case reports are generally not included in the profile. However, exceptions include discussion of acute-duration accidental or intentional exposure to near-fatal or fatal levels of mercury, and to describe portal-of-entry effects following acute-duration exposures.

ATSDR's approach for assessing study quality and weight-of-evidence evaluation is described in ATSDR's Guidance for the Preparation of Toxicological Profiles document (https://www.atsdr.cdc.gov/toxprofiles/guidance/profile_development_guidance.pdf). For

epidemiological studies, well-conducted and reported studies were considered for inclusion in the profile. Quality criteria were considered in selecting studies to include in the mercury profile and, in particular, for consideration as support for MRLs. In general, epidemiological studies that attempted dose-response assessments (e.g., regression models) were included in the profile if the following criteria were met: (1) reported estimates of variance in the dose-response metrics (e.g., standard error [SE], confidence level [CL]); (2) included adjustments for confounding; and (3) reported biomarker data. For studies used to derive MRLs, reporting of quality assurance of analytical methods was also required. For most studies included in the profile, these inclusion criteria were followed, although there are a few exceptions. For example, biomarkers were not available for some mercury poisoning outbreaks from the 1950s–1970s because mercury exposure was not recognized as the cause of symptoms at the time of exposure (e.g., Minamata disease). However, these studies are included because they identified severe neurological and neurodevelopmental effects in populations exposed to environmental methylmercury, providing the rationale for subsequent environmental and biomarker-based epidemiological investigations of these endpoints.

For animal studies, all well-conducted and reported studies were considered for inclusion, with the focus on relevant routes of exposure. A large amount of parenteral (injection) studies in animals exist, with most focusing on induction of renal toxicity using high doses of inorganic mercury salts. These studies are not included for dose-response assessments because they do not provide information about effects at low doses of mercury, and parenteral administration is not a relevant route for human exposure.

Mechanism of Toxicity. Mercury produces toxicity by a variety of mechanisms, which are discussed in depth in Section 2.21 and in discussions of specific categories of health effects. In general, these mechanisms include alteration or disruption of regulation of intracellular calcium homeostasis, cytoskeleton, mitochondrial function, oxidative stress, neurotransmitter release, and DNA methylation. Mercury binding to thiolate anions may underlie many of these alterations or disruptions since: (1) thiolates are present in almost every biological system, and (2) Hg^{2+} and CH_3Hg^{2+} have high affinity for the thiolate anion and formation of Hg^{2+} and CH_3Hg^{2+} S-conjugates.

Mercury binds to and disrupts the activity of enzymes, transporters, and other proteins that depend on functional thiol groups. Mercury can also displace other physiological metals (e.g., iron, zinc) that regulate enzyme activity through interactions with protein thiols. While binding to thiol groups is reversible, the binding kinetics are sufficiently fast enough that Hg^{2+} and CH_3Hg^{2+} migrate from one accessible thiolate anion to another.

Low molecular weight thiols also serve as important ligands for mercury transport in and out of cells. Conjugates of Hg^{2+} and CH_3Hg^{2+} with extracellular thiols (e.g., cysteine, glycinyl-cysteine, glutathione) are recognized by physiological transport systems for amino acids (e.g., molecular mimicry) and, once in cells, mercury can distribute to other critical intracellular thiol groups. Transport of mercury S-conjugates has been shown to be important in a variety of tissues, including brain, intestines, kidneys, liver, placenta, and RBCs. The high lipid solubility of elemental mercury (Hg^0) contributes to partitioning of inhaled mercury vapor into blood and delivery of Hg^0 to the brain where it can be oxidized to Hg^{2+} and form Hg^{2+}-thiol conjugates.

Toxicokinetics of Mercury Compounds. Humans are exposed to many forms of mercury, and these exhibit route-dependent and chemical-species-dependent toxicokinetics. The major categories discussed in this section are elemental mercury (Hg^0, e.g., mercury vapor) and inorganic mercuric (Hg^{2+}, e.g., mercuric chloride), inorganic mercurous (Hg^+, calomel), and organic mercuric (Hg^{2+}, e.g., methylmercury, dimethylmercury, phenylmercury) compounds.

Elemental mercury. Absorption of inhaled mercury vapor was estimated to range from 69 to 85% in human adults. Absorption of elemental mercury ingested as mercury amalgam was estimated to be 0.04% in human adults. Systemic absorption of mercury has been shown to occur in human adults following skin exposure to mercury vapor (approximately 2% of absorption from inhalation during a full-body immersion in mercury vapor) (Hursh et al. 1989).

Following inhalation exposure to mercury vapor, mercury distributes throughout the body, with the highest concentrations occurring in the kidneys. Vascular proximity of the heart and brain coupled with a limiting oxidation rate of Hg^0 in blood contributes to a first-pass effect on uptake of Hg^0 in these tissues following inhalation of mercury vapor. Inhaled mercury vapor can be transferred from the mother to the fetus and also from the mother to infants via maternal milk.

Absorbed Hg^0 is eliminated in exhaled air and by oxidation to mercuric mercury (Hg^{2+}). The major oxidative pathway for Hg^0 is catalyzed by the enzyme catalase. Following oxidation of Hg^0 in blood and tissues, Hg^{2+} is excreted in urine and feces.

Following inhalation of mercury vapor, mercury elimination kinetics exhibit multiple phases. The terminal half-time, thought to largely reflect urinary and fecal excretion of Hg^{2+}, has been estimated in

humans to range from 30 to 90 days. Several pharmacokinetics models of inorganic mercury have been published. Of these, two models were developed to predict the absorption and distribution of inhaled mercury vapor (Jonsson et al. 1999; Leggett et al. 2001).

Inorganic mercuric mercury. Following accidental inhalation exposures to mercuric oxide (^{203}HgO), mercury was detected in various body regions, including head, kidneys, pelvis, and in the legs, indicating systemic absorption. Absorption of mercury following ingestion of inorganic mercury compounds was estimated to range from 1 to 16% in human adults. Studies conducted in rodents have found that gastrointestinal absorption is higher in younger rats. Inorganic mercuric mercury was shown to be absorbed across isolated human and pig skin. Following ingestion of mercuric chloride, mercury distributes throughout the body, with the highest concentrations occurring in the kidneys and liver.

Inorganic mercury is found in human cord blood, placenta, and breast milk, indicating transfer to the fetus and infant, respectively. Exhaled Hg^0 was observed in mice following parenteral doses of mercuric chloride, suggesting that Hg^{2+} had been reduced to Hg^0. Salivary and gastrointestinal bacteria have been shown to methylate Hg^{2+}; however, the quantitative significance of methylation in the disposition of absorbed Hg^{2+} remains uncertain. The major routes of excretion of absorbed mercuric mercury are feces and urine.

Kinetics of elimination of absorbed inorganic mercuric mercury exhibits multiple phases. The terminal half-time has been estimated in humans to range from 49 to 120 days (Farris et al. 2008). Several pharmacokinetics models of inorganic mercury have been published. These models are based on studies of pharmacokinetics of absorbed inorganic mercuric mercury.

Inorganic mercurous mercury. No studies were located that provide quantitative information on the absorption, distribution, metabolism, or excretion of mercury following exposure to inorganic mercurous compounds. Pharmacological and cosmetic uses of calomel (mercurous chloride) ointments (skin lightening creams, acne) have resulted in elevated urinary mercury levels and mercury poisoning, indicating that absorption of mercury can occur following oral and/or dermal exposure to inorganic mercurous compounds. Toxicity may have been from absorbed inorganic mercuric mercury, as the low pH and high chloride concentration of the gastric environment favor oxidation of ingested Hg^1 to Hg^{2+}.

Organic Mercuric Mercury. No studies were found that have estimated absorption of inhaled organic mercuric mercury. Studies conducted in humans, monkeys, and rodents have shown that gastrointestinal

absorption of mercury is close to 100% following ingestion of methylmercury chloride or when incorporated into fish or other ingested protein. Dimethylmercury is rapidly absorbed through human skin.

Following ingestion of methylmercury, mercury distributes throughout the body, with the highest concentrations occurring in the liver, kidneys, and brain. Methylmercury is also found in human cord blood, placenta, and breast milk, indicating transfer to the fetus and infant, respectively. Studies conducted in humans and in a variety of other mammalian species have observed both methylmercury and inorganic mercury in tissues and excreta following exposure to methylmercury. Demethylation occurs in liver, phagocytes, brain, and other tissues. The major routes of excretion of absorbed methylmercury are feces, urine, and hair. Following exposure to phenylmercury, absorbed mercury is eliminated in bile, feces, urine, and hair.

Kinetics of elimination of absorbed methylmercury exhibits multiple phases. The terminal half-times have been estimated in humans to range from 50 to 130 days. Pharmacokinetics models of methylmercury have been developed for humans and a variety of other animal species.

Routes of Exposure and Mercury Sources. Relevant routes of exposure for humans vary based on the category of mercury compound.

- *Elemental mercury*. The most relevant route of exposure to elemental mercury is through inhalation of mercury vapor. Exposure of workers to elemental mercury vapor has occurred in several occupational settings, including chloralkali processing (i.e., production of chlorine and sodium hydroxide), fluorescent lamp production, gold mining and processing, lithium-6 purification (column exchange [COLEX] process), mercury amalgam dentistry, mercury battery production, natural gas production, recycling, and thermometer production. Humans can also be exposed to elemental mercury from inhalation and ingestion of mercury released from mercury amalgam dental restorations.
- *Inorganic mercury salts.* Oral exposure is the primary route of exposure to inorganic mercury salts. Exposure may occur through diet or contaminated environmental media (e.g., soil). Exposure to inorganic mercury salts is currently not a predominant exposure for the general U.S. population.
- *Organic mercury compounds*. Methylmercury is by far the predominant form for organic mercury exposure in populations. Exposure to methylmercury occurs worldwide through the diet, with fish as the main dietary source of methylmercury.

Epidemiological Studies. Numerous epidemiological studies have examined effects of environmental exposures to mercury compounds. The following provides a brief overview of the epidemiological database and important considerations for epidemiological studies.

Metrics of exposure (biomarkers). Humans are exposed to a mixture of methylmercury and inorganic mercury (primarily mercuric and elemental) in their local environments, with either being more or less pronounced under certain circumstances (e.g., occupational exposure to Hg^0 vapor, consumption of methylmercury in fish). Exposure to mercury that leads to absorption of mercury in any form can be detected from measurement of total mercury (inorganic plus organic) in blood or urine. A change in exposure will be reflected in a change in blood (BHg) or urine total mercury (UHg). Measurements of total mercury in blood and urine can be considered biomarkers of total mercury exposure. These measurements do not provide information to confidently estimate the magnitude of exposures specifically to methylmercury, inorganic mercury compounds, or elemental mercury.

Biomarkers that are more strongly correlated to methylmercury exposure are blood methylmercury concentration or total mercury concentrations in hair (HHg) or RBCs. Blood and hair are more significant depots for accumulation of methylmercury than inorganic mercury. Biomarkers that are more strongly correlated to exposure to inorganic forms of mercury (primarily mercuric and elemental) are inorganic mercury in blood (or plasma) and inorganic mercury or total mercury in urine. However, demethylation after absorption contributes inorganic mercury to blood and urine; this complicates distinguishing exposures to inorganic mercury from exposures to methylmercury based solely on measurements of total mercury in blood or urine.

In workers exposed to high levels of mercury vapor, elemental mercury is likely to be the dominant form, and total mercury in urine can serve as a reliable biomarker of exposure. Epidemiological studies of methylmercury have focused on populations that consume large amounts of fish or marine animals. In these populations, methylmercury is likely to be the dominant contributor to exposure, and total mercury in blood or hair can serve as a reliable exposure biomarker.

Duration of exposure. With few exceptions, the duration of exposure to mercury in epidemiological studies is considered to be chronic. Exceptions include intermediate-duration exposures in an occupational study in elemental mercury workers and studies on the Iraq methylmercury poisoning

outbreak. No epidemiological studies examining populations exposed to mercury for acute durations were identified.

Study populations and sources of exposure. All populations are exposed to a combination of elemental, inorganic, and organic mercury compounds; thus, no population is exposed to only one mercury category. In this profile, epidemiological study populations are classified as follows: (1) predominant exposure to elemental mercury; (2) predominant exposure to methylmercury; and (3) general populations in which the predominant form of mercury is unknown and cannot be discerned from the reported biomarker measurements. Details of these population are described below. Information on exposure of humans to inorganic mercury compounds is limited to reports of acute-duration accidental or intentional exposure to near-fatal or fatal levels. Clinical findings associated with these high-dose, acute-duration exposures are reviewed in Section 2.2.

Elemental Mercury. Populations exposed predominantly to elemental mercury consist of occupational exposures and exposures to mercury amalgam in dental patients. Studies of exposures to mercury vapor have been conducted in workers of various industries including chloralkali, fluorescent lamp production, gold mining and processing, lithium-6 purification (COLEX process), dentistry applications of mercury amalgam, mercury battery production, natural gas production, recycling, and thermometer production. In some occupational studies, work area or breathing zone mercury levels in a subset of the study group were reported. The most common biomarker reported is mercury concentration in urine (UHg; expressed in terms of μg/L or μg/g creatinine). The timing of measurement varied across studies. In some cross-sectional studies, these were based on measurements made at a single time, typically at the time of outcome assessment. For some retrospective studies, UHg estimates were derived from historical industrial hygiene monitoring data. In some studies, the individual subject data were aggregated into metrics of cumulative exposure (e.g., sum of quarterly average values for all exposure years) or exposure intensity (sum/exposure years). Most occupational studies have assessed health outcomes by comparison of exposed and reference (unexposed) groups. Inhalation is the primary route of exposure. Exposures of workers may be relatively constant during the workday (e.g., chloralkali workers) or highly intermittent (e.g., dental workers). For exposure of populations with amalgam fillings, biomarker levels are typically lower than those observed in occupational populations.

Methylmercury. Studies of associations between health outcomes and exposure to methylmercury have focused on populations in which methylmercury was the dominant contributor to total mercury exposure. These studies fall into two general categories: studies of outbreaks of mercury poisoning related to

exposure to methylmercury and studies of populations that consume large amounts of fish and/or marine mammals. Two major outbreaks of methylmercury poisoning have been extensively studied.

- *Minamata poisoning outbreak.* In the Minamata outbreak, discharges of wastewater from an acetaldehyde production facility into the Shiranui Sea located in the Kumamato Prefecture of Japan resulted in elevated levels of methylmercury in fish and shellfish (Harada 1995). Methylmercury entered the waste stream as a side product of the acetaldehyde production process, which used mercury sulfate as a reactant. In the mid-1950s, an outbreak of a neurological disorder (Minamata disease and congenital Minamata disease) occurred in the area. The timing of the outbreak appears to have been related to the expansion of acetaldehyde production at the facility (Harada 1995). Exposure to methylmercury resulted from ingestion of locally harvested fish and shellfish. Studies of health outcomes in this population focused on neurological and neurodevelopmental effects. Measurements of mercury in blood and hair were not made until several years following the period of most intense exposure and, therefore, do not provide reliable estimates of exposures that may have contributed to Minamata disease.
- *Iraq poisoning outbreak*. An outbreak of methylmercury poisoning occurred in Iraq in 1972–1973 as a result of widespread consumption of bread made from wheat that had been treated with a methylmercuric fungicide (Al-Mufti et al. 1976; Bakir et al. 1973; Clarkson et al. 1976). Studies of health outcomes in this population focused on neurological and neurodevelopmental effects. Based on measurements of methylmercury in flour used to bake contaminated bread and estimates of bread consumption, methylmercury intake was estimated to have ranged from 80 to 1,000 mg over a 3-month period (Al-Mufti et al. 1976). BHg levels in poisoning cases measured approximately 65 days after exposure ranged from 10 to 3,000 µg/L (Clarkson et al. 1976). Prenatal exposures were reconstructed from segmental analysis of single maternal hair strands and used to derive prenatal dose-response relationships for neurodevelopmental outcomes (Cox et al. 1989; Crump et al. 1995; Marsh et al. 1987).
- *Studies of populations with high fish diets.* Biomagnification of mercury levels in aquatic systems contributes to relatively high levels of methylmercury in predatory fish and marine mammals. As a result, methylmercury can be the dominant form of mercury exposure in populations that consume large amounts of these organisms. In these populations, BHg or HHg levels are typical biomarkers of methylmercury exposure. Several populations of high fish consumers have been extensively studied for associations between exposure to methylmercury and health outcomes. Examples include studies conducted on populations in the Republic of Seychelles, Faroe Islands, North Island New Zealand, Nunavik region of arctic Canada, and

Amazon River basin. In each of these populations, BHg or HHg levels positively correlated with consumption of fish.

Predominant Mercury Form Unknown (General Populations). Numerous epidemiological studies have examined association between mercury biomarkers and health effects in adults and children. Many of these studies do not identify the predominant form of mercury. In general populations that do not have mercury amalgam dental restorations, dietary exposure is assumed as the primary exposure. In people who have amalgams, mercury released from the amalgams will contribute to exposure. In people who have 7–13 amalgam restorations, amalgam mercury can contribute approximately half of the mercury absorbed from all sources (Mackert and Berglund 1997; Snapp et al. 1989). Biomarkers used to quantify exposures in studies of general populations vary and include BHg, HHg, and UHg. The study population sizes have varied greatly from <100 to almost 50,000 and included prospective studies and cross-sectional studies in large populations, such as participants in the U.S. National Health and Nutrition Examination Survey (NHANES) and the Korea National Health and Nutrition Examination Survey (KNHANES).

Potentials sources of bias. Bias can occur in epidemiological studies when the background risk of the outcome being measured is not the same in the exposed and reference groups. Confounders are factors that account for all or part of the difference in the measured outcome between groups and are not a direct effect of exposure. Not adjusting for confounders may attenuate or strengthen the apparent associations between mercury exposure and the outcome, depending on whether it is a negative or positive confounding variable. Confounders can be addressed in epidemiological studies using a variety of strategies including stratification and matching of subjects, or, in regression models, including these factors as co-variables in the models.

Because of the importance of dietary fish consumption as a source of exposure to methylmercury, fish consumption is a particularly important potential confounder between exposure to methylmercury and health outcomes. For example, fish contain nutrients that have been shown to be important modifiers of development (e.g., 3-omega long-chain polyunsaturated fatty acids, LCPUFA) (Cheatham 2008; Muldoon et al. 2014). In populations consuming marine mammals, dietary intake of polychlorinated biphenyls (PCBs) and selenium that accumulate in marine mammal tissue, can also be a source of confounding bias (Boersma and Lanting 2000; Park et al. 2010; Skröder et al. 2017).

The list of factors than can introduce bias into assessment outcome association with mercury exposure can be quite large. For example, assessing potential associations between mercury exposure and human

developmental outcomes involves accounting for many confounders. These factors may include (but are not limited to) child sex, birth weight, birth order, gestational age, and breastfeeding; maternal age, alcohol and tobacco use, and medical history; parental education, caregiver general intelligence, family income, family language; home learning, language, and social stimulation; exposure to other neurotoxins (e.g., lead, PCBs); nutritional factors (e.g., fish consumption); history of neurological disease or head injuries; and genetic factors that may influence mercury toxicity.

Effect modification. Effect modifiers occur when the relationship between an exposure and an outcome vary by a third variable (the effect measure modifier). For example, renal disease from any cause can affect blood pressure and could thereby interact with mercury to change blood pressure. A variable may act as both an effect modifier and a confounder, depending on a variety of factors. Effect modifiers may be investigated, often to identify susceptible populations or co-exposures that may interact with mercury and change the association of mercury exposure with a health outcome to produce a synergistic or antagonistic effect.

Studies in Laboratory Animals. Animal studies focus on the relevant exposure routes as discussed above for epidemiological studies. For elemental mercury vapor, the animal database consists of acute- and intermediate-duration inhalation studies. No adequate studies were identified for chronic-duration inhalation of elemental mercury vapor or for oral or dermal exposure to elemental mercury. The animal database for inorganic mercury salts includes acute-, intermediate-, and chronic-duration oral studies on mercuric chloride, with a few acute- and intermediate-duration oral studies conducted on mercuric sulfide and one acute-duration study conducted on mercuric acetate. In addition, two intermediate-duration inhalation studies were conducted on mercuric oxide. For organic mercury compounds, acute-, intermediate-, and chronic-duration oral studies were conducted in animals.

Most studies evaluated effects of methylmercury (chemical form not specified) or methylmercury chloride; other compounds tested include methylmercury hydroxide, methylmercuric sulfide, bis(methylmercury)sulfide, tris(methylmercury)sulphonium ion, and phenylmercuric acetate. For all animal studies, doses are expressed in terms of mercury, not the mercury compound that was administered. Additionally, exposure to methylmercury (chemical form not specified) or methylmercury chloride in oral animal studies is referred to as “methylmercury exposure” when discussing toxicity effects since methylmercury chloride rapidly dissociates upon ingestion. Specific mercury compounds tested in each study are included in the LSE tables.

Overview of Health Effects of Mercury Compounds. The health effects of mercury identified from studies in humans and animals are summarized below for the three chemical categories of mercury. For all forms of mercury, neurological and renal effects have been consistently observed in epidemiological and/or animal studies.

Elemental mercury. Neurological and renal effects have been observed in humans and animals exposed to elemental mercury vapor. Case reports of exposure to elemental mercury at fatal or near-fatal levels have reported severe adverse respiratory effects, including lung inflammation, pneumonitis, and respiratory failure due to pulmonary edema. No evidence for other targets of elemental mercury were identified in epidemiological or animal studies.

- **Neurological Effects:**
  - **Epidemiological studies.** Epidemiological studies provide consistent evidence of neurological effects in adults, including tremor, vision, nerve conduction, motor speed and coordination, cognitive performance (memory, integrative function), and subjective physiological symptoms (mood swings, irritability, nervousness, timidity, loss of confidence).
  - **Animal studies.** Some evidence of neurodevelopmental effects (altered learning and behavior, altered motor activity, impaired habituation) and impaired motor function and damage to the central nervous system in adult animals.
- **Renal Effects:**
  - **Epidemiological studies.** Some evidence of decrements in glomerular function and tubular injury.
  - **Animal studies.** Evidence of dose- and duration-dependent increases in severity of nephrotoxicity (damage to proximal tubules, distal tubules, and glomerular membrane, loss of brush border membranes, necrosis).

Inorganic mercury salts. Neurological and renal toxicity have been consistently observed in animals orally exposed to inorganic mercury salts. Other findings in animal studies provide some evidence of cardiovascular, immunological, and reproductive effects. In addition, there is some evidence of carcinogenicity in male rats. No epidemiological studies specific for exposure to inorganic mercury salts were identified.

- **Neurological Effects:** Consistent evidence of neurodevelopmental effects, including hyperactivity, impaired motor coordination, impaired memory, and decreased sociability. In adult animals, neurobehavioral effects have included hyperactivity, impaired coordination, and impaired learning and memory. Adult animals have also shown overt neurotoxic signs such as hindlimb crossing, ataxia, tremor, and partial paralysis as well as neuropathological changes to sensorimotor regions in the central nervous system (dorsal spinal route, cerebellum).
- **Renal Effects:** Consistent evidence of dose- and duration-dependent increases in severity of nephrotoxicity (damage to proximal tubules, distal tubules, and glomerular membrane, loss of brush border membranes, necrosis).
- **Cardiovascular Effects:** Evidence of increased blood pressure, altered cardiac function, positive inotropic effects, and altered baroreceptor reflex sensitivity.
- **Immunological Effects:** Evidence of immune stimulation and immune complex disease in genetically susceptible strains of mice.
- **Reproductive Effects:** Evidence of dose-dependent impairment of fertility and decreased sperm motility and number.
- **Cancer:** Some evidence of carcinogenicity in male rats (forestomach and thyroid tumors).

Organic mercury. Neurological and neurodevelopmental effects of organic mercury compounds are established as the most sensitive effect of exposure to organic mercury compounds.

- **Neurological Effects:**
    - **Epidemiological studies (children).** Evidence of cognitive, neuromotor and neurosensory effects associated with prenatal exposure to methylmercury.
    - **Epidemiological studies (adults).** Evidence of decreased performance on tests of fine motor coordination and speed, muscle strength, tactile sensation, color vision and visual contrast sensitivity, and memory and learning.
    - **Animals.** Consistent evidence of dose-dependent neurological effects (sensorimotor dysfunction, vision and hearing deficits, impaired learning and memory) and overt signs of neurotoxicity were observed (clumsiness, gross and fine motor incoordination, lethargy, hindlimb crossing, tremor, ataxia, partial paralysis). Developing animals are more sensitive to methylmercury-induced neurotoxic effects than adult animals.

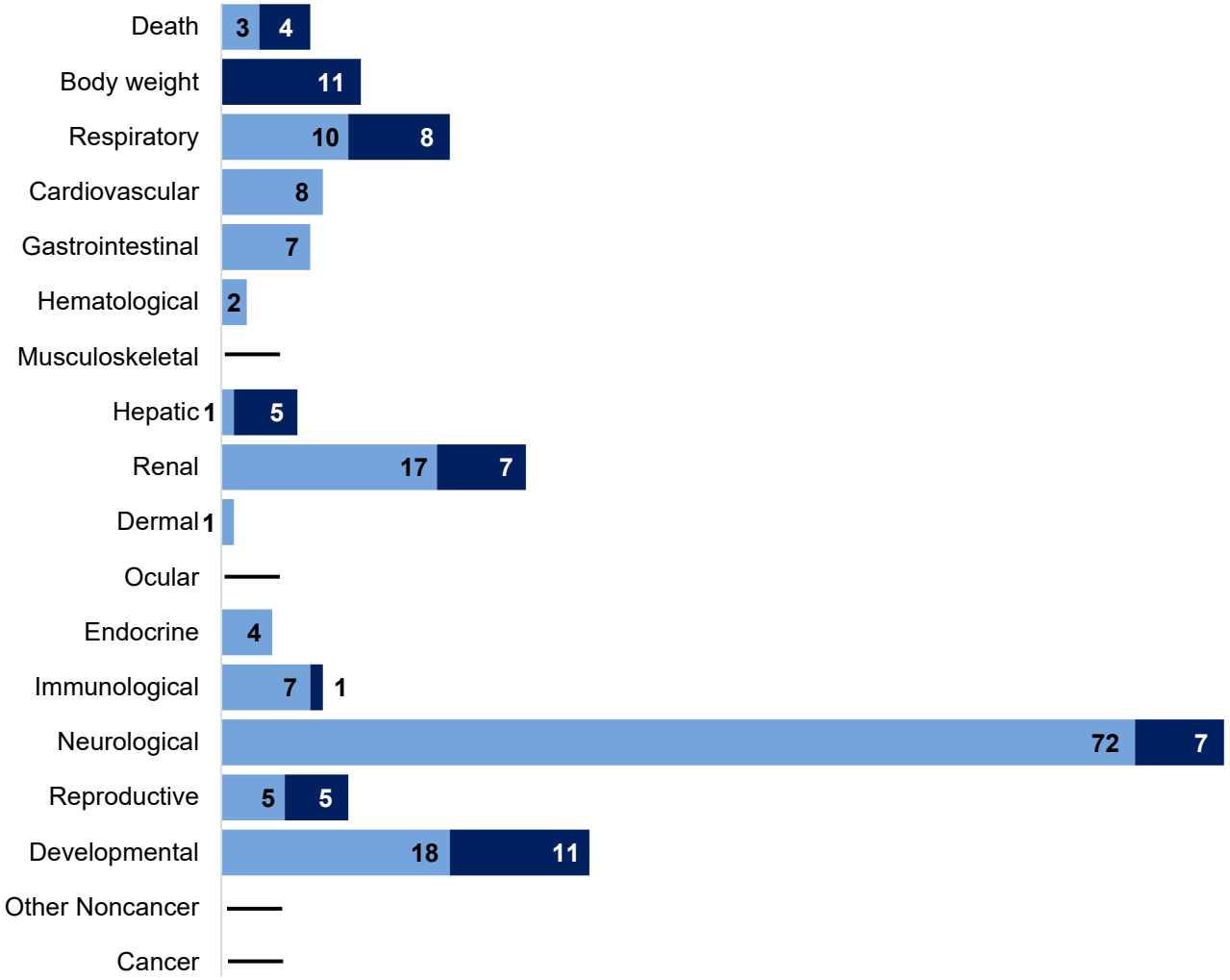
Other systems have not been as extensively studied, although there is some evidence of effects in humans and/or animals, including renal (animal), cardiovascular (humans and animals), immune (humans and

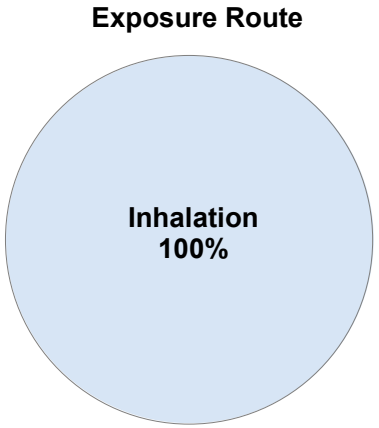
animals), reproductive (animal), and developmental (other than neurodevelopmental; humans and animals) effects. However, it does not appear that these effects are sensitive targets for environmental exposures to methylmercury. In general, these effects occur at much higher levels than those found in the environment.

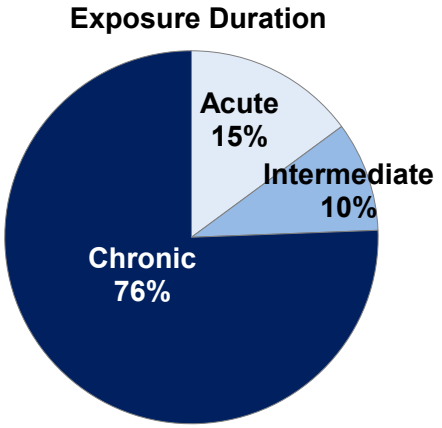
- **Renal Effects:**
  - **Animal studies.** Consistent evidence of dose- and duration-dependent increases in severity of nephrotoxicity (damage to proximal tubules, distal tubules, and glomerular membrane, loss of brush border membranes, necrosis).
- **Cardiovascular Effects:**
  - **Epidemiological studies.** Inconsistent evidence of small increases in blood pressure, clinical hypertension, and altered cardiac function.
  - **Animal studies.** Evidence of increased blood pressure, positive inotropism, and decreased baroreflex sensitivity.
- **Immunological Effects:**
  - **Epidemiological studies.** Some evidence of alterations in some immune markers (serum cytokine levels, immunoglobulins, and immune cell counts), but unclear if immune system function is affected.
  - **Animal studies.** Evidence of immune stimulation and immune complex disease in genetically susceptible strains of mice and some evidence of immune suppression in non-susceptible animals.
- **Reproductive Effects:**
  - **Animal studies.** Consistent evidence of dose-related impairment in fertility.
- **Developmental Effects (other than Neurodevelopmental):**
  - **Epidemiological studies.** Evidence of congenital effects (polydactyly, syndactyly, craniofacial malformations, microcornea, undescended testicles, enlarged colon, and protrusion of the coccyx) in the Minamata poisoning outbreak.
  - **Animal studies.** Consistent evidence of dose- and duration-dependent decreases in offspring survival, increased fetal malformations and variations (cleft palate, skeletal malformations [ribs, sternebrae], and hydronephrosis), and decreased fetal weight.

Figure 2-1. Overview of the Number of Studies Examining Elemental Mercury Health Effects in Chapter 2*

Most studies examined the potential neurological, developmental, and renal effects of elemental mercury
Fewer studies evaluated health effects in **animals** than **humans** (counts represent studies examining endpoint)



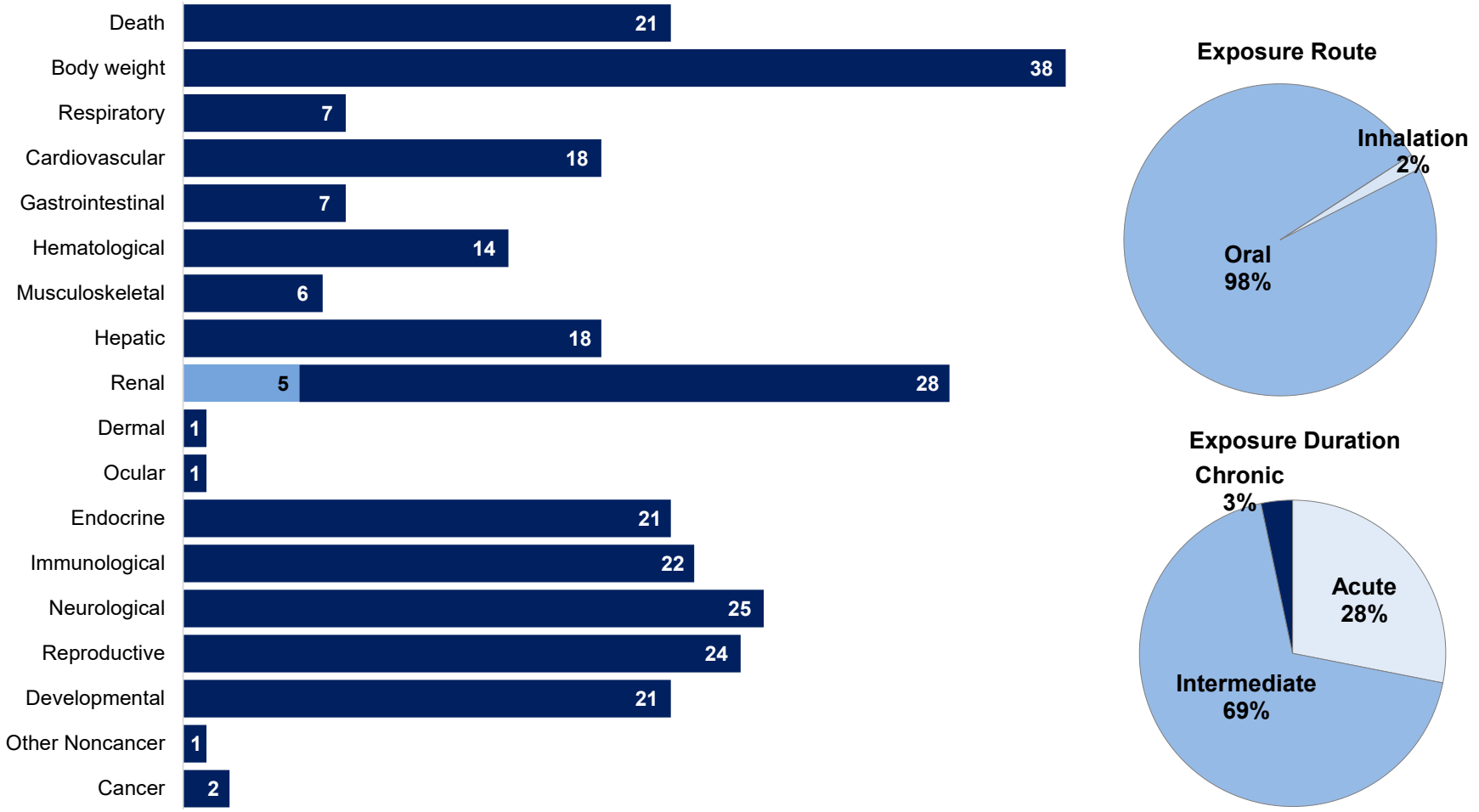




*Includes studies discussed in Chapter 2. A total of 155 studies (including those finding no effect) have examined toxicity; most studies examined multiple endpoints.

Figure 2-2. Overview of the Number of Studies Examining Inorganic Mercuric Salts Health Effects in Chapter 2*

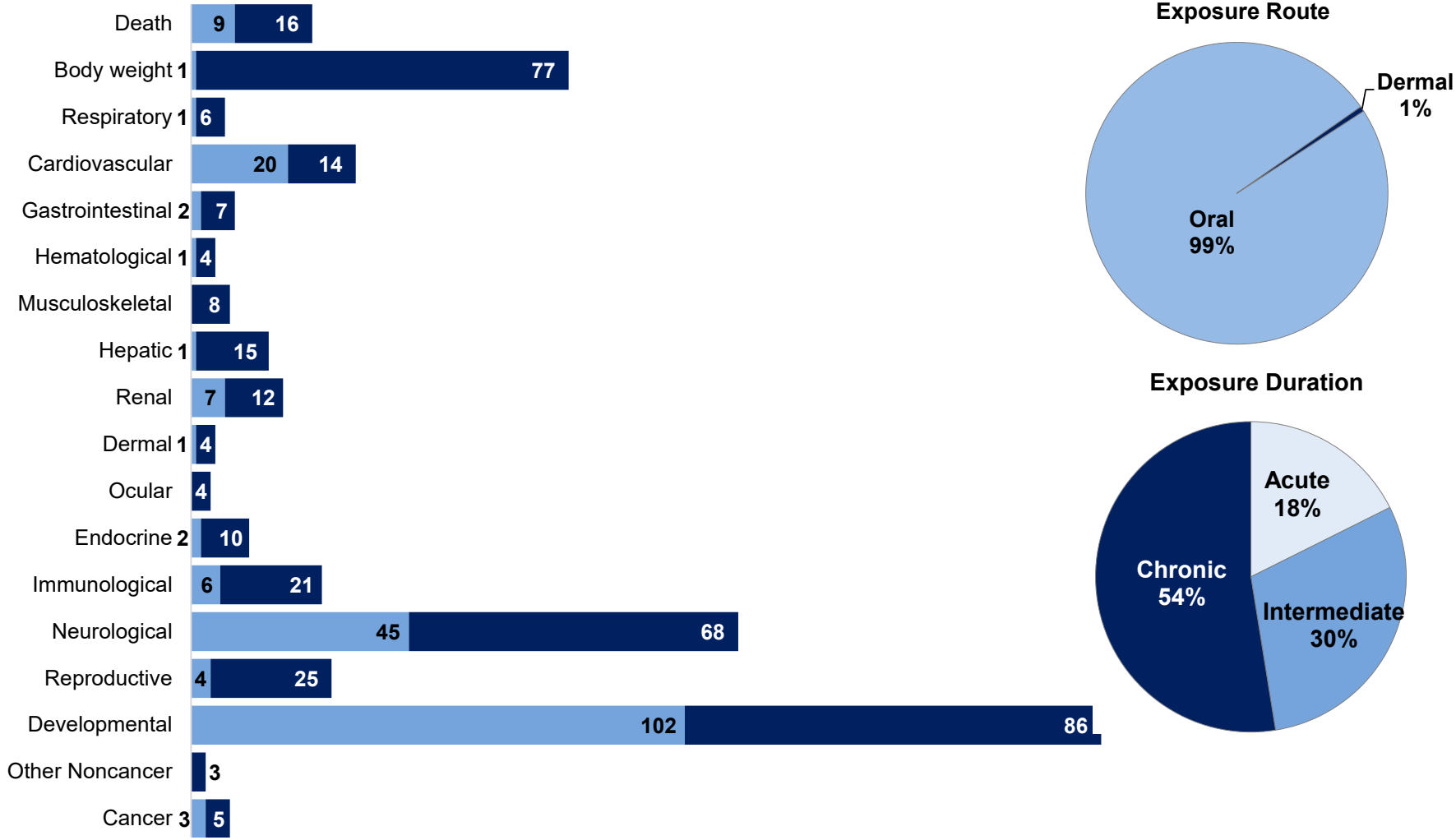
Most studies examined the potential body weight, renal, and reproductive effects of inorganic mercury
Fewer studies evaluated health effects in **humans** than **animals** (counts represent studies examining endpoint)



*Includes studies discussed in Chapter 2. A total of 101 studies (including those finding no effect) have examined toxicity; most studies examined multiple endpoints.

Figure 2-3. Overview of the Number of Studies Examining Organic Mercury Health Effects in Chapter 2*

Most studies examined the potential developmental, neurological, and body weight effects of organic mercury
Fewer studies evaluated health effects in humans than animals (counts represent studies examining endpoint)

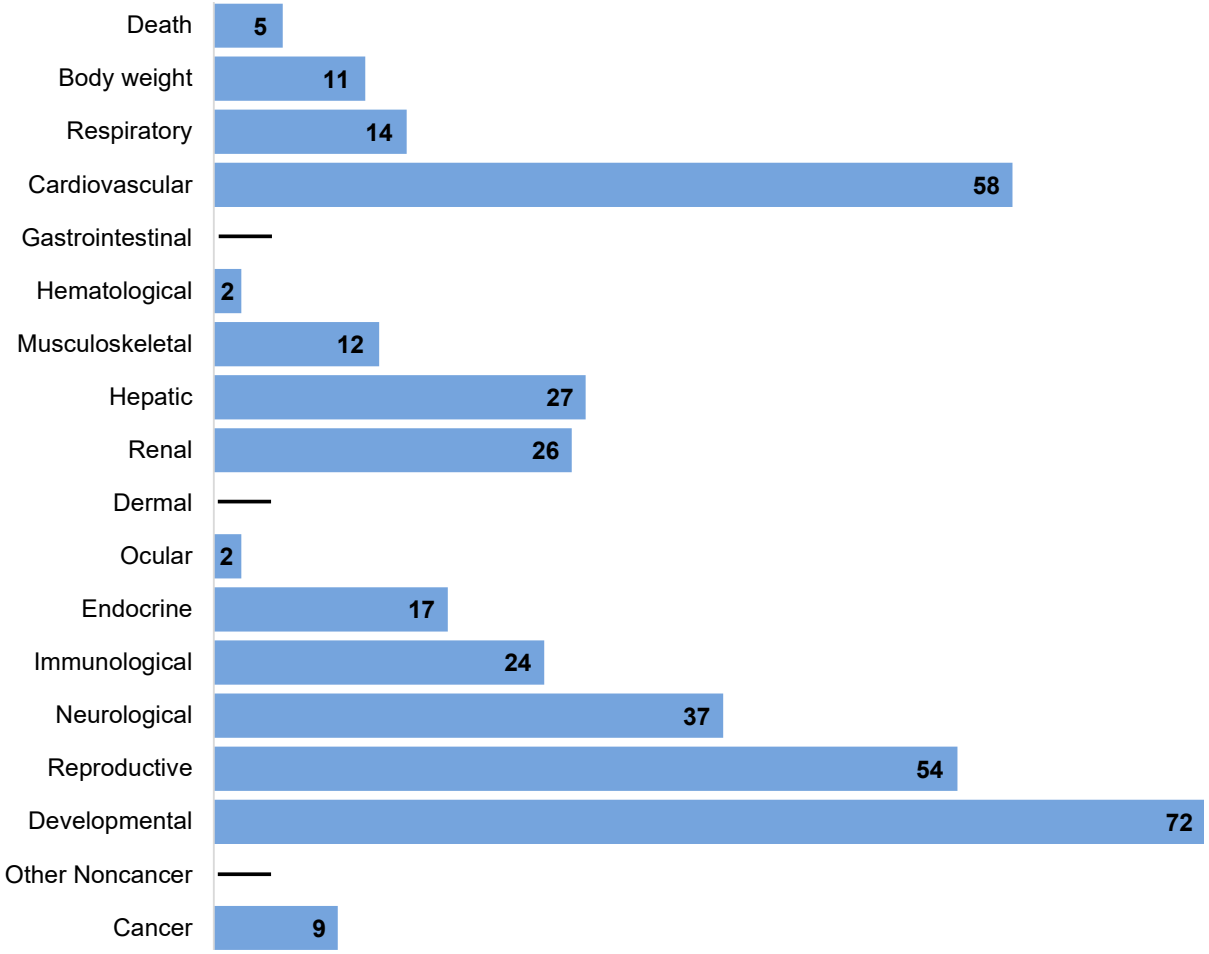


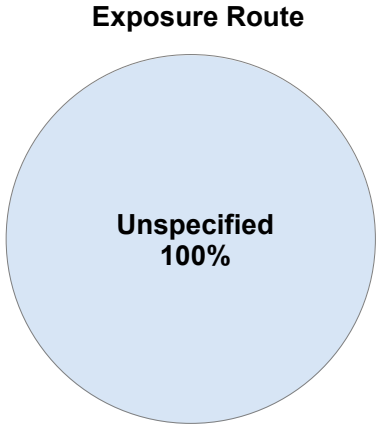
*Includes studies discussed in Chapter 2. A total of 312 studies (including those finding no effect) have examined toxicity; most studies examined multiple endpoints.

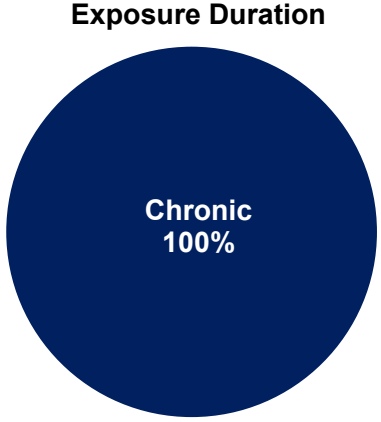
Figure 2-4. Overview of the Number of Studies Examining Mercury Health Effects—Unspecified General Population Exposure in Chapter 2*

Most studies examined the potential developmental, cardiovascular, and reproductive effects of mercury (unspecified mercury form and route of exposure)

General population studies in **humans** (counts represent studies examining endpoint)







*Includes studies discussed in Chapter 2. A total of 78 studies (including those finding no effect) have examined toxicity; most studies examined multiple endpoints.

Table 2-1. Levels of Significant Exposure to Elemental Mercury – Inhalation (mg Hg/m^3)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
ACUTE EXPOSURE									
Danielsson et al. 1993									**Elemental mercury**
1	Rat (Sprague-Dawley) 12 F	8 days GDs 11–14 and GDs 17–20 1 or 3 hours/day (WB)	0, 1.8	CS, BW, DX	Bd wt	1.8			
					Develop[b]		1.8		Decreased spontaneous locomotion, rearing, and total activity at 3 months; reduced novel environment habituation at 7 months
[Behavior assessed in adult offspring: activity (3 and 14 months), habituation (7 months), and spatial learning (4, 7, and 15 months)]									
Davis et al. 2001									**Elemental mercury**
2	Rat (Sprague-Dawley) 8–18 F	11 days 2 hours/day (N)	0, 1, 2, 4	BW, BC, OW, RX	Bd wt	2	4		17% decrease in final body weight
					Repro	1	2		Prolonged estrous cycle at ≥2 mg Hg/m3; decreased serum estradiol and increased serum progesterone at 4 mg Hg/m^3
Davis et al. 2001									**Elemental mercury**
3	Rat (Sprague-Dawley) 5–6 F	8 days (premating) 2 hours/day (N)	0, 2	BC, GN, RX	Repro	2			
Davis et al. 2001									**Elemental mercury**
4	Rat (Sprague-Dawley) 6 F	8 days (post-mating) 2 hours/day (N)	0, 1, 2	BC, GN, RX	Repro	2			
Davis et al. 2001									**Elemental mercury**
5	Rat (Sprague-Dawley) 6 F	1–8 days 2 hours/day (N)	0, 2	BC, OW, HP, RX	Repro		2		Prolonged estrous cycle after 6–8 days of exposure; immature corpora lutea during estrus and metestrus phases

Table 2-1. Levels of Significant Exposure to Elemental Mercury – Inhalation (mg Hg/m^3)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Fredriksson et al. 1992									**Elemental mercury**
6	Rat (Sprague-Dawley) 8–10 M	7 days PNDs 11–17 4 hours/day (WB)	0, 0.05	DX	Develop[b]		0.05		Increased spontaneous locomotion and decreased rearing at 2 months of age; decreased spontaneous locomotion and rearing at 4 months of age; and impaired spatial learning at 6 months of age
[Behavior assessed in adulthood: motor activity (2 and 4 months) and spatial learning (5 and 6 months)]									
Fredriksson et al. 1992									**Elemental mercury**
7	Rat (Sprague-Dawley) 8–10 M	7 days PNDs 11–17 1 hours/day (WB)	0, 0.05	DX	Develop[b]		0.05		Increased spontaneous locomotion and decreased rearing at 4 months of age; impaired spatial learning at 6 months of age
[Behavior assessed in adulthood: motor activity (2 and 4 months) and spatial learning (5 and 6 months)]									
Fredriksson et al. 1996									**Elemental mercury**
8	Rat (Sprague-Dawley) 12 F	6 days GDs 14–19 1.5 hours/day (WB)	0, 1.8	CS, BW, DX	Bd wt	1.8			
					Develop[b]		1.8		Increased spontaneous locomotion, rearing, and total activity at 4 months of age; impaired spatial learning at 4.5 months of age
[Behavior assessed in adult male offspring at 4–5 months of age]									
Herr et al. 2004									**Elemental mercury**
9	Rat (Long-Evans) 10–12 F	10 days GDs 6–15 2 hours/day (N)	0, 4	DX	Develop[b]	4			
[Sensory evoked potentials measured in adult offspring]									
Livardjani et al. 1991									**Elemental mercury**
10	Rat (Wistar) 32 M	2 hours (WB)	0, 27.0	LE, CS, BW, HP	Death			27	20/32 died prior to scheduled sacrifice (none survived longer than 5 days post-exposure)
					Bd wt			27	15–25% body weight loss

Table 2-1. Levels of Significant Exposure to Elemental Mercury – Inhalation (mg Hg/m^3)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
					Resp			27	Dyspnea and asphyxiation; lung edema, necrosis of alveolar epithelium, hyaline membranes, occasional fibrosis
[Animals sacrificed 1, 2, 3, 4, 5, 6, 7, or 15 days post-exposure (4/group)]									
Livardjani et al. 1991									**Elemental mercury**
11	Rat (Wistar) 32 M	1 hour (WB)	0, 26.6	LE, CS, BW, GN	Bd wt	26.6			
					Resp	26.6			
[Animals sacrificed 1, 2, 3, 4, 5, 6, 7, or 15 days post-exposure (4/group)]									
Morgan et al. 2002									**Elemental mercury**
12	Rat (Long-Evans) 5 F	2 hours GD 6 (N)	0, 1, 2, 4, 8	CS, BW, UR, OW, HP, DX	Bd wt	8			
					Resp	8			
					Hepatic	8			
					Renal	8			
					Develop	8			
Morgan et al. 2002									**Elemental mercury**
13	Rat (Long-Evans) 5 F	5 days GDs 6–10 2 hours/day (N)	0, 1, 2, 4, 8	CS, BW, UR, OW, HP, DX	Bd wt	4	8		10% decrease in maternal body weight
					Resp	8			
					Hepatic	8			
					Renal	8			
					Develop	8			
Morgan et al. 2002									**Elemental mercury**
14	Rat (Long-Evans) 10 F	10 days GDs 6–15 2 hours/day (N)	0, 1, 2, 4, 8	CS, BW, UR, OW, HP, DX	Bd wt	2	4	8	LOAEL: >10% decrease in maternal body weight SLOAEL: 17% maternal body weight loss
					Resp	8			
					Hepatic	8			

Table 2-1. Levels of Significant Exposure to Elemental Mercury – Inhalation (mg Hg/m^3)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
					Renal	2	4		Elevated maternal relative kidney weight (32% on GD 15); increased urinary protein and ALP
					Neuro	4	8		Mild tremor, lethargy, unsteady gait
					Develop	4	8		Increased resorptions, decreased litter size and pup weight
[50% of dams sacrificed on GD 15, 50% sacrificed on PND 1]									
Stankovic 2006									**Elemental mercury**
15	Mouse (129S/v) 6 F	4 hours (WB)	0, 0.5	HP, NX	Neuro		0.5		Reduced grip strength 4–7 months post-exposure, decreased motor axon diameter 7 months post-exposure
INTERMEDIATE EXPOSURE									
Newland et al. 1996									**Elemental mercury**
16	Monkey (Squirrel) 5–6 F	15–17 weeks Last 2/3 gestation 5 days/week 4 or 7 hours/day (WB)	0, 0.5, 1.0	DX	Develop[b]		0.5		Impaired operant training in offspring
[Offspring behavioral testing at 0.8–4 years old]									
Altunkaynak et al. 2015									**Elemental mercury**
17	Rat (Sprague-Dawley) 6 M	6 weeks 7 days/week 9 hours/day (WB)	0, 1	HP	Repro			1	Seminiferous tubule atrophy; damage to spermatogenic cells; decreased testicular and seminiferous tubule volume, decreased seminiferous tubule diameter; decreased Sertoli cells, spermatogonia, spermatocytes, and spermatids

Table 2-1. Levels of Significant Exposure to Elemental Mercury – Inhalation (mg Hg/m^3)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Altunkaynak et al. 2019									**Elemental mercury**
18	Rat (Wistar albino) 6 F	45 days 9 hours/day (WB)	0, 0.1	HP	Neuro		0.1		Histopathological changes in the cerebellum (gliosis, vacuolization, decreased Purkinje cells), decreased cerebellar volume
Kishi et al. 1978									**Elemental mercury**
19	Rat (Wistar) 12–14 M	12-42 weeks 5 day/week 3 hours/day (WB)	0, 3	CS, BW, HP, NX	Bd wt			3	Body weight loss (magnitude not reported)
					Resp	3			
					Hepatic	3			
					Renal		3		Dense black deposits in tubular cells, lysosomal inclusions, slight degeneration of tubular cells
					Neuro		3		Tremors; altered neurobehavior (decline in conditioned avoidance, increased escape response latency)
Raffee et al. 2021									**Elemental mercury**
20	Rat (SD) 7 M, 7 F	65 days 2 hours/day (WB)	0, 0.5	LE, CS, BW, BC, GN, HP	Death			0.5	Death of 2/7 males and 4/7 females
					Bd wt			0.5	22% body weight loss (from initial)
					Resp			0.5	Severe pulmonary lesions (emphysema; thickening, destruction, and obstruction of intra-alveolar septae; alveolar dilation; intra-alveolar edema and inflammatory cell infiltrate)

Table 2-1. Levels of Significant Exposure to Elemental Mercury – Inhalation (mg Hg/m^3)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Raffee et al. 2021									**Elemental mercury**
21	Rat (SD) 7 M, 7 F	21 days 2 hours/day (WB)	0, 0.5	LE, CS, BW, BC, GN, HP	Bd wt			0.5	15% body weight loss (from initial)
					Resp			0.5	Severe pulmonary lesions (emphysema; thickening, destruction, and obstruction of intra-alveolar septae; alveolar dilation; intra-alveolar edema and inflammatory cell infiltrate)
Sørensen et al. 2000									**Elemental mercury**
22	Rat (Wistar) 12 M	8 weeks 4–5 days/week 5 hours/day (WB)	0, 0.5	CS, BW, HP	Bd wt		0.5		17% decrease in body weight gain
					Neuro		0.5		Irritability, aggressiveness; loss of Purkinje and granular cells in cerebellum
Yahyazedeh et al. 2017									**Elemental mercury**
23	Rat (Wistar) 6 F	45 days 24 hours/day (WB)	0, 1	HP	Hepatic			1	Extensive hepatocyte degeneration; enlarged blood vessels, dilated sinusoids, increased perivascular connective tissue; increased liver volume; increased number and density of binucleated hepatocytes
Warfvinge et al. 1995									**Elemental mercury**
24	Mouse (SJL/N) 10–14 F	10 weeks 5 days/week 0.5–19 hours/day (WB)	TWA: 0, 0.01, 0.03, 0.06, 0.08, 0.1, 0.4	BC, BI, IX	Immuno	0.01	0.03		Serum antinucleolar antibodies at ≥0.03 mg Hg/m^3; increased serum immunoglobins and renal immune complex deposits at ≥0.06 mg Hg/m^3
[Autoimmune susceptible mouse strain; TWA doses were calculated due to varying daily exposure duration]									

Table 2-1. Levels of Significant Exposure to Elemental Mercury – Inhalation (mg Hg/m^3)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Yoshida et al. 2011									**Elemental mercury**
25	Mouse (C57BL/6) NS F	19 days GDs 0–18 6 hours/day (WB)	0, 0.03	DX	Develop[b]	0.03			
[Motor activity, learning, and memory assessed at PND 56]									
Yoshida et al. 2013									**Elemental mercury**
26	Mouse (C57BL/6) 6 F	20 days PNDs 1–20 24 hours/day (WB)	0, 0.057	DX	Develop[b]	0.057			
[Motor activity, learning, and memory assessed at 3 and 15 months]									
Yoshida et al. 2018									**Elemental mercury**
27	Mouse (C57BL/6J) 7–8 F	27 days PNDs 2–28 24 hours/day (WB)	0, 0.188	DX	Develop[b]		0.188		Decreased motor activity at PND 77
[Motor activity, learning, and memory assessed at PNDs 77–84]									
Fukuda 1971									**Elemental mercury**
28	Rabbit (NS) 6 M	13 weeks 4 days/week 6 hours/day (WB)	4.0	NX	Neuro		4		Clonus and tremors after 11 weeks, exaggerated reflexes

Table 2-1. Levels of Significant Exposure to Elemental Mercury – Inhalation (mg Hg/m^3)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
CHRONIC EXPOSURE									
Bast-Pettersen et al. 2005; Boogaard et al. 1996; Chapman et al. 1990; Ellingsen et al. 2001; Fawer et al. 1983; Langworth et al. 1992a; Wastensson et al. 2006, 2008									**Elemental mercury**
29	Human 18–85 per study	Occupational	0.00457–0.00874	NX	Neuro				Tremor; weighted median of 0.00492 mg Hg/m^3 (95% LCL of 0.00284 mg Hg/m^3)[c]

[a]The number corresponds to entries in Figure 2-5; differences in levels of health effects between male and females are not indicated in Figure 2-5. Where such differences exist, only the levels of effect for the most sensitive sex are presented.
[b]The neurodevelopmental effects are discussed in Section 2.16 (Neurological).
[c]Used to derive a chronic-duration inhalation MRL of 0.0003 mg Hg/m^3 (0.3 µg Hg/m^3) for elemental mercury; based on a 95% lower confidence limit of the weighted median of 0.00284 mg Hg/m^3 from seven occupational exposure studies and divided by an uncertainty factor of 10 for human variability; see Appendix A for more detailed information regarding the MRL.

Principal studies for the MRLs

ALP = alkaline phosphatase; BC = serum (blood) chemistry; Bd wt or BW = body weight; BI = biochemical changes; CS = clinical signs; Develop = developmental; DX = developmental toxicity; F = female(s); GD = gestation day; GN = gross necropsy; HP = histopathology; Immuno = immunological; IX = immune function; LCL = lower confidence limit; LE = lethality; LOAEL = lowest-observed-adverse-effect level; M = male(s); MRL = Minimal Risk Level; N = nose-only; Neuro = neurological; NOAEL = no-observed-adverse-effect level; NS = not specified; NX = neurological function; OW = organ weight; PND = postnatal day; Repro = reproductive; Resp = respiratory; RX = reproductive function; SLOAEL = serious lowest-observed-adverse-effect level; TWA = time-weighted average; UR = urinalysis; WB = whole body

Figure 2-5. Levels of Significant Exposure to Elemental Mercury – Inhalation
Acute (≤14 days)

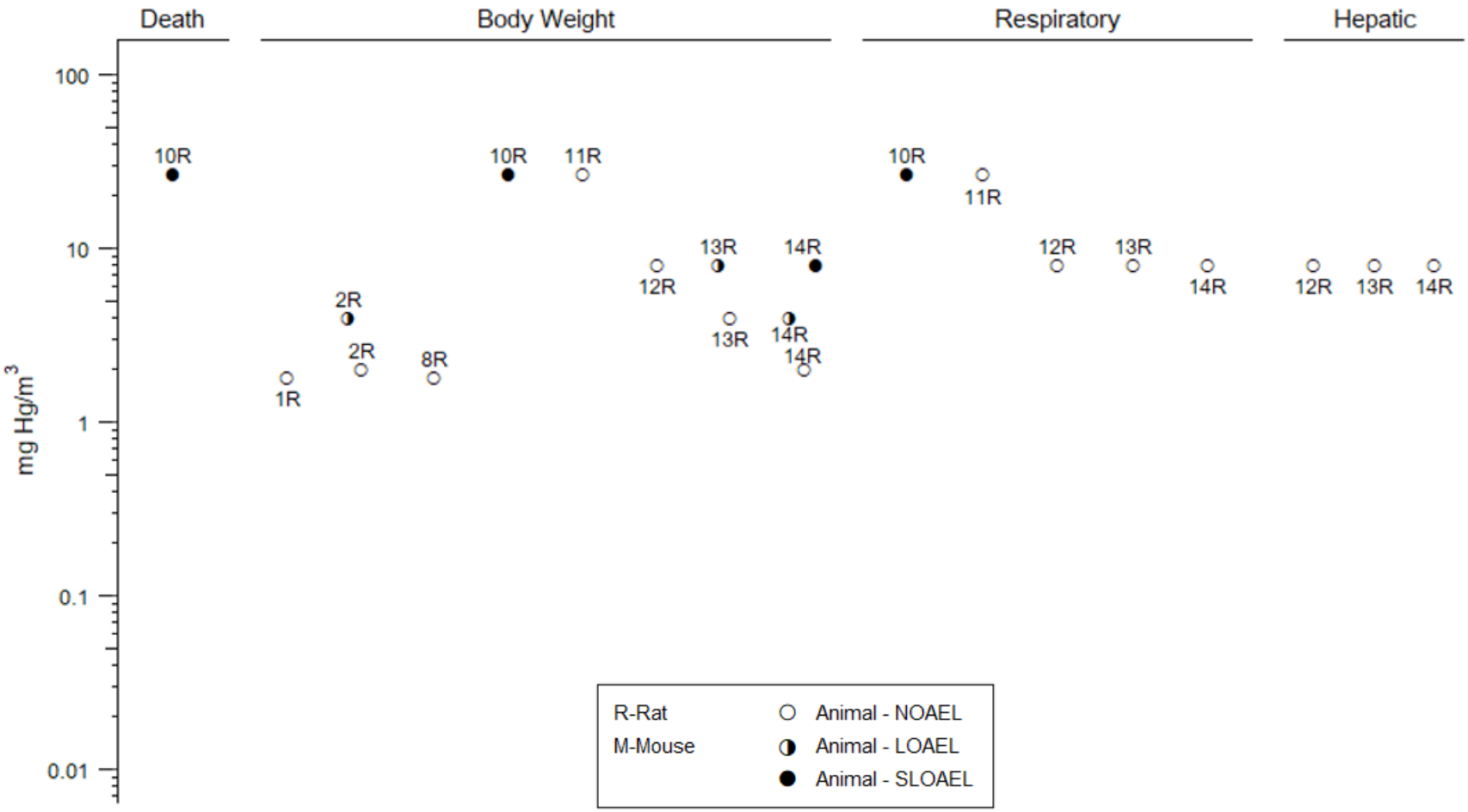


Figure 2-5. Levels of Significant Exposure to Elemental Mercury – Inhalation
Acute (≤14 days)

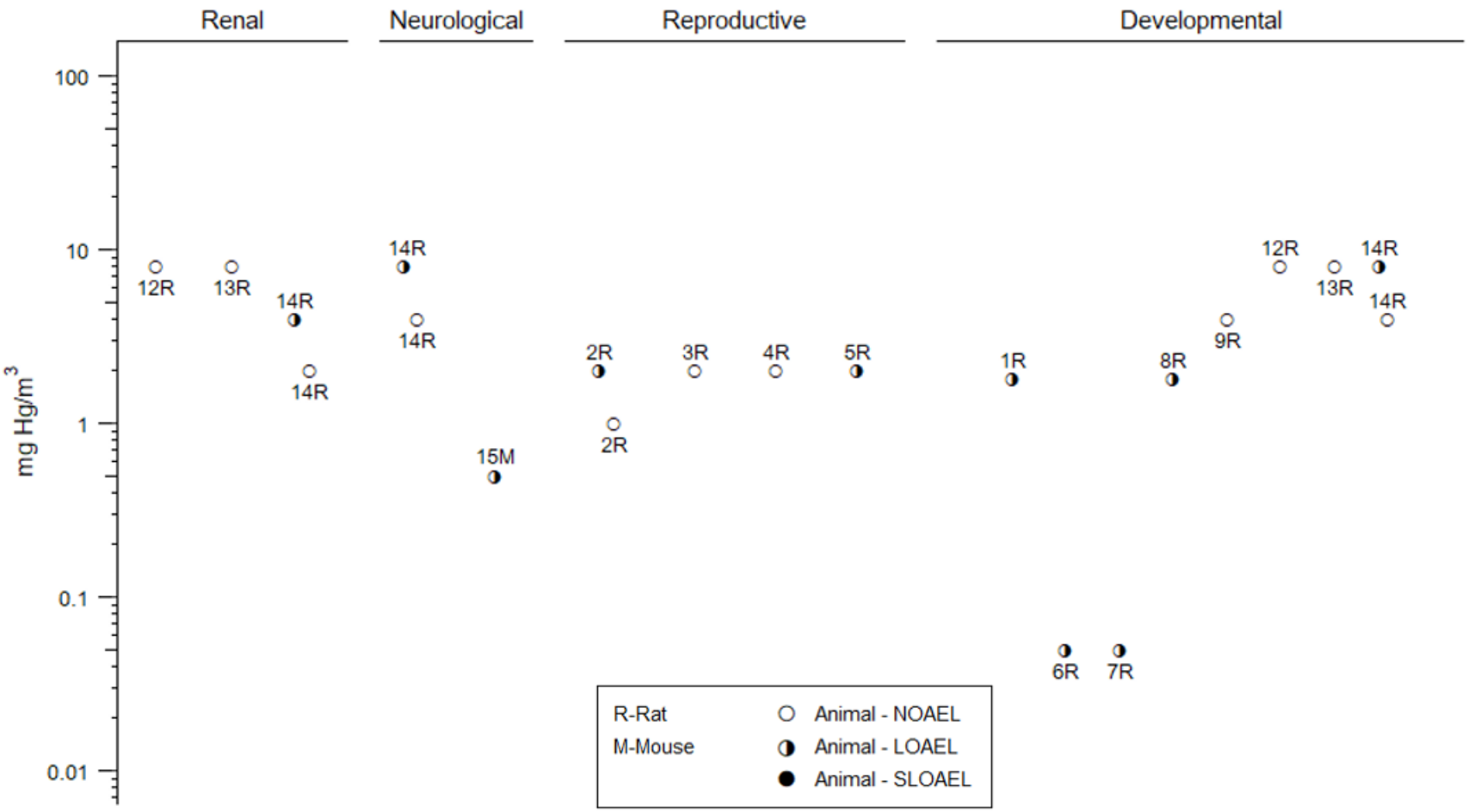


Figure 2-5. Levels of Significant Exposure to Elemental Mercury – Inhalation
Intermediate (15–364 days)

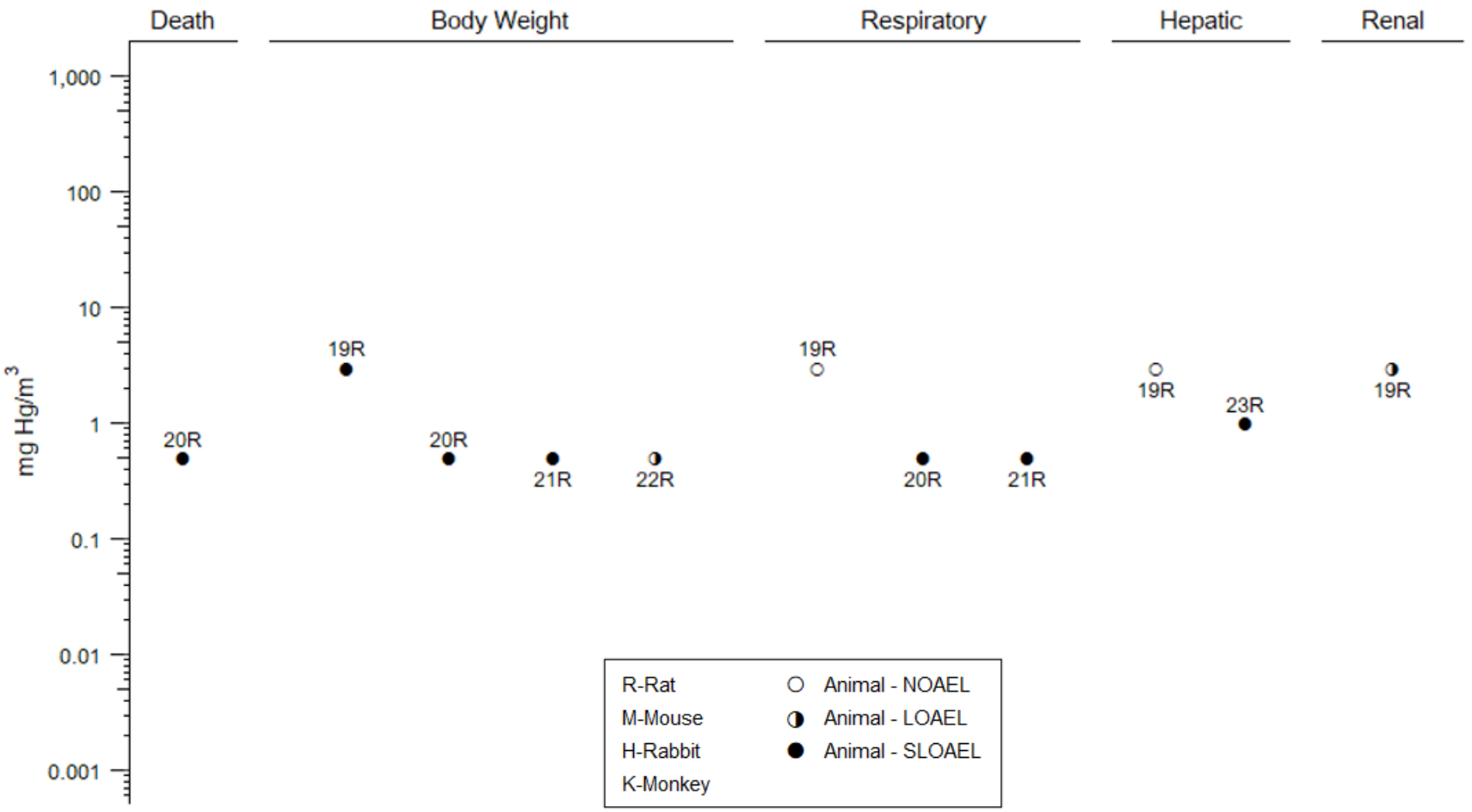


Figure 2-5. Levels of Significant Exposure to Elemental Mercury – Inhalation
Intermediate (15–364 days)

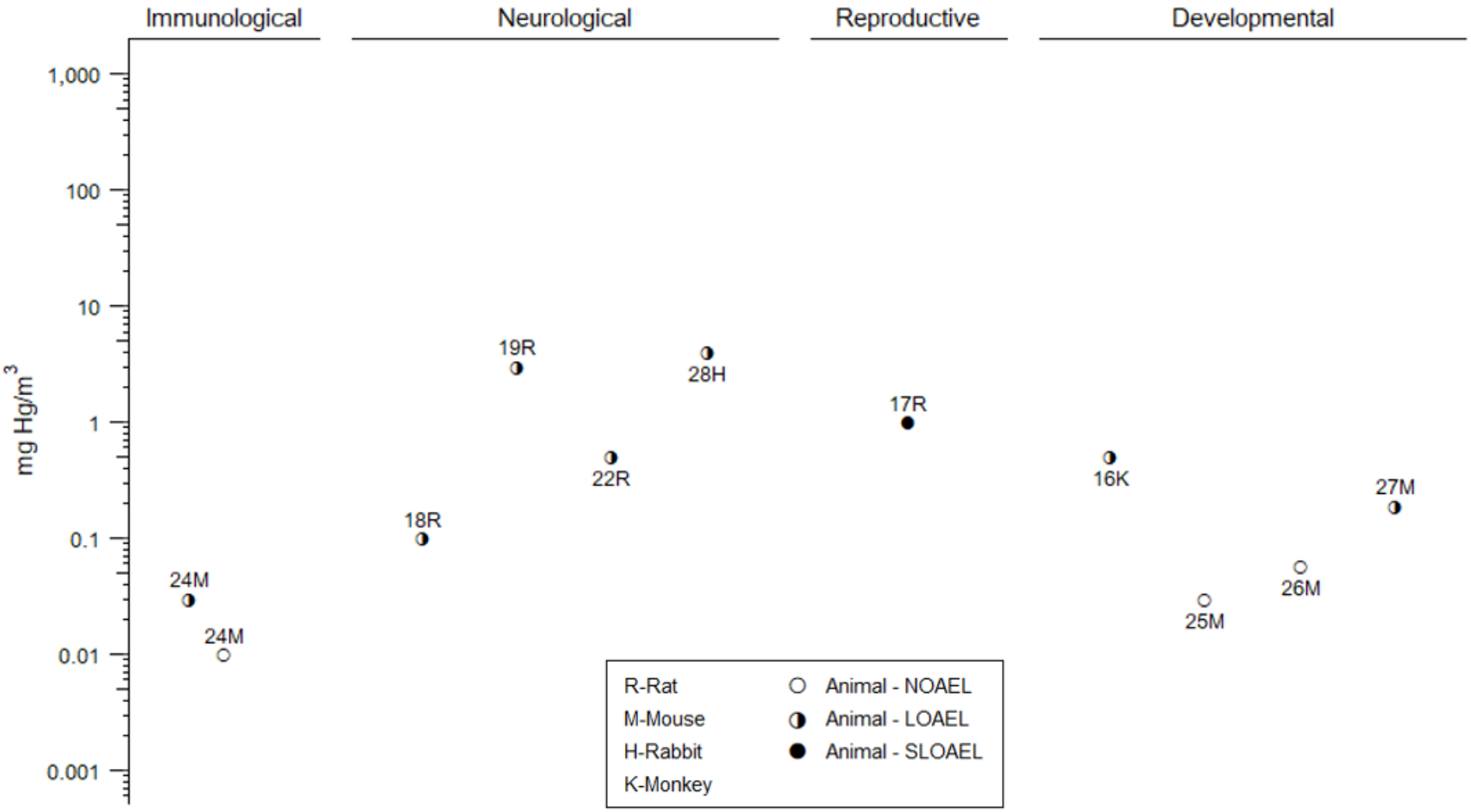


Figure 2-5. Levels of Significant Exposure to Elemental Mercury – Inhalation
Chronic (≥365 days)

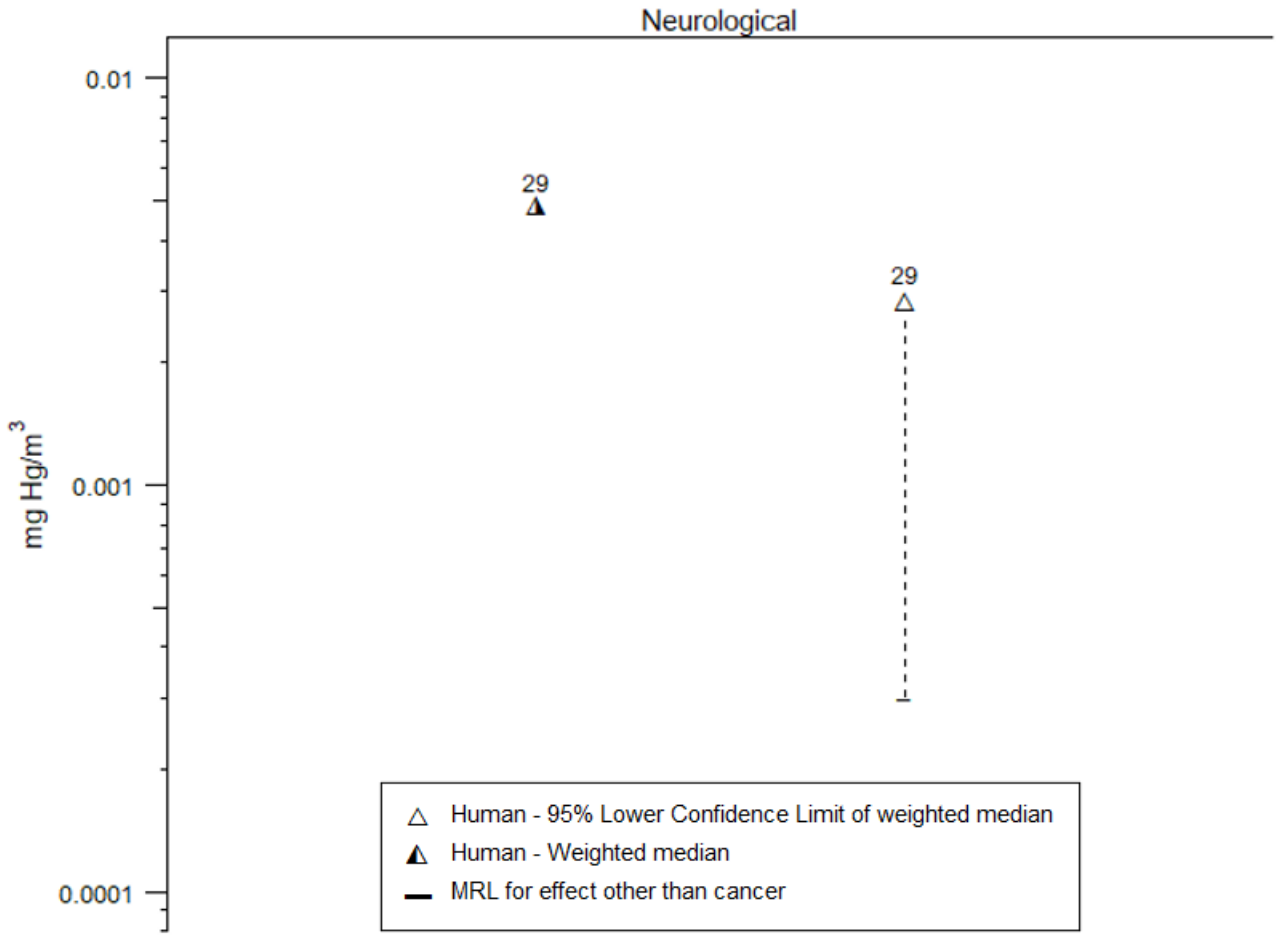


Table 2-2. Levels of Significant Exposure to Mercuric Oxide – Inhalation (mg Hg/m^3)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
INTERMEDIATE EXPOSURE									
Altunkaynak et al. 2016									**Mercuric oxide**
1	Rat (Wistar) 6 F	45 days 24 hours/day (WB)	0, 0.9	HP	Repro		0.9		38% reduction in ovary volume, 33–50% decrease in ovarian follicles, histopathological changes in ovaries
Altunkaynak et al. 2019									**Mercuric oxide**
2	Rat (Wistar) 6 F	45 days 9 hours/day (WB)	0, 1	HP	Neuro		1		Decreased cerebellar volume and cerebellar damage (gliosis, vacuolization, loss of Purkinje cells)

[a]The number corresponds to entries in Figure 2-6.

F = female(s); HP = histopathology; LOAEL = lowest-observed-adverse-effect level; Neuro = neurological; NOAEL = no-observed-adverse-effect level; Repro = reproductive; WB = whole body

Figure 2-6. Levels of Significant Exposure to Mercuric Oxide – Inhalation
Intermediate (15–364 days)

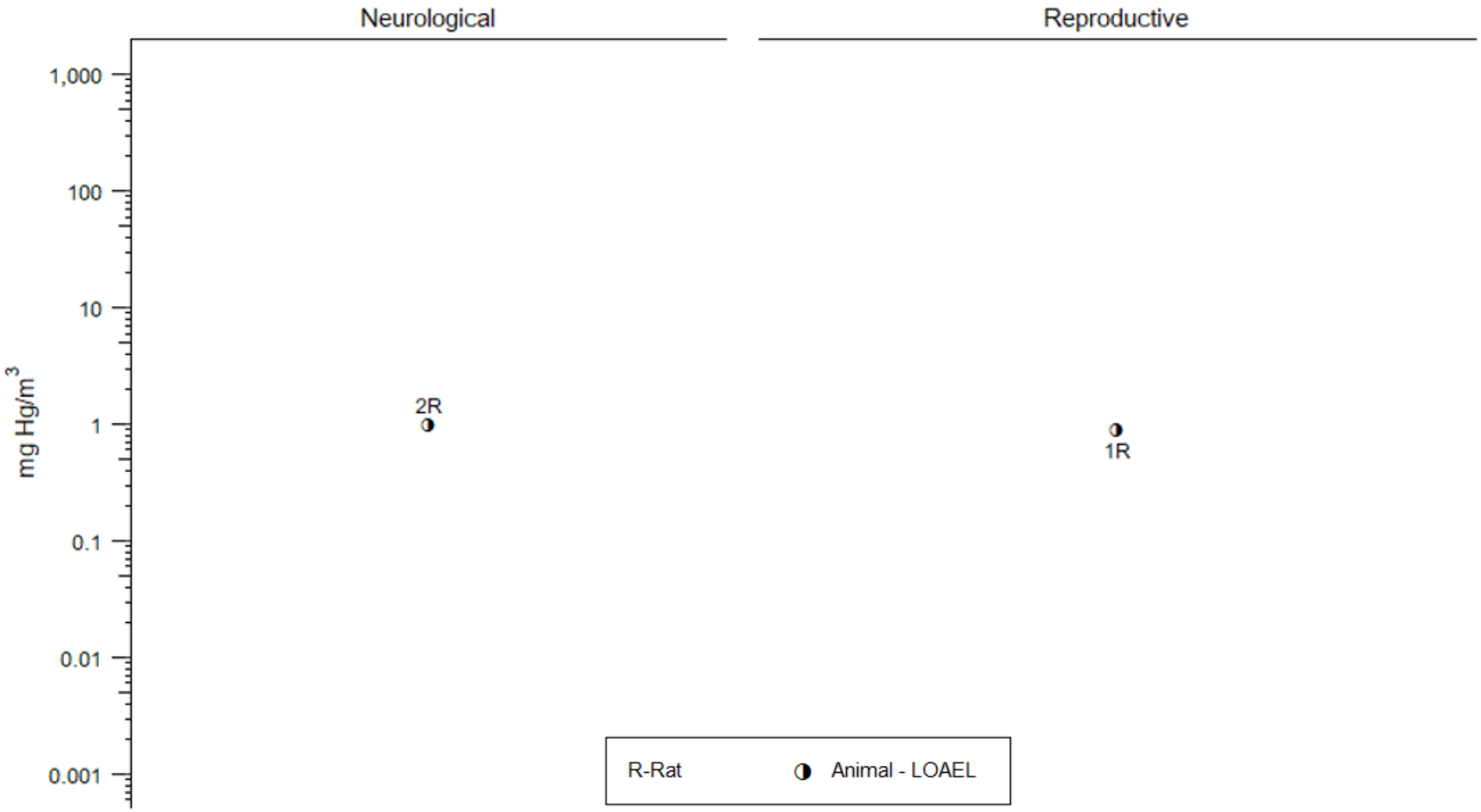


Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
ACUTE EXPOSURE									
Albasher et al. 2020									**Mercuric chloride**
1	Rat (Wistar albino) 7 M	7 days (W)	0, 0.3	BC, HP	Repro		0.3		24% decreased serum testosterone; histopathological changes in seminiferous tubules (vacuolation, degeneration of spermatogenic cells, detachment of spermatogenic cells from the basement membrane)
Boujbiha et al. 2009									**Mercuric chloride**
2	Rat (Wistar) 6 M	3 or 7 days (W)	0, 3, 6	BW, FI, WI, BC, BI, OW, HP, RX	Repro		3		Decreased sperm number and motility; non-monotonic changes in serum testosterone
Chang and Hartmann 1972									**Mercuric chloride**
3	Rat (Holtzman) 4 M	1–2 weeks (G)	0, 0.7	CS, BW, HP	Bd wt	0.7			
					Neuro		0.7		Ultrastructural changes in dorsal root ganglia and cerebellum
Chuu et al. 2007									**Mercuric sulfide**
4	Rat (Sprague-Dawley) 6 M	5 days (GW)	0, 860	NX	Neuro		860		Impairment of compound muscle action potential recovery after tetany
Chuu et al. 2007									**Mercuric sulfide**
5	Rat (Sprague-Dawley) 6 M	14 days (GW)	0, 860	BW, NX	Bd wt	860			
					Neuro		860		Transient suppression of compound muscle action potentials followed by incomplete recovery after tetany

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Dieter et al. 1992; NTP 1993									**Mercuric chloride**
6	Rat (Fischer-344) 5 M, 5 F	16 days 5 day/week (GW)	0, 0.923, 1.8, 4, 7.4, 15	LE, BW, GN, OW, HP	Death			15 M	2/5 died
					Bd wt	4	7.4	15	LOAEL: 17–18% decrease in body weight gain SLOAEL: 30–41% decrease in body weight gain in both sexes, 11% decrease in body weight in females
					Gastro	15			
					Renal	1.8 F	4 F	15 F	LOAEL: ≥17% increase in relative kidney weight SLOAEL: Acute renal necrosis
						0.923 M[b]	1.8 M	7.4 M	LOAEL: ≥17% increase in relative kidney weight SLOAEL: Acute renal necrosis $BMDL_{1SD}$=0.29 mg Hg/kg/day
Goldman and Blackburn 1979									**Mercuric chloride**
7	Rat (Long-Evans) 8–12 F	6 days (GW)	0, 7.4	OF	Endocr		7.4		Increased thyroid function (accelerated release and turnover of radiolabeled iodine)
Kostial et al. 1978									**Mercuric chloride**
8	Rat (albino) 6 B	Once (G)	Six unspecified dose levels	LE	Death			25.9	LD_{50} in 2-week-old rats
Kostial et al. 1978									**Mercuric chloride**
9	Rat (albino) 6 F	Once (G)	Six unspecified dose levels	LE	Death			77.7	LD_{50} in 3-week-old rats
Kostial et al. 1978									**Mercuric chloride**
10	Rat (albino) 6 F	Once (G)	Six unspecified dose levels	LE	Death			68.1	LD_{50} in 6-week-old rats

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Kostial et al. 1978									**Mercuric chloride**
11	Rat (albino) 6 F	Once (G)	Six unspecified dose levels	LE	Death			37	LD_{50} in 18-week-old rats
Kostial et al. 1978									**Mercuric chloride**
12	Rat (albino) 6 F	Once (G)	Six unspecified dose levels	LE	Death			37	LD50 in 54-week-old rats
Lecavalier et al. 1994									**Mercuric chloride**
13	Rat (Sprague-Dawley) 10 F	Once (GO)	0, 7.4, 9.24	LE, CS, BW, FI, BC, HE, OW, GN, HP	Bd wt	9.24			
					Resp	9.24			
					Cardio	9.24			
					Gastro	9.24			
					Hemato		7.4		9–10% decrease in erythrocyte count, hemoglobin, and hematocrit
					Musc/skel	9.24			
					Hepatic	9.24			
					Renal		7.4		Mild histopathological changes (protein casts, cellular casts, interstitial sclerosis)
					Dermal	9.24			
					Ocular	9.24			
					Endocr	9.24			
					Immuno	9.24			
					Neuro	9.24			
					Repro	9.24			
Mahour and Saxena 2009									**Mercuric chloride**
14	Rat (albino) 5–20 NS	Once NS	0, 0.684	HE	Hemato		0.684		Increased bleeding and clotting time; 10% increase in WBC count

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Mahour and Saxena 2009									**Mercuric chloride**
15	Rat (albino) 5–20 NS	7 or 14 days NS	0, 0.033	HE	Hemato		0.033		Increased bleeding and clotting time; 7–9% decrease in hemoglobin; 10–21% increase in ESR; 13% increase in WBC count (14 days only)
Papp et al. 2005									**Mercuric chloride**
16	Rat (Wistar) 8 F	11 days GDs 5–15 (GW)	0, 0.4, 0.8, 1.6	DX	Develop	1.6[c]			
[Neurophysiological recordings in male offspring at PND 84]									
Sun et al. 2018									**Mercuric chloride**
17	Rat (Sprague-Dawley) 10–15 M	2 weeks (G)	0, 3.10, 6.3, 12.6	LE, CS, BW, HP, NX	Death			12.6	Death of 4/15 animals
					Neuro			3.1	Limb paralysis in 2/10 animals; hypersensitivity to thermal and mechanical pain
Sun et al. 2018									**Mercuric chloride**
18	Rat (Sprague-Dawley) 10–15 M	1 week (G)	0, 3.10, 6.3, 12.6	LE, CS, BW, HP, NX	Immuno	3.1	6.3		Increased density of Langerhans cells (inflammatory cells) in hind paw skin samples
					Neuro	3.1	6.3		Decreased density of intraepidermal nerve fibers in hind paw skin samples
Chen et al. 2012									**Mercuric chloride**
19	Mouse (ICR) 16 M	2 weeks (GW)	0, 3.7	BC, BI, HP	Endocr		3.7		~17% increase in baseline plasma insulin and ~60% decrease in fasting plasma insulin; ~15% decrease in blood glucose and impaired glucose tolerance; apoptosis in pancreatic islet cells

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Chuu et al. 2001a									**Mercuric sulfide**
20	Mouse (NS) 8–10 M	7 days (G)	0, 86, 860	NX	Neuro	86	860		Reversible hearing loss
[Vehicle was saline]									
Hultman and Johansson 1991									**Mercuric chloride**
21	Mouse (DBA/2) 5 F	2 weeks (W)	0, 0.7	IX	Immuno	0.7			
[Autoimmune resistant mice]									
Hultman and Johansson 1991									**Mercuric chloride**
22	Mouse (SJL/N) 5 F	2 weeks (W)	0, 0.7	IX	Immuno		0.7		Increase in lymphoproliferation in response to T- and B-cell mitogens
[Autoimmune susceptible mouse strain]									
Jalili et al. 2020b									**Mercuric chloride**
23	Mouse (BALB/c) 6 M	14 days (IN)	0, 0.061	BW, BC, OW, HP	Bd wt			0.061	29% decrease
					Renal		0.061		Increased BUN and creatinine; renal lesions (renal tubular casts, intracellular vacuolization, renal vascular congestion, tubular detachment and dilation)
Kim et al. 2003									**Mercuric chloride**
24	Mouse (BALB/c) 4 M	14 days (W)	0, 0.06, 0.31, 1.39, 4.81	BW, BC, FI, WI, HE, OW	Hemato		0.06		11–19% decrease in RBC count at 0.06 mg Hg/kg/day; 91% increase in WBC count at 4.81 mg Hg/kg/day
					Hepatic	4.81			
					Renal	0.31	1.39		11% increase in relative kidney weight

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
					Immuno	0.06	0.31		Decreased T-lymphocytes, T-helper, and T-suppressor in spleen; decreased T-suppressor cells in thymus at ≥1.39 mg Hg/kg/day
Nielsen et al. 1991									**Mercuric chloride**
25	Mouse (NMRI) 10–20 F	Once (GW)	0, 5, 10, 20, 40	BI, HP	Renal	5	10	20	LOAEL: Regeneration of proximal tubule SLOAEL: Proximal tubule necrosis
NTP 1993									**Mercuric chloride**
26	Mouse (B6C3F1) 5 M, 5 F	16 days 5 day/week (GW)	0, 4, 7.4, 15, 30, 59	LE, BW, GN, OW, HP	Death			59	5/5 males and 4/5 females died within 2–4 days
					Bd wt	30			
					Gastro	30	59		Inflammation of forestomach; necrosis of forestomach and glandular stomach
					Renal		4		≥19% increase in relative kidney weight
								59 F	Acute renal necrosis
								30 M	Acute renal necrosis
					Immuno	30			
Sin et al. 1990									**Mercuric sulfide**
27	Mouse (Swiss albino) 6 F	10 days (GW)	0, 6	BC	Endocr		6		59% decrease in serum T3
Sin et al. 1990									**Mercuric chloride**
28	Mouse Swiss albino 6 F	10 days 1 times/day (GW)	0, 6	BC	Endocr		6		70% decrease in serum T3; 42% decrease in serum T4

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Zhao et al. 2021									**Mercuric chloride**
29	Mouse (Kunming) 6 F	3 days (W)	0, 24	BW, HP	Bd wt		24		17% decrease in body weight
					Gastro		24		Histopathological changes in cecum (atrophy of glands, mild-to-moderate necrosis; decreased goblet cells)
Gale 1974									**Mercuric acetate**
30	Hamster Golden 3–10 F	Once GD 8 (GW)	0, 2.5, 5, 15.8, 22.1, 31.5, 47.3, 63	DX	Develop	2.5	5	15.8	LOAEL: Decreased crown-rump length SLOAEL: Increased abnormal embryos and resorption
Chuu et al. 2001b									**Mercuric sulfide**
31	Guinea pig (Hartley) 14–90 F	7 days (G)	0, 8.6, 86, 860	HP, NX	Neuro	8.6	86		Abnormal vestibular ocular reflex, impaired equilibrium at ≥86 mg Hg/kg/day; Purkinje cell loss in cerebellum at 860 mg Hg/kg/day
[Vehicle was saline]									
Chuu et al. 2001b									**Mercuric sulfide**
32	Guinea pig (Hartley) 8–12 F	14 days (G)	0, 86	NX	Neuro		86		Abnormal vestibular ocular reflex
[Vehicle was saline]									
INTERMEDIATE EXPOSURE									
Agrawal and Chansouria 1989									**Mercuric chloride**
33	Rat (albino) 5 M	60 days (W)	0, 2.9, 5.8, 11.8	CS, BC, BI, OW	Endocr		2.9		31% increase in relative adrenal weight, 146% increase in adrenal corticosterone; nonmonotonic changes in plasma corticosterone
Agrawal and Chansouria 1989									**Mercuric chloride**
34	Rat (albino) 5 M	120 days (W)	0, 2.9, 5.8, 11.8	CS, BC, BI, OW	Endocr		2.9		19% increase in relative adrenal weight, 87 and 218% increase in plasma and adrenal corticosterone, respectively

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Agrawal and Chansouria 1989									**Mercuric chloride**
35	Rat (albino) 5 M	180 days (W)	0, 2.9, 5.8, 11.8	CS, BC, BI, OW	Endocr		2.9		14% increase in relative adrenal gland weight
Agrawal et al. 2014									**Mercuric chloride**
36	Rat (Wistar) 5 M	6 months 7 days/week (NS)	0, 0.4	BW, BC, BI, HE	Bd wt	0.4			
					Hemato		0.4		140% increase in WBC
					Hepatic		0.4		21–56% increase in AST, ALP, and LDH
Apaydin et al. 2016									**Mercuric chloride**
37	Rat (Wistar) 6 NS	28 days (GW)	0, 0.015	BC, BI, HP	Renal		0.015[d]		Altered serum chemistry (increased urea, uric acid, creatinine); tubular dilation and glomerular lobulation
Atkinson et al. 2001									**Mercuric chloride**
38	Rat (Sprague-Dawley) 15–25 M, 15–25 F	79–81 days/ generation 2 generations (GW)	M: 0, 0.37, 0.74, 1.31 F: 0, 0.55, 1.11, 1.98	CS, BW, FI, GN, OW, RX, DX	Death			1.98 F	50% mortality in F0 females
					Bd wt	0.55 F		1.11 F	Female: transient F0 body weight decreases up to ~21% during gestation at ≥1.11 mg Hg/kg/day
							0.37 M		Male: 16% decreased in adult F1 body weight at 0.37 mg Hg/kg/day; decreased F0 body weight at 1.31 mg Hg/kg/day
					Hepatic		0.55 F		>20% decrease in relative liver weight in F0 females
						1.31 M			
					Renal	0.55 F	1.11 F		>10% increase in relative kidney weights in F1 females
							0.37 M		>10% increase in relative kidney weights in F0 males
					Endocr	1.98 F			
						1.31 M			

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
					Repro		0.55 F	1.11 F	LOAEL: Decreased F0 fertility and implant efficiency, decreased F1 live birth index SLOAEL: ≥50% reduction in F0 fertility with reduced F1 implant efficiency, F2 live birth index
							0.37 M	0.74 M	LOAEL: Decreased F0 fertility SLOAEL: ≥50% reduction in F0 fertility, F0 relative seminal vesicle weight
					Develop			0.55	~20% reduction in F1 pup body weight at 0.55 mg Hg/kg/day; reduced PND 4 survival for F1 and F2 pups at 1.98 and 1.11 mg Hg/kg/day, respectively
Behzadfar et al. 2020									**Mercuric chloride**
39	Rat (Albino-Wistar) 7 M	21 days (GW)	0, 0.4, 0.8, 1.6	NX	Neuro		0.4		Impaired spatial learning
Bittencourt et al. 2021									**Mercuric chloride**
40	Rat (Wistar) 10–27 M	45 days (GW)	0, 0.277	LE, BW, HP, NX	Bd wt	0.277			
					Neuro		0.277		Decreased motor coordination, decreased cerebellar Purkinje cell density, neuronal apoptosis in cerebellum
Boscolo et al. 1989									**Mercuric chloride**
41	Rat (Wistar) 8 M	350 days (W)	0, 6, 24	CS, HP, OF	Cardio		6		Increased aortic blood pressure; positive cardiac inotropism; decreased baroreceptor reflex sensitivity
					Renal		6		Tubular degeneration and membranous glomerulonephritis

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Boscolo et al. 1989; Carmignani et al. 1989									**Mercuric chloride**
42	Rat (Sprague-Dawley) 8 M	350 days (W)	0, 6	CS, HP, OF	Cardio		6		Increased aortic blood pressure; positive cardiac inotropism; decreased baroreceptor reflex sensitivity
					Renal		6		Tubular degeneration and desquamation
Boujbiha et al. 2009, 2011									**Mercuric chloride**
43	Rat (Wistar) 6 M	15–90 days premating (W)	0, 3, 6	BW, FI, WI, BC, BI, OW, HP, RX	Repro		3	6	LOAEL: >10% increase in relative testes weight, sperm impairments, increased testicular testosterone, decreased serum and testicular estradiol, histopathological changes in testes, 36% decrease in viable embryos SLOAEL: 50% decrease in mating index and 76% decrease in viable embryos
[Mated to untreated females]									
Boujbiha et al. 2012									**Mercuric chloride**
44	Rat (Wistar) 6 M	90 days (W)	0, 5.5, 11	HE	Hemato	5.5	11		10% decrease in RBC count and hemoglobin, 7% decrease in hematocrit
Carmignani and Boscolo 1984									**Mercuric chloride**
45	Rat (Sprague-Dawley) 10 M	320 days (W)	0, 6	OF	Cardio		6		Positive cardiac inotropism, reduced baroreflex sensitivity
Carmignani and Boscolo 1984									**Mercuric chloride**
46	Rat (Sprague-Dawley) 10 M	350 days (W)	0, 6	OF	Cardio		6		Increased systolic and diastolic blood pressure, positive cardiac inotropism, reduced baroreflex sensitivity

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Carmignani et al. 1992									**Mercuric chloride**
47	Rat (Wistar) 8 M	180 days (W)	0, 24	CS, BW, HP, OF	Cardio		24		Increased systolic and diastolic blood pressure
					Renal		24		Mesangial proliferative glomerulonephritis
Chang and Hartmann 1972									**Mercuric chloride**
48	Rat (Holtzman) 4 M	11 weeks (G)	0, 0.7	CS, BW, HP	Bd wt			0.7	Body weight loss
					Neuro			0.7	Hind-limb crossing, ataxia, tremor; cellular degeneration and ultrastructural changes in dorsal root ganglia and cerebellum
Chehimi et al. 2012									**Mercuric chloride**
49	Rat (Wistar) 10 F	21 days GDs 1–21 (W)	0, 6.1, 9.6	WI, RX, DX	Repro		6.1		Reduced maternal care
					Develop[c]		6.1	9.6	LOAEL: 14% decrease in body weight, impaired/delayed sensorimotor development, decreased anxiety at PND 63 SLOAEL: 16% pup mortality and >20% decrease in body weight
Corrêa et al. 2020									**Mercuric chloride**
50	Rat (Wistar) 25 M	45 days (GW)	0, 0.277	BW, HP	Neuro			0.277	Loss of motor neurons and axonal damage in the spinal cord
Dieter et al. 1992; NTP 1993									**Mercuric chloride**
51	Rat (Fischer-344) 10 M, 10 F	26 weeks 5 days/week (GW)	0, 0.230, 0.462, 0.923, 1.8, 4	BW, BC, GN, OW, HP	Bd wt	4			
					Resp	4			
					Cardio	4			
					Gastro	4			
					Musc/skel	4			
					Hepatic	4			

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
					Renal		0.23		8–10% increase in relative kidney weight at 0.23 mg Hg/kg/day; increased severity of nephropathy in males at ≥0.923 mg Hg/kg/day; minimal nephropathy in females at 4 mg Hg/kg/day
					Endocr	4			
					Immuno	4			
					Neuro	4			
					Repro	4			
dos Santos Chemelo et al. 2021									**Mercuric chloride**
52	Rat (Wistar) 10 M	45 days (GW)	0, 0.277	BW, HE	Bd wt	0.277			
					Hemato		0.277		Increased leukocytes and decreased platelets
Galiciolli et al. 2022									**Mercuric chloride**
53	Rat (Wistar) 7–9 F	42 days GD 0–PND 21 (W)	0, 0.019, 0.094	BW, FI, WI, BC, BI, OW, DX	Bd wt	0.094			
					Renal		0.019		Increased absolute and relative kidney weight
					Develop	0.094			
Goldman and Blackburn 1979									**Mercuric chloride**
54	Rat (Long-Evans) 8–12 F	40 days (G)	0, 9.4	BW, OW, OF	Bd wt	9.4			
					Endocr		9.4		28% increase in absolute thyroid weight, increased thyroid activity (increased uptake of radiolabeled iodine), decreased thyroid T3 synthesis

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Goldman and Blackburn 1979									**Mercuric chloride**
55	Rat (Sprague-Dawley) 8–12 F	3 months (F)	0, 2.2	CS, BW, OF	Bd wt			2.2	37% decrease in final body weight
					Resp		2.2		Labored breathing
					Endocr		2.2		Impaired thyroid function (decreased uptake, release, and turnover of radiolabeled iodine)
					Neuro			2.2	Inactivity; abnormal gait; hind-limb spread
Heath et al. 2009									**Mercuric chloride**
56	Rat (Sprague-Dawley) 20 F	60 days (premating) (G)	0, 0.7, 1.5	CS, BW, BC, GN, OW, RX	Bd wt	1.5			
					Repro	0.7	1.5		15% decrease in implantation, increased dead/resorbed fetuses, 18% decrease in serum progesterone, 19% increase in pituitary LH
[Vehicle was 0.15% nitric acid]									
Heath et al. 2012									**Mercuric chloride**
57	Rat (Sprague-Dawley) 10–11 M	60 days Premating (G)	0, 0.7, 1.5	CS, BW, BC, RX	Bd wt	0.7	1.5		12% decrease in body weight
					Repro		0.7		30% decrease in testicular testosterone at 0.7 mg Hg/kg/day; 10% decrease in epididymis sperm counts; increased latency to impregnation and decreased fertility index at 1.5 mg Hg/kg/day
[Vehicle was 0.15% nitric acid]									
Ismail and El-Meligy 2021									**Mercuric chloride**
58	Rat (Albino) 10 F	21 days GDs 1–21 (GW)	0, 3	RX, DX	Repro			3	58% reduction in the number of fetuses/litter
					Develop			3	17% decrease in fetal body weight; severe microscopic and ultrastructural changes in fetal lungs (e.g., collapsed alveoli, cellular degeneration)

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Janse van Rensburg et al. 2020									**Mercuric chloride**
59	Rat (SD) 6 M	28 days (GW)	0, 0.13	HE	Hemato		0.13		Morphological alterations in erythrocytes, platelets, and fibrin networks
Jindal et al. 2011									**Mercuric chloride**
60	Rat (Wistar) 10 B	1 month (W)	0, 0.12	OF	Cardio		0.12		Altered left ventricular function; impaired baroreflex
Jonker et al. 1993									**Mercuric chloride**
61	Rat (Wistar) 5–10 M, 5–10 F	4 weeks (F)	M: 0, 5.8, 11.4, 20.9; F: 0, 6.1, 11.9, 23.6	BW, FI, WI, BC, HE, UR, OW, HP	Bd wt	6.1 F	11.9 F	23.6 F	LOAEL: 15% decrease in final body weight SLOAEL: 34% decrease in terminal body weight
						11.4 M		20.9 M	34% decrease in final body weight
					Hepatic	6.1 F	11.9 F		Increased serum ALP; increased AST at 23.6 mg Hg/kg/day
						11.4 M	20.9 M		Increased serum ALT and AST
					Renal		6.1 F		Nephrosis and proteinaceous casts, 16% increase in relative kidney weight
							5.8 M		Nephrosis and proteinaceous casts, 13% increase in relative kidney weight; ketones in urine
					Endocr	23.6 F			
						20.9 M			
Jonker et al. 1993									**Mercuric chloride**
62	Rat (Wistar) 5–10 M, 5–10 F	4 weeks (F)	M: 0, 0.61, 5.1; F: 0, 0.76, 5.5	BW, FI, WI, BC, UR, HE, OW, HP	Bd wt	5.5 F			
						5.1 M			
					Hemato	5.5 F			
						5.1 M			
					Renal		0.76 F		13% increase in relative kidney weight

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
						0.61 M	5.1 M		17% increase in relative kidney weight; ketones in urine and basophilic tubules in outer cortex
					Endocr	5.5 F 5.1 M			
Koopsamy Naidoo et al. 2019									**Mercuric chloride**
63	Rat (SD) 6 M	28 days (GW)	0, 0.848	HP	Resp		0.848		Histopathological and ultrastructural changes in lung tissue
Mahour and Saxena 2009									**Mercuric chloride**
64	Rat (albino) 5–20 NS	21 days NS	0, 0.033	HE	Hemato		0.033		13% decrease in RBC count, 5% decrease in hemoglobin, 17% increase in WBC count; 41% increase in ESR
Nunes et al. 2022									**Mercuric chloride**
65	Rat (Wistar) 10 M	45 days (GW)	0, 0.277	BW, HP	Bd wt	0.277			
					Musc/skel		0.277		Altered alveolar bone structure, increased trabecular volume with decreased trabecular space
Oliveira et al. 2012									**Mercuric chloride**
66	Rat (Wistar) 3–7 F	21 days GDs 0–20 (W)	0, 0.0002, 0.0004, 0.0085, 0.0301	BW, BC, OW, DX	Renal Develop	0.0301 0.0301			
Oliveira et al. 2016									**Mercuric chloride**
67	Rat (Wistar) 7–8 F	42 days GD 1–PND 21 (W)	0, 0.75, 3.8	DX	Develop[c]	3.8			
[Offspring motor coordination assessed PNDs 17–20]									

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Papp et al. 2005									**Mercuric chloride**
68	Rat (Wistar) 8 M	94 days GDs 5–15 and PNDs 2–28 (via dam) PNDs 29–84 (direct; 5 days/week) (GW)	0, 0.4, 0.8, 1.6	DX	Develop[c]		0.4		Decreased peripheral sensory nerve conduction velocity at PND 84 at ≥0.4 mg Hg/kg/day; decreased spontaneous sensory cortex potentials at ≥0.8 mg Hg/kg/day
Papp et al. 2005									**Mercuric chloride**
69	Rat (Wistar) 8 F	38 days GDs 5–15 and PNDs 2–28 (GW)	0, 0.4, 0.8, 1.6	DX	Develop[c]	1.6			
[Neurophysiological recordings in male offspring at PND 84]									
Perry and Erlanger 1974									**Mercuric chloride**
70	Rat (Long-Evans) 16 F	6 months (W)	0, 0.33, 0.66, 1.3, 3.3	OF	Cardio	3.3			
Raeeszadeh et al. 2021									**Mercuric chloride**
71	Rat (Wistar) 6 M	30 days (GW)	0, 1.5	BW, BC, HP	Bd wt		1.5		15% decrease in body weight accounting for differences in group start weights
					Hepatic			1.5	SLOAEL: Hepatic necrosis, hemorrhage, inflammatory cell inflammation; increased serum ALT (2.5-fold) and AST (2.3-fold)
					Renal			1.5	SLOAEL: Acute tubular necrosis, interstitial nephritis, glomerular damage and hyaline casts; increased serum urea, creatinine, and uric acid

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Ramalingam et al. 2003									**Mercuric chloride**
72	Rat (Wistar) 15 M	30 days (GW)	0, 0.7, 1.5	BC	Repro		0.7		Decreased serum testosterone and LH at ≥0.7 mg Hg/kg/day; decreased FSH and prolactin at 1.5 mg Hg/kg/day
Sabir et al. 2022									**Mercuric chloride**
73	Rat (NS) 5 B	30 days (IN)	0, 0.3	BC, UR, OW, OF, HP	Hepatic		0.3		Increased serum ALP (80%), ALT (102%), and bilirubin (332%)
					Renal			0.3	Relative kidney weight increased by ~50%; severe renal tubular degeneration and renal cell apoptosis; 45% reduction in glomerular filtration rate; elevated serum urea, uric acid, and creatinine; proteinuria and glucosuria
Sun et al. 2018									**Mercuric chloride**
74	Rat (Sprague-Dawley) 10–15 M	3 weeks (G)	0, 3.1, 6.3	LE, CS, BW, HP, NX	Immuno		3.1		Decreased density of skin LCs
					Neuro	6.3			
Szász et al. 2002									**Mercuric chloride**
75	Rat (Wistar) 5 F	7–8 weeks premating–PND 21 (W)	0, 0.6	CS, BW, FI, WI, RX, DX	Bd wt	0.6			
					Repro	0.6			
					Develop[c]		0.6		Increased susceptibility to seizure activity at PND 90
Takahashi et al. 2000a									**Mercuric chloride**
76	Rat (Wistar) 10 M	21 weeks (F)	0, 0.06, 0.17, 0.51, 1.7	BW, BC, UR, OW, OF	Bd wt	1.7			
					Cardio	0.51	1.7		23% increase in relative heart weight; elevated plasma angiotensin-II
					Hepatic		1.7		16% decrease in plasma HDL

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
					Renal		0.06		11% increase in relative kidney weight at 0.06 mg Hg/kg/day; elevated urinary protein at 1.7 mg Hg/kg/day
Takahashi et al. 2000b									**Mercuric chloride**
77	Rat (SHR Wistar) 18 M	12 weeks (F)	0, 0.07, 0.21, 0.72, 2.2	BW, BC, UR, OW, OF	Bd wt	2.2			
					Cardio		0.07		6–9% increase in systolic blood pressure (SBP) at 5 weeks; higher SBP but not significant at 12 weeks
					Hepatic		0.07		At 12 weeks: 18% decrease in plasma HDL; 45% decrease in plasma triglycerides
					Renal	0.72	2.2		At 12 weeks: Elevated relative kidney weight; elevated urinary amino acids and alkaline phosphatase
					Endocr	0.72	2.2		At 12 weeks: increased relative adrenal weight
[Spontaneously hypertensive rat strain]									
Teixeira et al. 2014									**Mercuric chloride**
78	Rat (Wistar) 10 M	45 days (GW)	0, 0.277	NX	Neuro		0.277		Reduced motor activity, impaired motor coordination
Teixeira et al. 2018									**Mercuric chloride**
79	Rat (Wistar) 20 M	45 days (GW)	0, 0.277	BW, BI, NX	Bd wt	0.277			
					Neuro		0.277		Impaired motor coordination and balance; apoptosis and loss of neurons and astrocytes in motor cortex
Teixeira et al. 2019									**Mercuric chloride**
80	Rat (Wistar) 10 M	45 days (GW)	0, 0.277	BW, BI, NX	Bd wt	0.277			
					Neuro		0.277		Decreased motor activity; impaired learning and memory

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Venter et al. 2020									**Mercuric chloride**
81	Rat (Sprague-Dawley) 6 M	28 days (GW)	0, 0.847	BW, HP	Bd wt	0.847			
					Immuno			0.847	Severe necrosis and decreased cellularity in spleen
Wildemann et al. 2015a									**Mercuric chloride**
82	Rat (Wistar) 5–6 M	4 weeks (W)	0, 0.005, 0.010, 0.021, 0.037, 0.244, 1.18, 2.07, 5.91	LE, BW, OW, OF	Death			5.91	100% mortality
					Bd wt	2.07		5.91	Weight loss
					Cardio	5.91			
					Renal	0.037	0.244		15% increase in relative kidney weight
Wildemann et al. 2015b									**Mercuric chloride**
83	Rat (Wistar) 5–6 M	4 weeks (W)	0, 0.038, 0.244	BW, OW, OF	Bd wt	0.244			
					Cardio	0.244			
Wildemann et al. 2016									**Mercuric chloride**
84	Rat (Wistar) 5–6 M	4 weeks (W)	0, 0.264, 2.955	BC, BI, UR, OF	Cardio	2.955			
					Hepatic	2.955			
					Renal	2.955			
Amirhosseini et al. 2021									**Mercuric chloride**
85	Mouse (Swiss-Webster) 8 F	5 weeks (W)	0, 0.148	IX	Immuno		0.148		Induced serum (IgG) antinucleolar antibodies; increased serum IgG; renal and spleen immune complex deposits
Chen et al. 2012									**Mercuric chloride**
86	Mouse (ICR) 16 M	4 or 6 weeks (GW)	0, 3.7	BC	Endocr		3.7		~70–95% decrease in plasma insulin; ~35% increase in blood glucose

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Dieter et al. 1983									**Mercuric chloride**
87	Mouse (B6C3F1) 10 M	7 weeks (W)	0, 0.4, 2, 11	BW, BC, BI, HE, OW, HP, IX	Bd wt	2	11		14% decrease in body weight
					Hemato		0.4		Nonmonotonic alterations in WBCs and lymphocytes (35% increase at 0.4 mg Hg/kg/day, 36% decrease at 11 mg Hg/kg/day)
					Hepatic	0.4	2		14% decrease in absolute liver weight; >50% increase in serum cholinesterase
					Renal	0.4	2		19% increase in absolute kidney weight at 2 mg Hg/kg/day; minimal renal nephropathy at 11 mg Hg/kg/day
					Endocr	11			
					Immuno	0.4	2		≥25% decrease in lymphoproliferation in response to T-cell mitogens at 2 mg Hg/kg/day; >60% decrease in antibody response to T-dependent antigen at 11 mg Hg/kg/day
					Neuro	11			
He et al. 2021									**Mercuric chloride**
88	Mouse (B10.S) 4–12 B	4 weeks (W)	0, 0.51, 2.7	HE, HP	Hemato	0.51	2.7		Increased RBCs, platelets, and hemoglobin; increased number and proliferation of erythropoietic progenitor cells in bone marrow
[Autoimmune-susceptible mice]									
He et al. 2021									**Mercuric chloride**
89	Mouse (DBA/2) 9 B	4 weeks (W)	0, 2.7	HE, HP	Hemato	2.7			

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Huang et al. 2011									**Mercuric chloride**
90	Mouse (ICR) 12–15 M	7 weeks PNDs 21–70 (GW)	0, 0.4	DX	Develop[c]		0.4		Hyperactivity, impaired motor coordination, and hearing impairment at PND 70
Huang et al. 2011									**Mercuric chloride**
91	Mouse (ICR) 12–15 F	10–17 weeks Premating through PND 21 (via dam) Select pups: PNDs 21–70 (direct) (GW)	0, 0.4	RX, DX	Repro		0.4		14% decrease in litter size
					Develop[c]		0.4 M		Effects at PND 70: 12–15% decrease in pup weight, increased motor activity and impaired hearing (both groups), impaired motor coordination (direct group only)
Hultman and Enestrom 1992									**Mercuric chloride**
92	Mouse (SJL/N) 7 F	10 weeks (W)	0, 0.07, 0.14, 0.28, 0.56	HP, IX	Immuno	0.07	0.14		Positive ANoA; evidence of immune-complex disease
[Autoimmune susceptible mice]									
Hultman and Nielsen 2001; Nielsen and Hultman 2002									**Mercuric chloride**
93	Mouse (A.SW) 8 M, 8 F	10 weeks (W)	M: 0, 0.121, 0.241, 0.464, 0.942; F: 0, 0.049, 0.105, 0.199, 0.401	BW, BC, BI, IX	Immuno	0.105 F	0.199 F		Positive ANoA; positive for ANA, splenic vessel immune deposits, polyclonal B-cell activation, and elevated IgE at ≥0.401 mg Hg/kg/day
						0.121 M	0.241 M		Positive ANoA; positive for ANA, splenic vessel immune deposits, polyclonal B-cell activation, and elevated IgE at ≥0.401 mg Hg/kg/day
[Autoimmune susceptible mice]									

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Hultman and Nielsen 2001; Nielsen and Hultman 2002									**Mercuric chloride**
94	Mouse (B10.S) 8 M, 8 F	10 weeks (W)	M: 0, 0.134, 0.232, 0.479, 0.962, 1.872; F: 0, 0.118, 0.218, 0.444, 0.954, 1.774	BW, BC, BI, IX	Immuno		0.118		Polyclonal B-cell activation at ≥0.118 mg Hg/kg/day; positive ANoA and ANA, splenic and renal immune deposits, and elevated IgE at ≥0.444 mg Hg/kg/day
[Autoimmune susceptible mice]									
Khan et al. 2004									**Mercuric chloride**
95	Mouse (C57BL/6) 25 M, 25 F	61–79 days (premating through lactation) (GW)	0, 0.18, 0.37, 0.74	CS, BW, FI, BC, HE, GN, OW, HP, RX	Bd wt	0.74			
					Hepatic	0.74			
					Renal	0.18 F	0.37 F		Increased relative kidney weight
							0.18 M		Increased relative kidney weight
					Endocr	0.74			
					Neuro	0.74			
					Repro			0.18	28% decrease in fertility index at 0.18 mg Hg/kg/day; 81% decrease in viability index at 0.74 mg Hg/kg/day
Li et al. 2019a									**Mercuric chloride**
96	Mouse (Kunming) 7 M	16 weeks (W)	0, 4.0, 8.10, 16.1	BC, HP	Renal			4	Renal tubular degeneration, necrosis, and hemorrhage; 40% increased serum BUN and 5% increased creatinine
Malqui et al. 2018									**Mercuric chloride**
97	Mouse (Swiss albino) 10 M	16–17 weeks GD 0–PND 21 (via dam) PND 21–PNDs 63–70 (direct) (W)	0, 3.3	WI, DX	Develop[c]		3.3		Increased anxiety and impaired memory and sociability in PND 63–70 offspring

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Mohammad Abu-Taweel and Al-Fifi 2021									**Mercuric chloride**
98	Mouse (Swiss-Webster) 10 F	35 days, GD 1–PND 15 (W)	0, 2.4	DX	Develop		2.4		At PND 40: Decreased motor activity and increased depression- and anxiety-like behaviors; elevated serum cortisol and corticosterone
NTP 1993									**Mercuric chloride**
99	Mouse (B6C3F1) 10 M, 10 F	6 months 5 days/week (GW)	0, 0.923, 1.8, 4, 7.4, 15	LE, BW, BC, GN, OW, HP	Bd wt	15 F			
						7.4 M	15 M		12% decrease in body weight
					Resp	15			
					Cardio	15			
					Gastro	15			
					Musc/skel	15			
					Hepatic	15			
					Renal	15 F			
						1.8 M	4 M		Cytoplasmic vacuolation of tubule epithelium, ≥19% increase in kidney weight
					Endocr	15			
					Immuno	15			
					Neuro	15			
					Repro	15			
Pilones et al. 2009									**Mercuric chloride**
100	Mouse (BALB/c) 6–7 F	3 weeks GDs 0–21 (W)	0, 1.5	DX	Develop[e]		1.5		Alteration in immune endpoints in offspring at PND 70 (increased splenocyte proliferation and IFNγ and IL-4 production in mitogen assay)

[DBF1 offspring; progeny of DBA/1 males × BALB/c females]

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Sin and Teh 1992									**Mercuric sulfide**
101	Mouse (Swiss albino) 20 F	4 weeks (GW)	0, 6	BW, BC	Bd wt	6			
					Endocr		6		28–41% decreased plasma T4
Son et al. 2010									**Mercuric sulfide**
102	Mouse (ICR) 5 M	4 weeks (GW)	0, 17, 170, 1,700	BW, FI, WI, BC, OW, HP	Bd wt	1,700			
					Hepatic	1,700			
					Immuno		17		Altered T-cell populations in spleen at ≥17 mg Hg/kg/day; hyperplasia and/or increased lymphoid density in spleen and thymus at 1,700 mg Hg/kg/day
Zhang et al. 2011									**Mercuric chloride**
103	Mouse (A.SW) 3–5 F	5 weeks GD 8–PND 21 (W)	0, 2.7	DX, IX	Immuno		2.7		Induction of serum IgG antibodies to brain antigens
					Develop[c,e]		2.7		Altered immune endpoints in offspring at PNDs 21 and 70 (induction of serum IgG antibodies to brain antigens; IgG deposits in brain, brain inflammation); hyperactivity in female offspring
[Autoimmune-susceptible mouse strain]									
Zhang et al. 2011									**Mercuric chloride**
104	Mouse (A/WySnJ) 3–5 F	5 weeks GD 8–PND 21 (W)	0, 2.7	DX, IX	Immuno	2.7			
					Develop[c,e]	2.7			
[Offspring immune and behavioral endpoints evaluated at PNDs 21 and 70]									

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Zhang et al. 2013									**Mercuric chloride**
105	Mouse (SJL/J) 7 F	5 weeks GD 8 to PND 21 (W)	0, 2.7	DX, IX	Immuno		2.7		Elevated serum IgG
					Develop[c,e]		2.7		Altered immune endpoints in offspring at PNDs 21 and 70 (elevated serum IgG, IgG deposits in brain, brain inflammation); decreased sociability
[Offspring were SFvF1; autoimmune susceptible SJL/J females × wild-type FVB males]									
Zhang et al. 2013									**Mercuric chloride**
106	Mouse (FVB) 6–7 F	5 weeks GD 8 to PND 21 (W)	0, 2.7	DX, IX	Immuno		2.7		Induction of serum IgG antibodies to brain antigens
					Develop[c,e]		2.7		Altered immune endpoints in offspring at PNDs 21 and 70 (elevated serum IgG, induction of serum IgG antibodies to brain antigens, IgG deposits in brain); decreased social interaction
[Offspring were FvSF1; autoimmune susceptible SJL/J males × wild-type FVB females]									
Zhao et al. 2020									**Mercuric chloride**
107	Mouse (Kunming) 6 F	90 days (W)	0, 15	BW, BC, HP	Bd wt			15	21% decrease in body weight
					Gastro		15		Histopathological changes in cecum and rectum (atrophy of glands, mild-to-moderate necrosis, apoptosis)
					Endocr		15		Decreased blood glucose
Chuu et al. 2001b									**Mercuric sulfide**
108	Guinea pig (Hartley) 8–12 F	21 days (G)	0, 86	NX	Neuro		86		Abnormal vestibular ocular reflex
[Vehicle was saline]									

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
CHRONIC EXPOSURE									
Dieter et al. 1992; NTP 1993									**Mercuric chloride**
109	Rat (Fischer-344) 60 M, 60 F	2 years 5 days/week (GW)	0, 1.8, 4	LE, BW, BC, UR, GN, OW, HP	Death			1.8 M	Decreased survival (21%) compared to control (52%)
					Bd wt	1.8 F	4 F		16% decrease in body weight
							1.8 M	4 M	LOAEL: 16% decrease in body weight SLOAEL: 22% decrease in body weight
					Resp	1.8	4		Nasal mucosa inflammatory lesions
					Cardio	4 F			
							1.8 M		Heart mineralization (secondary to marked renal impairment)
					Gastro	1.8 F	4 F		Epithelial hyperplasia and forestomach ancanthosis
							1.8 M		Epithelial hyperplasia ≥1.8 and forestomach ancanthosis at 4 mg Hg/kg/day
					Musc/skel	4 F			
							1.8 M		Fibrous osteodystrophy (secondary to marked renal impairment)
					Hepatic	4			
					Renal	4 F			
								1.8 M	Marked thickening of glomerular and tubular basement membranes; degeneration and atrophy of tubule epithelium
					Endocr	4 F			
							1.8 M		Parathyroid hyperplasia (secondary to marked renal impairment)

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
					Immuno	4			
					Neuro	4			
					Repro	4			
					Cancer			4 M	CEL: Forestomach squamous cell papilloma and thyroid follicular cell carcinoma in males; no exposure-related neoplastic lesions in females
Perry and Erlanger 1974									**Mercuric chloride**
110	Rat (Long-Evans) 16 F	1 year (W)	0, 0.33, 0.66, 1.3, 3.3	CS, BW, OF	Bd wt	1.3	3.3		13% decrease in final body weight
					Cardio	0.33	0.66		Increased systolic blood pressure
NTP 1993									**Mercuric chloride**
111	Mouse (B6C3F1) 60 M, 60 F	2 years 5 days/week (GW)	0, 4, 7.4	LE, BW, BC, UR, GN, OW, HP	Bd wt	7.4			
					Resp		4 F		Increased metaplasia in the olfactory epithelium; increased inflammatory lesions at 7.4 mg Hg/kg/day
						4 M	7.4 M		Increased metaplasia in the olfactory epithelium; increased inflammatory lesions
					Cardio	7.4			
					Gastro	7.4			
					Musc/skel	7.4			
					Hepatic	7.4			
					Renal		4		Increased incidence (females only) and/or severity of renal nephropathy; ≥20% increase in kidney weight
					Endocr	7.4			
					Immuno	7.4			

Table 2-3. Levels of Significant Exposure to Inorganic Mercury Salts – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
					Neuro	7.4			
					Repro	7.4			

[a]The number corresponds to entries in Figure 2-7; differences in levels of health effects and cancer effects between male and females are not indicated in Figure 2-7. Where such differences exist, only the levels of effect for the most sensitive sex are presented.
[b]Used to derive an acute-duration oral MRL. Using BMD modeling, BMD_{1SD} and $BMDL_{1SD}$ values of 0.64 and 0.29 mg Hg/kg/day, respectively, were calculated for elevated relative kidney weight in male rats. The $BMDL_{1SD}$ was adjusted for continuous exposure (5 days/7 days) to a $BMDL_{ADJ}$ of 0.21 mg Hg/kg/day and divided by an uncertainty factor of 100 (10 for animal to human, and 10 for human variability), resulting in an MRL of 0.002 mg Hg/kg/day.
[c]The neurodevelopmental effects are discussed in Section 2.16 (Neurological).
[d]Used to derive an intermediate-duration oral MRL. The LOAEL of 0.015 mg Hg/kg/day was divided by an uncertainty factor of 1,000 (10 for use of a LOAEL, 10 for animal to human, and 10 for human variability), resulting in an MRL of 0.00001 mg Hg/kg/day ($1x10^{-5}$ mg Hg/kg/day; 0.01 µg Hg/kg/day).
[e]Immunodevelopmental effects are discussed with adult immune system effects in Section 2.15 (Immunological).

Principal studies for the MRLs

ADJ = adjusted; ALP = alkaline phosphatase; ALT = alanine aminotransferase; ANA = antinuclear antibodies; ANoA = antinucleolar antibodies; AST = aspartate aminotransferase; B = both males and females; BC = serum (blood) chemistry; Bd wt or BW = body weight; BI = biochemical changes; BMD = benchmark dose; BMDL = 95% lower confidence limit on the BMD (subscripts denote benchmark response: i.e., $_{1SD}$ = exposure dose associated with a 1 SD change from the control); BUN = blood urea nitrogen; Cardio = cardiovascular; CEL = cancer effect level; CS = clinical signs; DX = developmental toxicity; Endocr = endocrine; ESR = erythrocyte sedimentation rate; (F) = feed (dietary); F = female(s); FI = food intake; FSH = follicle-stimulating hormone; (G) = gavage; (GO) = gavage in oil; (GW) = gavage in water; Gastro = gastrointestinal; GD = gestation day; GN = gross necropsy; HDL = high-density lipoprotein; HE = hematology; Hemato = hematological; HP = histopathology; IFNγ = interferon gamma; IgE = immunoglobulin E; IgG = immunoglobulin G; IL-4 = interleukin 4; Immuno = immunological; (IN) = ingestion; IX = immune function; LC = Langerhans cell; LD_{50} = lethal dose, 50% kill; LDH = lactate dehydrogenase; LE = lethality; LH = luteinizing hormone; LOAEL = lowest-observed-adverse-effect level; M = male(s); MRL = Minimal Risk Level; Musc/skel = musculoskeletal; Neuro = neurological; NOAEL = no-observed-adverse-effect level; NS = not specified; NX = neurological function; OF = organ function; OW = organ weight; PND = postnatal day; RBC = red blood cell; Repro = reproductive; Resp = respiratory; RX = reproductive function; SD = standard deviation; SLOAEL = serious lowest-observed-adverse-effect level; T3 = triiodothyronine; T4 = thyroxine; UR = urinalysis; (W) = drinking water; WBC = white blood cell; WI = water intake

Figure 2-7. Levels of Significant Exposure to Inorganic Mercury Salts – Oral
Acute (≤14 days)

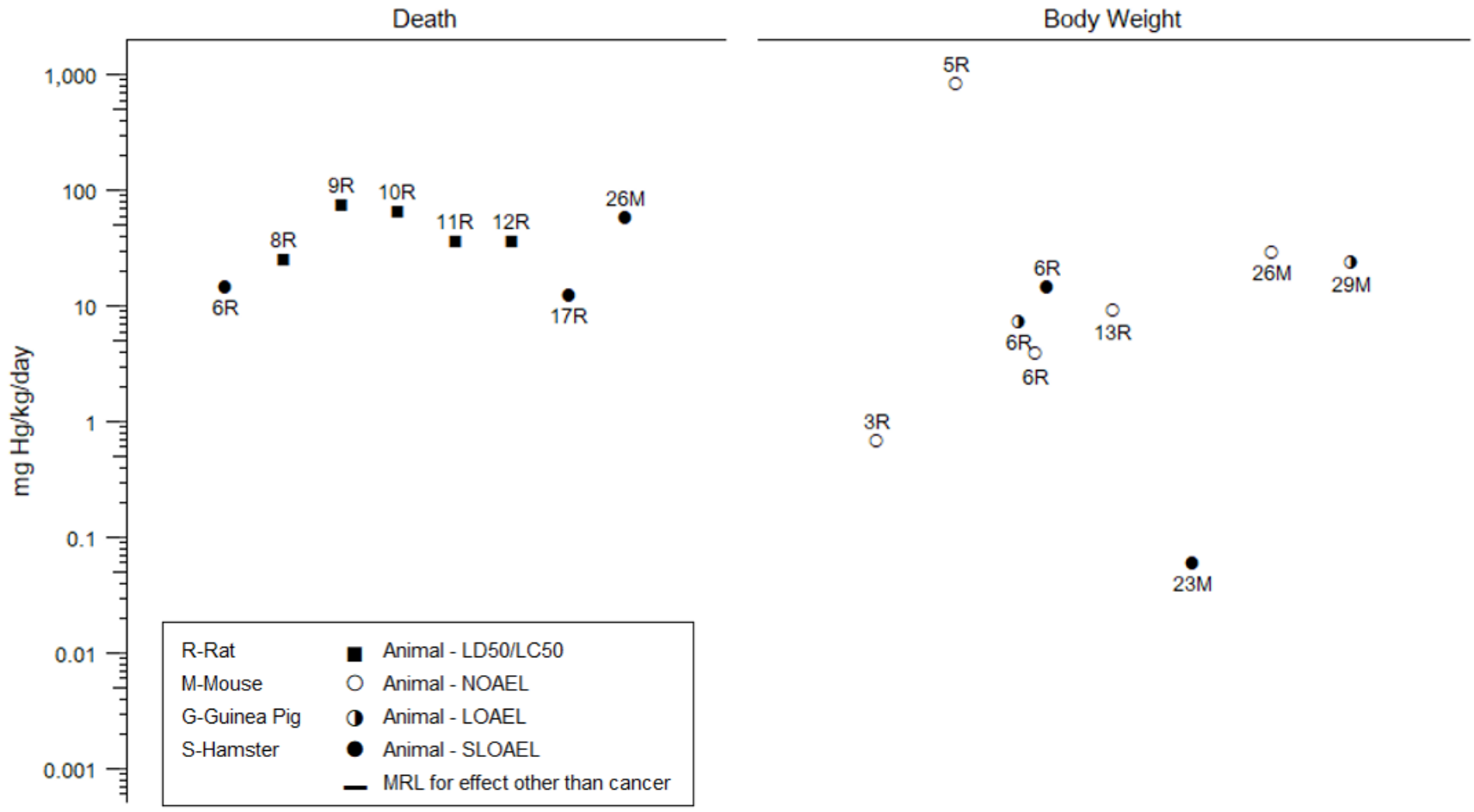


Figure 2-7. Levels of Significant Exposure to Inorganic Mercury Salts – Oral
Acute (≤14 days)

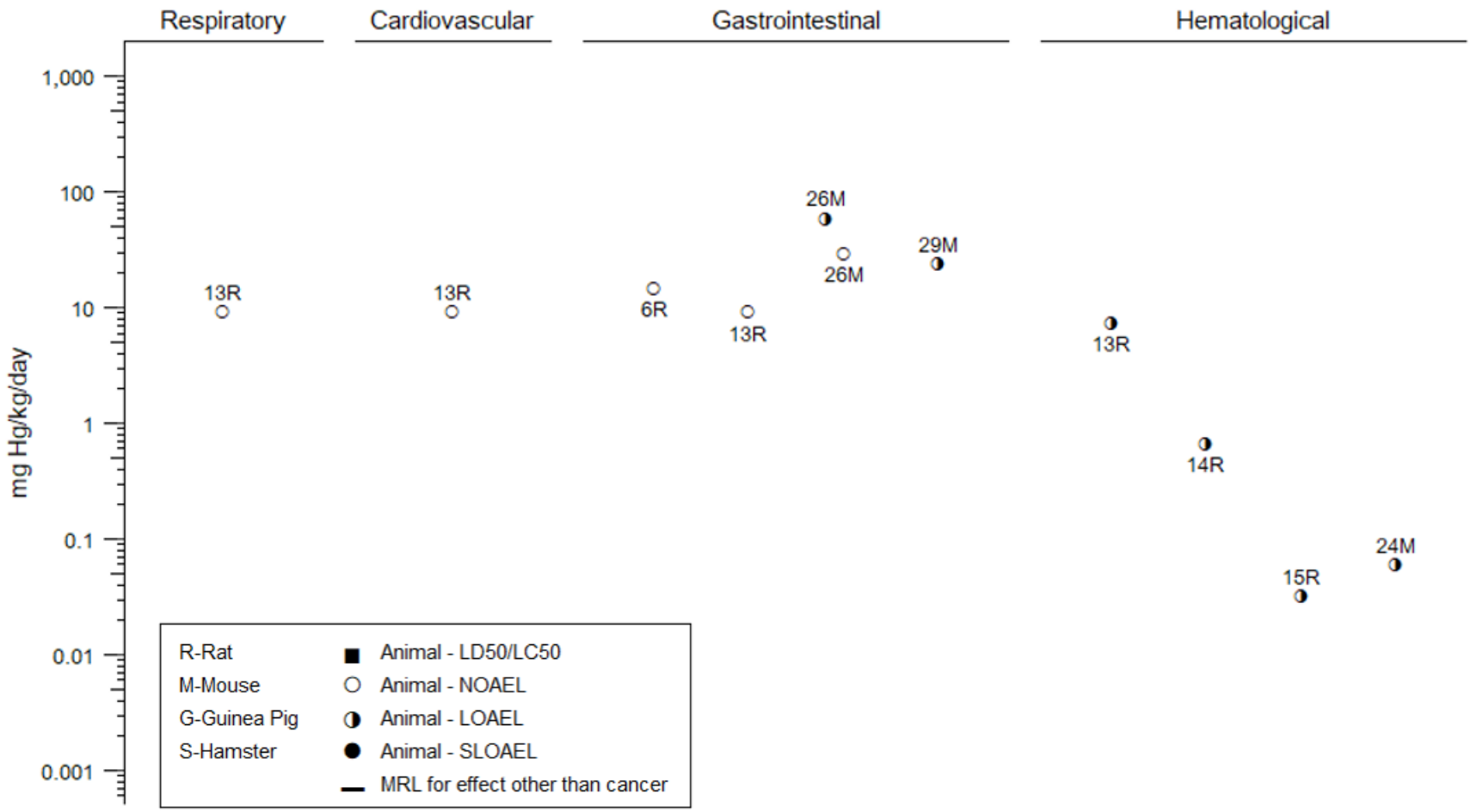


Figure 2-7. Levels of Significant Exposure to Inorganic Mercury Salts – Oral
Acute (≤14 days)

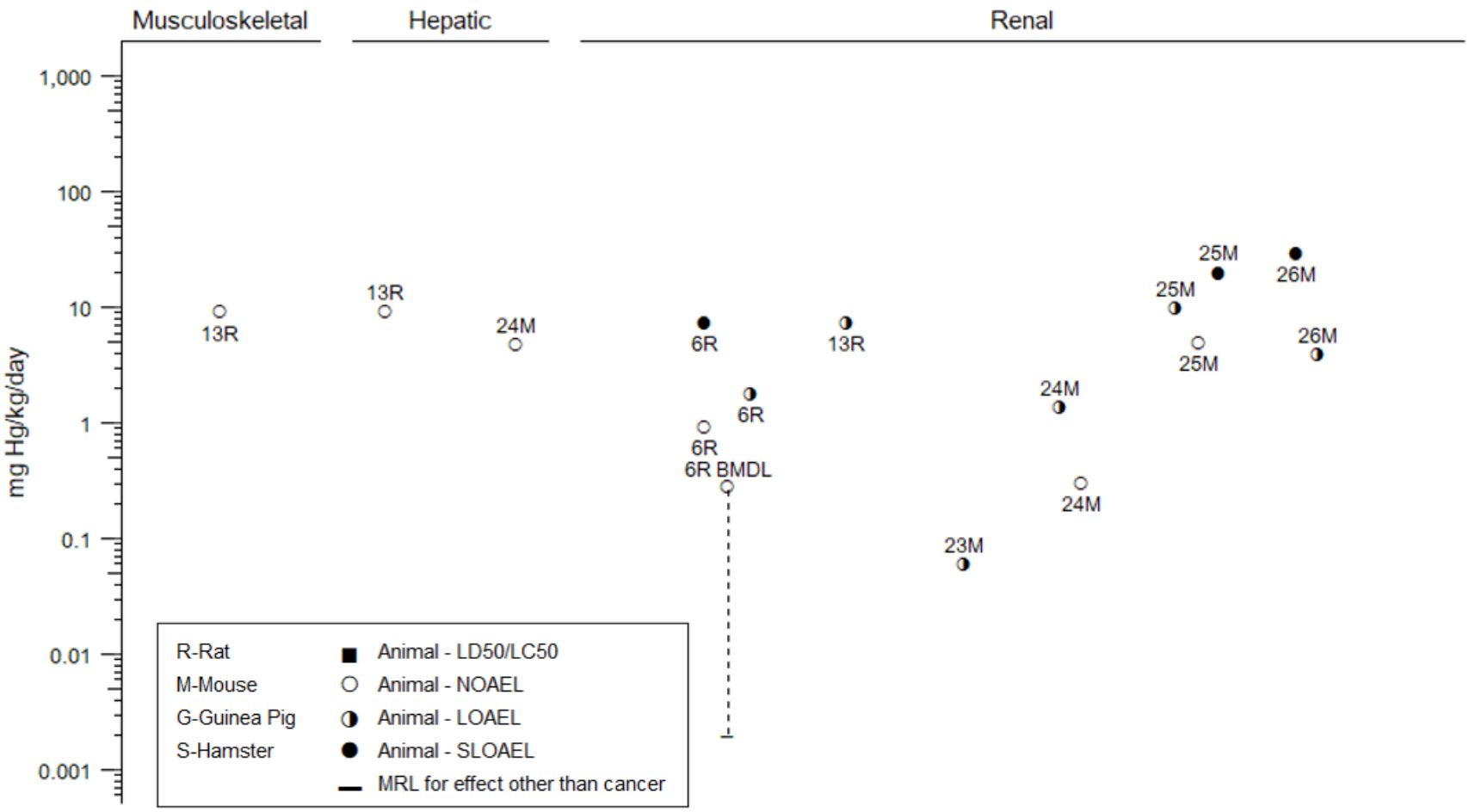


Figure 2-7. Levels of Significant Exposure to Inorganic Mercury Salts – Oral
Acute (≤14 days)

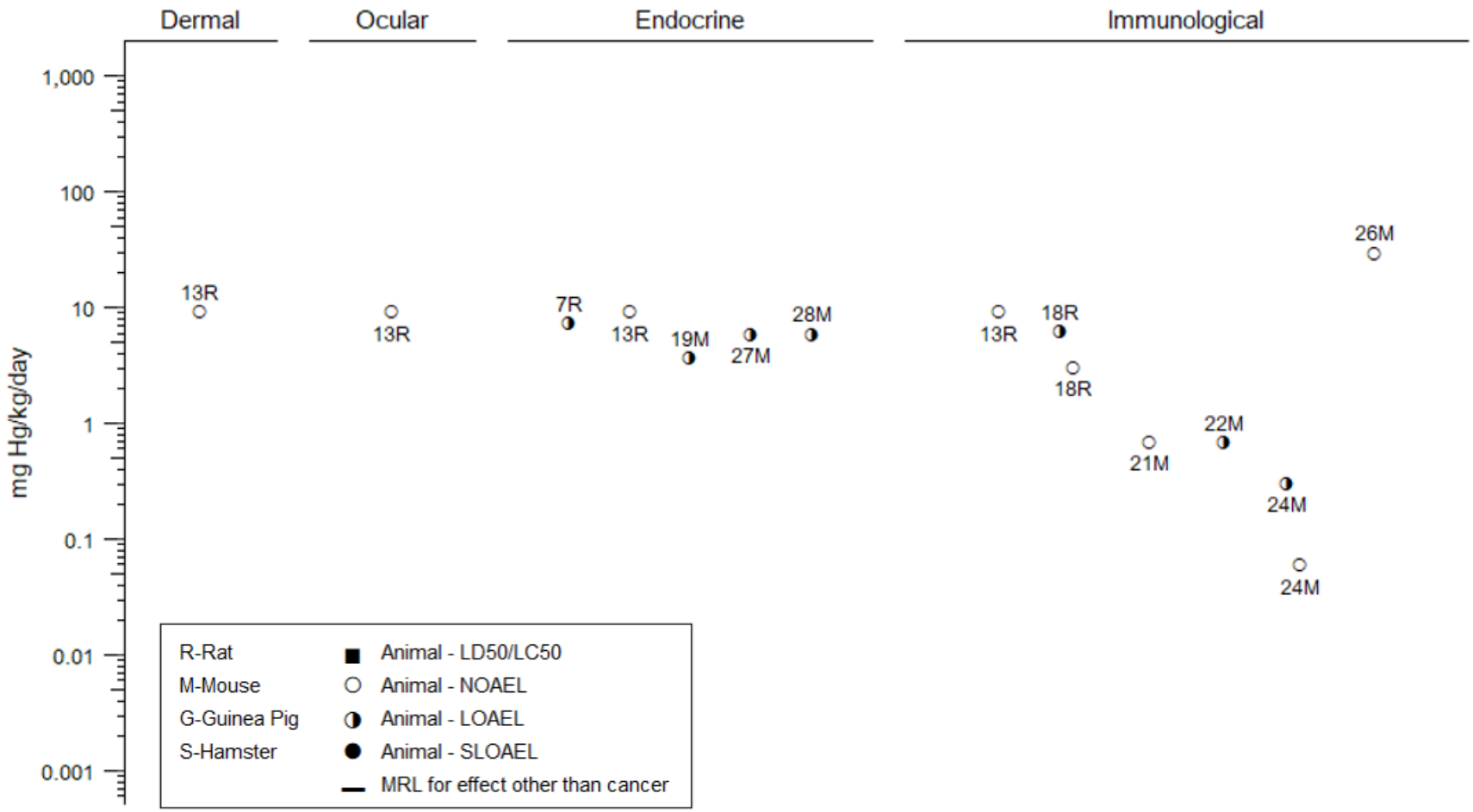


Figure 2-7. Levels of Significant Exposure to Inorganic Mercury Salts – Oral
Acute (≤14 days)

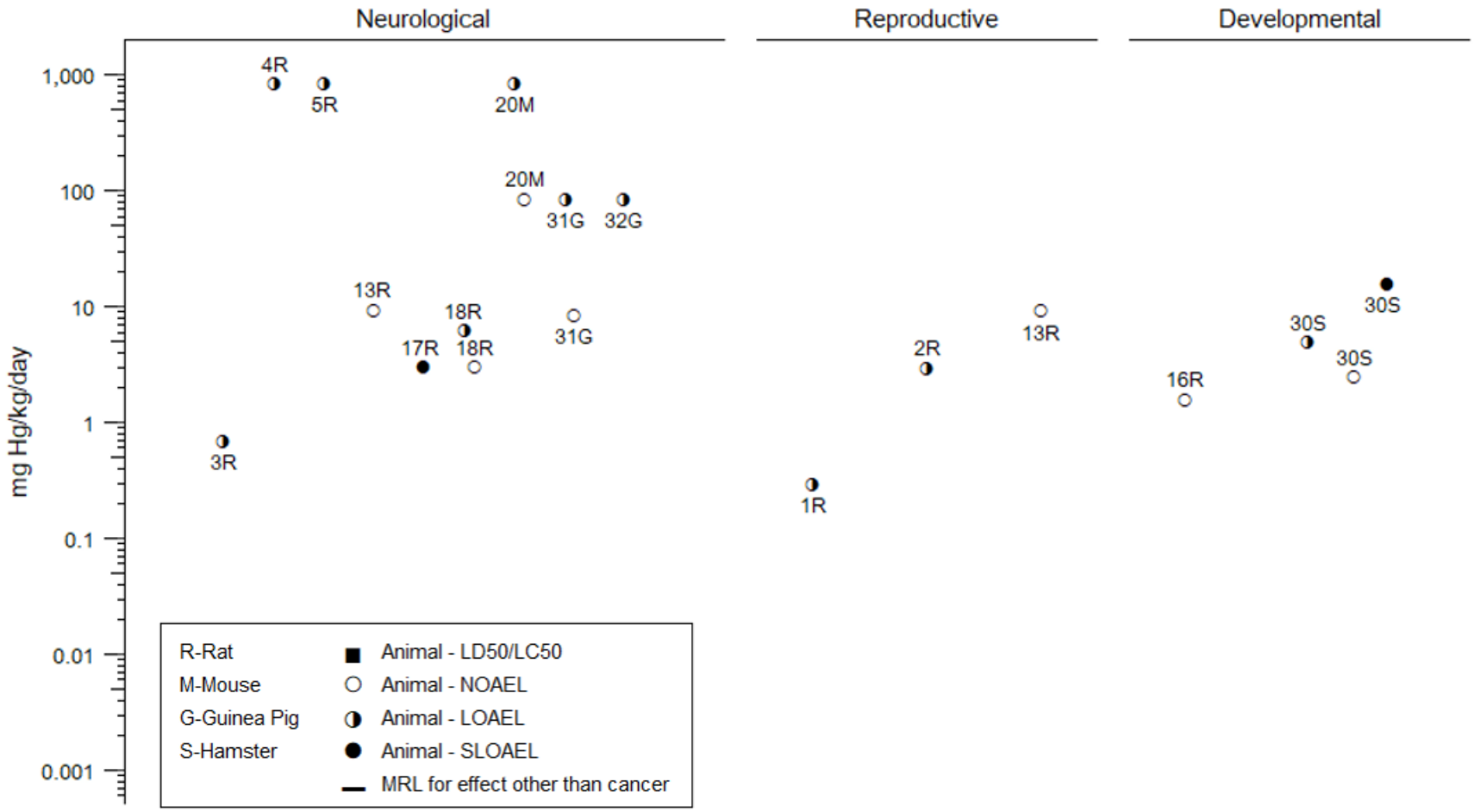


Figure 2-7. Levels of Significant Exposure to Inorganic Mercury Salts – Oral
Intermediate (15–364 days)

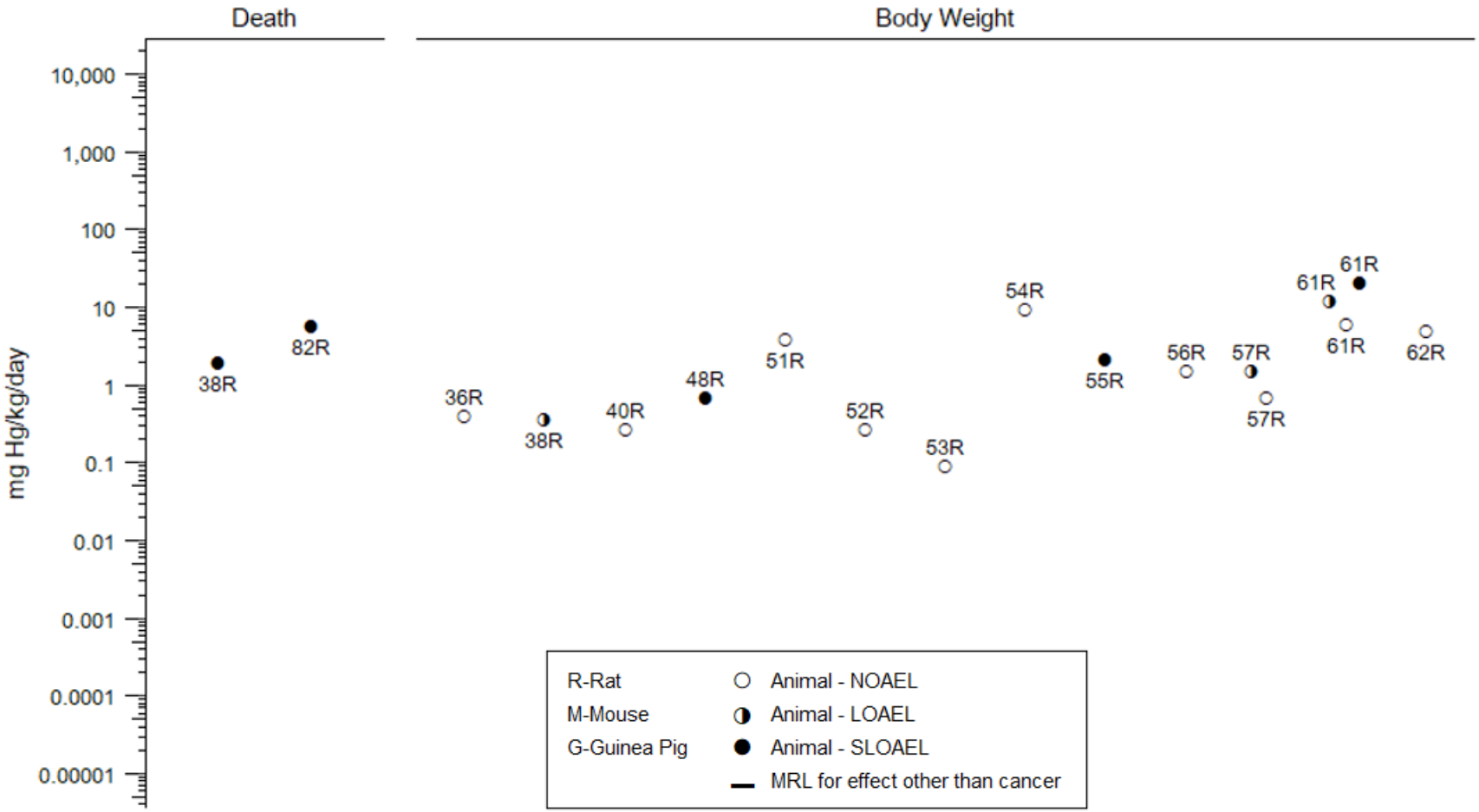


Figure 2-7. Levels of Significant Exposure to Inorganic Mercury Salts – Oral
Intermediate (15–364 days)

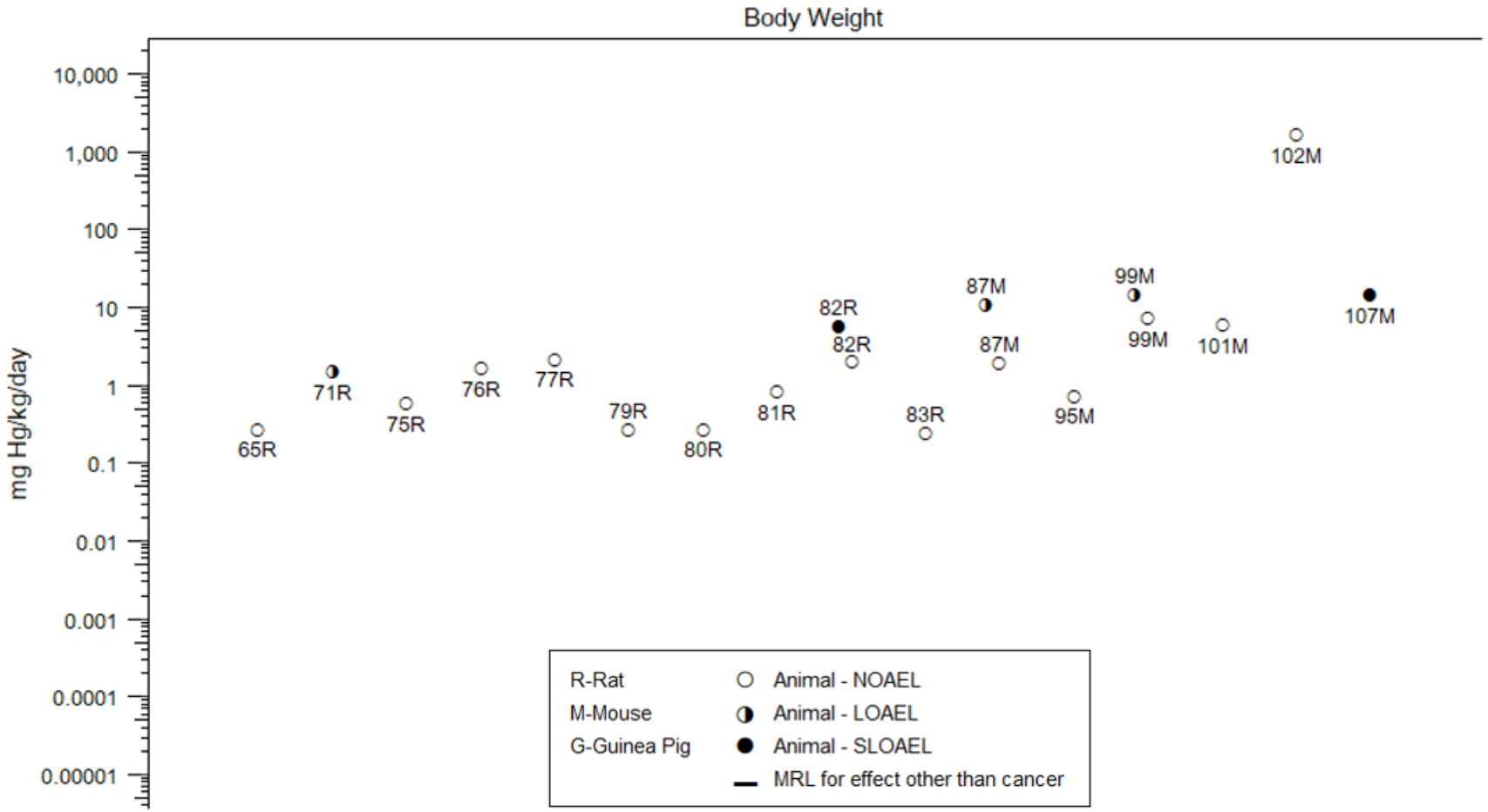


Figure 2-7. Levels of Significant Exposure to Inorganic Mercury Salts – Oral
Intermediate (15–364 days)

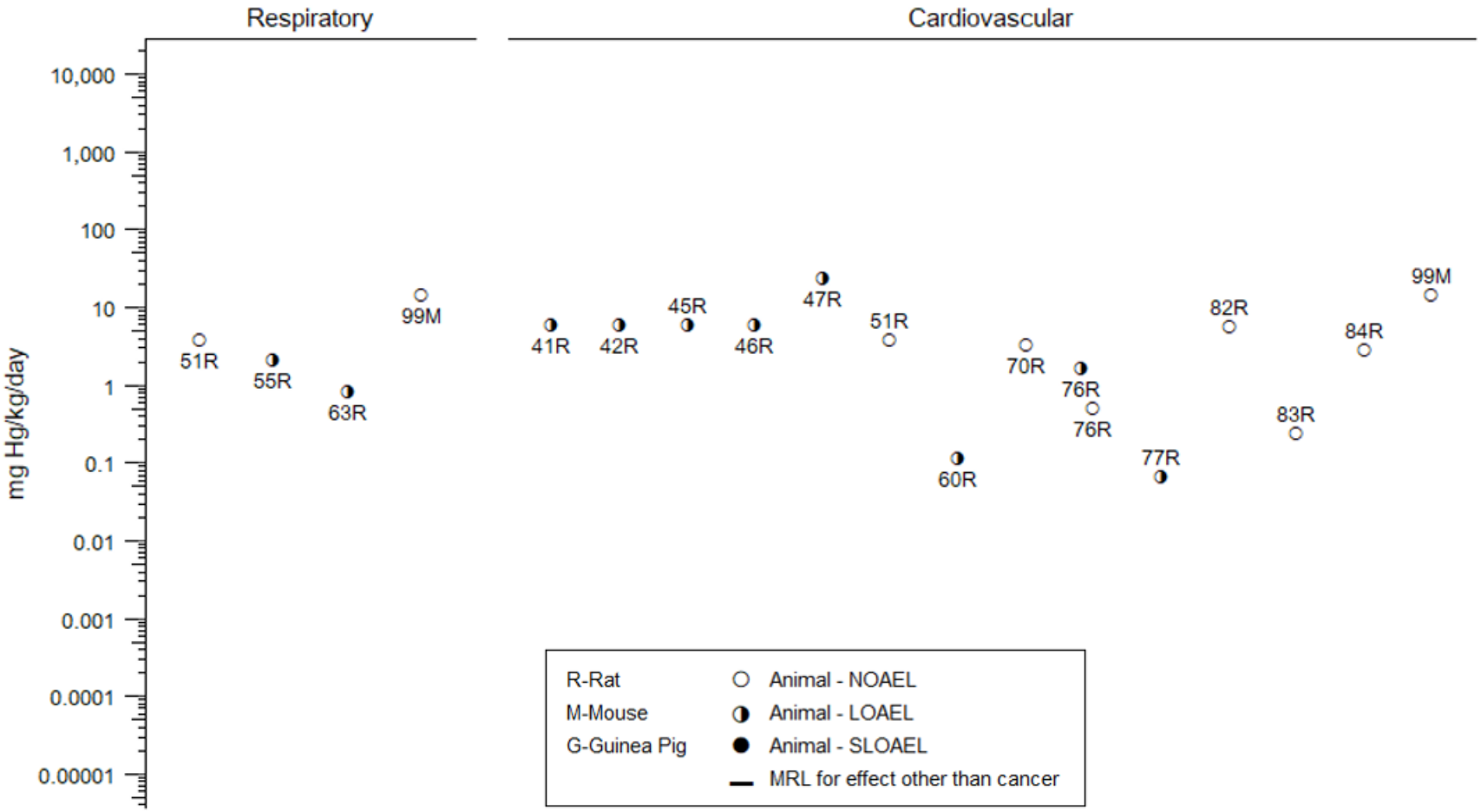


Figure 2-7. Levels of Significant Exposure to Inorganic Mercury Salts – Oral
Intermediate (15–364 days)

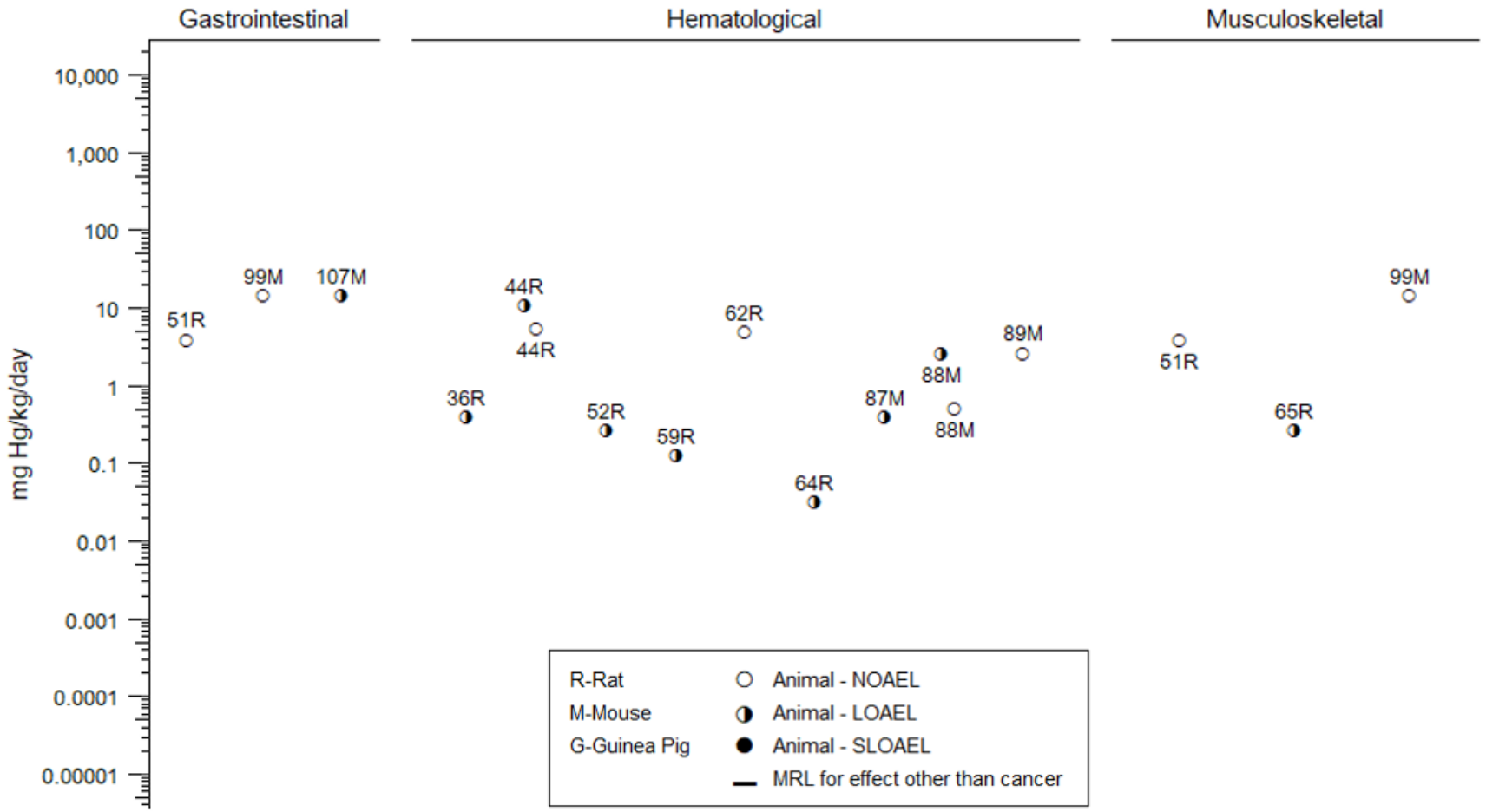


Figure 2-7. Levels of Significant Exposure to Inorganic Mercury Salts – Oral
Intermediate (15–364 days)

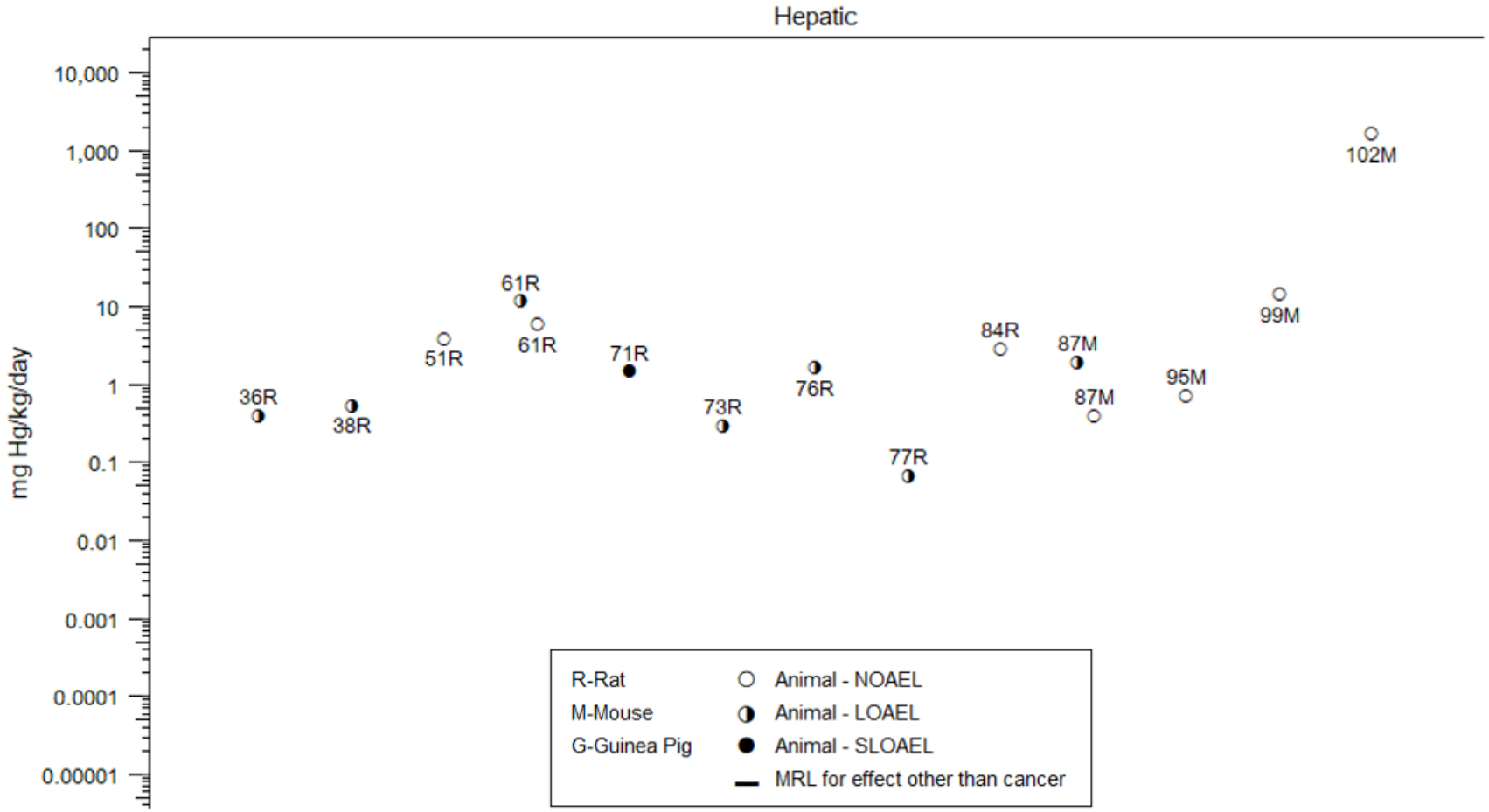


Figure 2-7. Levels of Significant Exposure to Inorganic Mercury Salts – Oral
Intermediate (15–364 days)

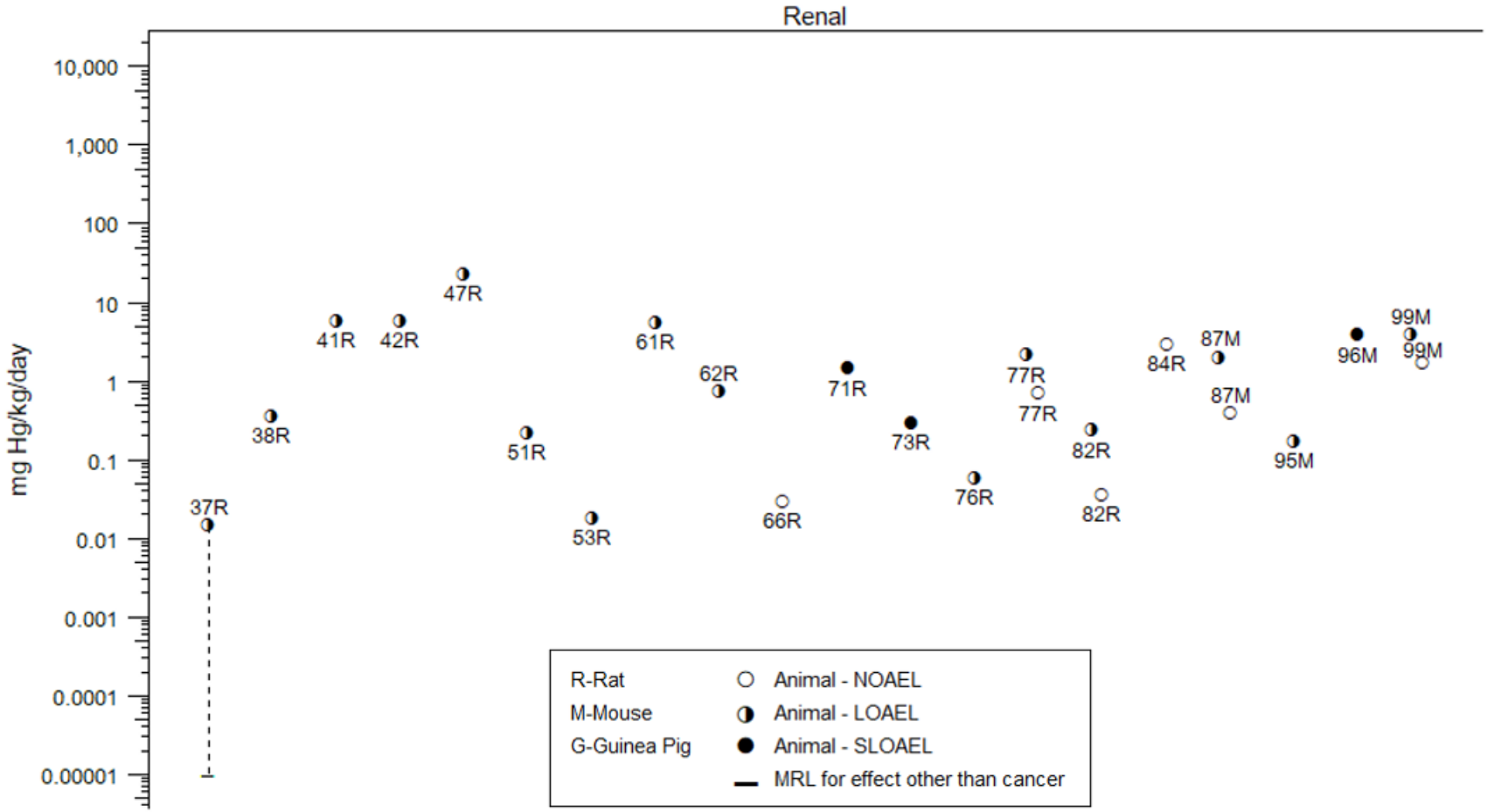


Figure 2-7. Levels of Significant Exposure to Inorganic Mercury Salts – Oral
Intermediate (15–364 days)

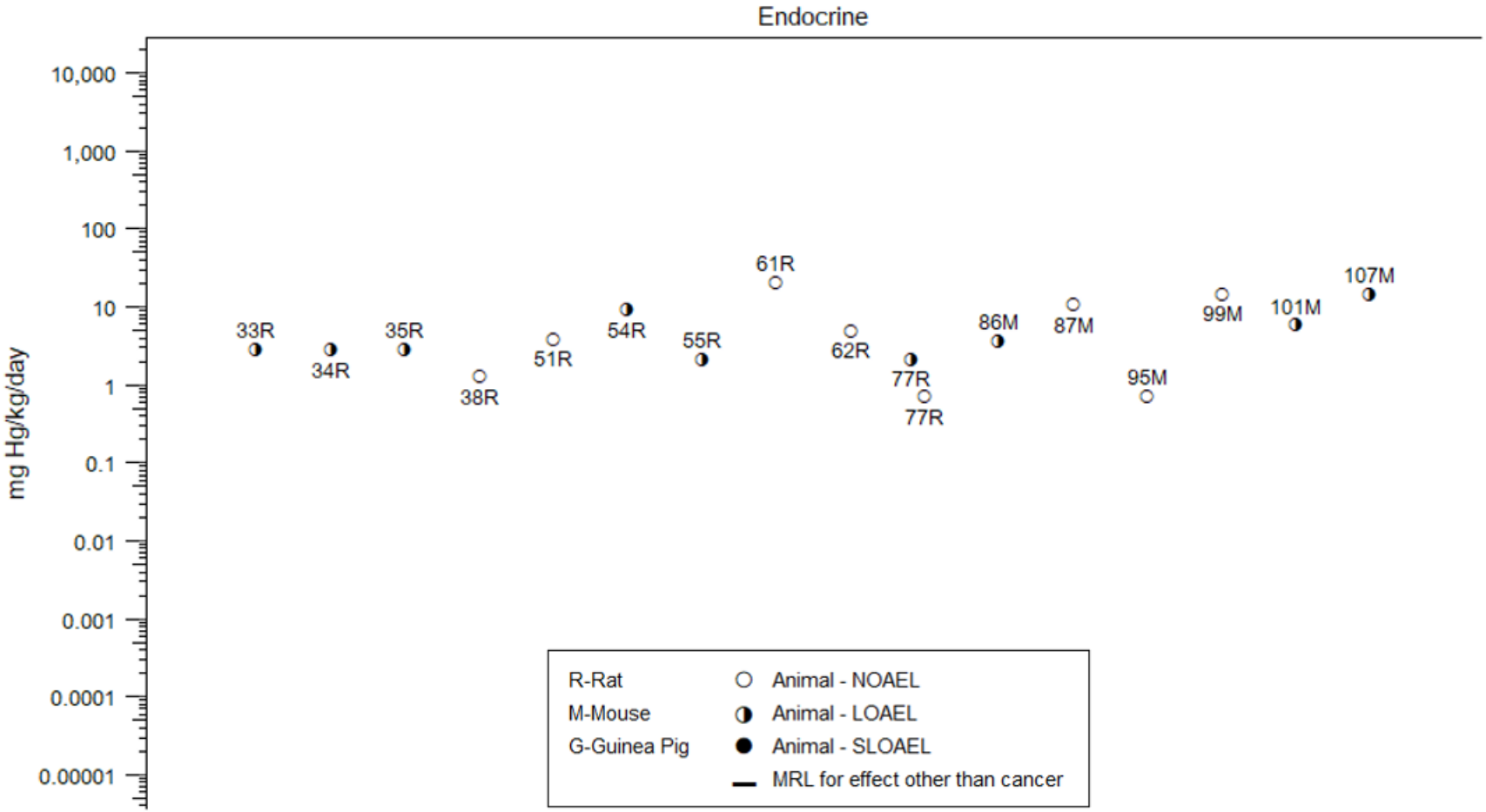


Figure 2-7. Levels of Significant Exposure to Inorganic Mercury Salts – Oral
Intermediate (15–364 days)

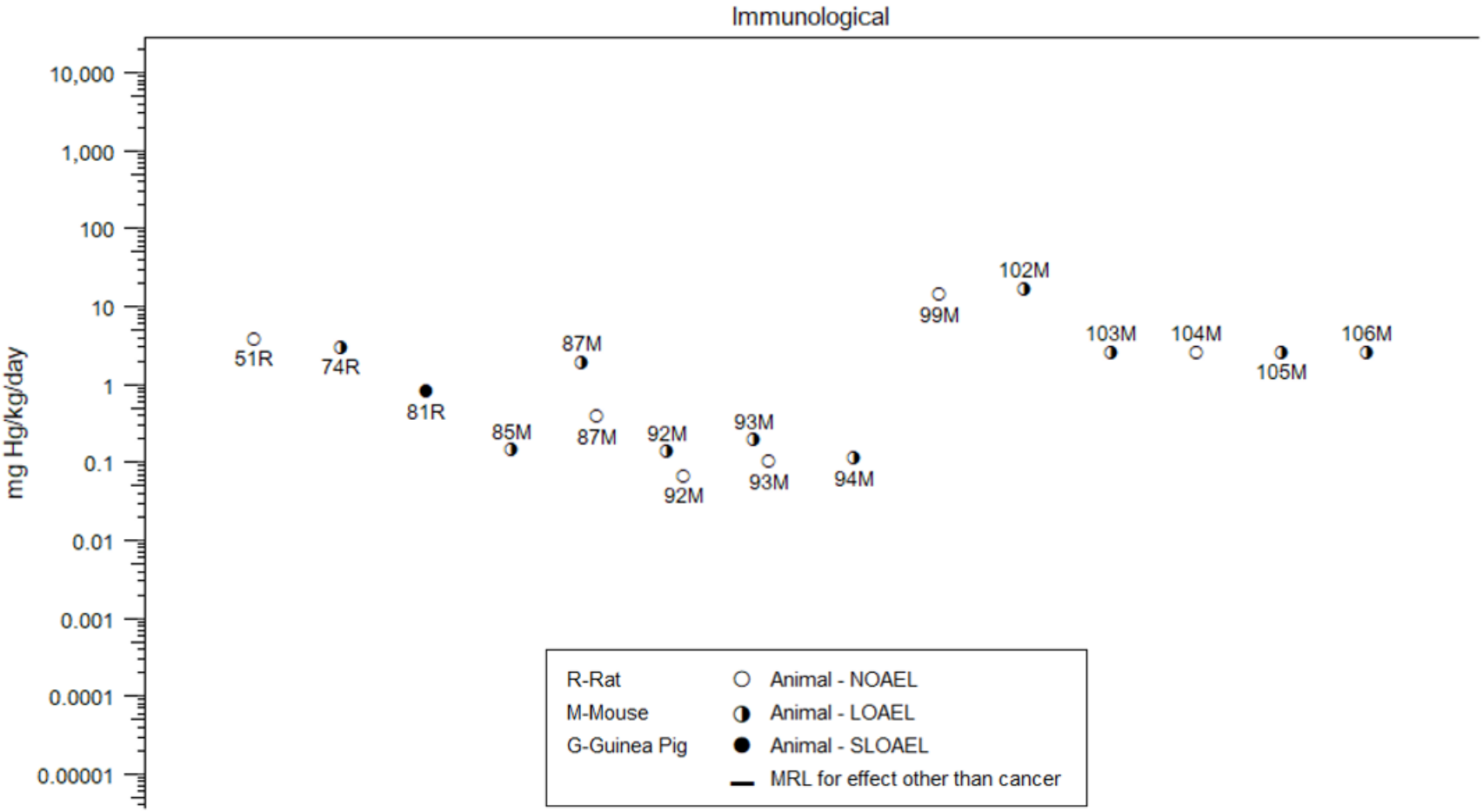


Figure 2-7. Levels of Significant Exposure to Inorganic Mercury Salts – Oral
Intermediate (15–364 days)

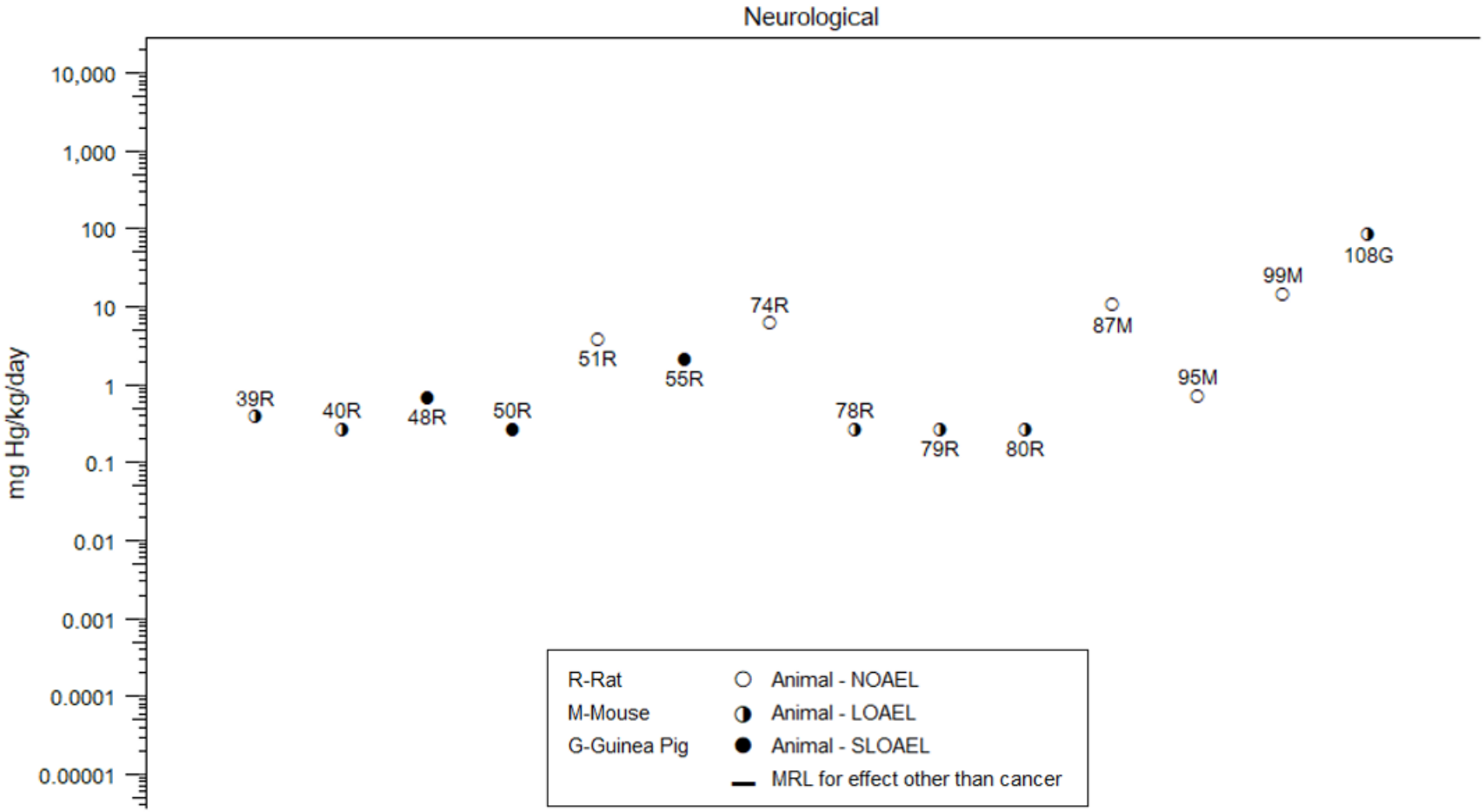


Figure 2-7. Levels of Significant Exposure to Inorganic Mercury Salts – Oral
Intermediate (15–364 days)

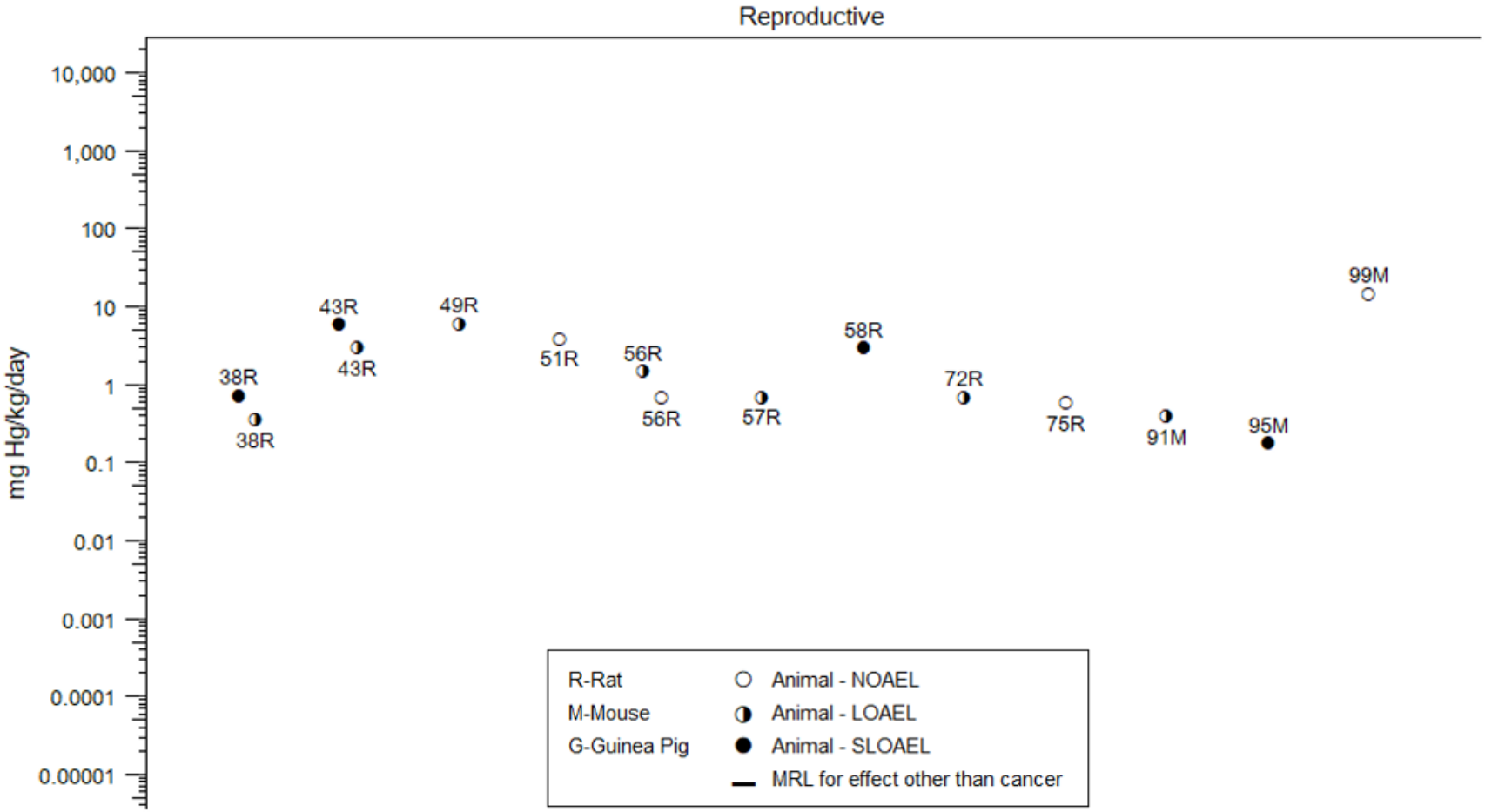


Figure 2-7. Levels of Significant Exposure to Inorganic Mercury Salts – Oral
Intermediate (15–364 days)

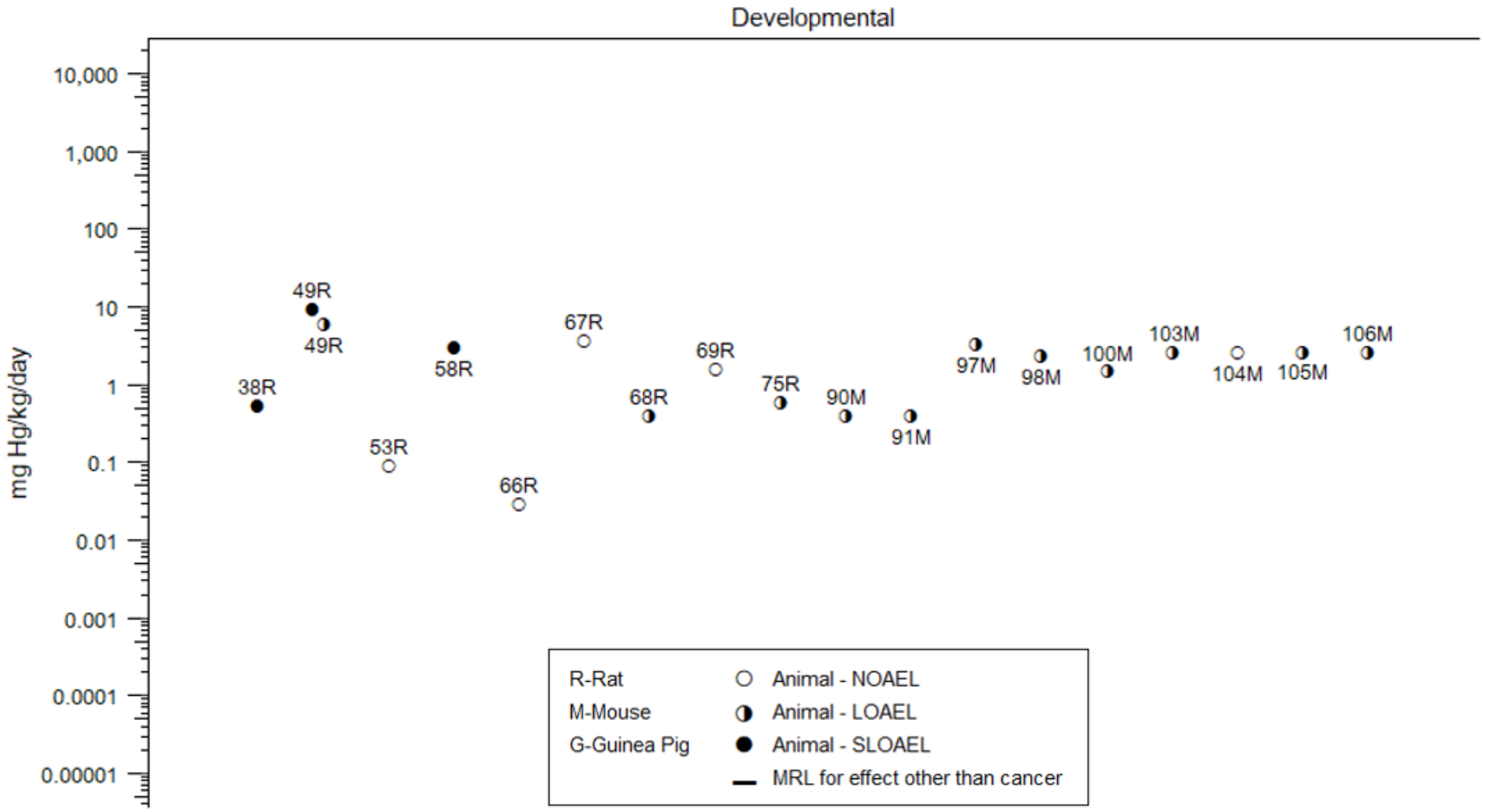


Figure 2-7. Levels of Significant Exposure to Inorganic Mercury Salts – Oral
Chronic (≥365 days)

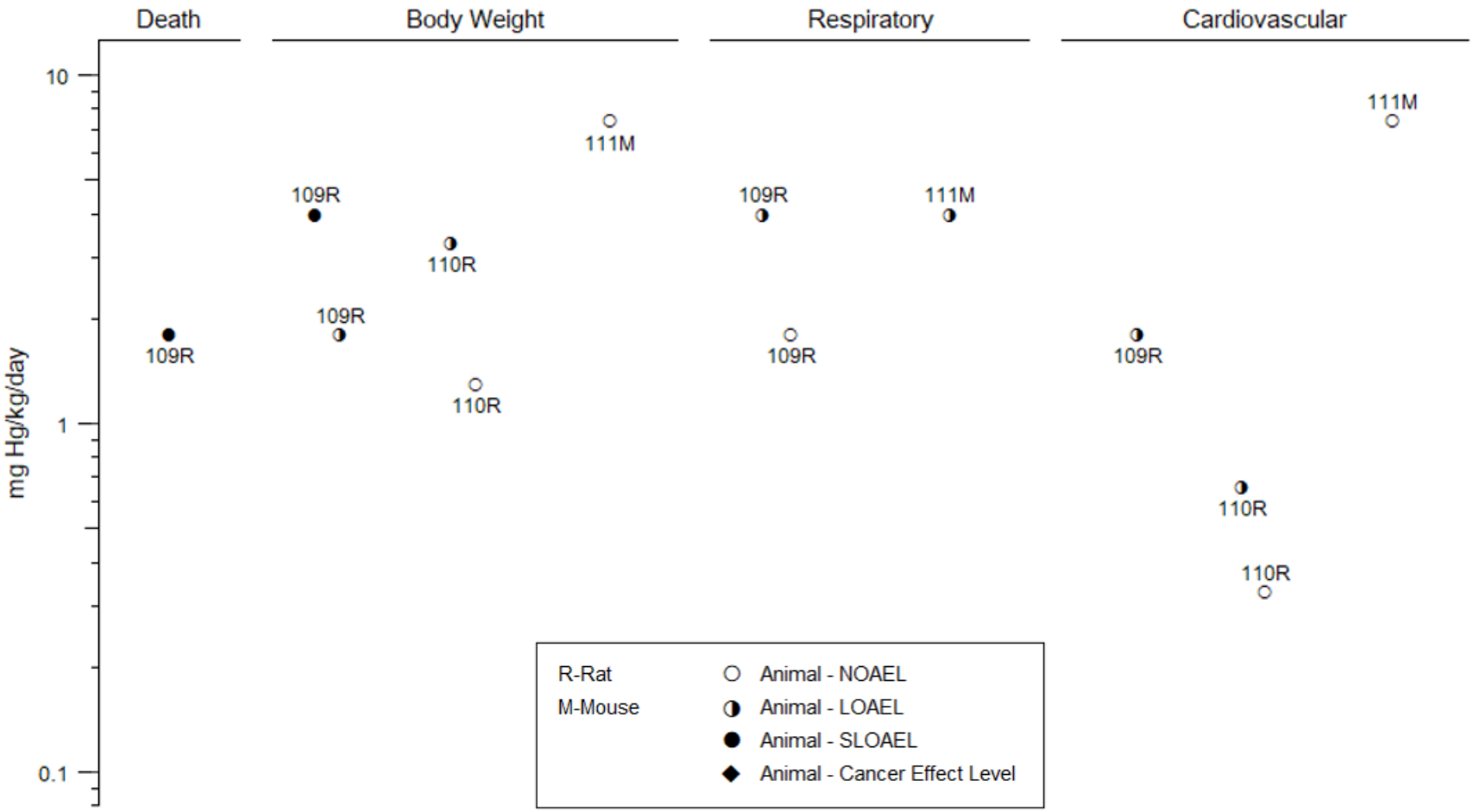


Figure 2-7. Levels of Significant Exposure to Inorganic Mercury Salts – Oral
Chronic (≥365 days)

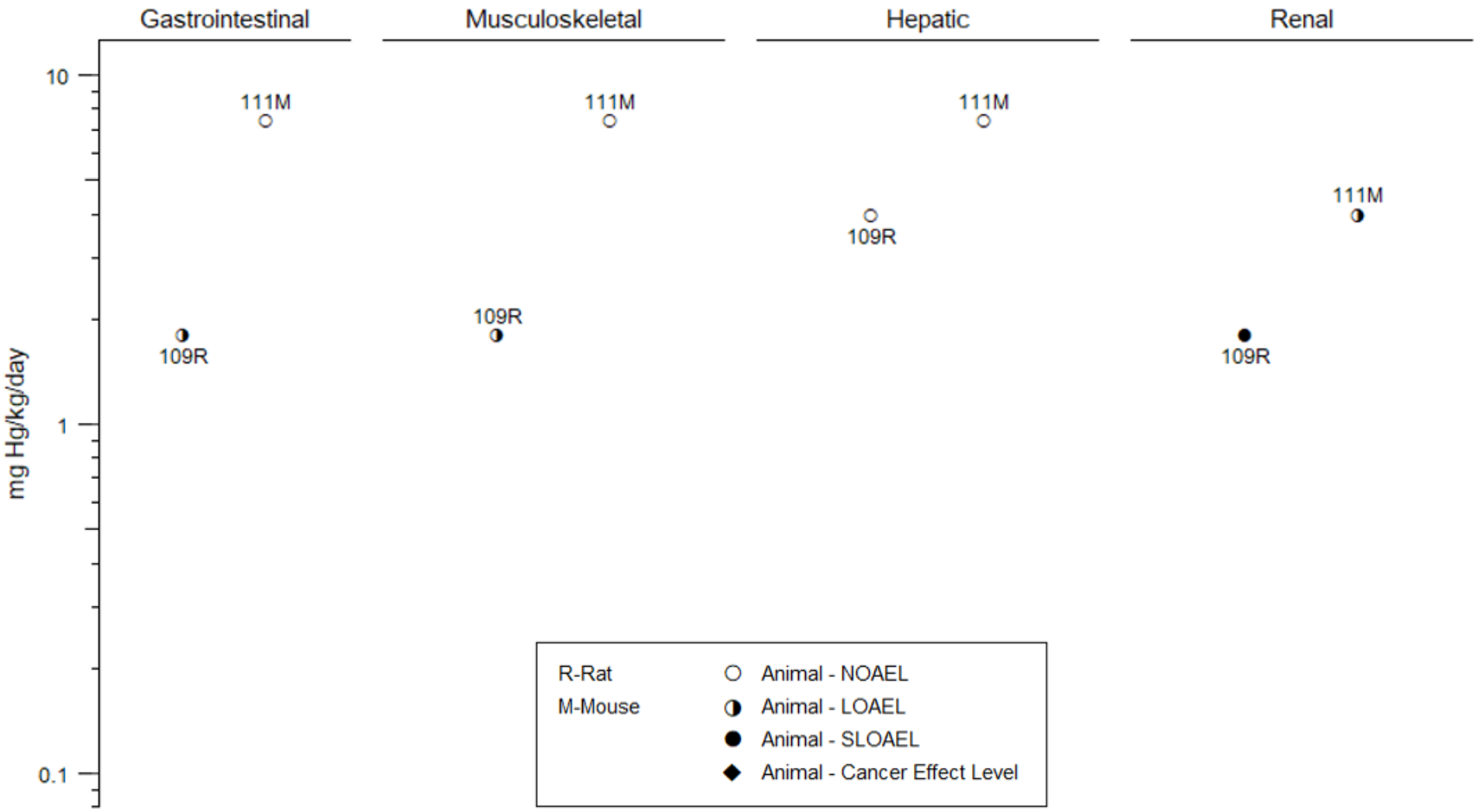


Figure 2-7. Levels of Significant Exposure to Inorganic Mercury Salts – Oral
Chronic (≥365 days)

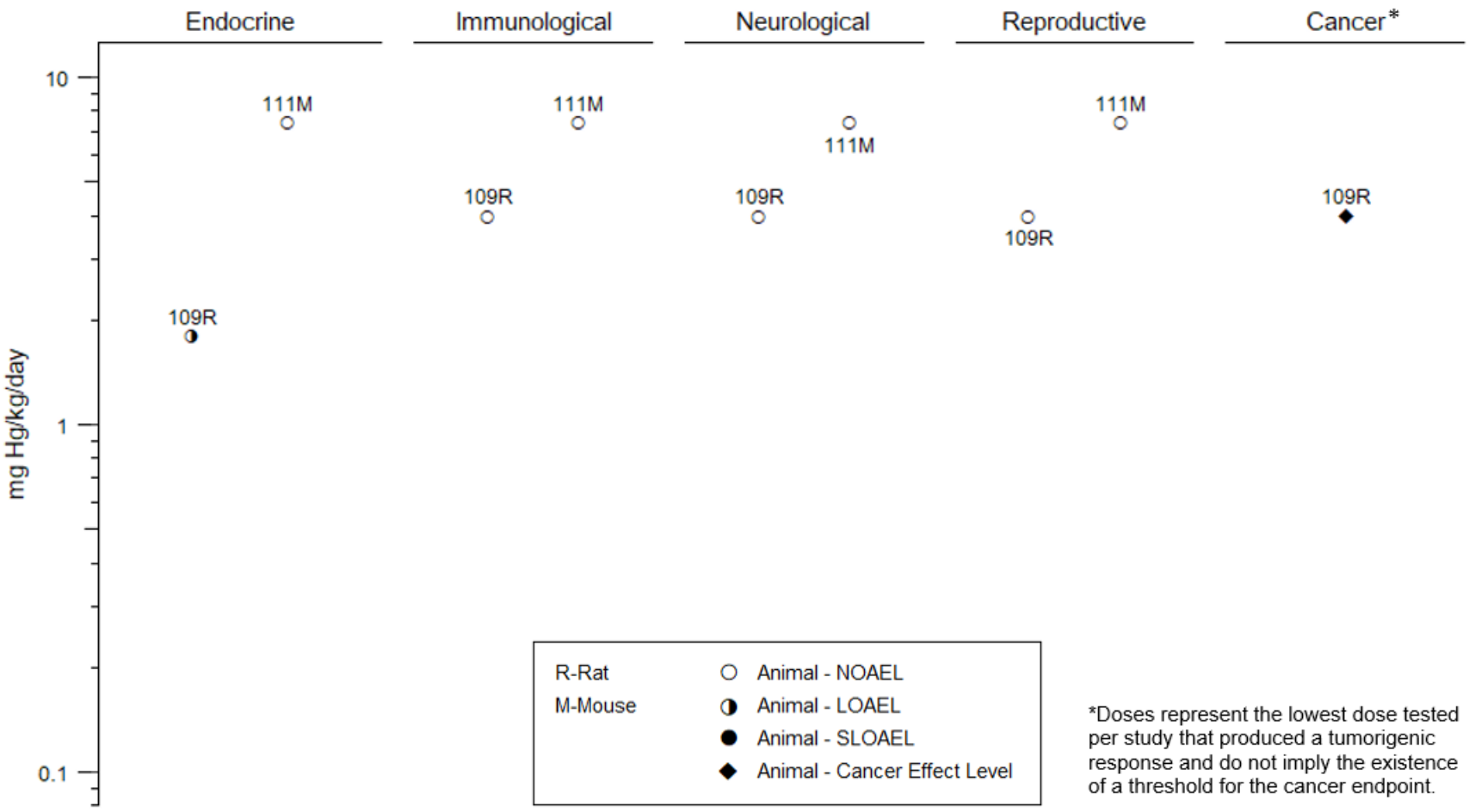


Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
ACUTE EXPOSURE									
Arito and Takahashi 1991									**Methylmercuric chloride**
1	Rat (Sprague-Dawley) 4–16 M	2 days (GW)	0, 1.32, 4, 12	BI, NX	Neuro	1.32	4		Decreased paradoxical sleep and increased slow-wave sleep
Arito and Takahashi 1991									**Methylmercuric chloride**
2	Rat (Sprague-Dawley) 6 M	2 days (GW)	12	CS	Cardio		12		10–18% decrease in heart rate for up to 16 days post-exposure (compared to pre-exposure values)
					Other noncancer		12		Hypothermia for >1 month post-exposure
Bornhausen et al. 1980									**Methylmercuric chloride**
3	Rat (Wistar) 10 M, 10 F	4 days GDs 6–9 (GW)	0, 0.004, 0.008, 0.035	DX	Develop[b]	0.004	0.008		Impaired operant conditioning at 4 months
Cagiano et al. 1990									**Methylmercuric chloride**
4	Rat (Sprague-Dawley) NS F	Once GD 15 (G)	0, 6.4	DX	Develop[b]		6.4		Decreased avoidance latency in offspring on PND 60
Carratu et al. 2006									**Methylmercury**
5	Rat (Sprague-Dawley) 9–10 F	Once GD 8 or 15 (G)	0, 7	BW, DX	Bd wt	7			
					Develop[b]			7	Decreased postnatal survival; 18% decrease in pup weight at PND 21 (GD 8 exposure only); decreased exploratory behavior and impaired habituation at PND 40
Carratu et al. 2008									**Methylmercury**
6	Rat (Sprague-Dawley) 10 F	Once GD 15 (G)	0, 7	DX	Develop[b]		7		Impaired associative learning and elevated corticosterone levels at PND 90

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Chang and Hartmann 1972									**Methylmercuric chloride**
7	Rat (Holtzman) 4 M	1–2 weeks (G)	0, 0.8	CS, BW, HP	Bd wt	0.8			
					Neuro		0.8		Ultrastructural changes in dorsal root ganglia and cerebellum
Chen et al. 2019a									**Methylmercuric chloride**
8	Rat (Sprague-Dawley) 6 M	5 days (G)	0, 9	BI, HP, RX	Repro		9		Decreased sperm count and motility; disruption of germinal epithelium in seminiferous tubules with reduced spermatozoa; increased germ cell apoptosis
[Vehicle was sodium carbonate]									
Chuu et al. 2007									**Methylmercury**
9	Rat (Sprague-Dawley) 6 M	5 days (GW)	0, 1.9	NX	Neuro		1.9		Impaired balance, suppression of compound muscle action potentials followed by incomplete recovery after tetany
Chuu et al. 2007									**Methylmercury**
10	Rat (Sprague-Dawley) 6 M	14 days (GW)	0, 1.9	BW, NX	Bd wt		1.9		~10% decrease in body weight
					Neuro		1.9		Impaired balance, suppression of compound muscle action potentials followed by incomplete recovery after tetany; transient decrease in motor nerve conduction velocity and nociception
Coluccia et al. 2007									**Methylmercuric chloride**
11	Rat (Sprague-Dawley) 8 M	10 days PNDs 14–23 (IN)	0, 0.6	DX	Develop[b]		0.6		Impaired associative learning (PND 90) and decreased rearing in open field (PNDs 31–45)
[Administered via micropipette as 1:1 ratio of MeHg:L-cysteine in 10% condensed milk]									

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Fehling et al. 1975									**Methylmercuric chloride**
12	Rat (Wistar) 10 M	2 days (G)	0, 10, 20	HP, NX	Neuro		10	20	SLOAEL: Decreased nerve conduction velocity and degeneration of peripheral nerves and dorsal nerve roots and ganglia LOAEL: Impaired balance and coordination
Fossato da Silva et al. 2011									**Methylmercury**
13	Rat (Wistar) 15 M	14 days (GW)	0, 0.5, 0.93, 2.8	BW, BC, OW, HP	Bd wt	2.8			
					Renal	0.93	2.8		18% increase in relative kidney weight
					Repro		0.5		Nonmonotonic sperm effects (decreased count and motility, increased abnormal) at ≥0.5 mg Hg/kg/day; 65% decrease in serum testosterone and 28% decrease in relative seminal vesicle weight at 2.8 mg Hg/kg/day
Fossato da Silva et al. 2012									**Methylmercury**
14	Rat (Wistar) 10 M	14 days (GW)	0, 0.5, 0.93, 2.8	BW, OW, HP	Bd wt	2.8			
					Repro		0.5		Inflammatory foci and thickening of epithelium in prostate at ≥0.5 mg Hg/kg/day; progressing to epithelial atrophy and dilation of glandular acini at 2.8 mg Hg/kg/day
Fredriksson et al. 1996									**Methylmercury**
15	Rat (Sprague-Dawley) 12 F	4 days GDs 6–9 (G)	0, 1.9	CS, BW, DX	Bd wt	1.9			
					Develop[b]	1.9			
[Behavior assessed in adult male offspring at 4–5 months of age]									

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Fuyuta et al. 1978									**Methylmercuric chloride**
16	Rat (Wistar) 20 F	8 days GDs 7–14 (GW)	0, 2, 4, 6	CS, BW, FI, WI, DX	Neuro	4		6	Spasms, gait disturbance, and hind limb crossing in dams
					Develop	2		4	Decreased fetal weight; increased incidence of fetal malformations
Kendricks et al. 2022									**Methylmercuric chloride**
17	Rat (Long-Evans) 12 M	9 days PNDs 1–10 (GW)	0, 0.064, 0.280	DX	Develop	0.064	0.280		Slower acquisition (Impaired learning) at PND 91
Khera 1973									**Methylmercuric chloride**
18	Rat (Wistar) 15–20 M	7 days (G)	0, 1, 2.5, 5	CS, BW, RX	Bd wt	5			
					Repro	2.5		5	Decreased fertility and decreased viable fetuses
[Males mated to untreated females after exposure]									
Lee and Han 1995									**Methylmercuric chloride**
19	Rat (Fischer-344) 30 F	Once GD 7 (G)	0, 8, 16, 24	LE, BW, DX	Death			16	17% maternal death
					Bd wt		8	16	LOAEL: 14% decrease in maternal body weight SLOAEL: >20% decrease in maternal body weight
					Develop			8	Decreased fetal survival; decrease in fetal weight and length, delayed ossification, spinal curvature
Miyakawa et al. 1974									**Methylmercuric sulfide**
20	Rat (Wistar) 5 M	10 days (IN)	0, 7	CS, BW, HP	Bd wt	7			
					Neuro			7	Ataxia and instability post-exposure; peripheral nerve degeneration
[Rats sacrificed 600 days post-exposure]									

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Nolen et al. 1972									**Methylmercuric chloride**
21	Rat (NS) 20 F	9 days GDs 6–14 (W)	0, 0.024, 0.23, 4.6	BW	Bd wt	0.23		4.6	55% decreased maternal weight gain
					Develop		0.024		Increased incidence of fetal urinary bladder defects and missing 5th sternebra
Post et al. 1973									**Methylmercuric chloride**
22	Rat (Sprague-Dawley) 15 M	Once (G)	0, 20	CS, HP, NX	Neuro		20		Transient lethargy and ataxia; impaired spatial learning; decreased motor activity
[Behavioral tests administered over a 60-day period post-exposure]									
Post et al. 1973									**Methylmercuric chloride**
23	Rat (Sprague-Dawley) 15 M	Once PND 15 or 21 (G)	0, 16	DX	Develop[b]		16		Transient lethargy and ataxia
[Behavioral tests administered over a 60-day period post-weaning]									
Sakamoto et al. 2020									**Methylmercuric chloride**
24	Rat (Wistar) 8 M	10 days PNDs 14–23 (IN)	0, 8	DX	Develop			8	>20% decrease in body weight; hind-limb paralysis and dystonia; impaired motor coordination; impaired memory; severe cerebral degeneration
Shinoda et al. 2019									**Methylmercuric chloride**
25	Rat (Wistar) 3 M	2 weeks 5 days/week (GW)	0, 5.4	HP	Neuro			5.4	Decreased number and area of axons and neuronal loss in dorsal root ganglion of lumbar spinal cord; Schwann cell proliferation of sensory nerve fibers
Shinoda et al. 2019									**Methylmercuric chloride**
26	Rat (Wistar) 3 M	5 days (GW)	0, 5.4	HP	Neuro	5.4			

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Stoltenburg-Didinger and Markwort 1990									**Methylmercuric chloride**
27	Rat (Wistar) NS F	4 days GDs 6–9 (G)	0, 0.02, 0.04, 0.4, 4	CS, HP	Develop[b]	0.04	0.4	4	SLOAEL: Altered behavior and dendritic spine abnormalities LOAEL: Increased startle response in adult offspring
Su et al. 1998									**Methylmercuric chloride**
28	Rat (Wistar) 4 NS	10 days (G)	0, 8	LE, CS, BW, HP	Death			8	14/34 rats died prior to scheduled sacrifice
					Bd wt			8	Body weight loss
					Musc/skel			8	Neurogenic atrophy of gluteal muscle
					Neuro			8	Ataxia, hind-limb crossing, weakness, degeneration of cortical and cerebellar neurons, large motor neurons in spinal cord, and myelinated fibers of spinal anterior roots
[Vehicle was L-cysteine; rats sacrificed at intervals 1–8 days post-exposure]									
Usuki et al. 1998									**Methylmercuric chloride**
29	Rat (Wistar) NS M	12 days (GW)	0, 4	CS, BW, HP	Death			4	50% death by 3 weeks post-exposure
					Bd wt			4	37% decrease in body weight
					Musc/skel			4	Muscle weakness and wasting
					Neuro		4		Weakness, hind-limb crossing
Zanoli et al. 1994									**Methylmercuric chloride**
30	Rat (Sprague-Dawley) NS F	Once GD 15 (G)	0, 6.4	DX	Develop[b]		6.4		Decreased passive avoidance latency in PND 42 offspring

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Belles et al. 2002									**Methylmercuric chloride**
31	Mouse (CD-1) 10–12 F	Once GD 10 (GW)	0, 9.99	BW, OW, DX	Bd wt	9.99			
					Develop			9.99	17% decrease in fetal weight; increased incidence of cleft palate; delayed ossification
Bellum et al. 2007									**Methylmercuric chloride**
32	Mouse (C57BL/6J) 22–29 B	5 days PNDs 29–33 (F)	0, 0.2, 0.8	DX	Develop[b]		0.2		Impaired balance and motor coordination on PND 38
Bellum et al. 2013									**Methylmercuric chloride**
33	Mouse (C57BL/6) 20–25 B	5 days (F)	0, 0.9	BI, NX	Neuro		0.9		Hypoactivity, motor incoordination
[Aged mice]									
Chen et al. 2012									**Methylmercuric chloride**
34	Mouse (ICR) 16 M	2 weeks (GW)	0, 1.6	BC, BI, HP	Endocr		1.6		~60–70% decrease in baseline and fasting plasma insulin; impaired glucose tolerance; apoptosis in pancreatic islet cells
Chuu et al. 2001a									**Methylmercury**
35	Mouse (NS) 8–10 M	7 days (G)	0, 0.2, 1.9, 9.3	LE, NX	Death			9.3	100% mortality
					Neuro		0.2	1.9	LOAEL: Reversible hearing loss SLOAEL: Persistent hearing loss
Das et al. 1997									**Methylmercuric chloride**
36	Mouse (Swiss-Webster) NS M	4 days (G)	0, 12	BW, BI, OW, HP	Bd wt			12	10% body weight loss
					Resp	12			22–23% increase in absolute and relative lung weight; reduced alveolar diameter and increased alveolar wall thickness; increased minimal surface tension

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Dietrich et al. 2005									**Methylmercuric chloride**
37	Mouse (Swiss) 13–14 M	7–14 days (W)	0, 4.7, 8.7	CS, WI, NX	Neuro		4.7		Impaired motor coordination, hypoactivity
Dore et al. 2001									**Methylmercuric chloride**
38	Mouse (C57BL/6) 10–21 F	3 days GDs 7–9 (G)	0, 3, 5	DX	Develop[b]		3	5	LOAEL: Impaired spatial memory at PND 49 SLOAEL: 28% decrease in postnatal survival
[Vehicle was phosphate-buffered saline]									
Dore et al. 2001									**Methylmercuric chloride**
39	Mouse (C57BL/6) 10–21 F	3 days GDs 12–14 (G)	0, 3, 5	DX	Develop[b]		3	5	LOAEL: Hypoactivity at PND 42 SLOAEL: 26% decrease in postnatal survival and impaired spatial learning at PNDs 49–98
[Vehicle was phosphate-buffered saline]									
Fischer et al. 2008									**Methylmercuric chloride**
40	Mouse (NMRI) NS M	Once PND 10 (GW)	0, 0.37, 3.7	DX	Develop[b]		0.37		Decreased motor activity and impaired learning and memory at 2–6 months of age at ≥0.37 mg Hg/kg/day; impaired exploratory habituation at 3.7 mg Hg/kg/day
Fuyuta et al. 1978									**Methylmercuric chloride**
41	Mouse (C57BL/6N) 9–10 F	8 days GDs 6–13 (GW)	0, 2, 4, 4.8, 6	CS, BW, FI, WI, DX	Develop			2	Increased incidence of fetal malformations
Fuyuta et al. 1979									**Methylmercuric chloride**
42	Mouse (ICR) 20 F	Once GD 10 (GW)	0, 8, 12, 16, 20	DX	Develop		8	12	SLOAEL: Cleft palate and decreased fetal weight LOAEL: Incomplete fusion of sternebrae

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Hughes and Annau 1976									**Methylmercury hydroxide**
43	Mouse (CFW) NS F	Once GD 8 (G)	0, 1, 2, 3, 5, 10	DX	Develop[b]	2	3	10	LOAEL: 35% decrease in litter size, 13% decrease in pup weight on PND 21, decreased conditioned avoidance SLOAEL: 73% decrease in litter size
Inouye et al. 1985									**Methylmercuric chloride**
44	Mouse (C3H/HeN) 10 F	Once on GD 13, 14, 15, 16, or 17 (GW)	0, 16	DX	Develop[b]			16	Decreased survival of offspring; neurological effects in offspring (impaired righting response, altered gait, hindlimb crossing, decreased brain weight, dilated lateral ventricles; smaller caudate putamen)
Ishihara et al. 2019									**Methylmercuric chloride**
45	Mouse (ICR) 10 M	2 weeks (IN)	0, 3.2	HP, NX	Neuro		3.2		Increased reactive astrocytes in inferior colliculus
Khera 1973									**Methylmercuric chloride**
46	Mouse (Swiss-Webster) 10–12 M	7 days (G)	0, 1, 2.5, 5	CS, BW, RX	Bd wt Repro	5 5			
[Males mated to untreated females after exposure]									
Khera and Tabacova 1973									**Methylmercuric chloride**
47	Mouse (Swiss-Webster) 6–17 F	12 days GDs 6–17 (GO)	0, 0.001, 0.01, 0.1, 1, 10	LE, CS, BW, DX	Death Develop	 1		10	100% maternal mortality

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Khera and Tabacova 1973									**Methylmercuric chloride**
48	Mouse (Swiss-Webster) 5–14 F	12 days GDs 6–17 (GO)	0, 0.001, 0.01, 1, 5	CS, BW, BI, DX	Develop[b]	0.01	1	5	LOAEL: Delayed cerebellar development SLOAEL: 100% stillbirth
Kim et al. 2000									**Methylmercury**
49	Mouse (BALB/c) 6 F	3 days GDs 12–14 (G)	0, 3	CS, DX	Develop[b]		3 M		Effects in male offspring: 15% reduction in body weight; decreased motor activity and decreased anxiety-like behaviors at PND 42; altered nocturnal rhythm at PNDs 84–98
Kim et al. 2000									**Methylmercury**
50	Mouse (C57BL/6Cr) 5–6 F	3 days GDs 12–14 (G)	0, 3	CS, DX	Develop[b]		3 M		Effects in male offspring: Decreased motor activity and rearing at PND 42; impaired spatial learning and memory at PND 56
Kim et al. 2000									**Methylmercury**
51	Mouse (C57BL/6J) 4 F	3 day GDs 12–14 (G)	0, 3	CS, DX	Develop[b]		3 M		Effects in male offspring: Impaired spatial learning on PND 56; increased grooming/preening behaviors on PND 42
Kirkpatrick et al. 2015									**Methylmercury**
52	Mouse (C57BL/6N) NS M	7–14 days (IN)	0, 4.6	BW, NX	Bd wt Neuro	4.6 4.6			
[Mice given MeHg-dosed cookies]									
Montgomery et al. 2008									**Methylmercuric chloride**
53	Mouse (C57BL/6) 6 F	11 days GDs 8–18 (F)	0, 0.009	DX	Develop[b]		0.009		Impaired learning and memory and decreased motor activity and coordination in adult offspring

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Moreira et al. 2012									**Methylmercury**
54	Mouse (C57BL/6) 8 M	14 days (W)	0, 5.6	BC, BI, NX	Hepatic		5.6		Elevated plasma total cholesterol
					Neuro	5.6			
Moreira et al. 2012									**Methylmercury**
55	Mouse (C57BL/6) 8 M	7 days (W)	0, 5.6	BC, BI, NX	Hepatic	5.6			
					Neuro	5.6			
Yasuda et al. 1985									**Methylmercuric chloride**
56	Mouse (JCL:ICR) 10 F	Once GD 10 or 12 (GW)	0, 10, 12, 16, 20	DX	Develop	12		16	Cleft palate; dilatation of renal pelvis; decreased fetal weight
Yasutake et al. 1991									**Methylmercuric chloride**
57	Mouse (C57BL/6N) 4–6 M, 4–6 F	Once (G)	0, 4, 8, 16, 24, 32, 40	LE, BC, HP, OF	Death			40 F	
								16 M	4/6 died
					Renal	24 F		32 F	Impaired renal function
						8 M		16 M	Impaired renal function; increased serum creatinine at ≥32 mg Hg/kg
Reuhl et al. 1981a									**Methylmercuric chloride**
58	Hamster (Golden Syrian) 10 F	Once GD 10; or 6 days GDs 10–15 (GW)	0, 1.6	DX	Develop[b]			1.6	Degeneration of cerebellar neurons in neonates
Reuhl et al. 1981b									**Methylmercuric chloride**
59	Hamster (Golden Syrian) 10 F	Once GD 10; or 6 days GDs 10–15 (GW)	0, 1.6	DX	Develop[b]			1.6	Degeneration of cerebellar neurons in adult offspring

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Inouye and Kajiwara 1988									**Methylmercuric chloride**
60	Guinea pig (Hartley) 5–9 F	Once GD 21, 28, 35, 42, or 49 (GW)	0, 11.5	CS, FI, DX	Develop			11.5	>30% total litter loss, 12–30% decrease in fetal body weight, abnormal fetal brain development
INTERMEDIATE EXPOSURE									
Charleston et al. 1994									**Methylmercury hydroxide**
61	Monkey (Macaca fascicularis) 4–5 F	6 months (IN)	0, 0.05	CS, OW, HP	Neuro		0.05		72% increase in reactive glia in the brain
Charleston et al. 1995									**Methylmercury**
62	Monkey (Macaca fascicularis) NS F	6 months (IN)	0, 0.05	HP	Neuro		0.05		72% increased number of reactive glia
Charleston et al. 1996; Vahter et al. 1994									**Methylmercury hydroxide**
63	Monkey (Macaca fascicularis) 4 F	6 months (IN)	0, 0.05	BC, BW, CS, GN, HE, HP	Bd wt	0.05			
					Hemato	0.05			
					Neuro		0.05		Decreased astrocytes in thalamus
Eto et al. 2001									**Methylmercury**
64	Monkey (Marmoset) 4 M	Up to 242 days (W)	0, 0.5	CS, BW, HP	Bd wt			0.5	Body weight loss
					Neuro		0.5		Mild ataxia; cerebral edema and gliosis, microcystic change in occipital white matter

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Mohamed et al. 1987									**Methylmercury**
65	Monkey (Macaca fascicularis) 3 M	20 weeks (IN)	0, 0.046, 0.065	CS, BW, BC, HP, RX	Bd wt	0.065			
					Repro		0.046		Increased sperm tail-defects; decreased spermatozoa motility; decreased sperm speed and forward progression
Petruccioli and Turillazzi 1991									**Methylmercuric chloride**
66	Monkey (Macaca fascicularis) 4–6 F	150 days (IN)	0, 0.0003, 0.0032, 0.04	CS, BW	Bd wt	0.04			
					Neuro	0.04			
Willes et al. 1978									**Methylmercuric chloride**
67	Monkey (Macaca fascicularis) 2 M, 2 F	28–29 days PNDs 0–28 or 29 (IN)	0, 0.5	DX	Develop[b]			0.5	Severe signs of neurotoxicity (loss of dexterity, decreased locomotor activity, ataxia, blindness, comatose); neuronal degeneration; body weight loss
Abd El-Aziz et al. 2012									**Methylmercuric chloride**
68	Rat (Sprague-Dawley) 8 F	3 weeks GDs 0–20 (GW)	0, 0.9, 1.8	DX	Develop		0.9		Incomplete skeletal ossification at ≥0.9 mg Hg/kg/day; 13–14% decrease in fetal weight, length, and head size and decrease in long bone width/length at 1.8 mg Hg/kg/day
Albores-Garcia et al. 2016									**Methylmercuric chloride**
69	Rat (Sprague-Dawley) 15 F	38 days GD 5–PND 21 (GW)	0, 0.2, 0.4	CS, DX	Develop[b]		0.2		Effects in PND 40 offspring: Impaired learning and memory at ≥0.2 mg Hg/kg/day; altered open field activity (decreased rearing) at 0.4 mg Hg/kg/day; no effect on PND 90

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Beyrouty et al. 2006									**Methylmercuric chloride**
70	Rat (Sprague-Dawley) 8 F	7–8 weeks (4 weeks premating–GD 20) (GW)	0, 0.5, 0.9	CS, BW, FI, DX	Bd wt	0.9			
					Develop	0.5	0.9		6–9% decrease in pup body weight gain from PND 4 to 41
[Offspring neurobehavior assessed PNDs 17–38]									
Bittencourt et al. 2019									**Methylmercuric chloride**
71	Rat (Wistar) 30 M	60 days (GO)	0, 0.04	BI, NX	Neuro		0.04		Impaired social and spatial memory; decreased number of mature neurons and astrocytes in hippocampus
Bittencourt et al. 2019									**Methylmercuric chloride**
72	Rat (Wistar) 30 M	60 days (GO)	0, 0.04	HP, NX	Neuro		0.04		Impaired social factual memory and spatial memory; decreased number of hippocampal neurons and astrocytes
Bittencourt et al. 2022									**Methylmercuric chloride**
73	Rat (Wistar) 27 M	60 days (GO)	0, 0.04	HP, NX	Neuro		0.04		Decreased motor activity, impaired motor coordination, reduced cerebellar density of Purkinje cells, mature neurons, astrocytes, microglia, oligodendrocytes and synaptic vesicles
Chang and Hartmann 1972									**Methylmercuric chloride**
74	Rat (Holtzman) 4 M	6 weeks (G)	0, 0.8	CS, BW, HP	Bd wt		0.8		Body weight loss
					Neuro			0.8	Hind-limb crossing, severe ataxia, tremor, partial paralysis; cellular degeneration and ultrastructural changes in dorsal root ganglia and cerebellum

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Chemelo et al. 2022									**Methylmercuric chloride**
75	Rat (Wistar) 4 F	42 days GD 0–PND 21 (F)	0, 0.03	DX	Develop		0.03		Alveolar bone loss, decreased osteocyte density and collagen in mandibles on PND 41
[Rats were given methylmercury-dosed cookies; controls were treated with vehicle-dosed cookies (ethanol)]									
Cheng et al. 2015									**Methylmercury**
76	Rat (Wistar) 3 F	6 weeks GD 1 to PND 21 (W)	0, 0.05, 0.23	RX, DX	Repro	0.23			
					Develop[b]	0.05	0.23		Delayed acquisition of neurodevelopmental reflexes; impaired motor coordination PNDs 34–35; increased motor activity in females on PND 36
da Silva et al. 2022									**Methylmercuric chloride**
77	Rat (Wistar) 3 F	42 days GD 0–PND 21 (F)	0, 0.03	DX	Develop			0.03	Loss of motor neurons and decreased myelination in the spinal cord at PND42
[Rats were given methylmercury-dosed cookies; controls were treated with vehicle-dosed cookies (ethanol)]									
de Oliveira Lopes et al. 2021									**Methylmercuric chloride**
78	Rat (Wistar) 15 M	60 days (GO)	0, 0.03	BW, HP	Bd wt	0.03			
					Musc/skel		0.03		Loss of alveolar bone volume and microstructure in mandible
Elsner 1991									**Methylmercuric chloride**
79	Rat (Wistar) 16 F	~60 days premating through lactation (W)	0, 0.19, 0.74	BW, RX, DX	Bd wt	0.74			
					Repro	0.74			
					Develop[b]		0.19		Impaired operant training and decreased ultrasonic vocalization in offspring

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Fagundes et al. 2022									**Methylmercuric chloride**
80	Rat (Wistar) 5 F	42 days GD 0–PND 21 (IN)	0, 0.03	DX	Develop		0.03		Decreased motor activity, impaired motor coordination, and impaired short-term memory in offspring on PND 41
[Rats were given methylmercury-dosed cookies]									
Freire et al. 2020									**Methylmercuric chloride**
81	Rat (Wistar) 9 M	60 days (GO)	0, 0.03	BW, HP, NX	Bd wt	0.03			
					Neuro		0.03		Decreased motor activity, moderate bristling of back hair; impaired motor coordination (balance); reduced number and altered morphology of astrocytes in visual cortex; decreased contrast index
Friedmann et al. 1998									**Methylmercuric chloride**
82	Rat (Brown Norway) 5–14 M	19 weeks 2 days/week (G)	0, 0.0008, 0.008, 0.08	CS, BW, BC, OW, RX	Bd wt	0.08			
					Repro	0.0008		0.008	No viable litters produced at 0.008 mg Hg/kg/day; 100% infertility, 8% decrease in absolute testes weight, 17% reduction in caudal sperm count, and 44% reduction in testicular testosterone at 0.08 mg Hg/kg/day
[Mated to untreated females during week 11]									
Fujimura et al. 2012									**Methylmercury**
83	Rat (Wistar) 3 F	6 weeks GD 1–PND 21 (W)	0, 0.05, 0.23, 0.5	RX, DX	Repro	0.23		0.5	No viable litters
					Develop[b]	0.05	0.23		Impaired motor coordination in PND 34–35 offspring

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Gandhi et al. 2013									**Methylmercury**
84	Rat (Wistar) 7–8 F	~17 days GD 5 until parturition (~GD 21) (G)	0, 0.5, 0.9, 1.9	CS, BW, DX	Bd wt	0.9		1.9	>50% decrease in maternal body weight gain
					Neuro	0.9		1.9	Incoordination, altered gait, hindlimb ataxia
					Develop		0.5	1.9	LOAEL: 12% decrease in mean litter weight on PND 1 SLOAEL: 100% full-litter resorption
Giménez-Llort et al. 2001									**Methylmercury hydroxide**
85	Rat (Sprague-Dawley) 7 F	22 days GD 7–PND 7 (W)	0, 0.5	BW, FI, WI, DX	Bd wt	0.5			
					Develop[c]		0.5		Increased motor activity at PND 14
Grotto et al. 2009a									**Methylmercuric chloride**
86	Rat (Wistar) 7 M	100 days (G)	0, 0.08	BW, BC, OF	Bd wt	0.08			
					Cardio		0.08		Increased systolic blood pressure
Ilback et al. 1991									**Methylmercury**
87	Rat (Sprague-Dawley) 8 F	~15 weeks 11 weeks premating through GD 21 (F)	0, 0.37	BW, DX	Bd wt	0.37			
					Develop[c]		0.37		45% increase in WBCs in offspring on PND 15
Ilback et al. 1991									**Methylmercury**
88	Rat (Sprague-Dawley) 8 F	15 days PNDs 1–15 (via dam) (F)	0, 0.37	BW, DX	Bd wt	0.37			
					Develop[c]		0.37		7% decrease in pup weight; 13% decrease in relative spleen weight; altered immune function in offspring (decreased splenic lymphoproliferative response to mitogen)

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Ilback et al. 1991									**Methylmercury**
89	Rat (Sprague-Dawley) 8 F	~17 weeks 11 weeks premating through PND 15 (F)	0, 0.37	BW, DX	Bd wt	0.37			
					Develop[c]		0.37		9% decrease in pup weight; altered immune function in offspring (increased thymic lymphoproliferative response to mitogen, decreased cell-mediated cytotoxicity)
Jindal et al. 2011									**Methylmercuric chloride**
90	Rat (Wistar) 10 B	1 month (G)	0, 0.5	OF	Cardio		0.5		Altered left ventricular function; impaired baroreflex
Kakita et al. 2000									**Methylmercuric chloride**
91	Rat (Wistar) 6 F	25 days premating–GD 19 (GW)	0, 0.8	DX	Develop[b]			0.8	Evidence of neuronal damage on PNDs 1 and 3 (not PNDs 7–180); decreased cell numbers in amygdala and hippocampus on PND 70; impaired associative learning at PND 180
Kendricks et al. 2020a									**Methylmercuric chloride**
92	Rat (Long-Evans) 8–11 M	39 days PND 21–60 (W)	0, 0.032, 0.320	DX	Develop	0.032			
[Attention and memory assessed at 7.5 months]									
Kendricks et al. 2020b									**Methylmercuric chloride**
93	Rat (Long-Evans) 12 M	39 days PND 21–60 (W)	0, 0.032, 0.320	DX	Develop	0.032			
[Operant learning assessed at 6 months]									

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Khera 1973									**Methylmercuric chloride**
94	Rat (Wistar) 14–19 M	95–125 days (G)	0, 0.1, 0.5, 1	CS, BW, RX	Bd wt	0.5		1	Body weight loss
					Repro	0.1		0.5	Decreased viable fetuses at ≥0.5 mg Hg/kg/day; decreased fertility at 1 mg Hg/kg/day
[Males mated to untreated females concurrent with exposure]									
Khera and Tabacova 1973									**Methylmercuric chloride**
95	Rat (Wistar) 35 F	Up to 122 days 2 generations (F)	0, 0.002, 0.01, 0.05, 0.25	CS, BW, HP, DX	Bd wt	0.25			
					Renal	0.25			
					Repro	0.25			
					Develop	0.05	0.25		Increased incidence of ocular lesions (delayed eyelid separation, suborbital edema, corneal opacity)
Larsen and Brændgaard 1995; Schiønning et al. 1998a									**Methylmercuric chloride**
96	Rat (Wistar) 10–18 M	19 days (GW)	0, 1.6	CS, BW, OW, HP	Bd wt			1.6	Body weight loss
					Neuro			1.6	Axonal destruction in dorsal root of spinal cord, loss of large motor neurons in dorsal root ganglia; clinical signs of neurotoxicity (apathy, hindlimb crossing, clumsiness, ataxia)
Moussa et al. 2010									**Methylmercury**
97	Rat (Wistar) 10 M	8 weeks (W)	0, 3.2	BW, BC, OW, HP	Bd wt			3.2	29% decrease in final body weight
					Repro		3.2		98% decrease in serum testosterone; 54–73% decrease in testicular testosterone

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Newland and Reile 1999; Newland and Rasmussen 2000; Newland et al. 2004									**Methylmercuric chloride**
98	Rat (Long-Evans) 10 F	~10–13 weeks 4–7 weeks premating–PND 16 (W)	0, 0.045, 0.6	RX, DX	Repro	0.6			
					Develop[b]		0.045		Acceleration of age-related cognitive decline in operant training in offspring from 6 months to 2.5 years
Oliveira et al. 2018									**Methylmercury**
99	Rat (Wistar) 5 F	35 days PNDs 31–65 (GW)	0, 0.037	DX	Develop		0.037		Decreased locomotor activity, bradykinesia, impaired motor coordination
Ortega et al. 1997a									**Methylmercuric chloride**
100	Rat (Sprague-Dawley) 6 M	8 weeks (W)	0, 0.0004, 0.04	BC, BW, IX	Bd wt	0.004			
					Immuno		0.0004		Biphasic lymphocyte response to mitogen PHA (544% increase at 0.0004 mg Hg/kg/day; 56% decrease at 0.04 mg Hg/kg/day)
Ortega et al. 1997a									**Methylmercuric sulfide**
101	Rat (Sprague-Dawley) 6 M	8 weeks (W)	0, 0.0004, 0.04	BC, BW, IX	Bd wt	0.04			
					Immuno		0.0004		278% increase in lymphocyte response to mitogen PHA at 0.0004 mg Hg/kg/day; no change at 0.04 mg Hg/kg/day
Ortega et al. 1997a									**Bis(methylmercury)sulfide**
102	Rat (Sprague-Dawley) 6 M	8 weeks (W)	0, 0.0004, 0.04	BC, BW, IX	Bd wt	0.04			
					Immuno		0.0004		300% increase in lymphocyte response to mitogen PHA at 0.0004 mg Hg/kg/day; no change at 0.04 mg Hg/kg/day

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Ortega et al. 1997a									**Tris(methylmercuric)sulphonium ion**
103	Rat (Sprague-Dawley) 6 M	8 weeks (W)	0, 0.0004, 0.04	BC, BW, IX	Bd wt	0.04			
					Immuno		0.0004		56% decrease in lymphocyte response to mitogen PHA
Ortega et al. 1997b									**Methylmercuric chloride**
104	Rat (Sprague-Dawley) 6 M	8 weeks (W)	0, 0.0004, 0.04	BC, IX	Endocr		0.0004		>100% increase in ACTH
					Immuno		0.0004		Biphasic lymphocyte response to mitogen Con-A (313% increase at 0.0004 mg Hg/kg/day; 67% decrease at 0.04 mg Hg/kg/day); >275% increase in IL-6 at both doses
Ortega et al. 1997b									**Bis(methylmercury)sulfide**
105	Rat (Sprague-Dawley) 6 M	8 weeks (W)	0, 0.0004, 0.04	BC, IX	Endocr		0.0004		>100% increase in ACTH
					Immuno		0.0004		>133% increase in lymphocyte response to Con-A; 300% increase in IL-6 at 0.04 mg Hg/kg/day
Ortega et al. 1997b									**Bis(methylmercury)sulfide**
106	Rat (Sprague-Dawley) 6 M	16 weeks (W)	0, 0.0004, 0.04	BC, IX	Endocr	0.04			
					Immuno		0.0004		Biphasic lymphocyte response to mitogen Con-A (69% decrease at 0.0004 mg Hg/kg/day; 200% increase at 0.04 mg Hg/kg/day); >140% increase in IL-6 at both dose levels

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Ortega et al. 1997b									**Methylmercuric chloride**
107	Rat (Sprague-Dawley) 6 M	16 weeks (W)	0, 0.0004, 0.04	BC, IX	Endocr		0.0004		149% increase in ACTH
					Immuno		0.0004		>75% decrease in lymphocyte response to mitogen Con-A at ≥0.0004 mg Hg/kg/day; 14-fold increase in IL-6 at 0.04 mg Hg/kg/day
Rosa-Silva et al. 2020a, 2020b									**Methylmercuric chloride**
108	Rat (Wistar) 10 M	45 days (GO)	0, 0.4	BW, FI, BC, NX	Bd wt		0.4		21% decrease in body weight with 8% decrease in food consumption
					Hepatic		0.4		174% increase in serum AST and 106% increase in serum ALT
					Neuro		0.4		Increased motor activity and increased anxiety-like behavior (at age PND 145 days)
Rosa-Silva et al. 2020a, 2020b									**Methylmercuric chloride**
109	Rat (Wistar) 10 F	87 days GD 1–PND 22 + PNDs 100–145 (GO)	0, 0.4	BW, FI, BC, NX, DX	Develop		0.4		25% decrease in body weight with 8% decrease in food consumption Hepatic: 220% increase in serum AST and 123% increase in serum ALT; increased motor activity and increased anxiety-like behavior at PND 145
Rossi et al. 1997									**Methylmercury hydroxide**
110	Rat (Sprague-Dawley) 8 F	22 days GD 7–PND 7 (W)	0, 0.474	BW, FI, WI, DX	Bd wt	0.474			
					Develop[b]	0.474 F			
							0.474 M		Decreased motor activity in male offspring at 6 months

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Sakamoto et al. 2002									**Methylmercury**
111	Rat (Wistar) 4–10 F	One generation 8 weeks premating through PND 30 (via dam) PNDs 31–55 (direct) (F)	0, 0.5	DX	Develop[b]		0.5		Impaired motor coordination and memory at PNDs 35–42; focal dysplastic lesions in cerebellum
Sakamoto et al. 2004									**Methylmercuric chloride**
112	Rat (Wistar) 12 M	30 days PNDs 1–30 (IN)	0, 0.8, 2, 4	DX	Develop[b]		0.8	4	LOAEL: Impaired associative learning at 6 weeks of age SLOAEL: Body weight loss, impaired motor coordination and hindlimb crossing/paralysis, widespread CNS degeneration and neuronal loss
[Via micropipette in water and condensed milk]									
Sakamoto et al. 2017									**Methylmercuric chloride**
113	Rat (Wistar) 5 M	5 weeks (W)	0, 0.3, 1.4	BW, HP	Bd wt	0.3		1.4	Body weight loss
					Neuro			1.4	Severe damage and degeneration of sensory regions of the spinal cord (dorsal root ganglia, posterior roots, posterior column)
Sakamoto et al. 2017									**Methylmercuric chloride**
114	Rat (Wistar) 10 M	5 weeks (W)	0, 1.9, 9.72	BW, HP	Bd wt	1.9		9.72	Body weight loss
					Neuro			9.72	Severe damage and degeneration of sensory regions of the spinal cord (dorsal root ganglia, posterior roots, posterior column)

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Santana et al. 2019									**Methylmercury**
115	Rat (Wistar) 20 M	60 days (GO)	0, 0.037	BW, HP, NX	Bd wt	0.037			
					Neuro		0.037		Decreased motor activity and impaired coordination; decreased density of neurons and astrocytes in motor cortex
Sitarek and Gralewicz 2009									**Methylmercuric chloride**
116	Rat (Wistar) 11–12 F	5 weeks GD 7–PND 21 (W)	0, 0.5, 1.9	CS, BW, FI, WI, DX	Bd wt	0.5			
					Neuro	0.5		1.9	Ataxia
					Develop	0.5	1.9		~8–10% decrease in PND 21 pup weight; delayed development of righting reflex
Szász et al. 2002									**Methylmercuric chloride**
117	Rat (Wistar) 5 F	7–8 weeks premating–PND 21 (W)	0, 0.3	CS, BW, FI, WI, RX, DX	Bd wt	0.3			
					Repro	0.3			
					Develop[b]		0.3		11% decrease in birth weight; increased susceptibility to seizure activity at PNDs 28 and 90
Tamashiro et al. 1986									**Methylmercuric chloride**
118	Rat (SHR/NCrj) 10 M, 10 F	26 days (NS)	0, 1.6	LE, CS, BW, NX, OF	Death			1.6 M	100% mortality
					Bd wt			1.6	Body weight loss; severe in males
					Cardio		1.6 F		Increased systolic blood pressure
					Neuro		1.6		Hind limb crossing, disturbed righting reflex, abnormal gait

[Spontaneous hypertensive rat strain]

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Tonk et al. 2010									**Methylmercuric chloride**
119	Rat (Wistar) 11–14 F	26 days GD 6–PND 10 (GO)	0, 0.08, 0.3, 0.6, 0.8, 1.2, 1.6	LE, CS, BW, DX	Death			1.6	5/11 dams sacrificed moribund
					Bd wt	0.8	1.2	1.6	LOAEL: Decreased maternal weight SLOAEL: Weight loss
					Neuro	1.2		1.6	Unsteady gait, partial hind limb paralysis
					Develop[c]		0.08	0.8	LOAEL: Altered functional immune endpoints in PND 21–70 offspring SLOAEL: Decreased body weight and prenatal/neonatal death
Vezér et al. 2005									**Methylmercuric chloride**
120	Rat (Wistar) 24 M	5 weeks 5 days/week (GW)	0, 0.5, 2.0	NX	Neuro		0.5		Decreased motor activity; altered acoustic startle response; altered electrophysiological responses in sensory cortices and hippocampus
Vilagi et al. 2000									**Methylmercuric chloride**
121	Rat (Wistar) 8 F	6 weeks GD 0–PND 21 (W)	0, 0.347	DX	Develop[b]			0.347	>20% decrease in F1 body weight at PND 28; decreased spontaneous and evoked cortical potentials in F1 pups at PND 28
Wakita 1987									**Methylmercuric chloride**
122	Rat (Wistar) 9 M	23–28 days (G)	0, 0.4	CS, BW, OF	Bd wt	0.4			
					Cardio		0.4		Persistent increases in systolic blood pressure post-exposure
Wang et al. 2022a									**Methylmercuric chloride**
123	Rat (Sprague-Dawley) 6 F	17 days GD5-PND1 (GW)	0, 0.48, 0.96, 1.9	DX	Develop[c]		0.48		PND 60: Impaired spatial memory, decreased neuronal density in hippocampus

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Wild et al. 1997									**Methylmercuric chloride**
124	Rat (Sprague-Dawley) NS M, F	14–16 weeks premating–PND 21 (W)	0, 0.0006, 0.06	BW, DX	Bd wt	0.06 F			
					Develop[c]		0.0006		Altered functional immune endpoints in PND 42 and 84 offspring (enhanced lymphoproliferation in response to mitogens; decreased NK cell activity)
Wild et al. 1997									**Bis(methylmercury)sulfide**
125	Rat (Sprague-Dawley) NS M, F	14–16 weeks premating–PND 21 (W)	0, 0.0003	BW, DX	Bd wt	0.0003 F			
					Develop		0.0003		Altered functional immune endpoints in PND 84 offspring (enhanced lymphoproliferation in response to mitogens)
Wildemann et al. 2015a									**Methylmercuric chloride**
126	Rat (Wistar) 5–9 M	4 weeks (W)	0, 0.002, 0.005, 0.009, 0.018, 0.036, 0.216, 0.879	BW, OW, OF	Bd wt	0.216		0.879	66% decrease in body weight gain
					Cardio	0.002	0.005		Elevated systolic blood pressure and pulse pressure at ≥0.005 mg Hg/kg/day; elevated diastolic blood pressure at ≥0.009 mg/kg/day
Wildemann et al. 2015b									**Methylmercuric chloride**
127	Rat (Wistar) 5–6 M	4 weeks (W)	0, 0.018, 0.216	BW, OW, OF	Bd wt	0.216			
					Cardio	0.018	0.216		Elevated systolic blood pressure and pulse pressure
Wildemann et al. 2016									**Methylmercuric chloride**
128	Rat (Wistar) 5–6 M	4 weeks (W)	0, 0.006, 0.285	BC, BI, UR, OF	Cardio		0.006		Elevated systolic blood pressure at ≥0.006 mg Hg/kg/day; elevated diastolic at 0.285 mg/kg/day
					Renal	0.006	0.285		Elevated urinary creatinine

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Wu et al. 2023									**Methylmercuric chloride**
129	Rat (Sprague-Dawley) 8 M	3 months (G)	0, 0.09	BW, BI, OW, HP, NX	Bd wt	0.09			
					Neuro		0.09		Impaired spatial memory; reduced hippocampal neurons in pyramidal layer
Yip and Chang 1981									**Methylmercuric chloride**
130	Rat (Charles River) 6 M	8 weeks (G)	0, 1.6	HP	Neuro			1.6	Extensive degeneration of dorsal root fibers
Algahtani et al. 2023									**Methylmercuric chloride**
131	Mouse (C57BL/6) 8 M	3 weeks PNDs 21–42 Oral	0, 0.08	DX	Develop	0.08			
Algahtani et al. 2023									**Methylmercuric chloride**
132	Mouse (BTBR) 8 M	3 weeks PNDs 21–42 Oral	0, 0.08	DX	Develop	0.08			
Al-Mazroua et al. 2022									**Methylmercuric chloride**
133	Mouse (C57BL/6) 6 M	28 days (IN)	0, 0.16	BC, BI, NX	Immuno		0.16		Increased serum IFN-γ
					Neuro	0.16			
[locomotor behavior]									
Berthoud et al. 1976									**Methylmercuric chloride**
134	Mouse (CD-1) 12 M	60 days (G)	0, 0.25, 1, 4	CS, BW, FI, HP	Neuro		0.25	1	LOAEL: Hindleg weakness SLOAEL: Motor incoordination and neuronal degeneration and microgliocytosis in subcortical regions of the brain

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Blakley et al. 1980									**Methylmercuric chloride**
135	Mouse (ICR) 9–10 M	3 weeks (W)	0, 0.08, 0.35, 1.7	BW, WI, GN, IX	Bd wt	1.7			
					Immuno		0.08		Suppressed immune response to antigens
Boomhower and Newland 2019									**Methylmercuric chloride**
136	Mouse (C57BL/6N) 12 M	39 days PNDs 21–59 (W)	0, 0.032, 0.32	DX	Develop		0.032		Impaired operant learning (faster minimum response times and higher saturation rates) on PND 200
Boomhower and Newland 2019									**Methylmercuric chloride**
137	Mouse (C57BL/6N) 12 M	39 days PNDs 24–62 (W)	0, 0.32	DX	Develop	0.32			
[Operant learning tested on PND 200]									
Bourdineaud et al. 2011									**Methylmercury**
138	Mouse (C57Bl/6) 12 M	2 months (F)	0, 0.00046, 0.0073	BW, NX	Bd wt	0.0073			
					Neuro	0.00046	0.0073		Impaired memory
Chen et al. 2012									**Methylmercuric chloride**
139	Mouse (ICR) 16 M	4 or 6 weeks (GW)	0, 1.6	BC	Endocr		1.6		~80–95% decrease in plasma insulin; ~25–40% increase in serum glucose
Dietrich et al. 2005									**Methylmercuric chloride**
140	Mouse (Swiss) 13–14 M	21 days (W)	0, 4.7, 8.7	LE, CS, BW, WI, NX	Death			8.7	100% mortality
					Bd wt			4.7	>10% body weight loss
					Neuro		4.7		Impaired motor coordination, hypoactivity, altered gait

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Franco et al. 2006									**Methylmercuric chloride**
141	Mouse (albino) 7 F	21 days PNDs 1–21 (via dam) (W)	0, 4.7	BW, WI, DX	Bd wt	4.7			
					Develop		4.7		Impaired motor coordination in PND 21 offspring
Ghizoni et al. 2018									**Methylmercuric chloride**
142	Mouse (Swiss) 21–22 F	42 days GD 1–PND 21 (W)	0, 1	BW, FI, WI, DX	Bd wt	1			
					Develop[b]		1		Impaired motor coordination (balance) in offspring on PND 22
Goulet et al. 2003									**Methylmercuric chloride**
143	Mouse (C57BL/6) 14–34 F	6 weeks GD 2–PND 21 (W)	0, 0.9, 1.3, 1.7	DX	Repro	1.3	1.7		18% decrease in number of pups/litter
					Develop[b]	1.7 F			
							0.9 M	1.7 M	LOAEL: Reduced locomotor activity SLOAEL: Impaired working memory at ≥1.3 mg Hg/kg/day; 14% reduction in postnatal survival at 1.7 mg/kg/day
[Neurobehavior assessed at PNDs 35–70]									
Havarinasab et al. 2007									**Methylmercuric chloride**
144	Mouse (A.SW) 5–7 F	30 days (W)	0, 0.420	BC, BI, IX	Immuno		0.42		Positive ANoA and ACA; elevated serum IgG1, IgG2a; polyclonal B-cell activation
[Autoimmune susceptible mice]									
Hirano et al. 1986									**Methylmercuric chloride**
145	Mouse (ICR) 6 M, 6 F	26 weeks (F)	M: 0, 0.0300, 0.150, 0.724 F: 0, 0.0254, 0.115, 0.627	CS, BW, GN, HP	Bd wt	0.724			
					Resp	0.724			
					Cardio	0.724			
					Gastro	0.724			
					Musc/skel	0.724			

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
					Hepatic	0.724			
					Renal	0.115	0.627		Epithelial degeneration and regeneration of the renal proximal tubules
					Dermal	0.724			
					Ocular	0.724			
					Endocr	0.724			
					Immuno	0.724			
					Neuro	0.724			
					Repro	0.724			
[Interim sacrifice group]									
Huang et al. 2011									**MethylImercury**
146	Mouse (ICR) 12–15 M	7 weeks PNDs 21–70 (GW)	0, 0.02	DX	Develop[b]		0.02		Hyperactivity, impaired motor coordination, and hearing impairment at PND 70
Huang et al. 2011									**MethylImercury**
147	Mouse (ICR) 12–15 F	10–17 weeks Premating through PND 21 (via dam) Select pups: PNDs 21–70 (direct) (GW)	0, 0.02	RX, DX	Repro		0.02		16% decrease in litter size
					Develop[b]			0.02 M	Effects at PND 70: 19–32% decrease in pup weight, decreased motor activity and impaired hearing (both groups), impaired motor coordination (direct group only)
Ilback 1991									**MethylImercury**
148	Mouse (BALB/c CUM) 8 F	12 weeks (F)	0, 0.77	BW, BC, OW, IX	Bd wt	0.77			
					Immuno		0.77		Reduced natural killer T-cell activity, enhanced T-cell lymphoproliferative response, 22% decrease in absolute thymus weight, and ~50% decrease in thymic cell number

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Ishihara et al. 2019									**Methylmercuric chloride**
149	Mouse (ICR) 10 M	4–8 weeks (IN)	0, 3.2	HP, NX	Neuro		3.2		Impaired motor coordination at 5–8 weeks; impaired auditory function, ventricular enlargement and reactive astrocytes in inferior colliculus
Kendricks and Newland 2021									**Methylmercuric chloride**
150	Mouse (C57BL/6) 8–10 M	37 days PNDs 22–59 (W)	0, 0.032, 0.400	DX	Develop	0.032	0.4		Impaired attention at 11–14 months
Kirkpatrick et al. 2015									**Methylmercury**
151	Mouse (C57BL/6N) NS M	21–28 days (IN)	0, 4.6	BI, NX	Bd wt	4.6			
					Neuro		4.6		Impaired motor coordination at 4 weeks
[Mice given MeHg-dosed cookies]									
Loan et al. 2023									**Methylmercuric chloride**
152	Mouse (C57BL/6) NS F (dams); 9–16 B (pups)	3 weeks GDs 0–21 (W)	0, 0.05	DX	Develop		0.05		Decreased frequency and length of ultrasonic pup vocalizations at PND 9; decreased socialization, increased stereotypical behaviors, and impaired reversal learning at PND 60
MacDonald and Harbison 1977									**Methylmercuric chloride**
153	Mouse (Swiss) 35–40 M	28 weeks (W)	0, 0.89, 9.5	CS, BW, WI, HP	Death			9.5	100% mortality by 4–5 weeks
					Bd wt	0.89		9.5	Body weight loss
					Gastro	9.5			
					Hepatic	9.5			
					Renal	0.89	9.5		Slight degenerative changes in proximal tubular epithelial cells
					Neuro			0.89	Severe neurotoxicity (clinical signs, behavioral signs, histopathologic cerebellar changes)

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Maqbool et al. 2019									**Methylmercuric chloride**
154	Mouse (NMRI) 6 M	4 weeks (GW)	0, 2.0, 4.0, 8.0	BC	Other noncancer		2		47% increased plasma insulin
Mitsumori et al. 1981									**Methylmercuric chloride**
155	Mouse (ICR) 60 M, 60 F	26 weeks (F)	0, 2.3, 4.5	LE, CS, HP	Death			4.5	51/60 males and 59/60 females died or were sacrificed moribund by study week 26
					Neuro			4.5	Clinical signs of neurotoxicity prior to death or sacrifice
Moreira et al. 2012									**Methylmercury**
156	Mouse (Swiss Albino) NS M	28 days (W)	0, 5.6	BC	Hepatic		5.6		Elevated plasma total cholesterol, HDL cholesterol, non-HDL cholesterol, and triglycerides
Moreira et al. 2012									**Methylmercury**
157	Mouse (C57BL/6) 6 M	21 days (W)	0, 5.6	BC, HP	Hepatic		5.6		Elevated plasma total cholesterol
					Renal		5.6		Glomerular shrinkage and tubular vacuolization
Moreira et al. 2012									**Methylmercury**
158	Mouse (C57BL/6) 8 M	21 days (W)	0, 5.6	BC, BI, NX	Hepatic		5.6		Elevated plasma total cholesterol
					Neuro		5.6		Decreased motor activity
Nascimento et al. 2022									**Methylmercuric chloride**
159	Mouse C57BL/6 60 M	30 days (W)	0, 0.21	BW, BC, BI, NX	Bd wt	0.21			
					Hepatic		0.21		Increased serum total cholesterol and triacylglycerol levels
					Immuno		0.21		Increase plasma TNF and LPS levels

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
					Neuro		0.21		Decreased motor activity and exploration, increased stereotypy, impaired spatial learning and memory
Rand et al. 2020									**Methylmercuric chloride**
160	Mouse (C57BL/6) 3–18 F	56 days 2 weeks prior to mating–PND 21 (W)	0, 0.13, 1.3	HP, DX	Musc/skel	1.3			
					Develop	0.13		1.3	PND 0: Decreased weight in males (~5%) and females (~8%) PND 60: decreased forelimb strength in both sexes; males with decreased rearing distance, and increased resting time in open field
Silva et al. 2021									**Methylmercuric chloride**
161	Mouse (C57BL/6) 8–15 F	15 days (W)	0, 2.7	BW, FI, WI, BC, HP, OF	Bd wt	2.7			
					Cardio		2.7		Elevated blood pressure, atherosclerotic lesions
					Hepatic		2.7		Elevated total cholesterol and non-HDL cholesterol
Thuvander et al. 1996									**Methylmercuric chloride**
162	Mouse (BALB/c) 27–72 F	15–16 weeks 10 weeks premating through PND 15 (F)	0, 0.098, 0.98	CS, BW, RX, DX	Bd wt	0.98			
					Repro	0.98			
					Develop[c]		0.098		Alterations in functional immune endpoints and thymocyte cell populations in offspring at ≥0.098 mg Hg/kg/day; 8% decrease in pup body weight at 0.98 mg Hg/kg/day

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Weiss et al. 2005									**Methylmercuric chloride**
163	Mouse (B6C3F1/HSD) 15–18 F	9–10 weeks Premating – PND 13 (W)	0, 0.2, 0.6	BW, RX, DX	Bd wt	0.6			
					Repro	0.6			
					Develop[b]		0.2		Impaired spatial learning and increased hindlimb splay at 5 and/or 15 months
Yoshida et al. 2011									**Methylmercury**
164	Mouse (C57BL/6) NS F	19 days GDs 0–18 (F)	0, 0.9	DX	Develop[b]		0.9		Male offspring: Increased activity, decreased anxiety, and impaired spatial learning at PND 56 Female offspring: Decreased activity at PND 56
Yoshida et al. 2018									**Methylmercuric chloride**
165	Mouse (C57BL/6J) 7–8 F	27 days PNDs 2–28 (F)	0, 0.9	DX	Develop[b]		0.9		Decreased motor activity at PND 77
Zhang et al. 2011									**Methylmercury**
166	Mouse (A.SW) 2–7 F	5 weeks GD 8–PND 21 (W)	0, 0.03, 0.06, 0.13	DX	Develop	0.06		0.13	Complete litter loss in 6/7 dams
[Autoimmune susceptible mouse strain]									
Zhang et al. 2011									**Methylmercury**
167	Mouse (A.SW) 3–5 F	5 weeks GD 8–PND 21 (W)	0, 0.06	DX, IX	Immuno	0.06			
					Develop[b,c]		0.06 F		Hyperactivity, cerebellar inflammation
						0.06 M			
[Autoimmune susceptible mouse strain; offspring immune and behavioral endpoints evaluated at PNDs 21 and 70]									
Zhang et al. 2011									**Methylmercury**
168	Mouse (A/WySnJ) 3–5 F	5 weeks GD 8–PND 21 (W)	0, 0.06	DX, IX	Immuno	0.06			
					Develop[b,c]	0.06			
[Offspring immune and behavioral endpoints evaluated at PNDs 21 and 70]									

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Koller et al. 1977									**Methylmercuric chloride**
169	Rabbit (New Zealand) 10 M, 10 F	14 weeks (F)	M: 0, 0.05, 0.53, 1.1 F: 0, 0.05, 0.49, 1.0	LE, CS, BW, BC, HE, HP, IX	Death			1	100% mortality
					Bd wt	0.05			
							0.49 F		Decreased body weight gain (13%)
								0.53 M	Decreased body weight gain (43%)
					Hemato	0.53			
					Renal	0.49	1		Mild-to-moderate proximal tubule necrosis
					Immuno	0.05	0.49		Decreased immune response to influenza infection
					Neuro	0.05		0.49	Ataxia and intermittent convulsions at ≥0.49 mg Hg/kg/day; cerebellar degeneration at ≥1.0 mg Hg/kg/day
Chang et al. 1974									**Methylmercury**
170	Cat 15–16 B	11 months (F)	0, 0.012	CS, BW, HP	Neuro			0.012	Serious clinical signs of neurotoxicity, degenerative brain lesions
Charbonneau et al. 1976									**Methylmercury**
171	Cat 4–5 M, 4–5 F	Up to 1 year (F)	0.003, 0.0084, 0.020, 0.046, 0.074, 0.176	LE, CS, BW, FI, WI, BC, UR, GN, HP	Death	0.074		0.176	100% sacrifice moribund by ~16 weeks
					Bd wt	0.176			
					Resp	0.176			
					Cardio	0.176			
					Gastro	0.176			
					Hemato	0.176			
					Hepatic	0.176			
					Renal	0.176			
					Endocr	0.176			
					Immuno	0.176			

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
					Neuro	0.046	0.074	0.176	LOAEL: Clinical signs of neurotoxicity first observed at ~40 weeks SLOAEL: Clinical signs of neurotoxicity first observed at ~14 weeks; serious clinical signs and degeneration in cerebral cortex, cerebellum, and dorsal root ganglia observed at ~16 weeks
Khera et al. 1974									**Methylmercuric chloride**
172	Cat 3 or 5 M, 2 or 6 F	44–243 days (G)	0, 0.25, 0.37, 0.5, 0.75, 1.0	CS, HP	Neuro			0.25	Degeneration in granule cells, Purkinje cells, and cerebral neurons; distorted myelination in cortical hemispheres
CHRONIC EXPOSURE									
Axelrad et al. 2007a, 2007b									**Methylmercury**
173	Human 238–917 per study	Chronic dietary intake; high fish consumers (F)	0.34–0.62	DX	Develop[b]	0.00041[d]			NOAEL is based on estimated mercury dose associated with a 1-point decrease in IQ (calculated from -0.18 IQ points per µg Hg/g hair)
[meta-analysis of three prospective birth cohorts]									
Burbacher and Mottet 1988; Burbacher et al. 2005									**Methylmercury hydroxide**
174	Monkey (*Macaca fascicularis*) 7–16 F	Up to ~4 years (two breeding cycles) (IN)	0, 0.04, 0.06, 0.08	BW, BC, NX, RX, DX	Bd wt	0.08			
					Neuro	0.06		0.08	Slight tremors, decreased sucking response, gross motor incoordination, apparent blindness
					Repro	0.04		0.06	54% decrease in number of viable pregnancies

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Burbacher et al. 1984									**Methylmercury hydroxide**
175	Monkey (*Macaca fascicularis*) 7–8 F	Up to 395 days (four menstrual cycles, mating, gestation) (IN)	0, 0.04, 0.08	CS, BW, NX, RX, DX	Bd wt	0.08			
					Neuro	0.04		0.08	Gross motor incoordination, decreased sucking responses, intention tremors, blindness
					Repro	0.04		0.08	Decreased number of viable pregnancies
					Develop	0.04			
Charleston et al. 1994									**Methylmercury hydroxide**
176	Monkey (*Macaca fascicularis*) 4–5 F	12 or 18 months (IN)	0, 0.05	CS, OW, HP	Neuro		0.05		Up to 152% increase in number of reactive glia in the brain
Charleston et al. 1995									**Methylmercury**
177	Monkey (*Macaca fascicularis*) NS F	12 or 18 months (IN)	0, 0.05	HP	Neuro		0.05		89–152% increased number of reactive glia
Charleston et al. 1996; Vahter et al. 1994									**Methylmercury hydroxide**
178	Monkey (*Macaca fascicularis*) 4–5 F	12 or 18 months (IN)	0, 0.05	BC, BW, CS, GN, HE, HP, OW	Bd wt	0.05			
					Hemato	0.05			
					Neuro		0.05		Increased microglia and decreased astrocytes in thalamus
Rice 1989c									**Methylmercuric chloride**
179	Monkey (*Macaca fascicularis*) 4 M, 1 F	6.5–7 years (starting at birth) (IN)	0, 0.05	CS, NX	Neuro		0.05		Clumsiness, impaired fine motor skills, and diminished touch and pinprick sensitivity at 13–14 years

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Rice 1998a; Rice and Hayward 1999									**Methylmercuric chloride**
180	Monkey (*Macaca fascicularis*) 1–2 B	Gestation–4 years of age 5 days/week (IN)	0, 0.010, 0.025, 0.050	DX	Develop[b]		0.01		Impaired auditory function and visual spatial discrimination in offspring at 10–19 years
Rice 1998b; Rice and Hayward 1999									**Methylmercuric chloride**
181	Monkey (*Macaca fascicularis*) 2–4 M, 1–2 F	7 years 5 days/week (C)	0, 0.050	NX	Neuro	0.05			
[Visual function and operant training assessed at 10–20 years]									
Rice and Gilbert 1982, 1990									**Methylmercuric chloride**
182	Monkey (*Macaca fascicularis*) 5 treated, 2 controls, NS	3–4 years (starting at birth) (IN)	0, 0.05	DX	Develop[b]		0.05		Spatial visual impairment at 3–4 years; 3/5 high luminance impairment, 3/5 high and middle frequency impairment; 5/5 low luminance impairment
Rice and Gilbert 1990									**Methylmercuric chloride**
183	Monkey 1–5 NS	Gestation–4–4.5 years old; 3 days/week during gestation; 5 days/week postnatally (IN)	0, 0.01, 0.025, 0.05	DX	Develop[b]	0.025		0.05	Overt neurotoxicity in 2/5 offspring
Rice and Gilbert 1992									**Methylmercuric chloride**
184	Monkey (*Macaca fascicularis*) 3–5 NS	7 years (starting at birth) (C)	0, 0.05	CS, NX	Neuro		0.05		Clumsiness and impaired high-frequency hearing at 13–14 years

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Solecki et al. 1991									**Phenyl mercuric acetate**
185	Rat (Wistar) 20 M	103 weeks (W)	0, 0.37, 3.7	LE, BW, HE, HP	Death			3.7	14/20 treated died, compared to 7/20 control
					Bd wt		0.37		Approximately 10% decrease in body weight gain
					Gastro	0.37	3.7		Ulcerative cecitis
					Hemato	0.37	3.7		Increased leukocytes; decreased erythrocytes, hemoglobin, and hematocrit
					Renal		0.37		Increased severity of chronic renal nephrosis
					Endocr	3.7			
					Cancer			3.7	CEL: Renal cell adenoma
Verschuuren et al. 1976									**Methylmercuric chloride**
186	Rat (NS) 25 M, 25 F	2 years (F)	M: 0, 0.006, 0.03, 0.16; F: 0, 0.007, 0.04, 0.18	LE, CS, BW, FI, BC, BI, UR, HE, OW, HP, NX	Bd wt	0.18 F			
						0.16 M			
					Resp	0.18 F			
						0.16 M			
					Cardio	0.18 F			
						0.16 M			
					Gastro	0.18 F			
						0.16 M			
					Hemato	0.18 F			
						0.16 M			
					Musc/skel	0.18 F			
						0.16 M			
					Hepatic	0.18 F			
						0.16 M			
					Renal	0.04 F	0.18 F		36% increase in relative kidney weight, decreased kidney enzyme activity

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
						0.03 M	0.16 M		30% increase in relative kidney weight, decreased kidney enzyme activity
					Dermal	0.18 F			
						0.16 M			
					Ocular	0.18 F			
						0.16 M			
					Endocr	0.18 F			
						0.16 M			
					Immuno	0.18 F			
						0.16 M			
					Neuro	0.18 F			
						0.16 M			
					Repro	0.18 F			
						0.16 M			
Hirano et al. 1986									**Methylmercuric chloride**
187	Mouse (ICR) 54 M, 54 F	104 weeks (F)	M: 0, 0.0300, 0.150, 0.724; F: 0, 0.0254, 0.115, 0.627	LE, CS, BW, GN, HP	Bd wt	0.724			
					Resp	0.724			
					Cardio	0.724			
					Gastro	0.724			
					Musc/skel	0.724			
					Hepatic	0.724			
					Renal	0.115 F	0.627 F		Epithelial degeneration and regeneration of the renal proximal tubules at 0.627 mg Hg/kg/day

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
						0.03 M	0.15 M		Epithelial degeneration and regeneration of the renal proximal tubules, urinary casts, and pelvic dilation at ≥0.15 mg Hg/kg/day; cystic kidney and epithelial regeneration and focal hyperplasia at 0.724 mg Hg/kg/day
					Dermal	0.724			
					Ocular	0.724			
					Endocr	0.724			
					Immuno	0.724			
					Neuro	0.115 F		0.627 F	Degeneration or fibrosis of sciatic nerve
						0.724 M			
					Repro	0.627 F			
						0.15 M	0.724 M		Decreased sperm in testes
					Cancer			0.724 M	CEL: Renal epithelial adenocarcinoma in males
Mitsumori et al. 1981									**Methylmercuric chloride**
188	Mouse (ICR) 60 M, 60 F	78 weeks (F)	0, 2.1, 4.1	CS, HP	Neuro		2.1 M		Clinical signs of neurotoxicity
					Cancer			2.1 M	CEL: kidney tumors (11 adenocarcinomas, 5 adenomas)

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
Mitsumori et al. 1990									**Methylmercuric chloride**
189	Mouse (B6C3F1) 60 M, 60 F	104 weeks (F)	M: 0, 0.0305, 0.139, 0.686 F: 0, 0.0265, 0.133, 0.601	LE, CS, BW, GN, HP	Death			0.686 M	50/60 males died versus 31/60 controls
					Bd wt	0.133 F	0.601 F		~10% decrease in body weight gain
					Resp	0.686			
					Cardio	0.686			
					Gastro	0.601 F			
						0.139 M	0.686 M		Stomach ulceration
					Musc/skel	0.686			
					Hepatic	0.686			
					Renal	0.133 F	0.601 F		Increased chronic nephropathy with epithelial cell degeneration; regeneration of the proximal tubules; interstitial fibrosis
						0.0305 M	0.139 M		Increased chronic nephropathy with epithelial cell degeneration; regeneration of the proximal tubules; interstitial fibrosis
					Dermal	0.686			
					Ocular	0.686			
					Endocr	0.686			
					Immuno	0.686			
					Neuro	0.601 F			
						0.139 M		0.686 M	Sensory neuropathy; cerebral and cerebellar necrosis; posterior paresis/paralysis

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
					Repro	0.601 F			
						0.139 M		0.686 M	Tubule atrophy of testes
					Cancer			0.686 M	CEL: renal epithelial cell adenomas and carcinomas
Weiss et al. 2005									**Methylmercuric chloride**
190	Mouse (B6C3F1/HSD × CBA/JHSD) F0: 15–18 F, F1: 16–28 M	Lifetime GD 0–PND 21 (via dam) PNDs 22–26 months (direct) (W)	0, 0.2, 0.6	NX	Neuro		0.2		Impaired spatial learning at ≥0.2 mg Hg/kg/day; impaired operant training and increased hindlimb splay at 0.6 mg Hg/kg/day
[Behavioral testing at 5, 15, and 26 months]									
Charbonneau et al. 1976									**Methylmercuric chloride**
191	Cat 4–5 M, 4–5 F	2 years (F)	0.003, 0.0084, 0.020, 0.046, 0.074	CS, BW, FI, WI, BC, UR, GN, HP	Death			0.074	100% sacrifice moribund by ~55 weeks
					Bd wt	0.074			
					Resp	0.074			
					Cardio	0.074			
					Gastro	0.074			
					Hemato	0.074			
					Hepatic	0.074			
					Renal	0.074			
					Endocr	0.074			
					Immuno	0.074			

Table 2-4. Levels of Significant Exposure to Organic Mercury – Oral (mg/kg/day)

Figure key[a]	Species (strain) No./group	Exposure parameters	Doses	Parameters monitored	Endpoint	NOAEL	Less serious LOAEL	Serious LOAEL	Effects
					Neuro	0.02	0.046	0.074	LOAEL: Decreased nociception and mild clinical signs SLOAEL: Ataxia, incoordination, impaired reflexes, and degeneration in cerebral cortex, cerebellum, and dorsal root ganglia

[a]The number corresponds to entries in Figure 2-8; differences in levels of health effects and cancer effects between male and females are not indicated in Figure 2-8. Where such differences exist, only the levels of effect for the most sensitive sex are presented.
[b]The neurodevelopmental effects are discussed in Section 2.16 (Neurological).
[c]The immunodevelopmental effects are discussed in Section 2.15 (Immunological).
[d]Used to derive a chronic-duration oral MRL of 0.1 µg Hg/kg/day for methylmercury; based on a NAEL of 0.00041 mg Hg/kg/day divided by a total uncertainty factor of 3 (for human variability). The NAEL represents an estimated mercury dose associated with a 1-point decrease in IQ, based on a meta-analysis of three prospective birth cohorts in populations with high fish consumption: Faroe Islands (Grandjean et al. 1997, 1999), Seychelles Islands (Myers et al. 2003), and New Zealand (Kjellstrom et al. 1989). See Appendix A for more detailed information regarding the MRL.

Principal studies for the MRLs

ACA = antichromatin antibodies; ACTH = adrenocorticotrophic hormone; ALT = alanine aminotransferase; ANoA = antinucleolar antibodies; AST = aspartate aminotransferase; B = both sexes; BC = serum (blood) chemistry; Bd wt or BW = body weight; BI = biochemical changes; (C) = capsule; Cardio = cardiovascular; CEL = cancer effect level; CNS = central nervous system; Con-A = concanavalin-A; CS = clinical signs; Develop = developmental; DX = developmental toxicity; Endocr = endocrine; (F) = feed (dietary); F = female(s); FI = food intake; (G) = gavage; (GO) = gavage in oil; (GW) = gavage in water; Gastro = gastrointestinal; GD = gestation day; GN = gross necropsy; HDL = high-density lipoprotein; HE = hematology; Hemato = hematological; HP = histopathology; IFN-γ = interferon gamma; IgG = immunoglobulin G; IL-6 = interleukin-6; Immuno = immunological; IQ = intelligence quotient; (IN) = ingestion; IX = immune function; LE = lethality; LOAEL = lowest-observed-adverse-effect level; LPS = lipopolysaccharide; M = male(s); MeHg = methylmercury; MRL = Minimal Risk Level; Musc/skel = musculoskeletal; Neuro = neurological; NAEL = no-adverse-effect level (estimated no-effect level); NK = natural killer; NOAEL = no-observed-adverse-effect level; NS = not specified; NX = neurological function; OF = organ function; OW = organ weight; PHA = phytohemagglutinin; PND = postnatal day; Repro = reproductive; Resp = respiratory; RX = reproductive function; SLOAEL = serious lowest-observed-adverse-effect level; TNF = tumor necrosis factor; UR = urinalysis; (W) = drinking water; WBC = white blood cell; WI = water intake

Figure 2-8. Levels of Significant Exposure to Organic Mercury – Oral
Acute (≤14 days)

Figure 2-8. Levels of Significant Exposure to Organic Mercury – Oral
Acute (≤14 days)

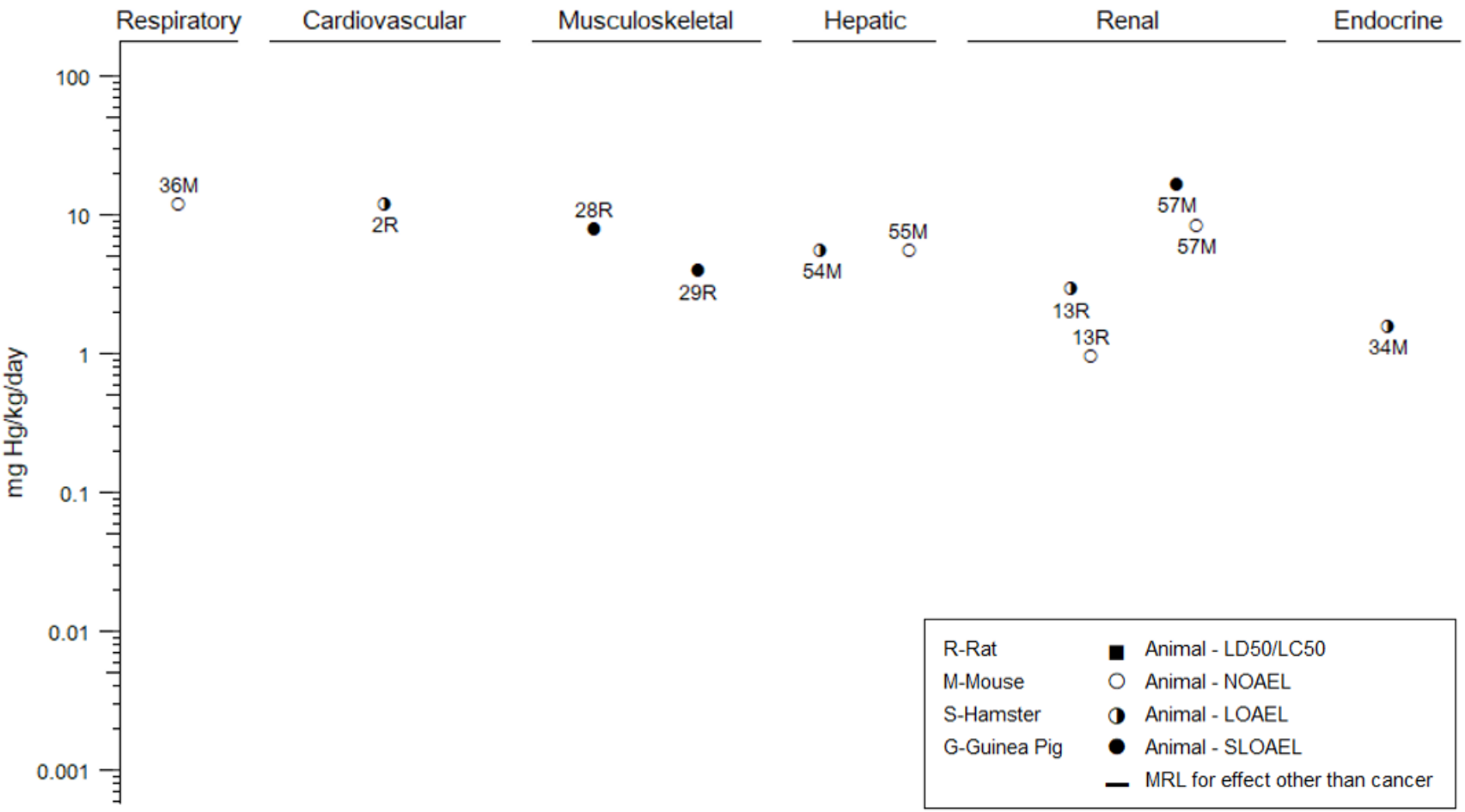


Figure 2-8. Levels of Significant Exposure to Organic Mercury – Oral
Acute (≤14 days)

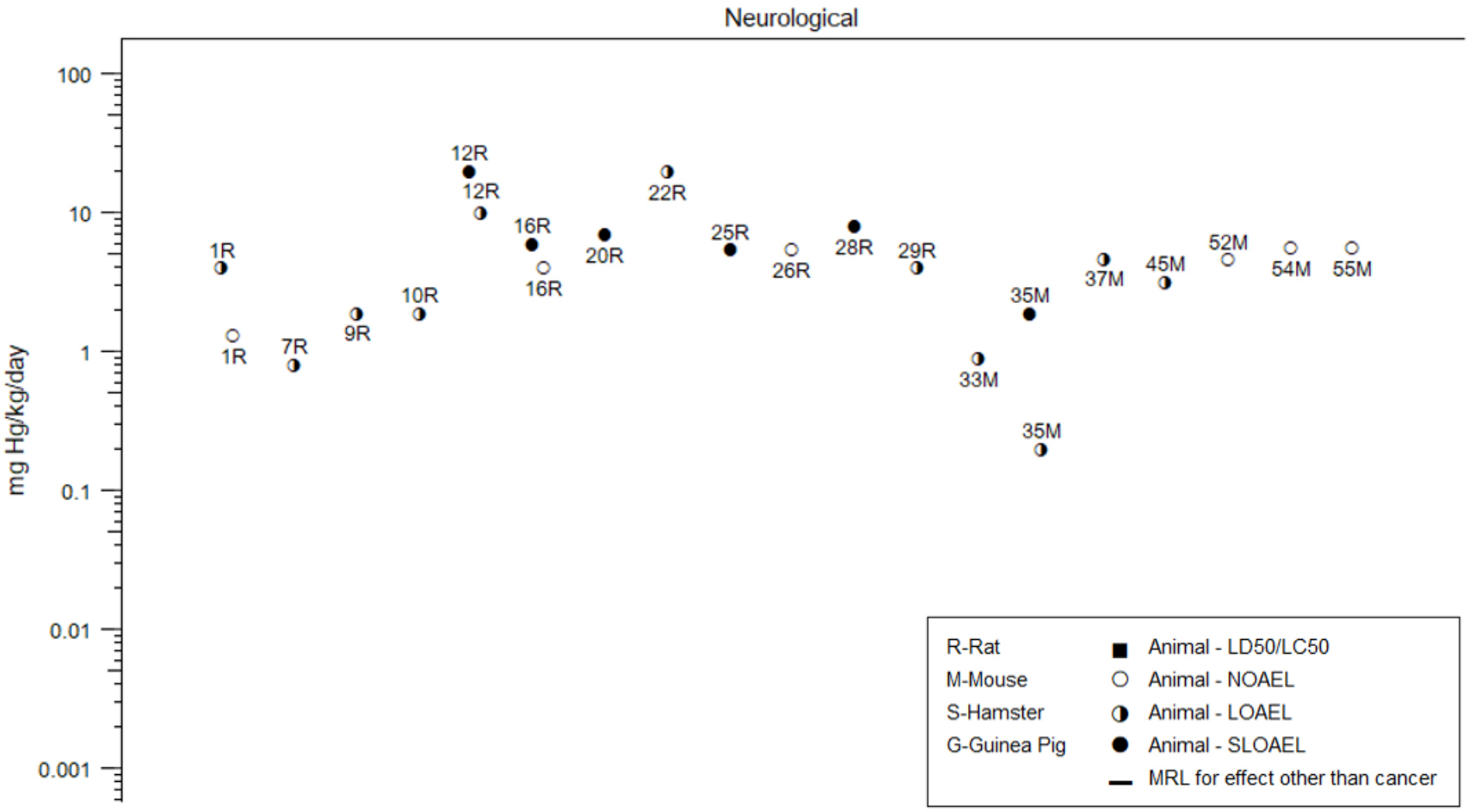


Figure 2-8. Levels of Significant Exposure to Organic Mercury – Oral
Acute (≤14 days)

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Acute (≤14 days)

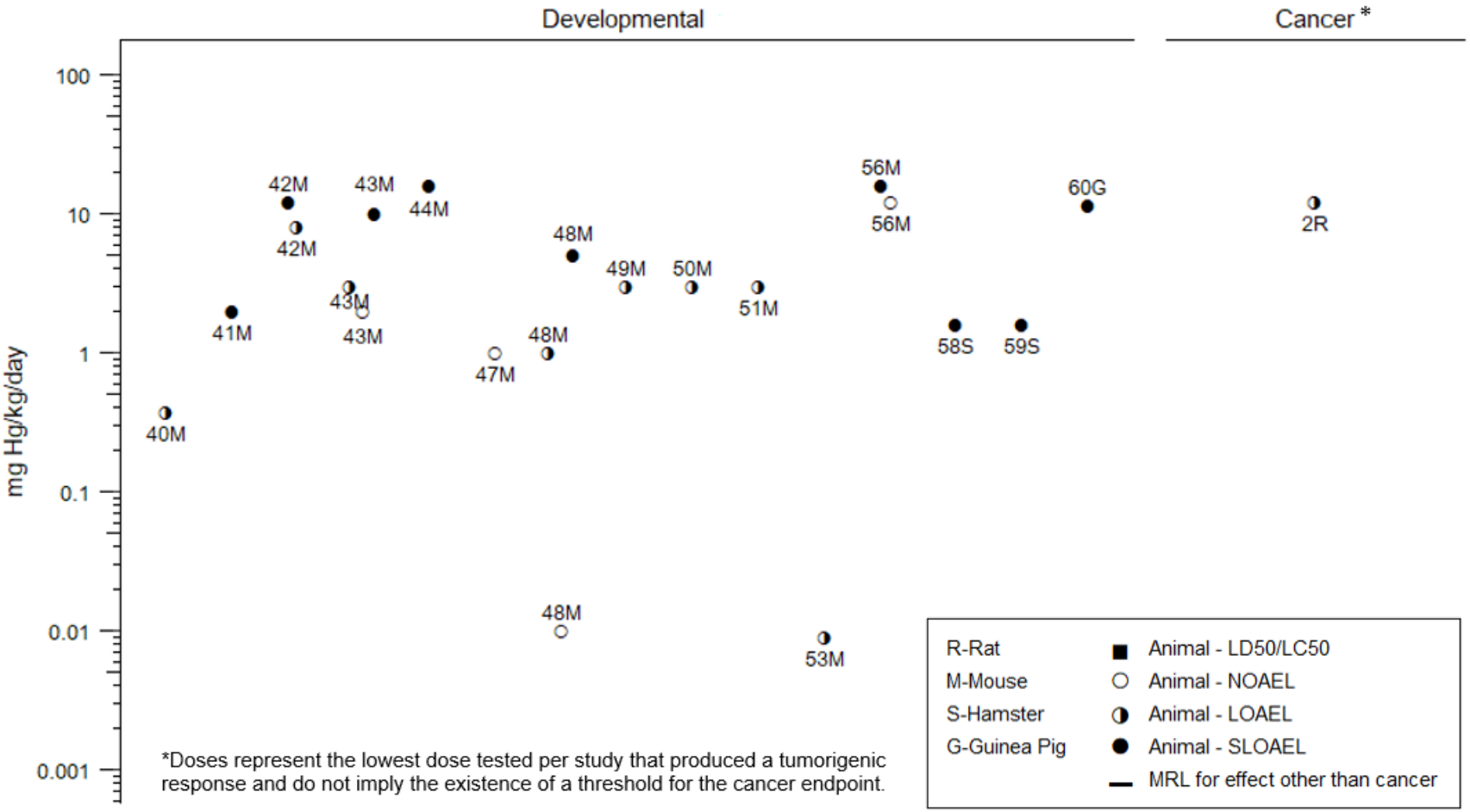


Figure 2-8. Levels of Significant Exposure to Organic Mercury – Oral
Intermediate (15–364 days)

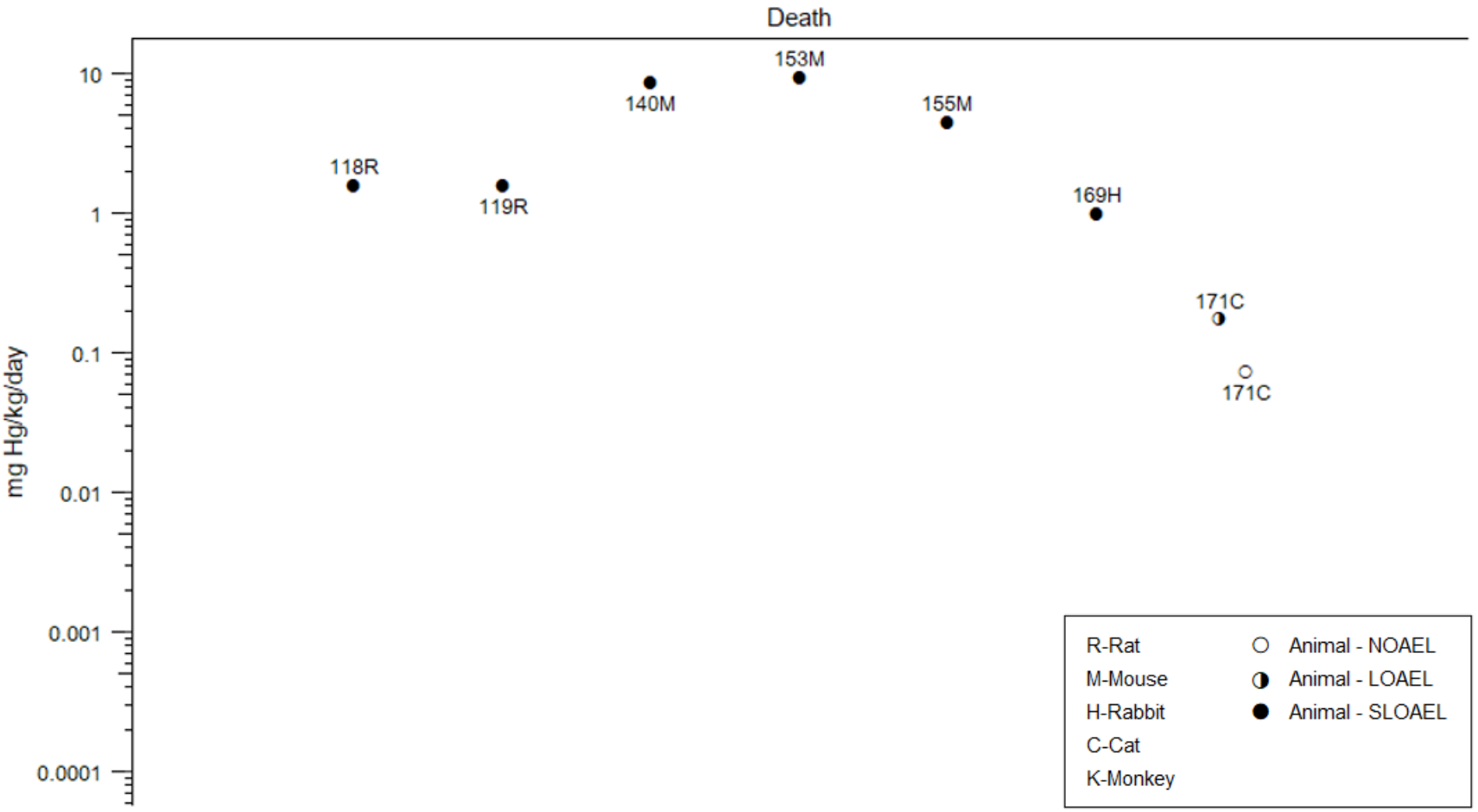


Figure 2-8. Levels of Significant Exposure to Organic Mercury – Oral
Intermediate (15–364 days)

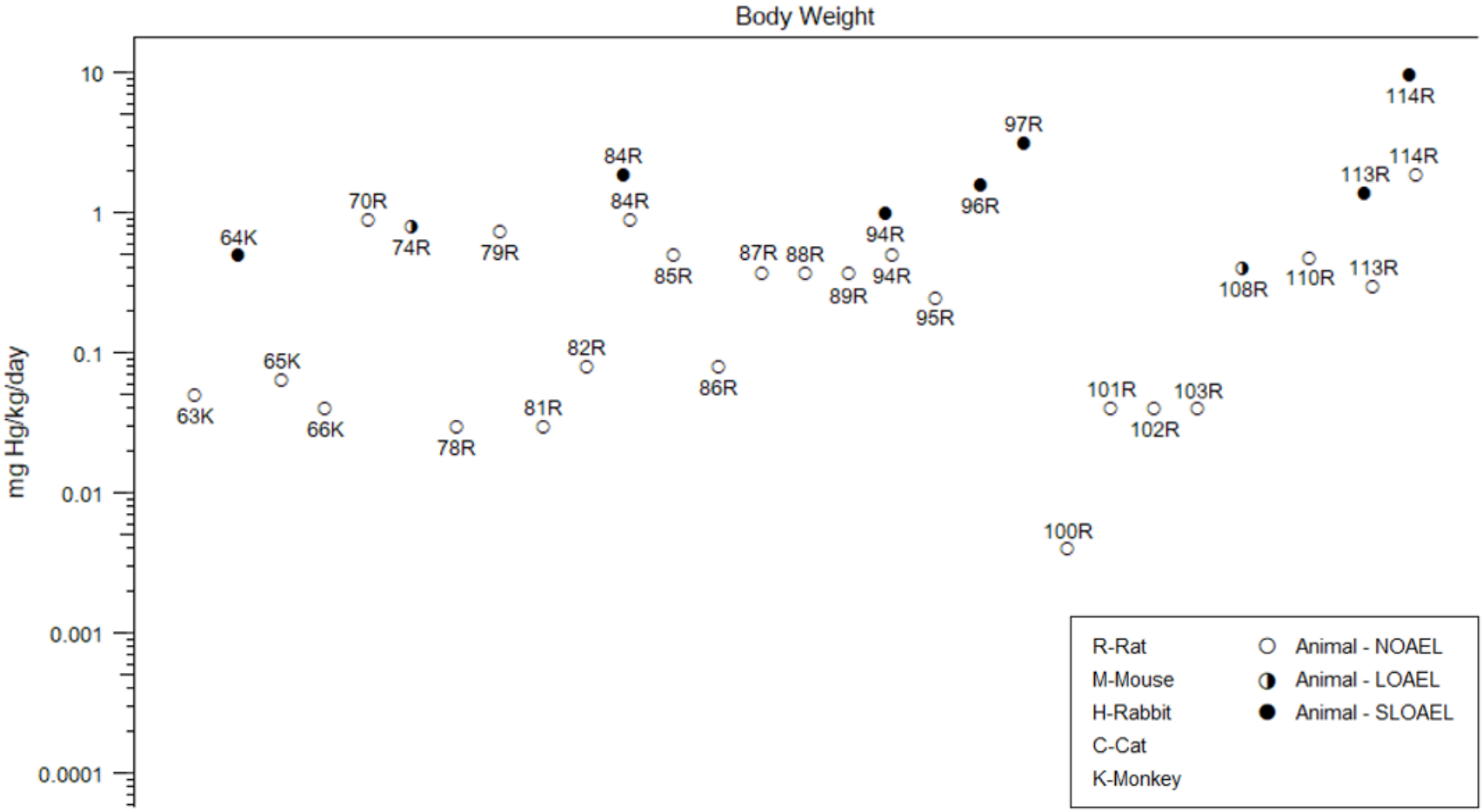


Figure 2-8. Levels of Significant Exposure to Organic Mercury – Oral
Intermediate (15–364 days)

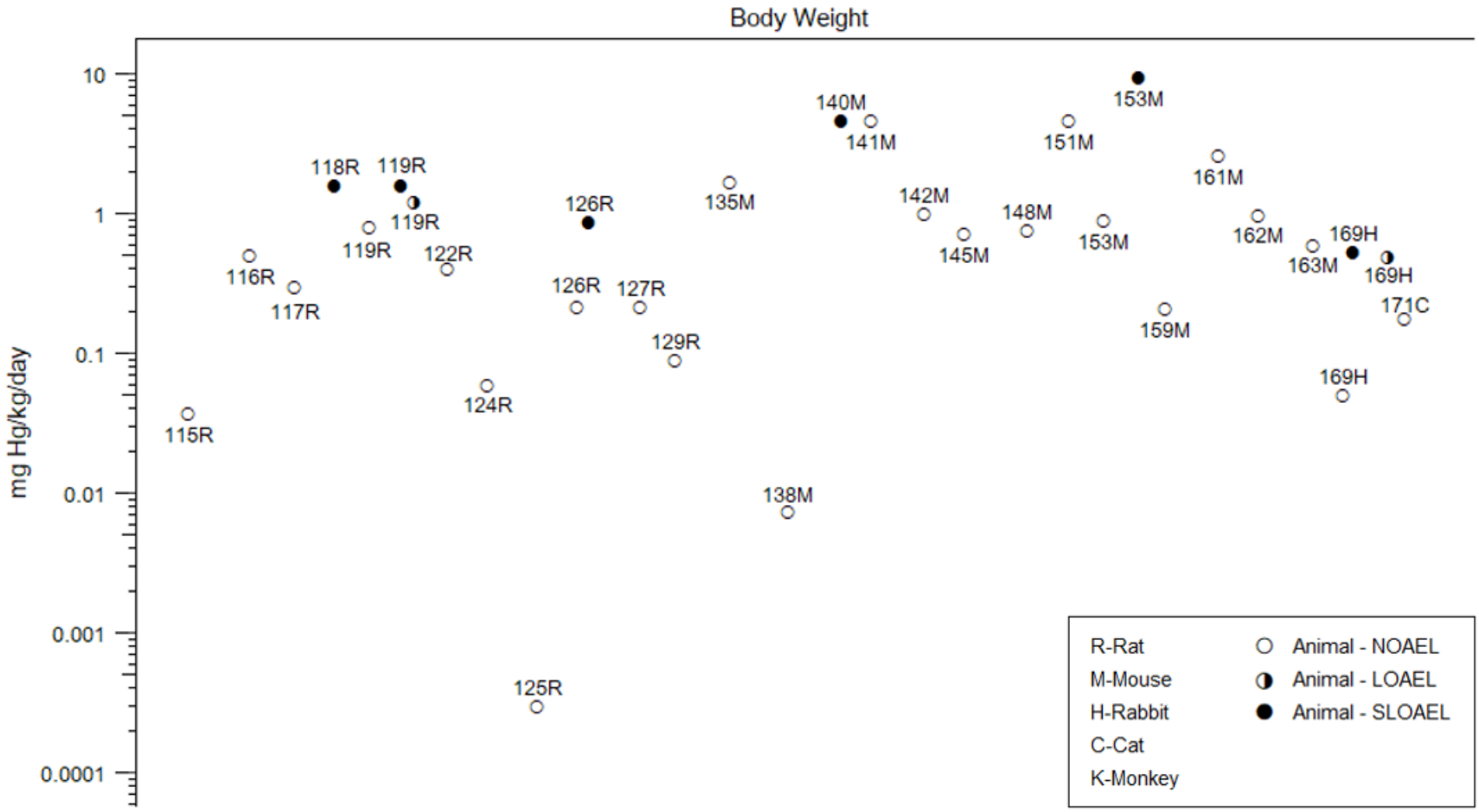


Figure 2-8. Levels of Significant Exposure to Organic Mercury – Oral
Intermediate (15–364 days)

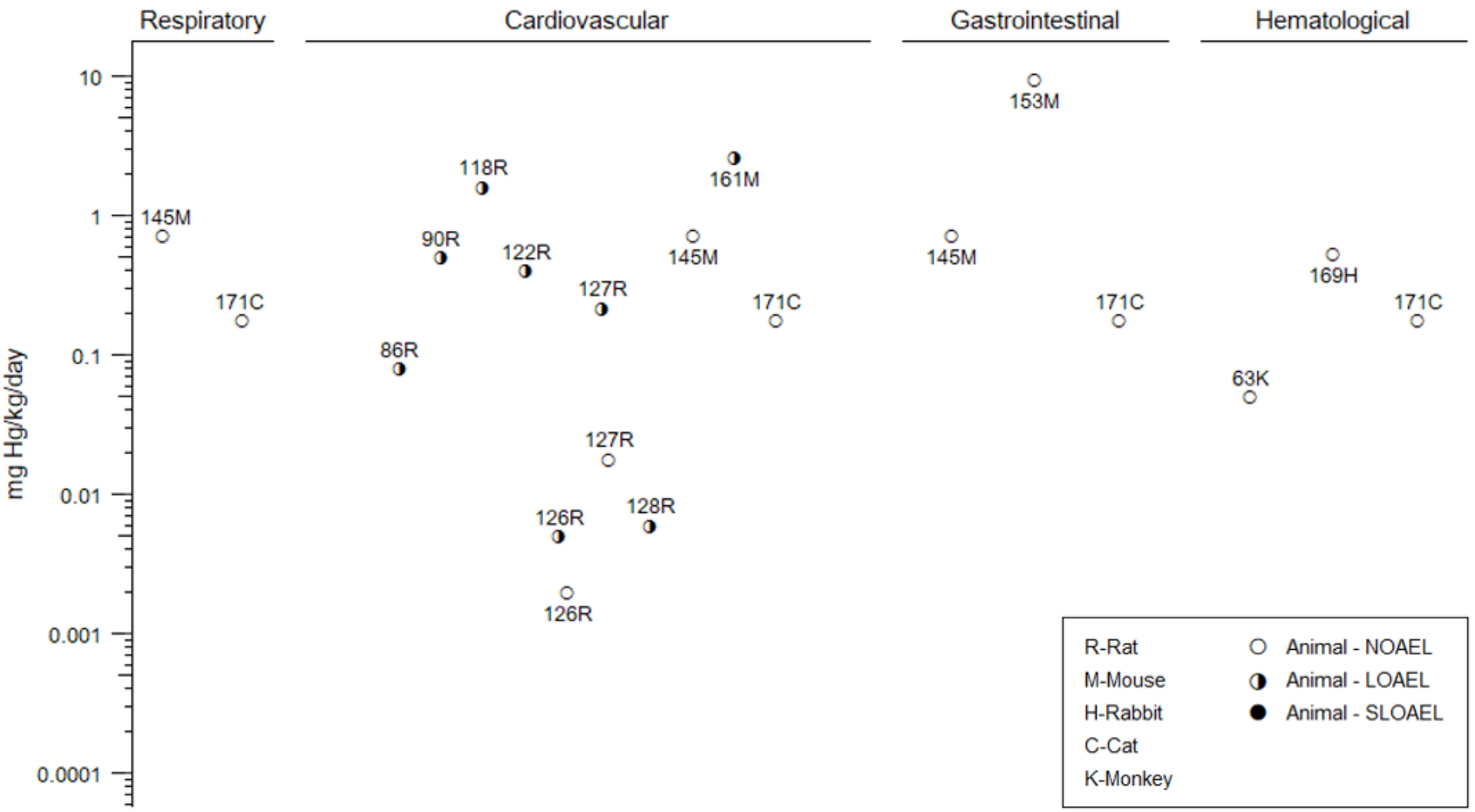


Figure 2-8. Levels of Significant Exposure to Organic Mercury – Oral
Intermediate (15–364 days)

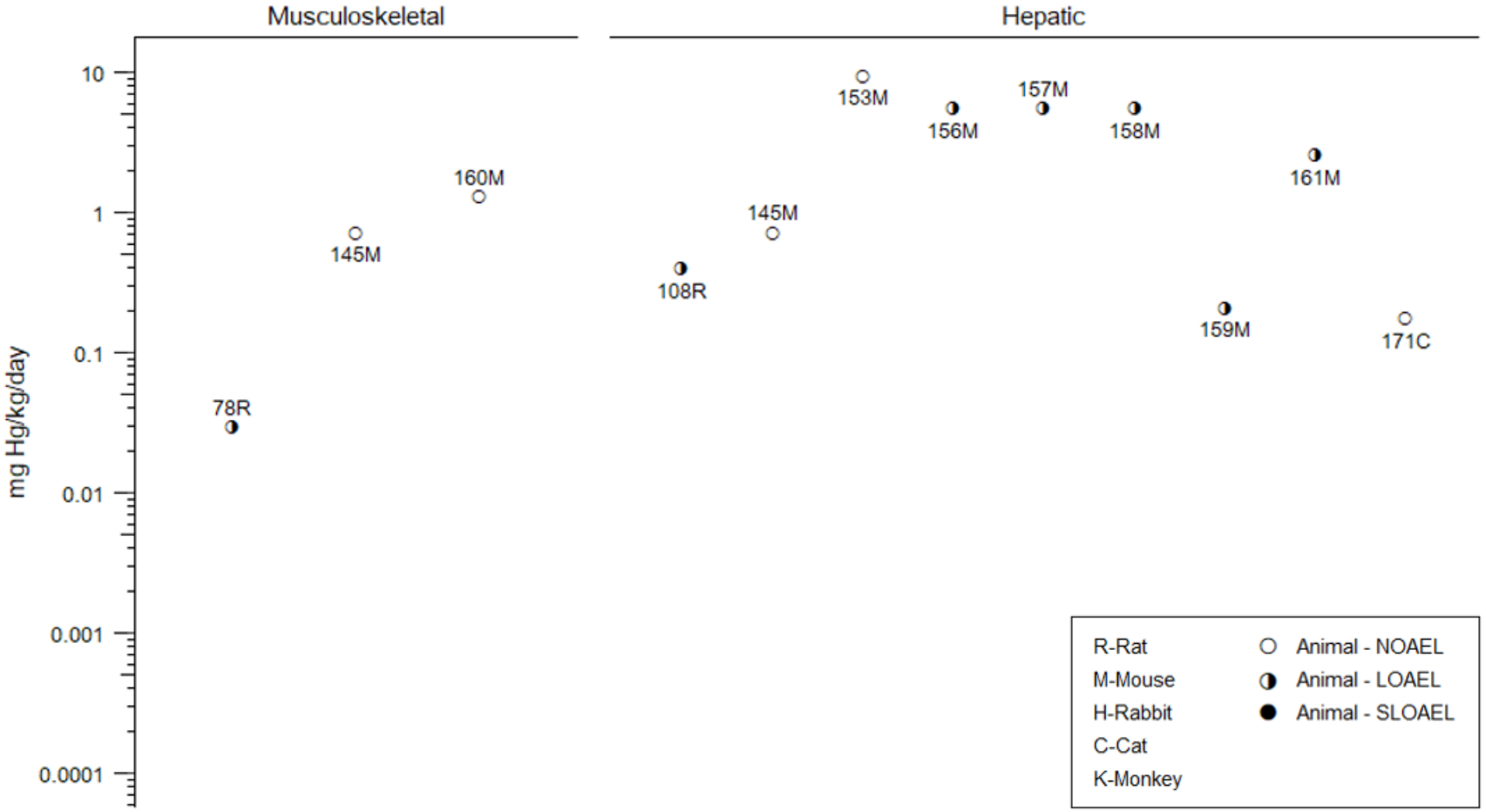


Figure 2-8. Levels of Significant Exposure to Organic Mercury – Oral
Intermediate (15–364 days)

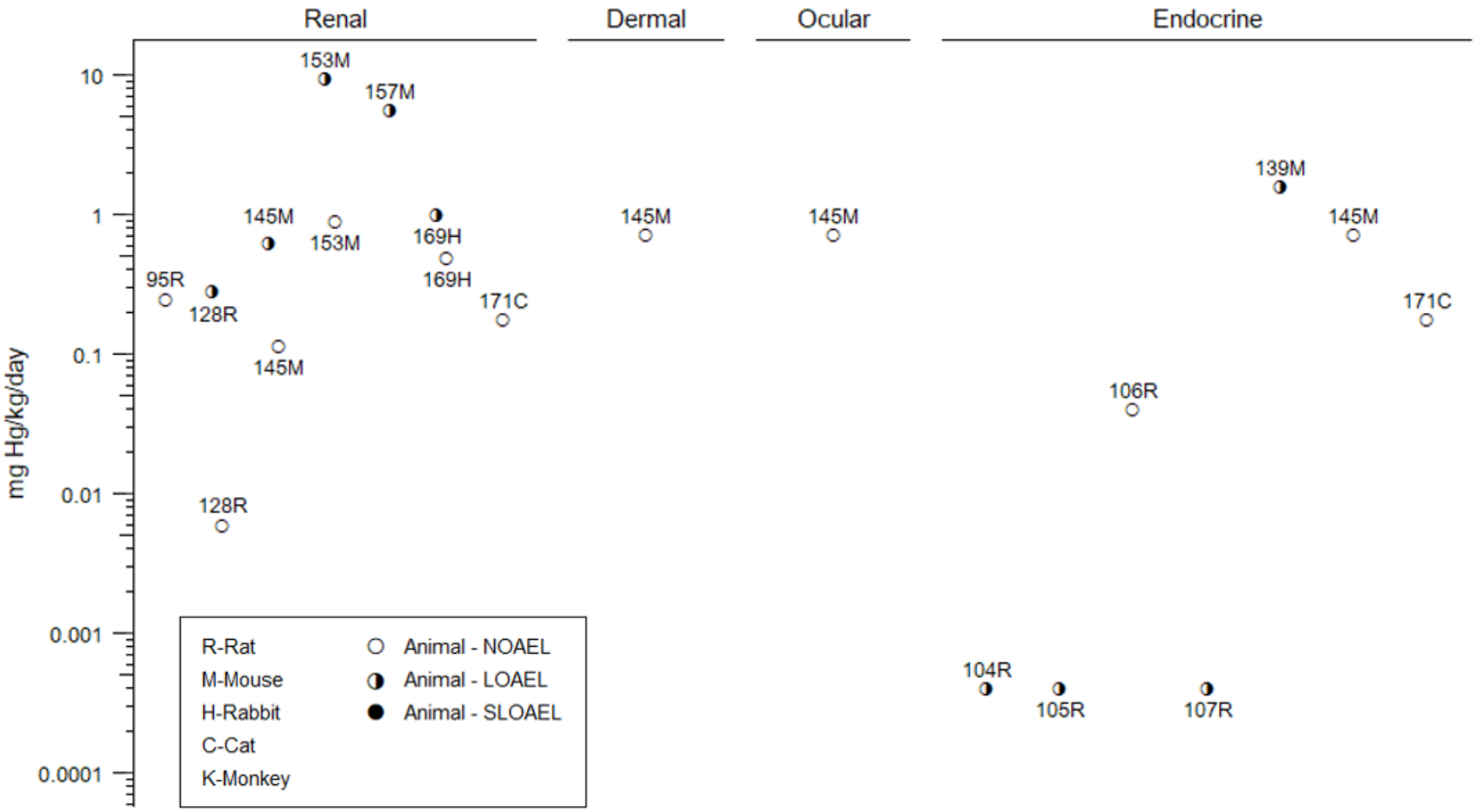
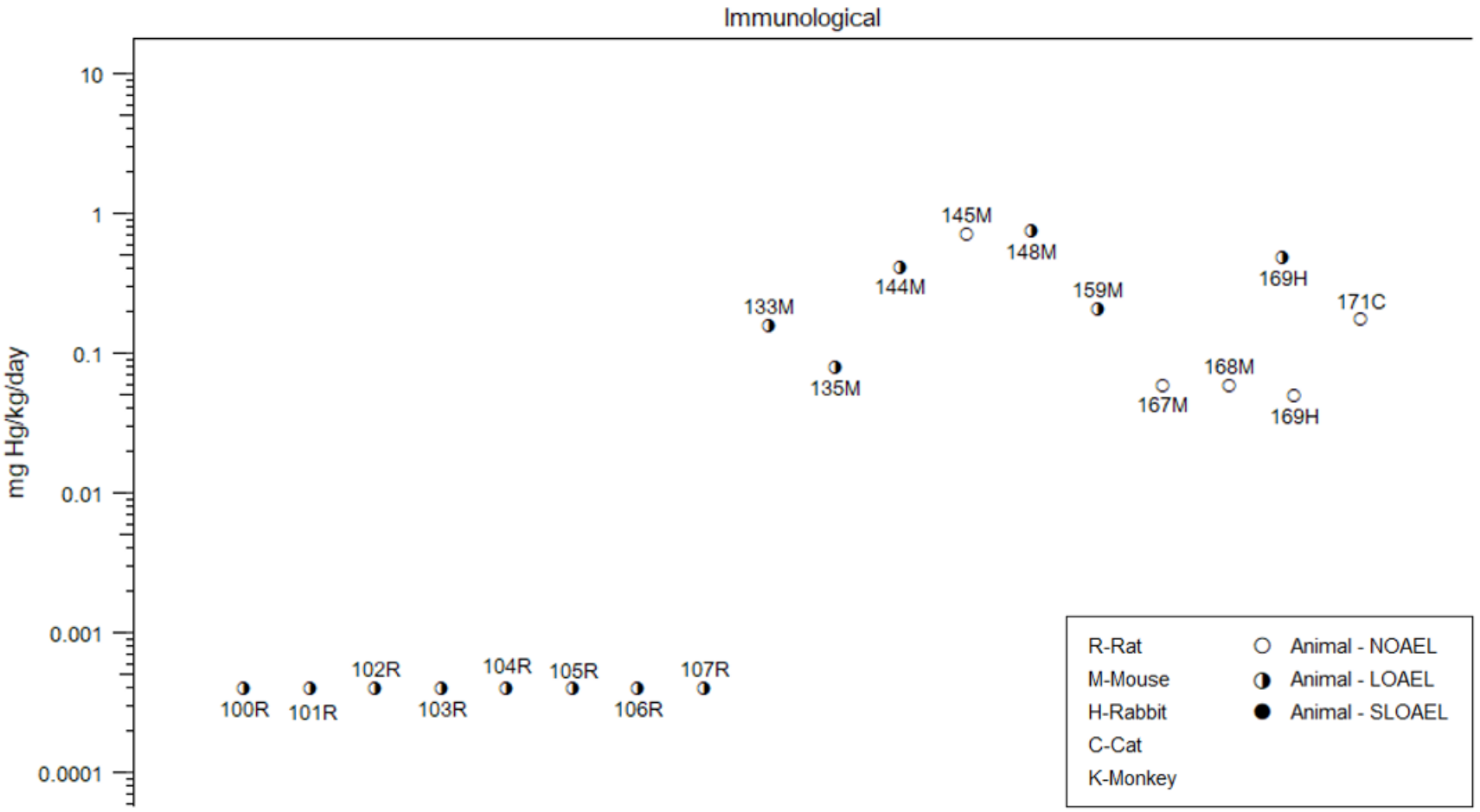


Figure 2-8. Levels of Significant Exposure to Organic Mercury – Oral
Intermediate (15–364 days)



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Intermediate (15–364 days)

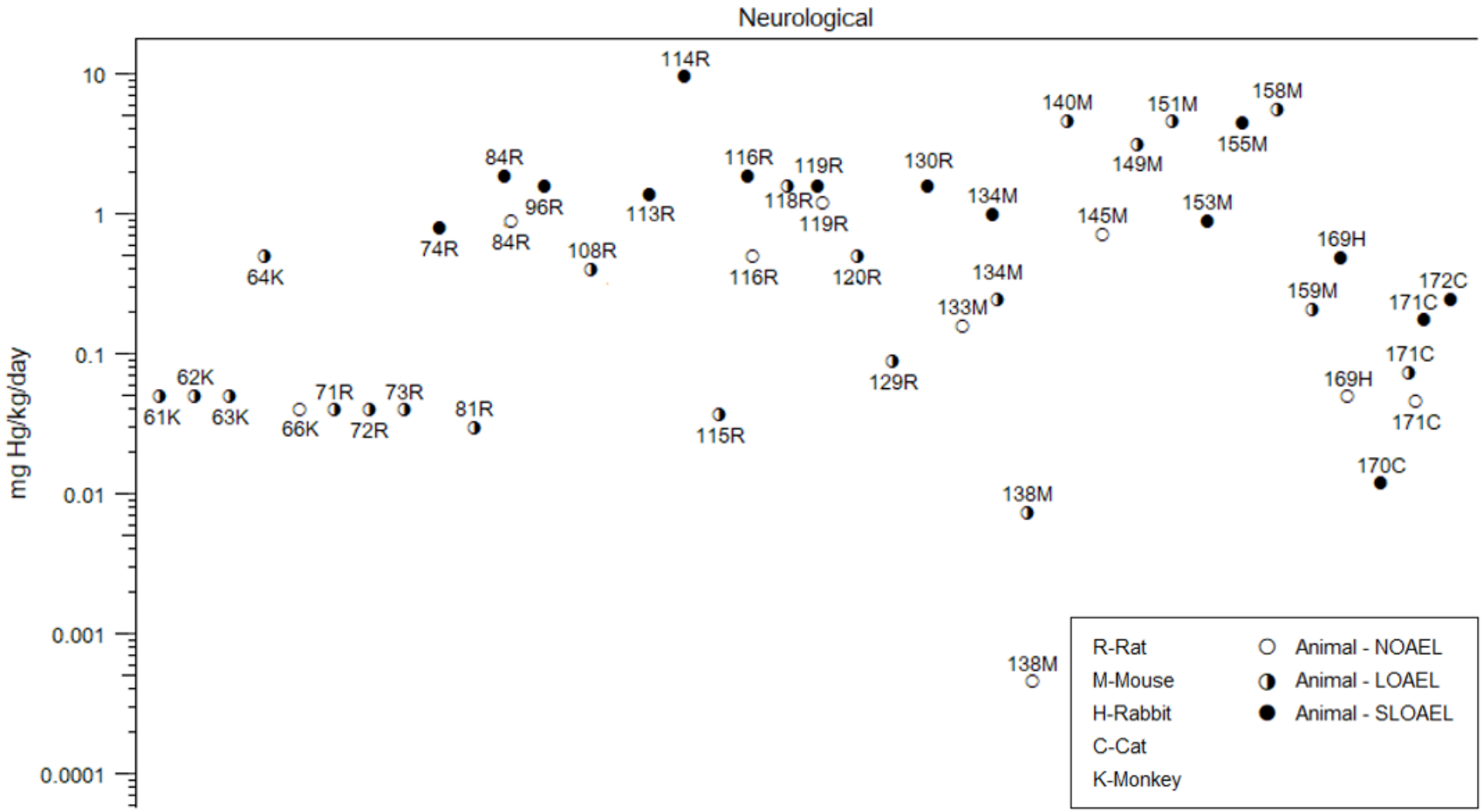


Figure 2-8. Levels of Significant Exposure to Organic Mercury – Oral
Intermediate (15–364 days)

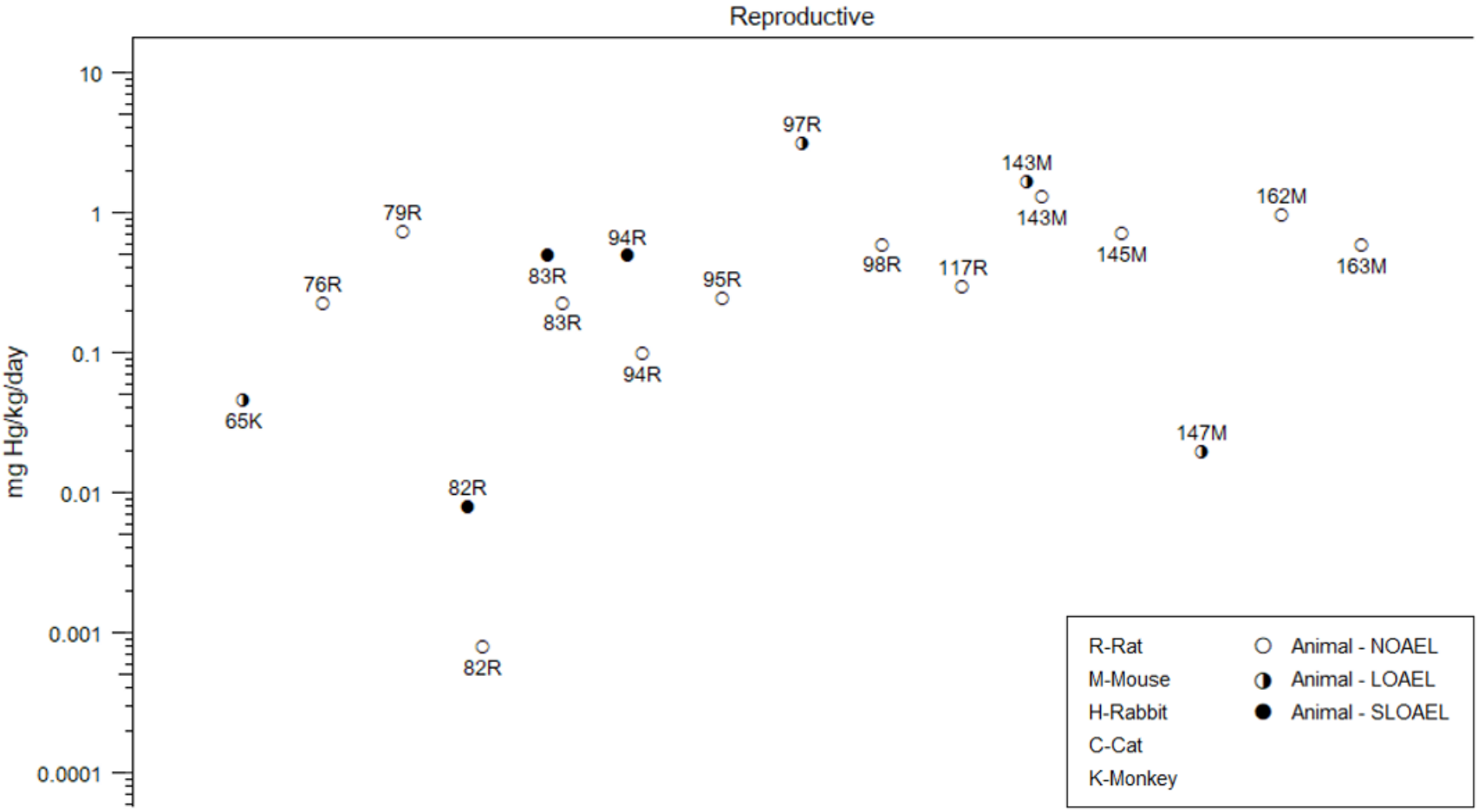


Figure 2-8. Levels of Significant Exposure to Organic Mercury – Oral
Intermediate (15–364 days)

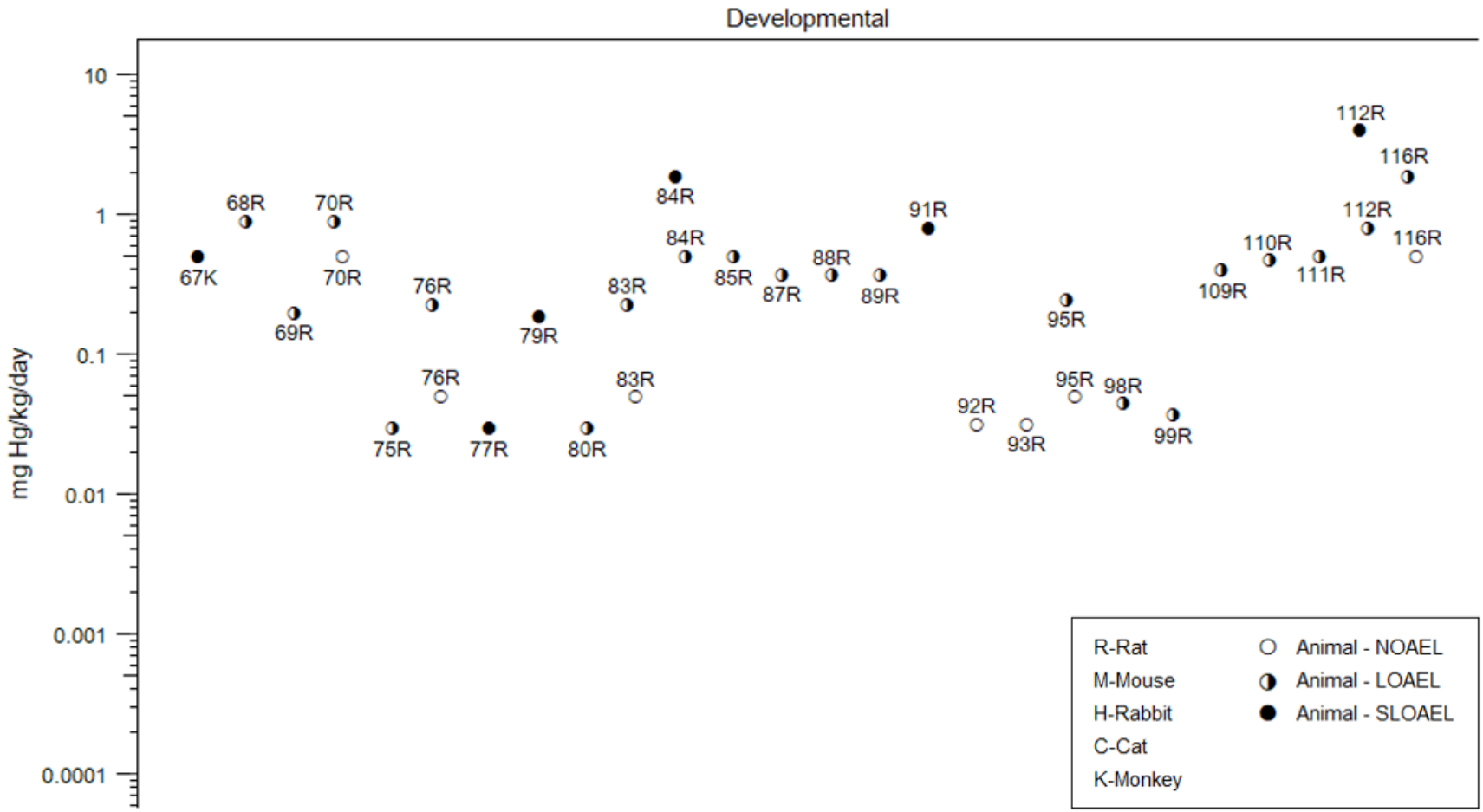


Figure 2-8. Levels of Significant Exposure to Organic Mercury – Oral
Intermediate (15–364 days)

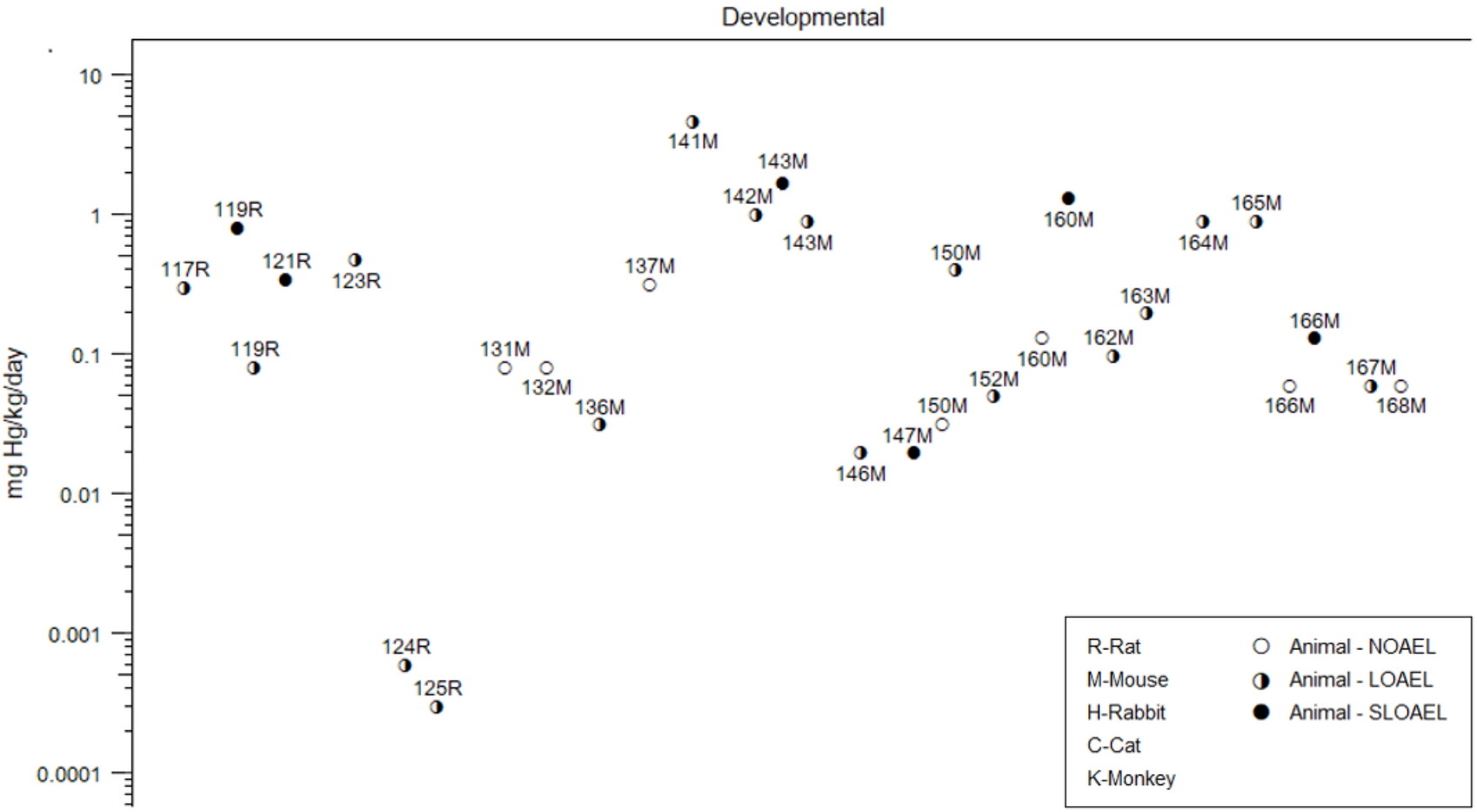


Figure 2-8. Levels of Significant Exposure to Organic Mercury – Oral
Intermediate (15–364 days)

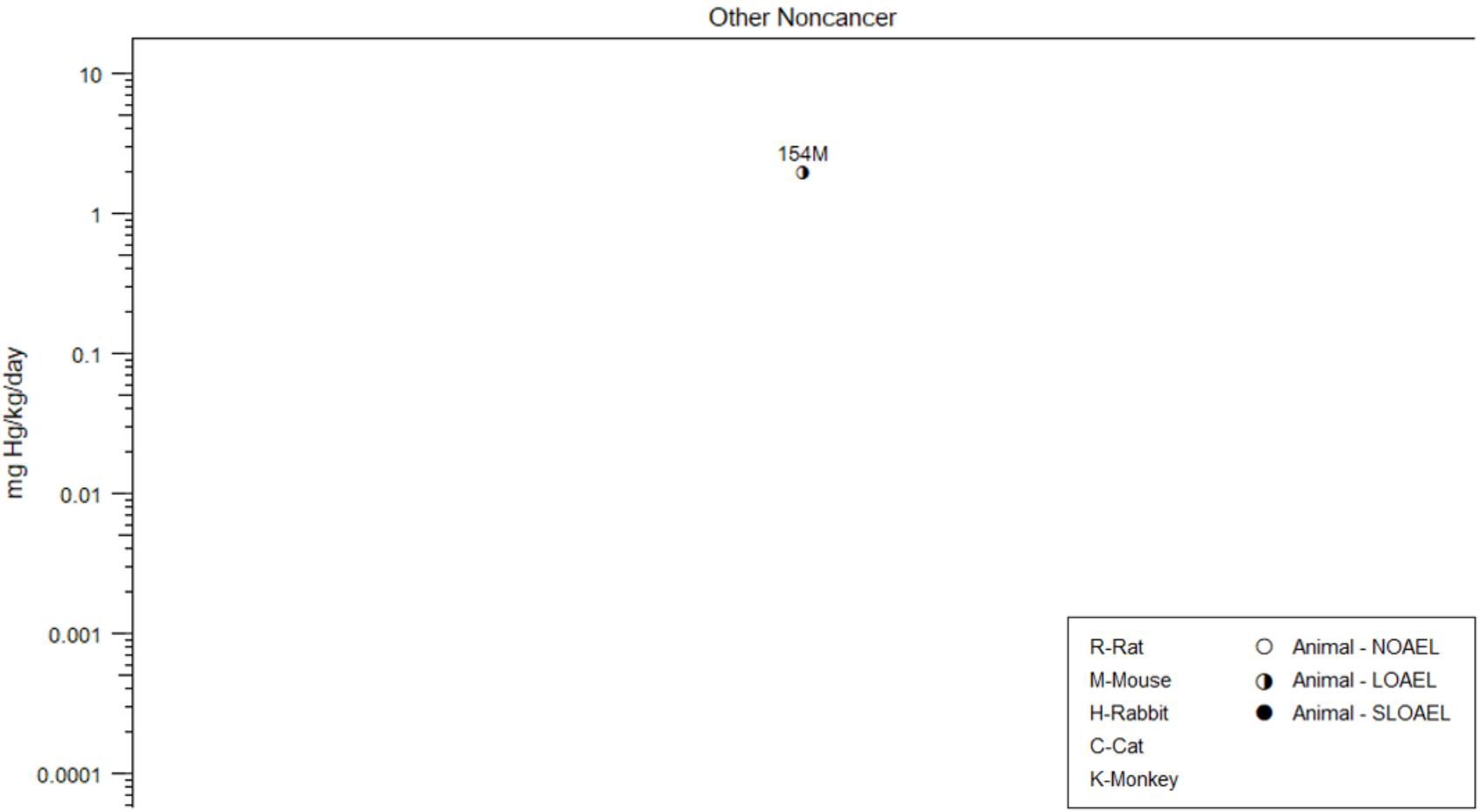
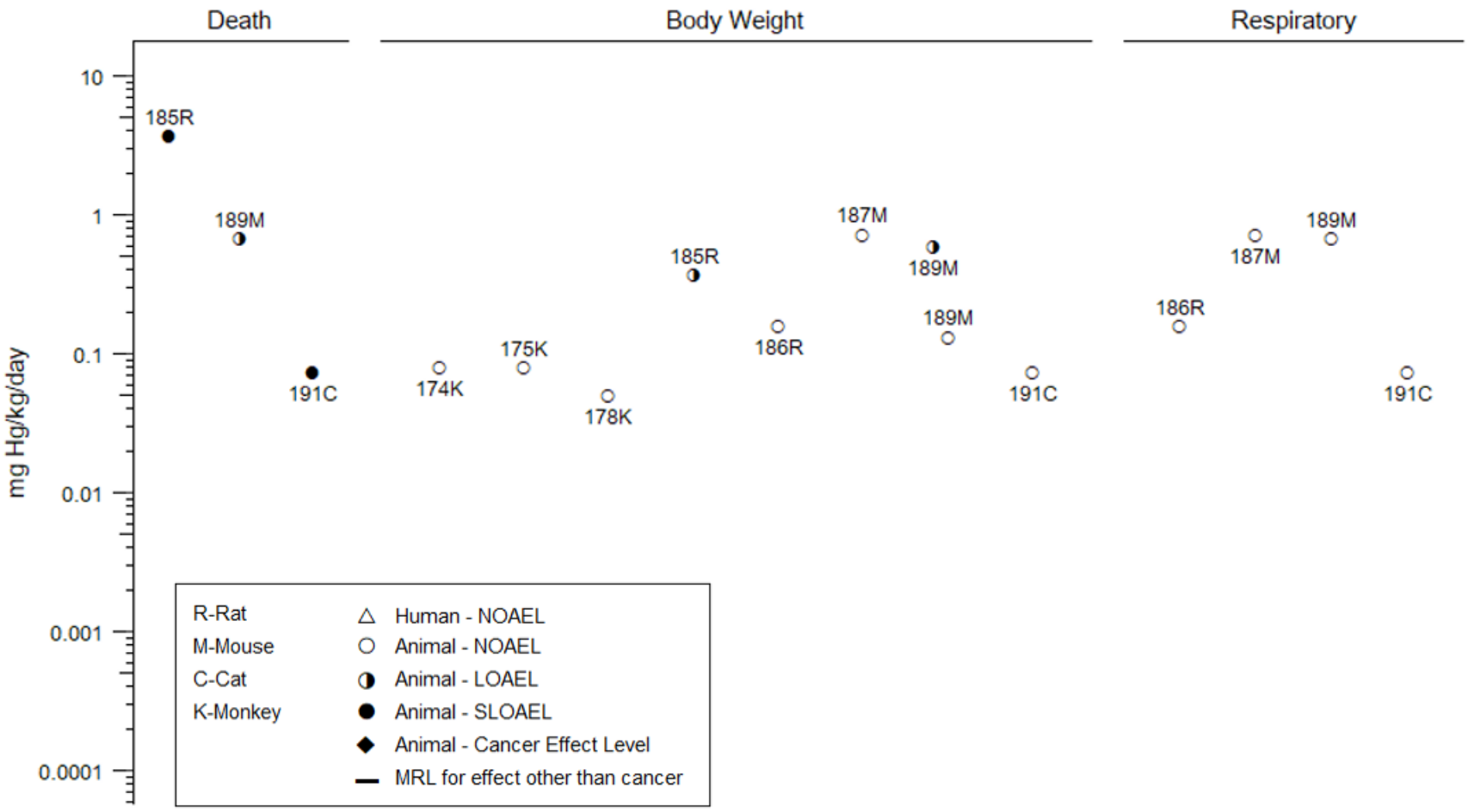


Figure 2-8. Levels of Significant Exposure to Organic Mercury – Oral
Chronic (≥365 days)



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Chronic (≥365 days)

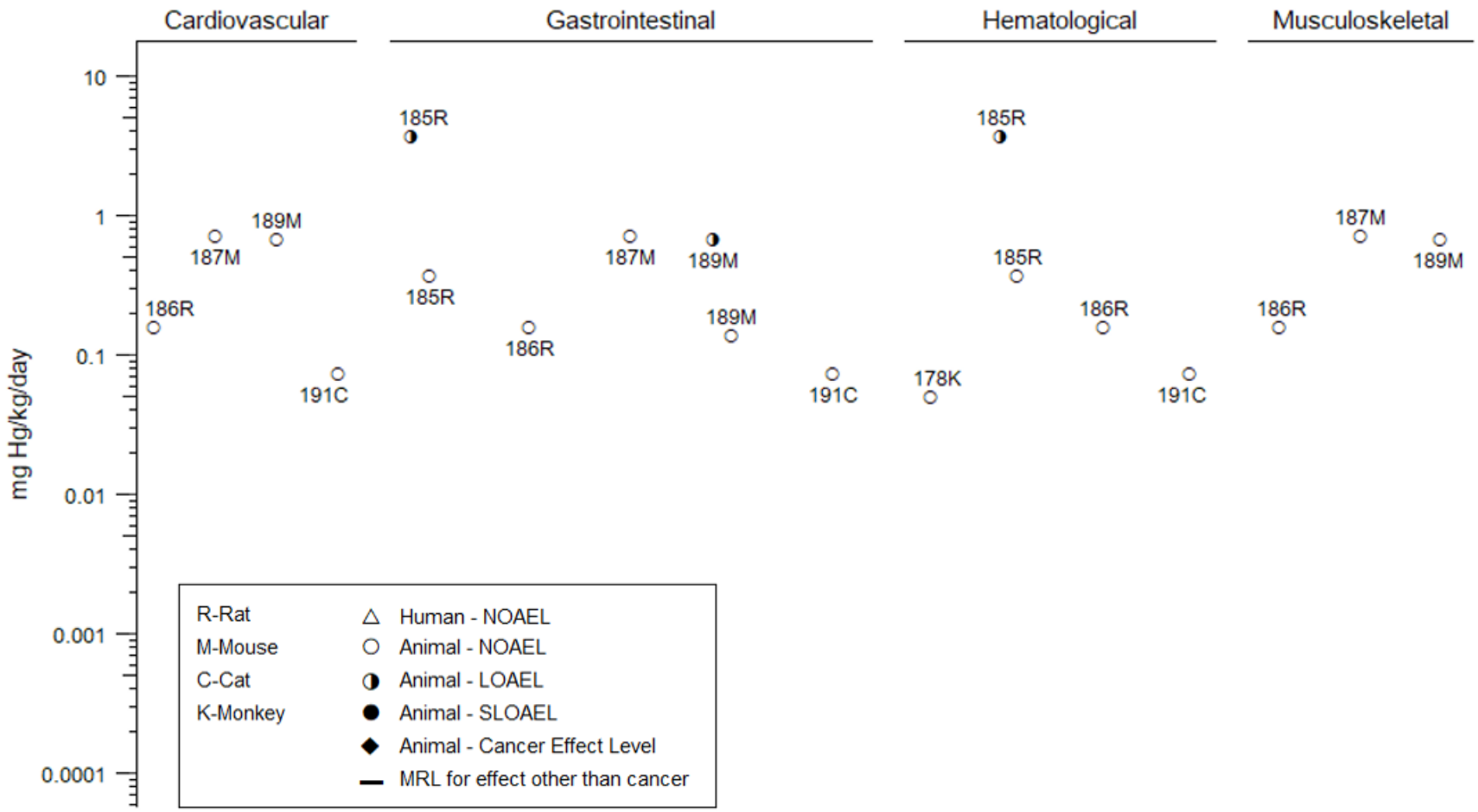


Figure 2-8. Levels of Significant Exposure to Organic Mercury – Oral
Chronic (≥365 days)

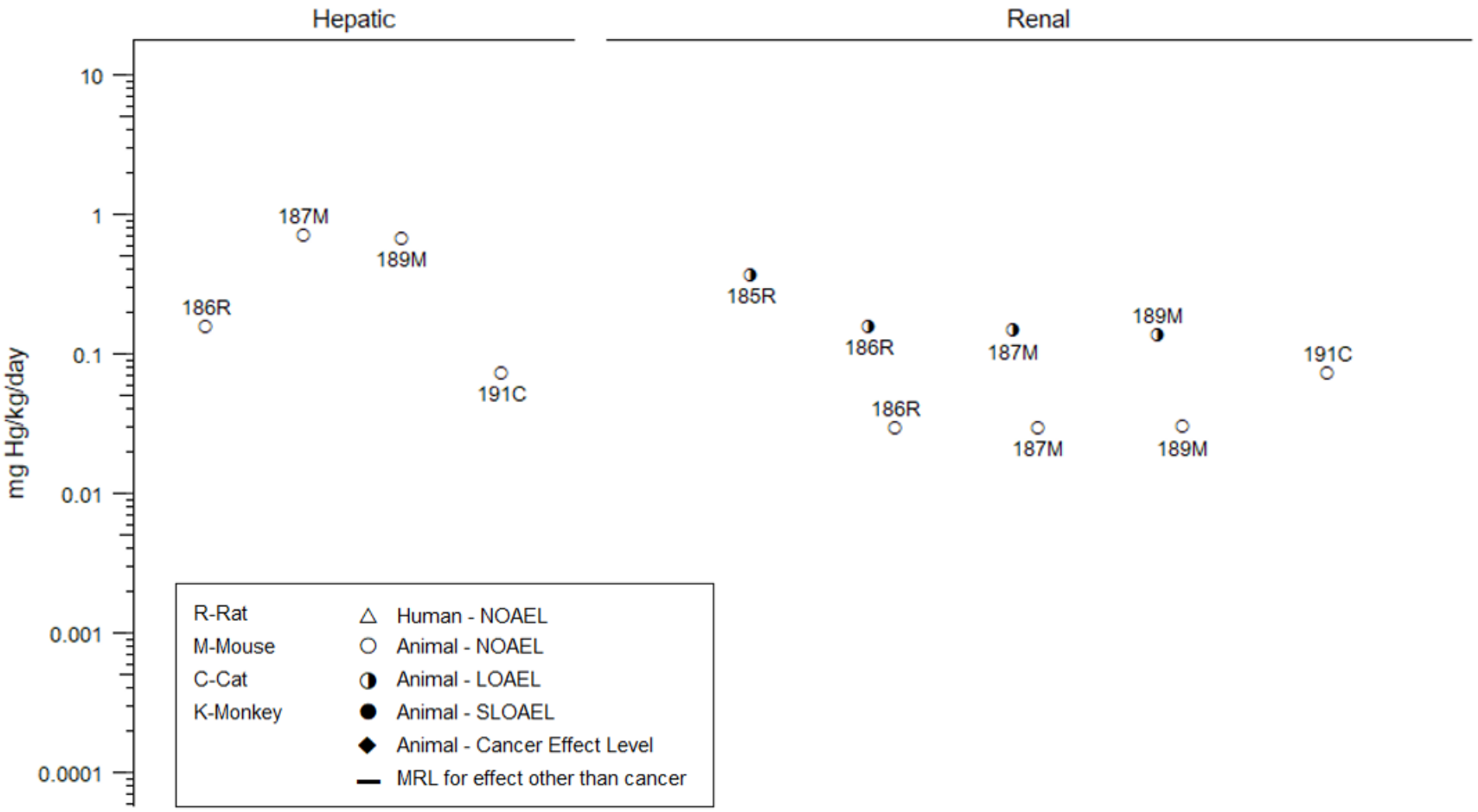


Figure 2-8. Levels of Significant Exposure to Organic Mercury – Oral
Chronic (≥365 days)

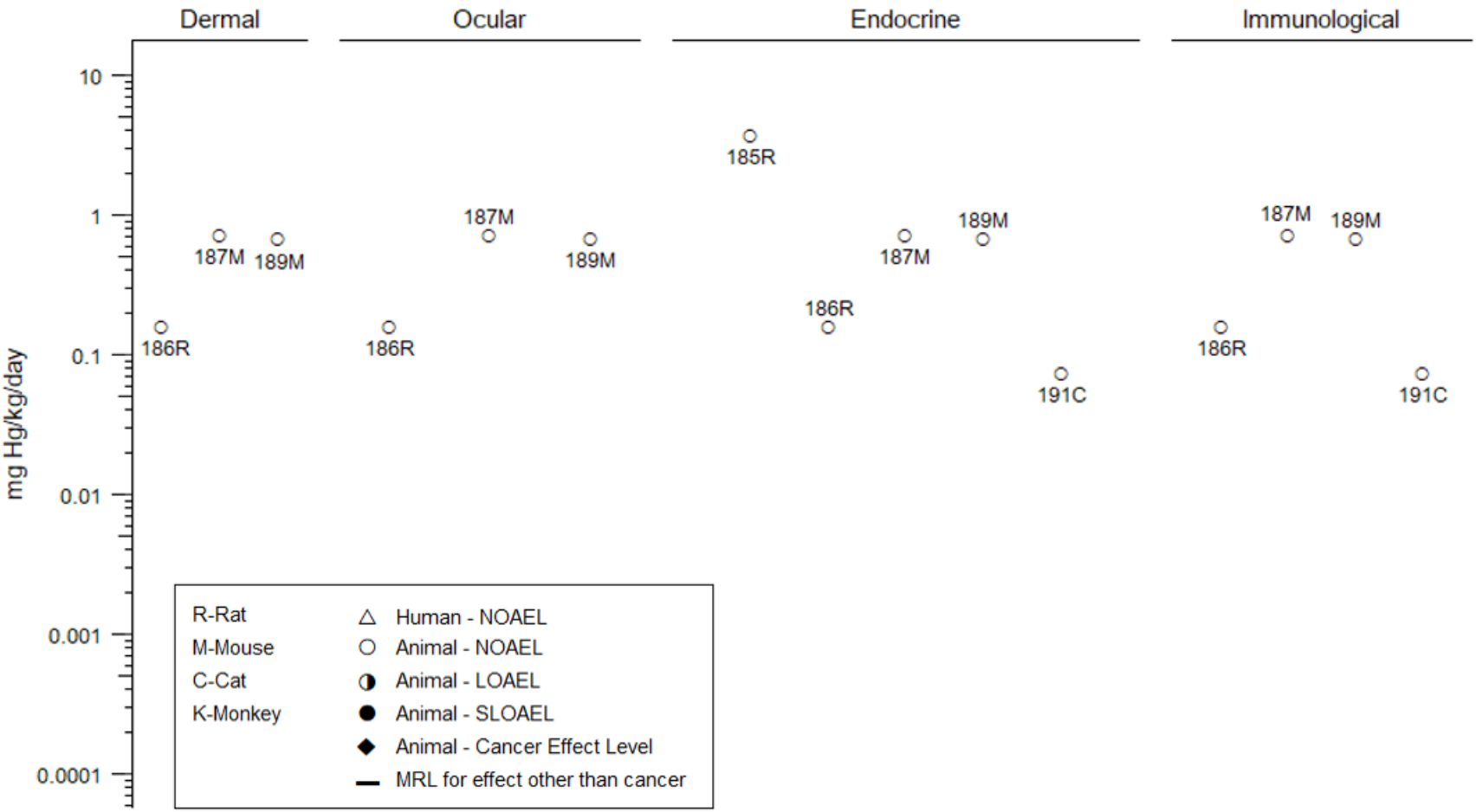


Figure 2-8. Levels of Significant Exposure to Organic Mercury – Oral
Chronic (≥365 days)

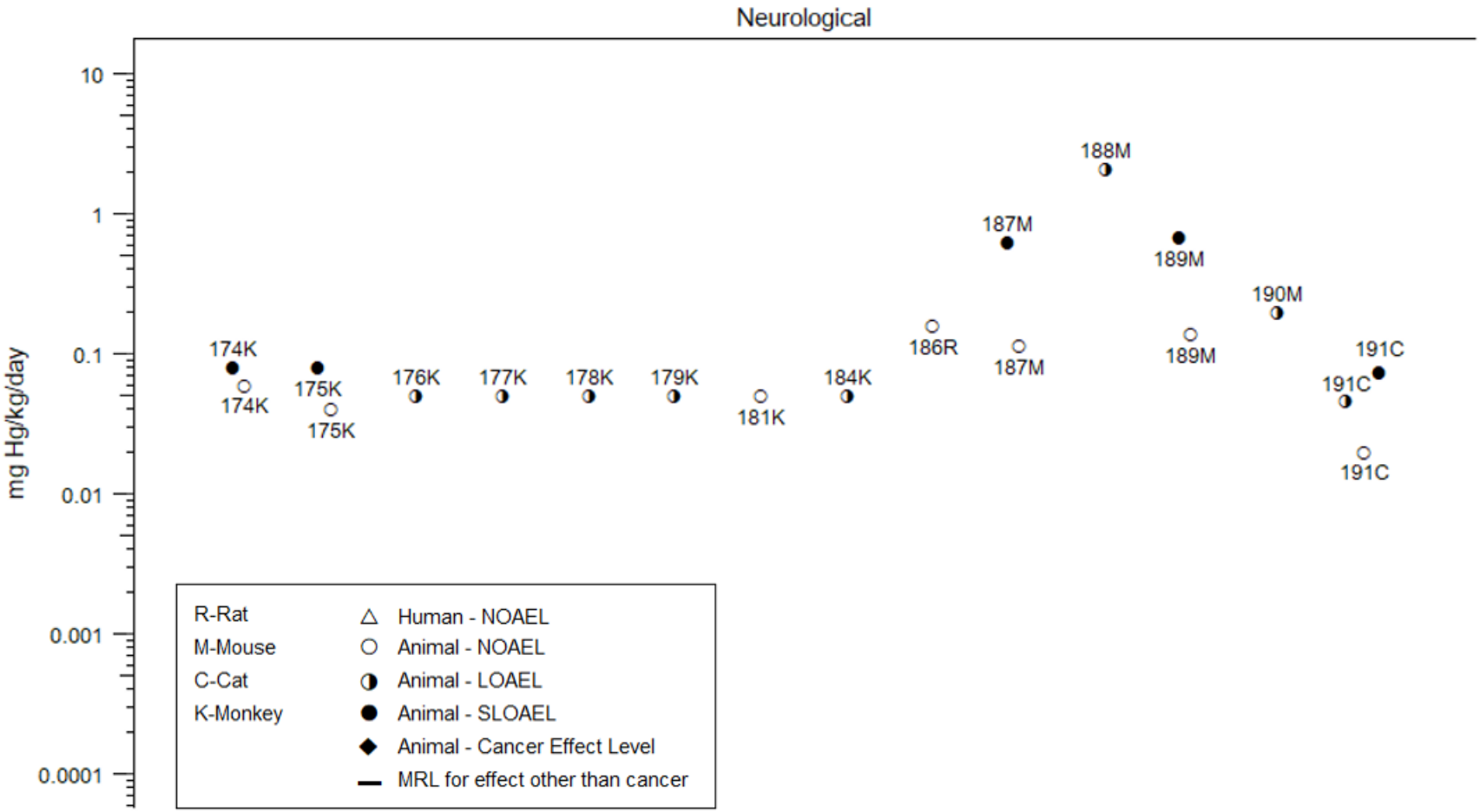


Figure 2-8. Levels of Significant Exposure to Organic Mercury – Oral
Chronic (≥365 days)

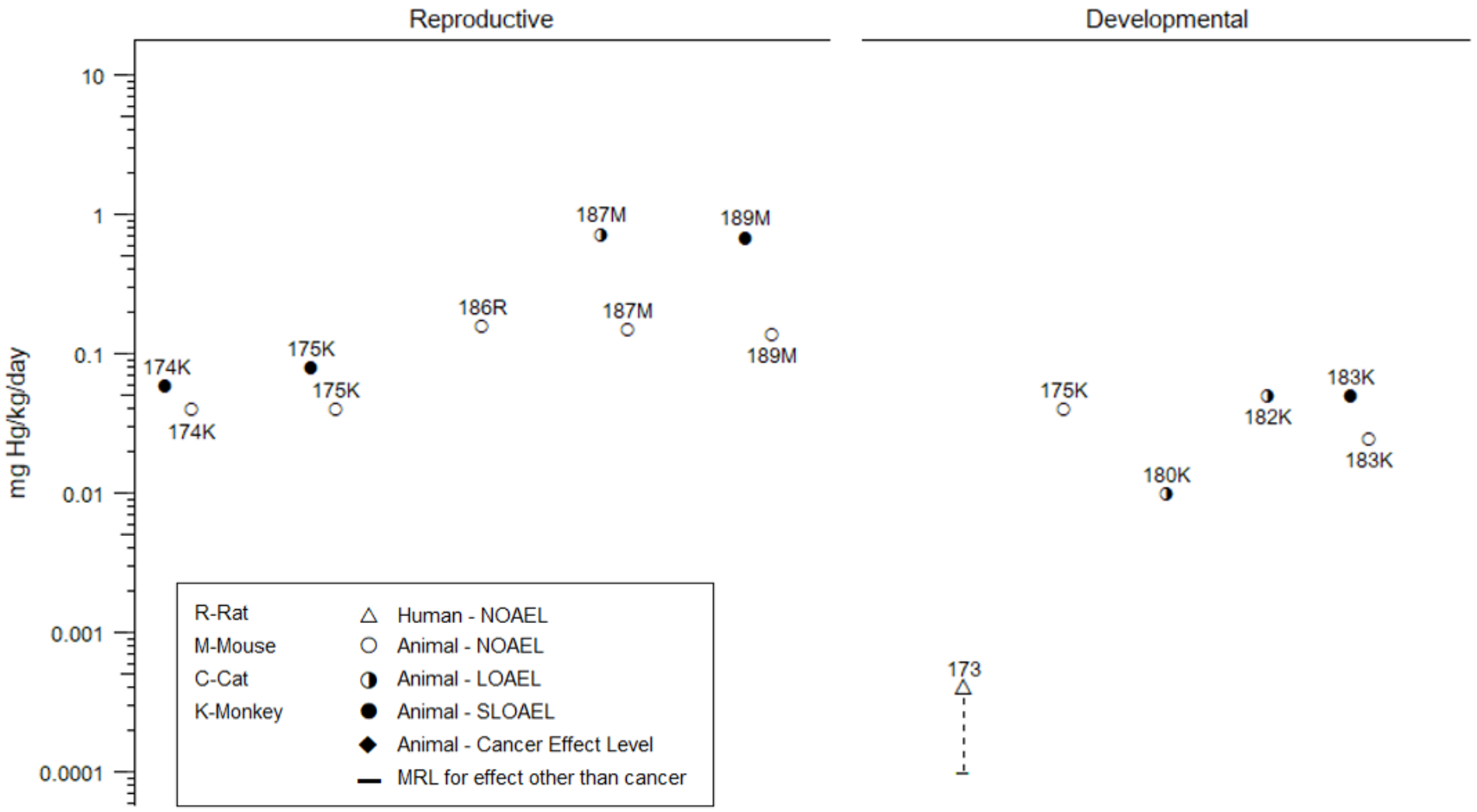
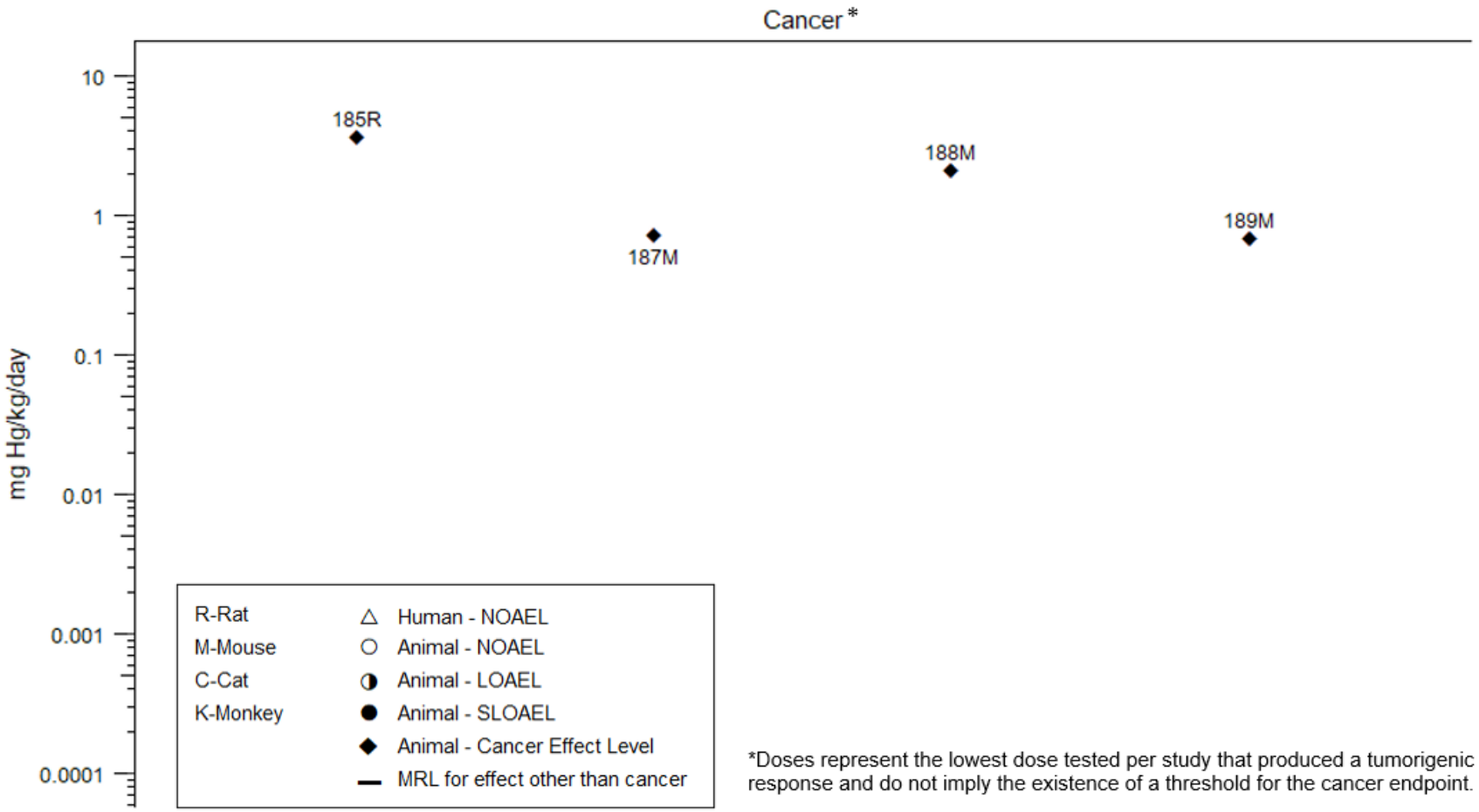


Figure 2-8. Levels of Significant Exposure to Organic Mercury – Oral
Chronic (≥365 days)



*Doses represent the lowest dose tested per study that produced a tumorigenic response and do not imply the existence of a threshold for the cancer endpoint.

2.2 ACUTE POISONING IN HUMANS

Case reports of accidental or intentional poisonings provide information on acute-duration exposure effects in humans. These reports include acute-duration exposure poisonings from elemental mercury vapor, ingestion of mercuric chloride, and dermal exposure to dimethylmercury. In these cases, exposures are at near-lethal or lethal levels. Yawei et al. (2021) summarized collective symptoms in 288 cases of poisoning from exposures to inorganic mercury (mercury vapor, mercuric or mercurous mercury). The most prominent symptoms were neurological, renal, respiratory, gastrointestinal, and dermatological.

Elemental Mercury. Numerous cases of poisoning from acute-duration exposures to elemental mercury vapor have been reported. Symptoms of toxicity in lethal cases included chills, fever, dyspnea, headache, gastrointestinal disturbances (cramps, diarrhea), erythema, disturbances of hearing and vision, hypertension, and pulmonary edema (Jung and Aaronson 1980; Kanluen and Gottlieb 1991; Pastor-Idoate et al. 2021; Rowens et al. 1991; Teng and Brennan 1959; Ursitti et al. 2022). Deaths were typically attributed to respiratory failure related to pulmonary edema.

Inorganic Mercuric Mercury. Numerous cases of poisoning from acute-duration ingestion of mercuric chloride have been described. A review of 45 published cases of acute mercuric chloride poisoning indicated that the primary systems with symptoms were the gastrointestinal tract, kidney, and brain (Cappelletti et al. 2019). Gastrointestinal tract effects observed following acute poisoning have included abdominal pain, nausea, diarrhea, ulceration, and hemorrhages of the upper and lower tract. Kidney effects have included oliguria, proteinuria, hematuria, casts, nephritis, and acute renal failure; and, at autopsy, renal proximal tubular atrophy and glomerular pathology. Symptoms of neurological effects have included disturbances of vision and behavior and seizures; at autopsy, brain abscesses in the cerebrum have also been observed. In most cases of poisoning, the dose ingested was not known; however, for some cases, the dose was estimated to have been ≥1 g of mercury (Cappelletti et al. 2019).

Organic Mercury. A lethal dose of dimethylmercury occurred following accidental contact to the dorsal surface of a latex gloved hand. The 48-year-old female chemistry professor reported the dose as “a few drops” of liquid dimethylmercury (Nierenberg et al. 1998; Siegler et al. 1999). Approximately 5 months after the exposure, the patient developed severe neurological symptoms that included deterioration of balance, gait and speech, paresthesia, and disturbances of vision and hearing (Nierenberg et al. 1998). The patient died 298 days following the exposure; autopsy revealed thinning of the cerebral cortex and

atrophy of the cerebellum (Siegler et al. 1999). The applied dose was reconstructed based on measurements of BHg made approximately 5 months following the accident and the estimated half-time of 75 days for HHg in the subject (Nierenberg et al. 1998). The applied dose was estimated to have been approximately 1,344 mg mercury contained in approximately 0.44 mL of liquid dimethylmercury (Nierenberg et al. 1998).

2.3 DEATH

Overview. Epidemiological studies evaluating associations between mercury exposure and specific causes of death are evaluated in subsequent sections of Chapter 2 when data are available (e.g., cardiovascular). This section reviews information on all-cause death or mortality (death not attributed to a specific underlying cause). Few epidemiological studies have assessed associations between mercury exposure and all-cause death. Most of the available studies did not provide biomarker data and did not adjust results for confounding factors. Available studies have evaluated all-cause death in workers exposed to elemental mercury, the Minamata population exposed to fish and shellfish with a high methylmercury content, the population in Iraq exposed to high levels of methylmercury in contaminated wheat, and general populations in Finland and Sweden. Studies show increases in all-cause death from exposure to methylmercury, but not for occupational exposures or in general populations.

Increased mortality in animals has been observed at high inhalation or oral exposure levels. Death following inhalation of high mercury vapor concentrations is associated with asphyxiation; no oral LC_{50} value is available. Oral LD_{50} values for mercuric chloride range from 25.9 to 77.7 mg Hg/kg/day, and death following chronic-duration oral exposure is associated with renal nephropathy. Mortality following oral exposure to methylmercury at high doses is associated with overt neurotoxicity and/or renal nephropathy. Oral LD_{50} values for methylmercury are not available.

The following summarizes results of epidemiological and animal studies on mortality.

- ***Elemental mercury***
  - Few studies have evaluated all-cause mortality in workers exposed to elemental mercury. No increases in deaths in workers were observed. Biomarker data were not available.
  - *Animal studies*
    - Death due to asphyxiation has been reported following acute-duration exposure to very high concentrations. No LC_{50} values were identified.

- ***Inorganic mercury salts***
  - *Epidemiology studies*
    - No epidemiological studies evaluating associations between exposure to inorganic mercury salts and death were identified.
  - *Animal studies*
    - Oral LD_{50} values for mercuric chloride in rats range from 25.9 to 77.7 mg Hg/kg/day.
    - Male rats are the most sensitive to lethal effects of mercuric chloride; with chronic-duration exposure, increased mortality is associated with increased severity of nephropathy.
    - Mercuric sulfide is not lethal to rats, mice, or guinea pigs at extremely high oral doses.
- ***Organic mercury***
  - Two long-term follow-up studies in populations with Minamata disease reported increases in all-cause mortality. Biomarker data are not available in this population.
  - All-cause death was elevated in the Iraq population exposed through methylmercury-contaminated wheat.
  - A study of a high fish-eating population found that HHg was associated with an increase in early death.
  - *Animal studies*
    - No LD_{50} values were identified.
    - Methylmercury is associated with increased mortality at high acute- and intermediate-duration doses associated with overt signs of neurotoxicity.
    - Following chronic-duration exposure, male mice are the most sensitive to lethal effects of methylmercury. Increased mortality is associated with increased severity of nephropathy.
- ***Predominant mercury form unknown (general populations)***
    - Studies conducted in populations in the United States, Finland, and Sweden found no associations between mercury biomarkers and all-cause death.

Confounding Factors. Numerous factors can influence results of epidemiological studies evaluating associations between mercury exposure and mortality, including age, sex, body mass index (BMI), ethnicity, poverty level, education, alcohol consumption, smoking status, hypertension, diabetes, family history of diseases, activity level, total cholesterol, postmenopausal status, nutritional status, and co-exposure with other metals (i.e., arsenic or cadmium). Failure to account for these factors when they are associated with both mortality and exposure to mercury may reduce or strengthen the apparent associations between mercury exposure and the outcome.

Elemental Mercury—Epidemiological Studies. Few epidemiological studies have evaluated mortality due to all causes in workers exposed to elemental mercury, with the available studies showing no increases in all-cause death (Barregard et al. 1990; Cragle et al. 1984; Ellingsen et al. 1993). Cumulative exposure was reported in studies reporting an exposure metric. Extrapolation of these study results to other populations is highly uncertain due to reporting inadequacies and lack of adjustments for confounding factors.

Elemental Mercury—Animal Studies. Rats, guinea pigs, and mice died from severe pulmonary edema following a 24–48-hour exposure to an unspecified concentration of metallic mercury vapor resulting from spillage of mercury droplets on the floor of a static exposure chamber (Christensen et al. 1937). Death due to asphyxiation was reported in 20/32 rats exposed to 27.0 mg Hg/m^3 for 2 hours; all remaining animals died within 5 days of exposure (Livardjani et al. 1991). No deaths occurred in rats similarly exposed for 1 hour (Livardjani et al. 1991). An intermediate-duration inhalation study in rats reported death of 6/14 animals exposed to 0.5 mg Hg/m^3 for 2 hours/day over 65 days (Raffee et al. 2021).

Inorganic Mercury Salts—Animal Studies. Oral LD_{50} values for mercuric chloride reported in female rats at 3, 6, 18, and 54 weeks of age are 77.7, 68.1, 37, and 37 mg Hg/kg/day, respectively. At 2 weeks of age, the oral LD_{50} in rats of unspecified sex was 25.9 mg Hg/kg/day (Kostial et al. 1978). However, in repeat-exposure studies, male rats appeared to be slightly more sensitive to the lethal effects of mercuric chloride, with 2/5 males and 0/5 females dying following gavage exposure to 15 mg Hg/kg/day for 4–5 days (NTP 1993). Mice showed slightly less toxicity, with no deaths at 14.8 mg Hg/kg, death in 1/5 males at 29 mg Hg/kg, and deaths in 5/5 males and 4/5 females at 59 mg Hg/kg when administered by gavage for up to 4 days (NTP 1993).

In intermediate-duration studies in rats and mice, no mortality was observed following exposure to gavage doses up to 4 or 15 mg Hg/kg/day, respectively (NTP 1993). Mortality was 100% in male rats exposed to mercuric chloride at drinking water doses of 5.91 mg Hg/kg/day for 4 weeks (Wildemann et al. 2015a). In a multigenerational study, 50% mortality was observed in F0 rat dams exposed to gavage doses of 1.98 mg Hg/kg/day for up to 81 days (Atkinson et al. 2001). Prior to death, rats showed signs of toxicity (e.g., significant decrease in body weight gain/weight loss, reduced food and water intake).

In a chronic-duration gavage study, decreased survival until scheduled sacrifice was observed in male F344 rats exposed to 1.8 or 4 mg Hg/kg/day (21 or 10%, respectively), compared to controls (52%);

increased mortality was associated with increased severity of nephropathy (Dieter et al. 1992; NTP 1993). Mortality was comparable to controls in similarly treated female rats. No effects on survival were observed in mice exposed to mercuric chloride at chronic-duration doses up to 7.4 mg Hg/kg/day, respectively (NTP 1993).

No exposure-related deaths followed repeated oral exposure to mercuric sulfide at doses up to 860 mg Hg/kg/day in rats (Chuu et al. 2007), 1,700 mg Hg/kg/day in mice (Chuu et al. 2001a; Son et al. 2010), or 86 mg Hg/kg/day in guinea pigs (Chuu et al. 2001b).

Organic Mercury—Epidemiological Studies. Associations between methylmercury exposure and all-cause death in populations with high fish diets have been evaluated in long-term (≥20 years), follow-up studies in the Minamata population (Futatsuka et al. 2005; Tamashiro et al. 1985, 1986). Unfortunately, no biomarkers or adjustments for contributing factors were reported, limiting the interpretation of study results. Increased standardized mortality ratios (SMRs) for all-cause death were reported by Futatsuka et al. (2005) and Tamashiro et al. (1985). The Futatsuka et al. (2005) study, which evaluated 1,500 patients diagnosed with Minamata disease, reported SMRs ranging from 1.14 (95% CI 1.03, 1.26) to 1.27 (95% CI 1.15, 1.41), based on two different control groups. Tamashiro et al. (1985) evaluated 1,483 patients with Minamata disease; SMRs were 1.27 (95% CI 1.12, 1.44) in males and 1.30 (95% CI 1.10, 1.53) in females. In contrast, when not limiting deaths to patients with Minamata disease, this study did not find increased SMRs in a large population living in the Minamata area (n=36,782).

Information on mortality is available on the Iraq population exposed to methylmercury for approximately 3 months through widespread consumption of wheat that had been treated with a methylmercuric fungicide (Al-Mufti et al. 1976; Bakir et al. 1973; Clarkson et al. 1976). Based on measurements of methylmercury in flour used to bake contaminated bread and estimates of bread consumption, methylmercury intake was estimated to have ranged from 80 to 1,000 mg over a 3-month period (Al-Mufti et al. 1976). Approximately 6,500 cases of mercury poisoning occurred, with approximately 459 related deaths (Clarkson et al. 1976). Greenwood (1985) evaluated mortality by comparing death registries in the 2 years prior to exposure to death registries during exposure through 2 years after. Individuals were considered exposed if BHg >5 µg/g or HHg >5 µg/g. The number of deaths was significantly increased following exposure. The biggest increase in mortality (4-fold increase) was in age ranges 1–10 and 11–20 years. When limiting to 3 months after exposure cessation, there were no increases in deaths.

A recent retrospective longitudinal study of a population of a First Nation community in Canada evaluated associations between HHg and premature death (Philibert et al. 2020). The study population consisted of 657 adults with HHg measurements over the period of 1970–1997. Over the course of the study duration, median HHg significantly declined in cases from 22.2 to 5.0 µg/g; the median HHg in controls declined from 7.1 to 2.6 µg/g, but this change was not significant. Analysis of longevity found that for each 6.25-µg/g increase in HHg, the age of death decreased by 1 year.

Organic Mercury—Animal Studies. No oral LD_{50} values were identified for organic mercury compounds; however, oral exposure has been associated with increased mortality at high doses.

In rats, a single exposure to 16 mg Hg/kg/day during gestation resulted in 17% maternal death (Lee and Han 1995). In repeat-dose studies, mortality was 41% in nonpregnant rats exposed to 8 mg Hg/kg/day for 10 days (Su et al. 1998), 50% in male rats exposed to 4 mg Hg/kg/day for 12 days (Usuki et al. 1998) and 27% in male rats exposed to 12.6 mg Hg/kg/day for 14 days (Sun et al. 2018). Furthermore, 100% mortality was observed in SHR/NCrj rats (spontaneously hypertensive strain) exposed to 1.6 mg Hg/kg/day for 26 days (Tamashiro et al. 1986), and 45% in pregnant rats exposed to 1.6 mg Hg/k/day during pregnancy and lactation (Tonk et al. 2010). Mortality in acute- and intermediate-duration studies was preceded by severe body weight effects and/or clinical signs of neurotoxicity. Mortality was comparable to controls in rats following chronic-duration exposure to methylmercury at doses up to 0.18 mg Hg/kg/day (Verschuuren et al. 1976). A chronic-duration study with phenylmercuric acetate reported a 50% increase in mortality associated with renal nephrosis in male rats at 3.7 mg Hg/kg/day (females not evaluated); no changes in survival were observed at doses up to 0.37 mg Hg/kg/day (Solecki et al. 1991).

In mice, a single oral dose exposure to methylmercury at 16 mg Hg/kg resulted in the death of 4/6 males but no deaths in females (Yasutake et al. 1991). No increase in mortality was observed in female mice until 40 mg Hg/kg was administered, at which dosage 4/6 females died (and 6/6 males died). Increased death in males was associated with impaired renal function. In other mouse studies, 100% mortality was observed in mice following acute-duration exposure to ≥9.3 mg Hg/kg/day (Chuu et al. 2001a; Khera and Tabacova 1973) and or intermediate-duration exposure to ≥8.7 mg Hg/kg/day (Dietrich et al. 2005; MacDonald and Harbison 1977). Intermediate-duration doses of 4.5 mg Hg/kg/day were associated with 85 and 98% mortality in male and female mice, respectively (Mitsumori et al. 1981). Moderate-to-severe signs of clinical neurotoxicity were observed prior to death in the intermediate-duration studies. One chronic-duration study reported a 31% increase in male B6C3F1 mouse mortality at dietary doses of

0.686 mg Hg/kg/day (Mitsumori et al. 1990), but another chronic-duration study reported survival comparable to controls in male ICR mice at dietary doses up to 0.724 mg Hg/kg/day (Hirano et al. 1986); both studies reported increased renal nephropathy and tumors in male mice. Female mouse survival in chronic-duration dietary studies was comparable to controls in both studies at doses up to 0.627 mg Hg/kg/day (Hirano et al. 1986; Mitsumori et al. 1990).

In a study designed to evaluate immune function, 80% of rabbits exposed to 1 mg Hg/kg/day died within 4 weeks of exposure (prior to influenza inoculation); the remaining 20% of rabbits died between 4 and 12 weeks of exposure (post-inoculation) (Koller et al. 1977). As observed in rodents, body weight effects and severe neurotoxicity preceded death; however, deaths post-inoculation may be attributed (in part) to decreased immune response to influenza infection.

In a chronic-duration study in cats, all animals exposed to 0.074 or 0.176 mg Hg/kg/day were sacrificed early due to overt signs of neurotoxicity after approximately 16 and 55 weeks of exposure, respectively (Charbonneau et al. 1976). One animal was similarly sacrificed at 0.046 mg Hg/kg/day after 38 weeks of exposure; the remaining animals in this group survived to terminal sacrifice.

Predominant Mercury Form Unknown (General Populations). Associations between mercury levels and all-cause mortality in general populations exposed to mercury have not been well-studied. However, available studies have been conducted in large study populations (n=1,397–26,056). Study results are summarized in Table 2-5. Prospective studies evaluated associations between mercury biomarkers and all-cause death in general populations of in the United States (using NHANES data), Finland, and Sweden (Ahlqwist et al. 1999; Bergdahl et al. 2013; Sun et al. 2021; Virtanen et al. 2005). None of these studies found positive associations between mercury levels all-cause mortality. A meta-analysis of data from the Bergdahl et al. (2013) and Virtanen et al. (2005) studies also did not find an association between mercury biomarkers and all-cause mortality (Hu et al. 2021). In Swedish women, an inverse relationship (decreasing death with increasing serum mercury [SHg]) was observed between SHg and all-cause death (Ahlqwist et al. 1999). In addition to prospective studies, a cohort study of a large population (n=26,056) using NHANES data did not find associations between BHg and all-cause mortality (Duan et al. 2020).

Table 2-5. Results of Epidemiological Studies Evaluating Exposure to Mercury (Predominant Mercury Form Unknown) and Death in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Ahlqwist et al. 1999 Prospective; 1,397 women (ages 38–60 years at baseline in 1968–1969), followed for approximately 24 years 1974–1975, 1980–1981, and 1992–1993) (Sweden)	SHg mean: 17.0 µg/L	All-cause death	↓ (SHg)
Bergdahl et al. 2013 Prospective; 1,462 women (ages 38–60 years); followed for approximately 32 years (Sweden)	SHg median: 1.38 µg/L	All-cause death	↔ (SHg)
Duan et al. 2020 Cohort; 26,056 adults; mean age 45.9 years; followed for an average of 7.4 years (NHANES 1999–2014)	BHg median: 0.90 µg/L	All-cause death	↔ (BHg)
Sun et al. 2021 Prospective cohort; 17,294 adults; mean age 45.9 years (NHANES 2003–2012)	BHg mean: 1.62 µg/L	All-cause death	↔ (BHg)
Virtanen et al. 2005 Prospective; 1,871 men (42–60 years of age at baseline), followed for approximately 14 years (Finland)	HHg <2.03 µg/g ≥2.03 µg/g	All-cause death	↔ (HHg, <2.03 µg/g) ↔ (HHg, ≥2.03 µg/g)

↓ = inverse association; ↔ = no association; BHg = blood mercury; HHg = hair mercury; NHANES = National Health and Nutrition Examination Survey; SHg = serum mercury

Mechanisms of Action. Mortality is likely the result of effects on multiple organ systems.

2.4 BODY WEIGHT

Overview. Few epidemiological studies have evaluated effects of mercury on body weight. In humans, data are limited to a single study in a population with high fish diets and studies of general populations, with no epidemiological studies identified for elemental mercury. Studies in general populations were

conducted in children, adolescents, and adults. Positive associations were observed between mercury exposure and body weight outcomes in adults; findings were inconsistent in children and adolescents.

Body weight is a well-studied endpoint in animals following inhalation and oral exposure. Body weight effects have been noted following inhalation exposure to elemental mercury and oral exposure to inorganic salts and organic mercury compounds. However, available data do not indicate that body weight is a sensitive effect of mercury toxicity since adverse effects are observed at exposure levels an order of magnitude higher than those associated with the most sensitive effects associated with exposure via the same route and duration. Following oral exposure to inorganic mercury salts or organic mercury, rats are more sensitive than mice. Limited data indicate that monkeys and rabbits may be more sensitive than rodents following oral exposure to organic mercury. It is not known whether there are more sensitive animals than rats following inhalation exposure, as rats are the only species that evaluated body weight via the inhalation route.

The following summarizes results of epidemiological and animal studies on body weight outcomes.

- ***Elemental mercury***
  - *Epidemiology studies*
    - No epidemiological studies evaluating associations between exposure to elemental mercury and body weight were identified.
  - *Animal studies*
    - Body weight effects were reported in rats following acute- or intermediate-duration exposures ≥4 or 0.48 mg Hg/m^3, respectively.
    - Body weight data are not available in other species.
- ***Inorganic mercury salts***
  - *Epidemiology studies*
    - No epidemiological studies evaluating associations between exposure to inorganic mercury salts and body weight were identified.
  - *Animal studies*
    - Body weight effects were consistently reported in rats at intermediate- or chronic-duration exposures ≥1.5 mg Hg/kg/day via gavage or drinking water, with inconsistent evidence for body weight effects at lower doses. In general, higher dietary doses were required to cause body weight effects.
    - Body weight effects in mice were only observed at high oral doses in males (>10 mg Hg/kg/day).

- ***Organic mercury***
  - *Epidemiology studies*
    - Two epidemiological studies did not find associations between BHg and BMI or waist circumference in a population of adults with high fish diets.
  - *Animal studies*
    - Decreases in body weight gain were observed in monkeys and rabbits after intermediate-duration exposure to ≥0.49 mg Hg/kg/day.
    - In rodents, body weight effects were noted in rats at acute-, intermediate-, and chronic-duration exposures ≥1.9, 0.8, and 0.37 mg Hg/kg/day, respectively. Mice are less sensitive, with body weight effects at acute-, intermediate-, and chronic-duration exposures ≥12, 4.7, and 0.6 mg Hg/kg/day, respectively.
- ***Predominant mercury form unknown (general populations)***
    - Epidemiological studies in adults reported positive associations between mercury exposure of general populations and body weight outcomes, including BMI, percent body fat, visceral adipose tissue, waist circumference, and overweight.
    - Results of studies in children and adolescents in general populations are inconsistent, with some studies finding positive associations between mercury biomarkers and BMI, waist to height ratio, and obesity, and other studies finding no associations.

Confounding Factors. Numerous factors contribute to body weight (or BMI), including age, sex, race, nutrition, diet, daily activity level, intercurrent illness, genetic pre-disposition for body type, income level, education, and alcohol and tobacco use. Failure to account for these factors when they are associated with both body weight and exposure may reduce or strengthen the apparent associations between mercury exposure and the outcome.

Elemental Mercury—Epidemiological Studies. No epidemiological studies evaluating associations between exposure to elemental mercury and body weight were identified.

Elemental Mercury—Animal Studies. Body weight effects have been reported in rats following acute-duration exposure to high concentrations. Male rats exposed to a lethal concentration of 27.0 mg Hg/m^3 for 2 hours showed body weight loss; no body weight effects were noted in rats similarly exposed for 1 hour (Livardjani et al. 1991). Maternal body weight loss was observed in rat dams exposed to 8 mg Hg/m^3 on gestation days (GDs) 6–10 or 6–15 (Morgan et al. 2002). At lower exposure levels, maternal body weight was decreased approximately 10–20% from GD 13 to postnatal day (PND) 3 in dams

exposed to 4 mg Hg/m^3 on GDs 6–15, but not GDs 6–10 (Morgan et al. 2002). No changes in maternal body weight were observed in rat dams following gestational exposure to concentrations ≤8 mg Hg/m^3 for 1 day or ≤4 mg Hg/m^3 for 3–10 days (Danielsson et al. 1993; Fredriksson et al. 1996; Morgan et al. 2002). In nonpregnant female rats, a 17% decrease in body weight was observed following intermittent exposure to 4 mg Hg/m^3 for 11 days (Davis et al. 2001).

In intermediate-duration studies, a 17% decrease in body weight gain was observed in male rats intermittently exposed to 0.05 mg Hg/m^3 for 8 weeks (Sørensen et al. 2000) and body weight loss was observed in male rats intermittently exposed to 3 mg Hg/kg/day for 12–42 weeks (Kishi et al. 1978).

Inorganic Mercury Salts—Animal Studies. Body weight effects were not observed in rats exposed to mercuric chloride at gavage doses up to 9.24 mg Hg/kg/day for 1 day (Lecavalier et al. 1994) or 0.7 mg Hg/kg/day for 7–14 days (Chang and Hartmann 1972). In intermediate- and chronic-duration studies, body weight and/or body weight gain decreases ≥10% were reported in rats exposed to mercuric chloride at doses ≥1.5 mg Hg/kg/day via gavage or drinking water (Raeeszadeh et al. 2021), with serious decreases (≥20%) at intermediate- and chronic-duration doses ≥5.91 and 4 mg Hg/kg/day, respectively (Heath et al. 2012; NTP 1993; Perry and Erlanger 1974; Wildemann et al. 2015a). There is inconsistent evidence for body weight effects in rats at lower gavage and drinking water doses, including decreased body weight in female F344 rats exposed to ≥0.462 mg Hg/kg/day for 6 months (NTP 1993), F0 and F1 male Sprague-Dawley rats exposed to 1.31 or ≥0.37 mg Hg/kg/day, respectively, in a 2-generation study (Atkinson et al. 2001), and male Holtzman rats exposed to 0.7 mg Hg/kg/day for 11 weeks (Chang and Hartmann 1972). Other studies reported no body weight effects in female Long-Evans rats exposed to 9.4 mg Hg/kg/day via gavage for 40 days (Goldman and Blackburn 1979), female Sprague-Dawley rats exposed to 1.5 mg Hg/kg/day for 60 days (Heath et al. 2009), or male Wistar rats exposed to intermediate-duration gavage or drinking water doses up to 0.4 mg Hg/kg/day (Agrawal et al. 2014; Teixeira et al. 2018, 2019; Wildemann et al. 2015b).

Body weight effects data in rats following intermediate-duration dietary exposure to mercuric chloride suggest differences between strains and sexes. In Sprague-Dawley rats, final body weight decreases of 37% were observed in females at 2.2 mg Hg/kg/day (Goldman and Blackburn 1979). In Wistar rats, body weight decreases >20% were observed in males at ≥11.4 mg Hg/kg/day and in females at 23.6 mg Hg/kg/day; no body weight effects were observed in Wistar rats at dietary doses up to 5.8 mg Hg/kg/day (Galiciolli et al. 2022; Goldman and Blackburn 1979; Jonker et al. 1993; Takahashi et al. 2000a, 2000b).

In pregnant Wistar rats, no maternal body weight effects were noted following drinking water exposure to 0.6 mg Hg/kg/day for 1 week prior to mating through PND 21 (Szász et al. 2002). In a 2-generation study in Sprague-Dawley rats, transient body weight decreases up to approximately 21% during gestation were observed in F0 females at gavage doses ≥1.11 mg Hg/kg/day (Atkinson et al. 2001).

Body weight effects in mice orally exposed to mercuric chloride were limited to males exposed to high doses. Body weight decreases of 12–14% were reported in male mice following intermediate-duration exposure to gavage doses of 15 mg Hg/kg/day (NTP 1993) or drinking water doses of 11 mg Hg/kg/day (Dieter et al. 1983). No body weight effects were observed in mice exposed to gavage doses up to 30 mg Hg/kg/day for 16 days, 6 mg Hg/kg/day for 4 weeks, or 1.7 mg Hg/kg/day for up to 2 years (NTP 1993; Sin and Teh 1992). In a 1-generation study, no body weight effects were noted in F0 male or female rats at gavage doses up to 0.74 mg Hg/kg/day (Khan et al. 2004).

Gavage exposure to mercuric sulfide was not associated with body weight effects in rats exposed to 860 mg Hg/kg/day for 14 days (Chuu et al. 2007) or mice exposed to doses up to 1,700 mg Hg/kg/day for 28 days (Son et al. 2010).

Organic Mercury—Epidemiological Studies. A prospective study of 3,083 Greenland Inuit adults (1,338 males, mean age 44 years; 1,745 females, mean age 43 years) did not find associations between BHg and BMI or waist circumference (Larsen et al. 2018).

Organic Mercury—Animal Studies. In primates, body weight loss was observed in marmoset monkeys exposed to methylmercury at 0.5 mg Hg/kg/day for up to 242 days (Eto et al. 2001). In macaque monkeys, no body weight effects were observed after intermediate- or chronic-duration exposure to methylmercury at doses up to 0.08 mg Hg/kg/day (Burbacher and Mottet 1988; Burbacher et al. 1984, 2005; Mohamed et al. 1987; Petruccioli and Turillazzi 1991).

In acute-duration oral studies in rats, body weight effects were not noted in any strain exposed to methylmercury at doses up to 1 mg Hg/kg/day (Chang and Hartmann 1972; Fossato da Silva et al. 2011, 2012; Khera 1973). Findings following methylmercury exposure at higher doses were inconsistent and differed between rat strains. In Sprague-Dawley rats, body weight decreases of approximately 10% were noted after a 14-day exposure to 1.9 mg Hg/kg/day (Chuu et al. 2007) and body weight loss was observed after a 10-day exposure to 8 mg Hg/kg/day (Su et al. 1998). In Wistar rats, a 37% decrease in body weight was observed after a 12-day exposure to 4 mg Hg/kg/day (Usuki et al. 1998); however, no body

weight effects were observed after exposure to doses up to 5 mg Hg/kg/day for 7 days (Khera 1973) or 2.8 mg Hg/kg/day for 14 days (Fossato da Silva et al. 2011, 2012). No body weight effects were observed in Wistar rats exposed to methylmercuric sulfide at doses up to 7 mg Hg/kg/day for 10 days (Miyakawa et al. 1974).

Fifteen intermediate-duration studies reported no exposure-related body weight effects in rats exposed to methylmercury compounds at doses up to 0.5 mg Hg/kg/day (LSE Table 2-4 for references). In contrast, Rosa-Silva et al. (2020a, 2020b) reported a 21% decrease in body weight in rats exposed to 0.4 mg Hg/kg/day for 45 days. Serious decreases in body weight or body weight gain (>20%) were consistently reported in all rat strains tested at intermediate-duration oral methylmercury doses ≥0.8 mg Hg/kg/day (Chang and Hartmann 1972; Khera 1973; Larsen and Brændgaard 1995; Moussa et al. 2010; Sakamoto et al. 2017; Schiønning et al. 1998a; Tamashiro et al. 1986; Wildemann et al. 2015a), with the exception of one study reporting no body weight effects following exposure to 1.9 mg Hg/kg/day for 5 weeks (Sakamoto et al. 2017). In chronic-duration studies, exposure to phenylmercuric acetate at doses of 0.37 mg Hg/kg/day resulted in an approximate 10% decrease in final body weight in male rats (Solecki et al. 1991); no body weight effects were noted in male or female rats chronically exposed to methyl mercuric chloride at doses up to 0.16 or 0.18 mg Hg/kg/day, respectively (Verschuuren et al. 1976).

In maternal rats, single methylmercury exposures during gestation were associated with body weight effects at doses ≥8 mg Hg/kg/day (Lee and Han 1995), but not 7 mg Hg/kg/day (Carratu et al. 2006). Following a 9-day exposure during gestation, a 55% decrease in maternal body weight gain was observed in rats exposed to 4.6 mg Hg/kg/day; no changes were observed in similarly exposed dams at 0.23 mg Hg/kg/day (Nolen et al. 1972). No maternal body weight effects were observed following exposure to doses up to 1.9 mg Hg/kg/day for 4 days during gestation (Fredriksson et al. 1996). Following intermediate-duration exposure during premating, gestation, and/or lactation periods, maternal body weight and/or body weight gain decreases ≥10% were observed at 1.2 mg Hg/kg/day with serious decreases (≥20%) at ≥1.6 mg Hg/kg/day (Gandhi et al. 2013; Tonk et al. 2010). Sitarek and Gralewicz (2009) also report a 30–40% decrease in maternal body weight after gestational and lactational exposure to 1.9 mg Hg/kg/day; however, findings were associated with a 10–20% decrease in food consumption. Body weight effects were observed at maternal doses up to 0.9 mg Hg/kg/day (see LSE Table 2-4 for references).

No body weight effects were observed in mice orally exposed to methylmercury at acute-duration doses up to 5 mg Hg/kg/day (Khera 1973; Kirkpatrick et al. 2015) or intermediate-duration doses up to 4.6 mg

Hg/kg/day (Blakley et al. 1980; Bourdineaud et al. 2011; Hirano et al. 1986; Ilback 1991; Kirkpatrick et al. 2015; MacDonald and Harbison 1977; Nascimento et al. 2022). Acute-duration exposure to 12 mg Hg/kg/day or intermediate-duration exposures ≥4.7 mg Hg/kg/day resulted in body weight loss in mice (Das et al. 1997; Dietrich et al. 2005; MacDonald and Harbison 1977). In chronic-duration studies, female B6C3F1 mice showed an approximate 10% decrease in final body weight following dietary exposure to 0.601 mg Hg/kg/day for 2 years; male B6C3F1 mice also showed a decrease in body weight at 0.686 mg Hg/kg/day, but findings were associated with decreased food consumption (Mitsumori et al. 1990). In ICR mice, no body weight effects were noted at chronic-duration doses up to 0.724 mg Hg/kg/day (Hirano et al. 1986). No body weight effects were noted in maternal mice following a single gestation exposure to 9.99 mg Hg/kg/day (Belles et al. 2002) or intermediate-duration exposure during premating, gestation, and/or lactation periods to doses up to 4.7 mg Hg/kg/day (Franco et al. 2006; Thuvander et al. 1996; Weiss et al. 2005).

Data in other species are limited. In an intermediate-duration oral study in rabbits, body weight gain was decreased by 13% in females at 0.48 mg Hg/kg/day and by 43% in males at 0.53 mg H/kg/day; no effects were observed in either sex at 0.05 mg Hg/kg/day (Koller et al. 1977). No body weight effects were noted in cats exposed to doses up to 0.176 mg Hg/kg/day approximately 16 weeks, 0.074 mg Hg/kg/day for approximately 55 weeks, or 0.046 mg Hg/kg/day for 2 years (Charbonneau et al. 1976).

Predominant Mercury Form Unknown (General Populations). Associations between mercury biomarkers and body weight have been evaluated in several cross-sectional studies; results are summarized in Table 2-6. Studies include large populations (n=1,567–11,159) of participants from NHANES (Fan et al. 2017; Wang et al. 2018) or KNHANES (Bae et al. 2016; Lee et al. 2016; Moon et al. 2022; Park and Lee 2013; Shin et al. 2018). Studies also evaluated body weight effects in children and adolescents (Cho 2021; Fan et al. 2017; Shin et al. 2018), with the remaining studies conducted in adults. Studies used BHg, SHg, UHg, and NHg as exposure biomarkers.

Table 2-6. Results of Epidemiological Studies Evaluating Body Weight Effects of Mercury Exposure (Predominant Mercury Form Unknown) in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Bae et al. 2016 Cross-sectional; 11,159 adults, 5,543 males and 5,616 females (KNHANES 2008–2012)	BHg mean Males: 5.07 µg/L Females: 3.59 µg/L	BMI	↑ (BHg, males) ↑ (BHg, females)
		Waist circumference	↑ (BHg, males) ↑ (BHg, females)
Cho 2021 Cross-sectional; 1,327 children and adolescents (672 males and 655 females), ages 10–18 years (KNHANES 2010–2013)	BHg mean Normal weight: 2.09 µg/L Overweight: 2.43 µg/L	BMI	↑ (BHg)
		Waist to height ratio	↑ (BHg)
Fan et al. 2017 Cross-sectional; 5,404 children (2,734 males and 2,659 females), ages 6–19 years (NHANES 2011–2014)	SHg mean: 0.65 µg/L	BMI	↔ (SHg)
Hernández-Mendoza et al. 2022 Cross-sectional; 86 adults, 27 males and 59 females, mean age 27 years (Mexico)	SHg mean Males: 0.95 µg/L Females: 0.9 µg/L	BMI	↔ (SHg, males and females)
Jeon et al. 2021 Cross-sectional; 495 adults, ages 40–69 years, 46% male (Korea)	NHg tertiles T1: 0.09–0.27 µg/g T2: 0.28–0.41 µg/g T3: 0.42–2.15 µg/g	Obesity	↑ (BHg,T3)
		Abdominal obesity	↑ (BHg,T3)
Lee et al. 2016 Cross-sectional; 9,228 adults, 4,283 males and 4,945 females (KNHANES 2007–2013)	BHg quartiles, males Q1: <3.04 µg/L Q2: 3.04–4.52 µg/L Q3: 4.52–6.84 µg/L Q4: ≥6.84 µg/L BHg quartiles, females Q1: <2.24 µg/L Q2: 2.24–3.17 µg/L Q3: 3.17–4.55 µg/L Q4: ≥4.55 µg/L	Overweight	↑ (BHg, males, Q1–Q4) ↑ (BHg, females, Q1–Q4)

Table 2-6. Results of Epidemiological Studies Evaluating Body Weight Effects of Mercury Exposure (Predominant Mercury Form Unknown) in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Moon et al. 2022 Cross-sectional; 3,787 adults, ≥19 years of age, 1,648 males and 2,139 females (KNHANES 2015–2017)	BHg quartiles Q1: <1.86 µg/L Q2: 1.86–<2.18 µg/L Q3: 2.18–4.44 µg/L Q4: ≥4.44 µg/L UHg quartiles Q1: <0.20 µg/L Q2: 0.23–<0.35 µg/L Q3: 0.35–0.64 µg/L Q4: ≥0.64 µg/L	Obesity	↑ (BHg, males, Q3–Q4) ↑ (BHg, females, Q4) ↑ (UHg, males, Q4) ↑ (UHg, females, Q2–Q4)
Park and Lee 2013 Cross-sectional; 4,522 adults, 2,217 males and 2,395 females (KNHANES 2008–2010)	BHg Gmean Males: 4.337 µg/L Females: 3.733 µg/L	Body fat (%)	↓ (BHg, males) ↔ (BHg, females)
Park et al. 2017 Cross-sectional; 200 adults, 96 males and 104 females (Korea)	BHg tertiles T1: 1.06–2.66 µg/L T2: 2.69–4.43 µg/L T3: 4.46–7.16 µg/L	Visceral adipose tissue	↑ (BHg)
Shin et al. 2018 Cross-sectional; 1,567 children and adolescents, 793 males and 774 females; ages 10–19 years (KNHANES 2010–2013)	BHg Gmean: 1.93 µg/L BHg quartiles boys Q1:<1.47 µg/L Q2: 1.47–1.93 µg/L Q3: 1.94–2.67 µg/L Q4: >2.67 µg/L BHg quartiles girls Q1: <1.39 µg/L Q2: 1.39–1.79 µg/L Q3: 1.80–2.41 µg/L Q4: >2.41 µg/L	Overweight/obesity	↑ (BHg, males and females, Q4)
		Abdominal obesity	↑ (BHg, males, Q4) ↔ (BHg, females, Q4)

↑ = positive association; ↓ = inverse association; ↔ = no association; BHg = blood mercury; BMI = body mass index; Gmean = geometric mean; KNHANES = Korean National Health and Nutrition Examination Survey; NHANES = National Health and Nutrition Examination Survey; NHg = toenail mercury; SHg = serum mercury; Q = quartile; T = tertile; UHg = urine mercury

Cross-sectional studies in children and adolescents were conducted in NHANES (Fan et al. 2017) and KNHANES (Cho 2021; Shin et al. 2018) participants. No association was observed between SHg and BMI in NHANES participants who had a mean SHg of 0.65 µg/L (Fan et al. 2017). In contrast, in the KNHANES population with higher mercury levels (4th BHg quartile: 4.08–4.77 µg/L), positive associations were observed for overweight/obesity in males and females and abdominal obesity in males,

but not females; no associations were observed at lower quartiles (Q1–Q3: 1.82–3.73 µg/L) (Shin et al. 2018). Similarly, Cho (2021) reported positive associations between BHg and BMI and waist to height ratio. It is difficult to directly compare the NHANES and KNHANES studies because different biomarkers were used. In adults, most studies showed positive associations between mercury biomarkers and several body weight outcomes, including BMI, percent body fat, visceral adipose tissue, waist circumference, and overweight, as summarized in Table 2-6.

Mechanisms of Action. A recent review by Moon (2017) noted that "mercury has no known physiological role in human metabolism." However, proposed mechanisms for mercury-induced effects on body weight include the following: (1) mitochondrial dysfunction; (2) oxidative stress; (3) insulin resistance; and (4) pancreatic β-cell dysfunction and apoptosis (Moon et al. 2017). In addition, based on a study in adipocyte cell lines, mercuric chloride may influence signaling events and subsequent metabolic activity in adipose tissue (Barnes et al. 2003).

2.5 RESPIRATORY

Overview. Few epidemiological and animal studies have evaluated respiratory effects of mercury. However, based on the available data, the respiratory tract does not appear to be a sensitive target of environmental exposures to mercury. Most epidemiological studies were conducted in general populations of children and examined associations between biomarkers and asthma, with only one study reporting positive associations between biomarkers and asthma. Case studies of acute-duration exposures to high levels of elemental mercury vapor in confined occupational or residential spaces indicate that damage to the respiratory tract can occur.

Studies evaluating respiratory effects in animals are available for inhalation exposure to mercury vapor and oral exposure to mercuric chloride or methylmercury. Consistent with human data, respiratory distress and lung damage have been reported following exposure to acute-duration lethal air concentrations of mercury vapor. Oral data do not indicate that the lung is a sensitive target of mercury toxicity in animal studies, although limited data indicate alveolar effects at high acute-duration methylmercury doses. Nasal lesions have been reported in both mice and rats following chronic-duration gavage exposure to mercuric chloride.

The following summarizes results of epidemiological and animal studies on respiratory outcomes.

- ***Elemental mercury***
  - *Epidemiology studies*
    - No epidemiological studies on respiratory effects of exposure to elemental mercury were identified.
    - Case studies show that acute-duration exposure to high levels of mercury vapor in confined occupational or residential spaces produces adverse respiratory effects, which can be severe.
  - *Animal studies*
    - Respiratory distress and lung damage were reported at acute-duration lethal air concentrations in one study.
    - Data are insufficient to determine if exposure to elemental mercury at nonlethal concentrations is associated with adverse respiratory effects.
- ***Inorganic mercury salts***
  - *Epidemiology studies*
    - No epidemiological studies evaluating associations between exposure to inorganic mercury salts and respiratory effects were identified.
  - *Animal studies*
    - One study reported labored breathing in rats following intermediate-duration dietary exposure to mercuric chloride.
    - Chronic-duration gavage exposure to mercuric chloride is associated with nasal lesions in both rats and mice.
    - There is no evidence of lung lesions following acute-, intermediate-, or chronic-duration gavage exposure to mercuric chloride in rats or mice.
- ***Organic mercury***
  - *Epidemiology studies*
    - Data are insufficient to determine if exposure to organic mercury is associated with adverse respiratory effects. The only identified study did not show an association between cord BHg and asthma in children.
  - *Animal studies*
    - One acute-duration study reported elevated lung weight and alveolar changes following oral exposure to high doses of methylmercury.
    - There is no evidence of lung lesions in cats, rats, or mice orally exposed to methylmercury for up to 2 years.

- ***Predominant mercury form unknown (general populations)***
    - Results of studies conducting pulmonary function tests are inconsistent, with some studies showing inverse associations between biomarkers and pulmonary function and other studies showing no associations.
    - Several studies evaluated outcomes related to asthma in children. Of the available studies, only one study found an association between biomarkers and asthma.
    - No associations were observed between respiratory symptoms (wheeze and cough) and gestational exposure to mercury.

Confounding Factors. The etiology for most respiratory diseases is multifactorial; therefore, several factors may contribute to clinical findings. These include poor housing conditions, exposure to allergens (e.g., pet dander, seasonal allergies), exposure to tobacco smoke and other respiratory irritants, and asthma compounded by obesity (Ali and Ulrik 2013). In addition, Aligne et al. (2000) reported that children living in urban settings have an increased risk of asthma. Failure to account for these factors when they are associated with both respiratory outcomes and exposure may attenuate or strengthen the apparent associations between mercury exposure and the outcome, depending on the direction of the effect of the variable on the outcome.

Elemental Mercury—Epidemiological Studies. Epidemiological studies evaluating effects of elemental mercury in respiratory effects meeting inclusion criteria were not identified (see inclusion criteria, Section 2.1). Several case studies of individuals reported adverse respiratory effects following acute-duration exposure (a few hours) to near-fatal or fatal elemental mercury vapor generated from heating elemental mercury to high temperatures in confined spaces in occupational or residential settings. Findings include the following: cough, wheeze, and shortness of breath (Haddad and Stenberg 1963; Kanluen and Gottlieb 1991; Milne et al. 1970); decreased pulmonary function, including decreased vital capacity (VC), forced expiratory volume (FEV), and FEV in 1 second (FEV_1) (Gore and Harding 1987; Lilis et al. 1985); restrictive lung disease (Hallee 1969; Lilis et al. 1985); lung inflammation classified as bronchiolitis, bronchitis, or pneumonitis (Gore and Harding 1987; King 1954; Milne et al. 1970; Rowens et al. 1991; Teng and Brennan 1959; Tennant et al. 1961); interstitial and alveolar fibrosis (Hallee 1969; Kanluen and Gottlieb 1991); and respiratory failure (Kanluen and Gottlieb 1991; Rowens et al. 1991; Teng and Brennan 1959). No information regarding respiratory effects at lower exposure levels (i.e., not near-fatal or fatal levels) of elemental mercury were identified.

Elemental Mercury—Animal Studies. Data on respiratory effects in animals following inhalation exposure to mercury vapor are limited. In rats, exposure to a lethal air concentration (27.0 mg Hg/m^3) for 2 hours resulted in dyspnea and asphyxiation. At necropsy, lung edema, necrosis of the alveolar epithelium and hyaline membranes, and occasional lung fibrosis were observed (Livardjani et al. 1991). In other studies, no evidence of respiratory distress or lung damage was observed in rats following nonlethal exposure to 26.6 mg Hg/m^3 for 1 hour (Livardjani et al. 1991), 8 mg Hg/m^3 for 2 hours/day for up to 10 days (Morgan et al. 2002), or 3 mg Hg/m^3 for 12–42 weeks (5 days/week; 3 hours/day) (Kishi et al. 1978). Emphysema, obstruction of intra-alveolar septae, alveolar dilation, and intra-alveolar edema and inflammatory cell infiltrate were observed in rats exposed to 0.5 mg Hg/m^3 for 2 hours/day for both 21 and 65 days of exposure (Raffee et al. 2021).

Inorganic Mercury Salts—Animal Studies. The only study located regarding respiratory function in animals after oral exposure to inorganic mercury salts described forceful and labored breathing, bleeding from the nose, and other unspecified respiratory difficulties in rats after dietary exposure to 2.2 mg Hg/kg/day as mercuric chloride for 3 months (Goldman and Blackburn 1979).

Nasal lesions were observed in both rats and mice following chronic-duration gavage exposure to mercuric chloride. Increased incidence of nasal mucosa inflammatory lesions was observed in rats at 4 mg Hg/kg/day and mice at 7.4 mg Hg/kg/day (NTP 1993). In mice, increased metaplasia in the olfactory epithelium was also observed in females at ≥4 mg/kg/day and in males at 7.4 mg/kg/day. No nasal lesions were observed in rats or mice following a 6-month exposure to gavage doses up to 4 or 15 mg/kg/day, respectively (NTP 1993).

For intermediate-duration exposure, histopathological changes, including increased type 1 collagen deposition, infiltration of inflammatory cells in the bronchus, decreased type III collagen and irregular elastic fibers, were observed in rats administered at 0.8480 mg Hg/kg/day via gavage for 28 days (Koopsamy Naidoo et al. 2019). Other studies found no changes in lung histology in rats exposed to mercuric chloride via gavage at acute-duration doses up to 9.24 mg Hg/kg/day, intermediate-duration doses up to 15 mg Hg/kg/day, or chronic-duration doses up to 4 mg Hg/kg/day (Lecavalier et al. 1994; NTP 1993). In mice, no changes in lung histology were observed following gavage exposure to intermediate-duration doses up to 59 mg Hg/kg/day or chronic-duration doses up to 7.4 mg Hg/kg/day (NTP 1993).

Organic Mercury—Epidemiological Studies. Data are not sufficient to determine if exposure to mercury in populations with high fish diets produces adverse respiratory effects, with only one study meeting inclusion criteria (see inclusion criteria, Section 2.1). A prospective study of 656 singleton births in the Faroe Islands did not find an association between cord BHg (mean 11.3 µg/L) and asthma at ages 5 and 7 years (Grandjean et al. 2010). Adjustments included parental smoking in the home and PCB exposure.

Organic Mercury—Animal Studies. One acute-duration study in mice reported a 22–23% increase in absolute and relative lung weight, reduced alveolar diameter, increased alveolar wall thickness, and increased minimal surface tension following gavage exposure to 12 mg Hg/kg/day as methylmercuric chloride for 4 days (Das et al. 1997).

No exposure-related changes in lung histology were observed following oral exposure to methylmercuric chloride in cats at doses up to 0.176 mg Hg/kg/day approximately 16 weeks, 0.074 mg Hg/kg/day for approximately 55 weeks, or 0.046 mg Hg/kg/day for 2 years (Charbonneau et al. 1976); rats at doses up to 0.18 mg Hg/kg/day for 2 years (Verschuuren et al. 1976), or mice at doses up to 0.724 mg Hg/kg/day for 2 years (Hirano et al. 1986; Mitsumori et al. 1990).

Predominant Mercury Form Unknown (General Populations). Respiratory effects of mercury in general populations have not been well studied. Available studies evaluated asthma and signs of respiratory effects in large populations (n ≥582) of children using prospective, longitudinal, and cross-sectional designs. Most studies did not find associations between mercury exposure and asthma, signs of respiratory effects, or pulmonary function, although there are a few exceptions. Studies are summarized in Table 2-7. Evidence for effects of mercury on respiratory function is inconclusive as there are few studies and these provide inconsistent results.

Only one prospective study evaluated pulmonary function (Miao et al. 2023). This study of Chinese college students showed an inverse association between pulmonary function tests and BHg (mean BHg: 1.4 µg/L), but no associations at lower exposures. A large longitudinal study that examined additional endpoints found positive associations between BHg and asthma and wheeze, but not asthma medication use or airway hyperresponsiveness (Kim et al. 2015a). A cross-sectional study (n=382) found inverse associations between UHg and pulmonary function parameters (e.g., FEV_1, FVC) (Zheng et al. 2023).

Other cross-sectional studies did not find associations between BHg and asthma, wheeze, or bronchial hyperresponsiveness (Heinrich et al. 2017; Wu et al. 2019); however, these studies did not conduct

pulmonary functions tests. Prospective and longitudinal studies evaluating effects of gestational exposure, based on cord BHg or maternal mercury biomarkers, and respiratory symptoms (wheeze and cough) did not find any associations (Carrasco et al. 2021; Emeny et al. 2019; Miyake et al. 2011; Shaheen et al. 2004).

Table 2-7. Results of Epidemiological Studies Evaluating Exposure to Mercury (Predominant Mercury Form Unknown) and Respiratory Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Studies based on current mercury measurements			
Chen et al. 2023a Cross-sectional; 9,556 adults (NHANES 2007–2012)	SHg Q1: <0.044 µg/L Q2: 0.44–0.79 µg/L Q3: 0.79–1.50 µg/L Q4: ≥1.50 µg/L	PRISm	↔ (SHg, Q4)
Chen et al. 2023b Cross-sectional; 1,227 children and adolescents, 6–17 years of age (NHANES 2007–2012)	UHg median: 0.292 µg/g creatinine	FEV_1	↔ (UHg)
		FVC	↔ (UHg)
		$FEF_{25–75\%}$	↔ (UHg)
		PEF	↔ (UHg)
Heinrich et al. 2017 Cross-sectional; 1,056 children 5–14 years of age (Germany)	BHg Gmean: 0.36 µg/L[a]	Asthma	↔ (BHg)
		Wheeze	↔ (BHg)
		Bronchial hyper-responsiveness	↔ (BHg)
Kim et al. 2015a Longitudinal; 4,350 children enrolled at 7–8 years of age, examined every 2 years through age 11–12 years (Korea 2005–2010)	BHg Gmean Ages 7–8: 2.02 µg/L Ages 9–10: 1.79 µg/L Ages 11–12: 1.96 µg/L	Asthma (age 9–10 years)	↑ (BHg at age 7–8 years) ↑ (BHg at age 9–10 years)
		Asthma (age 11–12 years)	↑ (BHg at age 7–8 years) ↔ (BHg at age 9–10 years) ↔ (BHg at age 11–12 years)
		Wheeze	↑ (BHg)[a]
		Asthma medication use (age 11–12 years)	↔ (BHg)[a]
		Airway hyper-responsiveness (age 11–12 years)	↑ (BHg)[a]
Miao et al. 2023 Prospective cohort; 1,800 college students; mean age 18.1 years (China)	BHg mean All: 0.8 µg/L Low: 0.4 µg/L Medium: 0.7 µg/L High: 1.4 µg/L	FEV_1	↓ (BHg, all, high) ↔ (BHg, low, medium)
		FVC	↓ (BHg, all, high) ↔ (BHg, low, medium)
		PEF	↓ (BHg, all, high) ↔ (BHg, low, medium)

Table 2-7. Results of Epidemiological Studies Evaluating Exposure to Mercury (Predominant Mercury Form Unknown) and Respiratory Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Nguyen 2023 Cross-sectional; 1,162 premenopausal women and 659 postmenopausal women (KNHANES 2009–2017)	SHg Gmean (µg/L) Premenopausal: 3.19 Postmenopausal: 3.08	FEV_1/FVC	↔ (SHg, premenopausal) ↔ (SHg, postmenopausal)
Pan et al. 2020 Cross sectional; 221 children (mean age: 12.5 years) (China)	BHg Gmean: 1.41 µg/L	FEV_1	↔ (BHg)
		FVC	↔ (BHg)
Wu et al. 2019 Cross-sectional; 5,866 children, 2–15 years of age (NHANES 2007–2012)	BHg mean: 0.54 µg/L	Asthma	↔ (BHg)
		Wheeze	↔ (BHg)
Zheng et al. 2023 Cross-sectional; 382 adults, mean age 56.69 years (China)	UHg mean (µg/g Cr) All: 0.21 Without PVD: 0.13 With PVD: 0.27	PVD	↑ (UHg)
		FEV_1	↓ (UHg)
		FVC	↓ (UHg)
		FEV_1/FVC	↓ (UHg)
Studies based on prenatal exposure measurements			
Carrasco et al. 2021 Longitudinal; children 4 years of age with prenatal BHg (n=1,868) and HHg at age 4 years (n=1,347) (Spain)	Cord BHg Gmean: 8.23 µg/L HHg Gmean: 0.97 µg/g	Wheezing	↔ (cord BHg) ↔ (HHg)
		Severe wheezing	↔ (cord BHg) ↔ (HHg)
		Persistent cough	↔ (cord BHg) ↔ (HHg)
Emeny et al. 2019 Prospective; 639–706 infants, assessed 0–4 months, 5–8 months, 9–12 months, >12 months (New Hampshire)	Maternal NHg Gmean: 0.02 µg/g	Wheeze	↔ (NHg)
Miyake et al. 2011 Prospective; mothers enrolled October 2002–March 2003; 582 mother-child; maternal and child exposure and child outcomes assessed at age 29–39 months (Japan)	HHg median Mother: 1.52 µg/g Child: 1.38 µg/g	Wheeze	↔ (HHg, mother and child)

Table 2-7. Results of Epidemiological Studies Evaluating Exposure to Mercury (Predominant Mercury Form Unknown) and Respiratory Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Shaheen et al. 2004 Prospective; mothers enrolled April 1991–December 1992; 1,755 newborns, assessed for wheeze at 18–30 months and 30–42 months of age (United Kingdom)	Cord BHg Gmean: 0.0127 µg/L	Wheeze	↔ (BHg, cord, 18–30 months) ↔ (BHg, cord, 30–42 months)

[a]Child age at time of BHg sampling not specified.

↑ = positive association; ↓ = inverse association; ↔ = no association; BHg = blood mercury; Cr = creatinine; FEV_1 = forced expiratory volume in 1 second; $FEF_{25–75\%}$ = the average flow from the point at which 25% of the FVC has been exhaled to the point at which 75% of the FVC has been exhaled; FVC = forced vital capacity; Gmean = geometric mean; HHg = hair mercury; KNHANES = Korea National Health and Nutrition Examination Survey; NHg = toenail mercury; NNHANES = National Health and Nutrition Examination Survey; PEF = peak expiratory flow; PRISm = preserved ratio impaired spirometry (FEV_1/FVC ≥0.7 and FEV_1 <80% predicted); PVD = pulmonary ventilation dysfunction (FVC <80%, FEV_1% <80%, and FEV_1/FVC <70%); Q = quartile; SHg = serum mercury; UHg = urine mercury

Mechanisms of Action. Epidemiological and animal studies do not provide strong evidence that exposure to mercury at environmental levels adversely affects the respiratory system, although exposure to near-fatal or fatal concentrations of mercury vapor produces respiratory damage. General mechanisms of toxicity of mercury (reviewed in Section 2.21) are likely involved in the development of toxicity to the respiratory system. In addition, immunomodulatory effects and subsequent cellular release of histamine and cytokines have been proposed as possible mechanisms of toxicity (Miyake et al. 2011).

2.6 CARDIOVASCULAR

Overview. Data on cardiovascular effects of mercury are available from studies in humans and animals. Numerous epidemiological studies have evaluated associations between biomarkers of mercury exposure and cardiovascular outcomes. Studies in humans are available for occupational exposures to elemental mercury, populations exposed primarily to methylmercury through high fish diets, and general populations with unspecified mercury exposures likely to be a combination of methylmercury in food and inorganic mercury from dental amalgams (elemental mercury) and other sources. Cardiovascular outcomes evaluated include blood pressure, cardiac function, or diagnosis of clinical hypertension or cardiovascular disease, and results are inconsistent for these outcomes. For blood pressure, the most

studied outcome, evidence for effects is conflicting, and studies that do show positive associations indicate that the magnitude of changes is small. Taken together, results of current epidemiological studies do not provide conclusive evidence that the cardiovascular system is a highly sensitive target for mercury. Limitations for epidemiological studies that provided results for cardiovascular and neurological endpoints are discussed in Section 2.16.1.

Studies evaluating functional cardiovascular endpoints in animals (blood pressure, baroreflex sensitivity, cardiac inotropism) are available for oral exposure to mercuric chloride or methylmercury. Overall, studies indicate that systolic and diastolic blood pressure are increased in a duration-dependent manner for mercuric chloride, and a dose- and duration-dependent manner for methylmercury. A limited number of studies indicate that both compounds also have positive inotropic effects and decreased baroreceptor reflex sensitivity. These data provide evidence that cardiovascular function in rats is altered following exposure to mercuric chloride and methylmercury.

The following summarizes results of epidemiological and animal studies on cardiovascular outcomes.

- ***Elemental mercury***
  - *Epidemiology studies*
    - Findings regarding effects on blood pressure are inconsistent, with no associations at the highest exposures and some positive associations at lower exposures.
    - Few studies investigated effects on cardiac function; data are insufficient to draw conclusions.
  - *Animal studies*
    - No adequate studies have evaluated cardiovascular effects of elemental mercury.
- ***Inorganic mercury salts***
  - *Epidemiology studies*
    - No studies on cardiovascular effects of exposure to inorganic mercury salts were identified.
  - *Animal studies*
    - Findings consistently show duration-dependent increases in systolic and diastolic blood pressure in rats.
    - A few studies have reported positive inotropism and decreased baroreflex sensitivity in rats.
    - No histopathological lesions have been identified in cardiovascular tissue following intermediate- or chronic-duration exposure in rats or mice.

- ***Organic mercury***
  - *Epidemiology studies*
    - Small increases in systolic and diastolic blood pressure have been reported in some studies; however, results are not consistent, and data do not provide clear evidence of a dose-response relationship between methylmercury exposure and increased blood pressure in populations with high fish diets. Associations between methylmercury exposure and prevalence of clinical hypertension are also inconsistent.
    - Data on effects of methylmercury on cardiac function are inconclusive, although some studies reported inverse associations for heart rate variability, which may lead to more serious cardiac effects.
    - No consistent evidence of associations between exposure and cardiovascular diseases has been reported.
  - *Animal studies*
    - Findings show dose- and duration-dependent increases in systolic and diastolic blood pressure in rats.
    - A few studies report positive inotropism and decreased baroreflex sensitivity in rats.
    - No histopathological lesions were identified in cardiovascular tissue following chronic-duration exposure in rats or mice.
- ***Predominant mercury form unknown (general populations)***
    - Evidence for effects of mercury exposure on blood pressure in general populations is inconclusive.
    - Most studies evaluating clinical hypertension reported no associations with mercury biomarkers, although a few studies reported increased risk of hypertension.
    - Evidence for associations between mercury exposure and cardiovascular disease is very limited, with most studies reporting no associations.
    - A study in children reported decreased heart rate variability, indicative of decreased parasympathetic modulation of the autonomic function of the heart.

Confounding Factors. For epidemiological studies, numerous factors affect cardiovascular function, including age, body mass, race, smoking, alcohol consumption, ongoing family history of cardiovascular disease, low density lipoprotein (LDL) cholesterol levels, diet (including n-3 polyunsaturated fatty acids and selenium), other diseases (e.g., renal disease), and co-exposure to substances (lead, PCBs) that may affect the cardiovascular system either directly or indirectly through effects on other systems (e.g., renal, neurological). Failure to account for these factors when they are associated with both cardiovascular

outcomes and exposure may attenuate or strengthen the apparent associations between mercury exposure and the outcome, depending on the direction of the effect of the variable on the outcome (e.g., Møller and Kristensen 1992). Although it is impractical to assess all possible confounders, epidemiological studies reviewed in this section include some of the adjustments listed above. No specific confounder or covariate was mandatory for the inclusion of the study into the profile; however, studies of cardiovascular outcomes that did not consider, at a minimum, age, body mass, race, smoking, alcohol consumption, and ongoing family history of cardiovascular disease are potentially more confounded than studies that did consider these variables.

In addition to potential confounding factors listed above, interpretation of study results is further complicated by the risks and benefits of fish consumption, particularly in populations with high fish diets. Fish contain high levels of n-3 polyunsaturated fatty acids and selenium, which are considered beneficial to cardiovascular health (Choi et al. 2008a, 2009; Hu et al. 2017). Therefore, cardiovascular effects of methylmercury may be offset by the beneficial effects of fatty acids and selenium (e.g., negative confounding) in high fish diets (Chan and Egeland 2004; Choi et al. 2008a; Guallar et al. 2002; Hu et al. 2017; Mozaffarian 2009; Smith et al. 2009; Virtanen et al. 2005). Several study authors noted that the balance between beneficial nutrients and methylmercury in high fish diets may contribute to the equivocal findings in some studies examining cardiovascular effects (Choi et al. 2008a; Guallar et al. 2002; Hu et al. 2017; Stern 2005; Virtanen et al. 2005).

Elemental Mercury—Epidemiological Studies. Studies evaluating effects of elemental mercury on cardiovascular function are summarized in Table 2-8. The database consists of several cross-sectional studies of dental professionals, miners, chloralkali workers, and adults with amalgam fillings. Population sizes in these studies are small (n=28–386), limiting the power to detect associations between elemental mercury and cardiovascular outcomes. All studies quantified exposure using UHg, with some studies also measuring BHg and/or HHg. Choice of biomarkers used in the studies may have impacted the strength and direction of the associations found. UHg has been shown to correlate with elemental mercury exposure in populations in which the main source of exposure was to elemental mercury (e.g., workers in mercury production and processing) (Section 3.3.1, Biomarkers of Exposure). UHg ranged from 0.94 µg/L in a study of U.S. dental professionals (Goodrich et al. 2013) to 51.4 µg/L in mercury-exposed Turkish adults, including dentists and "industrial" exposures (Yilmaz et al. 2016). Evidence for effects of elemental mercury on cardiovascular function is inconclusive.

Table 2-8. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Effects on Cardiovascular Outcomes

Reference, study type, and population	Biomarker	Outcome evaluated	Result[a]
Goodrich et al. 2013 Cross-sectional; 262 dental professionals (Michigan)	HHg mean: 0.45 µg/g UHg mean: 0.94 µg/L	SBP	↔ (HHg) ↓ (UHg)
		DBP	↑ (HHg) ↔ (UHg)
Kobal et al. 2004 Cross-sectional; 54 male mercury miners, 58 male controls (Slovenia)	UHg mean Workers: 2.1 µg/L Controls: 1.4 µg/L	SBP	↑ (workers versus controls)
		DBP	↑ (workers versus controls)
Piikivi 1989 Retrospective, cross-sectional; 41 chloralkali male workers, 41 male referents (Finland)	Means for workers BMeHg: 3.8 µg/L BIHg: 7.8 µg/L UHg: 19.3 µg/L Means for referents BMeHg: 2.9 µg/L BIHg: 0.9 µg/L UHg: 1.8 µg/L	SBP	↔ (workers versus referents)
		DBP	↔ (workers versus referents)
Poreba et al. 2012 Cross-sectional; 115 adult chloralkali workers (Poland)	UHg mean: 4.11 µg/g Cr	LVF	↓ (UHg)
Rajaee et al. 2015 Cross-sectional; 70 adult current and former mercury miners (Ghana)	HHg mean: 1.11 µg/g UHg mean: 37.6 µg/L	SBP	↔ (BHg, UHg)
		DBP	↔ (BHg, UHg)
Siblerud 1990 Cross-sectional; 101 adults with amalgam fillings, 51 adults with no amalgam fillings (Colorado)	HHg mean Amalgam: 1.43 µg/g No amalgam: 1.13 µg/g UHg mean Amalgam: 3.70 µg/L No amalgam: 1.23 µg/L	SBP	↑ (amalgam versus no amalgam)
		DBP	↑ (amalgam versus no amalgam)
		HR	↔ (amalgam versus no amalgam)
Xu et al. 2023a Cross-sectional; 386 dental professionals (United States)	Gmean BHg: 3.64 µg/L UHg: 1.44 µg/L HHg: 0.60 µg/g	SBP	↔ (BHg) ↔ (UHg) ↑ (HHg)
		DBP	↔ (BHg) ↔ (UHg) ↔ (HHg)

Table 2-8. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Effects on Cardiovascular Outcomes

Reference, study type, and population	Biomarker	Outcome evaluated	Result[a]
Yilmaz et al. 2016 Cross-sectional; 28 adults with exposure to Hg^0 (15 dentists, 10 workers with unspecified "industrial" exposure, and 3 individuals with chronic-duration exposure in office or home after fluorescent lightbulb break) and 28 control adults (Turkey)	BHg mean Exposed: 14.8 µg/L Controls: 0.9 µg/L HHg mean Exposed: 2.1 µg/g Controls: 0.2 µg/g UHg mean Exposed: 51.4 µg/L Controls: 1.3 µg/L	SBP	↔ (exposed versus controls)
		DBP	↔ (exposed versus controls)
		HRR	↓ (exposed versus controls)

[a]Biomarkers are not considered in outcome analyses for studies that assess outcomes by comparisons between exposure groups.

↑ = positive association; ↓ = inverse association; ↔ = no association; BHg = blood mercury; BIHg = blood inorganic mercury; BMeHg = blood methylmercury; Cr = creatinine; DBP = diastolic blood pressure; HHg = hair mercury; HR = heart rate; HRR = heart rate recovery (post-exercise); LVF = left ventricular function; SBP = systolic blood pressure; UHg = urine mercury

Blood pressure. Results of studies evaluating associations between occupational exposure to elemental mercury and blood pressure are inconsistent, with no apparent relationship between level of exposure (as reflected by biomarkers) and outcomes (Table 2-8). At the highest mean UHg evaluated, no differences were observed for systolic or diastolic blood pressure in mercury-exposed subjects, including dentists, workers with "industrial" exposures, and individuals with chronic-duration exposure in office or home after fluorescent lightbulb break (UHg: 51.4 µg/L), compared to controls (UHg: 1.3 µg/L) (Yilmaz et al. 2016). Similarly, no associations were observed between elemental mercury exposure and systolic or diastolic blood pressure in miners with mean UHg of 37.6 µg/L (Rajaee et al. 2015). However, increased blood pressure was observed at substantially lower UHg in a study of male miners with mean UHg of 2.1 µg/L, compared with controls with mean UHg of 1.4 µg/L (Kobal et al. 2004). This study found increases in both systolic (miners: 134.4 mmHg; controls: 125.9 mmHg) and diastolic (miners: 87.9 mmHg; controls: 81.2 mmHg;) blood pressure. In adults with amalgam fillings (mean UHg: 3.70 µg/L), average systolic and diastolic blood pressure were increased by 5.73 and 4.37 mmHg, respectively, compared to adults with no amalgam fillings (mean UHg: 1.23 µg/L) (Siblerud 1990). At the lowest UHg evaluated (0.94 µg/L) in U.S. dental professionals, an inverse association was reported for systolic blood pressure (decrease in blood pressure with increasing UHg), with no association for diastolic blood pressure (Goodrich et al. 2013). However, using HHg as the biomarker, associations between mercury and blood pressure showed different effects; no association was observed between HHg

and systolic blood pressure and a positive association was observed for HHg and diastolic blood pressure (Goodrich et al. 2013). The difference between the associations observed with UHg and HHg may reflect a contribution of exposure to methylmercury, which may have contributed to HHg.

Cardiac function. Few studies have investigated effects of elemental mercury on cardiac function; however, studies have not evaluated the same endpoints and findings in single studies have not been corroborated (Table 2-8). For heart rate, no differences were observed in adults with amalgam fillings compared to adults with no amalgam fillings (Siblerud 1990). Heart rate recovery during the first 3 minutes post-exercise was decreased in mercury workers compared to controls (Yilmaz et al. 2016). An inverse association was observed between elemental mercury exposure and left ventricular diastolic function in chloralkali workers; the study authors noted that workers did not clinically present with cardiac dysfunction (Poreba et al. 2012).

Cardiovascular disease. No studies evaluating the relationships between cardiovascular diseases and exposure to elemental mercury that included biomarker data and assessed appropriate confounders were identified.

Elemental Mercury—Animal Studies. No adequate studies evaluating cardiovascular effects in animals following exposure to elemental mercury were identified.

Inorganic Mercury Salts—Animal Studies. Studies in laboratory animals have evaluated effects of inorganic mercuric mercury (e.g., mercuric chloride) on cardiovascular function following intermediate-duration oral exposure. Results indicate that exposure to mercuric chloride alters some cardiovascular functions, including systolic and diastolic blood pressure, ventricular pressure, baroreflex sensitivity, and cardiac inotropism.

Effects of mercuric chloride on blood pressure may exhibit duration-dependence following exposure via drinking water; however, there is no clear evidence for increased magnitude of effect with increasing dose (Table 2-9). In rats, blood pressure was generally unaffected at oral doses up to 5.91 mg Hg/kg/day for 28 days, with the exception of a spurious 15% increase in diastolic blood pressure at doses of 0.264 mg Hg/kg/day, up to 1.3 mg Hg/kg/day for 182 days (Jindal et al. 2011; Perry and Erlanger 1974; Wildemann et al. 2015a, 2015b, 2016), or 6 mg Hg/kg/day for 320 days (Carmignani and Boscolo 1984). However, systolic and diastolic blood pressures were increased in rats exposed to 24 mg Hg/kg/day for 180 days or 6 mg Hg/kg/day for 350 days, and systolic blood pressure was increased in rats exposed to 0.66 or 1.3 mg

Hg/kg/day for 365 days; systolic blood pressure was not altered at 3.3 mg Hg/kg/day for 365 days, but this may have been due to poor general health at this dose (Carmignani and Boscolo 1984; Carmignani et al. 1992; Perry and Erlanger 1974). Aortic blood pressure was also increased in rats exposed to ≥6 mg Hg/kg/day for 350 days (Boscolo et al. 1989; Carmignani et al. 1989). No alterations in pulse pressure and/or heart rate were observed in these studies.

Table 2-9. Effects on Blood Pressure in Rats Exposed to Mercuric Chloride via Drinking Water Exposure

Duration; dose (mg Hg/kg/day)	ABP	SBP	DBP	Reference
28 days; dose: 0.005–0.244	–	↔ (M)	↔ (M)	Jindal et al. 2011; Wildemann et al. 2015a, 2015b
28 days; dose: 0.264	–	↔	↑ (M) (15[a])	Wildemann et al. 2016
28 days; dose: 1.18–2.07	–	↔ (M)	↔ (M)	Wildemann et al. 2015a
28 days; dose: 2.955	–	↔ (M)	↔ (M)	Wildemann et al. 2016
28 days; dose: 5.91	–	↔ (M)	↔ (M)	Wildemann et al. 2015a
180 days; dose: 24	–	↑ (M) (15[b])	↑ (M) (28[b])	Carmignani et al. 1992
182 days; dose: 0.33–1.3	–	↔ (F)	–	Perry and Erlanger 1974
320 days; dose: 6	–	↔ (M)	↔ (M)	Carmignani and Boscolo 1984
350 days; dose: 6	↑ (M) (32[b])	–	–	Boscolo et al. 1989; Carmignani et al. 1989
350 days; dose: 6	↑ (M) (43[b])	–	–	Boscolo et al. 1989
350 days; dose: 6	–	↑ (M) (35[b])	↑ (M) (32[b])	Carmignani and Boscolo 1984
350 days; dose: 24	↑ (M) (45[b])	–	–	Boscolo et al. 1989
365 days; dose: 0.33	–	↔ (F)	–	Perry and Erlanger 1974
365 days; dose: 0.66	–	↑ (F) (15[b])	–	Perry and Erlanger 1974
365 days; dose: 1.3	–	↑ (F) (13[b])	–	Perry and Erlanger 1974

Table 2-9. Effects on Blood Pressure in Rats Exposed to Mercuric Chloride via Drinking Water Exposure

Duration; dose (mg Hg/kg/day)	ABP	SBP	DBP	Reference
365 days; dose: 3.3	–	↔[c] (F)	–	Perry and Erlanger 1974

[a]Percent change compared to control, estimated from graphically presented data.
[b]Percent change compared to control, calculated from quantitative data.
[c]Lack of exposure-related effect may have been due to poor general health at this dose.

↑ = increased; ↔ = no change; – = not assessed; ABP = aortic blood pressure; DBP = diastolic blood pressure; F = female; M = male; SBP = systolic blood pressure

In dietary studies, no alterations in systolic blood pressure were observed in normotensive Wistar rats exposed to doses up to 2.2 mg Hg/kg/day as mercuric chloride for 21 weeks (Takahashi et al. 2000a). In similarly exposed spontaneously hypertensive Wistar rats, systolic blood pressure was significantly increased by 6–9% following exposure to ≥0.07 mg Hg/kg/day for 4 or 5 weeks; however, no significant effects were noted following exposure to doses up to 2.2 mg Hg/kg/day for 12 weeks (Takahashi et al. 2000b). Findings in spontaneously hypertensive rats are difficult to interpret due to the transient nature of observed effects in a rat strain prone to hypertension.

Alterations in cardiac function in rats exposed to mercuric chloride include increased left ventricular end diastolic pressure (LvEDP), positive inotropic effects, and/or altered baroreceptor reflex sensitivity at daily doses of 0.012–24 mg Hg/kg/day for exposure durations of 1 month to 350 days. LvEDP was significantly increased by 3-fold and the maximum differential of LvEDP to the left ventricular end systolic pressure (LvESP) was decreased by 56–62% in rats administered 0.12 mg Hg/kg/day by gavage for 1 month (Jindal et al. 2011). Sprague-Dawley and Wistar rats showed a significant 25–32% increase in the maximum rate of rise in the left ventricular pressure after exposure to 6 mg Hg/kg/day for 350 days, indicating increased contractility (positive inotropic response); however, these effects were not observed in Wistar rats similarly exposed to 24 mg Hg/kg/day for 180 or 350 days (Boscolo et al. 1989; Carmignani et al. 1989, 1992). It is unknown if the lack of effects in Wistar rats indicates a difference in strain susceptibility or a non-monotonic dose-response. Increased cardiac inotropic responses to cardiac drugs (e.g., isoprenaline) were also observed after exposure for 350 days to 6 mg Hg/kg/day in Sprague-Dawley rats (47–90% increase) and 24 mg Hg/kg/day in Wistar rats (87% increase); findings were not significant at 6 mg Hg/kg/day in Wistar rats (Boscolo et al. 1989; Carmignani et al. 1989). Decreased baroreceptor reflex sensitivity was also observed in Wistar and Sprague-Dawley rats after drinking water exposure to mercuric chloride, with ≥27% decrease in the change in aortic blood pressure at ≥6 mg

Hg/kg/day following exposure to various vasoactive drugs (e.g., norepinephrine, phenylephrine) (Boscolo et al. 1989; Carmignani and Boscolo 1984; Carmignani et al. 1989). No exposure-related changes in electrocardiogram parameters, stroke volume, cardiac output, left ventricular wall thickness, or carotid artery diameter or thickness were observed in rats following drinking water exposure to mercuric chloride at doses up to 5.91 mg Hg/kg/day for 4 weeks (Wildemann et al. 2015a, 2015b).

Oral exposure to inorganic mercury salts has not been associated with histopathological lesions in the rodent heart. In an acute-duration study, no treatment-related histopathological changes were observed in the hearts of rats exposed once to mercuric chloride at gavage doses up to 9.24 mg Hg/kg/day (Lecavalier et al. 1994). In intermediate-duration studies, no treatment-related histopathological changes were observed in the hearts of rats or mice exposed to mercuric chloride at gavage doses up to 4 or 15 mg Hg/kg/day, respectively (Dieter et al. 1992; NTP 1993). No treatment-related histopathological changes were observed in the hearts of mice exposed to mercuric chloride at gavage doses up to 7.4 mg Hg/kg/day for up to 2 years (NTP 1993). One chronic-duration study in rats reported heart mineralization in males following exposure to mercuric chloride at gavage doses ≥1.8 mg Hg/kg/day for up to 2 years; however, this lesion was considered secondary to severely impaired renal function (Dieter et al. 1992; NTP 1993). Similarly exposed female rats, which did not show renal impairment, did not have heart mineralization at gavage doses up to 4 mg Hg/kg/day.

No exposure-related changes in heart histology were observed following oral exposure to methylmercuric chloride in cats at doses up to 0.176 mg Hg/kg/day for approximately 16 weeks, 0.074 mg Hg/kg/day for approximately 55 weeks, or 0.046 mg Hg/kg/day for 2 years (Charbonneau et al. 1976).

Organic Mercury—Epidemiological Studies. Studies evaluating effects of methylmercury exposure on cardiovascular function (blood pressure, heart rate, and heart rate variability) in populations with high fish diets are summarized in Table 2-10. Studies of high fish consumers are categorized as two types based on the timing of biomarker measurement: (1) cross-sectional studies of adults assessing outcomes based on current exposure measurements (biomarkers measured at the time outcome measures were assessed) and (2) prospective birth cohort studies assessing outcomes in children or adolescents based on prenatal exposure measurements. Cross-sectional studies based on current biomarker measurements include small populations (n=42–732) of adults and adolescents, except for one larger population of 1,861 (Nielsen et al. 2012). The most common biomarker used to assess mercury exposure was BHg, although HHg and toenail mercury (NHg) have also been used in some studies (Basta et al. 2021; Choi et al. 2009; Fillion et al. 2006). Prospective birth studies include cohorts of children from the Faroe Islands and Seychelle

Islands; population sizes ranged from 95 to 897. The main biomarkers to assess prenatal exposure were cord BHg and maternal HHg at parturition.

Table 2-10. Epidemiological Studies Evaluating Associations between Mercury and Blood Pressure and Cardiac Function in Populations with High Fish Diets

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Studies based on current mercury measurements			
Basta et al. 2021 Cross-sectional; 200 participants ≥12 years of age (Brazilian Amazon community)	HHg range: 1.4–23.8 µg/g	Hypertension	↑ (HHg)
Choi et al. 2009 Cross-sectional; 42 whaling men (Faroe Islands)	BHg Gmean: 29.5 µg/L HHg Gmean: 7.31 µg/g NHg Gmean: 2.04 µg/g	SBP	↑ (BHg) ↔ (HHg, NHg)
		DBP	↑ (BHg, NHg) ↔ (HHg)
		HR	↔ (BHg, HHg, NHg)
		HRV	↔ (BHg, HHg, NHg)[a]
Fillion et al. 2006 Cross-sectional; 251 adults (Brazilian Amazon community)	HHg: ≥10–77.2 µg/g	SBP	↑ (HHg)
		DBP	↔ (HHg)
Hu et al. 2017 Cross-sectional study; 2,169 Inuit adults (Canada)	BHg Gmean: 7.0 µg/L 1st–99th percentile: 0.3–70 µg/L Low BHg: <20 µg/L High BHg: ≥20 µg/L Low BSe: <280 µg/L High BSe: ≥20 µg/L	Hypertension	↔ (low BHg + low BSe) ↔ (low BHg + high BSe) ↑ (high BHg + low BSe) ↑ (high BHg + high BSe)
Inoue et al. 2012 Cross sectional study; approximately 40,000 residents of Minamata, with approximately 1,000 with Minamata disease	Median HHg: 30 µg/g[b]	Hypertension	↔ (HHg) in 1953–1957 ↔ (HHg) in 1958–1962 ↑ (HHg) in 1963–1967 ↔ (HHg) in 1998–1970
Miller et al. 2018 Cross-sectional; 94 adults, avid seafood consumers (Long Island, New York)	BHg mean: 8.4 µg/L	HRV	↔ (BHg)
		QTc	↔ (BHg)

Table 2-10. Epidemiological Studies Evaluating Associations between Mercury and Blood Pressure and Cardiac Function in Populations with High Fish Diets

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Nielsen et al. 2012 Cross-sectional; Inuit adults; 812 men and 1,049 women (Greenland)	BHg quintile ranges Men Qi4: 27–49 µg/L Men Qi5: 50–280 µg/L Women Qi5: 36–170 µg/L	SBP	↔ (Men, BHg Qi5) ↔ (Women BHg Qi5)
		DBP	↓ (Men, BHg Qi4) ↔ (Women, BHg Qi5)
		PP	↔ (Men, BHg Qi5) ↔ (Women, BHg Qi5)
		Hypertension	↔ (Men, BHg Qi5) ↔ (Women, BHg Qi5)
Valera et al. 2008 Cross-sectional; 205 Nunavik Inuit adults (Quebec)	BHg mean: 27 µg/L	SBP	↑ (BHg)
		DBP	↔ (BHg)
		PP	↑ (BHg)
		HRV	↓ (BHg)
Valera et al. 2009 Cross-sectional; 732 Nunavik Inuit adults (Quebec)	BHg mean: 10 µg/L	SBP	↑ (BHg)
		DBP	↔ (BHg)
		PP	↑ (BHg)
Valera et al. 2011a Cross-sectional; 180 adults (French Polynesia)	BHg mean: 14.5 µg/L	SBP	↔ (BHg)
		DBP	↔ (BHg)
		PP	↔ (BHg)
		HR	↔ (BHg)
		HRV	↔ (BHg)
Valera et al. 2011a Cross-sectional; 101 adolescents (French Polynesia)	BHg mean: 8.1 µg/L	SBP	↔ (BHg)
		DBP	↔ (BHg)
		PP	↔ (BHg)
		HRV	↓ (BHg)
Valera et al. 2011b [adjustments included Pb, PCBs, and 3-n polyunsaturated fatty acids] Cross-sectional; 724 Cree Inuit adults (Quebec)	BHg mean: 3.1 µg/L HHg mean: 0.47 µg/g	SBP	↔ (BHg, HHg)
		DBP	↔ (BHg, HHg)
		PP	↔ (BHg, HHg)
		HRV	↓ (BHg, HHg)
Valera et al. 2013 Cross-sectional; 313 Inuit adults (Quebec) [adjustments included Pb, PCBs, and 3-n polyunsaturated fatty acids]	BHg mean: 15.4 µg/L BHg Q4: 28.4–112 µg/L	SBP	↔ (BHg)
		DBP	↔ (BHg)
		PP	↔ (BHg)
		HR	↑ (BHg, Q4)
Yorifuji et al. 2010 Cross-sectional; 120 adults (Minamata, Japan)	HHg Q4: >28.3 µg/g Hair samples were analyzed in 1960[c]	Hypertension	↔ (HHg, Q4)

Table 2-10. Epidemiological Studies Evaluating Associations between Mercury and Blood Pressure and Cardiac Function in Populations with High Fish Diets

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Zuk et al. 2021 Cross-sectional; 759 adult indigenous Canadians (312 males and 447 females)	BHg Gmean Males: 4.29 µg/L Females: 3.17 µg/L	SBP	↔ (BHg)
		Hypertension	↑ (BHg)
Studies based on prenatal exposure measurements			
Grandjean et al. 2004a (follow-up to Sørensen et al. 1999) Prospective birth cohort; 878 adolescents; blood pressure assessed at age 14 years (Faroe Islands)	BHg median (cord): 24.27 µg/L HHg median: Maternal at parturition[b]: 5.65 µg/g Child, age 14[c]: 0.96 µg/g	SBP	↔ (BHg, HHg)
		DBP	↔ (BHg, HHg)
		HR	↔ (BHg, HHg)
		HRV	↓ (BHg) ↔ (HHg)
Periard et al. 2015 Prospective birth cohort; 95 adults (age 19 years, 47 males, 48 females) (Seychelles Islands)	HHg mean Maternal during pregnancy: 6.7 µg/g Males, age 19: 11.2 µg/g Females, age 19: 7.9 µg/g	HRV	↔ (HHg)
Sørensen et al. 1999 Prospective birth cohort; 894–897 children; blood pressure assessed at age 7 years (Faroe Islands)	BHg mean (cord): 31.8 µg/L HHg mean (maternal at parturition): 5.65 µg/g[b]	SBP	↑ (BHg, HHg)
		DBP	↑ (BHg) ↔ (HHg)
Thurston et al. 2007 Prospective birth cohort; 644–559 children; blood pressure assessed at ages 12 and 15 years (Seychelles Islands)	HHg mean (maternal) for: Boys age 12: 6.6 µg/g Boys age 15: 6.5 µg/g Girls age 12: 7.0 µg/g Girls age 15: 7.0 µg/g	SBP	↔ (HHg)
		DPB	↔ (HHg, age 12 years) ↑ (HHg, boys, age 15 years) ↔ (HHg, girls, age 15 years)
Valera et al. 2012 Prospective birth cohort; 226 Nunavik Inuit children (Quebec) assessed at age 11 years (adjustments included Pb and PCBs)	BHg mean (cord): 21.5 µg/L BHg mean (age 11 years): 4.5 µg/L HHg mean (age 11 years): 1.3 µg/g	SBP	↔ (BHg, HHg)
		DBP	↔ (BHg, HHg)
		HRV	↔ (BHg, cord) ↓ (BHg, age 11 years) ↔ (HHg, age 11 years)

[a]The study authors considered results for HRV to be equivocal, possibly due to the small study population size.
[b]Reported by Grandjean et al. (1992).
[c]Biomarkers were not measured in this population; for reference, the median HHg in a healthy Minamata fishermen measured in 1960 was 30 µg/g, compared to a median HHg of 2.1 µg/g in the control population in 1960.

↑ = positive association; ↓ = inverse association; ↔ = no association; BHg = blood mercury; BSe = blood selenium; DBP = diastolic blood pressure; Gmean = geometric mean; HHg = hair mercury; HR = heart rate; HRV = heart rate variability; NHg = toenail mercury; Pb = lead; PCB = polychlorinated biphenyl; PP = pulse pressure; Q = quartile; Qi = quintile; QTc = QT interval duration; SBP = systolic blood pressure

Blood pressure. Results of cross-sectional studies in adult populations using current biomarker measurements provide conflicting evidence regarding associations between methylmercury exposure from fish consumption and blood pressure. For studies reporting positive associations, the mean or median BHg range was 10–29.5 µg/L, whereas the range for studies reporting no associations was 3.1–15.4 µg/L. However, results are not consistent and data do not provide clear evidence of a dose-response relationship between methylmercury exposure from fish and increased blood pressure. Furthermore, observed changes in blood pressure were small. The lowest mean BHg (10 µg/L) associated with increased blood pressure was reported in a study of Nunavik Inuit adults in Quebec, with positive associations between BHg and systolic blood pressure (Valera et al. 2009). Based on log transformed (base not reported) BHg, a 1% increase in BHg was associated with a 0.02 mmHg increase in systolic blood pressure. No association was observed for diastolic blood pressure. Similar results were observed in a smaller population of Nunavik Inuit adults (Valera et al. 2008).

For the highest mean BHg of 29.5 µg/L in a population of 42 whaling men from the Faroe Islands, BHg was positively associated with systolic and diastolic blood pressure (Choi et al. 2009). The magnitude of the association was reported in standardized beta coefficients (percent of standard deviation [SD] of outcome variable per 1 SD change in $\log_{10}$ BHg). The reported effect on systolic blood pressure was a 37.5% increase per 1 SD increase in $\log_{10}$ BHg. This would correspond to an increase of approximately 7 mmHg (0.375x18) in blood pressure per 1 SD increase in $\log_{10}$ BHg (approximately 90 µg/L). The reported effect on diastolic blood pressure was a 33.2% increase per 1 SD increase in $\log_{10}$ BHg. This would have corresponded to an increase in diastolic blood pressure of approximately 2.6 mmHg (0.332x8) per 1 SD increase in $\log_{10}$ BHg (approximately 90 µg/L increase in BHg; see legend of Table 2-10 for the basis for this estimate). No association between BHg and systolic or diastolic blood pressure was observed at mean BHg of 3.1–15.4 µg/L (Valera et al. 2011a, 2011b, 2013). Two of these studies adjusted for co-exposure to other chemicals that may also affect blood pressure (lead and PCBs) (Valera et al. 2011b, 2013). Using BHg data stratified by quintiles in a study of Inuit men and women, no association was observed for systolic blood pressure for the highest quintile in men and women; an inverse association was observed for diastolic blood pressure in men in the 4^{th} and 5^{th} quintiles, although no association was observed in women (Nielsen et al. 2012).

Prospective, prenatal exposure studies show inconsistent results regarding associations between methylmercury exposure from fish consumption and blood pressure in children and adolescents. Studies of the Faroe Island population evaluated blood pressure in children at 7 and 14 years of age (Grandjean et

al. 2004a; Sørensen et al. 1999). The study in 7-year-olds found a positive association between cord BHg and maternal HHg for systolic blood pressure and between cord BHg and diastolic blood pressure, with increases in systolic blood pressure of 13.9 mmHg and diastolic blood pressure of 14.6 mmHg for an increase in cord BHg from 1 to 10 µg/L (Sørensen et al. 1999). However, in the follow-up study assessing blood pressure at age 14 years, no association was observed between BHg, maternal HHg (at parturition), or child HHg (Grandjean et al. 2004a). In a population of children in the Seychelles Islands, no association was observed between prenatal exposure and systolic or diastolic blood pressure in girls at ages 12 and 15 years, or in boys at 12 years (Thurston et al. 2007). However, a positive association was observed between maternal HHg and diastolic blood pressure in boys at age 15; the study authors stated that biological significance of this finding is uncertain. No association between cord BHg and blood pressure was observed in a study of Nunavik Inuit children evaluated at age 11 years (Valera et al. 2012). This study also adjusted for exposure to lead and PCBs.

Hypertension. Associations between methylmercury exposure from fish consumption and clinical hypertension are inconsistent (Table 2-10). In a cross-sectional study of an Arctic Inuit population, the prevalence of hypertension was increased at BHg ≥20 µg/L, but not <20 µg/L (Hu et al. 2017); the increase appeared to be attenuated at higher blood selenium levels (≥280 µg/L) compared to lower blood selenium levels (<280 µg/L). Some evidence that severe exposure to methylmercury is associated with hypertension mortality was reported in a large study of the Minamata population (Inoue et al. 2012). In a population of approximately 46,000 residents of Minamata, including approximately 1,000 Minamata disease patients, the age-standardized mortality ratio (AMSR) for hypertension (ASMR 1.38; 95% CI 1.06, 1.64) was increased compared to a control group during the period of 1963–1967; however, AMSRs were not elevated for the periods 1953–1957, 1959–1962, or 1969–1970. A small study of Minamata residents with HHg measured in 1960 did not find an association between HHg and prevalence of hypertension as assessed in 1971 (Yorifuji et al. 2010). A positive association was observed between BHg and hypertension in a population of indigenous Canadians at mean BHg levels of 4.29 and 3.17 µg/L in males and females, respectively (Zuk et al. 2021). In contrast, a cross-sectional study of an Inuit population did not show associations between exposure and hypertension at higher BHg levels in males and females (Nielsen et al. 2012). In this study, associations were observed for the 4th and 5th quintiles in males (quintile 4: 27–49 µg/L; quintile 5: 50–280 µg/L) and the 5th quintile in females (36–170 µg/L).

Cardiac function. Associations between methylmercury exposure from fish consumption and cardiac function have been evaluated in cross-sectional and prospective birth cohort studies. Outcome variables include heart rate and heart rate variability. Cross-sectional studies reported conflicting results on heart

rate. A positive association between BHg and resting heart rate was reported in a population of Inuit adults from Quebec, with resting heart rate increased by 6.9 beats per minute in the highest BHg quartile relative to lower BHg quartiles (Valera et al. 2013); potential confounders considered in this study included co-exposure to other contaminants (lead and PCBs) and n-3 polyunsaturated fatty acids levels. No associations between methylmercury exposure and heart rate were observed for mean BHg in French Polynesian adults and Faroe Island whalers, respectively (Choi et al. 2009; Valera et al. 2011a). In addition, a prospective birth cohort study of the Faroe Island population did not find an association between cord BHg or maternal HHg and heart rate assessed at age 14 years (Grandjean et al. 2004a).

Several studies have evaluated the effects of methylmercury exposure and heart rate variability. Heart rate variability, which is mediated through the autonomic nervous system, reflects a balance between sympathetic and parasympathetic control (Gribble et al. 2015; Karita et al. 2018). Decreased heart rate variability may lead to cardiac arrhythmias and increased risk of ventricular fibrillation and sudden cardiac death (Karita et al. 2018; Valera et al. 2011a, 2012). Taken together, results of cross-sectional and prospective birth cohort studies do not provide compelling evidence that methylmercury exposure is associated with heart rate variability. Results of cross-sectional studies report conflicting results, with some studies showing inverse associations between exposure biomarkers and heart rate variability (Valera et al. 2008, 2011a, 2011b) and other studies reporting no associations (Choi et al. 2009; Miller et al. 2017, 2018; Valera et al. 2011a). The range of mean BHg for studies showing decreased heart rate variability (3.1–27 µg/L) is similar to the range for studies showing no change (8.4–29.5 µg/L); thus, results indicate that there is no apparent relationship between exposure level and outcome. In Faroe Island whalers with the highest reported mean BHg of 29.5 µg/L, study authors considered results on heart rate variability to be unclear; however, study power is limited by the small population size (n=42) (Choi et al. 2009). One study of Faroe Island adolescents and adults showed no association between BHg (mean 14.5 µg/L) and heart rate variability in adults, but an inverse association in adolescents at lower BHg (mean: 8.1 µg/L) (Valera et al. 2011a). Retrospective birth cohort studies also report inconsistent results on effects of methylmercury exposure and heart rate variability. Heart rate variability was inversely associated with current BHg, but not cord BHg or current HHg in 11-year-old Nunavik children (Valera et al. 2012). In a Faroe Island birth cohort with outcomes assessed at age 14 years, an inverse association was observed between cord BHg and heart rate variability, but not for maternal HHg at parturition or age 14 years child HHg (Grandjean et al. 2004a). Similarly, follow-up of the Seychelles Islands prospective cohort at age 19 years showed no association between maternal HHg during pregnancy or current HHg in males or females; cord BHg was not reported (Periard et al. 2015).

Cardiovascular disease. Few studies reporting biomarker data and confounding factors have evaluated associations between methylmercury exposure in populations with high fish diets and cardiovascular disease morbidity and mortality. However, results do not provide evidence that exposure to methylmercury is associated with cardiovascular disease. Studies of various Inuit populations have not found associations for myocardial infarction (Hu et al. 2017), stroke (Hu et al. 2017), or non-specific cardiovascular disease (Larsen et al. 2018).

Organic Mercury—Animal Studies. Alterations in cardiovascular function have been reported in rats following acute- and intermediate-duration oral exposure to methylmercuric chloride, with blood pressure as the most studied cardiovascular endpoint. Generally, results show that exposure to methylmercuric chloride increases systolic and diastolic blood pressure in a dose- and duration-dependent manner; pulse pressure is also increased in some studies, but with no apparent dose-related effect (Table 2-11). A 15-day drinking water exposure study in mice reported increased systolic (by ~18%) and diastolic (by ~22%) blood pressure and artherosclerotic lesions at 2.7 mg Hg/kg/day (Silva et al. 2021). In rats, systolic blood pressure was increased by 10–30% after exposure to doses of 0.005–1.6 mg Hg/kg/day for 26–28 days, and 40% after exposure to 0.08 mg Hg/kg/day for 100 days (Grotto et al. 2009a; Tamashiro et al. 1986; Wakita 1987; Wildemann et al. 2015a, 2015b, 2016). Diastolic blood pressure was slightly less sensitive, with significant increases of 22–31% with exposures to doses ≥0.009–0.879 mg Hg/kg/day for 28 days (not tested at other durations) (Wildemann et al. 2015a, 2015b, 2016). Pulse pressure increases of 10–20% were observed in a non-dose-related fashion in rats exposed to 0.005–0.216 mg Hg/kg/day, but not 0.879 mg Hg/kg/day (Wildemann et al. 2015a, 2015b). One study, however, did not observe changes in systolic or diastolic blood pressure or pulse pressure in rats exposed to 0.5 mg Hg/kg/day for 28 days (Jindal et al. 2011). No alterations in heart rate were observed in any of these studies.

Table 2-11. Effects on Blood Pressure in Laboratory Animals Exposed to Methylmercuric Chloride via Oral Exposure

Strain (sex)	Duration (days)	Route	Dose (mg Hg/kg/day)	SBP	DBP	PP	Reference
Rats							
SHR/NCrj[a] (F)	26	Oral NS	1.6	↑ (10%[b,c])	–	–	Tamashiro et al. 1986
Wistar (M)	28	DW	0.002	↔	↔	↔	Wildemann et al. 2015a
Wistar (M)	28	DW	0.005	↑ (14%[b])	↔	↑ (17%[b])	Wildemann et al. 2015a

Table 2-11. Effects on Blood Pressure in Laboratory Animals Exposed to Methylmercuric Chloride via Oral Exposure

Strain (sex)	Duration (days)	Route	Dose (mg Hg/kg/day)	SBP	DBP	PP	Reference
Wistar (M)	28	DW	0.006	↑ (17%[b])	↔	–	Wildemann et al. 2016
Wistar (M)	28	DW	0.009	↑ (20%[b])	↑ (22%[b])	↑ (20%[b])	Wildemann et al. 2015a
Wistar (M)	28	DW	0.018	↑ (19%[b])	↑ (21%[b])	↑ (18%[b])	Wildemann et al. 2015a
Wistar (M)	28	DW	0.018	↔	↔	↔	Wildemann et al. 2015b
Wistar (M)	28	DW	0.036	↔	↔	↑ (16%[b])	Wildemann et al. 2015a
Wistar (M)	28	G	0.08	↑ (10%[b])	–	–	Grotto et al. 2009a
Wistar (M)	28	DW	0.216	↑ (21%[b])	↑ (24%[a])	↑ (17%[a])	Wildemann et al. 2015a
Wistar (M)	28	DW	0.216	↑ (10%[b])	↔	↑ (10%[a])	Wildemann et al. 2015b
Wistar (M)	28	DW	0.285	↑ (30%[b])	↑ (30%[b])	–	Wildemann et al. 2016
Wistar (M)	28	G	0.4	↑ (20%[b,d])	–	–	Wakita 1987
Wistar (B)	28	G	0.5	↔	↔	↔	Jindal et al. 2011
Wistar (M)	28	DW	0.879	↑ (23%[b])	↑ (31%[b])	0	Wildemann et al. 2015a
Wistar (M)	100	G	0.08	↑ (40%[b])	–	–	Grotto et al. 2009a
Mice							
C57BL/6 (F)	15	DW	2.7	↑ (18%[b])	↑ (22%[b])	–	Silva et al. 2021

[a]Spontaneously hypertensive rat strain; blood pressure could not be adequately assessed in similarly exposed males due to 100% mortality.
[b]Percent change compared to control, estimated from graphically presented data.
[c]Blood pressure elevated after 21 days of exposure and 9 days post-exposure.
[d]Blood pressure elevations observed 42 days to ~1 year post-exposure.

↑ = increased; ↔ = no change; – = not assessed; B = both males and females; DBP = diastolic blood pressure; DW = drinking water; F = female(s); G = gavage; M = male(s); NS = not specified; PP = pulse pressure; SBP = systolic blood pressure

The effects of methylmercuric chloride on other cardiovascular functions have not been well-studied. LvEDP was significantly increased 3.7-fold with the maximum differential of LvEDP to LvESP decreased by 46–53% in rats administered gavage doses of 0.5 mg Hg/kg/day for 1 month (Jindal et al. 2011). Additionally, these rats showed a 46–53% attenuation of baroreceptor reflex sensitivity at 0.5 mg Hg/kg/day. Heart rate was decreased by 10–18% for up to 16 days in male rats following exposure to two

gavage doses of 12 mg Hg/kg (Arito and Takahashi 1991). Exposure to gavage doses of 0.5 mg Hg/kg/day for 1 month did not alter heart rate in male rats (Jindal et al. 2011), and no exposure-related changes in heart rate, stroke volume, cardiac output, electrocardiogram parameters, left ventricular wall thickness, or carotid artery diameter or thickness were observed.

Oral exposure to methylmercuric chloride has not been associated with histopathological lesions in the rodent heart. No treatment-related histopathological changes were observed in the hearts of rats or mice exposed chronically to dietary doses up to 0.1 or 0.724 mg Hg/kg/day, respectively (Hirano et al. 1986; Mitsumori et al. 1990; Verschuuren et al. 1976).

Predominant Mercury Form Unknown (General Populations). Numerous studies have evaluated the relationship between mercury exposure and cardiovascular effects in general populations. Outcomes evaluated were blood pressure parameters, clinical hypertension, and cardiovascular disease. Study designs include meta- and pooled analyses, prospective studies, and cross-sectional studies. Many studies evaluated large populations (n=2,114–>33,000). The most common biomarkers were BHg and HHg, with some studies measuring mercury in urine, toenails, serum, or erythrocytes. Mean BHg in these studies was <6 µg/L, which is lower than most studies evaluating exposures to methylmercury in populations with high fish diets (Table 2-10).

Blood pressure. Associations between mercury biomarkers and changes in blood pressure have been well-studied; however, evidence for effects of mercury exposure on blood pressure in general populations is inconclusive. A few studies showed associations between biomarkers and small increases in systolic and/or diastolic blood pressure, although most studies did not show associations (Table 2-12). The largest study, a pooled analysis of 33,298 adults from 23 studies of various population types (general populations, populations with high fish diets, and workers), showed positive associations between HHg and systolic and diastolic blood pressure (Hu et al. 2018). Pooled weighted mean differences (PWMD) in systolic or diastolic blood pressure were calculated as the inverse-variance weighted mean of individual differences between the mean pressure in the lowest and highest mercury category in each study. PWMDs were calculated separately for groups of studies in which the mean HHg was <2 or ≥2 µg/g. For studies with HHg ≥2 µg/g, the PWMD for systolic blood pressure was an increase of 2.20 (95% CI 0.90, 3.49) mm Hg. A dose-response model suggested that systolic blood pressure increased with HHg concentrations above 2–3 µg/g. For diastolic blood pressure, the PWMD was increased by 0.96 mmHg (95% CI 0.08, 1.85) for combined study categories (HHg: 2 and ≥2 µg/g). Similar small increases in blood pressure were observed in a prospective longitudinal study in women (Wang et al. 2021b), a large

cross-sectional study of Korean adults (Park and Choi 2016), and in a small cross-sectional study of pregnant women showing a positive association between blood methylmercury levels, but not blood inorganic mercury levels, and systolic blood pressure (Wells et al. 2017). A cross-sectional study in adults using NHANES data found positive associations between BHg and blood methylmercury and diastolic blood pressure, but not systolic blood pressure (Tang et al. 2022a). In a small cross-sectional study of adolescents with hypertension, UHg was associated with increased risk of higher diastolic and systolic blood pressures (Yalçin et al. 2022). However, other studies did not find associations or found inverse associations between mercury biomarkers and blood pressure outcomes, including large prospective birth cohort studies in children (Desai et al. 2021; Gregory et al. 2016; Kalish et al. 2014; Yao et al. 2020), a cross-sectional study in male adolescents (Castiello et al. 2020), and cross-sectional studies in adults (Mordukhovich et al. 2012; Park et al. 2013; Vupputuri et al. 2005). Most prospective birth cohorts do not show associations between gestational mercury exposure and blood pressure (Farzan et al. 2021; Gregory et al. 2016; Kalish et al. 2014). However, two studies found positive associations between maternal erythrocyte mercury and BHg and systolic blood pressure (Ma et al. 2023; Zhang et al. 2021b).

Table 2-12. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Blood Pressure in General Populations

Reference, study type, and population	Biomarker	Blood pressure outcome (biomarker)			
		SBP	DBP	PP	Hypertension
Studies based on current mercury measurements					
Al-Saleh et al. 2006 Case-control; 185 women (Saudi Arabia)	BHg mean Hypertensive: 3.5 µg/L Control: 3.7 µg/L	–	–	–	↔ (BHg)
Bautista et al. 2009 Cross-sectional; 101 adults (Wisconsin)	BHg Gmean: 1.16 µg/L HHg Gmean: 0.27 µg/g	–	–	–	↔ (BHg) ↑ (HHg)
Castiello et al. 2020 Cross-sectional; 133 male adolescents (ages 15–17 years) (Spain)	UHg Gmean: 0.03 µg/g creatinine	↔ (UHg)	↔ (UHg)	↔ (UHg)	–
Choi et al. 2015 Cross-sectional; 6,213 adults (KNHANES 2008–2010)	SHg mean Men: 5.7 µg/L Women: 4.0 µg/L	–	–	–	↑ (SHg, M, F)

Table 2-12. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Blood Pressure in General Populations

Reference, study type, and population	Biomarker	Blood pressure outcome (biomarker)			
		SBP	DBP	PP	Hypertension
Desai et al. 2021 Cross-sectional survey; 1,642 children, ages 8–17 years (NHANES 2009–2016)	BHg median: 0.37 µg/L	↔ (BHg)	↔ (BHg)	↔ (BHg)	–
Eom et al. 2014 Cross-sectional; 2,114 adults (South Korea)	BHg Gmean: 3.90 µg/L	–	–	–	↔ (BHg)
Hu et al. 2018 Pooled analysis; 9 studies, 21,757 adults[a]	HHg stratified <2 µg/g ≥2 µg/g	–	–	–	↔ (HHg)
Hu et al. 2018 Pooled analysis; 23 studies, 33,298 adults[b]	HHg stratified <2 µg/g ≥2 µg/g	↑ (HHg)	↑ (HHg)	–	–
Joo et al. 2022 Cross-sectional; 1,360 adolescents ages 12–17 years (KNHANES)	BHg median: 1.805 µg/L	–	–	–	↔ (BHg)
Kim et al. 2014 Cross-sectional; 3,800 adults (KNHANES 2008–2009)	BHg, mean: 5.44 µg/L	–	–	–	↔ (BHg)
Mordukhovich et al. 2012 Cross-sectional; 639 men; samples and assessments conducted 1999–2009 (NAS)	NHg median: 0.22 µg/g	↔ (NHg)	↔ (NHg)	↔ (NHg)	–
Mozaffarian et al. 2012 Prospective cohort; 1,624 male adults (HPFS cohort) and 4,421 female adults (NHS cohort) (United States)	NHg median Males: 0.30 µg/g Females: 0.21 µg/g	–	–	–	↔ (NHg, M, F)

Table 2-12. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Blood Pressure in General Populations

Reference, study type, and population	Biomarker	Blood pressure outcome (biomarker)			
		SBP	DBP	PP	Hypertension
Park and Choi 2016 Cross-sectional; 8,371 adults (KNHANES 2008–2012)	BHg Gmean Males: 4.70 µg/L Females: 3.26 µg/L	↑ (BHg, M, F)	↑ (BHg, M, F)	–	–
Park et al. 2013 Cross-sectional; 6,607 adults (NHANES 2003–2006)	BHg Gmean: 1.03 µg/L BHg Q4: 1.84–32.8 UHg Gmean: 0.51 µg/L UHg Q4: 1.03–50.2	↓ (BHg) ↓ (UHg)	↔ (BHg) ↔ (UHg)	–	↔ (BHg, Q4) ↔ (UHg, Q4)
Sanders et al. 2019 Cross-sectional; 2,709 adolescents (ages 12–19 years of age) (NHANES)	BHg mean: 0.41 µg/L	↔ (BHg)	–	–	–
Tang et al. 2022a Cross-sectional; 1,422 adult non-Hispanic Asians (with BHg levels) and 633 adult non-Hispanic Asians (with UHg levels) (NHANES 2011–2018	BHg Gmean: 1.95 µg/L BMeHg Gmean: 1.64 µg/L UHg Gmean: 0.433 µg/g creatinine	↔ (BHg) ↔ (BMeHg) ↔ (UHg)	↑ (BHg) ↑ (BMeHg) ↔ (UHg)	–	↑ (BHg) ↑ (BMeHg) ↔ (UHg)
Virtanen et al. 2012b Cross-sectional; 1,757 adults (Finland)	HHg mean: 1.42 µg/g	↔ (HHg)	↔ (HHg)	↔ (HHg)	–
Vupputuri et al. 2005 Cross-sectional; 1,240 women (NHANES 1999–2000)[d]	BHg median: 0.9 µg/L	↔ (BHg)	↔ (BHg)	–	–

Table 2-12. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Blood Pressure in General Populations

Reference, study type, and population	Biomarker	Blood pressure outcome (biomarker)			
		SBP	DBP	PP	Hypertension
Wang et al. 2021b Prospective longitudinal; 1,317 women (aged 45–56 years at enrollment), followed for 19–21 years (United States)	UHg median: 1.2 µg/L	↑ (UHg)	↑ (UHg)	–	–
Wells et al. 2017 Cross-sectional; 263 pregnant women (Baltimore, Maryland)	BMeHg Gmean: 0.95 µg/L BIHg Gmean: 0.13 µg/L	↑ (BMeHg) ↔ (BIHg)	↔ (BMeHg) ↔ (BIHg)	↑ (BMeHg) ↔ (BIHg)	–
Xu et al. 2021 Cross-sectional; 957 adults (≥21 years); GuLF study participants (United States)	BHg median: 0.9 µg/L	↔ (BHg)	↔ (BHg)	–	↔ (BHg)
Yalçin et al. 2022 Cross-sectional; 48 adolescents with hypertension and 38 controls; mean age 13.3 years for each group (Turkey)	UHg median (all participants): 0.19 µg/g creatinine	↑ (UHg)	↑ (UHg)	–	–
Yao et al. 2020 Cross-sectional; 7,061 children ages 8–17 years (NHANES 2007–2016)	BHg Gmean: 0.44 µg/L BMeHg Gmean: 0.24 µg/L UHg Gmean: 0.24 µg/L	↔ (BHg) ↔ (UHg) ↔ (BMeHg)	↓ (BHg) ↓ (BMeHg) ↓ (UHg)	–	↔ (BHg) – (BMeHg) ↔ (UHg)
Yen et al. 2022 Cross-sectional; 10 adult acute ischemic stroke patients (n=4 men; n=6 women); mean age: 57.7 years (Taiwan)	UHg mean (men): 0.7 µg/L UHg mean (women): 0.9 µg/L SHg mean (men): 6.1 µg/L SHg mean (women): 7.3 µg/L	↔ (SHg) ↔ (UHg)	↔ (SHg) ↔ (UHg)	–	↔ (SHg) ↔ (UHg)

Table 2-12. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Blood Pressure in General Populations

Reference, study type, and population	Biomarker	Blood pressure outcome (biomarker)			
		SBP	DBP	PP	Hypertension
Studies based on prenatal exposure measurements					
Farzan et al. 2021 Prospective birth cohort; 395 mother-child pairs; assessments at ages 5–6 years (New Hampshire)	Maternal NHg mean (GW 24): 0.129 µg/g Maternal NHg mean (PNW 6): 0.128 µg/g Child NHg mean (age 3 years): 0.055 µg/g Child UHg mean (ages 5–6 years): 0.071 µg/L	↔ (NHg, maternal) ↔ (NHg, child) ↔ (UHg, child)	↔ (NHg, maternal) ↔ (NHg, child) ↑ (UHg, child)	–	–
Gregory et al. 2016 Prospective birth cohort; children assessed at ages 7 years (n=1,754) and 17 years (n=1,102); mother enrollment with delivery expected between April 1991 and December 1992 (ALSPAC)	BHg median, maternal: 2.86 µg/L	↔ (maternal BHg)	↔ (maternal BHg)	–	–
Kalish et al. 2014 Prospective birth cohort; children assessed at early childhood (median age: 3.2 years; n=1,031) and mid-childhood (median age: 7.7 years; n=865); pregnant women enrolled between April 1999 and July 2002) (Massachusetts; Project Viva)[c]	ErHg mean, maternal (2nd trimester): 4.0 ng/g	↔ (maternal ErHg)[d]	–	–	–
Ma et al. 2023 Birth cohort; 2,534–2,680 mother-child pairs; children assessed at 5–6 years of age (China)	Maternal BHg median, 3rd trimester: 1.00 µg/L	↔(BHg, maternal)	↑ (BHg, maternal)	–	–

Table 2-12. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Blood Pressure in General Populations

Reference, study type, and population	Biomarker	Blood pressure outcome (biomarker)			
		SBP	DBP	PP	Hypertension
Zhang et al. 2021b Prospective birth cohort; 1,194 mother-infant pairs (assessment at most recent well-child visit (ages 3–15 years of age (Boston)	Maternal ErHg median: 2.15 µg/L Maternal ErHg quartiles Q1: <LOD–1.06 µg/L Q2: 1.07–2.14 µg/L Q3: 2.16–3.70 µg/L Q4: 3.72–27.80 µg/L	↑ (ErHg, maternal, Q4)	–	–	–

[a]Includes nine studies (five studies of general populations and four studies of populations with high fish diets); BHg and NHg biomarkers were converted to HHg equivalents.
[b]Includes 23 studies (13 studies of general populations, 6 studies of populations with high fish diets, and 3 studies of populations with occupation exposure to elemental Hg); BHg, NHg, and UHg were converted to HHg equivalents.
[c]Child blood pressure assessed at ages 3.2 and 7.7 years; no association observed for either age.
[d]Fish consumers (n=759) and non-fish consumers (n=481).

↑ = positive association; ↓ = inverse association; ↔ = no association; – = not reported; ALSPAC = Avon Longitudinal Study of Parents and Children (United Kingdom); BHg = blood mercury; BIHg = blood inorganic mercury; BMeHg = blood methylmercury; DBP = diastolic blood pressure; ErHg = erythrocyte mercury; F = female(s); Gmean = geometric mean; GuLF = Gulf Long-term Follow-up Study (Deepwater Horizon oil spill); GW = gestation week; HHg = hair mercury; HPFS = Health Professionals Follow-up Study; KNHANES = Korea National Health and Nutrition Examination Survey; LOD = limit of detection; M = male(s); NAS = Normative Aging Study; NHANES = United States National Health and Nutrition Examination Survey; NHg = toenail mercury; NHS = Nurses' Health Study; PNW = postnatal week; PP = pulse pressure; Q = quartile; SBP = systolic blood pressure; SHg = serum mercury; UHg = urine mercury

Hypertension. Of the several studies that have investigated associations between mercury exposure and clinical hypertension in general populations, three cross-sectional studies reported positive associations (Table 2-12). Using NHANES data, Tang et al. (2022a) observed positive associations between BHg and blood methylmercury, but not UHg, and hypertension. A large study of the KNHANES population showed an association between SHg levels and hypertension (Choi et al. 2015). A small cross-sectional study in adults reported an increased risk of hypertension (adjusted odds ratio [OR] 4.19; 95% CI 1.28, 13.76) associated with HHg, but not with BHg (Bautista et al. 2009). Other studies, including a pooled analysis of 21,757 adults from nine studies (Hu et al. 2018) and a large prospective cohort study in 3,427 adults from the United States (Mozaffarian et al. 2012), did not find associations between mercury biomarkers and hypertension. In a cross-sectional study of 1,360 adolescents, no association was observed between BHg and hypertension.

Cardiac function. Few studies have evaluated cardiac function in the general population. No arrhythmias were observed in a cross-sectional study of 60 adult traffic workers (mean age: 36.6 years; 88% male) with a mean BHg level of 3.2 µg/L (Regencia et al. 2022). Cardiac function was assessed by QT interval, JT interval, QRS duration, and electrocardiogram markers of ventricular repolarization and depolarization. A birth cohort study of 604 children (7–8 years old) from Hong Kong examined associations between BHg and heart rate variability (Chan et al. 2021). Heart rate variability was inversely associated with cord BHg ≥5.8 µg/L compared to cord BHg <5.8 µg/L. In contrast, BHg obtained at age 7–8 years was not associated with heart rate variability. Results suggest that decreased heart rate variability is related to prenatal exposure to mercury and to modulation of parasympathetic modulation of cardiac function. A cross-sectional study of 532 children aged 12 years found no association between BHg (mean: 1.26 µg/L) and resting heart rate in the full cohort (Liu et al. 2021a). When stratified by sex, an inverse association was observed between BHg (1.33 µg/L) and resting heart rate in boys, but not in girls (BHg 1.17 µg/L).

Cardiovascular disease. Results of numerous studies indicate that exposure of the general population to mercury is not associated with cardiovascular disease (myocardial infarction, stroke, angina, and other cardiovascular diseases) or mortality due to cardiovascular disease; studies are summarized in Table 2-13. No associations between mercury biomarkers and myocardial infarction were found in most studies, including prospective studies, cohort studies, and cross-sectional studies. In contrast, two studies of Finnish men found an association between HHg and myocardial infarction (Salonen et al. 1995; Virtanen et al. 2005) and one case-control study found an association for NHg (Guallar et al. 2002). No studies reported associations between mercury biomarkers and stroke. No convincing evidence was obtained for associations with other cardiovascular diseases (coronary artery disease, coronary heart disease, or cardiovascular disease), with most studies reporting no associations. For example, two large meta-analyses (n=5,830; 17,294) did not find associations between mercury biomarkers and cardiovascular disease, coronary heart disease, or mortality due to cardiovascular disease (Chowdhury et al. 2018; Mozaffarian and Rimm 2006; Sun et al. 2021). However, a small cross-sectional study reported an association between SHg and coronary artery disease, and a prospective study in Finnish men found an association between HHg and atherosclerosis (Asgary et al. 2017; Salonen et al. 2000). Virtanen et al. (2005) found a positive association between HHg and increased risk of cardiovascular disease in a Finish population. In contrast, a cross-sectional study of 891 Korean adults found an inverse association between HHg and decreased arterial stiffness (Park et al. 2022). The study authors proposed that nutrients in fish consumption may have contributed to this effect.

Table 2-13. Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Cardiovascular Disease and Mortality due to Cardiovascular Disease in General Populations

		Cardiovascular disease[a] (biomarker)			
Reference, study type, and population	Biomarker	MI	Stroke	Angina	Other results and endpoints[b]
Ahlqwist et al. 1999 Prospective; 1,397 women (Sweden)	SHg mean: 17.0 µg/L	↔ (SHg)[c]	↔ (SHg)	–	–
Asgary et al. 2017 Cross-sectional; 65 male cases, 65 controls (Iran)	SHg mean: 10.14 µg/L	–	–	–	↑ (SHg) CAD
Bergdahl et al. 2013 Cohort; 1,391 women (Sweden)	SHg median: 1.4 µg/L	↔ (SHg)[c]	↔ (SHg)[c]	–	–
Chen et al. 2018 Case-cohort; 662 cases; 2,494 controls (Southern United States)	SHg median Cases: 0.03 µg/L Controls: 0.03 µg/L	↔ (SHg)	–	–	–
Chowdhury et al. 2018 Meta-analysis; 11,410 adults from four studies	Ranges of study means BHg: 0.0039–3.54 µg/L HHg: 1.9 µg/g NHg: 0.25–0.63 µg/g	–	–	–	↔ (BHg, HHg, NHg)[d] CVD
Chowdhury et al. 2018 Meta-analysis; 9,169 adults from five studies		–	–	–	↔ (BHg, HHg, NHg)[d] CHD
Daneshmand et al. 2016 Prospective; 1,828 men (Finland)	HHg mean: 1.90 µg/g	–	↔ (HHg)	–	–

Table 2-13. Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Cardiovascular Disease and Mortality due to Cardiovascular Disease in General Populations

		Cardiovascular disease[a] (biomarker)			
Reference, study type, and population	Biomarker	MI	Stroke	Angina	Other results and endpoints[b]
Downer et al. 2017 Nested case-control; 147 cases, 267 controls (Spain)	NHg mean Cases: 0.63 µg/g Controls: 0.67 µg/g	–	–	–	↔ (NHg) CVD
Guallar et al. 2002 Case-control; 684 male cases, 724 male controls (9 countries)	NHg mean: 0.26 µg/g[e]	↑ (NHg)	–	–	–
Guo et al. 2022 Cross-sectional; 9,404 adults (NHANES 2003–2016)	UHg median: 0.33 µg/L	–	–	–	↔ (UHg) CVD
Hallgren et al. 2001 Prospective case-control; 78 cases, 156 controls (Sweden)	ErHg mean Cases: 4.44 µg/g Controls: 5.42 µg/g	↔ (ErHg)	–	–	–
Hu et al. 2021 Meta-analysis; >34,000 participants from 14 studies (17 countries)	HHg: >2 µg/g	–	↑ (HHg)[c]	–	↑ (HHg)[c] CVD
Kim et al. 2014 Cross-sectional; 3,800 adults (KNHANES 2008–2009)	BHg mean: 5.44 µg/L	↔ (BHg)	↔ (BHg)	↔ (BHg)	–

Table 2-13. Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Cardiovascular Disease and Mortality due to Cardiovascular Disease in General Populations

		Cardiovascular disease[a] (biomarker)			
Reference, study type, and population	Biomarker	MI	Stroke	Angina	Other results and endpoints[b]
Mozaffarian and Rimm 2006 Meta-analysis; 5,830 adults from five studies	SHg mean: 17.0 µg/L (one study) ErHg mean: 4.44 µg/g (one study) HHg: >2.03 µg/g (one study) NHg mean: 0.26–0.91 µg/g (range of means from two studies)	–	–	–	↔ (SHg, ErHg, HHg, NHg)[d] CHD
Mozaffarian et al. 2011 Nested case-control from two cohorts: adult male cases (n=1,211) and controls (n=1,211) from HPFS cohort; female cases (n=2,216) and controls (n=2,166) from NHS cohort (United States)	NHg median Cases: 0.23 µg/g Controls: 0.25 µg/g	–	↔ (NHg)	–	↔ (NHg) CHD ↔ (NHg) all CVD
Park et al. 2022 Cross-sectional: 891 adults (Korea)	HHg quintiles Qi1: ≤0.6 µg/g Qi2: 0.6–0.8 µg/g Qi3: 0.8–1.1 µg/g Qi4: 1.1–1.5 µg/g Qi5: >1.5 µg/g	–	–	–	↓ (HHg, Qi1) AS
Raymond et al. 2016 Cross-sectional; 154 men (United States)	BHg median: 2.5 µg/L HHg median: 0.5 µg/g	↑ (BHg) ↔ (HHg)	–	↔ (BHg, HHg)	↔ (BHg, HHg) CHD
Salonen et al. 1995 Cohort; 1,833 men (Finland)	HHg mean: 1.92 µg/g	↑ (HHg)[c]	–	–	↔ (HHg) CHD ↔ (HHg) CVD
Salonen et al. 2000 Prospective; 1,014 men (Finland)	HHg mean: 1.8 µg/g	–	–	–	↑ (HHg) ATH

Table 2-13. Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Cardiovascular Disease and Mortality due to Cardiovascular Disease in General Populations

		Cardiovascular disease[a] (biomarker)			
Reference, study type, and population	Biomarker	MI	Stroke	Angina	Other results and endpoints[b]
Sun et al. 2021 Prospective cohort; 17,294 adults (NHANES 2003–2012)	BHg mean: 1.62 µg/L	–	–	–	↔ (BHg) CVD[f]
Virtanen et al. 2005 Prospective; 1,871 men (Finland)	HHg T3: ≥2.03 µg/g	↑ (HHg)[f]	–	–	↑ (HHg)[e] CVD ↔ (HHg)[e] CHD
Virtanen et al. 2012a Prospective; 1,857 men (Finland)	HHg mean: 1.91 µg/g	↔ (HHg)	–	–	–
Wang et al. 2023a Cross-sectional; 3,268 non-Hispanic, white adults (NHANES 1999–2018)	BHg quartiles Q1: ≤0.49 µg/L Q2: 0.49–≤0.91 µg/L Q3: 0.91–≤1.80 µg/L Q4: >1.80 µg/L	–	–	–	↔ (BHg, Q4) ASCVD
Wennberg et al. 2011 Prospective, nested, case-control; 431 cases, 499 controls (Sweden)	ErHg median: 3.54 µg/L	↔ (ErHg)	–	–	–
Wennberg et al. 2012 Prospective, nested case-control; 572 cases, 1,041 controls (Sweden and Finland)	HHg median Sweden: 0.57 µg/g Finland: 1.32 µg/g	↑ (HHg)	–	–	–

Table 2-13. Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Cardiovascular Disease and Mortality due to Cardiovascular Disease in General Populations

		Cardiovascular disease[a] (biomarker)			
Reference, study type, and population	Biomarker	MI	Stroke	Angina	Other results and endpoints[b]
Yoshizawa et al. 2002 Nested case-control; 470 cases; 464 controls (United States)	NHg mean Dentists: 0.91 µg/g Controls: 0.45 µg/g	–	–	–	↔ (NHg) CHD

[a]Unless otherwise noted, associations are for nonfatal effects.
[b]Description as reported by the study authors.
[c]Fatal and nonfatal effects.
[d]Biomarkers in individual studies (BHg, HHg, or NHg) were not transformed to a single biomarker type. For example, BHg and NHg concentrations were not converted to an equivalent HHg concentration.
[e]Group mean HHg was not reported for separately for cases and controls.
[f]Fatal effects.

↑ = positive association; ↔ = no association; – = not reported; AS = arterial stiffness; ASCVD = atherosclerotic cardiovascular disease; ATH = carotid atherosclerosis; BHg = blood mercury; CAD = coronary artery disease; CHD = coronary heart disease; CVD = cardiovascular disease; ErHg = erythrocyte mercury; HHg = hair mercury; HPFS = Health Professionals Follow-up Study; KNHANES = Korea National Health and Nutrition Examination Survey; MI = myocardial infarction; NHANES = National Health and Nutrition Examination Survey; NHg = toenail mercury; NHS = Nurses' Health Study; Q = quartile; Qi = quintile; T = tertile; SHg = serum mercury; UHg = urine mercury

Mechanisms of Action. Possible mechanisms that may be involved in mercury-induced effects on cardiovascular function have been proposed (da Cunha Martins et al. 2018; Genchi et al. 2017; Grandjean et al. 2004a; Houston 2011; Kim and Park 2023; Omanwar and Fahim 2015; Roman et al. 2011; Virtanen et al. 2007). These include: (1) increased oxidative stress and lipid peroxidation due to an imbalance between production of reactive oxygen species (ROS) and anti-oxidative mechanisms; (2) endothelial cell damage and dysfunction resulting from impaired nitric oxide signaling, decreased enzymatic degradation of catecholamines, and increased intracellular levels of calcium, leading to altered coronary vascular reactivity; (3) altered function of the renin-angiotensin system by stimulation of angiotensin converting enzyme (ACE); (4) altered sodium channel function in cardiac muscle, vascular endothelium, or at other sites important for cardiovascular function; (5) inhibition of Na^+-K^+ ATPase on platelet membranes, leading to increased platelet aggregation and clotting disorders; (6) neurological damage, resulting in altered balance of sympathetic and parasympathetic control of heart rate; (7) increased formation of inflammatory mediators (e.g., prostaglandins and leukotrienes); (8) increased C-reactive protein; and (9) decreased expression of genes involved in anti-inflammatory responses. Control of cardiovascular

function is multi-factorial; therefore, numerous mechanisms are likely involved. For additional information on general mechanisms of toxicity, see Section 2.21 (General Mechanisms of Action).

2.7 GASTROINTESTINAL

Overview. Gastrointestinal effects of mercury have not been well-studied in humans or animals. No epidemiological studies meeting inclusion criteria were identified for any form of mercury (see inclusion criteria, Section 2.1). Case studies and information from reviews indicate that adverse gastrointestinal effects occur following exposure to mercury vapor or from ingestion of high doses of mercury compounds at levels that were near fatal or fatal. However, the gastrointestinal tract does not appear to be a target of lower, environmental exposures to mercury.

Studies evaluating gastrointestinal effects in animals are available for oral exposure to mercuric chloride and methylmercury. Damage to the gastrointestinal tract (ulceration, hyperplasia) has been reported in rodents following exposure to inorganic salts or organic mercury at high oral doses associated with mortality. There is no evidence of gastrointestinal effects at nonlethal oral doses.

The following summarizes results of epidemiological and animal studies on the gastrointestinal system.

- ***Elemental mercury***
  - *Epidemiology studies*
    - No epidemiological studies on gastrointestinal effects from exposure to elemental mercury were identified.
    - Case studies of individuals acutely exposed to fatal or near-fatal levels of mercury vapor reported nausea and vomiting.
  - *Animal studies*
    - No adequate studies have evaluated gastrointestinal effects of elemental mercury.
- ***Inorganic mercury salts***
  - *Epidemiology studies*
    - No epidemiological studies on gastrointestinal effects from exposure to inorganic mercury salts were identified.
    - Case studies of individuals acutely exposed to fatal or near-fatal levels of inorganic mercuric compounds reported abdominal pain, nausea, diarrhea, ulceration, and hemorrhages of the upper and lower gastrointestinal tract.

  - *Animal studies*
    - Gavage doses associated with increased mortality are associated with damage to the forestomach and glandular stomach in mice and with forestomach hyperplasia in rats.
    - No evidence of gastrointestinal effects at nonlethal oral doses was reported.
- ***Organic mercury***
  - *Epidemiology studies*
    - One epidemiological study found no associations between hair methylmercury and severe chronic gastritis or gastric atrophy.
  - *Animal studies*
    - Irritative effects (ulceration) in rats and mice have been reported at chronic-duration oral methylmercury doses associated with increased mortality.
    - No evidence of gastrointestinal effects at nonlethal oral doses was reported.
- ***Predominant mercury form unknown (general populations)***
    - No epidemiological studies on gastrointestinal effects from mercury exposure of general populations were identified.

Confounding Factors. The only studies that were identified regarding gastrointestinal effects of mercury are case reports. Confounding factors are not considered in case reports.

Elemental Mercury—Epidemiological Studies. Epidemiological studies evaluating gastrointestinal effects of elemental mercury and meeting inclusion criteria were not identified (see inclusion criteria, Section 2.1). Abdominal pain (classified by the study authors as a gastrointestinal effect) was observed in a population of gold miners in the Philippines (Cortes-Maramba et al. 2006); however, due to inadequate reporting, it is not possible to provide additional information on gastrointestinal findings. Several case reports of individuals exposed acutely to high levels of elemental mercury vapor generated from heating elemental mercury to high temperatures in confined spaces stated that exposed individuals had nausea, vomiting, and diarrhea (Bluhm et al. 1992; Gore and Harding 1987; Haddad and Stenberg 1963; Hallee 1969; King 1954; Teng and Brennan 1959). No information regarding gastrointestinal effects at low exposure levels of elemental mercury were identified.

Elemental Mercury—Animal Studies. No adequate studies evaluating gastrointestinal effects in animals following exposure to elemental mercury were identified.

Inorganic Mercury Salts—Human Studies. Studies evaluating gastrointestinal effects in populations exposed to inorganic mercury salts were not identified. However, as reviewed by Berlin et al. (2015), cases of accidental or intentional ingestion of near-fatal or fatal doses of mercuric salts indicate that the gastrointestinal tract is a target organ. Acute-duration exposure to mercuric salts at near-fatal or fatal doses has corrosive effects on the gastrointestinal tract, causing gastric and abdominal pain, bloody diarrhea, and necrosis of the intestinal mucosa.

Inorganic Mercury Salts—Animal Studies. In rats, increased incidence of forestomach hyperplasia was observed in male rats exposed to mercuric chloride at chronic-duration gavage doses associated with increased mortality (≥1.8 mg Hg/kg/day); findings were not observed in female rats at doses up to 4 mg Hg/kg/day (NTP 1993). No gross or microscopic changes in the gastrointestinal tract were observed in rats following acute- or intermediate-duration exposure to mercuric chloride at gavage doses up 15 mg Hg/kg/day (Lecavalier et al. 1994; NTP 1993).

In mice, inflammation of the forestomach and necrosis of the forestomach and glandular stomach were observed in mice exposed to mercuric chloride via gavage at a dose of 59 mg Hg/kg/day for 4–5 days; this dose was associated with increased mortality (NTP 1993). Drinking water studies in mice reported lesions, colorectal gland atrophy, and mild-to-moderate necrosis in the cecum at 24 mg Hg/kg/day for 3 days and 15 mg Hg/kg/day for 90 days respectively (Zhao et al. 2020, 2021). In contrast, no gross or microscopic changes in the gastrointestinal tract were observed in mice at gavage doses up to 30 mg Hg/kg/day for 16 days, 15 mg Hg/kg/day for 6 months, or 7.4 mg Hg/kg/day for 2 years (NTP 1993).

Organic Mercury—Epidemiological Studies. Little information on gastrointestinal effect of exposures to methylmercury from high fish diets is available. A cross-sectional study of 80 indigenous Arctic adults (mean age: 53.2 years) in Canada found no associations between hair methylmercury (mean: 0.565 µg/g; range: 0.063–2.07 µg/g) and severe chronic gastritis or gastric atrophy (Walker et al. 2021). Nausea and diarrhea were observed in a gold mining community in the Philippines exposed to mercury through ingestion of methylmercury in fish (Cortes-Maramba et al. 2006); interpretation of study results is not possible due to inadequate reporting.

Organic Mercury—Animal Studies. Two chronic-duration studies reported gastrointestinal effects consistent with local irritation at doses associated with increased mortality. The first study reported necrosis and ulceration of the cecum in rats following exposure to 3.7 mg Hg/kg/day via drinking water as phenylmercuric acetate (Solecki et al. 1991). The second study reported ulceration of the glandular

stomach in male mice following dietary exposure to methylmercuric chloride at 0.686 mg Hg/kg/day; this was not observed in female mice at dietary doses up to 0.601 mg Hg/kg/day (Mitsumori et al. 1990).

In other studies, no exposure-related histopathological changes in the gastrointestinal tract were observed following oral exposure to methylmercuric chloride in cats at intermediate-duration doses up to 0.176 mg or chronic-duration doses up to 0.074 mg Hg/kg/day (Verschuuren et al. 1976), or mice at intermediate- or chronic-duration doses up to 9.5 or 0.724 mg Hg/kg/day, respectively (Hirano et al. 1986; MacDonald and Harbison 1977).

Predominant Mercury Form Unknown (General Populations). Studies evaluating gastrointestinal effects of mercury exposure in general populations were not identified.

Mechanisms of Action. Mercury has a direct caustic effect to the intestinal mucosa and causes extensive precipitation of proteins. Mercury ingestion can destroy and/or modify the composition of intestinal flora (Rice et al. 2014; Seki et al. 2021; Zhao et al. 2020). Mercury exposure biomarkers have been associated with changes in intestinal microflora profiles (Laue et al. 2020; Rothenberg et al. 2016a, 2019). Mercury biomarkers have also been associated with changes in microbiome profiles observed in certain disease states including autism, gestational diabetes, and autoimmune disease (Khan and Wang 2020; Shen et al. 2022; Zhai et al. 2019; Zhang et al. 2021c). General mechanisms of toxicity of mercury (reviewed in Section 2.21) are likely involved in the development of toxicity to the gastrointestinal system.

2.8 HEMATOLOGICAL

Overview. Epidemiological and animal studies have evaluated hematological effects of mercury, although hematological effects have not been well-studied in humans. Furthermore, few epidemiological studies on hematological effects meet the inclusion criteria for this toxicological profile (see inclusion criteria, Section 2.1). Although there are plausible mechanisms for mercury to adversely affect erythrocytes, data from epidemiological studies are insufficient to determine if exposure to mercury produces adverse hematological effects in humans.

Effects of mercury on the hematological system in animals have been evaluated following acute- and intermediate-duration oral exposure to mercuric chloride and intermediate- and chronic-duration oral exposure to inorganic mercury salts. Available data suggesting impaired clotting, small decreases in RBC counts, and increased WBC counts in rodents exposed to mercuric chloride are of uncertain biological

relevance. Available data are inadequate to determine if exposure to organic mercury is associated with adverse hematological effects.

The following summarizes results of epidemiological and animal studies on hematological outcomes.

- ***Elemental mercury***
  - *Epidemiology studies*
    - Inadequate data are available to determine if exposure to elemental mercury is associated with adverse effects to the hematological system. One study showed increased lipid peroxidation in erythrocytes, but erythrocyte function was not assessed.
  - *Animal studies*
    - No studies evaluating hematological effects following exposure to elemental mercury were identified.
- ***Inorganic mercury salts***
  - *Epidemiology studies*
    - No epidemiological studies evaluating associations between exposure to inorganic mercury salts and hematological effects were identified.
  - *Animal studies*
    - A few studies reported impaired clotting in rats following oral exposure to mercuric chloride.
    - Some evidence of small decreases in RBC parameters (count, hemoglobin, hematocrit), but findings are of uncertain biological significance.
    - Inconsistent evidence for increased WBC counts in rodents following oral exposure to mercuric chloride.
- ***Organic mercury***
  - *Epidemiology studies*
    - Data are insufficient to determine if exposure to organic mercury is associated with adverse hematological effects. The only identified study showed an inverse association between HHg and blood hemoglobin; however, the study did not account for iron status, a major confounding factor.
  - *Animal studies*
    - Data are insufficient to determine if exposure to organic mercury is associated with adverse hematological effects. One study reported anemia in rats following chronic-duration exposure to phenylmercuric acetate but this finding is attributed to ulceration in the gastrointestinal tract.

- ***Predominant mercury form unknown (general populations)***
    - Inadequate data are available to determine if exposure of the general population to mercury is associated with adverse effects to the hematological system. One study showed a positive association between BHg and hemoglobin.

Confounding Factors. Numerous factors can complicate interpretation of studies on hematological function. These include nutritional status, negative iron balance, infectious or chronic diseases (e.g., malaria, obesity), micronutrient balance (e.g., vitamin D, vitamin A, vitamin B12, zinc, folate), and other environmental exposures (e.g., lead, cadmium, PCBs) (Weinhouse et al. 2017), which may also vary by mercury exposure status. Few of these factors were considered in the epidemiological studies reviewed in this section and no studies assessed iron balance as a confounding factor for changes in blood hemoglobin.

Elemental Mercury—Epidemiological Studies. Little information is available regarding effects of elemental mercury on the hematological system in humans, with only two studies meeting inclusion criteria for this toxicological profile (see inclusion criteria, Section 2.1); study results are summarized in Table 2-14. A prospective study of women with amalgam fillings found a positive association between SHg and blood hemoglobin at the baseline assessment but no association at the 22-year follow-up assessment (Ahlqwist et al. 1999). The toxicological significance of this increased blood hemoglobin is unclear. No associations were observed between SHg and leukocyte or platelet counts at the enrollment or follow-up assessments. Due to high participant attrition between the enrollment (n=1,462) and follow-up assessments (n=135), effects on blood hemoglobin reported in this study are difficult to interpret. A cross-sectional study of chloralkali workers found increased erythrocyte activities of glutathione peroxidase (GPX), superoxide dismutase (SOD), and glucose-6-phosphate dehydrogenase (G6PDH), and increased erythrocyte levels of malondialdehyde, compared to controls (Bulat et al. 1998). The study authors stated that results are consistent with increased lipid peroxidation.

Table 2-14. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Hematological Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Ahlqwist et al. 1999 Prospective; 1,462 women with amalgam fillings, enrolled in 1968–1969, and followed through 1980–1981(n=135 at follow-up) (Sweden)	SHg mean: 3.4 µg/L	Blood hemoglobin	↑ (SHg, baseline) ↔ (SHg, follow-up)
		Leukocyte count	↔ (SHg, baseline) ↔ (SHg, follow-up)
		Platelet count	↔ (SHg, baseline) ↔ (SHg, follow-up)
Bulat et al. 1998 Cross-sectional; 42 chloralkali workers and 75 controls (former Yugoslavia)	BHg mean Workers: 35.9 µg/L Controls: 4.6 µg/L UHg mean Workers: 41.1 µg/g Cr Controls: 4.8 µg/g Cr	Erythrocyte GPX	↓ (BHg, UHg, workers versus controls)
		Erythrocyte SOD	↓ (BHg, UHg, workers versus controls)
		Erythrocyte MDA	↑ (BHg, UHg, workers versus controls)
		Erythrocyte G6PDH	↓ (BHg, UHg, workers versus controls)

↑ = positive association; ↓ = inverse association; ↔ = no association; BHg = blood mercury; Cr = creatinine; G6PDH = glucose-6-phosphate dehydrogenase; GPX = glutathione peroxidase; MDA = malondialdehyde; SHg = serum mercury; SOD = superoxide dismutase; UHg = urine mercury

Elemental Mercury—Animal Studies. No studies were located regarding hematological effects in animals after exposure to elemental mercury.

Inorganic Mercury Salts—Animal Studies. Hematological findings following oral exposure to mercuric chloride are shown in Table 2-15. Limited rat data suggest a potential for impaired clotting following acute- or intermediate-duration oral exposure to mercuric chloride, but the effects lessened in severity with increased duration of exposure. Data suggest small decreases in RBC parameters in rodents following acute- or intermediate-duration oral exposure to mercuric chloride; however, the biological relevance of these small changes is unclear. There is inconsistent evidence for increased WBC counts in rodents following oral exposure to mercuric chloride.

Table 2-15. Hematological Effects in Rodents Orally Exposed to Mercuric Chloride

Strain (sex); duration; dose (mg Hg/kg/day)	Clotting measures[a]	RBC count[a]	Hemo-globin[a]	Hct[a]	WBC count[a]	Total lympho-cytes[a]	Reference
Rat (NS); 1 day; dose: 0.684	BT: ↑ (88) CT: ↑ (66)	↓ (3)	↔	–	↑ (10)	–	Mahour and Saxena 2009
Rat (F); 1 day; dose: 7.4	–	↓ (10)	↓ (9)	↓ (10)	–	–	Lecavalier et al. 1994
Rat (F); 1 day; dose: 9.24	–	↓ (9)	↔	↓ (8)	–	–	Lecavalier et al. 1994
Rat (NS); 7 days; dose: 0.033	BT: ↑ (21) CT: ↑ (26)	↓ (1)	↓ (7)	–	↑ (2)	–	Mahour and Saxena 2009
Rat (NS); 14 days; dose: 0.033	BT: ↑ (4) CT: ↑ (13)	↓ (2)	↓ (9)	–	↑ (13)	–	Mahour and Saxena 2009
Rat (NS); 21 days; dose: 0.033	BT: ↓ (2) CT: ↓ (18)	↓ (13)	↓ (5)	–	↑ (17)	–	Mahour and Saxena 2009
Rat (B); 28 days); dose: 0.61–0.76	–	↔	↔	–	↔	–	Jonker et al. 1993
Rat (B); 28 days; dose: 5.1–5.5	–	↔	↔	–	↔	–	Jonker et al. 1993
Rat (M); 45 days; dose: 0.277	↓ PLT (13)	↔	↔	–	↑ (45)	–	dos Santos Chemelo et al. 2021
Rat (M); 90 days; dose: 5.5	–	↓ (5)	↓ (5)	↓ (4)	–	–	Boujbiha et al. 2012
Rat (M); 90 days; dose: 11	–	↓ (10)	↓ (10)	↓ (7)	–	–	Boujbiha et al. 2012
Rat (M); 182 days; dose: 0.04	0 PLT	↔	↔	↔	↑ (140)	–	Agrawal et al. 2014
Mouse (M); 14 days; dose: 0.06	–	↓ (13)	–	–	↔	–	Kim et al. 2003
Mouse (M); 14 days; dose: 0.31	–	↓ (13)	–	–	↔	–	Kim et al. 2003

Table 2-15. Hematological Effects in Rodents Orally Exposed to Mercuric Chloride

Strain (sex); duration; dose (mg Hg/kg/day)	Clotting measures[a]	RBC count[a]	Hemo-globin[a]	Hct[a]	WBC count[a]	Total lympho-cytes[a]	Reference
Mouse (M); 14 days; dose: 1.39	–	↓ (11)	–	–	↔	–	Kim et al. 2003
Mouse (M); 14 days; dose: 4.81	–	↓ (19)	–	–	↑ (91)	–	Kim et al. 2003
Mouse (B10.S) (B); 28 days; dose: 2.7	↑ PLT (~29)	↑ (~38)	↑ (~37)	–	–	–	He et al. 2021
Mouse (DBA/2) (B); 28 days; dose: 2.7	↔ PLT	↔	↔	–	–	–	He et al. 2021
Mouse (M); 49 days: dose: 0.4	–	↔	–	–	↑ (35)	↑ (51)	Dieter et al. 1983
Mouse (M); 49 days; dose: 2	–	↔	–	–	↔	↔	Dieter et al. 1983
Mouse (M); 49 days; dose: 11	–	↓ (8)	–	–	↓ (36)	↓ (35)	Dieter et al. 1983

[a]Numbers in ( ) are percent change compared to control, calculated from quantitative data.

↑ = increased; ↓ = decreased; ↔ = no change; – = not assessed; B = both males and females; BT = bleeding time; CT = clotting time; F = female(s); Hct = hematocrit; M = male(s); NS = not specified; PLT = platelet; RBC = red blood cell; WBC = white blood cell

Increased bleeding and clotting times were observed in rats following a single oral exposure to 0.684 mg Hg/kg or repeated exposure to 0.033 mg Hg/kg/day for 1–3 weeks (Mahour and Saxena 2009). However, biological relevance is unclear as findings became less pronounced with increased duration of exposure. Scanning electron microscopy data from another 4-week study also suggest impaired clotting, showing platelet activation (spreading of platelets, formation of pseudopods) and a poorly developed fibrin network in rats exposed to 0.848 mg Hg/kg/day; fibrin fiber thickness did not differ between groups (Arbi et al. 2017). Due to the qualitative nature of scanning electron microscopy data, Arbi et al. (2017) was not included in the LSE table. No other studies identified measured clotting, but Agrawal et al. (2014) indicated no exposure-related changes to the number of platelets in mice exposed to 0.04 mg Hg/kg/day for 6 months (Agrawal et al. 2014). Morphological changes in rat platelets were observed at 0.13 mg Hg/kg/day for 28 days (Janse van Rensburg et al. 2020).

Several studies have reported changes in RBC parameters following oral exposure to mercuric chloride; however, the reported changes are small in magnitude and the toxicological relevance is unclear. In single exposure studies in rats, RBC counts were minimally (<5%) decreased at 0.684 mg Hg/kg and mildly (<20%) decreased at ≥7.4 mg Hg/kg (Lecavalier et al. 1994; Mahour and Saxena 2009). Hemoglobin and hematocrit were mildly decreased at ≥7.4 mg Hg/kg (Lecavalier et al. 1994). Following repeated exposure to 0.033 mg Hg/kg/day, RBC counts were minimally decreased after 1 or 2 weeks and mildly decreased after 3 weeks; hemoglobin levels were mildly decreased at all time points (no duration-dependency) (Mahour and Saxena 2009). Other intermediate-duration studies in rats report no changes in RBC count, hemoglobin levels, or hematocrit following exposure to 0.04 mg Hg/kg/day for 6 months (Agrawal et al. 2014) or doses up to 5.5 mg Hg/kg/day for 28 days (Jonker et al. 1993), and mild decreases in RBC parameters at doses ≤5.5 mg Hg/kg/day for 90 days (Boujbiha et al. 2012). In mice, mild decreases in RBC counts were reported following exposure to ≥0.06 mg Hg/kg/day for 2 weeks (Kim et al. 2003). In contrast, no changes in RBC counts were observed in mice exposed to doses up to 2 mg Hg/kg/day for 7 weeks; similar exposure to 11 mg Hg/kg/day resulted in a mildly decreased RBC count (Dieter et al. 1983). Moderate increases in RBC counts, hemoglobin, and platelets were observed at 2.7 mg Hg/kg/day for 4 weeks in BS.10 mice but not in DBA/2 mice (He et al. 2021).

The evidence for elevated WBC counts in rodents following oral exposure to mercuric chloride is inconsistent. In rats, WBC counts were mildly increased following a single exposure to 0.684 mg Hg/kg or repeated exposure to 0.033 mg Hg/kg/day for 2 or 3 weeks; exposure to 0.033 mg Hg/kg/day for 1 week resulted in minimal increases in WBC count (Mahour and Saxena 2009). Larger elevations in WBC count (>2-fold) were observed in rats exposed to 0.04 mg Hg/kg/day for 6 months or by 45% in rats exposed to 0.277 mg Hg/kg/day for 45 days (dos Santos Chemelo et al. 2021). However, other intermediate-duration studies in rats reported no changes in WBC counts at doses up to 5.5 mg Hg/kg/day for 28 days (Jonker et al. 1993). In mice, an increase in WBC count (~2-fold) was observed following exposure to 4.81 mg Hg/kg/day for 14 days; no changes were observed at ≤1.39 mg Hg/kg/day (Kim et al. 2003). A 7-week study in mice observed a non-monotonic response for WBC counts, with increases at 0.4 mg Hg/kg/day, no change at 2 mg Hg/kg/day and decreases at 11 mg Hg/kg/day (Dieter et al. 1983).

The erythrocyte sedimentation rate (ESR) was increased by 21, 10, and 41% in rats exposed to 0.033 mg Hg/kg/day for 7, 14, or 21 days, respectively (Mahour and Saxena 2009). This finding may be related to immune function, as elevated ESR is a marker for inflammation.

Organic Mercury—Epidemiological Studies. Data are not sufficient to determine if exposure to mercury in populations that consume high fish diets produces adverse hematological effects, with only one study meeting inclusion criteria for this toxicological profile (see inclusion criteria, Section 2.1). In a cross-sectional study, Weinhouse et al. (2017) evaluated the association between total HHg (median: 1.18 µg/g) and blood hemoglobin levels in a population of 83 children <12 years of age. This population, from the Peruvian Amazon, was primarily exposed through fish consumption. HHg was inversely associated with blood hemoglobin (β -0.18; 95% CI -0.31, -0.046). Several covariates, including age, sex, and micronutrients, were considered; however, iron status, a major confounding factor, was not assessed in this population.

Organic Mercury—Animal Studies. Hematological data following exposure to organic mercury compounds are very limited. Rats that received phenylmercuric acetate in their drinking water for 2 years showed decreases in hemoglobin, hematocrit, and RBC counts at a dose of 3.7 mg Hg/kg/day (Solecki et al. 1991). The anemia observed in this study may have been secondary to blood loss associated with the ulcerative lesions in the large intestine seen at this dose (Section 2.7, Gastrointestinal). In other studies, no hematological effects were noted following dietary exposure to methylmercury in rats at doses up to 0.18 mg Hg/kg/day for 2 years (Verschuuren et al. 1976), rabbits at doses up to 0.53 mg Hg/kg/day for 14 weeks (Koller et al. 1977), or cats at doses up to 0.176 mg Hg/kg/day for approximately 16 weeks, 0.074 mg Hg/kg/day for approximately 55 weeks, or 0.046 mg Hg/kg/day for 2 years (Charbonneau et al. 1976).

Predominant Mercury Form Unknown (General Populations). Studies evaluating hematological effects of mercury in general populations meeting inclusion criteria are summarized in Table 2-16. In a cross-sectional study of 4,522 adults from the 2008–2010 KNHANES population, positive associations were observed between BHg and hemoglobin in men and women (Park and Lee 2013). Mean BHg was 4.34 µg/L in men and 3.73 µg/L in women. A cross-sectional study of 2,026 adults from the 2011–2018 NHANES did not find an association between BHg and peripheral eosinophil counts (Wen et al. 2023). A subset of pregnancies from a prospective study found an association between increasing NHg in late pregnancy and frequency of regulatory T-cells and natural killer cells in cord blood (Movassagh et al. 2021). A cross-section study off children found an association between increasing BHg and increased peripheral lymphocyte counts (Kim et al. 2015d)

Table 2-16. Results of Epidemiological Studies Evaluating Exposure to Mercury (Predominant Mercury Form Unknown) and Hematological Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Kim et al. 2015d Cross-sectional; 311 children (South Korea)	BHg median: 2.19 µg/L	Cell counts Total leukocytes Segmented leukocytes Lymphocytes Monocytes Basophils Eosinophils	 ↔ (BHg) ↔ (BHg) ↑ (BHg) ↔ (BHg) ↔ (BHg) ↔ (BHg)
Movassagh et al. 2021 Prospective; subset of New Hampshire Birth Cohort Study (n=63 pregnant women) (United States)	NHg Gmean 0.072 µg/g	Cord blood T-cell frequency: T-helper T-regulatory Natural killer	 ↔ (NHg) ↑ (NHg) ↑ (NHg)
Park and Lee 2013 Cross-sectional; 5,533 adults, age ≥20 years, from 2008–2010 KNHANES (Korea)	BHg Gmean Women: 3.733 µg/L Men: 4.377 µg/L	Blood hemoglobin	↑ (BHg)
Wen et al. 2023 Cross-sectional; 2,026 adults, age ≥18 years, from 2011–2018 NHANES	BHg mean for eosinophil count quartiles Q1: 1.53 µg/L Q2: 1.40 µg/L Q3: 1.24 µg/L Q4: 1.13 µg/L	Eosinophil count	↔ (BHg)
Zhang et al. 2020a Cross-sectional; 73 children exposed to e-waste and 74 referents, age 3–7 years (China)	BHg median 1.46 µg/L	Peripheral cell counts: Lymphocyte Neutrophil Monocyte	 ↔ (BHg) ↑ (BHg) ↔ (BHg)

↑ = positive association; ↔ = no association; BHg = blood mercury; KNHANES = Korea National Health and Nutrition Examination Survey; NHANES = National Health and Nutrition Examination Survey; NHg = toenail mercury; Q = quartile

Mechanisms of Action. Epidemiological and animal studies do not provide strong evidence that mercury adversely affects the hematological system. However, mercury is transported into erythrocytes and has a high affinity for hemoglobin and other protein and non-protein sulfhydryls (Section 3.1, Toxicokinetics); therefore, there is the potential for mercury to adversely affect erythrocytes. Weinhouse et al. (2017) reviewed several possible mechanisms for mercury-induced adverse effects on erythrocytes, including:

(1) oxidative damage and inflammatory effects; (2) erythrocyte apoptosis; (3) decreased erythrocyte production; (4) decreased heme biosynthesis; (5) dysregulation of iron homeostasis; and (6) exacerbation of vitamin B12 or folate deficiency.

2.9 MUSCULOSKELETAL

Overview. Few epidemiological and animal studies have evaluated musculoskeletal effects of mercury. However, based on the available data, the musculoskeletal system does not appear to be a sensitive target of mercury exposure. No epidemiological studies were identified for elemental and organic mercury. A few studies in general populations evaluated associations between mercury biomarkers and indicators of bone mineral status, and risks of sarcopenia, and periodontitis. Results indicate mercury exposure does not adversely affect bone mineral. Data are inadequate to determine if mercury is associated with sarcopenia or periodontitis.

No primary musculoskeletal effects were observed in rodents following oral exposure to inorganic salts. Studies in rodents observed bone loss and altered bone microstructure in the mandible from methylmercuric chloride exposure. Effects secondary to renal impairment (mercuric chloride) and neurological impairment (methylmercury) included fibrous osteodystrophy and muscle weakness/atrophy, respectively. No inhalation studies were available.

The following summarizes results of epidemiological and animal studies on musculoskeletal outcomes.

- ***Elemental mercury***
  - *Epidemiology studies*
    - No epidemiological studies on musculoskeletal effects from exposure to elemental mercury were identified.
  - *Animal studies*
    - No studies evaluating musculoskeletal effects following exposure to elemental mercury were identified.
- ***Inorganic mercury salts***
  - *Epidemiology studies*
    - No epidemiological studies evaluating associations between exposure to inorganic mercury salts and musculoskeletal effects were identified.

  - *Animal studies*
    - No primary musculoskeletal effects were observed in rats or mice following acute-, intermediate-, or chronic-duration oral exposure to mercuric chloride.
    - Fibrous osteodystrophy was reported in male rats following chronic-duration exposure to mercuric chloride. This was considered secondary to marked renal impairment.
- ***Organic mercury***
  - *Epidemiology studies*
    - No epidemiological studies on musculoskeletal effects from exposure to organic mercury were identified.
  - *Animal studies*
    - Bone loss and altered microstructure were observed in the mandible of adult rats following intermediate-duration oral exposure to methylmercury. Similar effects were observed in offspring of rats after gestational and lactational exposure.
    - Muscle weakness and atrophy were reported in rats following acute-duration exposure to methylmercury. This was considered secondary to neurological impairment.
- ***Predominant mercury form unknown (general populations)***
    - Based on the limited data in adults, exposure of the general population to mercury is not associated with adverse effects on bone.
    - A study in children and adolescents found an inverse association between BHg and bone density in males, but not in females.
    - Results of single studies found positive associations between mercury biomarkers and sarcopenia and periodontitis.

Confounding Factors. Factors associated with bone mineral status that may also be associated with mercury exposure status include nutrition, age, pregnancy, menopausal status, activity level, and exposure to other chemicals that act on bone mineral (e.g., cadmium).

Elemental Mercury—Epidemiological Studies. No studies on musculoskeletal effects from exposure to elemental mercury were identified.

Elemental Mercury—Animal Studies. No studies were located regarding musculoskeletal effects in animals after exposure to elemental mercury.

Inorganic Mercury Salts—Animal Studies. Fibrous osteodystrophy was reported in male rats following chronic-duration exposure to mercuric chloride at gavage doses ≥1.8 mg Hg/kg/day; this finding is considered secondary to marked renal impairment observed at these doses (NTP 1993). Fibrous osteodystrophy was not observed in female rats at chronic-duration doses up to 4 mg Hg/kg/day; renal impairment was also not observed in females. In acute-duration exposure studies, no histopathological lesions in muscle or bone were observed in rats at doses up to 9.24 mg Hg/kg/day (Lecavalier et al. 194). Intermediate-duration exposure studies show conflicting results. A gavage study observed alterations in alveolar bone structure and decreased trabecular space were observed in rats exposed to 0.277 mg Hg/kg/day for 45 days (Nunes et al. 2022). However, no lesions in muscle or bone were found in rats at gavage doses up to 4 mg Hg/kg/day for 15 months (NTP 1993). In mice, no histopathological lesions in muscle or bone were observed at intermediate- or chronic-duration doses up to 15 or 7.4 mg Hg/kg/day, respectively (NTP 1993).

Organic Mercury—Animal Studies. Studies in rats have found adverse effects of methylmercury on bone. A study in adult rats exposed to 0.03 mg/kg/day as methylmercuric chloride by gavage (oil) for 60 days observed bone loss and microstructural changes in mandibular bone (de Oliveira Lopes et al. 2021). Microstructural changes were decreased trabecular number, trabecular thickness, and bone volume fraction. The root area of the bone was exposed and bone height was decreased. Similar effects on mandibular bone were observed in offspring of rats following gestational and lactational exposure (Chemelo et al. 2022). In this study, dams were administered cookies laced with methylmercuric chloride at a dose of 0.05 mg/kg/day for 41 days during gestation and lactation. Following exposure, mandibles in offspring showed increased spacing between trabeculae, decreased amount of trabecular bone, decreased osteocyte density, and reduced bone collagen.

In contrast, at higher doses, no exposure-related changes in muscle or bone histology were observed following oral exposure to methylmercuric chloride in cats at doses up to 0.176 mg Hg/kg/day for approximately 16 weeks, 0.074 mg Hg/kg/day for approximately 55 weeks, or 0.046 mg Hg/kg/day for 2 years (Charbonneau et al. 1976). No effects on muscle or bone histology were observed in rats at doses up to 0.18 mg Hg/kg/day for 2 years (Verschuuren et al. 1976). Similarly, studies in mice reported no effects on muscle or bone histology at doses up to 1.3 mg Hg/kg/day for 56 days (Rand et al. 2020) or 0.724 mg Hg/kg/day for 2 years (Hirano et al. 1986; Mitsumori et al. 1990).

Skeletal muscle weakness and wasting/atrophy were observed in rats exposed to methylmercuric chloride at gavage doses of ≥4 mg Hg/kg/day for 10–12 days (Su et al. 1998; Usuki et al. 1998). These findings are considered neurogenic in nature, as opposed to a direct toxic action of methylmercury on skeletal muscle. Effects occurred at doses associated with overt signs of neurotoxicity and mortality.

Predominant Mercury Form Unknown (General Populations). Few studies on musculoskeletal effects of mercury in general populations were identified. Cross-sectional studies evaluated associations between mercury biomarkers and bone outcomes (bone mineral density, bone resorption, and risks of osteopenia, osteoporosis, arthritis, and fracture), sarcopenia, and periodontitis; studies are summarized in Table 2-17. Several studies evaluated outcomes in KNHANES participants (Cho et al. 2012; Kim et al. 2016a; Lim et al. 2016; Yoo et al. 2016) and NHANES participants (Guan et al. 2023; Tang et al. 2022b; Xu et al. 2023b; Wei et al. 2021). BHg was used as the biomarker in all studies, except for one study that used HHg (Han et al. 2009).

Table 2-17. Results of Epidemiological Studies Evaluating Exposure to Mercury (Predominant Mercury Form Unknown) and Musculoskeletal Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Callan et al. 2015 Cross-sectional; 77 women ≥50 years of age (Australia)	BHg median: 2.04 µg/L	Bone resorption	↓ (BHg, Q2−Q4)
Cho et al. 2012 Cross-sectional; 481 post-menopausal women (KNHANES)	BHg, quartiles Q1: <2.67 µg/L Q2: ≥2.67−<3.74 µg/L Q3: ≥3.74−<5.23 µg/L Q4: ≥5.23 µg/L	Risk of osteoporosis	↓ (BHg, Q2−Q4)
Guan et al. 2023 Cross-sectional; 2,174 adults (NHANES 2013−2016)	BHg median: 1.52 µg/L	Risk of arthritis	↔ (BHg)
Han et al. 2009 Cross-sectional; 598 men and 730 women (Korea)	HHg, median With periodontitis: 1.11 µg/g No periodontitis: 0.97 µg/g	Risk of periodontitis	↑ (HHg, men) ↔ (HHg, women)
Jalili et al. 2020a Meta-analysis of 4 studies[a] with combined 4,348 adults	BHg[b]	Risk of osteopenia and osteoporosis	↔ (BHg)

Table 2-17. Results of Epidemiological Studies Evaluating Exposure to Mercury (Predominant Mercury Form Unknown) and Musculoskeletal Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Kim et al. 2016a Cross-sectional; 1,190 men ≥50 years of age (KNHANES)	BHg, quartiles Q1: <3.347 µg/L Q2: 3.347−5.337 µg/L Q3: 5.337−8.914 µg/L Q4: >8.014 µg/L	Bone mineral density	
		Total hip	↔ (BHg)
		Femur neck	↑ (BHg)
		Lumbar spine	↔ (BHg)
		Risk of osteopenia and osteoporosis	
		Total hip	↓ (BHg, Q4)
		Femur neck	↓ (BHg, Q4)
		Lumbar spine	↔ (BHg, Q4)
		Risk of facture	↔ (BHg, Q4)
Lim et al. 2016 Cross-sectional; 2,429 adults (KNHANES)	BHg, quartiles Q1: <2.549 µg/L Q2: 2.549−3.798 µg/L Q3: 3.798−5.710 µg/L Q4: >5.710 µg/L	Risk of osteopenia and osteoporosis	↔ (BHg, Q4)
Pollack et al. 2013 Cross-sectional; 248 premenopausal women (Buffalo, New York)	BHg, mean: 1.51 µg/L	Bone mineral density	
		Whole body	↔ (BHg)
		Total hip	↔ (BHg)
		Lumbar spine	↔ (BHg)
		Wrist	↔ (BHg)
		Risk of low bone mineral density	
		Whole body	↔ (BHg)
		Total hip	↔ (BHg)
		Lumbar spine	↓ (BHg)
		Wrist	↔ (BHg)
Tang et al. 2022b Cross-sectional; 8,665 adults, mean age 44.39 (NHANES 2005−2010)	BHg: 1.68 µg/L	Bone mineral density	
		Femur total	↑ (BHg)
		Femur neck	↑ (BHg)
		Trochanter	↑ (BHg)
		Intertrochanter	↑ (BHg)
		Spine total	↑ (BHg)
		Spine L1	↑ (BHg)
		Spine L2	↑ (BHg)
		Spine L3	↔ (BHg)
		Spine L4	↔ (BHg)
Wei et al. 2021 Cross-sectional; 2,545 adults, mean age 39.4 years (NHANES 2011−2016)	BHg, Gmean: 0.77 µg/L	Bone mineral density (lumbar spine)	↔ (BHg)

Table 2-17. Results of Epidemiological Studies Evaluating Exposure to Mercury (Predominant Mercury Form Unknown) and Musculoskeletal Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Xu et al. 2023b Cross-sectional: 2,818 children and adolescents, ages 12−19 years; 1,458 boys and 1,360 girls (NHANES 2011−2018)	BHg Low: <1.09 µg/L (boys) Low: <2.37 µg/L (girls) High: >1.09 µg/L (boys) High: >2.37 µg/L (girls)	Total bone mineral density	↓ BHg (high, boys) ↔ BHg (high, girls)
Yoo et al. 2016 Cross-sectional; 344 men and 360 women >65 years of age (KNHANES)	Men, BHg, quartile means Q1: 1.79 µg/L Q2: 2.95 µg/L Q3: 4.48 µg/L Q4: 9.69 µg/L Women, BHg, quartile means Q1: 1.79 µg/L Q2: 2.95 µg/L Q3: 4.41 µg/L Q4: 10.30 µg/L	Risk of sarcopenia	↑ (BHg, Q4, men and women)

[a]Studies included in the meta-analysis are Cho et al. (2012), Kim et al. (2016a), Lim et al. 2016, and Pollack et al. (2013).
[b]Mean BHg mean or range was not reported for the combined population. BHg levels are reported in the individual studies noted in footnote "a" above.

↑ = positive association; ↓ = inverse association; ↔ = no association; BHg = blood mercury; Gmean = geometric mean; HHg = hair mercury; KNHANES = Korean National Health and Nutrition Examination Survey; NHANES = National Health and Nutrition Examination Survey; Q = quartile

Associations between mercury and bone outcomes were evaluated in postmenopausal women (≥50 years of age), pre-menopausal women, men ≥50 years of age, adults ≥18 years of age, and children and adolescents (12–19 years of age). Results indicate that mercury exposure of general populations is not associated with adverse effects on bone; instead, mercury could possibly have a protective effect. In older women, inverse associations were observed between BHg and bone resorption and the risk of osteoporosis (Callan et al. 2015; Cho et al. 2012). In pre-menopausal women, no associations were observed between BHg and bone mineral density, and the risk of having a low bone mineral density of the lumbar spine was decreased (Pollack et al. 2013). In older men, an inverse association was observed between BHg and risk of osteopenia and osteoporosis of the hip and femur, and increasing BHg was associated with increasing bone mineral density of the femur (Kim et al. 2016a). The Tang et al. (2022b) study in a large NHANES population also showed that BHg was associated with increased bone mineral density in the femur and spine. However, no association was observed between BHg and the risk of

fracture. A meta-analysis of four studies did not find associations between BHg and the risk of osteopenia and osteoporosis in adults (Jalili et al. 2020a). Similarly, in adults ≥18 years of age, no associations were observed between BHg and the risk of osteopenia and osteoporosis (Lim et al. 2016), lumbar bone mineral density (Wei et al. 2021), or arthritis (Guan et al. 2023). A study in children and adolescents found an inverse association between BHg (>1.09 μg/L) and bone mineral density in boys, but no association in girls (BHg: >2.37) (Xu et al. 2023b). Taken together, results of these studies indicate that mercury exposure of general populations does not adversely affect bone mineral status.

Other studies found positive associations between HHg and the risk of periodontitis in men, but not women (Han et al. 2009), and between BHg and the risk of sarcopenia in men and women (Yoo et al. 2016). These findings have not been corroborated.

Mechanisms of Action. Mechanisms for possible positive effects of mercury on bone mineral status have not been well-investigated. It has been proposed that mercury may alter activity of osteoclasts and osteoblasts (Cho et al. 2012; Kim et al. 2016a).

2.10 HEPATIC

Overview. Hepatic effects of mercury have not been extensively studied in humans or animals. Few epidemiological studies have evaluated hepatic effects associated with mercury exposures, most likely because the liver does not appear to be a sensitive target organ for mercury, relative to other systems (e.g., nervous system). No epidemiological studies of hepatic effects that reported mercury biomarkers were identified for exposure to elemental mercury or in populations with high fish diets. A few studies on liver effects in general populations were identified; these studies evaluated associations between mercury biomarkers and dyslipidemias. Data are not adequate to determine if general exposure to mercury adversely affects the liver.

Studies evaluating hepatic effects are available for inhalation exposure to mercury vapor and oral exposure to mercuric chloride, mercuric sulfide, or methylmercury. There is limited evidence of moderate-to-severe liver damage following inhalation exposure to mercury vapor at high acute-duration concentrations or repeated exposure to lower concentrations. Available data do not indicate that the liver is a sensitive target of toxicity following oral exposure to inorganic mercury salts or organic mercury. There is no evidence of histopathological damage following oral exposure, and very limited evidence of

mild hepatic effects (altered clinical chemistry and serum lipids; altered lipid profiles; decreased liver weight).

The following summarizes results of epidemiological and animal studies on hepatic outcomes.

- ***Elemental mercury***
  - *Epidemiology studies*
    - A single study in dental workers found a positive association between mercury biomarkers and LDL cholesterol, but not for total cholesterol, high-density lipoprotein (HDL) cholesterol, or triglycerides.
  - *Animal studies*
    - Limited data indicate that acute-duration exposure to high concentrations or continuous exposure to low concentrations may cause moderate-to-severe liver damage.
- ***Inorganic mercury salts***
  - *Epidemiology studies*
    - No epidemiological studies evaluating associations between exposure to inorganic mercury salts and hepatic effects were identified.
  - *Animal studies*
    - Hepatic lesions have not been reported in rodents following exposure to mercuric chloride.
    - Evidence of mild hepatic effects in rodents following exposure to mercuric chloride (altered serum chemistry, decreased liver weight) is limited and inconsistent, especially at low oral doses.
    - One study found no adverse hepatic effects in mice exposed to extremely high levels of mercuric sulfide.
- ***Organic mercury***
  - *Epidemiology studies*
    - No studies reporting mercury biomarkers and hepatic endpoints in populations with high fish diets were identified.
    - No adverse hepatic effects were observed in a long-term follow-up study of the Minamata population; biomarkers were not reported.
  - *Animal studies*
    - Hepatic lesions have not been reported in cats or rodents following exposure to methylmercury.

  - Evidence of mild hepatic effects in rodents is very limited following exposure to methylmercury; one study reported decreased liver weight and one study reported a duration-related increase in serum cholesterol following exposure to moderate-to-high doses of methylmercury.
- ***Predominant mercury form unknown (general populations)***
  - Studies evaluating associations between mercury biomarkers and serum liver enzyme activities have inconsistent results. For studies showing positive associations between biomarkers and liver enzymes, the magnitude of changes was small and did not represent toxicologically significant increases.
  - Studies in adults found positive associations between BHg and total cholesterol and hypercholesterolemia, providing consistent evidence of a relationship between mercury and increased cholesterol.
  - In children and adolescents, positive associations were observed between BHg or SHg and total cholesterol and borderline hypercholesterolemia.

Confounding Factors. Numerous factors that can affect measures of hepatic function may also be associated with mercury exposure status. These include age, obesity, family history of liver disease, alcohol use, smoking, exposure to other chemicals, concurrent disease, and drug use, including prescription drugs and over-the-counter medications.

Elemental Mercury—Epidemiological Studies. A single study evaluated associations between mercury biomarkers and lipid levels in a population of 386 dental workers in the United States (Xu et al. 2023a); geometric mean BHg, UHg, and HHg levels were 3.64 µg/L, 0.25 µg/L, and 0.60 µg/g respectively. A positive association was observed between UHg and LDL cholesterol, but not for BHg or HHg. No associations were observed between mercury biomarkers and total cholesterol, HDL cholesterol, or triglycerides.

Elemental Mercury—Animal Studies. Serious liver effects have been noted in a two animal studies. Extensive hepatocyte degeneration was reported in female rats continuously exposed to 1 mg Hg/m^3 for 45 days (Yahyazedeh et al. 2017). Additional histopathological findings included enlarged blood vessels, dilated sinusoids, and increased perivascular connective tissue. Stereology showed increased liver volume in the sinusoids and decreased volume of the parenchyma. The numerical density and total number of hepatocytes were significantly decreased, but the mean numerical density and total number of binucleated hepatocytes were significantly elevated. The nuclear diameter of hepatocytes was

significantly decreased. A series of studies in rabbits reported hepatic effects ranging from moderate pathological changes to severe liver necrosis following exposure to 28.8 mg Hg/m^3 for 6–30 hours or 6 mg Hg/m^3 for 6–11 weeks (7 hours/day, 5 days/week) (Ashe et al. 1953). Mild pathological changes were observed at shorter exposure durations and following intermittent exposure to 3 mg Hg/m^3 for up to 12 weeks (Ashe et al. 1953). The usefulness of these results is limited because of small animal numbers per timepoint, lack of controls (in acute-duration studies), lack of incidence data, lack of details regarding observed pathological changes, and unclear distinction between primary and secondary effects (i.e., pathological changes secondary to induced shock). Due to lack of controls, acute-duration studies are not presented in the LSE table.

In other studies, no changes in liver histology were reported in rats following exposure to 8 mg Hg/m^3 for 2 hours/day for up to 10 days (Morgan et al. 2002) or 3 mg Hg/m^3 for 12–42 weeks (5 days/week; 3 hours/day) (Kishi et al. 1978).

Inorganic Mercury Salts—Animal Studies. Available data do not indicate that the liver is a sensitive target of toxicity in rodents orally exposed to mercuric chloride or sulfide.

No changes in liver weight or histology were observed in rats exposed to mercuric chloride at acute-duration doses up to 9.24 mg Hg/kg/day (Lecavalier et al. 1994) or intermediate- or chronic-duration doses up to 4 mg Hg/kg/day (NTP 1993), or in mice at intermediate- or chronic-duration doses up to 15 or 7.4 mg Hg/kg/day, respectively (NTP 1993). However, decreased liver weight has been reported following oral exposure to mercuric chloride in one rat and one mouse study. In a 2-generation study in rats, relative liver weights were decreased >20% in F0 females exposed to gavage doses ≥0.55 mg Hg/kg/day; no changes in liver weight were observed in F1 females at doses up to 1.98 mg Hg/kg/day or F0 or F1 males at doses up to 1.31 mg Hg/kg/day (Atkinson et al. 2001). In mice, absolute liver weight was decreased by 14 and 16% following exposure to 2 or 11 mg Hg/kg/day, respectively, as mercuric chloride in drinking water for 7 weeks (Dieter et al. 1983). Relative organ weights were not reported, but body weight effects were only noted at 11 mg Hg/kg/day. In 16-day gavage studies that only evaluated liver weight, no changes were observed in rats or mice at intermediate-duration doses up to 15 mg Hg/kg/day and 30 mg Hg/kg/day, respectively (NTP 1993). Similarly, no exposure-related changes in maternal liver weights were observed in rats exposed to doses up to 0.094 mg Hg/kg/day throughout gestation and lactation (Galiciolli et al. 2022). Due to lack of organ weight findings, these studies were not included as NOAELs in the LSE table (inadequate hepatic endpoint evaluation).

Altered hepatic clinical chemistry values (alkaline phosphatase [ALP], aspartate aminotransferase [AST], lactate dehydrogenase [LDH], cholinesterase) have been reported in rodents in some oral exposure studies, generally at high doses (Table 2-18). No changes in serum alanine aminotransferase (ALT), acid phosphatase, sorbitol dehydrogenase, and/or bilirubin were observed in studies included in Table 2-18. Acute-duration exposure to gavage doses up to 9.24 mg Hg/kg/day was not associated with adverse changes in serum chemistry; however, a significant decrease in serum LDH (non-adverse direction) was observed at ≥7.4 mg Hg/kg/day (Lecavalier et al. 1994). Dietary exposure to doses ≥11.9 mg Hg/kg/day resulted in increased serum ALP and AST levels in rats; no changes were observed at ≤11.4 mg Hg/kg/day (Jonker et al. 1993). Some 30-day gavage studies in rats reported increased ALP at doses ranging from 0.3 to 1.5 mg Hg/kg/day, and increased AST at 1.5 mg Hg/kg/day (Raeeszadeh et al. 2021; Sabir et al. 2022). Another study reported increased ALP, AST, and LDH in Wistar rats exposed to 0.4 mg Hg/kg/day via an unspecified oral route for 6 months (Agrawal et al. 2014). However, no alterations in hepatic serum chemistry were observed at intermediate- or chronic-duration gavage doses up to 4 mg Hg/kg/day (NTP 1993). In mice, alterations in clinical chemistry are limited to increased serum cholinesterase levels in males exposed to drinking water doses ≥2 mg Hg/kg/day (Dieter et al. 1983). In other studies, no changes in hepatic clinical chemistry were observed at intermediate- or chronic-duration doses up to 15 or 7.4 mg Hg/kg/day, respectively (Khan et al. 2004; Kim et al. 2003; NTP 1993).

Table 2-18. Hepatic Clinical Chemistry in Rodents Orally Exposed to Mercuric Chloride

Species; duration	Dose (mg Hg/kg/day)	ALP[a]	AST[a]	LDH[a]	Cholinesterase[a]	Reference
Rat; 1 day	7.4–9.24	↔	↔	↓ (38–54)	–	Lecavalier et al. 1994
Rat; 28 days	5.8	↔	↔	–	–	Jonker et al. 1993
Rat; 28 days	6.1	↔	↔	–	–	Jonker et al. 1993
Rat; 28 days	11.4	↔	↔	–	–	Jonker et al. 1993
Rat; 28 days	11.9	↑ (21)	↔	–	–	Jonker et al. 1993
Rat; 28 days	20.9	↑ (28)	↑ (16)	–	–	Jonker et al. 1993
Rat; 28 days	23.6	↑ (22)	↑ (18)	–	–	Jonker et al. 1993
Rat; 30 days	1.5	↑ (48)	↑ (125)	–	–	Raeeszadeh et al. 2021

Table 2-18. Hepatic Clinical Chemistry in Rodents Orally Exposed to Mercuric Chloride

Species; duration	Dose (mg Hg/kg/day)	ALP[a]	AST[a]	LDH[a]	Cholinesterase[a]	Reference
Rat; 30 days	0.3	↑ (80)	–	–	–	Sabir et al. 2022
Rat; 182 days	0.230	↔	↔	↔	↔	NTP 1993
Rat; 182 days	0.4	↑ (40)	↑ (56)	↑ (21)	–	Agrawal et al. 2014
Rat: 182 days	0.462–4	↔	↔	↔	↔	NTP 1993
Rat: 450 days	1.8–4	↔	–	–	↔	NTP 1993
Mouse; 14 days	0.06–4.81	–	↔	–	–	Kim et al. 2003
Mouse; 49 days	0.4	–	↔	↔	↔	Dieter et al. 1983
Mouse: 49 days	2	–	↔	↔	↑ (59)	Dieter et al. 1983
Mouse: 49 days	11	–	↔	↔	↑ (55)	Dieter et al. 1983
Mouse: 61–79 days	0.18–0.74	↔	↔	↔	–	Khan et al. 2004
Mouse; 182 days	0.923–15	↔	↔	–	–	NTP 1993
Mouse; 450 days	4–7.4	↔	–	–	↔	NTP 1993

[a]Numbers in ( ) are percent change compared to control, calculated from quantitative data.

↑ = increased; ↓ = decreased; ↔ = no change; – = not assessed; ALP = alkaline phosphatase; AST = aspartate aminotransferase; LDH = lactate dehydrogenase

Two intermediate-duration dietary studies evaluated serum lipids in wild-type and spontaneously hypertensive Wistar rats exposed to mercuric chloride (Takahashi et al. 2000a, 2000b). In spontaneously hypertensive rats, serum HDL and triglycerides were decreased in a dose-related manner at all tested doses (≥0.07 mg Hg/kg/day); however, HDL was not decreased in wild-type rats until doses of 1.7 mg Hg/kg/day and triglycerides were unaffected. No exposure-related changes in total cholesterol or LDL were observed in spontaneously hypertensive or wild-type rats at doses up to 2.2 or 1.7 mg Hg/kg/day (Takahashi et al. 2000a, 2000b). In other studies, no changes in total cholesterol were observed in rats at acute-duration gavage doses up to 9.24 mg Hg/kg/day (Lecavalier et al. 1994), or in mice at intermediate-duration water or gavage doses up to 11 or 0.74 mg Hg/kg/day, respectively (Dieter et al. 1983; Khan et al. 2004).

No liver histopathology was reported in rats exposed to 0.3 mg Hg/kg/day mercuric chloride for 30 days (Sabir et al. 2022), but hepatic necrosis, hemorrhage, and inflammatory cell inflammation were observed in rats exposed to 1.5 mg Hg/kg/day of mercuric chloride for 30 days (Raeeszadeh et al. 2021). No changes in hepatic clinical chemistry, weight, or histology were observed in mice exposed to mercuric sulfide at gavage doses up to 1,700 mg Hg/kg/day for 4 weeks (Son et al. 2010).

Organic Mercury—Epidemiological Studies. No studies evaluating hepatic effects in populations with high fish diets and reporting exposures based on mercury biomarkers were identified. A cross-sectional screening survey of the Minamata population (n=1,406) did not find an increase in the prevalence of liver disease or abnormal findings on ultrasonographic examinations; no mercury biomarkers were reported (Futatsuka et al. 1992).

Organic Mercury—Animal Studies. Available data do not indicate that the liver is a sensitive target of toxicity in rodents orally exposed to methylmercury. No changes in liver histology were observed in mice or cats at intermediate-duration doses up to 9.5 or 0.176 mg Hg/kg/day, respectively (Charbonneau et al. 1976; MacDonald and Harbison 1977), or in rats, mice, or cats at chronic-duration doses up to 0.18, 0.724, or 0.074 mg Hg/kg/day, respectively (Charbonneau et al. 1976; Hirano et al. 1986; Mitsumori et al. 1990; Verschuuren et al. 1976). One study in rats reports a 20% decrease in relative liver weight following exposure to 0.879 mg Hg/kg/day for 28 days (Wildemann et al. 2015a). No changes in liver weight were observed in rats or mice at acute-duration doses up to 2.8 and 9.99 mg Hg/kg/day, respectively or intermediate-duration doses up to 0.216 or 0.77 mg Hg/kg/day, respectively (Belles et al. 2002; Fossato da Silva et al. 2011; Ilback 1991; Wildemann et al. 2015a, 2015b). Studies evaluating liver weight in the absence of histology or clinical chemistry were not included in the LSE table due to inadequate endpoint evaluation.

Few studies have evaluated serum lipids in mice following acute- or intermediate-duration exposure; however, no other hepatic endpoints were evaluated (Moreira et al. 2012; Nascimento et al. 2022; Silva et al. 2021). A study in C57BL/6 mice reported increased total cholesterol (by ~30%) and non-HDL cholesterol (by ~40%), but no difference in HDL cholesterol, at 2.7 mg Hg/kg/day for 15 days (Silva et al. 2021). Total cholesterol and triacylglycerol levels were increased by approximately 40 and 150%, respectively, in C57BL/6 mice exposed to 0.21 mg Hg/kg/day for 30 days (Nascimento et al. 2022). In the Moreira et al. (2012) study, total cholesterol was increased approximately 40 and 80% in C57BL/6 mice after exposure to 5.6 mg Hg/kg/day for 14 or 21 days; no changes in total cholesterol were observed after a 7-day exposure, and no changes in HDL, non-HDL, or triglycerides were observed at any time

point. In Swiss mice, total cholesterol, HDL, non-HDL, and triglyceride levels were all increased by approximately 110, 135, 110, and 90%, respectively, following exposure to 5.6 mg Hg/kg/day for 28 days.

Predominant Mercury Form Unknown (General Populations). Several studies have evaluated associations between mercury exposure and hepatic effects in general populations. Outcomes evaluated include serum liver enzymes, serum lipid profiles, and hepatic diseases. In general, results show positive associations between mercury biomarkers and increased liver enzymes (ALT, AST, and gamma-glutamyltransferase [GGT]) and cholesterol. Two studies also examined associations between biomarkers and liver disease (Chung et al. 2020; Yang et al. 2021).

Serum hepatic enzymes. Studies examining potential associations between mercury exposure and serum hepatic enzymes are summarized in Table 2-19. Most studies examined large populations of adults using data national surveys (NHANES, KNHANES, Korean National Environmental Health Survey [KoNEHS]), with 2,953–17,137 participants; a few other studies examined smaller populations (≤550). Two studies were conducted in adolescents using NHANES data (Chen et al. 2019b; Yang et al. 2023) and a longitudinal birth cohort study examined associations between maternal BHg and serum hepatic enzymes (Stratakis et al. 2021). Total BHg concentrations ranged from 0.7 µg/L (mean) in NHANES studies of adults and adolescents (Li et al. 2023; Yang et al. 2023) to 4.33 µg/L (geometric mean at baseline) in a Korean population of adults (Choi et al. 2017). Results of associations between BHg and serum liver enzymes were inconsistent, although more studies found positive associations between BHg and increased ALT, AST, and GGT, than no associations However, the magnitude of changes in serum liver enzymes was very small. For example, GGT was increased by 10.3% compared to baseline at the 5-year follow-up period (Choi et al. 2017). Lee et al. (2014) reported that ALT increased by 1.067 U/L and AST increased 0.676 U/L per doubling of BHg; mean ALT 22.23 U/L and mean AST 22.21 U/L. These changes represent a small increase per doubling of BHg and do not represent toxicologically significant increases; the study authors classified changes in ALT and AST as subclinical. Given the inconsistent results and the small magnitude of changes, the liver does not appear to be a sensitive organ for mercury in the general population.

Table 2-19. Results of Epidemiological Studies Evaluating Exposure to Mercury (Predominant Mercury Form Unknown) and Hepatic Serum Enzymes in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated		
		ALT	AST	GGT
Chen et al. 2019b Cross-sectional; 6,389 adolescents, ages 12–17 years (NHANES 1999–2014)	BHg mean: 0.73 µg/L	↑ (BHg)	NR	NR
Choi et al. 2017 Longitudinal; 508 adults; biomarker and liver enzymes were assessed at baseline and at a 4-year follow-up (Korea)	BHg Gmean Baseline: 4.33 µg/L Follow-up: 4.08 µg/L	↔ (BHg)	↔ (BHg)	↑ (BHg)
Chung et al. 2023 Cross-sectional; 3,712 adults, 1,617 men and 2,095 women (KoNEHS)	BHg mean Men: 3.28 µg/L Women: 2.30 µg/L	↑ (BHg) men and women combined	↔ (BHg) men and women combined	NR
Kim et al. 2021a Cross-sectional; 2,953 adults (KoNEHS)	BHg quartiles Q1: 0.33–1.86 µg/L Q2: 1.86–2.81 µg/L Q3: 2.81–4.42 µg/L Q4: 4.43–125.49 µg/l UHg Q4: 0.62–8.70 µg/L	↑ (BHg, Q2) ↔ (UHg)	↑ (BHg, Q4) ↔ (UHg)	↑ (BHg, Q3) ↔ (UHg)
Lee et al. 2014 Cross-sectional; 6,689 adults (KNHANES)	BHg Gmean: 3.987 µg/L	↑ (BHg)	↑ (BHg)	NR
Lee et al. 2017a Longitudinal (panel); 550 elderly adults ≥60 years of age (Korea)	BHg Gmean: 2.78 µg/L Q4 men: ≥5.41 µg/L Q4 women: ≥3.53 µg/L	↑ (BHg, Q4) OR for abnormal ALT	↔ (BHg, Q4)	↔ (BHg, Q4)
Li et al. 2023 Cross-sectional: 15,328 adults (NHANES 2011–2018)	BHg median: 0.7 µg/L	↔ (BHg)	↑ (BHg)	↔ (BHg)
Lin et al. 2014a Cross-sectional; 3,769 adults (NHANES)	Median BHg (total): 0.94 µg/L BMeHg: 0.60 µg/L	↔ (BHg)	↔ (BHg)	↔ (BHg)
Moon et al. 2022 Cross-sectional: 3,740–3,745 adults (KoNEHS)	BHg median: 2.71 µg/l UHg median: 0.34 µg/L	↑ (BHg) ↑ (UHg)	↑ (BHg) ↔ (UHg)	↑ (BHg) ↑ (UHg)

Table 2-19. Results of Epidemiological Studies Evaluating Exposure to Mercury (Predominant Mercury Form Unknown) and Hepatic Serum Enzymes in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated		
		ALT	AST	GGT
Yang et al. 2021 Cross-sectional: 5,919 adults; 3,614 classified as non-obese and 2,305 classified as overweight (KoNEHS)	BHg Gmean: All: 1.15 µg/L Non-obese: 1.08 µg/L Overweight: 1.25 µg/L	↑ (BHg, all, non-obese, and overweight)	↑ (BHg, all, non-obese, and overweight)	↑ (BHg, all, non-obese, and overweight)
Yang et al. 2023 Cross-sectional; 1,143 children and adolescents 12–19 years of age, 565 males and 578 females (NHANES 2011–2016)	BHg mean: 0.7 µg/L	↔ (BHg) males ↑ (BHg) females	NR	NR
Zhou et al. 2022 Cross-sectional; 17,137 adults (NHANES 2007–2016)	BHg Gmean: 0.87 µg/L	↑ (BHg)	NR	NR
Studies based on prenatal exposure measurements				
Stratakis et al. 2021 Longitudinal birth cohort; 872 mother-child pairs; children assessed at 8 years of age (Europe)	Maternal BHg median: 2.0 µg/L	↑ (BHg, maternal)	↔ (BHg, maternal)	↑ (BHg, maternal)

↑ = positive association; ↔ = no association; ALT = alanine aminotransferase; AST = aspartate aminotransferase; BHg = blood mercury; BMeHg = blood methylmercury; GGT = gamma-glutamyltransferase; Gmean = geometric mean; KNHANES = Korean National Health and Nutrition Examination Survey; KoNEHS = Korean National Environmental Health Survey; NHANES = National Health and Nutrition Examination Survey; NR = not reported; OR = odds ratio; Q = quartile; UHg = urine mercury

Serum lipid profiles. Several recent cross-sectional studies of large general populations have evaluated associations between mercury biomarkers and dyslipidemia; studies are summarized in Table 2-20. Nearly all studies evaluated data from large national surveys, specifically NHANES, KNHANES, KoNEHS, and China National Human Biomonitoring (CHGBM). Population sizes in these studies range from 1,088 to 12,526 participants. Most studies were conducted in adult populations, although a few studies evaluated children and adolescents (Cho et al. 2020; Fan et al. 2017; Jin et al. 2021; Yang et al. 2023). Two studies evaluated populations with large age ranges. A study on an NHANES population had an age range of 0–80 years (Buhari et al. 2020) and a study on a Canadian population had an age range of 3–79 years. Most studies evaluated total cholesterol, hypercholesterolemia, LDL cholesterol, HDL cholesterol, and triglycerides; a few studies reported dyslipidemia as an outcome, without data on

specific lipid profiles. Biomarkers used to assess associations were BHg, SHg, UHg, and NHg. Total BHg concentrations ranged from the geometric mean of 0.35 µg/L (Sohn et al. 2020) to a 4th quartile range of 4.30–60.60 µg/L (Kim et al. 2022a).

Table 2-20. Results of Epidemiological Studies Evaluating Exposure to Mercury (Predominant Mercury Form Unknown) and Dyslipidemia in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Buhari et al. 2020 Cross-sectional; 19,591 participants ages 0–80 years of age (NHANES 2009–2012)	BHg mean: 1.42 µg/L T1 mean: 0.26 µg/L T2 mean: 0.68 µg/L T3 mean: 3.03 µg/L	Total cholesterol	↑ (BHg, T2)
		LDL	↔ (BHg)
		Triglycerides	↔ (BHg)
Bulka et al. 2019 Cross-Sectional; 1,088 adults (NHANES 2011–2014)	Gmeans, 2011–2012 BMeHg: 0.63 µg/L UHg: 18.9 ng/hour Gmeans, 2013–2014 BMeHg: 0.56 µg/L UHg: 16.8 ng/hour	High triglycerides	↔ (BMeHg) ↑ (UHg)
		Low HDL	↔ (BMeHg) ↑ (UHg)
Cakmak et al. 2023 Cross-sectional; 27,550 participants, ages 3–79 years (Canada)	BHg median: 0.57 µg/L	Total cholesterol	↑ (BHg)
		LDL	↑ (BHg)
		HDL	↑ (BHg)
		Triglycerides	↑ (BHg)
Cho et al. 2020 Cross-sectional; 1,890 adolescents (963 males and 927 females), ages 10–19 years (KNHANES)	BHg Gmean: 1.89 µg/L Males: 1.96 µg/L Females: 1.83 µg/L	Total cholesterol	↑ (BHg, M) ↔ (BHg, F)
		Hyper-LDL-cholesterolemia	↑ (BHg, M) ↔ (BHg, F)
		Total HDL	↔ (BHg, M, F)
		Hypo-HDL- cholesterolemia	↔ (BHg, M, F)
		Total triglycerides	↔ (BHg, M, F)
		Hypertriglyceridemia	↔ (BHg, M, F)
Fan et al. 2017 Cross-Sectional; 5,404 children and adolescents, ages 6–19 years (NHANES)	SHg mean: 0.65 µg/L	Total cholesterol	↑ (SHg, F, ages 6–12 years) ↑ (SHg, F, ages 13–19 years) ↑ (SHg, M, ages 13–19 years)
		LDL	↔ (SHg, all)
		HDL	↔ (SHg, all)
		Triglycerides	↔ (SHg, all)

Table 2-20. Results of Epidemiological Studies Evaluating Exposure to Mercury (Predominant Mercury Form Unknown) and Dyslipidemia in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Jin et al. 2021 Cross-sectional; 1,559 adolescents (806 males and 753 females), aged ages 10–18 years (KNHANES)	BHg Gmean: 1.88 µg/L	Borderline hypercholesterolemia	↑ (BHg)
		Borderline hyper-LDL-cholesterolemia	↔ (BHg)
Kang et al. 2021 Cross-sectional; 5,345 adults, 2,424 males and 2,921 females (KNHANES)	BHg stratifies as <2.75 and ≥2.75 µg/L	Dyslipidemia	↑ (BHg, all, M) ↔ (BHg, F)
Kim et al. 2022a Cross-sectional; 2,591 adults (KNHANES)	BHg quartiles Q1: 0.33–1.85 µg/L Q2: 1.86–2.77 µg/L Q3: 2.77–4.30 µg/L Q4: 4.30–60.60 µg/l UHg quartiles Q1: 0.01–0.23 µg/L Q2: 0.24–0.35 µg/L Q3: 0.36–0.64 µg/L Q4: 0.65–8.70 µg/L	Elevated total cholesterol	↑ (BHg, Q4) ↔ (UHg)
		Elevated LDL	↑ (BHg, Q2) ↔ (UHg)
		Elevated non-HDL	↑ (BHg, Q4) ↔ (UHg)
		Elevated triglycerides	↔ (BHg, UHg)
Lee et al. 2020a Cross-sectional; 6,454 adults (KNHANES)	BHg Gmean: 3.12 µg/L	Hyperlipidemia	↑ (BHg)
Liang et al. 2023 Cross-sectional; 12,526 adults (NHANES 2011–2020)	BHg median: 1.455 µg/L	Dyslipidemia[a]	↑ (BHg)
Park and Seo 2017 Cross-sectional; 232 adult males and 269 females; South Korea	NHg mean Males: 0.49 µg/g Females: 0.34 µg/g HSe: Low: ≤0.685 µg/g High: >0.685 µg/g	Hypercholesterolemia	↑ (NHg, low NSe) ↔ (NHg, high NSe)
		LDL-hypercholesterolemia	↑ (NHg, low NSe) ↔ (NHg, high NSe)
		HDH-hypocholesterolemia	↑ (NHg, low NSe) ↔ (NHg, high NSe)
		Hypertriglyceridemia	↔ (NHg, low NSe) ↔ (NHg, high NSe)

Table 2-20. Results of Epidemiological Studies Evaluating Exposure to Mercury (Predominant Mercury Form Unknown) and Dyslipidemia in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Sohn et al. 2020 Cross-sectional; 3,228 adults, 1,400 males and 1,828 females (KNHANES)	BHg Gmean All: 2.17 µg/L Males: 3.32 µg/L Females: 2.29 µg/l UHg Gmean All: 0.35 µg/L Males: 0.40 µg/L Females: 0.32 µg/L	Total cholesterol	↑ (BHg, M, F) ↑ (UHg, M) ↔ (UHg, F)
		LDL	↑ (BHg, M, F) ↑ (UHg, M, F)
		HDL	↑ (BHg, M) ↔ (BHg, F) ↔ (UHg, M, F)
		Triglycerides	↑ (BHg, M, F) ↑ (UHg, M, F)
Wang et al. 2023b Cross-sectional; 2,327 adults with hyperlipidemia and 966 without hyperlipidemia (NHANES 2007–2016)	UHg median: 0.383 µg/g Cr	Hyperlipidemia	↑ (UHg)
Wu et al. 2022 Cross-sectional; 10,780 adult participants in CNHBM (China)	BHg median: 1.18 µg/L	Triglycerides	↑ (BHg)
Yang et al. 2023 Cross-sectional; 1,143 children and adolescents 12–19 years of age, 565 males and 578 females (NHANES 2011–2016)	BHg mean: 0.7 µg/L	Total cholesterol	↑ (BHg)
		LDL	↑ (BHg)
		HDL	↔ (BHg)
		Triglycerides	↔ (BHg)

[a]Dyslipidemia defined as participants receiving any lipid-lowering medication, serum total cholesterol ≥200 mg/dL, and/or triglycerides ≥150 mg/dL, and/or LDL ≥130 mg/dL, and/or HDL <40 mg/dL in males, and/or HDL <50 mg/dL in females.

↑ = positive association; ↔ = no association; BHg = blood mercury; BMeHg = blood methylmercury; CNHBM = China National Human Biomonitoring; Cr = creatinine; F = females; Gmean = geometric mean; HDL = high-density lipoprotein; KNHANES = Korean National Health and Nutrition Examination Survey; LDL = low-density lipoprotein; M = males; NHANES = National Health and Nutrition Examination Survey; NHg = toenail mercury; NSe = toenail selenium; Q = quartile; SHg = serum mercury; T = tertile; UHg = urine mercury

Studies in adults found positive associations between BHg and total cholesterol and hypercholesterolemia (Table 2-20), providing consistent evidence of a relationship between mercury and increased cholesterol. Much less data are available for associations between UHg or NHg and total cholesterol, with inconsistent results. Most studies found positive associations between mercury biomarkers and LDL cholesterol, whereas inconsistent results were observed for HDL cholesterol and triglycerides. Bulka et al. (2019) is the only study evaluating associations between blood methylmercury and dyslipidemias. No associations

were observed between blood methylmercury and high triglycerides or low HDL cholesterol, but positive associations were observed for UHg. Park and Seo (2017) evaluated associations between NHg and dyslipidemias (hypercholesterolemia, LDL-hypercholesterolemia, HDL-hypocholesterolemia, and hypertriglyceridemia) and the potential modifying effect of selenium (measured in toenails) in a population of adults from Korea. Although the study authors stated that the study population had a high fish intake, no measurements were provided for BHg or HHg to compare exposures to biomarker levels reported in other populations with high fish diets that are reviewed in this profile (e.g., Faroe Islands or Seychelle Islands). Hypercholesterolemia and dyslipidemia were positively associated with NHg in participants with low, but not high, selenium. LDL-hypercholesterolemia was positively associated with NHg, and hair selenium did not affect the association. No associations were observed between NHg and HDL-hypocholesterolemia and hypertriglyceridemia in low- and high-selenium groups. In children and adolescents, positive associations were observed between BHg or SHg and total cholesterol and borderline hypercholesterolemia (Cho et al. 2020; Fan et al. 2017; Jin et al. 2021; Yang et al. 2023). Studies by Cho et al. (2020) and Yang et al. (2023) observed a positive association between BHg and LDL-cholesterol.

Liver disease. In addition to studies examining associations between mercury biomarkers and serum liver enzymes and plasma lipids, two cross-sectional studies evaluated associations between BHg levels and liver disease, including non-alcoholic fatty liver disease (NAFLD), hepatic stenosis, and hepatic fibrosis (Chung et al. 2020; Yang et al. 2021). Yang et al. (2021) found a positive association between BHg (mean: 1.15 µg/L) and NAFLD using KoNEHS data from 5,191 participants. The positive association was observed in non-obese participants (n=3,614; BHg geometric mean: 1.08 µg/L), but not for overweight participants (n=2,305; BHg geometric mean: 1.25 µg/L). In a population of 4,420 KNHANES participants (1,860 males and 2.560 females) with a mean BHg of 1.08 µg/L, a positive association was observed between BHg in men and women. No association was observed between BHg and hepatic fibrosis in men or women. Although both studies found positive associations between BHg and liver disease, data are inadequate to determine if there is a consistent relationship between mercury and liver disease.

Mechanisms of Action. General mechanisms of toxicity of mercury (reviewed in Section 2.21) are likely involved in the development of hepatic effects. These general mechanisms include increased ROS production and oxidative stress, degeneration of fatty acids, mitochondrial depolarization and ATP depletion, damage to hepatic cell membranes, and cell necrosis and death.

2.11 RENAL

Overview. The renal toxicity of mercury is well established. All forms of mercury are nephrotoxic, but inorganic forms appear to be more nephrotoxic than organic forms (Zalups 2000). Nephrotoxicity of mercury is characterized primarily by damage to the *pars recta* segment of the proximal tubule, with involvement of proximal convoluted tubules and distal tubule in severe toxicity (Berlin et al. 2015; Zalups and Diamond 2005). Damage to the *pars recta* segment of the proximal tubule is consistent with localized uptake of mercury in the renal cortex and outer stripe of the outer medulla (Section 3.1.2). In the proximal tubule, early changes include loss of the brush boarder membrane, resulting in urinary excretion of brush boarder enzymes, such as ALP and GGT. As damage to the proximal tubule becomes more severe and progresses to necrosis, intracellular enzymes, such as alanine aminopeptidase (AAP) and N-acetyl-β-D-glucosaminidase (NAG), are excreted in the urine. The glomerular basement membrane has also been shown to be a target of inorganic mercuric mercury in rabbits and some strains of rats (Druet et al. 1978; Roman-Franco et al. 1978; Sapin et al. 1977). The mechanism for mercury-induced glomerulonephritis in these animal models involves auto-immunity and deposition of immune complexes in the glomerular basement membrane. Although mercury has not been definitively shown to be a cause of glomerulonephritis in humans, were it to occur, the primary outcomes could include proteinuria and declines in glomerular filtration rate (GFR).

While it is established that mercury is nephrotoxic, results of epidemiological studies evaluating renal effects of mercury at occupational and environmental exposure levels are inconsistent with regard to markers of glomerular and tubular damage. There is some evidence that supports associations between elemental mercury exposure and adverse renal effects and between mercury exposure and renal effects in the general population; however, the kidney does not appear to be a sensitive target organ for mercury under these occupational and environmental exposure conditions. Epidemiological data are from studies evaluating associations between mercury and renal effects in workers exposed to elemental mercury, populations exposed to elemental mercury through dental amalgam fillings, and general populations exposed to unknown forms of mercury. Few studies have been conducted in populations exposed to mercury from high fish diets, presumably because the kidney is not a sensitive target organ for methylmercury at these environmental exposures. Although there are no epidemiological studies on populations exposed to inorganic mercury salts, case reports of accidental or intentional ingestion show severe renal damage from high-dose exposure. In this discussion, the following markers were interpreted to be indicative of changes in glomerular function: GFR; blood urea nitrogen (BUN), or serum urea nitrogen (SUN); serum creatinine and serum 2-microglobuin (β_2M); and urine protein and albumin. In

most studies in which GFR was assessed, GFR was estimated using equations relating GFR to serum creatinine and other factors that contribute to variance in GFR (e.g., body size, age, sex, race) (Levey et al. 2009). GFR estimated from these equations is referred to as eGFR to distinguish it from estimates based on measurements of clearance of GFR markers (e.g., creatinine, iothalamate). Decreases in GFR typically result in increases in BUN, SUN, serum creatinine, and serum β_2M. Increases in urinary excretion of protein or albumin is typically observed in association with impaired glomerular function (i.e., increased glomerular filtration of protein); however, impaired renal tubule processing of filtered protein can also contribute to proteinuria. Renal tubular damage was assessed from measurements of renal tubule cell proteins in urine, which are not typically released from renal tubule cells unless the cells are damaged. These proteins include AAP, ALP, glycosaminoglycans (GAG), NAG, and GGT. Renal tubular damage was assessed in some studies from measurements of urinary excretion of proteins that are typically removed from the glomerular filtrate unless tubular reabsorption of protein is disrupted. These include α_1-microglobulin (α_1M), β_2M, and retinol binding protein (RBP). A few studies have assessed serum uric acid, which can become elevated as a result of disruption of renal tubular transport of organic acids.

Nephrotoxicity of inorganic and organic mercury has been extensively studied in animal models (Berlin et al. 2015; Zalups and Diamond 2005). Inorganic mercuric mercury produces a lesion in the proximal tubule that is initially focused in the *pars recta*, with toxicity developing within 24 hours after a single dose of mercuric chloride. The rapid onset of this focal lesion has prompted use of mercuric chloride as a tool for studying structural and functional correlates to damage to the proximal tubule. As noted above, auto-immune glomerulonephritis has been observed in rabbits and some strains of rats following dosing with mercury chloride (Druet et al. 1978; Roman-Franco et al. 1978; Sapin et al. 1977).

The following summarizes results of epidemiological and animal studies on renal outcomes.

- ***Elemental mercury***
  - *Epidemiology studies*
    - Several studies in workers exposed to elemental mercury vapor provide some evidence of decrements in glomerular function and tubular injury, although conflicting results are reported.
    - Results of studies on populations with amalgam fillings (at lower exposures than mercury workers) also report some evidence of decrements in glomerular function and tubular injury; however, results are not consistent.

- Elemental mercury appears to be associated with glomerular and tubular damage, but the kidney is not a sensitive target for elemental mercury at exposure levels in these studies.
- *Animal studies*
  - Available studies indicate dose- and duration-dependent increases in the occurrence and severity of renal effects in animals, although some studies are limited based on lack of quantitative data and/or inadequate description of pathological lesions.
  - One study in maternal rats suggests impaired renal function following inhalation exposure based on urinalysis parameters.

- ***Inorganic mercuric salts***
  - *Epidemiology studies*
    - No epidemiological studies evaluating associations between exposure to inorganic mercury salts and renal effects were identified.
    - Severe renal damage has been reported in case studies of accidental or intentional ingestion of high doses of inorganic mercury salts.
  - *Animal studies*
    - There is consistent evidence of dose- and duration-dependent increases in the occurrence and severity of renal effects in animals.
- ***Organic mercury***
  - *Epidemiology studies*
    - Little information is available on effects of methylmercury exposure in populations with high fish diets.
    - Minamata disease is associated with renal dysfunction.
    - Limited information suggests that the kidney is not a highly sensitive target for methylmercury, even in populations with very high methylmercury exposures from fish.
  - *Animal studies*
    - Available studies indicate dose-dependent increases in the occurrence and severity of renal effects in animals, although some studies are limited based on lack of quantitative data.
    - Impaired renal function was reported in one study in mice at lethal/near-lethal acute-duration oral doses.
- ***Predominant mercury form unknown (general populations)***
    - Studies indicate that mercury exposure of the general population may be associated with glomerular and tubular damage, but results are inconsistent.

Confounding Factors. Inconsistencies in the reported outcomes for renal effects across studies may derive from several causes, including failure to account for confounding factors. Various factors that can affect kidney function may also be associated with mercury exposure status, including age, underlying diseases (e.g., hypertension), and concomitant exposure to other nephrotoxicants (e.g., lead, cadmium). Kidney function is also important for elimination of mercury since mercuric mercury is excreted in urine (Section 3.1.4). Decreased GFR or impaired renal tubular transport could decrease clearance of mercury and contribute to correlations between renal GFR or indicators of tubular damage and BH. This is an example of reverse causation, in which impaired renal function results in higher BHg levels due to decreased clearance.

In epidemiological studies in which GFR appears to have been severely depressed, reverse causation (lower mercury clearance contributing to higher mercury body burden) could be a substantial complication in interpreting causal relationships from statistical associations between BHg and GFR. Studies that evaluate associations between UHg and urinary renal outcome markers typically adjust the urinary concentrations relative to creatinine (e.g., μg Hg/g creatinine; mg albumin/g creatinine). This adjustment reduces autocorrelation resulting from interindividual variation in urine flow rate (L/day) similarly affecting the concentrations of mercury and the renal outcome marker (Diamond 1988). Autocorrelation would tend to strengthen the observed association between UHg and the urinary renal outcome marker.

Elemental Mercury—Epidemiological Studies. Studies evaluating effects of elemental mercury on renal function include cross-sectional and retrospective studies in workers, and cross-sectional studies, survey studies, and clinical trials in participants with amalgam fillings; studies are summarized in Table 2-21. Several of the studies summarized in Table 2-21 are of workers who participated in artisanal gold mining where exposure to elemental mercury would have occurred. However, these workers also may have been exposed to methylmercury formed from oxidation of elemental mercury released into the local environment. Most studies evaluated effects by comparison of exposed versus control groups. Based on UHg (the main biomarker in most studies), exposure of workers was greater than nonoccupational exposure from amalgam fillings. For example, the highest UHg in workers (23.7 μg/g creatinine) (Boogaard et al. 1996) is approximately 10-fold greater than the highest UHg in nonoccupational amalgam studies (2.94 μg/g creatinine) (Al-Saleh et al. 2013). In general, population sizes in worker studies (range 40–291) were smaller than in nonoccupational amalgam studies (range 46–801).

Table 2-21. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Renal Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Workers			
Afrifa et al. 2017 Cross-sectional; 61 male gold miners and 49 controls (Ghana)	BHg mean Workers: 18.37 µg/L Controls: 2.90 µg/L	eGFR	↓ (BHg)
		Urine protein	↑ (BHg)
		Microalbuminuria	↑ (BHg)
		Serum creatinine	↑ (BHg)
Boogaard et al. 1996 Cross-sectional; male natural gas workers, 18 high exposure, 22 low exposure, and 19 controls (The Netherlands)	UHg mean High: 23.7 µg/g Cr Low: 4.1 µg/g Cr Controls: 2.4 µg/g Cr	Urine albumin	↔ (UHg, high versus low and controls)
		Urine total protein	↔ (UHg, high versus low and controls)
		Urine NAG	↑ (UHg, high versus low and controls)
		Urine β_2M	↑ (UHg, high versus low)
Cardenas et al. 1993 Cross-sectional; male chloralkali workers, 44 workers and 49 controls (Belgium)	UHg Gmean Workers: 21.9 µg/g Cr Controls: 1.6 µg/g Cr	Serum creatinine	↓ (UHg, workers versus controls)
		Urine albumin	↔ (UHg, workers versus Ellingsen controls)
		Urine protein	↔ (UHg, workers versus controls)
		Urine β_2M	↓ (UHg, workers versus controls)
		Urine NAG	↔ (UHg, workers versus controls)
		Urine GAG	↓ (UHg, workers versus controls)
		Urine BBA[a]	↑ (UHg, workers versus controls)
		Urine BB50[a]	↑ (UHg, workers versus controls)
		Urine HF5[a]	↑ (UHg, workers versus controls)
Ellingsen et al. 2000a Cross-sectional; 47 chloralkali workers and 47 controls (Norway)	UHg mean Workers: 10.5 µg/g Cr Controls: 2.3 µg/g Cr	Urine albumin	↔ (UHg, workers versus controls)
		Urine β_2M	↔ (UHg, workers versus controls)
		Urine NAG	↑ (UHg, workers versus controls)
		Urine AAP	↔ (UHg, workers versus controls)
		Urine ALP	↔ (UHg, workers versus controls)
		Urine GAG	↔ (UHg, workers versus controls)

Table 2-21. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Renal Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Franko et al. 2005 Cross-sectional; male mercury miners, 33 active miners, 20 retired miners, and 53 controls (Slovenia)	UHg mean All miners: 2.12 µg/g Cr Active: 2.50 µg/g Cr Retired: 1.42 µg/g Cr Controls: 1.36 µg/g Cr	Urine albumin	↑ (UHg, all miners versus controls)
		Urine NAG	↔ (UHg, all miners versus controls)
		Urine α_1M	↑ (UHg, all miners versus controls)
Frumkin et al. 2001 Retrospective cohort; males and females, 147 chloralkali workers, 132 controls (Georgia)	UHg mean Workers: 2.76 µg/g Cr Controls: 2.31 µg/g Cr	Serum creatinine	↔ (UHg, workers versus controls)
		Urine albumin	↔ (UHg, workers versus controls)
		Urine NAG	↔ (UHg, workers versus controls)
		Urine AAP	↔ (UHg, workers versus controls)
		Urine RBP	↔ (UHg, workers versus controls)
Jarosinska et al. 2008 Cross-sectional; 179 chloralkali workers (Italy, Poland, Sweden)	UHg median in workers Italy: 4.6 Poland (1): 6.0 Poland (2): 45.9 Sweden: 3.8	Urine NAG	↑ (UHg)
		Urine α_1M	↑ (UHg)
Kobal et al. 2004 Cross-sectional; 54 mercury miners and 58 controls (Slovenia)	UHg mean Miners: 2.1 µg/L Controls: 1.4 µg/L	Urine albumin	↑ (UHg, miners versus controls)
		Urine NAG	↔ (UHg, miners versus controls)
		Urine α_1M	↑ (UHg, miners versus controls)
Piikivi and Ruokonen 1989 Cross-sectional; 60 male chloralkali workers and 60 matched controls (Finland)	UHg mean: Workers: 17.9 µg/g Cr Controls: 2.1 µg/g Cr	Urine albumin	↔ (UHg, workers versus controls)
		Urine NAG	↔ (UHg, workers versus controls)
Rodriguez et al. 2017 Cross-sectional; 164 gold miners and 127 controls (Columbia)	UHg median Miners: 3.9 µg/g Cr Controls: 1.5 µg/g Cr BHg median Miners: 7.0 µg/L Controls: 2.5 µg/L	Blood Cr	↔ (UHg, miners versus controls)
		Cr clearance	↔ (UHg, miners versus controls)
		GFR	↑ (UHg, miners versus controls) ↔ (UHg, BHg, multivariable regression)
		Urine albumin	↔ (UHg, miners versus controls)
		Urine β_2M	↔ (UHg, miners versus controls)

Table 2-21. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Renal Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Amalgam fillings			
Al-Saleh et al. 2012 Survey; 106 children with amalgam fillings and 76 children without amalgam fillings (Saudi Arabia)	UHg median Amalgam: 2.94 µg/g Cr No amalgam: 2.42 µg/g Cr	Urine NAG	↑ (UHg)
Barregard et al. 2008 Randomized clinical trial; 534 children, 267 receiving amalgam fillings and 267 receiving resin fillings over 5 years (Boston, Massachusetts)	HHg mean Amalgam: 0.4 µg/g No amalgam: 0.4 µg/g	Urine albumin	↔ (HHg, amalgam versus no amalgam)
		Microalbuminuria	↑ (HHg, amalgam versus no amalgam)
		Urine NAG	↔ (HHg, amalgam versus no amalgam)
		Urine α_1M	↔ (HHg, amalgam versus no amalgam)
		Urine GGT	↔ (HHg, amalgam versus no amalgam)
Eti et al. 1995 Cross-sectional; 100 adults, 66 with amalgam fillings and 34 without amalgam fillings (New York, New York)	UHg median Amalgam: 1 µg/L No amalgam: 0 µg/L	Urine NAG	↑ (UHg, amalgam versus no amalgam)
Herrstrom et al. 1995 Cross-sectional; 23 men with amalgam fillings and 23 men without amalgam fillings	UHg median Amalgam: 0.32 µg/g Cr No amalgam: 0.17 µg/g Cr	Urine albumin	↔ (UHg, amalgam versus no amalgam)
		Urine Cr	↔ (UHg, amalgam versus no amalgam)
		Urine NAG	↔ (UHg, amalgam versus no amalgam)
		Urine α_1M	↔ (UHg, amalgam versus no amalgam)
Mortada et al. 2002 Cross-sectional; 101 adults with amalgam fillings and 52 adults without amalgam fillings (Egypt)	UHg mean Amalgam: 1.79 µg/g Cr No amalgam: 0.48 µg/g Cr	Serum Cr	↔ (UHg, amalgam versus no amalgam)
		Serum β_2M	↔ (UHg, amalgam versus no amalgam)
		BUN	↔ (UHg, amalgam versus no amalgam)
		Urine albumin	↑ (UHg, amalgam versus no amalgam)
		Urine NAG	↑ (UHg, amalgam versus no amalgam)
		Urine β_2M	↔ (UHg, amalgam versus no amalgam)

Table 2-21. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Renal Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result
		Urine ALP	↔ (UHg, amalgam versus no amalgam)
		Urine GGT	↑ (UHg, amalgam versus no amalgam)
Woods et al. 2008 Randomized clinical trial 507 children, age 8–12 years (Portugal)	UHg mean Amalgam: 1.8 µg/g Cr No amalgam: 1.9 µg/g Cr	Urine albumin	↔ (amalgam versus no amalgam)
		Urine GGT-α	↔ (amalgam versus no amalgam)
		Urine GGT-π	↔ (amalgam versus no amalgam)
Ye et al. 2009 Cross-sectional; 403 children (ages 7–11 years), 198 with amalgam fillings and 205 without amalgam fillings (China)	UHg Gmean: Amalgam: 1.6 µg/g Cr No amalgam: 1.4 µg/g Cr	Urine albumin	↔ (UHg, amalgam versus no amalgam)
		Urine NAG	↔ (UHg, amalgam versus no amalgam)

[a]Brush border tubular antigens.

↑ = positive association; ↓ = inverse association; ↔ = no association; α_1M = α_1-microglobulin; β_2M = β_2-microglobulin; AAP = alanine aminopeptidase; ALP = alkaline phosphatase; BHg = blood mercury; BUN = blood urea nitrogen; Cr = creatinine; eGFR = estimated glomerular filtration rate; GAG = glycosaminoglycans; GFR = glomerular filtration rate; GGT = gamma-glutamyltransferase; Gmean = geometric mean; HHg = hair mercury; NAG = N-acetyl-β-D-glucosaminidase; RBP = retinol binding protein; UHg = urine mercury

Several studies in mercury workers provide some evidence of impaired glomerular function or renal tubular damage, although conflicting results are reported. For assessments of glomerular function, results are inconsistent. Some studies reported signs of impaired glomerular function, including decreased GFR, increased urine protein and albumin, microalbuminuria, decreased urine β_2M, and increased serum creatinine (Afrifa et al. 2017; Cardenas et al. 1993; Franko et al. 2005; Kobal et al. 2004), whereas other studies did not observe alterations in markers of glomerular function (Boogaard et al. 1996; Ellingsen et al. 2000a; Frumkin et al. 2001; Piikivi and Ruokonen 1989; Rodriguez et al. 2017). For studies showing altered glomerular function, the magnitude of changes is toxicologically significant. Afrifa et al. (2017) reported marked alterations in GFR markers in gold miners compared to controls; mean estimated GFR in exposed miners (BHg ≥5 µg/L) was 52.6% lower than the control group (BHg <5 µg/L), and mean urine protein and serum creatinine were higher by 68- and 2.3-fold, respectively. Given the very large differences in GFR between exposed and non-exposed subjects, reverse causation is a potential contributor to the relatively high age-adjusted ORs for low GFR reported in this study (263; 95% CL 48,

1,420). Urine albumin was higher by 1.33–1.6-fold in mercury miners than in controls (Franko et al. 2005; Kobal et al. 2004). Results of evaluations of occupational exposure and tubular damage are also inconsistent. Some studies showed altered urinary excretion of at least one marker of tubular damage, including increased urine NAG and α_1M, and decreased β_2M (Boogaard et al. 1996; Ellingsen et al. 2000a; Franko et al. 2005; Jarosinska et al. 2008; Kobal et al. 2004). In other studies, no changes indicative of tubular damage were observed (Franko et al. 2005; Frumkin et al. 2001; Piikivi and Ruokonen 1989; Woods et al. 2008). Although Cardenas et al. (1993) did not find elevated urinary markers of tubular damage, brush border tubular antigens in urine were increased, indicative of an immune response against the proximal tubule. Taken together, results suggest that studies of occupational exposures are inconsistent. Some studies have found associations between exposure to mercury and decreased GFR or tubular damage; however, these outcomes were not consistently observed across studies at similar exposures (based on exposure biomarkers). These inconsistencies may reflect differences in exposure levels as well as differences in study designs or the exposure markers utilized.

Several studies have examined associations between indicators of impaired glomerular function or tubular damage and exposures to elemental mercury from mercury amalgam restorations. Exposures to elemental mercury in these populations (UHg mean or median <3 μg/g creatinine) were lower than exposures observed in workers (UHg mean or median: 2–24 μg/g creatinine). A clinical trial reported microalbuminuria (urinary albumin >30 mg/g creatinine) in children in the amalgam group (Barregard et al. 2008) and a cross-sectional study reported increased urine albumin in adults with amalgam fillings compared to those with no amalgam fillings (Mortada et al. 2002). Other studies did not observe differences in glomerular function markers in children (Herrstrom et al. 1995) or adults (Ye et al. 2009) with amalgam fillings compared to no amalgam fillings. Urine NAG and/or GGT were increased in amalgam groups compared to no amalgam groups in children and adults (Al-Saleh et al. 2012; Eti et al. 1995; Mortada et al. 2002); however, other urinary markers of tubular damage (β_2M, ALP) were not increased (Mortada et al. 2002). In addition, other studies did not observe increased urinary excretion of any markers of tubular damage, including NAG, α_1M, GGT, and ALP (Barregard et al. 2006, 2008; Herrstrom et al. 1995; Ye et al. 2009). Together, these results do not provide consistent evidence of associations between low-level exposure to elemental mercury from amalgam fillings and renal effects.

Elemental Mercury—Animal Studies. Data following acute-duration exposure of rats to elemental mercury suggest that that occurrence and severity of renal effects are increased in a dose- and duration-dependent manner. A series of experiments evaluated maternal kidney effects in rats following exposure to elemental mercury vapor at concentrations up to 8 mg Hg/m^3 for 1, 5, or 10 days during pregnancy

(Morgan et al. 2002). After exposure to 1, 2, and 4 mg Hg/m^3 for 10 days (GDs 6–15), total urinary protein was increased 1.7-, 1.9-, and 1.8-fold, respectively, and urinary ALP activity was increased 7-, 2-, and 10-fold, respectively (urinalysis was not conducted at 8 mg Hg/m^3). Maternal relative kidney weights were significantly increased by >30% at ≥4 mg Hg/m^3; findings may be attributable in part to body weight effects (maternal weight gain decreases of 7–17% at ≥4 mg Hg/m^3). Absolute kidney weights were not reported. No histopathological lesions were observed in maternal kidneys at concentrations up to 8 mg Hg/m^3. No exposure-related renal effects were noted in dams similarly exposed for 1 day (GD 6) or 5 days (GDs 6–10). In nonpregnant rats, no exposure-related changes in kidney weight were observed in Sprague-Dawley rats following acute-duration exposure to concentrations up to 4 mg Hg/m^3 for 2 hours/day (Davis et al. 2001); however, renal function and histology were not evaluated in this study and a NOAEL for renal effects was therefore not included in the LSE table (inadequate endpoint evaluation).

Intermediate-duration studies in rats also provide evidence for dose- and duration-dependent increases in occurrence and severity of renal lesions, although no measures of renal function were conducted in intermediate-duration studies. In rats, slight degenerative changes (i.e., dense deposits in tubule cells and lysosomal inclusions) in the renal tubular epithelium were evident following exposure to 3 mg Hg/m^3 for 3 hours/day, 5 day/week for 12–42 weeks (Kishi et al. 1978). Akgul et al. (2016) also reported histopathological and stereological changes in renal glomeruli in male and female rats following exposure to 0.0487 mg Hg/m^3 for 45 days for an unspecified daily duration. Due to lack of exposure details, this study was not included in the LSE table, but findings are discussed below. Mercury-exposed rats showed reductions in the mean numerical density of glomeruli (-5%), total number of glomeruli (-7%), and mean volumes of glomeruli (-19%), cortex (-21%), and proximal tubule (-38%), compared to controls. Additionally, increased mean volume of medulla (29%) and distal tubule (250%) were seen in exposed rats, compared to controls. Histopathological findings, reported qualitatively only, included changes in vacuoles, pyknotic nuclei of glomerular and tubular cells, tubular necrosis, glomerular sclerosis, glomerular degeneration, and dilation of Bowman's space. In addition, kidneys of treated rats had cells with darkly stained cytoplasm, collecting tubules that were indistinguishable from cytoplasm borders, tubules with dead cells, and structures that were possible residue of dead cells. No pathological kidney changes were noted in control animals. Electron microscopy evaluations revealed pathological changes in the vacuole, nucleus, and mitochondria of distal tubule cells of exposed animals as well as cytoplasmic disorganization and damage to the podocytes, mesangial cells, glomerular cells, and basement membrane.

Inorganic Mercury Salts—Exposure of Humans. No epidemiological studies assessing associations between inorganic mercury salts and renal function were identified. As discussed in Section 2.1 (Introduction), exposure of humans to inorganic mercury salts in the environment is minimal relative to exposures to other forms of mercury and, as a result, it would be difficult to discern outcomes associated with exposure to inorganic mercury salts from outcomes contributed by exposures to other forms of mercury. However, the kidney, specifically the proximal tubule, is the primary target organ for inorganic mercury salts (Bhan and Sarkar 2005; Clarkson and Magos 2006; Clarkson et al. 2003). Case reports of acute-duration accidental or intentional ingestion of high doses of inorganic mercury salts show that renal damage can be very severe, including necrosis of the tubular epithelium and anuria, with complete collapse of renal function (Clarkson and Magos 2006; Magos and Clarkson 2006; Syversen and Kaur 2012).

Inorganic Mercury Salts—Animal Studies. The kidney is a clear target of toxicity for inorganic mercury. There is clear and consistent evidence of dose- and duration-dependent increases in occurrence and severity of renal effects in rats and mice following oral exposure to mercuric chloride.

Histopathological lesions have been reported in rats and mice following acute-, intermediate-, and chronic-duration oral exposure to mercuric chloride. In general, occurrence and severity of lesions appear to increase in a dose- and duration-related manner for specific exposure routes (e.g., gavage, diet, drinking water), beginning with mild histopathological damage after lower, shorter exposures (e.g., mild protein casts, cellular casts, interstitial sclerosis, tubular regeneration) and progressing to greater incidence and severity of renal nephropathy and necrosis with higher and/or longer durations (lesion types, incidence, and severity summarized in Tables 2-22 and 2-23). In both rats and mice, males appear more susceptible than females. In rats, renal lesions have been consistently observed following gavage exposure to ≥7.4 mg Hg/kg/day for 1–16 days (Dieter et al. 1992; Lecavalier et al. 1994; NTP 1993) or ≥0.923 mg Hg/kg/day for >180 days (Dieter et al. 1992; NTP 1993). One study qualitatively reported histopathological changes in the kidney in rats after gavage exposure to 0.015 mg Hg/kg/day for 28 days (Apaydin et al. 2016), but other repeat-dose studies did not confirm findings at doses <0.923 mg Hg/kg/day. Gavage studies in mice are less consistent, with renal lesions observed after single exposures ≥10 mg Hg/kg/day (Nielsen et al. 1991) but not until doses ≥30 mg Hg/kg/day following up to 12 doses over 16 days (NTP 1993). An acute-duration oral (not specified) study in mice reported renal lesions at 0.062 mg Hg/kg/day for 14 days (Jalili et al. 2020b). In longer-duration gavage studies, renal lesions were observed in mice at ≥4 mg Hg/kg/day (NTP 1993). In both rats and mice, renal lesions have been consistently observed following intermediate-duration dietary or drinking water exposure to >5 mg

Hg/kg/day. Most studies reported no renal effects at ≤2 mg Hg/kg/day (Boscolo et al. 1989; Carmignani et al. 1989; Dieter et al. 1983; Jonker et al. 1993; Khan et al. 2004), except for two studies that reported lesions at doses of 0.3 and 1.5 mg Hg/kg/day (Raeeszadeh et al. 2021; Sabir et al. 2022)

Table 2-22. Kidney Lesions in Rats[a] Orally Exposed to Mercuric Chloride

Duration; dose (mg Hg/kg/day)	Histology	Lesion details	Reference
Gavage studies			
1 day; dose: 7.4	↑ (F)	Mild protein casts, cellular casts, interstitial sclerosis[b]	Lecavalier et al. 1994
1 day; dose: 9.24	↑ (F)	Mild protein casts, cellular casts, interstitial sclerosis[b]	Lecavalier et al. 1994
16 days; dose: 0.923–4	↔ (M, F)		Dieter et al. 1992; NTP 1993
16 days; dose: 7.4	M: ↑ F: ↔	Acute renal necrosis M: 3/5 minimal, 2/5 mild (control 0/5)	Dieter et al. 1992; NTP 1993
16 days; dose: 15	↑ (M, F)	Acute renal necrosis M: 2/5 mild; 3/5 moderate F: 1/5 minimal; 4/5 mild (M, F control: 0/5)	Dieter et al. 1992; NTP 1993
28 days; dose: 0.015	↑ (NS)	Renal tubular dilation and glomerular lobulation[b]	Apaydin et al. 2016
30 days; dose: 0.3	↑ (NS)	Severe renal tubular degeneration and renal cell apoptosis	Sabir et al. 2022
30 days; dose: 1.5	↑ (M)	Tubular necrosis, interstitial nephritis, glomerular damage, and hyaline casts	Raeeszadeh et al. 2021
182 days; dose: 0.23–0.462	↔ (M, F)		Dieter et al. 1992; NTP 1993
182 days; dose: 0.923	M: ↑ F: ↔	Renal nephropathy M: 6/10 minimal; 4/10 mild (control 8/10 minimal)	Dieter et al. 1992; NTP 1993
182 days; dose: 1.8	M: ↑ F: ↔	Renal nephropathy M: 7/10 minimal; 3/10 mild (control 8/10 minimal)	Dieter et al. 1992; NTP 1993
182 days; dose: 4	↑ (M, F)	Renal nephropathy M: 6/10 minimal; 4/10 mild (control 8/10 minimal) F: 4/10 minimal (control 0/10)	Dieter et al. 1992; NTP 1993
450–730 days; dose: 1.8	M: ↑ F: ↔	M: Increased severity of nephropathy (32% increase in severity score at 15 months and 15% at 2 years)	Dieter et al. 1992; NTP 1993

Table 2-22. Kidney Lesions in Rats[a] Orally Exposed to Mercuric Chloride

Duration; dose (mg Hg/kg/day)	Histology	Lesion details	Reference
450–730 days; dose: 4	M: ↑ F: ↔	M: Increased severity of nephropathy (mild to marked; 68% increase in severity score at 15 months; 22% at 2 years)	Dieter et al. 1992; NTP 1993
Dietary studies			
28 days; dose: 0.61–0.76	↔ (M, F)		Jonker et al. 1993
28 days; dose: 5.1–5.5	M: ↑ F: ↔	Basophilic tubules in outer cortex M: 5/10 single-to-few; 5/10 several (control: 3/10 single-to-few)	Jonker et al. 1993
28 days; dose: 5.8–23.6	↑ (M, F)	Nephrosis and proteinaceous casts[b]	Jonker et al. 1993
Drinking water studies			
180 days; dose: 24	↑ (M)	Focal tubule degeneration, mesangial proliferative glomerulonephritis in 80% of glomeruli[b]	Carmignani et al. 1992
350 days; dose: 6	↑ (M)	Tubular degeneration and desquamation[b]	Boscolo et al. 1989; Carmignani et al. 1989
350 days; dose: 6	↑ (M)	Membranous glomerulonephritis in 30% of glomeruli and tubular degeneration[b]	Boscolo et al. 1989
350 days; dose: 24	↑ (M)	Membranous glomerulonephritis in 100% of glomeruli and tubular degeneration[b]	Boscolo et al. 1989

[a]Sexes evaluated are indicated in the results columns.
[b]Reported qualitatively only (incidence data not provided).

↑ = increase in histopathological lesions; ↔ = no change; F = female; M = male; NS = not specified

Table 2-23. Kidney Lesions in Mice[a] Orally Exposed to Mercuric Chloride

Duration; dose (mg Hg/kg/day)	Histology	Lesion details	Reference
Gavage studies			
1 day; dose: 5	↔ (F)		Nielsen et al. 1991
1 day; dose: 10	↑ (F)	Proximal tubule regeneration F: 10/10; severity grade 2/3 (control 0/10)	Nielsen et al. 1991

Table 2-23. Kidney Lesions in Mice[a] Orally Exposed to Mercuric Chloride

Duration; dose (mg Hg/kg/day)	Histology	Lesion details	Reference
1 day; dose: 20	↑ (F)	Proximal tubule degeneration F; 10/10; severity grade 2.5/3 Proximal tubule regeneration F: 10/10; severity grade 2.5/3 (control 0/10)	Nielsen et al. 1991
1 day; dose: 40	↑ (F)	Proximal tubule degeneration F; 10/10; severity grade 3/3 Proximal tubule regeneration F: 10/10; severity grade 0.25/3 (control 0/10)	Nielsen et al. 1991
2–4 days; Dose: 59	↑ (M, F)	Acute renal necrosis M: 5/5 (control 0/5) F: 5/5 (control 0/5)	NTP 1993
14 days; dose: 4–15	↔ (M, F)		NTP 1993
14 days; dose: 30	M: ↑ F: ↔	Acute renal necrosis M: 2/5 (control 0/5)	NTP 1993
61–79 days; dose: 0.18–0.74	↔ (M, F)		Khan et al. 2004
182 days; dose: 0.923–1.8	↔ (M, F)		NTP 1993
182 days; dose: 4–15	M: ↑ F: ↔	Dose-related increase in incidence and severity of cytoplasmic vacuolation in the renal tubule epithelium[b]	NTP 1993
450–730 days; dose: 4	↑ (M, F)	Renal nephropathy M: Severity grade increased 61% F: Severity grade increased by 117%; incidence increased, 43/50 versus 21/49	NTP 1993
450–730 days; dose: 7.4	↑ (M)	Renal nephropathy M: Severity grade increased 132% F: Severity grade increased by 164%; incidence increased, 42/50 versus 21/49	NTP 1993
Drinking water studies			
49 days; dose: 0.4–2	↔ (M)		Dieter et al. 1983
49 days; dose: 11	↑ (M)	Minimal renal nephropathy[b]	Dieter et al. 1983
112 days; dose: 4.0	↑ (M)	Tubular degeneration, necrosis, and hemorrhage	Li et al. 2019a
14 days; dose: 0.062 mg	↑ (M)	Tubular casts, intracellular vacuolization, vascular congestion, tubular detachment and dilation	Jalili et al. 2020b

[a]Sexes evaluated are indicated in the results columns.
[b]Reported qualitatively only (incidence data not provided).

↑ = increase in histopathological lesions; ↔ = no change; F = female; M = male; NS = not specified

Renal lesions associated with autoimmunity (e.g., IgG deposits in renal vessels) have been observed in mouse strains genetically susceptible to autoimmune disease following oral exposure to mercuric chloride. Due to the autoimmune nature of these lesions, these studies are discussed in Section 2.15. (Immunological) and are included in the LSE table as evidence of immune-complex disease.

Increased kidney weights have been consistently reported in rats following intermediate- and chronic-duration oral exposure to mercuric chloride. In general, findings are dose-dependent; however, duration of exposure does not seem to greatly impact magnitude of effect (Table 2-24). In male rats, significant dose-related increases in kidney weights were observed following repeated exposure to gavage doses ≥1.8 mg Hg/kg/day for 12 days (over 16 days) (Dieter et al. 1992; NTP 1993). Similarly, increased kidney weights were observed in intermediate- and chronic-duration gavage at doses of ≥0.23 and 1.8 mg Hg/kg/day, respectively (Atkinson et al. 2001;). Increased kidney weights were observed following dietary exposures at doses ≥5.1 mg Hg/kg/day for 28 days (Jonker et al. 1993) and at doses ≥0.06 mg Hg/kg/day following exposure for 35–147 days (Takahashi et al. 2000a, 2000b). For drinking water exposures, kidney weights were increased following exposure to doses ≥0.244 mg Hg/kg/day for 28 days (Wildemann et al. 2015a, 2016). No changes in kidney weight were observed in male rats at dietary doses of 0.61 mg Hg/kg/day for 28 days (Jonker et al. 1993).

The duration of exposure did not seem to affect the magnitude of kidney effects in female rats either. No change in kidney weight was observed following single gavage doses up to 0.24 mg Hg/kg/day (Lecavalier et al. 1994). In repeat-dose studies, significant dose-related increases in kidney weights were observed in female rats following gavage doses ≥4 mg Hg/kg/day for 12 days (over 16 days). Similarly, increased kidney weight was observed at all tested intermediate- and chronic-duration gavage doses in non-breeding female animals exposed to ≥0.23 and 1.8 mg Hg/kg/day, respectively. Dietary exposures at ≥0.76 mg Hg/kg/day in intermediate-duration studies also observed increased kidney weights (Dieter et al. 1992; Jonker et al. 1993; NTP 1993). Dose-related increases in kidney weights were observed in rat dams exposed to drinking water doses ≥0.019 mg Hg/kg/day throughout gestation and lactation (Galiciolli et al. 2022). However, in breeding females from a 2-generation study, no changes in kidney weight were observed in the F0 generation, but F1 females showed a significant increase in kidney weight at a gavage dose of 1.98 mg Hg/kg/day (Atkinson et al. 2001). Neither male nor female rats had significant changes in kidney weight at drinking water doses ≤0.037 mg Hg/kg/day (Oliveira et al. 2012; Wildemann et al. 2015a).

Table 2-24. Relative Kidney Weight and Clinical Chemistry in Rats Orally Exposed to Mercuric Chloride

Duration; dose (mg Hg/kg/day)	Relative kidney weight (sex) (percent change)[a]	BUN/ SUN	Serum creatinine	Serum uric acid	Reference
Gavage studies					
1 day; dose: 7.4–9.24	↔ (F)	–	–	↔ (F)	Lecavalier et al. 1994
16 days; dose: 0.923	↔ (F)	–	–	–	Dieter et al. 1992; NTP 1993
16 days; dose: 4	↑ (M) (19) ↑ (F) (38)	–	–	–	Dieter et al. 1992; NTP 1993
16 days; dose: 7.4	↑ (M) (35) ↑ (F) (34)	–	–	–	Dieter et al. 1992; NTP 1993
16 days; dose: 15	↑ (M, F) (43)	–	–	–	Dieter et al. 1992; NTP 1993
28 days; dose: 0.015	–	↑ (NS) (28)	↑ (NS) (17)	↑ (NS) (54)	Apaydin et al. 2016
79 days; dose: 0.55–1.11	↔ (F)	–	–	–	Atkinson et al. 2001
79 days; dose: 1.98	F0: ↔ (F) F1:↑ (F) (14)	–	–	–	Atkinson et al. 2001
81 days; dose: 0.37	F0: ↑ (M)(14) F1: ↔ (M)	–	–	–	Atkinson et al. 2001
81 days; dose: 0.74	F0: ↑ (M) (14) F1: ↔ (M)	–	–	–	Atkinson et al. 2001
81 days; dose: 1.31	F0: ↑ (M) (29) F1: ↔ (M)	–	–	–	Atkinson et al. 2001
182 days; dose: 0.23	↑ (M) (10) ↑ (F) (8)	↔ (M,F)	↔ (M) ↓ (F) (11)	–	Dieter et al. 1992; NTP 1993
182 days; dose: 0.462	↑ (M) (18) ↑ (F) (13)	–	–	–	Dieter et al. 1992; NTP 1993
182 days; dose: 0.923	↑ (M) (18) ↑ (F) (17)	↔ (M, F)	↔ (M) ↓ (F) (5)	–	Dieter et al. 1992; NTP 1993
182 days; dose: 1.8	↑ (M) (19) ↑ (F) (20)	–	–	–	Dieter et al. 1992; NTP 1993
182 days; dose: 4	↑ (M) (14) ↑ (F) (22)	↔ (M) ↓ (F) (11)	M: ↔ ↓ (F) (11[a])	–	Dieter et al. 1992; NTP 1993

Table 2-24. Relative Kidney Weight and Clinical Chemistry in Rats Orally Exposed to Mercuric Chloride

Duration; dose (mg Hg/kg/day)	Relative kidney weight (sex) (percent change)[a]	BUN/ SUN	Serum creatinine	Serum uric acid	Reference
450 days; Dose: 1.8	↑ (M) (20) ↑ (F) (18)	↔ (M, F)	–	–	Dieter et al. 1992; NTP 1993
450 days; Dose: 4	↑ M: (15) ↑ F: (18)	↔ (M, F)	–	–	Dieter et al. 1992; NTP 1993
Dietary studies					
28 days; dose: 0.61	↔ (M)	↔ (M)	↔ (M)	–	Jonker et al. 1993
28 days; dose: 0.76	↑ (F) (13)	↔ (F)	↔ (F)	–	Jonker et al. 1993
28 days; dose: 5.1–5.5	↑ (M) (17) ↑ (F) (20)	↔ (M, F)	↔ (M, F)	–	Jonker et al. 1993
28 days; dose: 5.8–6.1	M: ↑ (13) F: ↑ (16)	↔ (M, F)	↔ M, F)	–	Jonker et al. 1993
28 days; dose: 11.4–11.9	M: ↑ (17) F: ↑ (21)	↔ (M, F)	↔ (M, F)	–	Jonker et al. 1993
28 days; dose: 20.9–23.6	↑ (M) (25) ↑ (F) (22)	↔ (M, F)	↔ (M, F)	–	Jonker et al. 1993
35 days; dose: 0.07	↑ (M) (10)	–	–	–	Takahashi et al. 2000b
35 days; dose: 0.21	↑ (M) (14)	–	–	–	Takahashi et al. 2000b
35 days dose: 0.72	↑ (M) (16)	–	–	–	Takahashi et al. 2000b
35 days; dose: 2.2	↑ (M) (24)	–	–	–	Takahashi et al. 2000b
147 days dose: 0.06	↑ (M) (11)	↔ (M)	↔ (M)	–	Takahashi et al. 2000a
147 days dose: 0.17	↑ (M) (18)	↔ (M)	↔ (M)	–	Takahashi et al. 2000a
147 days dose: 0.51	↑ (M) (15)	↔ (M)	↔ (M)	–	Takahashi et al. 2000a
147 days dose: 1.7	↑ (M) (12)	↓ (M) (NS[b])	↔	–	Takahashi et al. 2000a
Drinking water studies					
21 days; dose: 0.0002–0.0301	↔	↔	–	–	Oliveira et al. 2012
28 days; dose: 0.005–0.01	↔ (M)	–	–	–	Wildemann et al. 2015a
42 days; dose: 0.019	↑ (F) (13)	↔ (F)	(F)	–	Galiciolli et al. 2022

Table 2-24. Relative Kidney Weight and Clinical Chemistry in Rats Orally Exposed to Mercuric Chloride

Duration; dose (mg Hg/kg/day)	Relative kidney weight (sex) (percent change)[a]	BUN/ SUN	Serum creatinine	Serum uric acid	Reference
28 days; dose: 0.021–0.037	↔ (M)	–	–	–	Wildemann et al. 2015a
42 days; dose: 0.094	↑ (F) (31)	↔ (F)	↔ (F)	–	Galiciolli et al. 2022
28 days; dose: 0.244–0.264	↑ (M) (15)	–	↔ (M)	–	Wildemann et al. 2015a
28 days; dose: 1.18	↑ (M) (26)	–	–	–	Wildemann et al. 2015a
28 days; dose: 2.07	↑ (M) (32)	–	–	–	Wildemann et al. 2015a
28 days; dose: 2.955	–	–	↔ (M)	–	Wildemann et al. 2016
28 days; dose: 5.91	↑ (M) (77[c])	–	–	–	Wildemann et al. 2015a

[a]Calculated from quantitative data or estimated from graphically reported data.
[b]Biological relevance of decreased BUN is unclear.
[c]Organ weight effects may be due in part to observed body weight loss; 100% mortality at this dose
↑ = increased; ↓ = decreased; ↔ = no change; – = not assessed; BUN = blood urea nitrogen; F = female; F0 = F0 generation; F1 = F1 generation; M = male; NS = not specified; SUN = serum urea nitrogen

Increased kidney weights have also been consistently reported in mice following acute-, intermediate-, and chronic-duration oral exposure to mercuric chloride. In general, findings are dose- and duration-dependent in male mice; however, findings in female mice are less consistent than effects in males (Table 2-25). In male BALB/c and B6C3F1 mice, significant dose-related increases in kidney weights were consistently observed following exposure to acute oral doses ≥1.39 mg Hg/kg/day, intermediate-duration oral doses ≥2 mg Hg/kg/day, and at all tested chronic-duration oral doses ≥4 mg Hg/kg/day (Dieter et al. 1983; Kim et al. 2003; NTP 1993). One study reported an unspecified increase in kidney weight in C57Bl/6 male mice at intermediate-duration gavage doses ≥0.18 mg Hg/kg/day (Khan et al. 2004)); however, no exposure-related changes were observed at intermediate-duration oral doses ≤1.8 mg Hg/kg/day in male B6C3F1 mice (Dieter et al. 1993; NTP 1993). In female B6C3F1 mice, elevated kidney weights were reported following 12 gavage exposures (over 16 days) or 15 months at doses ≥4 mg Hg/kg/day; however, kidney weights were not altered at doses up to 15 mg Hg/kg/day for 6 months (NTP 1993). In C57Bl/6 mice, elevated kidney weights were observed in females after exposure to doses ≥0.37 mg Hg/kg/day for 79 days (Khan et al. 2004).

Table 2-25. Kidney Weight and Clinical Chemistry in Mice[a] Orally Exposed to Mercuric Chloride

Duration; dose (mg Hg/kg/day)	Kidney weight[b,c]	BUN[b]	Reference
Gavage studies			
14 days; dose: 0.06–0.31	↔ (M)	–	Kim et al. 2003
14 days; dose: 1.39	↑ (M) (11)	–	Kim et al. 2003
14 days; dose: 4.81	↑ (M) (12)	–	Kim et al. 2003
16 days; dose: 4	↑ (M) (21) ↑ (F) (20)	–	NTP 1993
16 days; dose: 7.4	↑ (M) (25) ↑ (F) (27)	–	NTP 1993
16 days; dose: 15	↑ (M) (38) ↑ (F) (19)	–	NTP 1993
16 days; dose: 15	↑ (M) (31) ↑ (F) (29)	–	NTP 1993
61 days; dose: 0.18–0.74	↑ (NS)	–	Khan et al. 2004
79 days; dose: 0.18	↔ (F)	–	Khan et al. 2004
79 days; dose: 0.37–0.74	↑ (NS)	–	Khan et al. 2004
182 days; dose: 1.8	↔ (M, F)	↔ (M, F)	NTP 1993
182 days; dose: 4	↑ (M) (19[d]) ↔ (F)	↔	NTP 1993
182 days; dose: 7.4	↑ (M) (32) ↔ (F)	↔	NTP 1993
182 days; dose: 15	↑ (M) (46) ↔ (F)	↔	NTP 1993
450 days; dose: 4	↑ (M) (21[d]) ↑ (F) (24)	↔	NTP 1993
450 days; dose: 7.4	↑ (M) (39) ↑ (F) (28)	↓ (M) (20[e]) ↓ (F) (22[e])	NTP 1993
Drinking water studies			
49 days; dose: 0.4	↔ (M)	↔ (M)	Dieter et al. 1983
49 days; dose: 2	↑ (M) (19[f])	↓ (M) (13[e])	Dieter et al. 1983

Table 2-25. Kidney Weight and Clinical Chemistry in Mice[a] Orally Exposed to Mercuric Chloride

Duration; dose (mg Hg/kg/day)	Kidney weight[b,c]	BUN[b]	Reference
49 days; dose: 11	↑ (M) (23[f])	↓ (M) (13[e])	Dieter et al. 1983

[a]Sexes evaluated are indicated in the results columns.
[b]Numbers in ( ) are percent change compared to control, calculated from quantitative data.
[c]Relative-to-body organ weight, unless otherwise noted.
[d]Absolute kidney weight; change in relative kidney weight not significant at this dose.
[e]Biological relevance of decreased BUN is unclear.
[f]Absolute kidney weights; relative organ weights were not reported, body weights decreased at 11 mg Hg/kg/day.

↑ = increased; ↓ = decreased; ↔ = no change; – = not assessed; BUN = blood urea nitrogen; F = female; M = male; NS = not specified

No consistent alterations in renal clinical chemistry parameters were observed in rats or mice (Tables 2-24 and 2-25, respectively). One gavage study reported increased SUN, creatinine, and uric acid levels in rats (sex not specified) following exposure to 0.015 mg Hg/kg/day for 28 days (Apaydin et al. 2016). However, these findings have not been confirmed in other oral studies in rats or mice. No changes in serum uric acid were observed in rats following a single gavage exposure to doses up to 9.24 mg Hg/kg/day (Lecavalier et al. 1994). Increased levels of BUN were not observed in rats following intermediate- or chronic-duration oral doses up to 23.6 and 4 mg Hg/kg/day, respectively (Dieter et al. 1992; Galiciolli et al. 2022; Jonker et al. 1993; NTP 1993; Oliveira et al. 2012; Takahashi et al. 2000a), or in mice following intermediate- or chronic-duration oral doses up to 15 and 7.4 mg Hg/kg/day, respectively (Dieter et al. 1983; NTP 1993). Occasional observations of significantly decreased BUN are of unclear biological significance. Additionally, increases in serum creatinine were not observed in rats at intermediate-duration doses up to 23.6 mg Hg/kg/day (Dieter et al. 1992; Galiciolli et al. 2022; Jonker et al. 1993; NTP 1993; Takahashi et al. 2000a; Wildemann et al. 2016).

In general, most urinalysis findings in rats following oral exposure to mercuric chloride were inconsistent between studies and sexes (Table 2-26). Elevated urinary ALP was observed in male (but not female) rats after 12 gavage exposures (over 16 days) to 4 mg Hg/kg/day (Dieter et al. 1992; NTP 1993). Intermediate-duration studies show similar results for male rats exposed 2.2 mg Hg/kg/day in the diet for 84 days or ≥0.06 mg Hg/kg/day in the diet for 147 days (Takahashi et al. 2000a, 2000b). Urinary ALP was observed in female (but not male) rats at a gavage dose of 0.462 mg Hg/kg/day for 6 months or ≥1.8 mg Hg/kg/day for 15 months (Dieter et al. 1992; NTP 1993). Similarly, elevated urinary AST was observed in male (but not female) rats after 12 gavage exposures (over 16 days) to 4 mg Hg/kg/day, in

male (but not female) rats after exposure to 1.8 mg Hg/kg/day for 6 months, and in male and female rats after exposure to 4 mg Hg/kg/day for 15 months; no changes were observed in males or females exposed to 0.462 mg Hg/kg/day for 6 months (Dieter et al. 1992; NTP 1993). Occasional reports of elevated urinary creatinine, protein, amino acids, GGT, and LDH were reported; however, no exposure-related trends were observed within or across studies (Table 2-26). In a 28-day dietary study, urinary ketones were present in male rats exposed to ≥5.1 mg Hg/kg/day; ketones were not present in females at doses up to 23.6 mg Hg/kg/day (Jonker et al. 1993).

Table 2-26. Urinalysis in Rats[a] Orally Exposed to Mercuric Chloride

Duration; dose (mg Hg/kg/day)	Cr	TP	AA	ALP	AST	LDH	GGT	Reference
Gavage studies								
16 days; dose: 4	–	–	–	↑ (M) (80[b,c]) ↔ (F)	↑ (M) (83[c]) ↔ (F)	↔ (M,F)	(M, F)	Dieter et al. 1992; NTP 1993
182 days; dose: 0.462	–	–	–	↔ (M) ↑ (F) (570[c])	↔ (M, F)	↔ (M) ↑ (F) (70[c])	↔ (M) ↑ (F) (145[c])	Dieter et al. 1992; NTP 1993
450 days; dose: 1.8	↔ (M,F)	–	–	↔ (M) ↑ (F) (172[d])	↑ (M) (7[d]) F: 0	↔	↔	Dieter et al. 1992; NTP 1993
450 days; dose: 4	↔ (M.F)	–	–	↔ (M) ↑ (F) (61[d])	↑ (M) (29[c]) ↑ (F) (50[c])	↔	↓ (M) (52[c]) ↑ (F) (28[c])	Dieter et al. 1992; NTP 1993
Dietary studies								
28 days; dose: 0.61–23.6	–	↔ (M)	–	–	–	–	–	Jonker et al. 1993
35 days; dose: 0.07–2.2	–	↔ (M)	↔ (M)	–	–	–	–	Takahashi et al. 2000b
84 days; dose: 0.07	–	↔ (M)	↔ (M)	↔ (M)	–	–	↔ (M)	Takahashi et al. 2000b
84 days; dose: 0.21	–	↔ (M)	↑ (M) (40)	↔ (M)	–	–	↑ (M) (52[c])	Takahashi et al. 2000b
84 days; dose: 0.72	–	↔ (M)	↔ (M)	↔ (M)	–	–	↔ (M)	Takahashi et al. 2000b
84 days; dose: 2.2	–	↔ (M)	↑ (M) (63)	↑ (M) (100[c])	–	–	↔ (M)	Takahashi et al. 2000b
147 days; dose: 0.06	–	↔ (M)	–	↑ (M) (100)	–	–	–	Takahashi et al. 2000a
147 days; dose: 0.17	–	↔ (M)	–	↑ (M) (110[c])	–	–	–	Takahashi et al. 2000a

Table 2-26. Urinalysis in Rats[a] Orally Exposed to Mercuric Chloride

Duration; dose (mg Hg/kg/day)	Cr	TP	AA	ALP	AST	LDH	GGT	Reference
147 days; dose: 0.51	–	↔ (M)	–	↑ (M) (105[c])	–	–	–	Takahashi et al. 2000a
147 days; dose: 1.7	–	↑ (M) (90c)	–	↔ (M)	–	–	–	Takahashi et al. 2000a
Drinking water studies								
28 days; dose: 0.264	↑ (M) (86[c])	–	–	–	–	–	–	Wildemann et al. 2016
28 days; dose: 2.955	↔ (M)	–	–	–	–	–	–	Wildemann et al. 2016

[a]Sexes evaluated are indicated in the results columns.
[b]Numbers in ( ) are percent change compared to control, calculated from quantitative data.
[c]Percent change compared to control, estimated from graphically reported data.
[d]Percent change compared to control, calculated from quantitative data.

↑ = increased; ↓ = decreased; ↔ = no change; – = not assessed; AA = amino acids; ALP = alkaline phosphatase; AST = aspartate aminotransferase; Cr = creatinine; F = female; GGT = gamma-glutamyl transferase; LDH = lactate dehydrogenase; M = male; TP = total protein

Urinalysis was only conducted in mice exposed to mercuric chloride following gavage exposure for 15 months (NTP 1993); no consistent findings indicative of renal damage or impaired renal function were observed. Urinary ALP was significantly elevated by 63% in male mice at 4 mg Hg/kg/day; however, urinary ALP was not elevated in male mice at 7.4 mg Hg/kg/day or female mice at either dose. No exposure-related changes in urinary urea nitrogen, AST, LDH, or GGT were observed in males or females at either dose (NTP 1993).

Organic Mercury—Epidemiological Studies. Little information on renal effects of organic mercury in populations with high fish diets is available, presumably because most studies of high fish consumers have focused on evaluating outcomes in other more sensitive organ systems (e.g., neurological system and developing fetus). Anuria was reported following acute-duration ingestion of high doses of organic mercury (Magos and Clarkson 2006).

Studies of patients with Minamata disease provide some information regarding renal effects of chronic-duration methylmercury exposure, although studies did not provide data on associations with mercury exposure biomarkers. Reviews indicate that there is little clinical evidence of renal damage in the Minamata population, except some evidence of proteinuria and high urinary β_2M in severely affected patients (George 2011; Igata 1993). Increased urine levels of renal tubular epithelial antigen and β_2M

were observed in 19 Minamata disease patients, compared to 35 healthy controls, indicating that renal tubular function is associated with Minamata disease (Iesato et al. 1977). Follow-up studies of Minamata disease patients have examined long-term renal effects. In two studies following >1,000 patients with Minamata disease for at least 40 years, no effects were observed on creatinine clearance or the prevalence of renal disease (Futatsuka et al. 2000, 2005). In contrast, a study of 1,483 Minamata disease patients followed through 1981 reported increased mortality due to combined nephritis, nephrosis, and nephrotic syndrome, with SMRs (95% CI) of 3.23 (1.05, 7.54) in men and 4.74 (1.54, 11.07) in women (Tamashiro et al. 1985). Although limited data are available to evaluate associations between organic mercury and renal effects, the kidney appears to be less sensitive than other targets such as the nervous system and developing fetus.

Organic Mercury—Animal Studies. Nephrotoxicity has been observed in rats, mice, and rabbits following intermediate- and chronic-duration exposure. Impaired renal function was reported in one study in mice at lethal/near-lethal acute-duration doses.

Renal function was assessed in one acute-duration oral study in mice following gavage exposure to methylmercury. Impaired renal function (96–100% inhibition of phenolsulfonphthalein excretion) was observed in males 24 hours after a single exposure to ≥16 mg Hg/kg (Yasutake et al. 1991). In females, phenolsulfonphthalein excretion was decreased by approximately 60 and 90% at 32 and 40 mg Hg/kg, respectively. Renal impairment mostly occurred at doses associated with 67% mortality (≥16 mg Hg/kg in males and 40 mg Hg/kg in females); therefore, observed effects may be secondary to widespread toxicity rather than renal-specific damage. The study authors noted slight pathological changes in the kidney in rats exposed the methylmercury, but dose- and sex-specific data were not reported.

Damage to the renal proximal tubules and increased incidence and/or severity of chronic nephropathy have been observed in rats, mice, and rabbits following intermediate- and/or chronic-duration oral exposure to organic mercury (Table 2-27). In rats, chronic-duration drinking water exposure to phenylmercuric acetate resulted in increased severity of chronic renal nephrosis at ≥0.37 mg Hg/kg/day (Solecki et al. 1991). No exposure-related kidney lesions were observed in rats following dietary exposure to methylmercury at intermediate-duration doses up to 0.25 mg Hg/kg/day (Khera and Tabacova 1973) or chronic-duration doses up to 0.18 mg Hg/kg/day (Verschuuren et al. 1976). In mice, dietary exposure to methylmercury resulted in damage to the renal proximal tubules at intermediate-duration doses ≥0.627 mg Hg/kg/day and dose-related proximal tubule damage, urinary casts, pelvic dilatation, cystic kidney, and chronic nephropathy at chronic-duration doses ≥0.139 mg Hg/kg/day (Hirano et al.

1986; Mitsumori et al. 1990). Intermediate-duration drinking water exposure to methylmercury also resulted in damage to the proximal tubule at ≥5.6 mg Hg/kg/day (MacDonald and Harbison 1977; Moreira et al. 2012). Damage to the proximal renal tubule was also observed in rabbits following intermediate-duration exposure to methylmercury at dietary doses ≥1 mg Hg/kg/day (Koller et al. 1977). No exposure-related renal lesions were observed in cats following intermediate- or chronic-duration dietary exposure to methylmercury at doses up to 0.176 mg or 0.074 Hg/kg/day, respectively (Charbonneau et al. 1976).

Table 2-27. Kidney Lesions in Animals[a] Orally Exposed to Organic Mercury

Species; duration	Dose (mg Hg/kg/day)	Histology	Lesion details	Reference (compound)
Rat; 122 days	0.002–0.25	↔ (F)		Khera and Tabacova 1973 (MMC)
Rat; 721 days	0.37	↑ (M)	Chronic renal nephrosis >grade 2: 19/20 (control: 7/20)	Solecki et al. 1991 (PMA)
Rat; 721 days	3.7	↑ (M)	Chronic renal nephrosis >grade 2: 14/20 (control: 7/20)	Solecki et al. 1991 (PMA)
Rat; 730 days	0.006–0.18	↔ (M, F)		Verschuuren et al. 1976 (MMC)
Mouse; 21 days	5.6	↑ (M)	Glomerular shrinkage and tubular vacuolization[b]	Moreira et al. 2012 (MM)
Mouse; 182 days	0.0254–0.15	↔ (M, F)		Hirano et al. 1986 (MMC)
Mouse; 182 days	0.627	↑ (F)	Epithelial degeneration and regeneration of the renal proximal tubules[b]	Hirano et al. 1986 (MMC)
Mouse; 182 days	0.724	↑ (M)	Epithelial degeneration and regeneration of the renal proximal tubules; more severe than females[b]	Hirano et al. 1986 (MMC)
Mouse; 196 days	0.89	↔ (M)		MacDonald and Harbison 1977 (MMC)
Mouse; 196 days	9.5	↑ (M)	Slight degenerative changes in proximal tubular epithelial cells[b]	MacDonald and Harbison 1977 (MMC)
Mouse; 728 days	0.0254–0.115	↔ (M, F)		Hirano et al. 1986 (MMC)
Mouse; 728 days	0.0265–0.133	↔ (M, F)		Mitsumori et al. 1990 (MMC)
Mouse; 728 days	0.139	↑ (M)	Chronic nephropathy: 27/60 (control: 8/60)	Mitsumori et al. 1990 (MMC)

Table 2-27. Kidney Lesions in Animals[a] Orally Exposed to Organic Mercury

Species; duration	Dose (mg Hg/kg/day)	Histology	Lesion details	Reference (compound)
Mouse; 728 days	0.150	↑ (M)	Mild epithelial degeneration of the renal proximal tubules: 12/28 Increased incidence of urinary casts and pelvic dilatation[b]	Hirano et al. 1986 (MMC)
Mouse; 728 days	0.601	↑ (F)	Chronic nephropathy: 56/60 (control: 5/60)	Mitsumori et al. 1990 (MMC)
Mouse; 728 days	0.627	↑ (F)	Epithelial degeneration and regeneration of the renal proximal tubules: 19/60	Hirano et al. 1986 (MMC)
Mouse; 728 days	0.686	↑ (M)	Chronic nephropathy: 59/60 (control: 8/60)	Mitsumori et al. 1990 (MMC)
Mouse; 728 days	0.724	↑ (M)	Epithelial degeneration and regeneration of the renal proximal tubules: 40/59 Focal hyperplasia of tubular epithelium: 13/59 Cystic kidney: 8/59	Hirano et al. 1986 (MMC)
Rabbit; 98 days	0.05–0.52	↔ (M, F)		Koller et al. 1977 (MMC)
Rabbit; 98 days	1–1.1	↑ (M, F)	Mild-to-moderate proximal tubule necrosis: 20/20[c]	Koller et al. 1977 (MMC)
Cat; ~112 days	0.176	↔ (M, F)		Charbonneau et al. 1976 (MMC)
Cat; 730 days	0.0084–0.074	↔ (M, F)		Charbonneau et al. 1976 (MMC)

[a]Sexes evaluated are indicated in the results columns.
[b]Reported qualitatively only (incidence data not provided).
[c]Eight rabbits per sex died by 4 weeks; the remaining rabbits died by 12 weeks.

↑ = increase in histopathological lesions; ↔ = no change; F = female; M = male; MM = methylmercury; MMC = methylmercury chloride; PMA = phenylmercuric acetate

Data regarding alterations in kidney weights following oral exposure to organic mercury are limited. Relative kidney weights were significantly elevated by 18% in male rats following gavage exposure to methylmercury at 2.8 mg Hg/kg/day for 14 days; no changes were observed at ≤0.93 mg Hg/kg/day (Fossato da Silva et al. 2011). Following chronic-duration dietary exposure to methylmercury, relative kidney weights were significantly increased by 30% in males exposed to 0.16 mg Hg/kg/day and 36% in females exposed to 0.18 mg Hg/kg/day; no changes were observed at ≤0.04 mg Hg/kg/day (Verschuuren et al. 1976).

Adverse changes in renal clinical chemistry values following oral exposure to methylmercury were only observed in one acute-duration study in mice at doses associated with increased mortality. Serum creatinine was elevated in a dose-related manner in male mice following a single oral gavage exposure to methylmercury at doses ≥16 mg Hg/kg, doses that also resulted in ≥67% mortality (Yasutake et al. 1991). No changes in serum creatinine were observed in similarly exposed females at single doses up to 40 mg Hg/kg. In other studies, no adverse, exposure-related changes in renal clinical chemistry (e.g., creatinine, uric acid, urea, BUN) were observed in rats at chronic-duration dietary doses up to 0.18 mg Hg/kg/day (Verschuuren et al. 1976), mice at intermediate-duration drinking water doses up to 5.6 mg Hg/kg/day (Moreira et al. 2012), rabbits at intermediate-duration dietary doses up to 0.53 mg Hg/kg/day for 98 days (Koller et al. 1977), or cats at an intermediate-duration dose of 0.176 mg Hg/kg/day or chronic-duration dietary doses up to 0.074 mg Hg/kg/day (Charbonneau et al. 1976). No changes in urinalysis parameters were observed in rats at chronic-duration dietary doses up to 0.18 mg Hg/kg/day (Verschuuren et al. 1976) or cats at an intermediate-duration dose of 0.176 mg Hg/kg/day or chronic-duration dietary doses up to 0.074 mg Hg/kg/day (Charbonneau et al. 1976).

Rats given methylmercuric chloride in the diet for 2 years at a dose of 0.1 mg Hg/kg/day had decreased enzymes (ALP, ATPase, NADH- and NADPH-oxidoreductase, and AMPase) in the proximal convoluted tubules (Verschuuren et al. 1976).

Predominant Mercury Form Unknown (General Populations). Renal effects of mercury in general populations have not been extensively studied. Studies (summarized in Table 2-28) include prospective, cross-sectional, and retrospective cohort designs, and examined markers of glomerular function and tubular damage. Several studies were of large populations (n=800–30,000). Mercury exposure was assessed using BHg and UHg.

Table 2-28. Results of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Renal Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Al-Saleh et al. 2017 Cross-sectional; 944 lactating mother-infant pairs[a] (Saudi Arabia)	UHg Gmean Mothers: 0.955 µg/g Cr Infants: 0.635 µg/L	Urine albumin	↑ (UHg, mothers) ↔ (UHg, infants)
		Urine NAG	↑ (UHg, mothers) ↔ (UHg, infants)
		Urine α_1M	↑ (UHg, mothers) ↔ (UHg, infants)

Table 2-28. Results of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Renal Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
de Burbure et al. 2006 Cross-sectional; 804 children (age: 8.5–12.3 years) (France, Poland, Czech Republic)	UHg mean Exposed females: France: 1.19 µg/g Cr Poland: 0.06 µg/g Cr Czech Republic: 0.18 µg/g Cr Exposed males: France: 0.92 µg/g Cr Poland: 0.06µg/g Cr Czech Republic: 0.13 µg/g Cr Control males: France: 0.99 µg/g Cr Poland: 0.06 µg/g Cr Czech Republic: 0.26 µg/g Cr	Urine NAG	↑ (UHg)
Joo et al. 2022 Cross-sectional; 1,360 adolescents, age 12–17 years (KNHANES 2010–2017)	BHg median 1.805 µg/L	GFR	↔ (BHg)
Kim and Lee 2012 Cross-sectional; 5,924 adults (KNHANES 2008–2010)	BHg Gmean: 4.3 µg/L	GFR	↔ (BHg)
Kim et al. 2015b Cross-sectional; 1,797 adults (KNHANES 2011)	BHg mean: 4.35 µg/L	CKD	↔ (BHg)
Kort et al. 2022 Cross-sectional; 1,189 pregnant women age 16–45 years (Suriname)	BHg median by age: 16–24 years: 2.39 µg/L 25–29 years: 2.46 µg/L 30–34 years: 3.48 µg/L ≥35 years: 3.31 µg/L	SCr	↑ (BHg)
		BUN	↑ (BHg)
		Serum cystatin C	↔ (BHg)
Li et al. 2013 Cross-sectional; 54 participants living near a mercury mine and 47 controls (China)	BHg mean Near mine: 6.09 µg/L Control: 3.67 µg/L	SCr	↑ (BHg, exposed versus controls)
		SUN	↑ (BHg, exposed versus controls)

Table 2-28. Results of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Renal Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Li et al. 2015 Cross-sectional; 4,250 participants living near a mercury mine (China)	UHg Gmean: 8.32 µg/g Cr	SCr	↑ (UHg)
		BUN	↔ (UHg)
Lin et al. 2014b Cross-sectional; 1,046 adults (NHANES 2003–2004)	BHg range: <0.66–>1.64	GFR	↓ (BHg)
		Albuminuria	↔ (BHg)
Lin et al. 2023 Cross-sectional; 1,040 pregnant women (United States)	BHg median: 3.36 µg/kg blood	GFR	↔ (BHg)
Liu et al. 2022 Cross-sectional; 1,502 adult men (China)	UHg median: 0.69 µg/L	Kidney stones	↔ (UHg)
Nan et al. 2024 Cross-sectional; 9971 adults age ≥40 years (NHANES 2015–2016)	BHg median 0.74 µg/L	GFR	↔ (BHg)
		Albuminuria	↔ (BHg)
Ohno et al. 2007 Cross-sectional; 59 women (Japan)	UHg mean: 0.86 µg/g Cr HHg mean: 1.51 µg/g NHg mean: 0.59 µg/g	Urine NAG	↑ (UHg, HHg, NHg)
		Urine α_1M	↑ (UHg, HHg, NHg)
		Urine β_2M	↔ (UHg, HHg, NHg)
Pollack et al. 2015 Prospective cohort; 259 women followed for two menstrual cycles (Buffalo, New York)	BHg median: 1.1 µg/L BHg mean: 1.50 µg/L	GFR	↔ (BHg)
		BUN	↔ (BHg)
		SCr	↔ (BHg)
Sommar et al. 2013 Population-based, prospective nested case-referent; 118 cases and 378 referents (Sweden)	ErHg Gmean: Cases: 2.44 µg/L Referents: 3.06 µg/L	ESRD	↔ (ErHg)
Sun et al. 2019 Cross-sectional; 29,121 adults age ≥20 years (NHANES 2007–2016)	BHg median: 0.85 µg/L BMeHg median: 0.62 µg/L UHg median: 0.31 µg/L	Kidney stones	↔ (BHg) ↔ (BMeHg) ↔ UHg

Table 2-28. Results of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Renal Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Tan et al. 2023 Cross-sectional; 4,074 adults age ≥20 years (NHANES 2011–2016)	BHg Gmean 0.86 µg/L	Elevated serum uric acid	↔ (BHg)
Wei et al. 2022 Cross-sectional; 2,711 adults (China)	BHg Q2–Q3 range: 0.57–2.13 µg/L UHg Q2–Q3 range: 0.08 0.76 µg/g Cr	CKD	↑ (BHg) ↑ (UHg)
Xu et al. 2022c Cross-sectional; 14,871 adults age ≥18 years (NHANES 2011–2018)	BHg median: 0.78 µg/L	Elevated blood uric acid	↑ (BHg)
		Gout	↑ (BHg)
Zhang et al. 2020b Cross-sectional; 165 pregnant women living near a mercury mine and 65 referents (China)	UHg Gmean: Mining: 1.09 µg/L Reference: 0.29 µg/L	SCr	↑ (UHg)
Zhu et al. 2019 Cross-sectional; 2,926 adults age ≥20 years (NHANES 2009–2012)	BHg Q2–Q3 range: 0.539–1.876 µg/L UHg Q2–Q3 range: 0.205–0.853 µg/L	Elevated urine albumin	↔ (BHg) ↔ (UHg)

[a]415 infants and 41 mothers were excluded from the analysis because samples were not obtained, or sample volume was inadequate.

↑ = positive association; ↓ = inverse association; ↔ = no association; α_1M = α_1-microglobulin; β_2M = β_2-microglobulin; BHg = blood mercury; BUN = blood urea nitrogen; CKD = chronic kidney disease; Cr = creatinine; ErHg = erythrocyte mercury; ESRD = end-stage renal disease; GFR = glomerular filtration rate; Gmean = geometric mean; HHg = hair mercury; KNHANES = Korea National Health and Nutrition Examination Survey; Q = quartile; NAG = N-acetyl-β-D-glucosaminidase; NHANES = National Health and Nutrition Examination Survey; NHg = toenail mercury; SCr = serum creatinine; SUN = serum urea nitrogen; UHg = urine mercury

Similar to studies on elemental mercury, results of studies evaluating mercury exposure in general populations are inconsistent. Some evidence of altered glomerular function (increased urine albumin, serum creatinine, and SUN) was observed in cross-sectional studies (Al-Saleh et al. 2017; Kort et al. 2022; Li et al. 2013; Zhang et al. 2020b). However, no changes in metrics of glomerular function were observed in several large cross-sectional studies using the U.S. NHANES (Nan et al. 2024; Zhu et al. 2019) or KNHANES data (Joo et al. 2022; Kim and Lee 2012), or in other cross-sectional or prospective

studies evaluating markers of glomerular function (Lin et al. 2014b; Pollack et al. 2015). One study based on NHANES found an association between BHg and increasing GFR (Sanders et al. 2019; n=2,709).

Several studies focused on cohorts of pregnant women. Kort et al. (2022) found that increasing BHg was associated with increasing serum creatinine and BUN in a cross-sectional study of 1,189 pregnant women. A smaller study of pregnant women who resided in a gold inning area found that increasing UHg was associated with increasing serum creatinine (Zhang et al. 2020b). Lin et al. (2023) found no association between BHg and GFR in a cross-sectional study of 140 pregnant women.

Studies of chronic kidney disease have found mixed results. A cross-sectional study (n=2,711 adults) found an association between increasing BHg or UHg and chronic kidney disease (Wei et al. 2022). Kim et al. (2015b) found no association between BHg and chronic kidney disease in a cross-sectional study of 1,797 adults. Sommar et al. (2013) found no association between erythrocyte mercury and end-stage renal disease in a prospective case-referent study (118 cases, 378 referents). Liu et al. (2022) (n=357 with nephrolithiasis and 1,145 without nephrolithiasis) did not find an association between UHg and OR of nephrolithiasis (kidney stones).

The few cross-sectional studies evaluating markers of tubular damage found positive associations between UHg and urine NAG, and α_1M (Al-Saleh et al. 2017; de Burbure et al. 2006; Ohno et al. 2007). Several studies evaluated associations between mercury exposure biomarkers and serum uric acid and/or gout based on data from NHANES (Gao et al. 2022; Sanders et al. 2019; Tan et al. 2023; Xu et al. 2022c) or KNHANES (Jung et al. 2019; Park and Kim 2021). The largest of these studies (Xu et al. 2022c) (n=14,781) found associations between increasing BHg and ORs of hyperuricemia and gout. Results of several smaller studies have been mixed. Tan et al. (2023) (n= 4,074), Gao et al. (2022) (n=4,794) and Jung et al. (2019) (n=2,682) found no associations between BHg and serum uric acid. Park and Kim (2021) (n=4,784) found a beta coefficient association with the doubling of BHg at the 3rd and 4th quartiles with serum uric acid in females but not in males.

While not all studies in general populations have found associations between mercury exposure biomarkers and biomarkers of renal function, collectively, the epidemiology of renal outcomes indicates that mercury exposure of the general population may be associated with glomerular and tubular damage.

Mechanisms of Action. Numerous mechanisms for renal toxicity have been proposed (Barnett and Cummings 2018; Jan et al. 2011; Zalups 2000); these include decreased function of renal transporters;

blockage of aquaporins (water channels); decreased renal content of glutathione; formation of ROS, leading to lipid peroxidation and oxidative stress leading to cellular injury; decreases in the activity of SOD, catalase, GPX, and glutathione disulfide reductase, leading to enhanced susceptibility of renal epithelial cells to oxidative injury; interference with mitochondrial respiratory function; altered intracellular distribution of calcium; inactivation of the plasma membrane (Na^+K^+)-stimulated ATPase; increased expression of stress proteins; and interactions between mercury and cellular microtubular networks.

An important contributing factor to the nephrotoxicity of mercury is that absorbed mercuric mercury accumulates in the renal proximal tubule with the highest concentrations occurring in the region of the kidney (inner cortex and outer stripe of the outer medulla) where mercury-induced tubule damage is initiated (Berlin et al. 2015; Zalups and Diamond 2005). This region of the kidney receives a relatively high dose of mercury regardless of the form of mercury absorbed. This includes inorganic mercuric mercury following absorption and oxidation of elemental mercury, as well as absorbed methylmercuric mercury, and inorganic mercuric mercury produced from demethylation of absorbed methylmercury (Section 3.1.2). Accumulation of mercuric mercury in the kidneys is facilitated by several membrane transport systems in the proximal tubule that recognize S-conjugates of mercuric mercury as transport substrates. These transport systems, coupled with oxidative metabolism of mercury compounds to mercuric mercury species, and the high affinity of mercuric mercury for the thiolate anion explain why mercury in most of its forms can be nephrotoxic at a sufficiently high absorbed dose (Berlin et al. 2015). The exact mechanisms by which mercury impairs renal cellular function and damages the proximal tubule have not been fully characterized and are likely to involve many different molecular targets, as discussed above. Central to these mechanisms are ligand exchange reactions that enable mercuric mercury to distribute to membrane and intracellular sulfhydryl groups that are important in the structure or catalytic activity of structural proteins and enzymes critical to cell metabolism and function (Carty and Malone 1979).

2.12 DERMAL

Studies of dermal effects associated with an immunological mechanism of action (e.g., dermal hypersensitivity reactions and acrodynia) are discussed in Section 2.15 (Immunological).

Overview. One epidemiological study of elemental mercury investigating associations between biomarkers and non-immunological dermal effects was identified; this study evaluated effects in a

population of dentists. No epidemiological studies were identified for populations with high fish diets or general populations. Data are insufficient to determine if non-immunological dermal effects are associated with mercury exposure.

A few animal studies evaluating dermal effects are available for oral exposure to mercuric chloride or methylmercury. Available data do not indicate that the skin is a sensitive target of mercury toxicity following oral exposure.

The following summarizes results of epidemiological and animal studies on dermal outcomes.

- ***Elemental mercury***
  - *Epidemiology studies*
    - One epidemiological study found an increased risk of self-reported dermal hyperpigmentation in dentists exposed to elemental mercury, compared to controls.
  - *Animal studies*
    - No studies evaluating dermal effects following exposure to elemental mercury were identified.
- ***Inorganic mercury salts***
  - *Epidemiology studies*
    - No epidemiological studies evaluating associations between exposure to inorganic mercury salts and dermal effects were identified.
  - *Animal studies*
    - Available data are inadequate to assess potential dermal effects following exposure to inorganic mercury salts.
- ***Organic mercury***
  - *Epidemiology studies*
    - No epidemiological studies on non-immunological dermal effects of exposure to organic mercury compounds were identified.
    - Case reports have noted rashes in individuals exposed to phenylmercury.
  - *Animal studies*
    - No evidence of dermal effects was found in rodents following intermediate- or chronic-duration oral exposure to methylmercury.
- ***Predominant mercury form unknown (general populations)***
    - No epidemiological studies of general populations evaluating non-immunological dermatological changes in general populations exposed to mercury were identified.

Confounding Factors. One epidemiological study evaluating non-immunological dermal effects from exposure to elemental mercury in dentists was identified (Neghab et al. 2011). Covariates considered in this study as potential cofounders were age, marital status, number of personal amalgam fillings, and dental clinic type.

Elemental Mercury—Epidemiological Studies. One epidemiological study evaluating dermatological effects of elemental mercury was identified (Neghab et al. 2011). This cross-sectional study compared self-reported dermal symptoms (dermatitis, eczema, and hyperpigmentation) in exposed dentists (n=106; median UHg: 3.16 µg/g creatinine) to a control group of physician general practitioners (n=94; median UHg: 2.18 µg/g creatinine) from Iran. The OR for hyperpigmentation in exposed dentists compared to controls was 4.62 (95% CI 1.2, 17.68), although no increased risk was observed for dermatitis or eczema. Results of this study have not been corroborated.

Elemental Mercury—Animal Studies. No studies were located regarding dermal effects in animals after exposure to elemental mercury.

Inorganic Mercury Salts—Animal Studies. No exposure-related changes in skin histology were observed in rats exposed once to mercuric chloride at gavage doses up to 9.24 mg Hg/kg/day (Lecavalier et al. 1994). No additional studies evaluating dermal effects in animals after exposure to inorganic mercury compounds were identified.

Organic Mercury—Epidemiological Studies. Epidemiological studies evaluating dermatological effects of exposures to methylmercury from high fish diets were not identified. A case report of three individuals exposed to phenylmercury through weed killers and pharmaceutical ointments reported pruritic papular rashes (Morris 1960). No biomarkers were evaluated and the underlying mechanism of action for the rashes was not identified.

Organic Mercury—Animal Studies. No exposure-related changes in skin histology were observed in rats following chronic-duration exposure to doses up to 0.18 mg Hg/kg/day (Verschuuren et al. 1976) or mice following intermediate- or chronic-duration exposure up to 0.724 mg Hg/kg/day (Hirano et al. 1986; Mitsumori et al. 1990).

Predominant Mercury Form Unknown (General Populations). No epidemiological studies of general populations evaluating non-immunological dermatological changes in general populations exposed to mercury were identified.

Mechanisms of Action. Mechanisms of potential non-immunological dermatological changes associated with mercury exposure have not been established.

2.13 OCULAR

Studies evaluating neurological ocular effects are reviewed in Section 2.16 (Neurological).

Overview. Two epidemiological studies that investigated associations between biomarkers and non-neurological ocular effects were identified; both studies evaluated effects in a general population. No epidemiological studies were identified for populations exposed to elemental mercury or in populations with high fish diets. Data are insufficient to determine if adverse non-neurological ocular effects are associated with mercury exposure. The clinically distinct brownish discoloration of the lens known as mercurialentis (Byrns and Pennings 2017; El-Sherbeeny et al. 2006) is not discussed below as it is not associated with adverse ocular effects; Section 3.3.1 (Biomarkers of Exposure) for additional details.

A few animal studies evaluating ocular effects are available for oral exposure to mercuric chloride or methylmercury. Available data do not indicate that the eye is a sensitive target of mercury toxicity following oral exposure. Observed visual impairment in primates following oral exposure to methylmercury are considered neurological in nature and are discussed in Section 2.16 (Neurological).

The following summarizes results of epidemiological and animal studies on non-neurological ocular outcomes.

- ***Elemental mercury***
  - *Epidemiology studies*
    - No epidemiological studies on non-neurological ocular effects of exposure to elemental mercury were identified.
  - *Animal studies*
    - No studies evaluating ocular effects following exposure to elemental mercury were identified.

- ***Inorganic mercury salts***
  - *Epidemiology studies*
    - No epidemiological studies on non-neurological ocular effects of exposure to inorganic mercury salts were identified.
  - *Animal studies*
    - Available data are inadequate to assess potential ocular effects following oral exposure to inorganic mercury salts.
- ***Organic mercury***
  - *Epidemiology studies*
    - No epidemiological studies on non-neurological ocular effects of exposure to organic mercury compounds were identified.
  - *Animal studies*
    - No evidence of ocular damage was found in rodents following intermediate- or chronic-duration oral exposure to methylmercury.
- ***Predominant mercury form unknown (general populations)***
    - Two large epidemiological studies of the general population found positive associations between BHg and dry eye symptom disease in higher versus lower BHg groups.
    - Data are inadequate to determine if non-neurological ocular effects are associated with mercury exposure in general populations.

Confounding Factors. One epidemiological study regarding non-neurological ocular effects of mercury was identified (Chung and Myong 2016). Covariates considered in this study as potential confounders were age, gender, education, household income, smoking status, alcohol consumption, sleeping time, perceived stress status, and history of atopy.

Elemental Mercury—Epidemiological Studies. Epidemiological studies evaluating non-neurological ocular effects in populations exposed to elemental mercury were not identified.

Elemental Mercury—Animal Studies. No studies were located regarding ocular effects in animals after exposure to elemental mercury.

Inorganic Mercury Salts—Animal Studies. No histopathological changes in the eye were observed in rats exposed once to mercuric chloride at gavage doses up to 9.24 mg Hg/kg/day (Lecavalier et al. 1994).

No additional studies evaluating ocular effects in animals after exposure to inorganic mercury were identified.

Organic Mercury—Epidemiological Studies. Epidemiological studies evaluating non-neurological ocular effects of exposures to methylmercury from high fish diets were not identified.

Organic Mercury—Animal Studies. No histopathological changes in the eye were observed in rats following chronic-duration exposure to doses up to 0.18 mg Hg/kg/day (Verschuuren et al. 1976) or mice following intermediate- or chronic-duration exposure up to 0.724 mg Hg/kg/day (Hirano et al. 1986; Mitsumori et al. 1990).

Predominant Mercury Form Unknown (General Populations). Two studies evaluating associations between mercury biomarkers and non-neurological ocular effects were located (Chung and Myong 2016; Jung and Lee 2019). In a cross-sectional study of a KNHANES population (n=4,761 adults) with a median BHg of 3.7 µg/L, the odds of self-reported dry eye symptoms (persistent dryness or eye irritation) were increased in the high (BHg ≥3.7 µg/L) relative to the low (BHg <3.7 µg/L) exposure groups (OR 1.324; 95% CI 1.059, 1.655). Jung and Lee (2019) evaluated associations between BHg and dry eye disease in a large cross-sectional study using KNHANES data from 2010–2012. With data stratified by BHg tertiles, a positive association (OR 1.39; 95% CI 1.02–1.89) between BHg and dry eye disease was observed for the highest BHg tertile (≥4.919 µg/L) compared to the lowest BHg tertile (<2.85 µg/L).

Mechanisms of Action. Chung and Myong (2016) speculated that the following mechanisms could be involved in the development of dry eye: (1) altered conjunctival mucus; (2) induction of conjunctival inflammation; (3) recruitment and activation of inflammatory and immune cells on the ocular surface; and (4) depletion of antioxidant proteins (e.g., metallothionein) in the lacrimal glands and conjunctiva.

2.14 ENDOCRINE

Overview. Data on endocrine effects of mercury are available from studies in humans and animals. Compared to other systems, effects of mercury on endocrine functions have not been well investigated in humans. Studies are available in workers exposed to elemental mercury, a population with a high fish diet, and in general populations with exposure to unspecified forms of mercury. Epidemiological studies have focused on associations between mercury biomarkers and thyroid function and glucose homeostasis.

Studies of effects on thyroid function and glucose homeostasis report inconsistent findings and do not provide evidence that the endocrine system is a sensitive target for mercury.

A few animal studies have evaluated endocrine function following oral exposure to inorganic salts or organic mercury compounds. Based on the limited number of studies and endpoints assessed, limited information on dose- or duration-response (e.g., single exposure level study design), and/or inconsistent findings between studies, available data are insufficient to determine if the endocrine system is a sensitive target for mercury.

The following summarizes results of epidemiological and animal studies on endocrine outcomes.

- ***Elemental mercury***
  - *Epidemiology studies*
    - A few studies evaluating effects of elemental mercury exposure on thyroid function provide conflicting results, with most studies showing no differences in thyroxine (T4), triiodothyronine (T3), and thyroid-stimulating hormone (TSH) levels between workers and controls.
  - *Animal studies*
    - No studies evaluating endocrine effects following exposure to elemental mercury were identified.
- ***Inorganic mercury salts***
  - *Epidemiology studies*
    - No epidemiological studies evaluating associations between exposure to inorganic mercury salts and endocrine effects were identified.
  - *Animal studies*
    - Data are insufficient to determine if exposure to inorganic mercury salts is associated with adverse endocrine effects. A limited number of studies suggest that inorganic mercury salts may alter thyroid, pancreatic, or adrenocortical function; however, findings are inconsistent across studies, doses, and/or durations.
- ***Organic mercury***
  - *Epidemiology studies*
    - Data are insufficient to determine if exposure to organic mercury is associated with adverse endocrine effects. The only identified study showed a very small increase in the risk of increased fasting glucose levels and type 2 diabetes in a population with a high fish diet.

- *Animal studies*
  - Data are insufficient to determine if exposure to organic mercury is associated with adverse endocrine effects. One study suggested that organic mercury may impair pancreatic function, while another provided limited evidence of adrenocortical dysfunction.
- ***Predominant mercury form unknown (general populations)***
  - Several studies have evaluated the effects of mercury exposure on thyroid function, specifically thyroid hormones in general populations. Evidence for associations between exposure to mercury and thyroid function is conflicting, with inconsistent results across studies.
  - Effects of mercury exposure on glucose homeostasis has been evaluated in several studies. Most results showed no associations between mercury and type 2 diabetes or all diabetes, including a large meta-analysis. For studies showing associations, one studies showed a positive association between biomarkers and type 2 diabetes, while another study showed an inverse relationship. Two studies showed positive associations between mercury biomarkers and insulin resistance.

Confounding Factors. Several factors that may be associated with mercury exposure status can complicate interpretation of studies on thyroid function. These include selenium status (selenium-containing enzymes are involved in thyroid hormone homeostasis), negative iodine balance (iodine deficiency is rare in the United States), underlying thyroid disease, genetic predisposition for thyroid disease, and some pharmaceutical agents. The epidemiological studies reviewed in this section have not considered most of these potential confounders. For glucose homeostasis, there are numerous potential confounding factors. These include body weight/BMI (obesity), age, diet, family history of diabetes, age, exercise, high blood pressure, and low HDL cholesterol. Most epidemiological studies reviewed below include some of these adjustments when appropriate. No specific confounder or covariate was mandatory for the inclusion of the study into the profile; however, studies of thyroid and glucose homeostasis outcomes that did not consider the aforementioned potential confounders are potentially more confounded than studies that did consider these variables.

Elemental Mercury—Epidemiological Studies. Studies evaluating effects of elemental mercury on endocrine function are summarized in Table 2-29. The database consists of a few cross-sectional studies examining associations between exposure to elemental mercury and markers of thyroid function in miners, chloralkali workers, and dentists. Worker populations in these studies were small ($n \leq 80$),

limiting the power to detect associations between exposure to elemental mercury and thyroid effects. Primary outcome measures to evaluate thyroid function included measurements of plasma or serum levels of T4, T3, and TSH, with comparisons between exposed workers and controls.

Table 2-29. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Effects on Thyroid Hormones

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Afrifa et al. 2018 Cross-sectional; 80 gold miners and 57 controls (Ghana)	BHg median Miners: 8.0 µg/L Controls: 1.0 µg/L	T4[a]	↓ (BHg, miners versus controls)
		T3[a]	↓ (BHg, miners versus controls)
		TSH	↔ (BHg, miners versus controls)
Barregard et al. 1994a Cross-sectional; 41 male chloralkali workers and 41 matched controls (Sweden)	UHg mean Workers: 27 µg/g Cr Controls: 3.4 µg/g Cr	Free T4	↔ (BHg, workers versus controls)
		Free T3	↔ (BHg, workers versus controls)
		TSH	↔ (BHg, workers versus controls)
Ellingsen et al. 2000b Cross-sectional; 47 chloralkali workers and 47 controls (Norway)	UHg median Workers: 10.5 µg/g Cr Controls: 2.3 µg/g Cr	Free T4	↔ (UHg, workers versus controls)
		Free T3	↔ (UHg, workers versus controls)
		Reverse T3	↑ (UHg, workers versus controls)
		Anti-TPO	↓ (UHg, workers versus controls)
Erfurth et al. 1990 Cross-sectional; 9 male dentists and 11 controls and 11 chloralkali workers and 10 controls (Sweden)	UHg mean Dentists: 2.3 µg/g Cr Controls: 0.71 µg/g Cr UHg mean, Workers Workers: 46 µg/g Cr Controls: 1.1 µg/g Cr	Free T4	↔ (UHg, workers or dentists versus respective controls)
		Free T3	↔ (UHg, workers or dentists versus respective controls)
		TSH	↔ (UHg, workers or dentists versus respective controls)

[a]Not specified if total or free T4 and T3.

↑ = increased levels; ↓ = decreased levels; ↔ = no difference; Anti-TPO = thyroid peroxidase antibodies; BHg = blood mercury; Cr = creatinine; T3 = triiodothyronine; T4 = thyroxine; TSH = thyroid-stimulating hormone; UHg = urine mercury

Evidence for effects on the thyroid gland in workers exposed to elemental mercury is inconclusive. Three studies did not find differences in T4, T3, or TSH levels in workers compared to controls (Barregard et al. 1994a; Ellingsen et al. 2000b; Erfurth et al. 1990). Ellingsen et al. (2000b) observed a 15% increase in reverse T3 (a thyroid hormone metabolite) in chloralkali workers compared to controls (Ellingsen et al.

2000b); however, in the absence of effects on T4 and T3, the clinical significance of this finding is uncertain. In contrast to the studies showing no effects on T4 and T3 levels in exposed chloralkali workers, a study in gold miners (median BHg 8 µg/L) reported decreases in T4 and T3 of 39 and 43%, respectively, compared to controls (median BHg 1 µg/L), although TSH levels were similar between miners and controls (Afrifa et al. 2018).

Elemental Mercury—Animal Studies. No studies were located regarding endocrine effects in animals after exposure to elemental mercury.

Inorganic Mercury Salts—Animal Studies. A limited number of studies in laboratory animals have evaluated effects of inorganic mercury salts on thyroid, pancreas, and adrenocortical function following acute- or intermediate-duration oral exposure. Additional data regarding endocrine gland weight and/or histology are available from acute-, intermediate-, and chronic-duration oral studies. Overall, available data are insufficient to determine if exposure to inorganic mercury salts is associated with adverse endocrine effects due to the limited number of studies, limitations of study design (e.g., single exposure level), and/or inconsistent findings.

Thyroid function has been evaluated in a limited number of studies in rats and mice following acute- and intermediate-duration oral exposure to mercuric chloride or mercuric sulfide (Table 2-30). In a series of experiments, Goldman and Blackburn (1979) evaluated thyroid function in female rats following acute- or intermediate-duration exposure to mercuric chloride. Increased thyroid function, as evidence by increased iodine uptake, release, and/or turnover, was observed following gavage exposure to 7.4 or 9.4 mg Hg/kg/day for 6 or 40 days, respectively. However, decreased iodine uptake, release, and turnover were observed following dietary exposure to 2.2 mg Hg/kg/day for 90 days. It is unclear if the opposing effects were attributable to exposure route (gavage versus dietary) and/or evidence of non-monotonic dose or duration effects (since only one dose was tested at each duration, biphasic responses cannot be evaluated). Evidence for decreased T3 synthesis in the thyroid was also observed following exposure to 9.4 mg Hg/kg/day for 40 days (not evaluated at other durations). In mice, significant decreases in plasma T3 were observed following acute-duration gavage exposure to 6 mg Hg/kg/day as mercuric chloride or mercuric sulfide; plasma T4 was also decreased with mercuric chloride exposure (Sin et al. 1990). However, in an intermediate-duration study with mercuric sulfide, significant decreases were observed in plasma T4, but not T3, 1–4 weeks post-exposure to 6 mg Hg/kg/day (Sin and Teh 1992). In addition to thyroid effects, a 90-day drinking water study with mercuric chloride reported significantly decreased

blood glucose (by 19%) at 15 mg Hg/kg/day (Zhao et al. 2020). Study designs in mice are inadequate to assess dose- or duration-dependence of observed effects.

Table 2-30. Thyroid Function and Hormone Levels in Female Rats and Mice Orally Exposed to Inorganic Mercury Salts

Species; Duration	Dose (mg Hg/kg/day)	T3[a]	T4[a]	Iodine uptake[a]	Iodine release Half-life[a]	Iodine turnover rate[a]	Reference (compound)
Rat; 6 days	7.4	–	–	–	↓ (69)	↑ (200)	Goldman and Blackburn 1979 (MC)
Rat; 40 days	9.4	↓ Thyroid (19)	↔ Thyroid	↑ (108)	–	–	Goldman and Blackburn 1979 (MC)
Rat; 90 days	2.2	–	–	↓ (27)	↑ (56)	↓ (37)	Goldman and Blackburn 1979 (MC)
Mouse; 10 days	6	↓ Plasma (70)	↓ Plasma (42)	–	–	–	Sin et al. 1990 (MC)
Mouse; 10 days	6	↓ Plasma (59)	↔ Plasma	–	–	–	Sin et al. 1990 (MS)
Mouse; 28 days	6	↔	↓ Plasma (28–41[b])	–	–	–	Sin and Teh 1992 (MS)

[a]Numbers in ( ) are percent change compared to control, calculated from quantitative data.
[b]Measured 1–4 weeks post-exposure.

↑ = increased; ↓ = decreased; ↔ = no change; – = not assessed; MC = mercuric chloride; MS = mercuric sulfide; T3 = triiodothyronine; T4 = thyroxine

One study showed a 28% increase in absolute thyroid weight in female rats following gavage exposure to mercuric chloride at 9.4 mg Hg/kg/day for 40 days; relative organ weights were not reported but no body weight effects were noted (Goldman and Blackburn 1979). Based on evidence of increased thyroid function in this study, elevated thyroid weights are considered treatment related. Thyroid weights were not assessed in other identified studies.

In a series of experiments, Agrawal and Chansouria (1989) evaluated adrenocortical function in male rats exposed to mercuric chloride via drinking water for 60, 120, or 180 days (Table 2-31). Corticosterone levels in the adrenal gland were significantly elevated in a dose- and duration-dependent manner after exposure to ≥2.9 mg Hg/kg/day for 60–120 days. Plasma corticosterone levels also showed a significant, dose-related increase following exposure for 120 days, but findings were biphasic at 60 days (levels increased at 2.9 mg Hg/kg/day but decreased at ≥5.8 mg Hg/kg/day). After 180 days of exposure, adrenal

and plasma corticosterone levels were comparable to controls. The study authors considered recovery at 180 days an indication of acquired resistance to mercury. Agrawal and Chansouria (1989) also reported significantly elevated relative adrenal weights after exposure to 2.9 mg Hg/kg/day for 60, 120, or 180 days, but findings do not show a clear dose- or duration-dependence (Table 2-31). Altered relative adrenal gland weight findings should be interpreted with caution because neither absolute adrenal gland weights nor body weights were reported. Other studies do not show exposure-related changes in adrenal gland weights in male or female rats following exposure to mercuric chloride at intermediate-duration dietary doses up to 20.9 or 23.6 mg Hg/kg/day, respectively (Jonker et al. 1993), or gavage doses up to 1.65 mg Hg/kg/day (Atkinson et al. 2001). In mice, no exposure-related changes in adrenal gland weight were observed following intermediate-duration exposure to mercuric chloride at gavage doses up to 0.74 mg Hg/kg/day (Khan et al. 2004).

Table 2-31. Corticosterone levels and Adrenal Gland Weight in Rodents[a] Orally Exposed to Mercuric Chloride

Species Duration	Dose (mg Hg/kg/day)	Plasma corticosterone[b]	Adrenal corticosterone[b]	Adrenal weight[b]	Reference
Rat (B) 28 days	0.61–23.6	–	–	↔ (M, F)	Jonker et al. 1993
Rat (M) 60 days	2.9	↑ (M) (33)	↑ (M) (146)	↑ (M) (31)	Agrawal and Chansouria 1989
Rat (M) 60 days	5.8	↓ (M) (31)	↑ (M) (157)	↑ (M) (34)	Agrawal and Chansouria 1989
Rat (M) 60 days	11.8	↓ (M) (60)	↑ (M) (203)	↑ (M) (27)	Agrawal and Chansouria 1989
Rat (B) 79–81 days	0.37–1.98	–	–	↔ (M, F)	Atkinson et al. 2001
Rat (M) 120 days	2.9	↑ (M) (87)	↑ (M) (218)	↑ (M) (19)	Agrawal and Chansouria 1989
Rat (M) 120 days	5.8	↑ (M) (42)	↑ (M) (313)	↑ (M) (10)	Agrawal and Chansouria 1989
Rat (M) 120 days	11.8	↑ (M) (20)	↑ (M) (372)	↑ (M) (51)	Agrawal and Chansouria 1989
Rat (M) 180 days	2.9	↔ (M)	↔ (M)	↑ (M) (14)	Agrawal and Chansouria 1989
Rat (M) 180 days	5.8	↔ (M)	↔ (M)	↑ (M) (30)	Agrawal and Chansouria 1989
Rat (M) 180 days	11.8	↔ (M)	↔ (M)	↑ (M) (31)	Agrawal and Chansouria 1989

Table 2-31. Corticosterone levels and Adrenal Gland Weight in Rodents[a] Orally Exposed to Mercuric Chloride

Species Duration	Dose (mg Hg/kg/day)	Plasma corticosterone[b]	Adrenal corticosterone[b]	Adrenal weight[b]	Reference
Mouse (B) 61–79 days	0.18–0.74	–	–	↔ (M, F)	Khan et al. 2004

[a]Sexes evaluated are indicated in the results columns.
[b]Numbers in ( ) are percent change compared to control, calculated from quantitative data.

↑ = increased; ↓ = decreased; ↔ = no change; – = not assessed; B = both males and females; F = female(s); M = male(s)

Pancreatic function was evaluated in one study in mice following exposure to mercuric chloride at a gavage dose of 3.7 mg Hg/kg/day for 14 days (Chen et al. 2012). Fasting insulin levels were significantly decreased by 60%. In a glucose tolerance test (after fasting), blood glucose levels were significantly elevated by 45–70% when measured 30–150 minutes after glucose administration. For reference, baseline insulin levels were increased by 17% and baseline glucose levels were decreased 15% in treated mice, compared to controls. However, exposure to the same dose for 28 or 42 days resulted in duration-dependent increases of 70–95% in baseline insulin levels and a 35% increase in baseline glucose levels; glucose tolerance was not tested in longer-duration studies (Chen et al. 2012). After the 14-day exposure, apoptosis in pancreatic islet cells was significantly increased. In other studies, blood glucose levels were unaltered by exposure to mercuric chloride in rats at acute-duration doses up to 9.24 mg Hg/kg/day (Lecavalier et al. 1994) and in mice at intermediate-duration doses up to 0.74 mg Hg/kg/day (Khan et al. 2004).

Parathyroid hyperplasia was observed in male rats following chronic-duration exposure to mercuric chloride at dietary doses ≥1.8 mg Hg/kg/day; however, this lesion was considered secondary to impaired renal function observed in male rats at ≥1.8 mg Hg/kg/day (Dieter et al. 1992; NTP 1993). Parathyroid hyperplasia was not observed in similarly exposed female rats (with normal renal function) at doses up to 4 mg Hg/kg/day (Dieter et al. 1992; NTP 1993). No exposure-related parathyroid lesions were observed following intermediate-duration gavage doses up to 4 or 15 mg Hg/kg/day in rats or mice, respectively (Dieter et al. 1992; Khan et al. 2004; NTP 1993), or chronic-duration gavage doses up to 7.4 mg Hg/kg/day in mice (NTP 1993).

No exposure-related histopathological changes were observed in the pancreas or the thyroid, adrenal, or pituitary glands following exposure to mercuric chloride at acute-duration dietary doses up to 9.24 mg

Hg/kg/day (Lecavalier et al. 1994); intermediate-duration gavage doses up to 4 or 15 mg Hg/kg/day in rats or mice, respectively (Dieter et al. 1992; Khan et al. 2004; NTP 1993); or chronic-duration gavage doses up to 4 or 7.4 mg Hg/kg/day in rats or mice, respectively (Dieter et al. 1992; NTP 1993).

Organic Mercury—Epidemiological Studies. Data are not sufficient to determine if exposure to mercury in populations with high fish diets produces adverse effects to the endocrine system, with only two studies meeting inclusion criteria for this toxicological profile (inclusion criteria, Section 2.1) (Cordier et al. 2020; Jeppesen et al. 2015). Jeppesen et al. (2015) examined measures of glucose tolerance in 2,640 Inuit adults from Greenland with a median BHg of 16.5 µg/L. Results showed that, for each 5 µg/L in total BHg, the odds of impaired fasting glycemia (fasting plasma glucose ≥6.1 and <6.9 mmol/L and 2-hour challenge plasma glucose <7.8 mmol/L) and type 2 diabetes (fasting plasma glucose ≥7.0 mmol/L or 2-hour challenge plasma glucose ≥11.1 mmol/L) were increased by 3% (adjusted OR 1.03; 95% CI 1.02, 1.05) and 2% (adjusted OR 1.02; 95% CI 1.01, 1.04), respectively. No increased risk was observed for impaired glucose tolerance (fasting plasma glucose <7.0 and <6.9 mmol/L and 2-hour challenge plasma glucose ≥7.8 and <11.1 mmol/L; adjusted OR 0.97; 95% CI 0.94, 1.0). A cross-sectional study of Inuit (n=877) and Cree (n=788) adults did not find associations between BHg and type 2 diabetes (Cordier et al. 2020). Median BHg levels in the Inuit and Cree population were 10.3 and 3.00 µg/L, respectively.

Organic Mercury—Animal Studies. A very limited number of studies in laboratory animals have evaluated effects of organic mercury on pancreatic and adrenocortical function following acute- or intermediate-duration oral exposure. Additional data regarding endocrine gland weight and/or histology are available from intermediate- and chronic-duration oral studies. Available data are insufficient to determine if organic mercury adversely affects the endocrine system in laboratory animals.

Pancreatic function was evaluated in mice following exposure to methylmercury at a gavage dose of 1.6 mg Hg/kg/day for 14 days (Chen et al. 2012). Baseline and fasting insulin levels were significantly decreased by 60–70%. In a glucose tolerance test (after fasting), blood glucose levels were significantly elevated by 30–65% when measured 30–150 minutes after glucose administration (no changes in baseline blood glucose levels). Exposure to the same dose for 28 or 42 days resulted in duration-dependent increases of 80–95 and 25–40% in baseline insulin and glucose levels, respectively; glucose tolerance was not tested in longer-duration studies (Chen et al. 2012). After the 14-day exposure, apoptosis in pancreatic islet cells was significantly increased. Dose-dependent increases in plasma insulin were found in male NMRI mice exposed for 4 weeks, with increases of 47% at 2 mg Hg/kg/day to 191% at 8.0 mg Hg/kg/day (Maqbool et al. 2019). Fasting blood glucose was significantly elevated (by 44%) at 8.0 mg

Hg/kg/day but was not significantly increased at lower doses; however, this finding is inconsistent with increased plasma insulin levels.

One study evaluated adrenocortical function in male rats following exposure to methylmercuric chloride or bis(methylmercury)sulfide at drinking water doses of 0.0004 or 0.04 mg Hg/kg/day for 8 or 16 weeks (Ortega et al. 1997b). Following exposure to methylmercuric chloride, serum levels of adrenocorticotropic hormone (ACTH) were significantly increased by >100% at ≥0.0004 mg Hg/kg/day after 8 or 16 weeks; however, findings did not have an increasing response with dose. For bis(methylmercury) sulfide, a dose-dependent 105–220% increase in ACTH was observed at ≥0.0004 mg Hg/kg/day after 8 weeks only. No consistent dose-response relationship was found for serum corticosterone for either compound after 8 or 16 weeks of exposure.

No exposure-related changes in endocrine organ weight and/or histology were observed following dietary exposure to methylmercury at intermediate-duration doses up to 0.627 or 0.176 mg Hg/kg/day in mice or cats, respectively (Charbonneau et al. 1976; Hirano et al. 1986), or chronic-duration doses up to 0.18, 0.686, or 0.074 mg Hg/kg/day in rats, mice, or cats, respectively (Charbonneau et al. 1976; Hirano et al. 1986; Mitsumori et al. 1990; Verschuuren et al. 1976). Additionally, no exposure-related changes in adrenal gland weight or histology were observed in rats following chronic-duration exposure to phenylmercuric acetate at drinking water doses up to 3.7 mg Hg/kg/day (Solecki et al. 1991).

Predominant Mercury Form Unknown (General Populations). Endocrine effects of mercury on endocrine effects in general populations have not been well-studied. Available studies have examined associations between mercury exposure and thyroid function and glucose homeostasis. Studies on thyroid function used cross-sectional or cohort designs and measured plasma or serum levels of T4, T3, TSH, and thyroid autoantibodies. Glucose homeostasis was assessed by examining type 2 diabetes and insulin resistance in prospective and cross-sectional studies and in meta-analyses. Nearly all studies evaluated large populations (n ≥1,100); biomarkers were BHg, UHg, HHg, and NHg.

Thyroid function. Studies examining associations between mercury exposure in general populations and thyroid function are summarized in Table 2-32. Due to the small number of studies and conflicting results, evidence for effects of mercury exposure on thyroid function are inconclusive. All studies used cross-sectional and case-control designs. Results of studies on thyroid hormones (T4, T3, TSH) yield conflicting results. A study using NHANES 2007–2008 data examined the relationship between BHg and blood methylmercury in adults and adolescents (Chen et al. 2013). In adolescents, inverse associations

were observed between total BHg and total T4 and free T3 and between blood methylmercury and free T3, although there were no associations between BHg or blood methylmercury and TSH. Nascimento et al. (2018) also examined a population of adolescents and found an inverse relationship between BHg and T4 and a positive association for TSH. In adults, total BHg and blood methylmercury were inversely associated with total T4, total T3, and free T3 in adults. However, no associations were observed between TSH and total BHg or blood methylmercury in adolescents or adults; therefore, the clinical significance of the inverse associations between mercury and T4 and T3 is unclear. In contrast, no effects on T4 and T3 in a large NHANES population in adults (Kim et al. 2022b) or on T4, T3, or TSH in a population of pregnant Spanish women were observed (Llop et al. 2015). Three studies of the NHANES 2007–2008 population evaluated associations between mercury exposure and thyroid auto-antibodies, with conflicting results (Chen et al. 2013; Gallagher and Meliker 2012; Kim et al. 2021b). No associations were observed between BHg or blood methylmercury levels and anti-thyroglobulin (anti-Tg) or anti-thyroid peroxidase (anti-TPO) in adults or adolescents (Chen et al. 2013; Kim et al. 2021b). However, the Gallagher and Meliker (2012) study of women reported an increase in anti-Tg, but not anti-TPO.

Table 2-32. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Thyroid Hormones in General Populations

Reference, study type and population	Biomarker	Outcome evaluated	Result
Castiello et al. 2020 Cross-sectional; 133 male adolescents (ages 15–17 years) (Spain)	UHg Gmean: 0.03 µg/g creatinine	Free T4	↔ (UHg)
		T3	↔ (UHg)
		TSH	↔ (UHg)
		Free T3:TSH ratio	↔ (UHg)
Chen et al. 2013 Cross-sectional: 1,109 adolescents (NHANES 2007–2008)	BHg Gmean: 0.47 µg/L	T4	↓ (BHg) ↔ (BMeHg)
		Free T4	↔ (BHg, BMeHg)
		T3	↔ (BHg, BMeHg)
		Free T3	↓ (BHg) ↓ (BMeHg)
		TSH	↔ (BHg, BMeHg)
		Tg	↔ (BHg, BMeHg)
		Anti-Tg	↔ (BHg, BMeHg)
		Anti-PO	↔ (BHg, BMeHg)

Table 2-32. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Thyroid Hormones in General Populations

Reference, study type and population	Biomarker	Outcome evaluated	Result
Chen et al. 2013 Cross-sectional: 4,409 adults (NHANES 2007–2008)	BHg Gmean: 0.96 µg/L	T4	↓ (BHg, BMeHg)
		Free T4	↔ (BHg, BMeHg)
		T3	↓ (BHg, BMeHg)
		Free T3	↓ (BHg, BMeHg)
		TSH	↔ (BHg, BMeHg)
		Tg	↔ (BHg, BMeHg)
		Anti-Tg	↔ (BHg, BMeHg)
		Anti-TPO	↔ (BHg, BMeHg)
Gallagher and Meliker 2012 Cross-sectional; 2,047 women (NHANES 2007–2008)	BHg quintiles: Qi1: ≤40 µg/L Qi2: >0.40–≤0.68 µg/L Qi3: >0.68–≤1.06 µg/L Qi4: >1.06–≤1.18 µg/L Qi5: >1.18–≤15.10 µg/L	Anti-Tg	↑ (BHg, Qi5)
		Anti-TPO	↔ (BHg)
		Thyrotropin	↔ (BHg)
Liu et al. 2021b Case-control; 197 adults with thyroid tumor or goiter and 197 controls (China)	UHg median Cases: 0.27 µg/L Controls: 0.38 µg/L	T4	↔ (UHg)
		Free T4	↔ (UHg)
		TSH	↔ (UHg)
Llop et al. 2015 Cohort; 1,407 pregnant women (Spain)	Cord BHg Gmean: 7.7 µg/L	Free T4 (M)	↔ (cord BHg)
		Free T3 (M)	↔ (BHg)
		TSH (M)	↔ (BHg)
Kim et al. 2021b Cross-sectional; 1,254 adults, 630 men and 624 women (NHANES 2015–2017)	BHg Gmean All: 2.85 µg/L Men: 3.44 µg/L Women: 3.26 µg/L UHg Gmean All: 0.44 µg/L Men: 0.46 µg/L Women: 0.42 µg/L	T4	↔ (BHg, males, females) ↔ (UHg, males) ↑ (UHg, females)
		Free T4	↑ (BHg, males) ↔ (BHg, females) ↔ (UHg, males, females)
		T3	↔ (BHg, males) ↑ (BHg, females) ↓ (UHg, males, females)
		Free T3	↔ (BHg, males, females) ↔ (UHg, males, females)
		TSH	↔ (BHg, males, females) ↔ (UHg, males, females)
		Tg	↓ (BHg, males) ↔ (BHg, females) ↔ (UHg, males, females)
		Anti-Tg	↔ (BHg, males, females) ↔ (UHg, males, females)
		Anti-TPO	↔ (BHg, males, females) ↔ (UHg, males, females)

Table 2-32. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Thyroid Hormones in General Populations

Reference, study type and population	Biomarker	Outcome evaluated	Result
Kim et al. 2022b Cross-sectional; 4,378 adults, 2,399 men and 1,988 women (NHANES 2007–2012)	NHg Gmean: Men: 0.99 µg/L Women: 0.88 µg/L	T4	↔ (BHg, males, females)
		T3	↔ (BHg, males, females)
		T3:T4 ratio	↔ (BHg, males, females)
Nascimento et al. 2018 Cross-sectional: 54 children and adolescents ages 5–15 years (Brazil)	HHg mean Low: 0.2 µg/g High: 0.9 µg/g	T4	↓ (UHg)
		TSH	↑ (HHg)

↑ = positive association; ↓ = inverse association; ↔ = no association; Anti-Tg = thyroglobulin antibodies; Anti-TPO = thyroid peroxidase antibodies; BHg = blood mercury; Gmean = geometric mean; BMeHg = blood methylmercury; HHg = hair mercury; M = maternal; NHANES = National Health and Nutrition Examination Survey; Qi = quintile; T3 = triiodothyronine; T4 = thyroxine; Tg = thyroxin-binding globulin; TSH = thyroid-stimulating hormone; UHg = urine mercury

Glucose homeostasis. Studies evaluating effects of mercury exposure of general populations on glucose homeostasis (type 2 diabetes, insulin resistance, and β-cell function) report conflicting results, with most studies showing no associations; studies are summarized in Table 2-33. Type 2 diabetes is the most studied outcome for effects of mercury exposure on glucose homeostasis. Results are conflicting, but study results generally indicate that alteration in glucose homeostasis is not a sensitive effect of mercury in general populations. A large meta-analysis did not find associations between biomarkers and all diabetes (Guo et al. 2023). Two prospective studies of U.S. populations, with 18–20-year follow-up periods, provide conflicting results (He et al. 2013; Mozaffarian et al. 2013). He et al. (2013) reported a positive association between NHg and type 2 diabetes, whereas Mozzaffarian et al. (2013), in a larger study population, did not find an association. Mozzaffarian et al. (2013) conducted a meta-analysis of combined data from both studies, with results showing no association. A cross-sectional study of Taiwanese adults reported a positive association between erythrocyte mercury and type 2 diabetes (Tsai et al. 2019), although a cross-sectional study of Korean adults did not find an association between BHg and type 2 diabetes (Moon 2013). Kim et al. (2015c) reported a positive association between NHg and insulin resistance in men, but not in women, whereas Moon (2013) did not find associations between BHg and insulin resistance or β-cell function in adults. A large cross-sectional study (n=30,994) of adults reported inverse relationship between BHg and blood methylmercury and type 2 diabetes (Zhang et al. 2021a).

Table 2-33. Overview of Epidemiological Studies Evaluating Associations between Mercury Exposure (Predominant Mercury Form Unknown) Glucose Homeostasis in General Populations

Reference, study type and population	Biomarker	Outcome evaluated			
		Insulin resistance	β-cell function	Type 2 diabetes	Diabetes mellitus
Chang et al. 2011 Cross-sectional; 1,449 adults (Taiwan)	BHg mean: 10.8 µg/L	↑ (BHg)	–	–	–
Guo et al. 2023 Meta-analysis of eight studies with combined 40,891 subjects	No combined quantitative data reported for biomarkers; biomarkers in individual studies were BHg, ErHg, UHg, and HHg	–	–	↔ (meta-analysis)[a]	–
He et al. 2013 Prospective; 3,875 adults, followed for 18 years; free of diabetes in 1987 with follow-up until 2005; CARDIA cohort, (United States)	NHg quintile median: Qi1: 0.073 µg/g Qi2: 0.139 µg/g Qi3: 0.213 µg/g Qi4: 0.331 µg/g Qi5: 0.607 µg/g	–	–	↑ (NHg, Qi5)	–
Kim et al. 2015c Cross-sectional; 2,643 men and 2,745 women (KNHANES 2008–2010)	Men BHg quartile median Q1: 2.6 µg/L Q2: 4.3 µg/L Q3: 6.1 µg/L Q4: 11.5 µg/L Women BHg quartile median Q1: 2.0 µg/L Q2: 3.0 µg/L Q3: 4.2 µg/L Q4: 7.5 µg/L	↑ (BHg, men, Q4) ↔ (BHg, women)	–	–	–
Lee et al. 2017d Cross-sectional; 5,184 adults, 2,523 men and 2,661 women (KNHANES)	BHg mean Men: 5.88 µg/L Women: 4.11 µg/L BHg quartiles: Men: Q1: 0.68–3.54 µg/L Q2: 3.55–5.13 µg/L Q3: 5.14–7.41 µg/L Q4: 7.42–56.97 µg/L	↑ (BHg, men, Q4) ↔ (BHg, women)	–	–	–

Table 2-33. Overview of Epidemiological Studies Evaluating Associations between Mercury Exposure (Predominant Mercury Form Unknown) Glucose Homeostasis in General Populations

Reference, study type and population	Biomarker	Outcome evaluated			
		Insulin resistance	β-cell function	Type 2 diabetes	Diabetes mellitus
	Women: Q1: 0.76–2.54 µg/L Q2: 2.55–3.56 µg/L Q3: 3.57–4.94 µg/L Q4: 4.95–33.93 µg/L				
Moon 2013 Cross-sectional; 2,851 adults without diabetes and 333 adults with diabetes (KNHANES 2009–2010)	BHg mean with diabetes: 4.42 µg/L BHg mean, without diabetes: 4.37 µg/L	↔ (BHg)	↔ (BHg)	↔ (BHg)	−
Moon et al. 2022 Cross-sectional; 3,787 adults, ≥19 years of age, 1,648 males and 2,139 females (KNHANES 2015–2017)	BHg quartiles Q1: <1.86 µg/L Q2: 1.86–<2.81 µg/L Q3: 2.81–<4.44 µg/L Q4: ≥4.44 µg/L UHg quartiles: Q1: <0.20 µg/L Q2: 0.20–<0.35 µg/L Q3: 0.35–<0.64 µg/L Q4: ≥0.64 µg/L	−	−	−	↑ (BHg men, Q3) ↑ (BHg, women, Q4) ↑ (UHg, men, Q4) ↑ (UHg, women, Q2)
Mozaffarian et al. 2013 Prospective cohort; 9,267 adults without diabetes at study enrollment (2,541 men and 6,726 women) from the HPFS (men) and NHS (women) cohorts, with follow-up of approximately 20 years (United States)	NHg median Men: 0.30 µg/g Women: 0.21 µg/g	−	−	↔ (NHg)	−

Table 2-33. Overview of Epidemiological Studies Evaluating Associations between Mercury Exposure (Predominant Mercury Form Unknown) Glucose Homeostasis in General Populations

Reference, study type and population	Biomarker	Outcome evaluated			
		Insulin resistance	β-cell function	Type 2 diabetes	Diabetes mellitus
Mozaffarian et al. 2013 Meta-analysis; combined data from He et al. (2013) and Mozaffarian et al. (2013); 13,142 adults (United States)	Combined NHg not reported; see individual study biomarker data	−	−	↔ (NHg)	−
Tsai et al. 2019 Cross-sectional; 646 adults (Taiwan NAHSIT 2005–2008)	ErHg Gmean with diabetes: 18.95 ErHg Gmean without diabetes: 13.21	−	−	↑ (ErHg)	−
Valcke et al. 2019 Cross-sectional; 70 adults, 42 men and 28 women (Canada)	BHg Gmean Men: 0.82 µg/L Women: 0.58 µg/L UHg Gmean Men: 0.33 µg/g Cr Women: 0.65 µg/g Cr	−	−	↔ (BHg, men and women) ↔ (UHg, men and women)	−
Zhang et al. 2021a Cross-sectional; 30,994 adults with total BHg measurements and 15,327 adults with BMeHg measurements	BHg mean: 1,57 µg/L BMeHg mean:1.38 µg/L Total BHg quartiles: Q1: ≤0.44 Q2: 0.45–0.84 Q3: 0.85–1.69 Q4: >1.69 BMeHg quartiles: Q1: ≤0.22 Q2: 0.23–0.57 Q3: 0.585–1.43 Q4: >1.43	−	−	↓ (BHg, Q3) ↓ (BMeHg, trend)	−

[a]Includes both type 2 diabetes and diabetes mellitus.

↑ = positive association; ↔ = no association; – = not reported; BHg = blood mercury; BMeHg = blood methylmercury; CARDIA = Coronary Artery Risk Development in Young Adults; ErHg = erythrocyte mercury; Cr = creatinine; Gmean = geometric mean; HHg = hair mercury; HPFS = Health Professionals Follow-up Study; KNHANES = Korea National Health and Nutrition Examination Survey; NAHSIT = National Nutrition and Health survey in Taiwan; NHg = toenail mercury; NHS = Nurses' Health Study; Q = quartile; Qi = quintile; UHg = urine mercury

Mechanisms of Action. Numerous mechanisms have been proposed that may be involved in mercury-induced effects on thyroid function (Afrifa et al. 2018; Chen et al. 2013; Gallagher and Meliker 2012;

Llop et al. 2015; Soldin et al. 2008; Tan et al. 2009; Zhu et al. 2000). These include: (1) inhibition of the biosynthesis of thioredoxin reductase; (2) binding of mercury to sulfhydryl (SH)-containing ligands in the thyroid; (3) reduced TSH production; (4) inhibition of deiodinases; (5) inhibition of TPO and lysosomal enzymes; and (6) decreased iodine uptake. In addition, mercury has been shown to significantly accumulate in the pituitary and thyroid glands, providing a toxicokinetic mechanism for mercury-induced effects (Kosta et al. 1975).

Potential mechanisms for effects of mercury on pancreatic β-cell function were recently reviewed by Schumacher and Abbott (2017). Proposed mechanisms for β-cell dysfunction include: (1) disruption of cell protein structure and function due to binding of mercury to sulfhydryl groups; (2) inhibition of mitochondrial enzymes; (3) depolarization of mitochondrial membranes; (4) decreased mitochondrial ATP synthesis; and (5) decreased insulin gene expression. These mechanisms can contribute to increased formation of ROS, causing metabolic and oxidative stress to pancreatic β-cells. Mercury biomarkers have also been associated with changes in microbiome profiles observed in gestational diabetes (Zhang et al. 2021c).

2.15 IMMUNOLOGICAL

Overview. Epidemiological and animal studies have investigated effects of mercury on the immune system. Epidemiological studies are available in workers exposed to elemental mercury and in dental workers or children exposed to amalgams, populations with a high fish diet, and in general populations in which the chemical form of mercury exposures are unknown. Immunological endpoints examined were primarily serum antibodies, immunoglobulins, cytokines, and immune cell counts; and findings are often conflicting. The toxicological and clinical significance of associations between mercury biomarkers and these endpoints has not been established. Studies in general populations also examined associations between mercury exposure biomarkers and immunological diseases. Dermal sensitization has been shown in skin patch tests in general populations. Epidemiological studies evaluating associations between mercury biomarkers and thyroid antibodies are discussed in Section 2.14 (Endocrine).

Studies evaluating immune function in animals are available for inhalation exposure to mercury vapor and oral exposure to mercuric chloride, mercuric sulfide, or methylmercury. Oral exposure to mercuric chloride or methylmercury results in the induction of autoimmunity in mouse strains prone to autoimmune disease. Mercury-induced autoimmunity is characterized by the presence of serum antinucleolar antibodies (ANoAs), antinuclear antibodies (ANAs), and/or antichromatin antibodies

(ACAs); polyclonal B-cell activation; elevated serum immunoglobulins; and (with mercuric chloride only) immune complex deposits in the kidney and spleen. Very limited evidence from inhalation studies suggests that elemental mercury can also stimulate the immune system and result in formation of immune complexes. In non-susceptible animals, the majority of data indicate that oral exposure to methylmercury results in immune suppression following exposure during development or adulthood (e.g., decreased antibody production, lymphoproliferative responses; natural killer cell activity); however, there is limited evidence that very low exposure levels may stimulate T-cell immune responses. Available data in non-susceptible animals following oral exposure to inorganic mercury salts are insufficient to determine potential exposure-related effects on the immune system. No inhalation data were available in non-susceptible animals.

The following summarizes results of epidemiological and animal studies on immunological outcomes.

- ***Elemental mercury***
  - *Epidemiology studies*
    - No associations were observed between occupational exposure to elemental mercury or exposure to amalgam and immune system effects. Available studies did not examine the same immunological endpoints; therefore, data are insufficient to draw conclusions on the immunological effects of elemental mercury.
  - *Animal studies*
    - A single study in a mouse strain genetically susceptible to autoimmune disease reported general stimulation of the immune system and formation of immune complexes following intermediate-duration inhalation exposure. No other studies evaluating potential immune effects from exposure to mercury vapor were available.
- ***Inorganic mercury salts***
  - *Epidemiology studies*
    - No epidemiological studies evaluating associations between exposure to inorganic mercury salts and immunological effects were identified.
  - *Animal studies*
    - Immune stimulation and immune complex disease can occur in mouse strains genetically susceptible to autoimmune disease following oral exposure to mercuric chloride.
    - Data in wild-type mice are limited, but report alterations in T- and B-cell subpopulations in immune organs and altered immune responses (some stimulated, some suppressed) following oral exposure to mercuric chloride.

- One study reported alterations in splenic and thymic histology and cell populations in wild-type mice following oral exposure to mercuric sulfide at high doses. No other studies evaluating potential immune effects from exposure to mercuric sulfide were available.

- ***Organic mercury***
  - *Epidemiology studies*
    - Associations between BHg and some immunological markers (serum cytokine levels, immunoglobulins, and immune cell counts) were observed; however, it is not known if immune system function was altered in these study populations.
    - Data are insufficient to determine if exposure to organic mercury is associated with adverse immunological effects.
  - *Animal studies*
    - Immune stimulation in the absence of immune complexes can occur in mouse strains genetically susceptible to autoimmune disease following developmental or post-pubertal (adult) exposure.
    - One developmental study in wild-type mice reports immune stimulation in offspring following exposure during gestation plus lactation.
    - Developmental exposure in rats and adult exposure in wild-type animals are generally associated with immune suppression (decreased antibody production, lymphoproliferative responses; natural killer cell activity); however, limited data suggest that very low doses may be associated with immune stimulation (increased immune responses to T-cell antigens).
- ***Predominant mercury form unknown (general populations)***
    - Studies examining immune diseases found associations between mercury biomarkers and atopic dermatitis (but not eczema), systemic lupus erythematosus (SLE), and celiac disease seropositivity.
    - A few studies found associations between mercury biomarkers and other immunological endpoints (serum cytokines, antibodies, and immune cell counts). The clinical significance of these findings has not been established.
    - Several studies in general populations indicate that mercury exposure induces dermal sensitization based on positive skin patch tests to elemental and/or inorganic mercuric salts.

Confounding Factors. The immune system is responsive to a multitude of environmental and physiological factors, which can be confounding factors in studies of associations between mercury exposure and immunological outcomes. Potential confounders that have been considered in some studies, but not consistently across studies, include age, sex, smoking, physical activity, allergen exposures, history of inflammatory and immune diseases, socioeconomic status (SES) factors, recreational activities, and co-exposures to other chemicals. No specific confounder or covariate was mandatory for the inclusion of the study into the profile; however, studies of immunological outcomes that did not consider the aforementioned potential confounders are potentially more confounded than studies that did consider these variables.

Elemental Mercury—Epidemiological Studies. Immune effects of elemental mercury have not been well studied and few epidemiological studies meeting inclusion criteria were identified (inclusion criteria summarized in Section 2.1). Studies were conducted in chloralkali workers (Barregard et al. 1997; Langworth et al. 1992b; Vimercati et al. 2001), miners (Sanchez Rodriguez et al. 2015),), and children or adults with amalgam fillings (Chen et al. 2021; Shenker et al. 2008); results are summarized in Table 2-34. Studies evaluated several different endpoints, including immune cell counts and function; and serum antibodies, immunoglobulins, immune complexes, cytokines and inflammatory conditions (e.g., primary Sjogren's syndrome). No studies found associations between mercury biomarkers and immunological endpoints. However, studies did not evaluate the same immunological endpoints; therefore, data are not sufficient to determine if occupational exposure to elemental mercury or exposure to amalgam is associated with adverse effects to the immune system.

Table 2-34. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Immunological Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Barregard et al. 1997 Cross-sectional; 41 male chloralkali workers and 41 male controls (Sweden)	BHg mean Workers: 9.2 µg/L Controls: 3.4 µg/L UHg mean Workers: 27 µg/g Controls: 3.4 µg/g	Serum ANA	↔ (workers versus controls)
		Serum CIC	↔ (workers versus controls)
Chen et al. 2021 Case-control; 5,848 cases of primary Sjogren's syndrome and 5848 controls; age ≥18 years (China)	None	PSS diagnosis	↔ (amalgam restorations versus none)

Table 2-34. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Immunological Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Langworth et al. 1992b Cross-sectional; 89 chloralkali workers and 75 controls (Sweden)	BHg median Workers: 11 µg/L Controls: 3 µg/L UHg median Workers: 25.4 µg/g Cr Controls: 1.9 µg/g Cr	Serum IgA	↔ (workers versus controls)
		Serum IgG	↔ (workers versus controls)
		Serum IgM	↔ (workers versus controls)
Sanchez Rodriguez et al. 2015 Cross-sectional; 164 gold miners and 127 controls (Columbia)	BHg median Miners: 7.03 µg/L Controls: 2.46 µg/L UHg median Miners: 3.96 µg/g Cr Controls: 1.48 µg/g Cr HHg median Miners; 0.79 µg/g Controls: 0.39 µg/g	Elevated serum ANA	↔ (miners versus controls)
		Elevated serum RF	↔ (miners versus controls)
Shenker et al. 2008 Randomized clinical trial; 59 children (6–10 years of age at baseline); 29 children randomized to amalgam fillings and 30 randomized to control composite fillings (New England)	BHg, baseline mean Amalgam: 0.4 µg/L Composite: 0.4 µg/L UHg, 5-year mean Amalgam: 0.85 µg/g Cr Composite: 0.68 µg/g Cr	Lymphocyte function	↔ (amalgam versus composite)
		Monocyte function	↔ (amalgam versus composite)
		Neutrophil function	↔ (amalgam versus composite)
Vimercati et al. 2001 Cross-sectional; 19 mercury workers and 25 controls	UHg mean Workers: 9.7 µg/L Controls: 2.4 µg/L	Monocyte-macrophage cell count[a]	↔ (workers versus controls)
		Cytokines	
		IL-8	↔ (workers versus controls)
		GM-CSF	↔ (workers versus controls)
		TNF-α	↔ (workers versus controls)
		NK cell count	↔ (workers versus controls)

[a]Includes the following cell types: leukocytes, lymphocytes, monocytes, CD13, CD14, CD15, CD33D, and CD45.

↔ = no association; ANA = antinuclear antibodies; BHg = blood mercury; CIC = circulating immune complex; Cr = creatinine; GM-CSF = granulocyte-macrophage colony-stimulating factor; HHg = hair mercury; Ig = immunoglobulin; IL = interleukin; PSS = primary Sjogren's syndrome; RF = rheumatoid factor; NK cell = natural killer cell; TNF-α = tumor necrosis factor-alpha; UHg = urine mercury

Elemental Mercury—Animal Studies. A single study evaluating immunological endpoints following inhalation exposure to elemental mercury reported a general stimulation of the immune system in a mouse

strain genetically susceptible to autoimmune disease (Warfvinge et al. 1995). In this study, susceptible SJL/N mice were exposed to 0.3, 0.05, or 1 mg Hg/m^3 for 0.5–19 hours/day, 5 days/week, for 10 weeks (time-weighted average [TWA] concentrations of 0.01–0.4 mg Hg/kg/day). All mice exposed to TWA concentrations ≥0.03 mg Hg/kg/day (absorbed dose of 0.170 mg Hg/kg/week) showed positive ANoA; this was not observed at the TWA concentration of 0.01 mg Hg/kg/day (absorbed dose of 0.075 mg/kg/day). Mice exposed to TWA concentrations ≥0.06 mg Hg/kg/day also showed B-cell stimulation (increased serum immunoglobins) and glomerular disease accompanied by vascular immune complex deposits.

Inorganic Mercury Salts—Animal Studies. Data from oral studies indicate that exposure to mercuric chloride can result in immune stimulation and immune complex disease in mouse strains genetically susceptible to autoimmune disease. Positive antinucleolar antibody (ANoA) and/or antinuclear antibody (ANA) and immune complex effects (e.g., renal, splenic, and cardiac vessel immune deposits, renal mesangium deposits) were observed in susceptible strains of mice at ≥0.14 mg Hg/kg/day for up to 10 weeks (Amirhosseini et al. 2021; Hultman and Enestrom 1992; Hultman and Nielsen 2001; Nielsen and Hultman 2002). Additional effects included polyclonal B-cell activation in mice at ≥0.118 mg Hg/kg/day, and elevated serum IgE mice at ≥0.942 mg Hg/kg/day. Another series of studies reported induction of serum IgG antibodies to brain antigens and/or elevated serum IgG in dams and offspring in susceptible mouse strains following gestational and lactation exposure to 2.7 mg Hg/kg/day (Zhang et al. 2011, 2013). Additional findings in offspring only included IgG deposits in the brain and brain inflammation. Immune stimulation was not observed in similarly exposed wild-type A/WySnJ dams or offspring (Zhang et al. 2011). However, immune stimulation (increased splenocyte proliferation and interferon gamma (IFNγ) and interleukin-4 (IL-4) production in mitogen assay) was observed in wild-type DBF1 adult offspring (progeny of DBA/1 males × BALB/c females) following exposure to 1.5 mg Hg/kg/day throughout gestation (Pilones et al. 2009).

Data on immunotoxicity in wild-type adult mice following exposure to mercuric chloride is limited. In an acute-duration study, changes in immune cell populations of the spleen and thymus were observed in BALB/c mice following exposure to mercuric chloride for 14 days, including dose-related changes in T-lymphocytes (CD3+), T-helper (CD4+), and T-suppressor (CD8+) cells in the spleen at ≥0.31 mg Hg/kg/day and CD4-/CD8+ suppressor cells in the thymus at ≥1.39 mg Hg/kg/day (Kim et al. 2003). In an intermediate-duration study, dose-related increases in splenocyte proliferation in response to the B-cell antigen *Escherichia coli* lipopolysaccharide (LPS) were observed in B6C3F1 mice exposed to ≥2 mg Hg/kg/day, respectively, for 7 weeks (Dieter et al. 1983). Non-dose-dependent decreases in mitogenic

response to T-cell antigens (concanavalin A, phytohemagglutinin) and mixed lymphocyte responses were also observed at ≥2 mg Hg/kg/day. In the plaque-forming assay, exposed mice showed a 60% decrease in the antibody response to a T-dependent antigen (sheep red blood cells) at 11 mg Hg/kg/day; no changes in the antibody response to the B-cell antigen LPS were observed. No exposure-related changes in serum IgG, IgM, or IgA were observed (Dieter et al. 1983).

No histopathological changes in the bone marrow, thymus, or spleen were observed in rats after acute-, or chronic-duration oral exposure to mercuric chloride doses up to 9.23, 4, or 4 mg Hg/kg/day, respectively, or in mice after chronic-duration oral exposure to doses up to 7.4 mg Hg/kg/day, respectively (NTP 1993). Intermediate-duration studies in rats describe severe necrosis and decreased cellularity in the spleen at 0.847 mg Hg/kg/day (Venter et al. 2020), while other studies report no histological effects on the bone marrow, thymus, or spleen at doses up to 4 mg Hg/kg/day (Dieter et al. 1983, 1992). Son et al. (2010) found treatment-related changes in T-lymphocyte populations in the spleen in mice exposed to ≥17 mg Hg/kg/day, including increased CD4+CD8+ and CD8 single-positive lymphocytes. There were no treatment related changes in T-lymphocytes of the thymus. Pathological findings observed at 1,700 mg Hg/kg/day included enlargement of the spleen and marked hyperplasia of the white pulp, increased cellular density in the splenic lymphoid follicles, and increased density of lymphoid cells in the thymus. There was no exposure-related effect on splenocyte or thymocyte proliferation.

One study evaluated immune endpoints in ICR mice following oral exposure to mercuric sulfide for 4 weeks (Son et al. 2010). Treatment-related changes in T-lymphocyte populations in the spleen were observed at ≥17 mg Hg/kg/day, including increased CD4+CD8+ and CD8 single-positive lymphocytes. There were no treatment related changes in T-lymphocytes of the thymus. Pathological findings observed at 1,700 mg Hg/kg/day included enlargement of the spleen and marked hyperplasia of the white pulp, increased cellular density in the splenic lymphoid follicles, and increased density of lymphoid cells in the thymus. There was no exposure-related effect on splenocyte or thymocyte proliferation.

Organic Mercury—Epidemiological Studies. Few studies have evaluated immunological effects in populations with high fish diets; studies meeting inclusion criteria are summarized in Table 2-35 (inclusion criteria, Section 2.1). Studies consist of two prospective studies in children (Hui et al. 2016; Oulhote et al. 2017a), one cross-sectional study in mother-infant pairs (Nyland et al. 2011), two prospective cohort studies in pregnant women (McSorley et al. 2018, 2020), and a cohort of children (Wyatt et al. 2019). Endpoints examined include serum levels of cytokines (Hui et al. 2016; McSorley et al. 2018, 2020; Nyland et al. 2011) and immunoglobulins (Hui et al. 2016; Nyland et al. 2011), immune

cell counts (Oulhote et al. 2017a), anti-nuclear proteins (McSorley et al. 2020), and antibody response to vaccinations (Wyatt et al. 2019).

Table 2-35. Results of Epidemiological Studies Evaluating Immunological Effects in Populations with High Fish Diets

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Hui et al. 2016 Prospective; 407 children from a high fish-eating population; cytokines measured at ages 6–9 years (China)	BHg median Cord: 9.2 µg/L Current: 2.6 µg/L	Cytokines	
		IL-4	↔ (BHg, cord and current)
		IL-5	↔ (BHg, cord and current)
		IL-6	↔ (BHg, cord and current)
		IL-8	↔ (BHg, cord and current)
		IL-10	↔ (BHg, cord), ↓ (BHg, current)
		IL-13	↔ (BHg, cord and current)
		TNF-α	↔ (BHg, cord and current)
McSorley et al. 2018 Prospective cohort; 1,158 pregnant women assessed at 28 weeks of gestation (Seychelles)	BHg mean: 18.14 µg/L	Th1 cell cytokines	
		IL-1β	↓ (BHg)
		IL-2	↓ (BHg)
		IFN-γ	↔ (BHg)
		TNF-α	↓ (BHg)
		Total	↓ (BHg)
		Th2 cell cytokines	
		IL-4	↓ (BHg)
		IL-5	↔ (BHg)
		IL-10	↓ (BHg)
		Total	↔ (BHg)
		Th1:Th2 cytokine ratio	↓ (BHg)
		Other cell cytokines	
		CRP	↓ (BHg)
		IL-6	↔ (BHg)
		MCP-1	↔ (BHg)
		TARC	↑ (BHg)
		sFlt-1	↔ (BHg)
		VEGF-D	↑ (BHg)
McSorley et al. 2020 Prospective cohort; 497 mother-child pairs assessed at age 19 years (Seychelles)	HHg mean Maternal: 6.84 µg/g Child: 10.23 µg/g	ANA	↔ (BHg maternal) ↑ (BHg child)
		A-RNP	↔ (BHg maternal) ↔ (BHg child)
		Immunoglobulins	
		IgG	↔ (BHg maternal, child)
		IgM	↔ (BHg maternal) ↓ (BHg child)
		IgA	↔ (BHg maternal, child)

Table 2-35. Results of Epidemiological Studies Evaluating Immunological Effects in Populations with High Fish Diets

Reference, study type, and population	Biomarker	Outcome evaluated	Result
		Cytokines	
		IL-1 beta	↔ (BHg maternal, child)
		IL-2	↔ (BHg maternal, child)
		IL-6	↔ (BHg maternal, child)
		IL-10	↔ (BHg maternal)
		TNF-α	↑ (BHg child)
		IFN-γ	↔ (BHg maternal, child)
		NF-α:IL-10 ratio	↔ (BHg maternal) ↓ (BHg child)
		CRP	↔ (BHg maternal) ↑ (BHg child)
Nyland et al. 2011 Cross-sectional; 61 mother-infant pairs (Brazilian Amazon); fetal and immune responses were assessed	BHg Gmean Maternal: 6.90 µg/L Cord: 9.63 µg/L	IgG	↓ (BHg, maternal and cord)
		IgA, IgE, IgM	↔ (BHg, maternal and cord)
		ANA	↓ (BHg, maternal and cord)
		Cytokines	
		IL-1β	↑ (BHg, maternal and cord)
		IL-6	↑ (BHg, maternal and cord)
		IL-1ra	↔ (BHg, maternal and cord)
		TNF-α	↑ (BHg, maternal and cord)
		IFN-γ	↔ (BHg, maternal and cord)
Oulhote et al. 2017a Prospective 53 mother-child pairs; endpoints assessed at 5 years of age (Faroe Islands)	BHg Gmean Maternal: 3.066 µg/L Cord: 4.649 µg/L Child age 5-years: 2.328 µg/L HHg Gmean Maternal: 0.748 µg/L Child age 5-years: 0.611 µg/L Maternal exposure based on a composite factor of cord and maternal BHg and maternal HHg; child exposures based on a composite of child BHg and HHg at 5 years of age	WBC counts	
		Neutrophils	↔ (BHg, maternal and cord)
		Basophils	↔ (BHg, maternal and cord)
		Eosinophils	↔ (BHg, maternal and cord)
		Lymphocytes	↓ (BHg, maternal) ↔ (BHg, cord)
		Monocytes	↔ (BHg, maternal and cord)
		Total WBCs	↓ (BHg, maternal) ↔ (BHg, cord)
		Lymphocyte counts	
		CD3	↓ (BHg, maternal) ↔ (BHg, cord)
		CD4	↓ (BHg, maternal) ↔ (BHg, cord)
		CD8	↔ (BHg, maternal and cord)
		CD4-RTE	↓ (BHg, maternal) ↔ (BHg, cord)
		NK cells	↔ (BHg, maternal and cord)
		B-lymphocytes	↓ (BHg, maternal) ↔ (BHg, cord)

Table 2-35. Results of Epidemiological Studies Evaluating Immunological Effects in Populations with High Fish Diets

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Wyatt et al. 2019 Longitudinal study of children, age 4–8 years (n=98), Peru	HHg Mean:1.5 µg/g	Post-vaccination diphtheria-specific antibodies response	↓ (BHg, child with malnutrition)
		Post-vaccination measles-specific antibody response	↓ (BHg, child with malnutrition)
		Post-vaccination pertussis-specific antibody response	↓ (BHg, child with malnutrition)

↑ = positive association; ↓ = inverse association; ↔ = no association; ANA = anti-nuclear antibodies; A-RNP = anti-ribonuclear protein; BHg = blood mercury; CD3 = T-cells; CD4 = t-helper cells; CD8 = t-cytotoxic cells; CD4-RTE = CD4+ recent thymic emigrant cells; CRP = C-reactive protein; Gmean = geometric mean; IFN-γ = interferon-gamma; Ig = immunoglobulin; IL = interleukin; MCP-1 = monocyte chemotactic protein-1; NK cells = natural killer cells; sFlt-1 = soluble fms-like tyrosine kinase-1; TARC = thymus- and activation-regulated chemokine; Th1 = T-helper cell 1 (cell-mediated immunity); Th2 = T-helper cell 2 (humoral immunity); TNF-α = tumor necrosis factor-alpha; VEGF-D = vascular endothelial growth factor-D; WBC = white blood cell

Plasma cytokine levels are the only immunological endpoint evaluated in more than one study; however, results are conflicting. Inverse associations were observed between BHg and several cytokines in a cohort of pregnant women (McSorley et al. 2018); however, the study authors noted that changes were small and of unknown clinical significance. A follow-up of children in this cohort at age 19 years found associations between increasing child HHg level (but not maternal HHg levels) and decreasing serum IgM, increasing interleukin-10, and increasing C-reactive protein (McSorley et al. 2020). No associations were observed in this study for other immunological endpoints including serum levels of other cytokines (interleukins, tumor necrosis factors) or antibodies (IgA, IgG, anti-nuclear proteins). In contrast, a prospective study in children did not find any associations between cord or child BHg and several interleukins and tumor necrosis factor-alpha (Hui et al. 2016), and positive associations were observed between maternal and cord BHg and some cytokines in mothers and infants in a cross-sectional study (Nyland et al. 2011). In addition to plasma cytokine levels, Nyland et al. (2011) also reported an inverse association between mother and cord BHg and plasma IgG levels, but not IgA, IgE, or IgM; the toxicological significance of this association was not established. For cell counts, inverse associations were observed between maternal and child BHg and total leukocyte and total lymphocyte counts, and some lymphocyte subpopulation counts (CD3, CD4, and B cells) (Oulhote et al. 2017a). Cell counts for CD4-RTE also were inversely associated with BHg in mothers, but not in children. Although associations between BHg and some immunological endpoints were observed, it is not known if alterations in immune markers or cell counts are associated with compromised immune system function in

these study populations. A study of children who resided in the Amazonian River Basin, where exposure to dietary methylmercury occurs as a result of wastes from gold mining operations, found decreased antibody response to diphtheria, measles, and pertussis vaccinations in association with a combination of malnutrition and increasing HHg (Wyatt et al. 2019).

Organic Mercury—Animal Studies. Most available data are from oral intermediate-duration studies. Data indicate that exposure to methylmercury can result in immune stimulation in the absence of an immune complex formation in mouse strains genetically susceptible to autoimmune disease. There is limited evidence of immune stimulation in wild-type mice following developmental exposure. Developmental exposure in rats and exposure during adulthood in rats, mice, and rabbits is generally associated with immune suppression; however, there are limited data for immune stimulation at very low doses.

Polyclonal B-cell activation and serum ANoA and ACA were observed in autoimmune susceptible A.SW mice at 0.420 mg Hg/kg/day immediately after a 30-day exposure to methylmercury; ANoA was still detected 8 weeks post-exposure. Serum IgG was elevated immediately and 2 weeks after the 30-day exposure; serum IgE was not significantly elevated. No significant increases in tissue immune complex deposits were observed in the kidneys or spleen at any timepoint (Havarinasab et al. 2007). Another study evaluated immune stimulation in A.SW dams and offspring following gestational and lactation exposure to methylmercury at 0.06 mg Hg/kg/day (Zhang et al. 2011). No evidence of serum IgG antibodies to brain antigens or IgG deposition in the brain was observed in dams or offspring; however, cerebellar inflammation was observed in exposed female offspring and IL-12 was decreased in male offspring at PND 21. Exposure-related changes were not observed in similarly exposed wild-type A/WySnJ dams or offspring (Zhang et al. 2011).

Functional immune assays in rats and wild-type mice following developmental exposure to methylmercury indicate a complicated pattern of immunomodulatory effects, including nonmonotonic findings and differential findings between rats and mice (Table 2-36). In rats, low exposure levels during gestation and lactation periods are associated with increased lymphoproliferative responses to T-cell mitogens, with smaller or no effect at higher exposure levels (Ilback et al. 1991; Tonk et al. 2010; Wild et al. 1997). No clear pattern was observed for cytokine release in response to T-cell mitogens (Tonk et al. 2010). Exposure during the postnatal period only was associated with a decreased response in rat offspring (Ilback et al. 1991). Other findings in rat offspring following gestational plus lactational exposure generally indicate immune suppression, including decreased lymphoproliferation in response to

B-cell mitogens, decreased antibody production and cytokine release in response to the Keyhole Limpet hemocyanin antigen, and decreased natural killer cell activity (Ilback et al. 1991; Tonk et al. 2010; Wild et al. 1997). Data in wild-type mice following developmental exposure are limited to a single study, which reports decreased lymphoproliferative responses to T-mitogens at low doses, with increased responses at higher doses, increased lymphoproliferative responses to B-mitogens, increased antibody production following influenza inoculation, and increased natural killer cell activity (Thuvander et al. 1996).

Table 2-36. Functional Immune Assays in Rodents Orally Exposed to Methylmercury During Development[a]

Species; duration	Dose (mg Hg/kg/day)	T-cell mitogen	B-cell mitogen	CK production	AB production	NKC activity	Reference (compound)
Rat; 15 days [PNDs 1–15]	0.37	Con A Th: ↔ Sp: ↓ (32)[b] [PND 15]	LPS: ↔	–	–	Sp: ↔	Ilback et al. 1991 (MM)
Rat 26 days [GD 6–PND 10]	0.08	Con A: ↔	LPS: ↔	Con A: ↑ (20)[c] [PND 70] KHL: ↔ [PND 63]	KHL: ↓ (30)[c] [PND 35]	Sp: ↔ [PND 70]	Tonk et al. 2010 (MMC)
Rat 26 days [GD 6–PND 10]	0.3	Con A: ↔	LPS: ↓ (8)[c] [PND 42]	Con A: ↓ (6)[c] [PND 70] KHL: ↓ (28)[c] [PND 63]	KHL: ↓ (55)[c] [PND 35]	Sp: ↓ (>5)[d] [PND 70]	Tonk et al. 2010 (MMC)
Rat 26 days [GD 6–PND 10]	0.6	Con A: ↔	LPS: ↓ (21)[c] [PND 42]	Con A: ↑ (24)[c] [PND 70] KHL: ↓ (34)[c] [PND 63]	KHL: ↓ (70)[c] [PND 35]	Sp: ↓ (>5)[d] [PND 70]	Tonk et al. 2010 (MMC)
Rat 26 days [GD 6–PND 10]	0.8	Con A: ↔	LPS: ↓ (32)[c] [PND 42]	Con A: ↑ (26)[c] [PND 70] KHL: ↓ (36)[c] [PND 63]	KHL: ↓ (75)[c] [PND 35]	Sp: ↓ (>5)[d] [PND 70]	Tonk et al. 2010 (MMC)
Rat 26 days [GD 6–PND 10]	1.2	Con A: ↔	LPS: ↓ (22)[c] [PND 42]	Con A: ↑ (28)[c] [PND 70] KHL: ↓ (3)[c] [PND 63]	KHL: ↓ (55)[c] [PND 35]	Sp: ↓ (>5)[d] [PND 70]	Tonk et al. 2010 (MMC)

Table 2-36. Functional Immune Assays in Rodents Orally Exposed to Methylmercury During Development[a]

Species; duration	Dose (mg Hg/kg/day)	T-cell mitogen	B-cell mitogen	CK production	AB production	NKC activity	Reference (compound)
Rat 26 days [GD 6–PND 10]	1.6	Con A: ↔	LPS: ↓ (>5)[d] [PND 70]	Con A: ↑ (96)[c] [PND 70] KHL: ↓ (54)[c] [PND 63]	KHL: ↓ (95)[c] [PND 35]	Sp: ↓ (>5)[d] [PND 70]	Tonk et al. 2010 (MMC)
Rat 105 days [8 weeks PM–PND 21]	0.0006	Con A: ↔ PWM ↑ (250)[b] [PND 42] ↑ (110)[b] [PND 84]	–	–	–	Sp: ↓ (56)[b] [PND 84]	Wild et al. 1997 (MMC)
Rat 105 days [8 weeks PM–PND 21]	0.003	Con A: ↑ (9)[b] PWM ↑ (120)[b] [PND 84]	–	–	–	Sp: ↔	Wild et al. 1997 (MM2S)
Rat 105 days [8 weeks PM–PND 21]	0.06	Con A: ↑ (290)[b] [PND 42] PWM ↑ (160)[b] [PND 42] ↑ (88)[b] [PND 84]	–	–	–	Sp: ↓ (56)[b] [PND 84]	Wild et al. 1997 (MMC)
Rat 105 days [11 weeks PM–GD 21]	0.37	Con A: ↔	LPS: ↔	–	–	Sp: ↔	Ilback et al. 1991 (MM)
Rat 119 days [11 weeks PM–PND 15]	0.37	Con A Th: ↑ (47)[b] Sp: 0 [PND 15]	LPS: ↔	–	–	Sp: ↓ (42)[b] [PND 15]	Ilback et al. 1991 (MM)
Mouse 112 days [10 weeks PM–PND 15]	0.098	Con A Th: ↔ Sp:↓ (45)[b] [PND 50]	LPS: ↔	–	Influenza: ↑ (11)[b] [14 dpi] 0 [35 dpi]	Sp: ↔	Thuvander et al. 1996 (MMC)

Table 2-36. Functional Immune Assays in Rodents Orally Exposed to Methylmercury During Development[a]

Species; duration	Dose (mg Hg/kg/day)	T-cell mitogen	B-cell mitogen	CK production	AB production	NKC activity	Reference (compound)
Mouse 112 days [10 weeks PM–PND 15]	0.98	Con A Th: ↔ Sp: ↑ (50)[b] [PND 50]	LPS: S: ↑ (35)[b] [PND 22] S: ↑ (25)[b] [PND 50]	–	Influenza: ↔ [14 or 35 dpi]	Sp: ↑ (255)[b] [PND 22] Sp: ↔ [PND 50]	Thuvander et al. 1996 (MMC)

[a]Studies with exposure prior to puberty only, including studies that evaluate adult animals after developmental exposure. These findings are listed under "Develop" in the LSE table.
[b]Percent change compared to control, calculated from quantitative data.
[c]Percent change compared to control, estimated from graphically presented data.
[d]Dose-specific data not reported; data based on reported BMD_5 values.

↑ = increased; ↓ = decreased; ↔ = no change; – = not assessed; AB = antibody; BMD = benchmark dose; Con A = concanavalin A (T-cell mitogen); dpi = days post-infection; GD = gestation day; KHL = Keyhole Limpet hemocyanin; LPS = *Escherichia coli* lipopolysaccharide (B-cell mitogen); LSE = Level of Significant Exposure; MM = methylmercury; MM2S = bis(methylmercury)sulfide; MMC = methylmercuric chloride; NKC = natural killer cell; PM = premating; PND = postnatal day; PWM = pokeweed mitogen (T-cell mitogen); Sp = spleen/splenocytes; Th = thymus/thymocytes

Studies evaluating functional immune assays in animals following exposure during adulthood are reviewed in Table 2-37. Intermediate-duration functional immune assays in laboratory animals orally exposed to methylmercury during adulthood generally show dose-related suppression of immune function, including suppressed antibody production in response to antigen exposure, decreased IgM- and IgG producing cells in the spleen during the plaque forming assay, and decreased natural killer cell activity in the blood and the spleen (Blakley et al. 1980; Ilback 1991; Koller et al. 1977).

In an 8-week exposure to methylmercuric chloride, it was observed that male rats had an initial increase in the lymphoproliferative response to T-cell mitogens at 0.0004 mg/kg/day prior to proliferative suppression at the higher dose (0.04 mg/kg/day) (Ortega et al. 1997b). Different response patterns were observed with different forms of methylmercury [methylmercury chloride, methylmercury sulfide, bis(methylmercury)sulfide, tris(methylmercuric)sulphonium ion] (Ortega et al. 1997a, 1997b). One study reported increased lymphoproliferation in mice in response to a B-cell mitogen; no change was observed for T-cell mitogen responses (Ilback 1991).

Table 2-37. Functional Immune Assays in Laboratory Animals Orally Exposed to Methylmercury During Adulthood

Species; duration	Dose (mg Hg/kg/day)	Mitogen	HG titers	AB production	PFA	NKC activity	Reference (compound)
Rat; 56 days	0.0004	PHA: ↑ (533)[a] Con A: ↑ (313)[a]	–	–	–	–	Ortega et al. 1997a, 1997b (MMC)
Rat; 56 days	0.0004	PHA: ↑ (267)[a]	–	–	–	–	Ortega et al. 1997a (MMS)
Rat; 56 days	0.0004	PHA: ↑ (300)[a] Con A: ↑ (150)[a]	–	–	–	–	Ortega et al. 1997a, 1997b (MM2S)
Rat; 56 days	0.0004	PHA: ↓ (56)[a]	–	–	–	–	Ortega et al. 1997a (MM3S)
Rat; 56 days	0.04	PHA: ↓ (67)[a] Con A: ↓ (67)[a]	–	–	–	–	Ortega et al. 1997a, 1997b (MMC)
Rat; 56 days	0.04	PHA: ↔	–	–	–	–	Ortega et al. 1997a (MMS)
Rat; 56 days	0.04	PHA: ↔ Con A: ↑ (280)[a]	–	–	–	–	Ortega et al. 1997a, 1997b (MM2S)
Rat; 56 days	0.04	PHA: ↓ (56)[a]	–	–	–	–	Ortega et al. 1997a (MM3S)
Rat; 112 days	0.0004	Con A: ↓ (79)[a]	–	–	–	–	Ortega et al. 1997b (MMC)
Rat; 112 days	0.0004	Con A: ↓ (69)[a]	–	–	–	–	Ortega et al. 1997b (MM2S)
Rat; 112 days	0.04	Con A: ↓ (86)[a]	–	–	–	–	Ortega et al. 1997b (MMC)
Rat; 112 days	0.04	Con A: ↑ (173)[a]	–	–	–	–	Ortega et al. 1997b (MM2S)
Mouse; 21 days	0.08	–	SRBC: ↓ (23)[b] LPS: ↓ (31)[b]	LPS: ↓ (39)[b] [28 dpi]	PFA[c]: 1°:↓ (43)[b] 2°:↓ (19)[b]	–	Blakley et al. 1980 (MMC)

Table 2-37. Functional Immune Assays in Laboratory Animals Orally Exposed to Methylmercury During Adulthood

Species; duration	Dose (mg Hg/kg/day)	Mitogen	HG titers	AB production	PFA	NKC activity	Reference (compound)
Mouse; 21 days	0.35	–	SRBC: ↓ (43)[b] LPS: ↓ (45)[b]	LPS: ↓ (53)[b] [28 dpi]	PFA[c]: 1°:↓ (56)[b] 2°:↓ (27)[b]	–	Blakley et al. 1980 (MMC)
Mouse; 21 days	1.7	–	SRBC: ↓ (36)[b] LPS: ↓ (45)[b]	LPS: ↓ (56)[b] [28 dpi]	PFA[c]: 1°:↓ (58)[b] 2°:↓ (24)[b]	–	Blakley et al. 1980 (MMC)
Mouse; 84 days	0.77	Con A Th: ↔ Sp: ↑ (20)[b] LPS: ↔	–	–	–	Bl: ↓ (75)[b] Sp: ↓ (44)[b]	Ilback 1991 (MM)
Rabbit; 98 days	0.05	–	–	Influenza: ↔	–	–	Koller et al. 1977 (MMC)
Rabbit; 98 days	0.49	–	–	1°:↓ (50)[b] [7 dpi] 2°:↓ (50)[b] [24 dpi]	–	–	Koller et al. 1977 (MMC)
Rabbit; 98 days	0.53	–	–	1°:↓ (75)[b] [7 dpi] 2°:↓ (50)[b] [24 dpi]	–	–	Koller et al. 1977 (MMC)

[a]Percent change compared to control, estimated from graphically presented data.
[b]Percent change compared to control, calculated from quantitative data.
[c]Primary (1°) response is production of IgM-producing cells in the spleen; secondary (2°) response is production of IgG-producing cells in the spleen.

↑ = increased; ↓ = decreased; ↔ = no change; – = not assessed; AB = antibody; Bl = blood; Con A = concanavalin A (T-cell mitogen); dpi = days post-infection; HG = hemagglutination; Ig = immunoglobulin; LPS = *Escherichia coli* lipopolysaccharide (B-cell mitogen); MM = methylmercury; MM2S = bis(methylmercury)sulfide; MM3S = tris(methylmercuric)sulphonium ion; MMC = methylmercuric chloride; MMS = methylmercury sulfide; NKC = natural killer cell; PFA = plaque-forming assay with SRBCs; PHA = phytohemagglutinin (T-cell mitogen); Sp = spleen; Th = thymus; SRBC = sheep red blood cell

Plasma IL-6 was elevated in rats exposed to ≥0.0004 mg Hg/kg/day as methylmercuric chloride or 0.004 mg Hg/kg/day as bis(methylmercury)sulfide for 8 weeks (Ortega et al. 1997b). With exposure for 16 weeks, plasma IL-6 levels were significantly elevated with exposure to ≥0.0004 mg Hg/kg/day as bis(methylmercury)sulfide (although there was not an increasing response at the higher dose) or 0.04 mg Hg/kg/day as methylmercuric chloride. These results are difficult to interpret due to lack of a clear dose- and duration-dependence. Nascimento et al. (2022) reported increased levels of plasma tumor necrosis factor (TNF) and circulating lipopolysaccharide (LPS) in mice exposed to 0.21 mg Hg/kg/day as

methylmercuric chloride for 30 days, compared to controls; no additional immunological endpoints were assessed. Increased serum IFN-γ was observed in mice exposed to 0.16 mg Hg/kg/day methylmercuric chloride for 28 days (Al-Mazroua et al. 2022).

Data for spleen and thymic weight and cellularity following developmental or adult exposure to methylmercury are presented in Table 2-38. There is limited evidence of increased thymus weight and/or cellularity in rodents following intermediate-duration developmental exposure to methylmercury (Thuvander et al. 1996; Tonk et al. 2010; Wild et al. 1997). In contrast, decreased thymus weight and cellularity were reported in a single intermediate-duration adult exposure study (Ilback et al. 1991). Available data are not adequate to assess dose- or duration-dependence of thymic changes for either exposure paradigms. No consistent, exposure-related changes in spleen weight or cellularity have been observed in rodents following developmental or adult exposure (Table 2-38).

Table 2-38. Immune Organ Weight and Cellularity in Rodents Orally Exposed to Methylmercury

Species; duration	Dose (mg Hg/kg/day)	Spleen weight	Spleen cellularity	Thymus weight	Thymus cellularity	Reference (compound)
Developmental exposure[a]						
Rat; 15 days [PNDs 1–15]	0.37	Relative: ↓ (13)[b] [PND 15]	↔	↔	↔	Ilback et al. 1991 (MM)
Rat; 26 days [GD 6–PND 10]	0.08	Relative: ↔ [PNDs 21–70]	↔	Relative: 0 [PNDs 21–70]	–	Tonk et al. 2010 (MMC)
Rat; 26 days [GD 6–PND 10]	0.3	Relative: ↓ (>5)[c] [PND 21]	↔	Relative: 0 [PNDs 21–70]	–	Tonk et al. 2010 (MMC)
Rat; 26 days [GD 6–PND 10]	0.6–1.6	Relative: ↓ (>5)[c] [PNDs 21–42]	↑ (>5)[b] [PND 42]	Relative: ↑ (>5)[c] [PND 70]	–	Tonk et al. 2010 (MMC)
Rat; 105 days [8 weeks PM–PND 21] (W)	0.0006	Absolute ↑ (62)[d] [PND 42]	–	Absolute ↑ (105)[d] [PND 42]	–	Wild et al. 1997 (MMC)
Rat; 105 days [8 weeks PM–PND 21]	0.0003	Absolute ↔ [PNDs 42–84]	–	Absolute ↑ (56)[d] [PND 42]	–	Wild et al. 1997 (MM2S)

Table 2-38. Immune Organ Weight and Cellularity in Rodents Orally Exposed to Methylmercury

Species; duration	Dose (mg Hg/kg/day)	Spleen weight	Spleen cellularity	Thymus weight	Thymus cellularity	Reference (compound)
Rat; 105 days [8 weeks PM–PND 21]	0.06	Absolute ↑ (122)[d] [PND 42]	–	Absolute ↑ (105)[d] [PND 42]	–	Wild et al. 1997 (MMC)
Rat; 105 days [11 weeks PM–GD 21]	0.37	↔	↔	↔	↔	Ilback et al. 1991 (MM)
Rat; 119 days [11 weeks PM–PND 15]	0.37	↔	↔	↔	↔	Ilback et al. 1991 (MM)
Mouse; 112 days [10 weeks PM–PND 15]	0.098	Absolute: ↑ (28)[b] [PND 10]	↑ (30)[b] [PND 10] ↑ (25)[b] [PND 22]	Absolute: ↔ [PNDs 10–50]	↑ (33)[b] [PND 22]	Thuvander et al. 1996 (MMC)
Mouse; 112 days [10 weeks PM–PND 15]	0.98	↔	↔	↔	↔	Thuvander et al. 1996 (MMC)
Post-pubertal (adult) exposure						
Rat; 28 days	0.002–5.91	Relative: ↔	–	–	–	Wildemann et al. 2015a (MMC)[e]
Rat; 730 days	0.006–0.16	Relative: ↔	–	–	–	Verschuuren et al. 1976 (MMC)
Mouse; 84 days	0.77	Absolute: ↔	↔	Absolute: ↓ (22)[b]	↓ (50)[b]	Ilback 1991 (MM)

[a]Studies are listed under "Develop" in the LSE table.
[b]Percent change compared to control, calculated from quantitative data.
[c]Dose-specific data not reported; data based on reported BMD_5 values.
[d]Percent change compared to control, estimated from graphically presented data.
[e]NOAEL for immune effects not included in LSE table; the only immune endpoint evaluated was spleen weight (endpoint assessment too limited for evaluation of adversity).

↑ = increased; ↓ = decreased; ↔ = no change; – = not assessed; BMD = benchmark dose; GD = gestation day; LSE = Level of Significant Exposure; MM = methylmercury; MM2S = bis(methylmercury)sulfide; MMC = methylmercuric chloride; NOAEL = no-observed-adverse-effect level; PM = premating; PND = postnatal day

There is limited evidence for changes in subpopulations of immune cells in the thymus following developmental exposure to methylmercury. In a gestation plus lactation exposure study in wild-type mice, exposed offspring showed decreased number and percentages of CD8+ cells, CD4+ cells, and

natural killer cells and increased ratio of CD4+/CD8+ cells in the spleen during the postweaning period (Tonk et al. 2010). Dose-specific data were not reported, but benchmark doses (BMDs) associated with a benchmark response (BMR) of 5% ranged from 0.14 to 0.52 mg Hg/kg/day. Another study reported a decreased percentage of CD4+ cells and CD4+CD8+ cells at PND 10 and an increased percentage of CD8+ cells at PNDs 22 and 50 in wild-type mouse offspring following maternal exposure to ≥0.098 mg Hg/kg/day and 0.98 mg Hg/kg/day, respectively, for 11 weeks premating through PND 15 (Thuvander et al. 1996).

No histopathological changes in the bone marrow, thymus, or spleen were observed in rats at chronic-duration methylmercury doses up to 0.18 mg Hg/kg/day (Verschuuren et al. 1976), or wild-type mice after intermediate- or chronic-duration doses up to 0.724 mg Hg/kg/day (Hirano et al. 1986; Mitsumori et al. 1990). In other species, no histopathological changes in the spleen were observed following exposure to methylmercury for intermediate-durations at dietary doses up to 1.1 mg Hg/kg/day in rabbits (Koller et al. 1977) or 0.176 mg Hg/kg/day in cats (Charbonneau et al. 1976), or chronic-durations at dietary doses up to 0.074 mg Hg/kg/day in cats (Charbonneau et al. 1976).

Predominant Mercury Form Unknown (General Populations). Studies of general populations have examined associations between mercury biomarkers and several immune endpoints including immunological diseases, ANAs, and serum cytokines (Table 2-39). Studies used prospective and cross-sectional designs and evaluated effects in children and adults. A few studies examined the same endpoints (eczema, ANA titers, and cytokines), and the most common biomarker was BHg.

Table 2-39. Results of Epidemiological Studies Evaluating Exposure to Mercury (Predominant Mercury Form Unknown) and Immunological Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Crowe et al. 2015 Cross-sectional; 52 patients with SLE (Northern Ireland)	UHg mean: 1.1 ng/g Cr HHg mean: 1.5 µg/g	SLE activity	↔ (UHg, HHg)
		SLE damage	↔ (UHg) ↓ (HHg)
Gallagher et al. 2013 Cross-sectional; males and females ages 12–85 (NHANES 2003–2004)	BHg mean, females ANA+: 1.30 µg/L ANA−: 1.47 µg/L BHg, males not reported	Serum ANA	↔ (BHg, males and females)

Table 2-39. Results of Epidemiological Studies Evaluating Exposure to Mercury (Predominant Mercury Form Unknown) and Immunological Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Hui et al. 2016 Prospective; 407 children; cytokines measured at ages 6–9 years (China)	Cord BHg median: 9.2 µg/L	Plasma cytokines IL-4 IL-5 IL-6 IL-8 IL-10 IL-13 TNF-α	 ↔ (cord BHg) ↔ (cord BHg) ↔ (cord BHg) ↔ (cord BHg) ↔ (cord BHg) ↔ (cord BHg) ↔ (cord BHg)
Kamycheva et al. 2017 Cross-sectional; 3,643 children and 11,040 adults (NHANES 2009–2012)	BHg mean, children CD+: 0.47 µg/L CD-: 0.64 µg/L BHg mean, adults CD+: 1.32 µg/L CD-: 1.64 µg/L	CD	↓ (BHg, children) ↔ (BHg, adults)
Miyake et al. 2011 Prospective; 582 mother-child; maternal and child exposure and child outcomes assessed at age 29–39 months (Japan)	HHg median Mother: 1.52 µg/g Child: 1.38 µg/g	Eczema	↔ (HHg, mother and child)
Miyazaki et al. 2023 Prospective; 94,794 mother-infant pair; child outcomes assessed at ages ≤3 years (Japan)	BHg median Maternal: 3.6 µg/kg	Atopic dermatitis	↔ (BHg)
		Food allergies	↔ (BHg)
		Asthma	↔ (BHg)
		Allergic rhinitis	↔ (BHg)
		Any allergic disease	↔ (BHg)
Monastero et al. 2017 Cross-sectional; 287 adults (Long Island, New York)	BHg median: 4.58 µg/L	Serum cytokines IL-1β IL-1ra IL-4 IL-10 IL-17 IFN-γ TNF-α	 ↔ (BHg) ↔ (BHg) ↔ (BHg) ↔ (BHg) ↔ (BHg) ↔ (BHg) ↔ (BHg)
		Serum ANA	↔ (BHg)
Park and Kim 2011 Cross-sectional; 127 adults with lifetime prevalence of atopic dermatitis and 176 with atopic dermatitis diagnosed in the past year (Korea)	BHg tertiles T1: <3.56 µg/L T2: 3.56–6.04 µg/L T3: >6.04 µg/L	Atopic dermatitis (lifetime prevalence)	↑ (BHg, T3)
		Atopic dermatitis (1-year prevalence)	↑ (BHg, T3)

Table 2-39. Results of Epidemiological Studies Evaluating Exposure to Mercury (Predominant Mercury Form Unknown) and Immunological Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Shaheen et al. 2004 Prospective; 1,755 newborns, assessed for eczema at 18–30 months of age (ALSPAC, United Kingdom)	Cord BHg Gmean: 0.0127 µg/L	Eczema	↔ (cord BHg)
Somers et al. 2015 Cross-sectional; 1,352 females, ages 16–49 years (NHANES 1999–2004)	BHg quartiles (µg/L) Q1: <0.4 Q2: 0.4–0.8 Q3: 0.9–1.5 Q4: 1.6–32.8 UHg quartiles (µg/L) Q1: <0.0029 Q2: 0.0029–0.0063 Q3: 0.0063–0.0135 Q4: 0.0137–0.8873 HHg tertiles (µg/g) T1: <0.11 T2: 0.11–0.27 T3: 0.271–5.96	Serum ANA	↑ (BHg, Q4) ↔ (UHg, Q4) ↑ (HHg, T3)
Stratakis et al. 2021 Cohort; mother-child pairs participating in the HELIX cohort; mean child age: 8.1 years; children were stratified into Group 1 (n=669; low risk for NAFLD) and Group 2 (n=123; high risk for NAFLD) (France, Greece, Lithuania, Norway, Spain, United Kingdom)	BHg median (maternal during pregnancy) Group 1: 1.8 µg/L Group 2: 2.7 µg/L	Serum cytokines IL-1β IL-6 IL-8 TNF-α	 ↑ (BHg, Group 2) ↑ (BHg, Group 2) ↑ (BHg, Group 2) ↑ (BHg, Group 2)
Wang et al. 2022b Meta-analysis; number of studies included per outcome: atopic dermatitis, 5; eczema, 6; wheeze 7; and asthma, 4	BHg, HHg, UHg NR	Atopic dermatitis Eczema Wheeze Asthma	↑ ↔ ↑ ↔

Table 2-39. Results of Epidemiological Studies Evaluating Exposure to Mercury (Predominant Mercury Form Unknown) and Immunological Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Zhang et al. 2020a	BHg median 1.46 µg/L	Serum cytokines (all adjustments)	
Cross-sectional; 73 children exposed to e-waste and 74 referents, age 3–7 years (China)		IL-1β	↔ (BHg)
		IL-6	↔ (BHg)
		IL-8	↔ (BHg)
		TNF-α	↔ (BHg)
		IL-1RA	↔ (BHg)
		IL-4	↔ (BHg)
		IL-10	↔ (BHg)
		IL-13	↔ (BHg)

↑ = positive association; ↓ = inverse association; ↔ = no association; ALSPAC = Avon Longitudinal Study of Parents and Children; ANA = antinuclear antibodies; BHg = blood mercury; CD = celiac disease; CD+ = celiac disease seropositive; CD- = celiac disease seronegative; Gmean = geometric mean; HELIX = European Early-Life Exposome; HHg = hair mercury; IFN-γ = interferon-gamma; IL = interleukin; NAFLD = nonalcoholic fatty liver disease; NHANES = National Health and Nutrition Examination Survey; NR = not reported; Q = quartile; SLE = systemic lupus erythematosus; T = tertile; TNF-α = tumor necrosis factor-alpha; UHg = urine mercury

Epidemiological studies evaluating autoimmune diseases in general populations have investigated associations between mercury biomarkers and atopic dermatitis, eczema, SLE, and celiac disease seropositivity. The largest prospective study evaluated 94,794 mother-infant pairs for allergic disease at ages ≤3 years (Miyazaki et al. 2023). This study found no associations between maternal BHg and diagnosis of atopic dermatitis, food allergies, asthma, allergic rhinitis, or any allergic disease. Two prospective studies in newborns that were followed through ages 18–39 months did not find associations between cord BHg or HHg and eczema (Miyake et al. 2011; Shaheen et al. 2004). A cross-sectional study of 303 adult atopic dermatitis patients found that atopic dermatitis was positively associated with BHg in adults with a life-long prevalence of atopic dermatitis and adults with a diagnosis within the past year (Park and Kim 2011). No association was observed between UHg or HHg and SLE activity, although HHg was inversely associated with SLE damage (Crowe et al. 2015). A large cross-sectional study in NHANES children and adults found an inverse association between BHg and celiac disease seropositivity in children and no association in adults (Kamycheva et al. 2017). A meta-analysis of 4–7 studies examining associations between metal exposure biomarkers and allergic diseases found that increased mercury exposure was associated with increased pooled ORs for atopic dermatitis and wheeze, but not asthma or eczema (Wang et al. 2022b).

Three studies evaluated associations between mercury biomarkers and serum levels of ANA. A cross-sectional study of women reported positive associations between the highest BHg quartile and highest HHg tertile and serum ANA, but no association for the highest UHg quartile (Somers et al. 2015). The risks (OR) of a positive ANA were 2.51 (95% CI 1.04, 6.03) and 3.75 (95% CI 1.06, 13.28) for the fourth BHg quartile and the third HHg tertile, respectively. Study authors considered the positive association between mercury biomarkers and ANA titers to be indicative of subclinical autoimmunity, although the incidence of autoimmune disease in this population was not reported. In contrast, no associations were observed between BHg and positive ANA in other cross-sectional studies of men and women (Gallagher et al. 2013; Monastero et al. 2017).

Three studies examined the relationship between BHg and plasma cytokine levels in children (Hui et al. 2016; Monastero et al. 2017; Stratakis et al. 2021). A prospective study evaluated associations between maternal BHg and child plasma cytokine levels at age 8 years (Stratakis et al. 2021). Children were stratified into two groups: those at low risk and those at high risk for nonalcoholic fatty liver disease (NAFLD). This study found positive associations between maternal BHg and cytokine levels (IL-1β, IL-6, IL-8, and tumor necrosis factor-alpha [TNF-α]) in children with high risk of NAFLD. No associations were observed, except for an inverse association between current BHg and plasma IL-10 in a prospective study of children (Hui et al. 2016). A cross-sectional study evaluating immune cell counts in children reported a positive association between BHg and total lymphocyte count, but no associations for counts of total leukocytes, segmented leukocytes, monocytes, basophils, or eosinophils (Kim et al. 2015d). The clinical significance of these findings has not been established.

Several studies show that mercury induces dermal sensitization based on positive skin patch tests to elemental and/or inorganic mercuric salts; study results are summarized in Table 2-40. The specific form or forms of mercury that produced the initial sensitization cannot be determined. However, exposures were most likely to a combination of elemental and methylmercury exposures; therefore, the study populations are classified as general populations. Studies were conducted in populations with known elemental mercury exposure (Kawahara et al. 1993), sensitivity to amalgam (Kawahara et al. 1993; Laine et al. 1997; Nordlind and Liden 1992; Skoglund and Egelrud 1991; Thanyavuthi et al. 2016; Tiwari et al. 2018), and general populations (Handley et al. 1993; Mori et al. 2007; Nonaka et al. 2011).

Table 2-40. Results of Skin Patch Tests to Mercury Compounds in General Populations

Reference and population	Challenge chemical	Result
Handley et al. 1993; 441 patients with suspected contact dermatitis (Northern Ireland)	$HgCl_2$, $HgNH_2Cl$, Hg^0	+ (14/441 patients to one or more compounds)
Kawahara et al. 1993; 12 male dental students (Japan)	$HgNH_2Cl$	+ (3/12 patients)
Koch and Bahmer 1999; 19 patients with oral lichenoid lesions (Germany)	$HgCl_2$ and $HgNH_2Cl$	+ (15/19 patients)
Laine et al. 1997; 118 patients with oral lichenoid lesions (Finland)	$HgNH_2Cl$	+ (80/118 patients)
Mori et al. 2007; 580 students (Japan)	$HgCl_2$	+ (55/580 subjects)
Nonaka et al. 2011; 930 adults (Japan)	$HgCl_2$	+ (94/930 subjects)
Nordlind and Liden 1992; 12 patients with oral lesions	$HgCl_2$, Hg^0	+ (5/12 patients)
Skoglund and Egelrud 1991; 24 patients with oral lesions	$HgNH_2Cl$	+ (8/12 patients)
Thanyavuthi et al. 2016; 53 patients with oral lichenoid lesions (Thailand)	Hg^0	+ (19/53 patients)
Tiwari et al. 2018; 68 patients with oral lichen planus (Australia)	Hg^0	+ (24/68 patients)

+ = positive skin patch test

In addition to studies showing positive skin patch to dermal mercury challenge, acrodynia, a syndrome that may involve a hypersensitivity reaction to mercury, is occasionally observed in infants and young children exposed to different forms of mercury (as reviewed by Jao-Tan and Pope 2006). Acrodynia, also known as “pink disease” due to characteristic pink coloration of toes and fingers, is of more historical interest, as it typically has been associated with mercury exposure through discontinued mercury-containing pharmaceuticals (e.g., teething and diaper powders, antihelminthics, ointments) and preservatives. However, acrodynia has been observed following inhalation exposure to elemental mercury in accidental spills. Symptoms of acrodynia include pink, perspiring, swollen, and peeling hands and feet. Epidemiological studies on associations of acrodynia with environmental exposures to mercury were not identified.

Mechanisms of Action. Effects of mercury on the immune system are complex, as mercury has been shown to both stimulate and inhibit the immune system function (Havarinasab and Hultman 2005). Several mechanisms have been proposed for mercury-induced effects on immune function (Fournie et al. 2002; Havarinasab and Hultman 2005; reviewed by Maqbool et al. 2017; Silbergeld et al. 2005; Vas and Monestier 2008). These include: (1) proliferation and activation of T and B cells, leading to increased serum IgG and IgE; (2) increased ANAs and ANoAs; (3) dysregulation of lymphocyte signal-transduction pathways; (4) altered gene expression of cytokines; (5) induction of protein kinase C (PKC), leading to phosphorylation of numerous proteins; (6) PKC-induced alteration of L-type calcium channels, resulting in increased intracellular calcium; (7) inhibition of nitric oxide production; (8) increased formation of ROS and lipid peroxidation; and (9) alteration of the intestinal microbiome (Khan and Wang 2020).

2.16 NEUROLOGICAL

Overview. Neurological effects of mercury exposure have been recognized for centuries, and occupational toxicity of mercury has a long history (Clarkson and Magos 2006). In the 19th century hatting industry, mercury was used to produce felt hats and workers in this industry commonly exhibited slurred speech, tremors, irritability, shyness, depression, and other neurological symptoms, a syndrome known as "Mad Hatter's Disease" (NIOSH 2010). This section on neurological effects is divided into two sections: Section 2.16.1, Neurodevelopmental Effects; and Section 2.16.2, Neurological Effects in Adults. Data on neurodevelopmental and neurological effects of mercury are available from clinical case studies, epidemiology studies, and studies in animals. Epidemiological studies have been conducted in workers, general populations, and populations known to consume large amounts of fish, seafood, or marine mammals, in which dietary intake of methylmercury is expected to be the dominant source of mercury exposure. Neurotoxicity of mercury has been extensively studied in animal models.

The following summarizes results of epidemiological and animal studies on neurodevelopmental and neurological outcomes.

- ***Elemental mercury***
  - *Epidemiology studies*
    - Intermediate-duration exposures to mercury vapor (50–400 µg Hg/m^3) has produced cases of severe neurological and cognitive effects in children.
    - Studies of cognitive function in children exposed to elemental mercury released from mercury amalgam dental restorations have yielded mixed results. Most studies found no association between exposure (number or restorations or biomarkers) and cognition.

- Studies of neurological function in adults have been conducted in workers in various industries who were exposed to mercury vapor. Collectively, these studies provide evidence for associations between exposure to mercury vapor and several categories of neurological effects, including tremor, vision, nerve conduction, motor speed and coordination, cognitive performance (memory, and integrative function), and subjective physiological symptoms (mood swings, irritability, nervousness, timidity, loss of confidence).

- *Animal studies*
  - Limited neurodevelopmental studies in animals have reported altered learning and behavior (altered motor activity, impaired habituation) in monkeys, rats, and mice following gestational or early postnatal exposure to metallic mercury vapor.
  - Few studies have evaluated effects of exposure to elemental mercury and neurological outcomes in adult animals. Available data suggest impaired motor function and damage to the central nervous system, particularly the cerebellum.

- ***Inorganic mercury***
  - *Epidemiology studies*
    - No epidemiological studies evaluating associations between exposure to inorganic mercury salts and neurological effects were identified.
    - Case studies of individuals acutely exposed to fatal or near-fatal levels of inorganic mercuric compounds reported disturbances of vision and behavior and seizures; at autopsy, brain abscesses in the cerebrum have also been observed.
  - *Animal studies*
    - Neurobehavioral changes are consistently reported in rodents following oral exposure to mercuric chloride during development, including hyperactivity, impaired motor coordination, impaired memory, and decreased sociability. There is limited evidence for altered neurophysiology at comparable doses (increased auditory thresholds, decreased peripheral nerve conduction, induction of seizure activity).
    - Neurobehavioral changes (hyperactivity, impaired coordination, impaired learning and memory) have been reported in rodents following oral exposure to mercuric chloride during adulthood at doses similar to those associated with developmental findings; however, lower doses have not been evaluated in developmental studies.
    - Overt signs of neurotoxicity (hindlimb crossing, ataxia, tremor, partial paralysis) and neuropathological changes to sensorimotor regions in the central nervous system (dorsal

spinal route, cerebellum) have been reported in adult animals following oral exposure to mercuric chloride at doses higher than those associated with neurobehavioral changes.

- Oral exposure to mercuric sulfide can result in neurological effects in adult rodents at doses markedly higher than those associated with mercuric chloride toxicity, including impaired coordination, altered neurophysiology (decreased nerve conduction, increased auditory thresholds), and cerebellar damage.
- Available data following inhalation exposure to mercuric oxide are too limited to draw conclusions.

- ***Organic mercury***
  - *Epidemiology studies*
    - Severe neurodevelopmental effects occurred in association with maternal ingestion of methylmercury in seafood (congenital Minamata disease) and from ingestion of wheat contaminated with a methylmercury fungicide (Iraq outbreak). In both incidents, levels of exposure were sufficient to produce frank neurological effects in adults.
    - Cognitive and neurosensory effects have been observed in association with prenatal exposures to methylmercury in high fish and marine mammal consumers in the absence of evidence of maternal toxicity. Results of these studies have been inconsistent, with some studies finding associations between mercury exposure biomarkers (BHg or HHg) and declines in tests of cognitive or neurosensory function, some studies finding improved function, and some studies finding no associations with mercury exposure biomarkers. Differences in outcomes may be due to differences in confounders and how they were controlled in regression models, and may also arise where groups (e.g., people of a specific sex or age) are differentially susceptible to mercury. Potential confounders include fish intake and related nutritional factors (e.g., 3-omega polyunsaturated long-chain fatty acids), co-exposure to other contaminants in fish or marine mammals (PCBs, selenium), and social variables affecting child development. Potential effect measure modifiers include genetic susceptibility factors.
    - Studies of associations between exposure to methylmercury and neurological function in adults have also been conducted in populations that consume large amounts of fish or marine mammals. Collectively, these studies provide evidence for associations between exposure to methylmercury and decreasing performance on tests of fine motor coordination and speed, muscle strength, tactile sensation, color vision and visual contrast sensitivity, and memory and learning.

- *Animal studies*
  - Neurobehavioral and neurophysiological effects have been observed in multiple species following acute-, intermediate-, and chronic-duration exposure to methylmercury, including sensorimotor dysfunction (altered motor activity, impaired coordination, impaired reflexes), vision and hearing deficits, and impaired learning and memory. At higher doses, overt signs of neurotoxicity were observed (clumsiness, gross and fine motor incoordination, lethargy, hindlimb crossing, tremor, ataxia, partial paralysis).
  - Neuropathological changes were observed in both the central and peripheral nervous system, at doses above those associated with neurobehavioral changes. Central lesions were observed, primarily, in regions associated with sensorimotor and movement control (e.g., cerebellum, motor cortex, subcortical regions, dorsal ganglion, and nerve roots of the spinal cord).
  - In both primates and rodents, developing animals are more sensitive to methylmercury-induced neurotoxic effects than adult animals.
- ***Predominant mercury form unknown (general populations)***
  - Studies of general populations, in which exposures to mercury derive from a variety of potential sources (e.g., mercury amalgam restoration, diet) have found inconsistent associations between biomarkers of exposure and performance on tests of cognitive function.
  - The different outcomes in cognitive development may reflect differences in how well confounders were adjusted for and whether effect measure modification was investigated. Potential confounders include fish consumption and related nutritional factors, and exposure to other chemicals (e.g., selenium, PCBs).
  - Few studies of neurological effects in general adult populations have been reported precluding conclusive statements.

Confounding Factors. Numerous factors can complicate interpretation of statistical associations between mercury exposure (or biomarkers of exposure) and neurological outcomes (Castoldi et al. 2008). These include a variety of factors that can affect performance on tests of cognitive or neurosensory function that, if not homogenously distributed in the study population, can bias findings. These factors include (but are not limited to) child sex; birth weight; birth order; gestational age and child age; breastfeeding; maternal age, alcohol, and tobacco use, and medical history; parental education; caregiver general intelligence; family income; family language; home learning, and social stimulation; exposure to other neurotoxins

(e.g., lead, PCBs); nutritional factors (e.g., fish consumption); history of neurological disease or head injuries; and genetic factors that may influence toxicity of mercury.

Some factors can introduce confounding bias because they are also associated with mercury exposure. For example, the dominant source of exposure to methylmercury in most populations is through consumption of contaminated fish. However, fish also contain nutrients that have been shown to be important modifiers of development. These include 3-omega LCPUFA, iodine, iron, selenium, and vitamin E (Cheatham 2008; Choi et al. 2008a; Muldoon et al. 2014; Strain et al. 2021). In populations in which consumption of marine mammals contributes to dietary mercury intake (e.g., Faroe Islands, Nunavik), dietary intake of PCBs and selenium, which accumulate in marine mammal tissue, can also be a source of confounding bias (Boersma and Lanting 2000; Park et al. 2010; Skröder et al. 2017). Unless otherwise specified, studies summarized in this section of the profile have considered potential confounders in assessments of associations of outcomes with mercury exposure.

In addition to confounding factors, design and statistical factors must also be considered when interpreting studies that measure multiple outcomes in the same cohorts (Puty et al. 2019). As the number of outcomes tested increases, the probability of finding a statically significant association by chance increases, even if there is no underlying causal association (Thurston et al. 2022). For example, Thurston et al. (2022) examined 85 neurodevelopmental outcomes in a 9–24-year follow-up of the Seychelles Child Development Study (SCDS). While some statically significant associations were found based on regression slope 95% confidence limits, none of the outcomes were significantly associated with mercury exposure after the Bonferroni correction for multiple comparisons was applied to the type 1 error p-value threshold for significance.

2.16.1 Neurodevelopmental Effects

Elemental Mercury—Epidemiological Studies. Cases of severe neurological and cognitive effects in children exposed to elemental mercury vapor have been reported. Available epidemiological studies have focused on associations between exposures to elemental mercury released from mercury amalgam dental restorations and cognitive function in children. These studies have yielded mixed results. Most studies found no associations between exposure (number or restorations or biomarkers) and cognitive function.

Poisoning case studies. A case study of two children, ages 13 and 15 years, who were accidentally exposed to mercury vapor for a period of 3 months observed cognitive deficits that improved 1 year after

exposure and treatment with a mercury complexing agent, 2,3-dimercaptosuccinic acid (DMSA) (Yeates and Mortensen 1994). Exposure resulted from vaporization of elemental mercury that had been spilled from a container in the residence. Exposure levels measured in the residence ranged from 50 to 400 µg Hg/m^3. At diagnosis, the 15-year-old patient had a UHg level of 1,314 µg Hg/L and BHg levels that ranged from 10 to 30 µg Hg/L. The 13-year-old patient had a UHg level of 624 µg Hg/L and a BHg level of 69 µg Hg/L. Both patients presented with rash (consistent with acrodynia, further discussed in Section 2.15, Immunological), anorexia, tremor, and paresthesia. Cognitive testing of the 15-year-old at diagnosis (Wechsler Intelligence Scale for Children, Revised [WISC-R]) indicated a full-scale IQ of 79 compared to a value of 101 measured at age 9 years, with the largest deficit on the digit span test of attention and short-term memory. Following DMSA chelation therapy and a period of 1 year following exposure, full-scale IQ increased to 93 with most of the improvement attributed to performance on the digit span test. Cognitive testing of the 13-year-old patient indicated a full-scale IQ of 79, which did not improve when retested 1 year later and after DMSA chelation therapy.

Exposures to mercury amalgam dental restorations. Studies evaluating effects of elemental mercury on neurological development include several longitudinal studies of associations between metrics of exposure from child or maternal mercury amalgam dental restorations and cognitive function and behavior, and one study that evaluated exposures to mercury in a gold mining community (Table 2-41). In the study populations, exposures included elemental mercury released from amalgams as well as exposures to other forms of mercury (e.g., dietary methylmercury). As a result of this mixed exposure, reported biomarkers such as urinary or HHg cannot be interpreted as specific metrics of exposures to amalgam mercury and most studies included an exposure metric directly related to amalgams such as number of amalgam surfaces, or compared outcomes between groups of people who had mercury amalgam restorations and groups with restorations made of other materials. In some studies, biomarkers more specific to methylmercury exposure, such as HHg, were used to adjust the models for potential confounding by methylmercury exposure (Bellinger et al. 2006, 2007a, 2008; Watson et al. 2011, 2012). This adjustment was particularly important in studies of the Seychelle Islands cohort, which had relatively high exposures to methylmercury (mean prenatal HHg 6–7 µg Hg/g; Watson et al. 2011, 2012). Some studies adjusted measurements of associations for exposures to lead (Bellinger et al. 2006, 2007a, 2008; Surkan et al. 2009); however, other potential chemical exposures associated with mercury exposure that might have contributed to outcomes were not considered. Most studies included analysis of covariates such as age, sex, race, birth weight, SES, caregiver education and/or IQ, and metrics of home environment as potential confounders.

Table 2-41. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) in Populations with Mercury Amalgam Dental Restorations and Neurodevelopmental Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Bellinger et al. 2006, 2007b, 2008; Surkan et al. 2009 Randomized clinical trial (NECAT); 534 children, 267 receiving amalgam fillings and 267 receiving resin fillings at age 6–10 years; neurological testing at 5 years following restoration; Boston, Massachusetts, Farmington, Maine	UHg mean Amalgam: 0.99 µg/g Cr No amalgam: 0.61 µg/g Cr HHg mean Female: 0.31 µg/g Male: 0.32 µg/g Amalgam surface-years mean: 31.7	IQ	↔ (amalgam versus no amalgam) ↔ (UHg, HHg) ↔ (surface-years)
		Learning and memory	↔ (amalgam versus no amalgam) ↔ (UHg, HHg) ↔ (surface-years)
		Visuomotor	↔ (amalgam versus no amalgam) ↔ (UHg, HHg) ↔ (surface-years)
		Competence	↔ (amalgam versus no amalgam)
		Internalization	↓ (amalgam versus no amalgam)
		Externalization	↔ (amalgam versus no amalgam)
DeRouen et al. 2006 Randomized clinical trial; 507 children, 253 receiving amalgam fillings and 254 receiving resin fillings at age 8–10 years; annual neurological testing through 7 years following dental mercury amalgam or resin restorations; Portugal	UHg mean at baseline Amalgam: 1.8 µg/g Cr No amalgam: 1.9 µg/g Cr UHg mean at 2 years following restoration (peak exposure) Amalgam: 3.2 µg/g Cr No amalgam: 1.5 µg/g Cr	Learning and memory	↔ (amalgam versus no amalgam)
		Attention	↔ (amalgam versus no amalgam)
		Visuomotor	↔ (amalgam versus no amalgam)
		Non-verbal IQ	↔ (amalgam versus no amalgam)
Orlando et al. 2023 SCDNS follow-up at age 9 years (n=210)	Maternal or child amalgam surface areas	Auditory brainstem response	↔ (amalgam surface area)
		Otoacoustic emissions	↔ (amalgam surface area)
Watson et al. 2011 Prospective cohort of 587 mother-child pairs recruited with follow-up at age 66 months; 249 mothers had amalgam restorations present during pregnancy; Seychelles	HHg mean Prenatal: 6.8 µg/g (based on Davidson et al. 1998) Amalgam group Number of maternal amalgam surfaces (mean): 5.12	General cognitive	↔ (amalgam surfaces)
		Language	↔ (amalgam surfaces)
		Reading and arithmetic	↔ (amalgam surfaces)
		Visuomotor	↔ (amalgam surfaces)
		Adaptive behavior	↔ (amalgam surfaces)

Table 2-41. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) in Populations with Mercury Amalgam Dental Restorations and Neurodevelopmental Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Watson et al. 2012 Prospective cohort of 242 mother-child pairs recruited with follow-up at age 9 and 30 months; 196 mothers had amalgam restorations present during pregnancy; Seychelles	HHg mean Prenatal: 6.8 µg/g (based on Davidson et al. 1998) Amalgam group Number of maternal amalgam surfaces (mean): 8.49	Mental development index	↔ (amalgam surfaces)
		Psychomotor development index	↔ (amalgam surfaces)
Woods et al. 2012, 2014 Randomized clinical trial; 239 children, 121 boys and 118 girls, receiving amalgam fillings or resin fillings at age 8–12 years; neurological testing at 7 years following restoration; Portugal Note: Subjects included children from a dental amalgam clinical trial (DeRouen et al. 2006) with CPOX4 genotyping; amalgam status was not reported.	UHg mean at baseline Boys: 1.65 µg/g Cr Girls: 1.98 µg/g Cr UHg mean at 2 years following restoration (peak exposure) Boys: 2.17 µg/g Cr Girls: 2.86 µg/g Cr UHg mean at 7 years following restoration Boys: 1.25 µg/g Cr Girls: 1.77 µg/g Cr	Attention	Boys: ↓ (cumulative UHg) Girls: ↔ (cumulative UHg)
		Visual-spatial	Boys: ↓ (cumulative UHg) Girls: ↔ (cumulative UHg)
		Learning and memory	Boys: ↓ (cumulative UHg) Girls: ↔ (cumulative UHg)
		Motor	Boys: ↔ (cumulative UHg) ↑ (cumulative UHg and CPOX4 genotype) Girls: ↔ (cumulative UHg)
Woods et al. 2013, 2014 Randomized clinical trial; 239 children, 120 boys and 119 girls, receiving amalgam fillings or resin fillings at age 8–12 years; neurological testing at 7 years following restoration; Portugal Note: Subjects included children from a dental amalgam clinical trial (DeRouen et al. 2006) with MT1M and MT2A genotyping; amalgam status not reported	UHg mean at baseline Boys: 1.68 µg/g Cr Girls: 1.97 µg/g Cr UHg mean at 2 years following restoration (peak exposure) Boys: 2.18 µg/g Cr Girls: 2.86 µg/g Cr UHg mean at 7 years following restoration Boys: 1.26 µg/g Cr Girls: 1.76 µg/g Cr	Visual spatial	Boys: ↔ (cumulative UHg) ↑ (cumulative UHg and MT2A genotype) Girls: ↔ (cumulative UHg)
		Learning and memory	Boys: ↔ (cumulative UHg) ↑ (cumulative UHg and MT1M genotype) ↑ (cumulative UHg and MT2M genotype) Girls: ↔ (cumulative UHg)

Table 2-41. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) in Populations with Mercury Amalgam Dental Restorations and Neurodevelopmental Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Ye et al. 2009 Cross-sectional cohort of 403 children ages 7–11 years; 198 with amalgam fillings and 205 without amalgam fillings; Shanghai	UHg median Amalgam: 1.6 µg/g Cr No amalgam: 1.4 µg/g Cr	CBCL	↔ (amalgam versus no amalgam)
		EPQ	↔ (amalgam versus no amalgam)
		Academic math score	↔ (amalgam versus no amalgam)
		Academic language	↔ (amalgam versus no amalgam)

↑ = positive association; ↓ = inverse association; ↔ = no association; CBCL = Child Behavior Checklist; Cr = creatinine; CPOX = coproporphyrinogen; EPQ = Eysenck Personality Questionnaire; HHg = hair mercury; IQ = intelligence quotient; MT = metallothionein; NECAT = New England Children's Amalgam Trial; SCDNS = Seychelles Child Development Nutrition Study; UHg = urine mercury

Outcomes were based on a variety of tests that measured various domains of cognitive function or nerve function, including verbal and non-verbal IQ, learning and memory, visual-spatial and visual-motor function, hearing, and psychosocial behavior. In some studies, as many as 20–30 different tests were administered, introducing the potential for random outcomes of "significant" associations based on p-levels. Therefore, interpretation of these studies requires consideration of the overall outcomes and consistencies or inconsistencies in outcomes across tests of similar domains of cognitive function. Most studies did not find consistent evidence for associations between exposures to mercury from amalgams and cognitive function (Bellinger et al. 2006, 2007b, 2008; DeRouen et al. 2006; Orlando et al. 2023; Surkan et al. 2009; Watson et al. 2011, 2012). The exception were studies reported by Woods et al. (2012, 2013), which found decreased performance on some tests of attention, learning and memory, and visuomotor function in association with increased cumulative urinary mercury, based on analysis of data from a mercury amalgam random clinical trial (DeRouen et al. 2006). Woods et al. (2012, 2013) also found interactions between cumulative urinary mercury and genotypes for coproporphyrinogen (CPOX), an enzyme in the heme metabolism pathway, and metallothionein (MT), an inducible metal binding protein. Cumulative urinary mercury was used as the exposure metric, without adjustment for other potential sources of urinary mercury unrelated to amalgams. The highest mean urinary mercury levels were observed in the amalgam group in the 2-year follow-up, 3.2 µg Hg/g creatinine, compared to the baseline (prior to restorations), 1.8 µg Hg/g creatinine (DeRouen et al. 2006). This suggests that more than half of the urinary mercury may have derived from sources other than amalgam mercury. Adjustments for other potential contributors to cognitive performance outcomes were not reported. An

analysis of data from this same study compared cognitive performance in restoration groups and did not find differences in performance between mercury amalgam and resin restoration groups (DeRouen et al. 2006).

Elemental Mercury—Animal Studies. Neurodevelopmental studies have found altered learning and behavior in monkeys, rats, and mice following gestational or early postnatal exposure to metallic mercury vapor; however, data are limited and/or inconsistent between studies and testing paradigms. One study reported neurodevelopmental effects in squirrel monkeys following gestational exposure to metallic mercury vapor. Long-term impairment in operant training performance in a lever-press paradigm was observed in monkey offspring at 0.8–4 years of age following intermittent exposure to 0.5 or 1 mg Hg/m^3 (5 days/week; 4 or 7 hours/day) during the last two-thirds or more of the gestation period (Newland et al. 1996). No difference in sensitivity to reinforcer ratios was identified in the steady state, but there was much more variability in the steady-state performance of exposed monkeys, with exposed monkeys producing smaller or slower transitions than controls. The magnitude and stability of lever-press durations for controls and exposed monkeys were indistinguishable early in the study, but at the end, the exposed monkeys had longer lever-press durations and the session-to-session variability was much greater. One monkey's exposure began during the third week of gestation (earlier than any of the others) and its behavior was so erratic that some of the analyses could not be accomplished. The median maternal BHg levels were 0.025–0.09 µg Hg/g at 0.5 mg Hg/m^3 and 0.12–0.18 µg Hg/g at 1 mg Hg/m^3. Offspring BHg levels were not reported.

Alterations in neurobehavior have been observed in rats and mice following gestational or early postnatal exposure to metallic mercury vapor, including altered motor activity, impaired spatial learning, and decreased habituation to a novel environment. However, findings have been inconsistent between studies and different testing paradigms.

Increased motor activity (total, horizontal, and vertical) was reported in 4-month-old male rat offspring following intermittent exposure to 1.8 mg Hg/m^3 during GDs 14–19 (Fredriksson et al. 1996). Exposure to the same vapor level during GDs 11–14 plus GDs 17–20 resulted in decreased motor activity in 3-month-old male and female rat offspring (Danielsson et al. 1993). When rats were postnatally exposed to 0.05 mg Hg/m^3 during PNDs 11–17 for 1–4 hours/day, total and vertical (rearing) activity was increased in 4-month-old males exposed for 1 hour/day and 2-month-old males exposed for 4 hours/day, but decreased in 4-month-old males exposed for 4 hours/day; vertical activity was decreased in each group of rats (Fredriksson et al. 1992). No changes were observed in motor activity in 2-month-old males

exposed for 1 hour/day. In mice, total motor activity was decreased in 11-week-old females following continuous exposure to 0.188 mg Hg/m^3 from PND 2 to 28 (Yoshida et al. 2018); no changes were observed in female mice exposed to 0.03 mg Hg/m^3 during GDs 0–18 or 0.057 mg Hg/m^3 during PNDs 1–20 (Yoshida et al. 2011, 2013).

Impaired spatial learning was observed in male and female rats following gestational exposure to 1.8 mg Hg/m^3 (GDs 14–19 or GDs 11–14 plus GDs 17–20) or postnatal exposure to 0.05 mg Hg/m^3 (PNDs 11–17) when evaluated using the radial arm maze at 4–6 months of age, as indicated by increased latency to finish and increased number of errors (Danielsson et al. 1993; Fredriksson et al. 1992, 1996). Impaired spatial learning was also observed in male rat offspring exposed to 1.8 mg Hg/m^3 during GDs 14–19 (1.5 hours/day) when evaluated using a swim maze at 4.5 months of age (increased latency to escape) (Fredriksson et al. 1996). However, no deficits in the swim maze were observed in male or female rat offspring exposed to 1.8 mg Hg/m^3 during GDs 11–14 plus GD 17–20 (1 or 3 hours/day) when evaluated at 7 and 15 months of age (Danielsson et al. 1993) or male rats exposed to 0.05 mg Hg/m^3 on PNDs 11–17 (1 hour/day) when evaluated at 5 months (Fredriksson et al. 1992). In mice, no changes in spatial learning were observed in female mice at 2–15 months of age following gestational or postnatal exposures up to 0.03 or 0.188 mg Hg/m^3, respectively (Yoshida et al. 2011, 2013, 2018).

Decreased habituation, as indicated by sustained activity in a novel environment over time as opposed to expected decreases in exploratory behavior, was observed in male and female rat offspring following exposure to 1.8 mg Hg/m^3 during GDs 11–14 plus GDs 17–20 (3 hours/day) (Danielsson et al. 1993). Similar effects were not noted when exposure was only 1 hour/day.

No changes in passive avoidance learning were observed in female mice at 2–15 months of age following gestational or postnatal exposures up to 0.03 or 0.188 mg Hg/m^3, respectively (Yoshida et al. 2011, 2013, 2018). No changes in sensory evoked potentials (visual, auditory, cortical and cerebellar somatosensory, or peripheral nerve) were observed in adult offspring of rats exposed to metallic mercury vapor at 4 mg Hg/m^3 for 2 hours/day during GDs 6–15 (Herr et al. 2004).

No exposure-related changes in reflex ontogeny (e.g., surface righting, negative geotaxis) were observed in rats following acute-duration gestational inhalation exposure to 1.8 mg Hg/m^3 for 1–5 hours/day (Danielsson et al. 1993; Fredriksson et al. 1996).

Inorganic Mercury—Animal Studies. Several studies have evaluated potential neurodevelopmental effects of gestational and/or early postnatal exposure to mercuric chloride in rats and mice. While only a limited number of studies evaluated each endpoint, available data suggest potential associations between developmental exposure to mercuric chloride and hyperactivity, impaired motor coordination, impaired memory, and decreased sociability in rodents. Studies evaluating electrophysiological endpoints are limited and reported mixed findings.

Increased motor activity during open field testing has been reported in male ICR mice following exposure to a gavage dose of 0.4 mg Hg/kg/day throughout gestation and lactation, during GD 1–PND 70, or postnatally only from PNDs 21–70 (Huang et al. 2011). Effects were most prominent with exposure during GD 1–PND 70. Increased stereotypical behavior during open field testing was observed in both groups with post-weaning exposure. Increased locomotor activity was also observed in autoimmune susceptible mouse offspring exposed to 2.7 mg Hg/kg/day during GD 8–PND 21 via maternal drinking water, but not similarly exposed wild-type mice (Zhang et al. 2011). Another drinking water study did not observe overall increases in locomotor activity in male Swiss mice following drinking water exposure to 3.3 mg Hg/kg/day during GD 0–PND 70; however, the time spent in the periphery of the open field was significantly increased, suggesting increased anxiety (Malqui et al. 2018). Offspring were observed to have increased anxiety and depressive behaviors in the light-dark chamber test, forced swim test, tail suspension test, and elevated plus maze when dams (Swiss mice) were exposed to 2.4 mg Hg/kg/day from GD 1 to PND 15 (Mohammad Abu-Taweel and Al-Fifi 2021). The PND 40 male offspring of mercuric-chloride-exposed mouse dams showed decreased activity and exploratory behaviors in an open field. In contrast to findings by Malqui et al. (2018) and Mohammad Abu-Taweel and Al-Fifi (2021), decreased anxiety was observed in the elevated plus maze in PND 63 female rat offspring following maternal exposure to ≥6.1 mg Hg/kg/day during GDs 1–21 (Chehimi et al. 2012).

Impaired motor coordination in the rotarod test was observed in PND 70 male mice following exposure to 0.4 mg Hg/kg/day via gavage during GD 1–PND 70 or PNDs 21–70 (Huang et al. 2011). No effects on motor coordination were observed in similarly exposed mice during GD 1–PND 21 only (Huang et al. 2011). In rats, sensorimotor development and balance and motor coordination (while walking on the rim of a beaker at PNDs 17–20) were normal in offspring following maternal drinking water exposure to doses up to 3.8 mg Hg/kg/day during GD 1–PND 21 (Oliveira et al. 2016). However, dose-related delays in sensorimotor development were observed in female rat offspring following maternal exposure to ≥6.1 mg Hg/kg/day during GDs 1–21, including delayed rooting reflex, vibrissae placing response, righting reflex, grip strength, and negative geotaxis (Chehimi et al. 2012).

Decreased sociability, particularly decreased preference for a novel stranger, was observed in PND 70 mice exposed to ≥2.7 mg Hg/kg/day during both gestational and postnatal periods (Malqui et al. 2018; Zhang et al. 2013). These findings may be secondary to increased anxiety, supported by increased self-grooming (stereotypical behavior) during sociability testing at 3.3 mg Hg/kg/day (Malqui et al. 2018). Alternatively, decreased preference for novelty may be due to impaired memory since performance was also impaired in mice exposed to 3.3 mg Hg/kg/day in the Y-maze spontaneous alternation and object recognition tests (Malqui et al. 2018).

One study reported impaired auditory function (increased auditory thresholds) in male mice following exposure to a gavage dose of 0.4 mg Hg/kg/day throughout gestation and lactation, during GD 1–PND 70, or postnatally only from PNDs 21–70 (Huang et al. 2011). Effects were most prominent with exposure during GD 1–PND 70.

No exposure-related changes in electrophysiological recordings, including spontaneous and evoked sensory potentials (somatosensory, visual, and acoustic) and tail nerve conduction velocity and refractory period, were observed in adult male rat offspring following exposure during gestation or gestational plus lactation at maternal doses up to 1.6 mg Hg/kg/day during GDs 5–15 (Papp et al. 2005). However, when offspring exposed during gestation and lactation were additionally exposed postweaning (PNDs 29–84), dose-related decreases in peripheral sensory nerve conduction velocity were observed at doses ≥0.4 mg Hg/kg/day, and decreased spontaneous sensory cortex potentials were observed at ≥0.8 mg Hg/kg/day (Papp et al. 2005). In another study, induction of epileptiform activity was promoted in PND 90 rat offspring following gestational and lactational exposure to 0.6 mg Hg/kg/day; no changes in epileptiform activity were observed at PND 28 and baseline cortical activity was comparable to control at both time points (Szász et al. 2002).

No changes in reflex ontogeny were observed in rat offspring following drinking water exposure to doses up to 3.8 mg Hg/kg/day during GD 0–PND 21 (Oliveira et al. 2016). No other identified studies specifically evaluated reflex ontogeny following developmental exposure to mercuric chloride.

Organic Mercury—Epidemiological Studies. Human epidemiological studies provide strong support for the developing nervous system being a sensitive target of methylmercury. Severe neurodevelopmental effects occurred in association with maternal ingestion of methylmercury in seafood (congenital Minamata disease) (Harada 1995) and from ingestion of wheat contaminated with a methylmercury

fungicide (Iraq outbreak) (Amin-Zaki et al. 1974). In both incidents, exposure levels were sufficient to produce severe neurological effects in adults.

Studies of lower levels of prenatal exposures have largely focused on populations consuming large amounts of marine fish or mammals. In these populations, the dominant source of the mercury body burden derives from consumption of methylmercury in fish or marine mammals, providing a strong basis for use of blood or HHg as a biomarker of methylmercury exposure. Results of these studies have been inconsistent, with some studies finding associations between mercury exposure biomarkers (BHg or HHg) and declines in tests of cognitive or neurosensory function, and other studies finding improved function or no associations with mercury. Differences in outcomes may be due to differences in confounders and how they were controlled in regression models. These variables include fish intake and related nutritional factors (e.g., 3-omega polyunsaturated long-chain fatty acids), co-exposure to other contaminants in fish or marine mammals (selenium, PCBs), and social variables affecting child development. In addition, genetic susceptibility factors may act as effect measure modifiers, impacting the associations observed between mercury and a health outcome.

Epidemiological studies have evaluated neurodevelopmental effects in the following populations with high dietary methylmercury exposure, relative to most general populations: Minamata, Japan; Iraq; Seychelle Islands; Faroe Islands; North Island, New Zealand; Nunavik region of arctic Canada; Amazon River basin, Madeira, and Portugal. Meta-analyses of the studies of high fish consumers have estimated effect sizes for prenatal methylmercury exposure and IQ (Axelrad et al. 2007a, 2007b; Cohen et al. 2005; Ryan 2008).

Minamata, Japan. Discharges of wastewater from an acetaldehyde production facility into the Shiranui Sea located in the Kumamato Prefecture of Japan, that occurred in the mid-1950s resulted in exposure of pregnant women to methylmercury ingested in locally contaminated fish and shellfish (Harada 1995). Severe neuromotor and cognitive impairments resembling cerebral palsy were observed in infants exposed prenatally (Harada 1995). Patients diagnosed with congenital Minamata disease showed a common set of signs which included severe cognitive impairments, primitive reflex, cerebellar ataxia, disturbances in physical growth and nutrition, dysarthria (speech and vocalization impairment), limb deformities, hyperkinesia (restlessness), hypersalivation, strabismus (abnormal eye alignment), paroxysmal symptoms, and pyramidal symptoms (Harada 1995). Measurements of mercury in blood and hair were not made until several years following the period of most intense exposure and, therefore, do not provide reliable estimates of exposures that may have contributed to congenital Minamata disease.

Methylmercury levels in umbilical cord tissue of congenital Minamata disease patients ranged from 0.15 to 4.65 µg Hg/g dry weight (Harada et al. 1999). Long-term follow-up of congenital Minamata disease patients have observed neuromotor and cognitive impairments as adults, including hand tremor, postural sway, low scores on cognitive processing speed, and more rapid declines in cognitive function with age (Iwata et al. 2016; Yorifuji et al. 2015, 2016, 2018). The follow-up studies have included small numbers of subjects (<20), limiting the power to associate clinical outcomes with measures of exposure. In a study of 22 congenital Minamata disease patients (age range 42–57 years), low performance on the digit symbol-coding test of the Wechsler Adults Intelligent Scale III were observed in subjects from pregnancies in which cord tissue methylmercury levels ranged from 0.1 to 2 µg Hg/g dry weight (Yorifuji et al. 2015). In a study of 18 congenital Minamata disease patients (mean age 50 years), low scores on tests of fine motor control were observed in subjects from pregnancies who had a mean umbilical cord tissue level of 0.7 µg Hg/g dry weight (Yorifuji et al. 2016).

Iraq. An outbreak of methylmercury poisoning occurred in Iraq in 1971–1972 as a result of widespread consumption of wheat that had been treated with a methylmercuric fungicide (Al-Mufti et al. 1976; Bakir et al. 1973; Clarkson et al. 1976). Approximately 6,500 cases of mercury poisoning occurred, with approximately 459 related deaths (Clarkson et al. 1976). Sixty-five days after exposure, BHg levels in poisoning cases ranged from 10 to 3,000 µg Hg/L (Clarkson et al. 1976). Cases of neurological abnormalities in infants exposed prenatally were reported which included impaired motor function, hyperreflexia, and delayed attainment of development milestones (walking, speech) and, at the highest exposure levels, seizures (Amin-Zaki et al. 1974, 1978, 1981; Marsh et al. 1987). BHg levels in infant cases ranged from approximately 10 to 1,600 µg Hg/L (Amin-Zaki et al. 1981). Prenatal exposures were reconstructed from segmental analysis of single maternal hair strands and used to derive prenatal dose-response relationships for neurodevelopmental outcomes (Cox et al. 1989; Crump et al. 1995; Marsh et al. 1987). Cox et al. (1989) constructed prenatal mercury dose response models based on observations of 83 mother-infant pairs (Marsh et al. 1987). The dose metric used in these models was the estimated maximum HHg level during gestation. Outcome metrics were attainment of developmental milestones (age of walking) or scores from a clinical examination for signs of neurological abnormalities (e.g., muscle tone, reflexes). Based on a threshold model ("hockey-stick" model), Cox et al. (1989) concluded that the best estimate of the threshold for delayed walking (not walking by age 18 months) was 7.3 µg Hg/g hair (95% CL: 0, 13.6). However, confidence limits on the threshold estimate were sensitive to the estimated background response (probability of delay in walking when there is no prenatal exposure to mercury). For the upper 95% limit on the estimated background response (0.04), the threshold was estimated to be 9 µg Hg/g (95% CL: 4, 190). The best estimate of the threshold for an abnormal score on

neurological examination (score >3 of 11) was 10 µg Hg/g (95% CL: 9, 287). Based on a logit model applied to the same data, HHg levels of 5 and 50 µg Hg/g were associated with excess risks of 2.5 and 19%, respectively, for delayed walking, and 2.3 and 13%, respectively for abnormal neurological signs (Cox et al. 1989). Data from 81 mother-infant pairs were analyzed using an outcome metric that was a composite score for delayed walking (age >18 months), delayed talking (age >24 months), and neurological signs (score >3 of 11; Marsh et al. 1987). An analysis of covariance showed an increase in composite score with increasing HHg levels (range 1–674 µg Hg/g) with a higher slope for males compared to females. In males, when stratified by maximum prenatal HHg, scores were 2.6-fold higher in children from pregnancies in which HHg ranged from 23 to 72 µg Hg/g (score 1.14), compared to pregnancies in which HHg was 1 µg Hg/g (score 0.43).

Crump et al. (1995) utilized data on 81 mother-infant pairs (Marsh et al. 1987) to estimate BMDs for delayed walking (age >18 months), delayed talking (age >24 months), and neurological signs score (score >3 of 11). The lower confidence limits on the BMDs (BMDLs) were 73 µg Hg/g for delayed walking, 54 µg Hg/g for delayed talking, and 80 µg Hg/g for neurological signs, when the background response probability was 0.05 and the quantal BMR was 0.1. The large differences in the dose-response thresholds estimated by Cox et al. (1989) and Crump et al. (1995) demonstrate the importance of model selection in estimating a statistically based NOAEL from these data.

Seychelle Islands. Two prospective studies of methylmercury and neurodevelopmental outcomes have been conducted in the Republic of Seychelles: the SCDS and the Seychelles Child Development Nutrition Study (SCDNS). A summary of the major outcomes of the Seychelles studies are presented in Table 2-42. Oceanic fish consumption, typically consumed at every meal, is the major contributor to methylmercury exposure in the Seychelle population. Maternal fish intake in the SCDNS cohort was estimated from a food use questionnaire and 4-day diet diary. The median was 77 g Hg/day (range 0–346 g Hg/day) (Davidson et al. 2008b). Marine mammals were not consumed and there were no other local sources of PCB exposure (Shamalaye et al. 2004). PCBs were not detectable in cohort serum samples (Davidson et al. 1998).

Table 2-42. Results of Epidemiological Studies Evaluating Exposure to Methylmercury and Neurodevelopmental Effects—Prospective Birth Cohorts in the Seychelle Islands

Reference, age at follow-up	Biomarker	Outcome evaluated	Result[a]
SCDS (listed in order of follow-up age)			
Myers et al. 1995 SCDS follow-up at age 6.5 months (n=779)	HHg median Maternal: 5.9 µg/g	DDST	↔ (HHg, maternal)
Davidson et al. 1999 SCDS follow-up at age 6.5 months (n=740)	HHg median Maternal: 5.9 µg/g	FTII (2 metrics)	↔ (HHg, maternal) ↔ (HHg, maternal with maternal x caregiver intelligence and x family income)[b]
Axtell et al. 1998; Myers et al. 1997 SCDS follow-up at age 19 months (n=738)	HHg median Maternal: 5.8 µg/g	Age of talking	↔ (HHg, maternal)
		Age of walking	↔ (HHg, maternal) ↑ (HHg, maternal ≤7 µg/g) ↓ (HHg, maternal >7 µg/g)
Davidson et al. 1995, 1999 SCDS follow-up at age 19 months (n=738)	HHg median Maternal: 5.9 µg/g	BSID MDI	↔ (HHg, maternal) ↑ (HHg, maternal with caregiver intelligence and x family income)[b]
		BSID PDI	↔ (HHg, maternal)
Davidson et al. 1995, 1999 SCDS follow-up at age 29 months (n=736)	HHg median Maternal: 5.9 µg/g	BSID MDI	↔ (HHg, maternal)
		BSID PDI	↔ (HHg, maternal)
		BSID IBR	↔ (HHg, maternal) ↔ (HHg, maternal with maternal x caregiver intelligence and x family income)[b]
Axtell et al. 2000; Davidson et al. 1998 SCDS follow-up at age 66 months (n=711)	HHg mean Maternal: 6.8 µg/g Child (age 66 months): 6.5 µg/g	BVMGT	↔ (HHg, maternal) ↔ (HHg, child, females) ↓ (HHg, child, males)
		CBCL	↔ (HHg, maternal) ↑ (HHg, maternal ≤15 µg/g) ↓ (HHg, maternal >15 µg/g) ↔ (HHg, child)
		MSCA GCI	↔ (HHg, maternal) ↔ (HHg, child) ↑ (HHg, child ≤10 µg/g) ↓ (HHg, child >10 µg/g)
		PLS	↑ (HHg, maternal) ↓ (HHg, maternal ≤10 µg/g) ↑ (HHg, maternal >10 µg/g) ↑ (HHg, child)

Table 2-42. Results of Epidemiological Studies Evaluating Exposure to Methylmercury and Neurodevelopmental Effects—Prospective Birth Cohorts in the Seychelle Islands

Reference, age at follow-up	Biomarker	Outcome evaluated	Result[a]
		WJTA	↔ (HHg, maternal) ↑ (HHg, child)
Myers et al. 2000 SCDS follow-up at age 66 months (n=711)	HHg mean Maternal: 6.8 µg/g Child (age 66 months): 6.5 µg/g	CBCL (10 subscales)	↔ (HHg, maternal) ↔ (HHg, child)
Palumbo et al. 2000 SCDS follow-up at age 66 months (n=711)	HHg mean Maternal: 6.8 µg/g Child (age 66 months): 6.5 µg/g	MSCA verbal	↔ (HHg, maternal)
		MSCA perceptual	↔ (HHg, maternal) ↔ (HHg, child)
		MSCA memory	↔ (HHg, maternal) ↑ (HHg, child)
		MSCA quantitative	↔ (HHg, maternal) ↔ (HHg, child)
		MSCA motor	↔ (HHg, maternal) ↔ (HHg, child)
Young et al. 2020 SCDS follow-up at age 66 months (n=544)	HHg mean Maternal: 6.8 µg/g Child: 6.5 µg/g	Language development PLS consonant distortion error	
		Initial consonant	↔ (HHg, maternal) ↔ (HHg, child)
		Final consonant	↔ (HHg, maternal) ↔ (HHg, child)
Strain et al. 2021 SCDS follow-up at age 7 years (n=1,237)	HHg mean Maternal: 3.91 µg/g	BNT	↔ (HHg, maternal)
		CBCL	↔ (HHg, maternal)
		CELF-5	↔ (HHg, maternal)
		KBIT-2	↔ (HHg, maternal)
		SCQ	↔ (HHg, maternal)
		SRS-2	↔ (HHg, maternal)
		WJTA-III	↔ (HHg, maternal)
Myers et al. 2003; Huang et al. 2005 SCDS follow-up at age 9 years (n=643)	HHg mean Maternal: 6.9 µg/g	BOT	↔ (HHg, maternal)
		BNT	↔ (HHg, maternal)
		CVLT	↔ (HHg, maternal)
		CBCL	↔ (HHg, maternal)
		CTRS (hyperactivity index)	↓ (HHg, maternal) ↑ (HHg, maternal, ≤5 µg/g) ↓ (HHg, maternal, >5 µg/g)
		Finger tapping	↔ (HHg, maternal)
		GPB (dominant hand)	↔ (HHg, maternal) ↓ (HHg, maternal, ≤10 µg/g) ↑ (HHg, maternal, >10 µg/g)

Table 2-42. Results of Epidemiological Studies Evaluating Exposure to Methylmercury and Neurodevelopmental Effects—Prospective Birth Cohorts in the Seychelle Islands

Reference, age at follow-up	Biomarker	Outcome evaluated	Result[a]
		GPB (non-dominant hand)	↑ (HHg, maternal, males) ↓ (HHg, maternal, ≤5 µg/g, males) ↑ (HHg, maternal, >5 µg/g, males) ↔ (HHg, maternal, females)
		HAPDT	↔ (HHg, maternal)
		Trail making	↔ (HHg, maternal)
		VMI	↔ (HHg, maternal)
		WJTA	↔ (HHg, maternal)
		WISC-III FSIQ	↔ (HHg, maternal)
		WRAML	↔ (HHg, maternal)
van Wijngaarden et al. 2009 SCDS follow-up at age 9 years (n=643)	HHg mean Maternal: 6.9 µg/g (as reported by Myers et al. 2003)	OR for total abnormal cases any domain (1st or 99th test score)	↔ (maternal Hg)
		OR for abnormal cognition cases	↔ (maternal Hg)
		OR for abnormal motor function cases	↔ (maternal Hg)
Davidson et al. 2010 SCDS follow-up at age 9 years (n=437–456 for academic achievement scores; 225 for SACMEQ)	HHg mean Maternal: 6.89 µg/g Child (age 9 years): 6.09 µg/g	Mathematics score	↔ (HHg, maternal) ↑ (HHg, child; female) ↔ (HHg, child; male)
		Social studies score	↔ (HHg, maternal) ↓ (HHg, child)
		English language score	↔ (HHg, maternal) ↔ (HHg, child)
		French language score	↓ (HHg, maternal) ↑ (HHg, child; female) ↔ (HHg, child; male)
		Kreol language score	↔ (HHg, maternal) ↔ (HHg, child)
		Science score	↔ (HHg, maternal) ↔ (HHg, child)
		SACMEQ: reading comprehension	↔ (HHg, maternal) ↑ (HHg, child; female) ↓ (HHg, child; male)
		SACMEQ: mathematics	↔ (HHg, maternal) ↔ (HHg, child; female) ↓ (HHg, child; male)

Table 2-42. Results of Epidemiological Studies Evaluating Exposure to Methylmercury and Neurodevelopmental Effects—Prospective Birth Cohorts in the Seychelle Islands

Reference, age at follow-up	Biomarker	Outcome evaluated	Result[a]
Davidson et al. 2006a SCDS longitudinal analysis, age 19 months to 9 years (n=738, 736, 735, 711, and 643 at 19, 29, 66, and 107 months, respectively)	HHg mean Maternal: 6.8 µg/g Child (age 66 months): 6.5 µg/g Child (age 107 months): 6.1 µg/g	Global cognition based on BSID MDI, MSCA GCI, WISC-III FSIQ, WJTA, WRAML	↔ (HHg, maternal) ↑ (HHg, child, males at 66 months) ↓ (HHg, child, females at 107 months)
Myers et al. 2009 SCDS follow-up at age 9 years (n=483)	HHg mean Child (age 66 months): 6.5 µg/g Child (age 107 months): 6.1 µg/g	WISC IQ for various metrics of HHg:	
		AUC	↔ (HHg, child)
		Brain growth weighted	↔ (HHg, child)
		High versus low	↔ (HHg, child)
Myers et al. 2020 SCDS follow-up at age 9 years (n=643)	HHg mean Maternal: 6.8 µg/g Child (age 107 months): 6.1 µg/g	CBCL subscale:	
		Social problems	↓ (HHg, maternal) ↔ (HHg, child)
		Thought problems	↔ (HHg, maternal) ↑ (HHg, child)
		Somatic complaints	↔ (HHg, maternal) ↔ (HHg, child)
		Withdrawn	↔ (HHg, maternal) ↔ (HHg, child)
		Anxious/ depressed	↔ (HHg, maternal) ↔ (HHg, child)
		Attention problems	↔ (HHg, maternal) ↔ (HHg, child)
		Delinquent behaviors	↔ (HHg, maternal) ↔ (HHg, child)
		Aggressive behaviors	↔ (HHg, maternal) ↔ (HHg, child)
		Externalizing	↔ (HHg, maternal) ↔ (HHg, child)
		Internalizing	↔ (HHg, maternal) ↔ (HHg, child)

Table 2-42. Results of Epidemiological Studies Evaluating Exposure to Methylmercury and Neurodevelopmental Effects—Prospective Birth Cohorts in the Seychelle Islands

Reference, age at follow-up	Biomarker	Outcome evaluated	Result[a]
van Wijngaarden et al. 2013 SCDS follow-up at age 10 years (n=537)	HHg mean Maternal: 6.8 µg/g	TSRSS for ASD (5 metrics)	↔ (HHg, maternal)
Davidson et al. 2008a SCDS follow-up at age 11 years (n=613)	HHg mean Maternal: 6.83 µg/g Child (age 11 years): 6.97 µg/g	BVMGT	↔ (HHg, maternal) ↔ (HHg, child)
Davidson et al. 2010 SCDS follow-up at age 17 years (n=351–384)	HHg mean Maternal: 6.89 µg/g Child (age 17 years): 8.00 µg/g	Seychelles academic achievement scores (6 subjects)	↔ (HHg, maternal) ↔ (HHg, child)
Davidson et al. 2011; Huang et al. 2018 SCDS follow-up at age 17 years (n=462)	HHg mean Maternal: 6.89 µg/g Child (age 17 years): 7.98 µg/g	CANTAB (4 tests)	↓ (HHg, maternal; IED) ↓ (HHg, maternal, ≤12 µg/g; IED) ↔ (HHg, maternal; all other tests) ↔ (HHg, child)
		CVLT (2 tests)	↔ (HHg, maternal) ↑ (HHg, maternal, ≤8 µg/g; calculation) ↔ (HHg, child)
		WJTA (6 tests)	↑ (HHg, maternal; calculation) ↑ (HHg, maternal, ≤15 µg/g; calculation) ↔ (HHg, maternal, >15 µg/g; calculation) ↓ (HHg, child; passage comprehension)
		Behavioral endpoints (6 endpoints)	↓ (HHg, maternal; substance use, male) ↓ (HHg, maternal; incidents/year) ↑ (HHg, maternal; referrals/year) ↔ (HHg, child)

Table 2-42. Results of Epidemiological Studies Evaluating Exposure to Methylmercury and Neurodevelopmental Effects—Prospective Birth Cohorts in the Seychelle Islands

Reference, age at follow-up	Biomarker	Outcome evaluated	Result[a]
Orlando et al. 2014 SCDS follow-up at age 19 years (n=517)	HHg mean Maternal: 6.89 µg/g Child (age 19 years): 10.32 µg/g	Pure tone hearing	↔ (HHg, maternal)
		Auditory brainstem response	↔ (HHg, maternal)
		Otoacoustic emissions	↔ (HHg, maternal)
van Wijngaarden et al. 2017 SCDS follow-up at age 22 years (n=571)	HHg mean Maternal: 6.83 µg/g Child (age 22 years) 5.17 µg/g	CANTAB (7 tests, 23 metrics)	↑ (HHg, maternal, reaction time) ↑ (HHg, maternal, delayed match to sample) ↔ (HHg, maternal, all other tests) ↑ (HHg, child, IED) ↔ (HHg, child, all other tests)
		BNT	↔ (HHg, maternal) ↔ (HHg, child)
		Profile of mood states (2 metrics)	↔ (HHg, maternal) ↔ (HHg, child)
		Healthy behavior (4 metrics)	↔ (HHg, maternal) ↔ (HHg, child)
van Wijngaarden et al. 2017 SCDS follow-up at age 24 years (n=577)	HHg mean Maternal: 6.80 µg/g Child (age 24 years): 4.95 µg/g	Stroop interference	↔ (HHg, maternal) ↔ (HHg, child)
		Barkley ADHD rating (4 metrics)	↔ (HHg, maternal ↔ (HHg, child)
		Visual attention (5 metrics)	↔ (HHg, maternal) ↔ (HHg, child)
		Auditory attention (5 metrics)	↓ (HHg, maternal, mean response time) ↔ (HHg, child)
		Finger tapping (2 metrics)	↔ (HHg, maternal) ↔ (HHg, child)
		Healthy behavior (3 metrics)	↔ (HHg, maternal) ↔ (HHg, child)
Thurston et al. 2022 SCDS follow-up at ages 9, 10.5, 17, 19, 22, and 24 years (n=312–550)	HHg TWA Child (6 months to 5.5 years): 5.34 µg/dL Adult (17–24 years): 7.13 µg/dL	After Bonferroni correction for multiple comparisons (85 tests performed):	
		Executive function	↔ (HHg, TWA child) ↔ (HHg, TWA adult)
		Attention	↔ (HHg, TWA child) ↔ (HHg, TWA adult)
		BNT	↔ (HHg, TWA child) ↔ (HHg, TWA adult)
		BVMGT	↔ (HHg, TWA child) ↔ (HHg, TWA adult)

Table 2-42. Results of Epidemiological Studies Evaluating Exposure to Methylmercury and Neurodevelopmental Effects—Prospective Birth Cohorts in the Seychelle Islands

Reference, age at follow-up	Biomarker	Outcome evaluated	Result[a]
		Before Bonferroni correction for multiple comparisons:	
		CPT risk-taking	↑ (HHg, TWA child, 9 years)
		WCST errors	↑ (HHg, TWA adult, 17 years)
		BVGMT errors	↓ (HHg, TWA child, 10.5 years)
		CANTAB Visual processing false alarms	↑ (HHg, TWA adult, 17 years)
		CANTAB IED total errors	↑ (HHg, TWA adult, 22 years
		CANTAB IED total trials	↑ (HHg, TWA adult, 22 years)
		BNT total score	↓ (HHg, TWA child, 22 years) ↓ (HHg, TWA adult, 22 years)
		BNT no cue score	↓ (HHg, TWA child, 22 years) ↓ (HHg, TWA adult, 22 years)
		TOVA auditory response time variance	↑ (HHg, TWA child, 24 years)
		TOVA visual response time mean	↑ (HHg, TWA child, 24 years)
		TOVA visual response time variance	↑ (HHg, TWA child, 24 years)
		WJTA passage comp	↓ (HHg, TWA adult, 17 years)
SCDNS			
Davidson et al. 2008b SCDNS follow-up at age 5 months (n=215)	HHg mean Maternal: 5.7 µg/g	FTII (2 metrics)	↔ (HHg, maternal)
		VEXP (2 metrics)	↔ (HHg, maternal)
Davidson et al. 2008b SCDNS follow-up at age 9 months (n=226)	HHg mean Maternal: 5.7 µg/g	FTII (2 metrics)	↔ (HHg, maternal)
		VEXP (2 metrics)	↔ (HHg, maternal)
		BSID MDI	↔ (HHg, maternal)
		BSID PDI	↔ (HHg, maternal)

Table 2-42. Results of Epidemiological Studies Evaluating Exposure to Methylmercury and Neurodevelopmental Effects—Prospective Birth Cohorts in the Seychelle Islands

Reference, age at follow-up	Biomarker	Outcome evaluated	Result[a]
Strain et al. 2015 SCDNS follow-up at age 20 months (n=1,265)	HHg mean Maternal: 3.92 µg/g	BSID MDI	↔ (HHg, maternal)
		BSID PDI	↔ (HHg, maternal)
		CDI	↔ (HHg, maternal)
		BSID IBR	↔ (HHg, maternal)
Davidson et al. 2008b SCDNS follow-up at age 25 months (n=218)	HHg mean Maternal: 5.7 µg/g	DSA (4 metrics)	↔ (HHg, maternal)
Davidson et al. 2008b SCDNS follow-up at age 30 months (n=228)	HHg mean Maternal: 5.7 µg/g	BSID MDI	↔ (HHg, maternal)
		BSID PDI	↓ (HHg, maternal)
Strain et al. 2012 SCDNS follow-up at age 5 years (n=225)	HHg mean Maternal: 5.7 µg/g	Finger tapping (2 metrics)	↔ (HHg, maternal)
		PLS (3 metrics)	↔ (HHg, maternal)
		WJTA	↔ (HHg, maternal)
		KBIT (2 metrics)	↔ (HHg, maternal)
		CBCL	↔ (HHg, maternal)
Strain et al. 2021 SCDNS follow-up at age 7 years (n=1,237)	HHg mean Maternal: 3.91 µg/g	BNT	↔ (HHg, maternal)
		CBCL	↔ (HHg, maternal)
		CELF-5	↔ (HHg, maternal)
		KBIT-2	↔ (HHg, maternal)
		SCQ	↔ (HHg, maternal)
		SRS-2	↔ (HHg, maternal)
		WJTA-III	↔ (HHg, maternal)
		SRS	↔ (HHg, maternal)
		SCQ	↔ (HHg, maternal)
		Trail making	↔ (HHg, maternal)
Orlando et al. 2023 SCDNS follow-up at age 9 years (n=210)	HHg mean Maternal: 5.87 µg/g	Pure tone hearing	↔ (HHg, maternal)
		Auditory brainstem response	↔ (HHg, maternal)
		Otoacoustic emissions	↔ (HHg, maternal)

[a]Interpretation of neurobehavioral test scores:
Age of talking or walking: increased age = delay in development
Barkley ADHD: higher score = lower performance
BNT: higher score = higher performance
BOT: higher score = higher performance
BSID IBR: higher score = higher performance
BSID MDI: higher score = higher performance
BSID PDI: higher score = higher performance

Table 2-42. Results of Epidemiological Studies Evaluating Exposure to Methylmercury and Neurodevelopmental Effects—Prospective Birth Cohorts in the Seychelle Islands

Reference, age at follow-up	Biomarker	Outcome evaluated	Result[a]

BVMGT: higher score = lower performance
CANTAB: higher score = lower performance
CBCL: higher score = lower performance
CDI: higher score = higher performance
CELF-5: higher score = higher performance
CPT: higher score = lower performance
CTRS: higher score = lower performance
CVLT: higher score = higher performance
DDST: milestones evaluated against a standard; below standard = delayed development
DSA: higher score = higher performance
Finger tapping: higher score = higher performance
FTII: higher score = higher performance
GPB: higher score = lower performance
HAPDT: higher score = higher performance
KBIT-2: higher score = higher performance
MSCA: higher score = higher performance
PLS: higher score = higher performance
SCQ: higher score = higher performance
SRS-2: higher score = higher performance
Stroop interference: higher score = higher performance
TOVA: higher score = lower performance
Trail making: higher score = higher performance
TSRSS: higher score = higher performance
VEXP: higher score = higher performance
VMI: higher score = higher performance
WCST: higher score = higher performance
WJTA: higher score = higher performance
WRAML: higher score = higher performance

[b]This study examined potential effect modification from caregiver intelligence, family income, and home environment on the association between maternal hair mercury and neurodevelopmental outcomes.

↑ = positive association; ↓ = inverse association; ↔ = no association; x represents interaction; ADHD = attention deficit/hyperactivity disorder; ASD = autism spectrum disorder; AUC = area under the curve; BNT = Boston naming test; BOT = Bruininks-Oseretsky Test of Motor Proficiency; BSID = Bayley Scales of Infant Development; BVMGT = Bender Visual Motor Gestalt Test; CANTAB = Cambridge Neuropsychological Test Automated Battery; CBCL = Child Behavior Checklist; CPT = Continuous Performance Test; CDI = MacArthur-Bates Communicative Development Inventories; CELF-5 = Clinical Evaluation of Language Fundamentals; GCI = Global Cognition Index; CTRS = Connors' Teacher Rating Scale; CVLT = California Verbal Learning Test; DDST = Denver Developmental Screening Test; DSA = Delayed Spatial Alternation; FSIQ = full scale intelligence quotient; FTII = Fagan Test of Infant Intelligence; GPB = grooved pegboard; HAPDT = Haptic Discrimination Test; HHg = hair mercury; IBR = Infant Behavior Record; IED = Intra-extra dimensional set shift; KBIT = Kauffman Brief Intelligence Test; MDI = BSID Mental Development Index; MSCA = McCarthy Scales of Children's Abilities; OR = odds ratio; PDI = BSID Psychomotor Development Index; PLS = Preschool Language Scale; SACMEQ = Southern and Eastern African Consortium for Monitoring Educational Quality; SCDNS = Seychelles Child Development Nutrition Study; SCDS = Seychelles Child Development Study; SCQ = Social Communication Questionnaire; SRS = Social Responsiveness Scale; TOVA = Tests of Variables of Attention; TSRSS = Total Social Responsiveness Social Scores; TWA = time-weighted average; VEXP = Visual Expectation Paradigm; VMI = Visual Motor Integration; WCST = Wisconsin Card Sorting Test; WISC-III = Wechsler Intelligence Scales for Children, 3rd edition; WJTA = Woodcock-Johnson Test of Achievement; WRAML = Wide Range Assessment of Memory and Learning

The SCDS included a cohort of 779 mother-infant pairs (6 months post-partum), recruited in 1989–1990. Neurodevelopmental outcomes were initiated at age 6 months and continued through age 24 years (Myers

et al. 1995; van Wijngaarden et al. 2017). The primary methylmercury exposure metric has been average maternal gestational HHg. Methylmercury accounted for >80% of total mercury in hair (Cernichiari et al. 1995). Annual median maternal HHg measured over the period 1986–1989 ranged from 5.9 to 8.2 µg Hg/g; the highest observed value was 36 µg Hg/g (Cernichiari et al. 1995). The main cohort followed from age 6 months and later had a median prenatal maternal level of 5.9 µg Hg/g (range 0.5–26.7 g Hg/day) (Myers et al. 1995). Approximately half of the maternal HHg were ≤6 µg Hg/g, while the highest 15% (approximately 95 women) were >12 µg Hg/g; therefore, power to discern significant associations was higher at HHg <12 µg Hg/g. Neurodevelopmental outcomes were assessed using a variety of tests, which changed as the children aged. These included tests of learning and memory, visual-motor function, auditory function, developmental milestones (e.g., age of waking, age of talking), intellectual achievement, and behavior (e.g., signs of attention deficit/hyperactivity disorder or autism spectrum disorder; referrals for substance use, mental health, antisocial behavior, or self-injury). Outcome associations were adjusted for covariates that included (in most studies): child sex, birth weight, birth order, gestational age, medical history, and breastfeeding; maternal age, alcohol and tobacco use, and medical history; and parental education, caregiver general intelligence (Raven's Progressive Matrices), family income, family language, home learning, and social stimulation (Home Observation Measurement of the Environment; HOME score).

In addition to the SCDS, a second prospective study, the SCDNS, evaluated associations between prenatal mercury exposure (maternal HHg), nutrition, and cognitive outcomes (Davidson et al. 2008b; Strain et al. 2008). This study included 300 pregnant women recruited in 2001, with follow-up of infants and children from age 5 months to age 5 years. As in the SCDS, the highest HHg during pregnancy was used as the exposure metric. Mean prenatal maternal HHg level was 5.7 µg/g (range 0.2–18.5 µg/g). Mean maternal fish consumption was 77 g/day (range 0–346 g/day), estimated based on a food use questionnaire and 4-day diet recall (Davidson et al. 2008b). Prenatal maternal nutritional variables associated with child development were assessed in regression models of mercury exposure and developmental outcomes. These included arachidonic acid (AA), choline, Ω-3 and Ω-6 LCPUFAs, docosahexaenoic acid (DHA), thyroid hormone status, and iron status. Neurodevelopmental outcomes were assessed from tests of learning and memory, visual-motor function, and behavior.

Seychelles Child Development Study (SCDS). In general, the SCDS has not found consistent evidence for associations between exposure to methylmercury and neurodevelopmental outcomes at any age thus far studied. This conclusion is supported by cross-sectional follow-ups of the cohort from ages 6.5 months to 24 years (Davidson et al. 1995, 1998, 1999, 2008a, 2010, 2011; Huang et al. 2005; Myers et al. 1995

1997, 2000, 2003, 2009, 2020; Orlando et al. 2014; Palumbo et al. 2000; Thurston et al. 2022; van Wijngaarden et al. 2009, 2013, 2017; Young et al. 2020), longitudinal analyses of individual outcome metrics (Axtell et al. 1998; Davidson et al. 1998; Myers et al. 1997), and longitudinal analysis of metrics of global cognition based on aggregation of outcome metrics (Davidson et al. 2006a). Accounting for error in measuring HHg (and other covariates) had no appreciable effect on dose-response models assessed at age 66 months (Huang et al. 2003).

Although linear regression models consistently found no association between exposure (maternal or child HHg) and cognitive development, nonlinear models of cognitive test scores suggested that performance improved or declined in association with prenatal maternal HHg or child HHg, depending on the hair level (Axtell et al. 1998, 2000; Davidson et al. 1998, 2006a; Huang et al. 2005, 2007, 2018; Myers et al. 1997, 2003, 2020). For some outcomes, performance declined at lower HHg (e.g., ≤7 μg Hg/g), but improved at higher levels; and, for some outcomes, the opposite pattern was observed. At age 66 months, lower performance was not evident in a subgroup of the cohort that had a mean HHg of 15.3 μg Hg/g (>85th percentile) (Davidson et al. 1998). It is uncertain if these nonlinear patterns reflect actual dose-level effects or differential statistical power across the HHg range; or, possibly, random outcomes from the numerous (>20) tests evaluated (Axtell et al. 2000; Davidson et al. 2006b; Huang et al. 2005, 2007). Age of walking increased with increasing prenatal maternal HHg over the range of 1–7 μg Hg/g, however; the effect size was <1 day and the association was not evident at higher levels of HHg (Axtell et al. 1998). Aggregating scores of cognitive performance into metrics of global cognitive function (Davidson et al. 2006a) or dichotomizing test scores into a binomial metric (benchmark response) also revealed no associations in cognitive development and prenatal maternal HHg <20 μg Hg/g (Crump et al. 2000; van Wijngaarden et al. 2006, 2009).

Further complicating the interpretation of associations with mercury exposure were interactions between social variables (e.g., HOME score, caregiver intelligence, SES) and prenatal mercury exposure (Davidson et al. 2004; Huang et al. 2007, 2018; Love et al. 2017). For example, when assessed at age 9 years, performance on tests of motor skills improved in association with increasing maternal mercury in approximately half of children who had an average HOME score; however, performance declined in response to HHg in children who had below average HOME scores (Huang et al. 2007). Given the large number of potential effect modifiers on the cognitive outcomes assessed, the possibility of non-homogeneous susceptibility to methylmercury exposures has been considered in the SCDS (Engstrom et al. 2016; Huang et al. 2007, 2018; Love et al. 2017). The number of maternal mercury amalgam restorations was not associated with performance on tests of cognitive abilities (Watson et al. 2011).

BMD modeling of data from follow-ups up to age 66 months (Crump et al. 2000) and 9 years (van Wijngaarden et al. 2006) evaluated dose-response models for more than 20 cognitive performance endpoints. Based on endpoints measured in follow-ups through age 66 months, the mean BMDL for 144 endpoints was 25 µg Hg/g (range 19–30 µg Hg/g) maternal HHg, when the background response probability was 0.05 and the quantal benchmark response was 0.1 (Crump et al. 2000). Based on the follow-up at age 9 years, the mean BMDL for 26 endpoints was 20.1 µg Hg/g (range 17.2–22.5 µg Hg/g) HHg (van Wijngaarden et al. 2006).

Seychelles Child Development Nutrition Study (SCDNS). The SCDNS found an association between increasing maternal HHg and decreasing psychomotor development index (PDI of the Bayley Scales of Infant Development) when assessed at age 30 months (Davidson et al. 2008b). However, the mercury association was modified by an interaction with maternal omega-3 fatty acid status (Strain et al. 2008). Increasing maternal serum omega-3 levels (or decreasing omega-6/omega-3 ratio) was associated with increases in PDI at age 9 months and the association persisted when maternal HHg was included in the model. At age 30 months, the association between PDI and maternal omega-3 levels was not evident (Strain et al. 2008). At ages 5 and 7 years, increasing maternal DHA and Ω-3 LCPUFA continued to be associated with improved performance on the preschool language scale, whereas no association was found with HHg (Strain et al. 2012, 2021). Analysis of the data from the follow-ups at ages 9 and 30 months showed that increasing maternal DHA levels were associated with improved PDI and mental development index (MDI) scores; however, the benefit of increasing maternal DHA (increasing scores) was attenuated with increasing maternal HHg. Neurobehavioral endpoints were re-examined at age 7 years in a second cohort from the SCDNS (Strain et al. 2021). The study did not find associations between maternal mercury hair levels (mean 2.91 µg/g; range 0.01, 31.66) and scores of tests that evaluated executive function, cognition, and linguistic skills. The study found improved scores in association with maternal serum omega-3 levels and no interaction between serum omega-3 levels and maternal HHg. Hearing function was evaluated at age 9 years and no associations were found between pre- or postnatal HHg levels and auditory brainstem responses or otoacoustic emissions (Orlando et al. 2014). These observations suggest that nutritional benefits of the relatively high fish consumption of the cohort may have weakened possible associations between measured neurodevelopmental outcomes and prenatal mercury exposure.

Faroe Islands. A prospective study of methylmercury and neurodevelopmental outcomes has been conducted in the Faroe Islands (Faroes study). A summary of the major outcomes of the Faroes study are

presented in Table 2-43. Consumption of marine fish and mammals (e.g., pilot whale) is the major contributor to methylmercury exposure in the Faroes population (Grandjean et al. 1992). The Faroes study included a cohort of 1,022 singleton births pairs recruited in 1986–1987. Assessment of neurodevelopmental outcomes began with pediatric observations at age 2 weeks and cognitive function testing conducted periodically, with the most recent follow-up at age 22 years (Steuerwald et al. 2000; Oulhote et al. 2017b). The primary methylmercury prenatal exposure metric has been total mercury in cord blood, which was predominantly (>80%) methylmercury (Grandjean et al. 1992). Maternal HHg was also measured and used as an exposure metric in some analyses. The median cord BHg concentration was 24 µg Hg/L and interquartile range (IQR) was 13–40 µg Hg/L; approximately 25% of the cord mercury levels were >40 µg Hg/L (Grandjean et al. 1992). Cord BHg levels (µg Hg/L) were approximately 5 times maternal HHg measured at parturition (median 4.5 µg Hg/g, IQR: 2.5, 7.7) (Grandjean et al. 1992). Based on a dietary survey, the average daily consumption in the Faroe Island population was 72 g fish/day and 12 g whale/day (Grandjean et al. 1992). Mercury levels in blood and hair were correlated with the number of fish meals per week and number of whale meals per week and were not correlated with number of mercury amalgam dental restorations (Grandjean et al. 1992; Weihe et al. 1996). Although both fish and whale consumption correlated with BHg levels, the largest fraction of the variance in blood and HHg was explained by variance in consumption of pilot whale, whereas fish consumption was a less important explanatory variable.

Table 2-43. Results of Epidemiological Studies Evaluating Exposure to Methylmercury and Neurodevelopmental Effects—Prospective Birth Cohort in the Faroe Islands

Reference (listed in order of age at follow-up)	Biomarker	Outcome evaluated	Result[a]
Steuerwald et al. 2000 Follow-up at age 2 weeks (n=182)	BHg Gmean Cord: 20.4 µg/L	Neurologic optimality score	↓ (BHg, cord)
Grandjean et al. 1995 Follow-up at age 12 months (n=583)	BHg median Cord: not reported HHg Gmean: Maternal: 4.47 µg/g Child (age 12 months): 0.9–1.3 µg/g	Age of sitting	↔ (BHg, cord) ↔ (HHg, maternal) ↓ (HHg, child) ↓ (duration of nursing)
		Age of crawling	↔ (BHg, cord) ↔ (HHg, maternal) ↓ (HHg, child) ↓ (duration of nursing)
		Age of standing	↔ (BHg, cord) ↔ (HHg, maternal) ↓ (HHg, child) ↓ (duration of nursing)

Table 2-43. Results of Epidemiological Studies Evaluating Exposure to Methylmercury and Neurodevelopmental Effects—Prospective Birth Cohort in the Faroe Islands

Reference (listed in order of age at follow-up)	Biomarker	Outcome evaluated	Result[a]
Grandjean et al. 1997, 1998, 1999, 2003 Follow-up at age 7 years (n=917)	BHg Gmean Cord: 22.9 µg/L HHg Gmean Maternal: 4.27 µg/g Low-level mercury exposure considered maternal HHg <10 µg/g	VEPL	↔ (BHg, cord)
		BAEPL	↑ (BHg, cord)
		Postural sway	↔ (BHg, cord)
		HRV	↔ (BHg, cord)
		NES FTT	↓ (BHg, cord) ↔ (BHg, cord; low-level only)
		NES HECT	↔ (BHg, cord) ↔ (BHg, cord; low-level only)
		NES CPT (reaction time)	↑ (BHg, cord) ↑ (BHg, cord; low-level only)
		WISC-R (digit span)	↓ (BHg, cord) ↓ (BHg, cord; low-level only)
		WISC-R (similarities)	↔ (BHg, cord) ↔ (BHg, cord; low-level only)
		WISC-R (block design)	↔ (BHg, cord) ↔ (BHg, cord; low-level only)
		BVMGT (copy)	↔ (BHg, cord) ↔ (BHg, cord; low-level only)
		BVMGT (reproduction)	↔ (BHg, cord) ↓ (BHg, cord; low-level only)
		BNT	↓ (BHg, cord) ↓ (BHg, cord; low-level only)
		CVLT	↓ (BHg, cord) ↓ (BHg, cord; low-level only)
		NVAPMS	↔ (BHg, cord) ↔ (BHg, cord; low-level only
		CBCL	↔ (BHg, cord)
Yorifuji et al. 2013 Follow-up age at 7 years (n=139)	BHg Gmean Cord: 22.8 µg/L HHg Gmean Maternal: 4.6 µg/g	VEPL	↔ (BHg, cord) ↑ (HHg, maternal)
Grandjean et al. 2014 Follow-up at age 7 years (n=694)	BHg Gmean Cord: 22.3 µg/L Child (age 7 years): 8.36 µg/L	NES FTT	↓ (BHg, cord) ↔ (BHg, child)
		NES HECT	↑ (BHg, cord) ↔ (BHg, child)

Table 2-43. Results of Epidemiological Studies Evaluating Exposure to Methylmercury and Neurodevelopmental Effects—Prospective Birth Cohort in the Faroe Islands

Reference (listed in order of age at follow-up)	Biomarker	Outcome evaluated	Result[a]
		NES CPT (reaction time)	↑ (BHg, cord) ↔ (BHg, child)
		WISC-R (digit span)	↔ (BHg, cord) ↔ (BHg, child)
		WISC-R (similarities)	↔ (BHg, cord) ↔ (BHg, child)
		WISC-R (block design)	↔ (BHg, cord) ↔ (BHg, child)
		BVMGT (copy)	↔ (BHg, cord) ↔ (BHg, child)
		BVMGT (reproduction)	↔ (BHg, cord) ↓ (BHg, child)
		BNT	↓ (BHg, cord) ↔ (BHg, child)
		CVLT	↔ (BHg, cord) ↔ (BHg, child)
Oulhote et al. 2019 Follow-up at age 7 years (n=503)	BHg Gmean Cord: 13.0 µg/L Child (age 5 years): 2.68 µg/L	BNT (without cues)	↓ (BHg, cord) ↔ (BHg, child)
		BNT (with cues)	↓ (BHg, cord) ↔ (BHg, child)
		SDQ (total)	↔ (BHg, cord) ↔ (BHg, child)
Debes et al. 2006 Follow-up at age 14 years (n=860)	BHg Gmean Cord: 22.5 µg/L HHg Gmean Maternal: 4.21 µg/g	NES FTT	↓ (BHg, cord) ↓ (HHg, maternal)
		CATSYS FTT (reaction time)	↔ (BHg, cord) ↑ (HHg, maternal)
		NES CPT (reaction time)	↑ (BHg, cord) ↑ (HHg, maternal)
		Digit span	↔ (BHg, cord) ↔ (HHg, maternal)
		Spatial span	↑ (BHg, cord) ↑ (HHg, maternal)
		ST-BI copying	↔ (BHg, cord) ↔ (HHg, maternal)
		WISC-R (block design)	↔ (BHg, cord) ↔ (HHg, maternal)
		WISC-R (similarities)	↔ (BHg, cord) ↔ (HHg, maternal)
		BNT	↓ (BHg, cord) ↔ (HHg, maternal)
		CVLT	↔ (BHg, cord) ↔ (HHg, maternal)

Table 2-43. Results of Epidemiological Studies Evaluating Exposure to Methylmercury and Neurodevelopmental Effects—Prospective Birth Cohort in the Faroe Islands

Reference (listed in order of age at follow-up)	Biomarker	Outcome evaluated	Result[a]
Julvez et al. 2010; Debes et al. 2006 Follow-up at age 14 years (n=860)	BHg Gmean Cord: 22.5 µg/L Child (age 7 years): 9.00 µg/L Child (age 14 years): 4.08 µg/L HHg Gmean Maternal: 4.21 µg/g Child (age 7 years): 2.99 µg/g Child (age 14 years): 0.92 µg/g	NES CPT (reaction time during 1–2 minutes of testing)	↔ (BHg, cord) ↔ (BHg, child) ↔ (HHg, maternal) ↔ (HHg, child)
		NES CPT (reaction time during 3–6 minutes of testing)	↑ (BHg, cord) ↔ (BHg, child) ↑ (HHg, maternal) ↔ (HHg, child)
		NES CPT (reaction time during 7–10 minutes of testing)	↑ (BHg, cord) ↔ (BHg, child) ↑ (HHg, maternal) ↔ (HHg, child)
		NES CPT (reaction tine during 3–10 minutes of testing)	↑ (BHg, cord) ↔ (BHg, child) ↑ (HHg, maternal) ↔ (HHg, child)
Murata et al. 2004a Follow-up at age 14 years (n=859)	BHg Gmean: Cord: 22.6 µg/L HHg median Maternal: 4.22 µg/g Child (age 14 years): 0.96 µg/g	BAEPL	↑ (BHg, cord) ↑ (HHg, maternal) ↑ (HHg, child)
Debes et al. 2016 Follow-up at age 22 years (n=814)	BHg Gmean Cord: 22.91 µg/L Child (age 22 years): 2.53 µg/L HHg Gmean Maternal: 4.24 µg/g Child (age 22 years): 0.68 µg/g	WJTA (concept formation)	↔ (BHg, cord) ↔ (HHg, maternal)
		WJTA (synonyms, antonyms)	↓ (BHg, cord) ↓ (HHg, maternal)
		WJTA (numbers reversed)	↔ (BHg, cord) ↔ (HHg, maternal)
		WJTA (word memory)	↔ (BHg, cord) ↔ (HHg, maternal)
		WJTA (spatial)	↔ (BHg, cord) ↔ (HHg, maternal)
		WMS (spatial span)	↔ (BHg, cord) ↔ (HHg, maternal)
		WISC-R (block design)	↔ (BHg, cord) ↔ (HHg, maternal)

Table 2-43. Results of Epidemiological Studies Evaluating Exposure to Methylmercury and Neurodevelopmental Effects—Prospective Birth Cohort in the Faroe Islands

Reference (listed in order of age at follow-up)	Biomarker	Outcome evaluated	Result[a]
		CVLT	↔ (BHg, cord) ↔ (HHg, maternal)
		WFRT	↔ (BHg, cord) ↔ (HHg, maternal)
		RSPM	↓ (BHg, cord) ↓ (HHg, maternal)
		BNT	↓ (BHg, cord) ↔ (HHg, maternal)
		NES CPT (reaction time)	↔ (BHg, cord) ↔ (HHg, maternal)
		NES (finger tapping)	↔ (BHg, cord) ↔ (HHg, maternal)

[a]Interpretation of neurobehavioral test scores:
Age of crawling, sitting or walking: increased age = delay in development
BAEPL: higher score = lower performance
BVMGT: higher score = lower performance
BNT: higher score = higher performance
CATSYS FTT: higher score = higher performance
CBCL: higher score = lower performance
CVLT: higher score = higher performance
Digit span: higher score = higher performance
HRV: higher score = lower performance
NES CPT: longer response time = lower performance
NES FTT: higher score = higher performance
NES HECT: higher score = higher performance
Neurologic optimality score: higher score = higher performance
NVAPMS: higher score = more negative mood
Postural sway: higher score = lower performance
RSPM: higher score = lower performance
Spatial span: higher score = higher performance
ST-BI copying: higher score = higher performance
VEPL: higher score = lower performance
WFRT: higher score = higher performance
WISC-R: higher score = higher performance
WJTA: higher score = higher performance
WMS: higher score = higher performance

↑ = positive association; ↓ = inverse association; ↔ = no association; BAEPL = Brainstem auditory evoked potential latencies; BHg = blood mercury; BNT = Boston naming test; BVMGT = Bender Visual Motor Gestalt Test; CATSYS FTT = Catsys (equipment name) Finger Tapping Test; CBCL = Child Behavior Checklist; CPT = Continuous Performance Test; CVLT = California Verbal Learning Test; FTT = Finger Tapping Test; Gmean = geometric mean; HECT = Hand Eye Coordination Test; HHg = hair mercury; HRV = heart rate variability; NES = Neurobehavioral Evaluation Systems; NVAPMS = Nonverbal Analogue Profile of Mood States; RSPM = Raven Standard Progressive Matrices; SDQ = Strengths and Difficulties Questionnaire; ST-BI = Stanford-Binet; VEPL = visual evoked potential latencies; WFRT = Warrington's Face Recognition Test; WISC-R = Wechsler Intelligence Scale for Children, Revised; WJTA = Woodcock-Johnson Test of Achievement; WMS = Wechsler Memory Scale

Neurodevelopmental outcomes were assessed using a variety of tests that changed as the children aged. These included tests of learning and memory, visual-motor function, auditory function, autonomic nervous function, developmental milestones (e.g., sitting, crawling, standing), intellectual achievement, and behavior. Outcome associations were adjusted for covariates that included (in most studies, depending on the outcome measured): child age, sex, and birth weight; breastfeeding; maternal age, alcohol and tobacco use, and medical history; and caregiver general intelligence (Raven's Progressive Matrices).

The Faroe Islands study found associations between prenatal (cord) BHg and decreasing performance on tests of cognitive function assessed at age 7 years (Grandjean et al. 1997, 1998, 2003, 2014; Oulhote et al. 2019), 14 years (Debes et al. 2006; Julvez et al. 2010), and 22 years (Debes et al. 2016). The associations were not consistently observed in all tests of cognitive function and tended to cluster in domains of fluid reasoning (e.g., identifying rules for visual similarities and differences), comprehension and knowledge (e.g., naming, word synonyms and antonyms), decision and reaction speed, and motor coordination (Debes et al. 2016). For example, tests that consistently showed associations with cord mercury included the Boston Naming Test, Woodcock-Johnson test of synonyms and antonyms, Neurobehavioral Evaluation Systems Continuous Performance Test Hit Reaction Time latencies, and Neurobehavioral Evaluation Systems Finger Tapping test. At ages 7 and 14 years, the size of the effect was estimated to be approximately 5–10% of the test score SD per doubling of cord BHg (Debes et al. 2006; Grandjean et al. 1997, 1999; Oulhote et al. 2019). Latencies of brainstem auditory evoked potentials measured at age 7 or 14 years increased in association with increasing prenatal or child HHg (Grandjean et al. 1997; Murata et al. 2002, 2004a). BMD modeling was applied to auditory evoked potentials observed at age 7 and 14 years (Murata et al. 2002, 2004a). At age 7 years, estimated BMDLs ranged from 7 to 9 µg Hg/g maternal HHg when the background response probability was 0.05 and the quantal BMR was 0.05; and from 12 to 14 µg Hg/g when the BMR was 0.1. At age 14 years, the BMDL was 10 µg Hg/g for BMR 0.1 and 0.05 background response. When the data from the 7-year follow-up of the Faroes study was combined with the data from the Madeira Portugal study (described below), the BMDL (BMR 0.1) ranged from 16 to 17 µg Hg/g hair (Murata et al. 2002).

A variety of factors have been explored to assess potential bias in the associations observed in the Faroe Islands study. Exposure measurement error based on estimation of biomarker imprecision was estimated to exceed laboratory measurement error, which would tend to attenuate dose-slopes and bias estimates of effect sizes downward (Grandjean and Budtz-Jorgensen 2007; Grandjean et al. 2004b). The observed associations with cognitive test outcomes persisted after excluding subjects who had large variability in

HHg during pregnancy (Grandjean et al. 2003). Postnatal HHg correlated with duration of breastfeeding; however, breastfeeding was not a significant explanatory variable for cognitive test outcomes in the cohort (Grandjean et al. 1995; Jensen et al. 2005). Blood selenium levels correlated with BHg levels and whale consumption (Grandjean et al. 1992); however, prenatal selenium level (cord blood) was not a significant explanatory variable for cognitive test outcomes in the cohort (Choi et al. 2008b). Cord blood PCB concentration correlated with BHg levels; however, associations between cord BHg levels and cognitive tests scores persisted after adjustment for cord blood PCB concentrations (Grandjean et al. 1997). Analysis of data from the 7-year follow-up found no evidence of interactions between mercury and exposure to PCBs and long-chain perfluoroalkyls (Oulhote et al. 2019). Adjustment for cord serum Ω-3 LCPUFA strengthened associations between prenatal mercury exposure and cognitive test scores or brainstem evoked potential latencies (Yorifuji et al. 2013). Improved cognitive performance was associated with higher aerobic capacity (maximum oxygen utilization; VO_{2Max}); however, the association was attenuated with increasing prenatal mercury exposure (Oulhote et al. 2017b).

North Island New Zealand. A prospective study of methylmercury exposure and neurodevelopmental outcomes was conducted in North Island, New Zealand (Kjellstrom et al. 1989). The original cohort consisted of 10,930 children and mother pairs recruited in 1978. Consumption of marine fish was the major contributor to methylmercury exposure in this population. The prenatal exposure metric was that average total mercury in maternal hair during pregnancy. A subset of 935 high consumer subjects was selected based on consumption >3 fish meals per week. HHg levels in this group ranged from 0.24 to 86.4 μg Hg/g. A high exposure subset of 73 high consumers was selected based on HHg >6 μg Hg/g, from which 38 were tested at age 4 years, along with a set of 31 matched referents from mothers who consumed no more than one fish meal per week and matched for maternal ethnic group, age, residence time in New Zealand, tobacco smoking, and child birth date and sex. Assessment of neurodevelopmental outcomes occurred at age 4 and 6 years. Mean HHg was 8.8 μg Hg/g (range 6.0–86.4 μg Hg/g) in the high exposure group and 1.9 μg Hg/g (range 0.5–6.1 μg Hg/g) in the reference group. At age 4 years, children were assessed for performance on the Denver Developmental Screening Test (DDST; function, language, and personal-social behavior), Sheridan-Gardiner Letter Matching Test or Miniature Toy Test (vision), and tactile sensory function (touch, temperature), and the parent was surveyed with a questionnaire on child health and neurological signs (Kjellstrom et al. 1986). The OR for abnormal or questionable scores on the DDST at age 4 years (n=31, relative matched referents) was 6.5 ($p<0.005$). Performance of high-exposure children on vision and sensory function tests were not different from matched referents.

At age 6 years, 61 children in the high-exposure group were re-evaluated along with a set of 3 referent groups (n=58–60), each matched with the high-exposure group for maternal ethnic group, age, residence time in New Zealand, tobacco smoking, and child birth date and sex (Kjellstrom et al. 1989). Geometric mean maternal HHg was 8.3 µg Hg/g (range 6–86 µg Hg/g) in the high-exposure group (follow-up Group 1). HHg levels in the three referent groups were as follows: Group 2 (consumed >3 fish meals per week): 4.5 µg Hg/g (range 3–6 µg Hg/g); Group 3 (consumed >3 fish meals per week): 2.0 µg Hg/g (range 0.1–3 µg Hg/g), and Group 4 (consumed ≤3 fish meals per week): 2.0 (µg Hg/g (range 0.1–3 µg Hg/g). Geometric mean cord blood lead levels in the four groups were as follows: Group 1: 4.9 µg Pb/L (geometric standard deviation [GSD] 1.4); Group 2: 5.5 µg Pb/dL (GSD 1.3); Group 3: 6.5 µg Pb/dL (GSD 1.4); and Group 4: 5.7 µg Pb/dL (GSD 1.2). The study did not evaluate associations between blood lead levels and outcomes. Children were assessed for performance on tests of academic attainment, language development, motor coordination, intelligence, and behavior. Language development was assessed from performance on the Test of Language Development (TOLD; phonology, syntax, semantics) and Peabody picture vocabulary test (word knowledge). Intelligence was assessed using the McCarthy scales and Weschler Intelligence Scale for Children (WISC). Outcome associations were adjusted for significant covariates; variables explored included maternal ethnic group, age, smoking and alcohol consumption, residence time in New Zealand, social class, language spoken at home, siblings, duration of breastfeeding, and child sex, birth weight, maturity at birth, and Apgar score. Maternal HHg was associated with lower scores on the TOLD spoken language quotient (β -5.48, p=0.0064), WISC full-scale IQ (β -4.41, p=0.019), and McCarthy perceptual scale (β -4.23, p=0.0034). When the high-exposure group (Group 1) was split into two maternal HHg categories, 6–<10 or ≥10 µg Hg/g, a larger fraction of variance in the TOLD and WISC tests were explained by the higher HHg category. Performance on TOLD spoken language quotient was inversely associated with HHg in the lower HHg category, whereas performance on both the TOLD spoken language quotient and WISC full scale was inversely associated with HHg ≥10 µg Hg/dL. Children scored as having an abnormal Denver test at age 4 years had lower WISC full scale IQ scores at age 6 years.

Crump et al. (1998) analyzed data on 237 children from the original North Island New Zealand study (age 6–7 years) to estimate BMDLs for cognitive outcomes. The cohort included 61 children born to mothers who consumed fish more than 3 times per week and who had HHg ≥6 µg Hg/g, matched to 176 control children from mothers who had HHg <6 µg Hg/g (matched for ethnicity, place of residence of mother, and maternal smoking). Outcome measures used in the analysis were the scores on a subset of 5 of the 26 tests administered in the original study: TOLD (spoken language quotient), Wechsler Intelligence Scale (performance and full sale IQ), and McCarthy Scales of Children's Abilities (perceptual and motor).

Estimated BMDLs for the five tests ranged from 7.4 to 10 µg Hg/g when the background response probability was 0.05 and the quantal BMR was 0.1.

Nunavik region of arctic Canada. A prospective study of methylmercury exposure and neurodevelopmental outcomes was conducted in the Nunavik region of arctic Canada (Nunavik study). A summary of the major outcomes of the Nunavik study are presented in Table 2-44. Consumption of marine fish and mammals was the major contributor to methylmercury exposure in the Nunavik population (Blanchet and Rochette 2008). The Nunavik study included a cohort of pregnant women recruited in 1995–2001, as part of the Nunavik Environmental Contaminants and Child Development Study (NECCDS), Arctic Cord Blood Monitoring Program (Muckle et al. 1998), and Nunavik Preschool Study (Saint-Amour et al. 2006). Assessment of neurodevelopmental outcomes began at age 6.5 months with periodic follow-ups, the most recent at age 11 years (Boucher et al. 2010, 2012a, 2012b, 2014, 2016; Despres et al. 2005; Ethier et al. 2012; Jacobson et al. 2015).

Table 2-44. Results of Epidemiological Studies Evaluating Exposure to Methylmercury and Neurodevelopmental Effects—Prospective Birth Cohort in the Nunavik Region of Arctic Canada

Reference (listed in order of age at follow-up)	Biomarker	Outcome evaluated[a]	Result
Boucher et al. 2010 Follow-up at age 11 years (n=118)	BHg mean Cord: 21.5 µg/L Child (11 years): 4.69 µg/L	Auditory oddball test	↔ (BHg, cord) ↔ (BHg, child)
		Test EEG ERP amplitude	↓ (BHg, cord) ↔ (BHg, child)
		Test EEG ERP latency	↑ (BHg, cord) ↔ (BHg, child)
Boucher et al. 2012a Follow-up at age 11 years (n=196)	BHg mean Cord: 21.2 µg/L Child (11 years): 4.6 µg/L	Go/no go test	↔ (BHg, cord) ↔ (BHg, child)
		Test EEG ERP amplitude	↔ (BHg, cord) ↔ (BHg, child)
		Test EEG ERP latency	↔ (BHg, cord) ↔ (BHg, child)
Boucher et al. 2012b Follow-up at age 11 years (n=279)	BHg mean Cord: 21.6 µg/L Child (11 years): 4.6 µg/L	TRF internalizing	↔ (BHg, cord) ↔ (BHg, child)
		TRF externalizing	↔ (BHg, cord) ↔ (BHg, child)
		TRF attention	↔ (BHg, cord) ↔ (BHg, child)
		ADHD inattentive	↑ (BHg, cord)
		ADHD hyperactive-impulsive	↑ (BHg, cord)
		ODD or CD	↔ (BHg, cord)

Table 2-44. Results of Epidemiological Studies Evaluating Exposure to Methylmercury and Neurodevelopmental Effects—Prospective Birth Cohort in the Nunavik Region of Arctic Canada

Reference (listed in order of age at follow-up)	Biomarker	Outcome evaluated[a]	Result
Boucher et al. 2014 Follow-up at age 6.5 and 11 months (n=94)	BHg mean Cord: 22.5 µg/L	FTII	0 (BHg, cord)
		A not B test	↓ (BHg, cord)
		BSID MDI	↔ (BHg, cord)
		BSID PDI	↔ (BHg, cord)
Boucher et al. 2016 Follow-up at age 11 years (n=265)	BHg mean Cord: 21.4 µg/L Child (11 years): 4.8 µg/L	SAFB	↔ (BHg, cord) ↔ (BHg, child)
		NES FTT	↔ (BHg, cord) ↓ (BHg, child)
		ST-BI copying	↔ (BHg, cord) ↔ (BHg, child)
Despres et al. 2005 Follow-up at age 4–6 years (n=110)	BHg mean Cord: 22.2 µg/L	Reaction time	↔ (BHg, cord)
		Postural sway	↔ (BHg, cord)
		Alternating movements	↔ (BHg, cord)
		Pointing tremor	↑ (BHg, cord)
Ethier et al. 2012 Follow-up at age 11 years (n=149)	BHg mean Cord: 21 µg/L Child (11 years): 5 µg/L	VEP amplitude	↑ (BHg, cord)
		VEP latency	↑ (BHg, cord)
Jacobson et al. 2015 Follow-up at age 11 years (n=282)	BHg mean Cord: 21.8 µg/L Child (11 years): 4.7 µg/L	WISC-IV (FSIQ)	↓ (BHg, cord) ↔ (BHg, child)

[a]Interpretation of neurobehavioral test scores:
A not B test: higher score = higher performance
BSID MDI: higher score = higher performance
BSID PDI: higher score = higher performance
CD: higher score = more behavioral problems
FTII: higher score = higher performance
NES FTT: higher score = higher performance
ODD: higher score = more behavioral problems
SAFB: higher score = higher performance
ST-BI copying: higher score = higher performance
TRF: higher score = more behavioral problems
WISC-IV: higher score = higher performance

↑ = positive association; ↓ = inverse association; ↔ = no association; ADHD = attention deficit/hyperactivity disorder; BHg = blood mercury; BSID = Bayley Scales of Infant Development; CD = Conduct Disorder; EEG ERP = electroencephalogram event related potential; FSIQ = full scale intelligence quotient; FTII = Fagan Test of Infant Intelligence; MDI = BSID Mental Development Index; NES = Neurobehavioral Evaluation Systems; FTT = Finger Tapping Test; ODD = Oppositional Deviant Disorder; PDI = BSID Psychomotor Development Index; SAFB = Santa Ana Form Board; ST-BI = Stanford-Binet; TRF = Teacher Report Form; VEP = visual evoked potential; WISC-IV = Wechsler Intelligence Scale for Children, 4th edition

The primary methylmercury prenatal exposure metric has been total mercury in cord blood. Based on results from the Arctic Cord Blood Monitoring Program, the geometric mean (GM) cord BHg concentration was 23 µg Hg/L and the IQR was 12–27 µg Hg/L (Muckle et al. 2001). Cord BHg levels (µg Hg/L) were approximately 5 times maternal HHg measured during the third trimester (GM 4.4 µg Hg/g; IQR 2.4, 6.0) (Muckle et al. 2001). Based on a dietary survey of Nunavik population, the average daily consumption was approximately 50 g/day of fish and 22 g/day of marine mammals (Blanchet and Rochette 2008).

Neurodevelopmental outcomes were assessed using a variety of tests that changed as the children aged. These included tests of learning and memory, visual-motor function, auditory function, and behavior problems (e.g., attention deficit/hyperactivity disorder). Outcome associations were adjusted for covariates that included (in most studies, depending on the outcome measured): sex; age at testing; cord and current blood lead, selenium, DHA, and PCBs; SES; maternal marital status; education; caregiver general intelligence (Raven's Progressive Matrices); tobacco smoking and marijuana use during pregnancy; and HOME score.

The Nunavik study found associations between increasing prenatal (cord) BHg and slower reaction times in tests of visual and auditory information processing tasks (Boucher et al. 2010, 2014, 2016; Ethier et al. 2012), pointing tremor (Despres et al. 2005), full scale IQ (Jacobson et al. 2015), and higher symptom scores for attention deficit/hyperactivity disorder (Boucher et al. 2012b). In some studies of information processing, increased latency of electrophysiological (e.g., EEG) event response potentials were evident, suggesting a possible effect of exposure on behavioral reaction time (Boucher et al. 2010, Ethier et al. 2012). At age 11 years, the size of the mercury effect on IQ (WISC) was a decrease of 4.8 points in children whose cord BHg had been ≥7.5 µg Hg/L, compared to children whose cord BHg had been <7.5 µg Hg/L (Jacobson et al. 2015).

A variety of factors have been explored to assess potential bias in the associations observed in the Nunavik study. Cord BHg was correlated with cord PCB, lead, selenium, and DHA levels (Boucher et al. 2010). Cord PCB levels were independently associated with many of the outcomes measured. In some studies, associations with cord mercury were no longer evident when cord or child blood PCB levels were included as covariates (Boucher et al. 2012a, 2016; Despres et al. 2005). Cord PCBs and lead interacted with cord mercury in explaining variance in some cognitive outcomes (Boucher et al. 2012a). Nutrients such as cord blood DHA and selenium tended to strengthen associations between cord mercury levels and response latency and IQ outcomes (Boucher et al. 2010; Jacobson et al. 2015). When stratified by

breastfeeding duration, children who were breastfed for <3 months tended to show stronger associations with cord mercury levels (Boucher et al. 2010). These observations suggest that associations between cognitive performance outcomes and prenatal mercury exposures can be modified by co-exposure to other agents that may independently affect cognitive performance (e.g., PCBs, lead, nutrients).

Amazonian riverine populations. Studies of methylmercury exposure and neurodevelopmental outcomes have been conducted in populations living in Amazon River basins (Amazonian studies). These include several cross-sectional studies of children from birth cohorts who resided in various river basins, with neurodevelopmental assessments in infancy and various later ages, with the oldest cohort being 14 years of age. Exposure to methylmercury in these populations derived primarily from methylation of inorganic mercury released to local aquatic ecosystems from alluvial gold mining (Marques et al. 2007). A summary of the major outcomes of the Amazonian studies are presented in Table 2-45.

Table 2-45. Results of Epidemiological Studies Evaluating Exposure to Methylmercury and Neurodevelopmental Effects—Amazonian River Basin Studies

Reference, study type, and population	Biomarker	Outcome evaluated	Result[a]
Hoshino et al. 2015 Cross-sectional cohort of 58 individuals (age range 1–47 years); Brazil	HHg median 10.91 µg/g	Tympanometry	↔ HHg
		Acoustic reflexes	↔ HHg
		Pure tone audiometry	↔ HHg
		Transient otoacoustic emissions	↔ HHg
Marques et al. 2007 Prospective study of birth cohort, follow-up at age 6 months (n=100); Brazil	HHg median Maternal: 5.40 µg/g Child (birth): 1.59 µg/g Child (6 months): 1.81 µg/g	GDS	↔ (HHg, birth) ↔ (HHg, 6 months)
Marques et al. 2015 Prospective study of birth cohort, follow-up at age 6 months (n=294), Brazil	HHg median (female, male) Child (birth): 0.79, 0.81 µg/g Child (6 months): 0.98, 0.97 µg/g	BSID MDI	↔ (HHg, birth) ↔ (HHg, 6 months)
		BSID PDI	↔ (HHg, birth) ↔ (HHg, 6 months)
Marques et al. 2015 Prospective study of birth cohort, follow-up at age 24 months (n=294); Brazil	HHg median (female, male) Child (birth): 0.79, 0.81 µg/g Child (6 months): 0.98, 0.97 µg/g Child (24 months): 1.75, 1.72 µg/g	BSID MDI	↔ (HHg, birth) ↔ (HHg, 6 months) ↔ (HHg, 24 months)
		BSID PDI	↔ (HHg, birth) ↔ (HHg, 6 months) ↔ (HHg, 24 months)

Table 2-45. Results of Epidemiological Studies Evaluating Exposure to Methylmercury and Neurodevelopmental Effects—Amazonian River Basin Studies

Reference, study type, and population	Biomarker	Outcome evaluated	Result[a]
Dorea et al. 2012 Cross-sectional cohort study of children, 1–6 months of age (n=281); Brazil	HHg mean (infant) Itapua: 3.95 µg/g Bom Futuro: 1.85 µg/g Porto Velho: 3.84 µg/g	GDS	↔ (HHg, current age)
Cordier et al. 2002 Cross-sectional cohort of children age 5–12 years (n=378); French Guiana	HHg geometric mean (maternal) Upper Maroni: 12.7 µg/g Camopi: 6.7 µg/g Awala: 2.8 µg/g	ST-BI copying	↓ (HHg, maternal)
		NES FTT	↔ (HHg, maternal)
		Leg coordination	↔ (HHg, maternal)
		Digit span (forward)	↔ (HHg, maternal)
Chevrier et al. 2009 Pooled analysis of children, age 7 to 12 years (n=395); Brazil, French Guiana	HHg mean Maternal: 10.3 µg/g Child: 9.8 µg/g	ST-BI copying error	↑ (HHg, maternal) ↑ (HHg, child)
Dorea et al. 2014 Cross-sectional cohort study of children, 12–24 months of age (n=299); Brazil	HHg median (infant) Itapua: 3.5 µg/g Bom Futuro: 2.2 µg/g	GDS	↔ (HHg, infant)
		Age of talking	↔ (HHg, current age)
		Age of walking	↔ (HHg, current age)
dos Santos Freitas et al. 2018 Cross-sectional cohort study of children, 7–14 years of age (n=176); Brazil	HHg mean (child) Tapajos basin: 4.5 µg/g Tocantins basin: 0.49 µg/g	Color vision	↔ (HHg, current age)
dos Santos-Lima et al. 2020 Cross-sectional cohort study of children, 6–14 years of age (n=263); Brazil	HHg mean (child) 3.1 µg/g	WISC IQ	↓ (HHg, child)
		WISC digit span	↓ (HHg, child)
		Block tapping	↓ (HHg, child)
		Phonology	↓ (HHg, child)
		Word generation	↓ (HHg, child)

Table 2-45. Results of Epidemiological Studies Evaluating Exposure to Methylmercury and Neurodevelopmental Effects—Amazonian River Basin Studies

Reference, study type, and population	Biomarker	Outcome evaluated	Result[a]
Reuben et al. 2020 Longitudinal cohort study of children, 5–12 years of age (n=163); Peru	HHg mean (child) 2.06 µg/g	Visual-motor integration	↔ (HHg, child)
		Cognitive ability	↓ (HHg, child)

[a]Interpretation of neurobehavioral test scores:
Block tapping: higher score = higher performance
BSID MDI: higher score = higher performance
BSID PDI: higher score = higher performance
Digit span: higher score = higher performance
GDS: higher score = higher performance
NES FTT: higher score = higher performance
Phonology: higher score = higher performance
ST-BI copying: higher score = higher performance
ST-BI copying error: higher error score = lower performance
Word generation: higher score = higher performance

↑ = positive association; ↓ = inverse association; ↔ = no association; BSID = Bayley Scales of Infant Development; HHg = hair mercury; GDS = Gesell Developmental Scales; IQ = intelligence quotient; MDI = BSID Mental Development Index; NES FTT = Neurobehavioral Evaluation System Finger Tapping Test; PDI = BSID Psychomotor Development Index; ST-BI = Stanford-Binet Bead Memory test; WISC = Wechsler Intelligence Scales for Children

The primary methylmercury prenatal exposure metric in these studies has been total mercury in hair. In riverine populations in the Madeira Basin, the median maternal HHg was 12 µg Hg/g (range 1– 131 µg Hg/g) and correlated with newborn HHg (median 3 µg Hg/g; range 0.1–19 µg Hg/g) (Marques et al. 2013a). In the Madeira Basin population, the median number of fish meals per week was 5 (range 0–7) and number of fish meals per week correlated with maternal HHg (Marques et al. 2013b). Neurodevelopmental outcomes were assessed using a variety of tests that changed as the children aged. These included developmental milestones (e.g., age of talking and walking) and tests of learning and memory, vision, and visual-motor function. Outcome associations were adjusted or stratified for covariates that included (in most studies, depending on the outcome measured): sex, age at testing, breastfeeding, SES, maternal marital status, education, general intelligence caregiver general intelligence (Raven's Progressive Matrices), tobacco smoking, and HOME score.

Studies of Amazonian populations have found associations between prenatal (maternal) or child HHg and performance on tests of cognitive ability (Chevrier et al. 2009; Cordier et al. 2002; dos Santos-Lima et al. 2020; Reuben et al. 2020,). A study of families residing in an artisanal and small-scale gold mining

region of Amazonian Peru evaluated associations between child (mean age 8 years; n=163) HHg and visual-motor coordination, general cognitive ability, and physical health (Reuben et al. 2020). The mean HHg was 2.06 µg Hg/g (range 0.08, 14.61). Increasing HHg was associated with decreasing scores of the Spanish language Woodcock-Johnson Tests of Cognitive Abilities (β = -2.59 points per ln[µg Hg/g hair], 95% CI -4.52, -0.66). In a pooled analysis of children, age 7–12 years, from Amazonian Brazil and French Guiana, the size of the association was an increase of 1.2 in error score on the Stanford-Binet copying test for an increase in child HHg concentration of 10 µg Hg/g (Chevrier et al. 2009). In a population from Amazonian Brazil, age 5–12 years, the effect was a decrease of 2.98 in performance score on the on the Stanford-Binet copying test for an increase in child HHg concentration of 10 µg Hg/g (Cordier et al. 2002). In a cross-sectional study of children 6–14 years of age, increasing HHg was associated with decreasing WISC IQ (dos Santos-Lima et al. 2020). Scores on other tests of cognitive development were not associated with mercury exposure, including Bayley Scales of Infant Development at age 6–12 months (Marques et al. 2015), Gesell Development Scales at age 6–20 months (Dorea et al. 2012, 2014; Marques et al. 2015), age of talking or walking (Dorea et al. 2014), various tests of visual-motor coordination at age 5–12 years (Cordier et al. 2002), or color vision at age 7–14 years (dos Santos Freitas et al. 2018). The above studies did not explore the potential impacts of other exposures (e.g., lead, PCBs) or nutritional factors that may have also correlated with fish consumption.

Madeira, Portugal. Cognitive function was studied in a cross-sectional cohort of 149 mothers and children who resided in Madeira, a fishing village in Portugal (Murata et al. 1999a, 2004b). Fish consumption was a major contributor to exposure to methylmercury in this population. Maternal fish consumption ranged from <1 meal per week (25%) to ≥5 meals/week and correlated with maternal HHg (22%; Murata et al. 1999a). Increasing maternal HHg (median 9.6 µg Hg/g) was associated with delays in brainstem auditory and visual evoked potentials measured at age 7 years. Murata et al. (2002) estimated BMDLs (BMR 0.1) of 14 and 19 µg Hg/g hair for the increased latency of auditory evoked potentials. When the data from the Madeira cohort were combined with the data from the 7-year follow-up of the Faroe Islands study, BMDL estimates (BMR 0.1) ranged from 16 to 17 µg Hg/g hair (Murata et al. 2002).

Artisanal gold mining. Studies have been conducted of neurodevelopment outcomes in populations exposed to mercury released from artisanal gold mining operations (Counter 2003; Counter et al. 1998, 2002, 2006, 2012; Nyanza et al. 2021; Ramirez et al. 2000, 2003; Reuben et al. 2020). In artisanal mining, gold is extracted from a substrate (e.g., pulverized ore, sediment, soil) by mixing the substrate with elemental mercury to form mercury-gold amalgam. The amalgam is washed, sedimented, and

roasted to vaporize the elemental mercury out of the amalgam. This process can result in direct exposures of mine workers to mercury vapor. Exposures of the general population to methylmercury can also occur as a result of methylation of inorganic mercury released to local aquatic ecosystems (Ramirez et al. 2000). Although human exposures to wastes from artisanal goldmines can be a mixture of elemental mercury, inorganic mercuric mercury, and methylmercury, studies of neurodevelopmental outcomes in children residing near gold mine operations are included in the discussion of epidemiological studies of methylmercury because methylmercury is likely to have been a major source of exposures in these populations (Counter et al. 1998; Ramirez et al. 2000).

A prospective study examined developmental milestones and cognitive performance in children from a birth cohort of 78 pregnancies in an area in Philippines where mercury amalgam was used to extract gold from ore (Tagum study) (Ramirez et al. 2000, 2003). In a subset of the cohort (n=12), the mean cord BHg level was 53 µg Hg/L (range 20–130 µg Hg/L). The mean level in fetal meconium (n=36) was 49 µg Hg/L (range 20–200 µg Hg/L). The follow-up conducted at age 2 years (n=48) evaluated cognitive performance based on a cognitive adaptive test (CAT), clinical linguistic auditory milestone scale (CLAMS), and full-scale developmental quotient (FSDQ), and compared outcomes to a control group (from Saranggani, a coastal area not impacted by gold mining waste). Mean BHg levels in the children were higher in the control group (3.25 µg Hg/L) compared to the children from the Tagum region (2.6 µg Hg/L); however mean HHg were higher in the Tagum area (1.28 µg Hg/g) compared to the control group (0.66 µg Hg/g). Mean scores on CAT, CLAMS, and FSDQ were lower in the exposed group. ORs (not adjusted for potential covariates) for "abnormal scores" with the control group (n=88) as the reference, were 4.8 (95% CI 2.03, 11.4) for CLAMS, 1.26 (95% CI 0.32, 1.97) for CAT, and 3.10 (95% CI 0.85, 11.2) for FSDQ. Adjusted ORs were not reported, although a comparison of means between the exposed and control groups were reported for various SES and childcare variables.

A study of families living in an artisanal and small-scale gold mining area of Peru evaluated performance in children at mean age 8 years (n=163; Reuben et al. 2020). The study evaluated associations between child HHg and visual-motor integration, cognitive ability, and physical health. The mean HHg was 2.06 µg Hg/g (range 0.08, 14.61). Decreasing general cognitive ability, measured by a Spanish-language Woodcock-Johnson Tests of Cognitive Abilities, was associated with increasing HHg after adjustment for potential confounding variables (β, -2.59 points per ln µg/g; 95% CI -4.52, -0.66).

Several cross-sectional studies of children residing near gold mining operations in Ecuador have been conducted (Counter et al. 1998, 2002, 2006, 2012). These studies were largely ecological in design in

that they compared mean outcomes between children who resided near gold mines and had higher mercury levels than a control group that did not reside near goldmines. In general, associations between outcomes and BHg (or HHg) were not adjusted for potential covariates. In a population from the Nambija gold mining area, the mean BHg level (n=77; mean age 9 years) was 18 µg Hg/L (range 2–89 µg Hg/L) (Counter et al. 2002). Brainstem auditory evoked responses in children who had BHg levels >20 µg Hg/L (median) showed longer latencies than in children who had BHg levels <20 µg Hg/L (Counter 2003). Children from the Nambija and Portovelo mining areas had lower scores on the Raven's Coloured Progressive Matrices (RCPM), a test of visual-spatial processing, than children from other areas (e.g., Peru, Puerto Rico, United States) (Counter et al. 2006). RCPM scores were also lower among children who had BHg levels >5 µg Hg/L or HHg >2 µg Hg/g compared to children who had lower mercury levels (Counter et al. 2006). Increasing brainstem-mediated acoustic stapedius reflex thresholds in children correlated with increasing BHg (Counter et al. 2012).

A prospective birth cohort that resided in an artisanal gold mining areas of Tanzania assessed Bayley Scales of Infant Development (BSID) scores in infants at age 6–12 months (Nyanza et al. 2021). Increasing maternal BHg levels (median 1.2 µg/L) were associated with increasing prevalence ratio of impaired language, social behavior, and global neurodevelopment.

Meta-analyses. Cohen et al. (2005) conducted a meta-analysis of outcomes of the Faroe Islands study, Seychelles Child Development Study, and North Island New Zealand study. Outcomes from various domains of cognitive function were aggregated into a weighted IQ metric and the meta outcome was expressed as the change in IQ points as a fraction of the outcome SD per 1 µg Hg/g increase in maternal HHg. The meta average effect size was a decrease in 0.043 SD per µg Hg/g. For a SD of 15 IQ points, the meta estimate corresponds to approximately 0.7 IQ points per µg Hg/g (range 0–1.5 IQ points per µg Hg/g). A follow-up to the Cohen et al. (2005) meta-analysis included outcomes from the Faroe Islands study at age 7 years, Seychelles Child Development Study at age 9 years, and North Island New Zealand study at age 6 years (Axelrad et al. 2007a, 2007b; Ryan 2008). The meta estimate for the effect size was -0.18 IQ points per increase of 1 µg Hg/g hair (95% CI -0.378, -0.009). Murata et al. (2002) pooled data on auditory evoked potentials observed at age 7 years in the Faroe Islands and Madeira Portugal studies and estimated BMDLs (BMR 0.1) that ranged from 16 to 17 µg Hg/g hair.

Organic Mercury—Animals Studies. Numerous studies have identified the nervous system as a target of methylmercury toxicity in nonhuman primates and rodents following developmental exposures. Collectively, these studies provide conclusive evidence that methylmercury is associated with adverse neurodevelopmental effects. Neurodevelopmental effects are observed at doses at or below those associated with adverse neurological effects of exposure during adulthood.

Neurodevelopmental effects have been reported in macaque monkeys following prenatal and/or postnatal exposure to methylmercury compounds (Table 2-46). The most sensitive effects were impaired spatial visual discrimination and progressive hearing loss at doses ≥0.01 mg Hg/kg/day (Burbacher et al. 2005; Rice 1998a; Rice and Gilbert 1992); no impairments in peripheral vision and no negative changes in temporal visual discrimination were observed at 0.05 mg Hg/kg/day (Rice and Gilbert 1982, 1990). Mild deficits in operant training were observed in adult monkeys exposed to 0.04–0.08 mg Hg/kg/day during gestation; however, a NOAEL/LOAEL determination cannot be made because the study authors combined all exposed monkeys for data presentation and analysis (Gilbert et al. 1996). In other studies, no impairments in operant training were observed following pre- and postnatal exposure to 0.05 mg Hg/kg/day (Rice 1998b; Rice and Hayward 1999). Overt clinical signs of neurotoxicity were observed at developmental exposures ≥0.05 mg Hg/kg/day (Rice and Gilbert 1990; Willes et al. 1978) and diffuse neuronal degeneration in the cerebral cortex (especially the calcarine, insular, pre-, and postcentral gyri, and occipital lobe), cerebellum, basal ganglia, thalamus, amygdala, and lateral geniculate nuclei were observed at developmental exposures of 0.5 mg Hg/kg/day (Willes et al. 1978).

Table 2-46. Neurodevelopmental Effects[a] in Male and Female Primates Following Oral Exposure to Methylmercury Compounds

Species (sex), exposure duration, and time of examination	Overt clinical signs[b]	Learning/ memory[b]	Auditory function[b]	Visual function[b]	Neuro-pathology[b]	Reference (compound)
Macaca fascicularis; up to 29 days from birth; examined 2 weeks post-exposure	+ L: 0.5 (8.0–9.4)	–	–	–	+ L: 0.5 (8.0–9.4)	Willes et al. 1978 (MMC)
M. fascicularis; 165 days during gestation; examined at 8–15 years	–	↓ L: 0.04–0.08[c] (1.04–2.45)	–	↓ L: 0.04–0.08[c] (1.04–2.45)	–	Burbacher et al. 2005; Gilbert et al. 1996 (MMH)

Table 2-46. Neurodevelopmental Effects[a] in Male and Female Primates Following Oral Exposure to Methylmercury Compounds

Species (sex), exposure duration, and time of examination	Overt clinical signs[b]	Learning/ memory[b]	Auditory function[b]	Visual function[b]	Neuro-pathology[b]	Reference (compound)
M. fascicularis; up to 1,460 days from birth (i.e., 4 years old); examined at 3–5.5 years	–	–	–	↓ L: 0.05 (0.6–0.9)	–	Rice and Gilbert 1982; Rice and Gilbert 1990 (MMC)
M. fascicularis; up to 1,625 days from gestation through age 4 years; examined at 4.3–19 years	+ L: 0.05 (0.8)	↔ N: 0.05 (0.8)	↓ L: 0.01 (0.21)	↓ L: 0.01 (0.21)	–	Rice 1998a; Rice and Gilbert 1990 (MMC)
M. fascicularis; up to 2,555 days from birth (i.e., 7 years old); examined at 10–20 years	–	↔ N: 0.05 (0.8)	–	↔ N: 0.05 (0.8)	–	Rice 1998b; Rice and Hayward 1999 (MMC)

[a]Studies with exposure prior to puberty only, including studies that evaluate adult animals after developmental exposure. These findings are listed under "Develop" in the LSE table.
[b]NOAEL (N) or LOAEL (L) for dose administered in mg Hg/kg/day (blood level in mg Hg/L).
[c]The study authors combined dose groups for data presentation and analysis; NOAEL/LOAEL determinations could not be made.

↓ = decreased; ↔ = no change; – = not assessed; + = present; Develop = developmental; LOAEL = lowest-observed-adverse-effect level; LSE = Levels of Significant Exposure; MMC = methylmercuric chloride; MMH = methylmercury hydroxide; NOAEL = no-observed-adverse-effect level

Twenty studies have evaluated neurobehavioral effects in rodents following acute-duration developmental exposure to methylmercury compounds during gestation or early postnatal periods (Table 2-47). Reported exposure-related effects included decreased motor activity and coordination, impaired learning and memory, delayed or altered reflexes, and altered nocturnal rhythms; findings for anxiety were inconsistent (some reported an increase, others a decrease). In most acute-duration neurodevelopmental studies in rodents, no overt clinical signs of neurotoxicity were reported. Exceptions were "abnormal" walking posture and transient lethargy and ataxia observed in neonatal mice following a single exposure to 16 mg Hg/kg/day during gestation or early postnatal development (Inouye et al. 1985; Post et al. 1973) and hindlimb paralysis and dystonia in neonatal rats exposed to 8 mg Hg/kg/day on PNDs 14–23 (Sakamoto et al. 2020). In rats, the most sensitive effect was impaired operant conditioning (associative learning which is learning by association) following exposure to 0.008 mg Hg/kg/day during GDs 6–9 (Bornhausen et al. 1980). In mice, the most sensitive effects were noted at a comparable gestational dose

of 0.009 mg Hg/kg/day (during GDs 8–18), and included hypoactivity, impaired motor coordination, impaired spatial learning, and increased anxiety (Montgomery et al. 2008).

Table 2-47. Neurobehavioral Effects in Rodents Following Acute-Duration Oral Exposure to Methylmercury Compounds During Development

Species; duration	Motor activity, coordination[a]	Anxiety[a]	Associative learning[a]	Spatial/ working learning and memory[a]	Other[a]	Reference (compound)
Gestational exposure						
Rat; 1 day, GD 15	↔ (N: 6.4)	–	↓ (L: 6.4)	–	–	Cagiano et al. 1990; Zanoli et al. 1994 (MMC)
Rat; 1 day, GD 8 or 15	↓ (L: 7)	↔ (N: 7)	↓ (L: 7)	↓ (L: 7)	Reflexes, ASR, PPI ↔ (N: 7)	Carratu et al. 2006, 2008 (MM)
Rat; 4 days, GDs 6–9	–	–	↓ (L: 0.008)	–	–	Bornhausen et al. 1980 (MMC)
Rat; 4 days, GDs 6–9	↓ (L: 4)	–	0 (L: 4)	↓ (L: 4)	ASR ↑ (L: 4)	Stoltenburg-Didinger and Markwort 1990 (MMC)
Rat; 4 days, GDs 6–9	↔ (N: 1.9)	–	–	↔ (N: 1.9)	Reflexes ↔ (N: 1.9)	Fredriksson et al. 1996 (MM)
Mouse; 1 day, GD 8	↔ (N: 5)	–	↓ (L: 3)	↔ (N: 5)	–	Hughes and Annau 1976 (MMH)
Mouse; 1 day, GD 13, 14, 15, 16, or 17	↓ (L: 16)	–	–	–	Righting reflex ↓ (L: 16)	Inouye et al. 1985 (MMC)
Mouse; 3 days, GDs 7–9	↔ (N: 5)	↔ (N: 5)	–	↓ (L: 3)	–	Dore et al. 2001 (MMC)
Mouse; 3 days, GDs 12–14	↓ (L: 3)	↔ (N: 5)	–	↓ (L: 5)	–	Dore et al. 2001 (MMC)
Mouse; 3 days, GDs 12–14	↓ (L: 3)	↓ (L: 3)	–	↓ (L: 3)	Altered nocturnal rhythm (L: 3)	Kim et al. 2000 (MM)
Mouse; 11 days, GDs 8–18	↓ (L: 0.009)	↑ (L: 0.009)	–	↓ (L: 0.009)	–	Montgomery et al. 2008 (MMC)
Postnatal exposure						
Rat; 1 day, PND 15 or 21	↔ (N: 16)	–	–	↔ (N: 16)	–	Post et al. 1973 (MMC)

Table 2-47. Neurobehavioral Effects in Rodents Following Acute-Duration Oral Exposure to Methylmercury Compounds During Development

Species; duration	Motor activity, coordination[a]	Anxiety[a]	Associative learning[a]	Spatial/ working learning and memory[a]	Other[a]	Reference (compound)
Rat; 9 days, PND 1–10	–	–	↓ (L: 0.280)	↔ (N: 0.280)	–	Kendricks et al. 2022 (MMC)
Rat; 10 days, PND 14–23	↓ (L: 6.3)	–	–	↓ (L: 6.3)	–	Sakamoto et al. 2020 (MMC)
Rat; 10 days, PNDs 14–23	↓ (L: 0.6)	↔ (N: 0.6)	↓ (L: 0.6)	–	Nociception ↔ (N: 0.6)	Coluccia et al. 2007 (MMC)
Mouse; 1 day PND 10	↓ (L: 0.37)	–	–	↓ (L: 0.37)	–	Fischer et al. 2008 (MMC)
Mouse; 5 days, PNDs 29–33	↓ (L: 0.2)	–	–	–	–	Bellum et al. 2007 (MMC)

[a]NOAEL (N) or LOAEL (L) dose in mg Hg/kg/day for endpoint category. Associative learning is learning by association.

↑ = increased; ↓ = decreased; ↔ = no change; – = not assessed; ASR = acoustic startle reflex; GD = gestation day; LOAEL = lowest-observed-adverse-effect level; MM = methylmercury; MMC = methylmercuric chloride; MMH = methylmercury hydroxide; NOAEL = no-observed-adverse-effect level; PND = postnatal day; PPI = paired-pulse inhibition

Thirty-five studies have evaluated neurobehavioral effects in rodents following intermediate-duration developmental exposure during gestation and/or early postnatal periods (Table 2-48). Reported exposure-related effects included decreased motor coordination, impaired learning and memory, and delayed reflex ontogeny; findings for motor activity were inconsistent (some reported increases, others decreases). In most studies, no overt clinical signs of neurotoxicity were reported in intermediate-duration neurodevelopmental studies in rodents. An exception was hindlimb crossing and paralysis observed in neonatal rats following direct exposure to 4 mg Hg/kg/day from PND 1 to 30 (Sakamoto et al. 2002). The most sensitive neurobehavioral effects following intermediate-duration developmental exposure were observed in mice following exposure to 0.02 mg Hg/kg/day during gestation and/or early postnatal development, including altered motor activity and impaired motor coordination (Huang et al. 2011). Impaired hearing, as indicated by decreased auditory brainstem responses, was also observed at this exposure level. The only other neurophysiological study identified in rodents following developmental exposure reported elevated epileptiform activity following maternal exposure to 0.3 mg Hg/kg/day for 7–8 weeks premating through PND 21; baseline cortical activity was comparable (Szász et al. 2002).

Table 2-48. Neurobehavioral Effects in Rodents Following Intermediate-Duration Oral Exposure to Methylmercury Compounds During Development

Species; duration	Motor activity[a]	Motor coordination[a]	Associative learning (OC, AA, PA)[a]	Spatial/ working learning, and memory[a]	Other[a]	Reference (compound)
Gestational exposure						
Rat; 25 days, PM–GD 19	–	–	↓ (L: 0.8)	↔ (N: 0.8)	–	Kakita et al. 2000 (MMC)
Rat; 49–56 days, PM–GD 20 (gavage)	↔ (N: 1)	–	–	–	FOB, ASR ↔ (N: 1)	Beyrouty et al. 2006 (MMC)
Mouse; 19 days, GDs 0–18 (diet)	M: ↑; F: ↓ (L: 0.9)	–	↔ (N: 0.9)	↓ (L: 0.9)	Anxiety ↓ (L: 0.9)	Yoshida et al. 2011 (MM)
Mouse; 21 days, GDs 0–21	0 (N: 0.05)	–	–	↓ (L:0.05)	Socialization and pup vocalizations ↓ (L: 0.05) Stereotypy ↑ (L: 0.05) Anxiety ↔ (N: 0.05)	Loan et al. 2023
Gestational plus postnatal exposure						
Rat; 17 days, GD 5–PND 1	–	–	–	↓ (L: 0.48)	–	Wang et al. 2022a (MMC)
Rat; 22 days, GD 7–PND 7	↑ (L: 0.5)	–	–	–	–	Giménez-Llort et al. 2001 (MMH)
Rat; 22 days, GD 7–PND 7	↓ (L: 0.474)	–	–	↔ (N: 0.474)	–	Rossi et al. 1997 (MMH)
Rat; 35 days, GD 7–PND 21	–	–	–	–	Reflex ontogeny ↓ (L: 1.9)	Sitarek and Gralewicz 2009 (MMC)
Rat; 38 days, GD 5–PND 21	↓ (L: 0.4)	–	↓ (L: 0.2)	↓ (L: 0.2)	–	Albores-Garcia et al. 2016 (MMC)
Rat; 42 days, GD 1–PND 21	↑ (L: 0.23)	↓ (L: 0.23)	–	↔ (N: 0.23)	Reflex ontogeny ↓ (L: 0.23)	Cheng et al. 2015; Fujimura et al. 2012 (MM)
Rat; 42 days GD 0–PND 21	↓ (L: 0.03)	↓ (L: 0.03)	↓ (L: 0.03)	–	–	Fagundes et al. 2022 (MMC)
Rat; 42 days, GD 1–PND 22 +PNDs100–145	–	–	–	–	Anxiety ↑ (L: 0.4)	Rosa-Silva et al. 2020a, 2020b (MMC)
Rat; 60 days, PM–PND 21	↑ (L: 0.74)	–	↓ (L: 0.74)	↔ (N: 0.74)	–	Elsner 1991 (MMC)

Table 2-48. Neurobehavioral Effects in Rodents Following Intermediate-Duration Oral Exposure to Methylmercury Compounds During Development

Species; duration	Motor activity[a]	Motor coordination[a]	Associative learning (OC, AA, PA)[a]	Spatial/ working learning, and memory[a]	Other[a]	Reference (compound)
Rat; 70–91 days, PM–PND 16	–	–	↓ (L: 0.045)	–	Reflex ontogeny (N: 0.6)	Newland and Reile 1999; Newland and Rasmussen 2000; Newland et al. 2004 (MMC)
Rat; 111 days PM–PND 55	–	↓ (L; 0.5)	↓ (L: 0.5)	↔ (N: 0.5)	–	Sakamoto et al. 2002 (MM)
Mouse; 35 days, GD8–PND 21	0 (N: 0.06)	–	–	–	–	Zhang et al. 2011 (MM)
Mouse[b]; 35 days, GD 8–PND 21	↑ (L: 0.06)	–	–	–	–	Zhang et al. 2011 (MM)
Mouse; 41 days, GD 2–PND 21	↓ (L: 0.9)	↔ (N: 1.7)	–	↓ (L: 0.9)	–	Goulet et al. 2003 (MMC)
Mouse; 42 days, GD 1–PND 21	–	↓ (L: 1)	–	–	–	Ghizoni et al. 2018 (MMC)
Mouse; 56 days, GD 14–PND 21	↓ (L: 1.3)	↔ (N: 1.3)	–	–	Motor strength, rearing ↓ (L: 1.3)	Rand et al. 2020 (MMC)
Mouse; 63–70 days, PM–PND 13	–	↓ (L: 0.2)	↔ (N: 0.6)	↓ (L: 0.2)	–	Weiss et al. 2005 (MMC)
Mouse; 70, PM–PND 21	↓ (L: 0.02)	(N: 0.02)	–	–	–	Huang et al. 2011 (MM)
Mouse; 119 days, PM–PND 70	↓ (L: 0.02)	↓ (L: 0.02)	–	–	–	Huang et al. 2011 (MM)
Postnatal exposure						
Rat; 30 days, PNDs 1–30	–	↓ (L: 4)	↓ (L: 0.8)	–	–	Sakamoto et al. 2004 (MMC)
Rat; 35 days PNDs 31–65	↓ (L: 0.037)	↓ (L: 0.037)	–	–	–	Oliveira et al. 2018 (MM)
Mouse[c]; 21 days PNDs 21–42	–	–	–	–	Socialization ↓ (L: 0.08) Stereotypy ↑ (L: 0.08)	Algahtani et al. 2023 (MMC)
Mouse; 21 days, PNDs 1–21	↓ (L: 4.7)	↓ (L: 4.7)	–	–	–	Franco et al. 2006 (MMC)

Table 2-48. Neurobehavioral Effects in Rodents Following Intermediate-Duration Oral Exposure to Methylmercury Compounds During Development

Species; duration	Motor activity[a]	Motor coordination[a]	Associative learning (OC, AA, PA)[a]	Spatial/ working learning, and memory[a]	Other[a]	Reference (compound)
Mouse; 27 days, PNDs 2–28	↓ (L: 0.9)	–	↔ (N: 0.9)	↔ (N: 0.9)	Anxiety ↔ (N: 0.9)	Yoshida et al. 2018 (MMC)
Mouse; 37 days PNDs 22–59	–	–	↔ (N: 0.400)	–	Attention ↓ (L: 0.400)	Kendricks and Newland 2021 (MMC)
Mouse; 39 days PNDs 21–60	–	–	↔ (N: 0.320)	–	Attention ↔ (N: 0.320)	Kendricks et al. 2020a, 2020b (MMC)
Mouse; 39 days, PNDs 21–59	–	–	↓ (L: 0.032)	–	–	Boomhower and Newland 2019 (MMC)
Mouse; 39 days PNDs 24–62	–	–	↔ (N: 0.32)	–	–	Boomhower and Newland 2019 (MMC)
Mouse; 49 days, PNDs 21–70	↑ (L: 0.02)	↓ (L: 0.02)	–	–	–	Huang et al. 2011 (MM)

[a]NOAEL (N) or LOAEL (L) dose in mg Hg/kg/day for endpoint category.
[b]Autoimmune susceptible mouse strain.
[c]Exposure-related effects observed in BTBR mice (strain with increased baseline "autistic-like" traits of repetitive behavior and decreased socialization); exposure-related effects were not observed in similarly-exposed "social" C57BL/6 mice.

↑ = increased; ↓ = decreased; ↔ = no change; – = not assessed; AA = active avoidance learning, ASR = acoustic startle reflex; FOB = functional observation battery; GD = gestation day; LOAEL = lowest-observed-adverse-effect level; MM = methylmercury; MMC = methylmercuric chloride; MMH = methylmercury hydroxide; NOAEL = no-observed-adverse-effect level; OC = operant conditioning; PA = passive avoidance learning; PM = premating; PND = postnatal day

Evaluation of the oral neurodevelopmental database indicates that of the sensitive effects identified following acute- and intermediate-duration exposure to methylmercury compounds (Tables 2-47 and 2-48), the most consistently reported findings included impaired operant conditioning in rats, impaired spatial learning and memory in mice, motor incoordination in rats and mice, and hearing deficits in mice. Additional details on neurobehavioral testing and dose-response information for these consistently observed and sensitive neurodevelopmental effects in rodents following developmental exposure to methylmercury can be found in Table 2-49 and are discussed below.

Table 2-49. Dose-Response Data for Sensitive and Consistently Observed Neurobehavioral Effects in Rodents following Oral Exposure to Methylmercury During Development

Reference; species; exposure duration	Assay/outcome measured (evaluation timing, sex)	Dose (mg Hg/kg/day)	Result (percent change compared to control)
Operant conditioning in rats			
Bornhausen et al. 1980 Rat; GDs 6–9	DRH [2/1] performance[a] (4 months, B)	0.004–0.008	↔
	DRH [4/2] performance (4 months, B)	0.004	↔
		0.008	M: ↓ (24.4)[b] F: ↓ (28.3)[b]
		0.035	M: ↓ (37.9)[b] F: ↓ (25.7)[b]
	DRH [8/4] performance (4 months, B)	0.004	↔
		0.008	M: ↓ (10.0)[b] F: ↓ (15.0)[b]
		0.035	M: ↓ (57.2)[b] F: ↓ (24.6)[b]
Kendricks et al. 2022 Rat; PNDs 1–10	SDR: time to acquisition of criterion for reversal learning[c] (PND 91, M)	0.064	↔
		0.280	↑ (138)[d]
Elsner 1991 Rat; 14 days premating through PND 21	DRF performance[e] at 60–120 or 60–100 g (PND 300, M)	0.19 or 0.74	↔
	DRF performance at 60–80 g (PND 300, M)	0.19	↓ (25)[b]
		0.74	↓ (25)[b]
Fagundes et al. 2022 Rat; GD 0–PND 21	Acquisition of inhibitory avoidance: latency of step down (PND 41, M; short-term memory at 1.5 hours)	0.03	↓ (67)[d]
	Acquisition of inhibitory avoidance: latency of step down (PND 41, M; long-term memory at 24 hours)	0.03	↓ (85)[d]
Newland and Rasmussen 2000 Rat; 10–13 weeks premating through PND 16	MFFR reinforcement rate (PND 120 or >400, F)	0.045	PND 120: ↔ PND >400: ↓ (13)[d]
		0.6	PND 120: 0 PND >400: ↓ (19)[d]

Table 2-49. Dose-Response Data for Sensitive and Consistently Observed Neurobehavioral Effects in Rodents following Oral Exposure to Methylmercury During Development

Reference; species; exposure duration	Assay/outcome measured (evaluation timing, sex)	Dose (mg Hg/kg/day)	Result (percent change compared to control)
Newland et al. 2004 Rat; 10–13 weeks premating through PND 16	CRI: acquisition of choice for 1:4 transition (half maximal reinforcers)[f] (1.7 or 2.3 years, B)	0.045	1.7 years: ↔ 2.3 years: ↑ (98)[d]
		0.6	1.7 years: ↔ 2.3 years: ↑ (118)[b]
	CRI: acquisition of choice for 1:4 transition (half maximal reinforcers) (1.7 or 2.3 years, B)	0.045	1.7 years: ↔ 2.3 years: ↑ (92)[b]
		0.6	1.7 years: ↔ 2.3 years: ↑ (76)[b]
Spatial learning and memory in mice			
Hughes and Annau 1976 Mouse, GD 8	MWM, escape latency [learning phase] (PND 56, NS)	1–5	↔
Fischer et al. 2008 Mouse; PND 10	MWM, escape latency on training day 4 (learning phase) (4 months, M)	0.37	↑ (36)[d]
		3.7	↑ (143)[d]
	MWM, escape latency on training day 5 (reversal learning) (4 months, M)	0.37	↔
		3.7	↑ (89)[d]
	Radial arm maze, time to acquire all pellets (5 months, M)	0.37	↔
		3.7	↑ (54)[b]
Dore et al. 2001 Mouse; GDs 7–9	T-maze, sessions to reach training criteria (PND 49, F)	3	↑ (110)[d]
		5	↑ (110)[d]
	Radial arm maze, correct arm choices/incorrect arm choices (PND 98, F)	3	↔
		5	↔
Dore et al. 2001 Mouse; GDs 12–14	T-maze, sessions to reach training criteria (PND 49, F)	3	↔
		5	↑ (70)[d]
	Radial arm maze, correct arm choices/incorrect arm choices (PND 98, F)	3	↔
		5	Trial 3: ↓ (15)[d]
Kim et al. 2000 Mouse; GDs 12–14	MWM, escape latency (learning phase) (PND 56, F)	3	↔
Kim et al. 2000 Mouse; GDs 12–14	MWM, escape latency (learning phase) (PND 56, F)	3	Day 1: ↔ Day 2: ↑ (12)[d] Day 3: ↑ (22)[d] Day 4: ↑ (27)[d] Day 5: ↑ (75)[d]

Table 2-49. Dose-Response Data for Sensitive and Consistently Observed Neurobehavioral Effects in Rodents following Oral Exposure to Methylmercury During Development

Reference; species; exposure duration	Assay/outcome measured (evaluation timing, sex)	Dose (mg Hg/kg/day)	Result (percent change compared to control)
Kim et al. 2000 Mouse; GDs 12–14	MWM, escape latency (learning phase) (PND 56, F)	3	Day 1: ↔ Day 2: ↑ (166)[d] Day 3: ↑ (57)[d] Day 4: ↑ (122)[d] Day 5: ↔
Montgomery et al. 2008 Mouse; GDs 8–18	MWM, escape latency (learning phase) (5–7 months, B)	0.009	Day 1: ↔ Day 2: ↔ Day 3: ↑ (27)[d] Day 4: ↑ (30)[d] Day 5: ↑ (34)[d] Day 6: ↑ (132)[d]
	MWM, time in cued quadrant (memory phase) (5–7 months, B)	0.009	Probe 1: ↓ (16)[d] Probe 2: ↓ (12)[d] Probe 3: ↓ (13)[d]
Yoshida et al. 2011; Mouse; GDs 0–18	MWM, escape latency (learning phase) (PND 56, B)	0.9	M: Day 4: ↑ (60)[d] Days 1–3, 5: ↔ F: ↔
Loan et al. 2023 Mouse; GDs 0–21	MWM, escape latency on training day 4 (learning phase) (PND 60, B)	0.05	↔
	MWM, time in cued quadrant (memory phase) (PND 60, B)	0.05	↔
	MWM, escape latency on training day 2 (reversal learning) (PND 60, B)	0.05	↔
	MWM, ratio of time spent in wrong (old) target during reversal probe (PND 60, B)	0.05	↑ (5)[d]
Yoshida et al. 2018 Mouse; PNDs 2–28	Radial arm maze, arm choice errors (PND 84, F)	0.9	↔
Goulet et al. 2003 Mouse: GD 2–PND 21	T-maze, sessions to reach training criteria (PND 42, B)	0.9	↔
		1.7	↔
Weiss et al. 2005 Mouse; 4 weeks premating through PND 13	T-maze, mice reaching training criteria within 55 sessions (5 or 15 months, M)	0.2	5 months: ↔ 15 months: ↓ (75)[b]
		0.6	5 or 15 months: ↓ (50)[b]

Table 2-49. Dose-Response Data for Sensitive and Consistently Observed Neurobehavioral Effects in Rodents following Oral Exposure to Methylmercury During Development

Reference; species; exposure duration	Assay/outcome measured (evaluation timing, sex)	Dose (mg Hg/kg/day)	Result (percent change compared to control)
Motor coordination in rats and mice			
Carratu et al. 2006 Rat; GD 8 or 15	Rotarod, fall latency (PND 40, B)	7	↔
Sakamoto et al. 2004 Rat; PNDs 1–3	Rotarod, fall latency (PND 35, M)	0.8 or 2	↔
		4	↓ (82)[b]
Sakamoto et al. 2020 Rat; PNDs 14–23	Rotarod, fall latency (PND 21, M)	6.3	↔
	Rotarod, fall latency (PND 24, M)	6.3	↓ (67)[d]
Oliveira et al. 2018 Rat; PNDs 31–65	Rotarod, latency to first fall on trial 1 (PND 66, F)	0.037	↓ (62)[d]
	Rotarod, latency to first fall on trial 2 (PND 66, F)	0.037	↓ (75)[d]
	Rotarod, latency to first fall on trial 3 (PND 66, F)	0.037	↔
	Vertical pole, descent latency (PND 66, F)	0.037	↑ (80)[d]
	Beam walking, crossing latency on 5 mm square beam (PND 66, F)	0.037	↑ (45)[d]
	Beam walking, crossing latency on 11 mm round beam (PND 66, F)	0.037	↑ (105)[d]
Cheng et al. 2015; Fujimura et al. 2012 Rat; GD 1–PND 21	Rotarod, % mice staying on rod for 60 seconds (PNDs 34–35, B)	0.05	↔
		0.23	M: ↓ (50)[b] F: ↓ (26)[b]
Fagundes et al. 2022 Rat; GD 0–PND 21	Rotarod, latency to first fall (PND 41, M)	0.03	↓ (84)[d]
	Rotarod, number of falls (PND 41, M)	0.03	↑ (200)[d]
Sakamoto et al. 2002 Rat; 8 weeks premating through PND 55	Rotarod, % mice staying on rod for 60 seconds (PND 35, B)	0.5	↓ (75)[b]
Dore et al. 2001 Mouse; GDs 7–9 or 12–14	Rotarod, fall latency (PND 42, F)	3 or 5	↔

Table 2-49. Dose-Response Data for Sensitive and Consistently Observed Neurobehavioral Effects in Rodents following Oral Exposure to Methylmercury During Development

Reference; species; exposure duration	Assay/outcome measured (evaluation timing, sex)	Dose (mg Hg/kg/day)	Result (percent change compared to control)
Bellum et al. 2007 Mouse; PNDs 29–33	Rotarod, fall latency (PND 38, B)	0.2	↔
		0.8	Day 1: ↓ (23)[d] Day 2: ↔ Day 3: ↓ (36)[d]
	Footprint analysis, angle of foot placement (PND 38, B)	0.2	↑ (55)[d]
		0.8	↔
	Vertical pole, percent of mice that fell before 90° (PND 38, B)	0.2	↑ (40)[b]
		0.8	↑ (37)[b]
Montgomery et al. 2008 Mouse; GDs 8–18	Rotarod, fall latency (2 months, B)	0.009	↔
	Rotarod, time spent on rod (2 months, B)	0.009	Day 1: ↓ (40)[d] Day 2: ↓ (20)[d] Day 3: ↓ (48)[d]
	Footprint analysis, foot angle (2 months, B)	0.009	↓ (40)[d]
Franco et al. 2006 Mouse; PNDs 1–21	Rotarod, fall latency (PND 21, B)	4.7	↓ (37)[b]
Rand et al. 2020 Mouse; 12 weeks prior to mating–PND 21	Rotarod, average time (PND 60, B)	0.12 or 1.3	↔
	Rotarod, average speed (PND 60, B)	0.13 or 1.3	↔
Goulet et al. 2003 Mouse; GD 2–PND 21	Rotarod, fall latency (PND 42, B)	0.9	↔
		1.7	↔
Ghizoni et al. 2018 Mouse; GD 0–PND 21	Rotarod, number of falls (PND 22, B)	1	↑ (110)[d]
Weiss et al. 2005 Mouse; 4 weeks premating through PND 13	Footprint analysis, hindlimb splay (5, 15, or 25 months, M)	0.2	5 months: ↔ 15 months: ↑ (12)[d] 25 months: ↔
		0.6	5 months: ↔ 15 months: ↑ (18)[d] 25 months: ↔
Huang et al. 2011 Mice; PNDs 21–70	Rotarod, fall latency (PND 70, M)	0.02	↓ (18)[d]
Huang et al. 2011 Mice; 4 weeks premating through PND 21	Rotarod, fall latency (PND 70, M)	0.02	↔

Table 2-49. Dose-Response Data for Sensitive and Consistently Observed Neurobehavioral Effects in Rodents following Oral Exposure to Methylmercury During Development

Reference; species; exposure duration	Assay/outcome measured (evaluation timing, sex)	Dose (mg Hg/kg/day)	Result (percent change compared to control)
Huang et al. 2011 Mice; 4 weeks premating through PND 70	Rotarod, fall latency (PND 70, M)	0.02	↓ (31)[d]
Auditory function in mice			
Huang et al. 2011 Mice; PNDs 21–70	Hearing threshold (PND 70, M)	0.02	↑ (698)[d]
	ABR absolute latency (PND 70, M)	0.02	Wave III: ↔ Wave V: ↑ (37)[d]
	ABR interwave latency [Waves I–V] (PND 70, M)]	0.02	↑ (9)[d]
Huang et al. 2011 Mice, 4 weeks premating through PND 21	Hearing threshold (PND 70, M)	0.02	↑ (637)[d]
	ABR absolute latency (PND 70, M)	0.02	Wave III: ↑ (6)[d] Wave V: ↑ (37)[d]
	ABR interwave latency [Waves I–V] (PND 70, M)]	0.02	↑ (10)[d]
Huang et al. 2011 Mice; 4 weeks premating through PND 70	Hearing threshold (PND 70, M)	0.02	↑ (1,096)[d]
	ABR absolute latency (PND 70, M)	0.02	Wave III: ↑ (6)[d] Wave V: ↑ (62)[d]
	ABR interwave latency [Waves I–V] (PND 70, M)]	0.02	↑ (15)[d]

[a]DRH performance was calculated by the following formula: [(number of reinforcements ×100)/lever presses during ON periods] x lever presses required for one reward.
[b]Calculated from quantitative data.
[c]Criterion for initial learning in the visual discrimination task was >85% correct responses on the reinforcing lever in each of three consecutive sessions; criterion for reversal learning was 85% correct responses on the newly designated "correct" lever for three consecutive trials.
[d]Estimated from graphically presented data.
[e]DRF performance was calculated by the following formula: number of correct responses/total number of trial responses.
[f]Acquisition of choice is defined as the allocation of behavior between two response alternatives, as it was undergoing a transition.

↑ = increased; ↓ = decreased; ↔ = no change; ABR = auditory brainstem response; B = both males and females; CRI = concurrent random interval (e.g., 180 seconds/180 seconds or 860 seconds/100 seconds) schedule of reinforcement; DRF = differential reinforcement of force range; DRH = differential reinforcement of high rates (lever presses/second) to gain food reward; F = female; GD = gestation day; M = male; MFFR = multiple fixed ratio food reward lever press task; MWM = Morris water maze; NS = not specified; PND = postnatal day; SDR = spatial discrimination reversal

Dose-related impairments in operant conditioning in rats were consistently observed following developmental exposure to oral doses ≥0.008 mg Hg/kg/day (Bornhausen et al. 1980; Elsner 1991;

Fagundes et al. 2022; Kendricks et al. 2022; Newland and Rasmussen 2000; Newland et al. 2004). In contrast, while one study in male C57BL/6 mice reported deficiencies in associative learning via fixed-ratio operant conditioning following exposure to 0.032 mg Hg/kg/day from PND 21 to 59, no effect on learning was observed at 0.32 mg Hg/kg/day from PND 24 to 62 (Boomhower and Newland 2019). Other studies in mice did not observe deficits in operant training following developmental exposure to oral doses up to 0.9 mg Hg/kg/day (Kendricks and Newland 2021; Kendricks et al. 2020a, 2020b; Yoshida et al. 2018). However, transient effects on attention were reported in mice following developmental exposure to 0.400 mg Hg/kg/day, but not 0.320 mg Hg/kg/day (Kendricks and Newland 2021; Kendricks et al. 2020a, 2020b).

When assessed using the Morris water maze (MWM), impairments in spatial learning and/or memory were consistently observed in C57BL/6 mice following gestational exposure to oral doses ≥0.009 mg Hg/kg/day (Kim et al. 2000; Loan et al. 2023; Montgomery et al. 2008; Yoshida et al. 2011). In NMRI mice, impaired spatial learning in the MWM was observed following early postnatal exposure to oral doses ≥0.37 mg Hg/kg/day (Fischer et al. 2008). No changes in spatial learning were observed in BALB/c or CFW mice exposed to doses up to 3 or 5 mg Hg/kg/day, respectively, during gestation (Hughes and Annau 1976; Kim et al. 2000). Based on reported findings in the T-maze and radial arm maze following oral methylmercury exposure (Dore et al. 2001; Fischer et al. 2008; Goulet et al. 2003; Weiss et al. 2005; Yoshida et al. 2018), these tests appear to be less sensitive and/or less consistent measures of methylmercury-induced spatial learning impairments in mice compared to the MWM. Observed deficits in spatial learning were less consistent in rats. Impaired spatial learning and/or memory were observed in the MWM in adult Sprague-Dawley rats following developmental exposure to 0.56 mg Hg/kg/day from GD 5 to PND 1 (Wang et al. 2022a) or ≥0.2 mg Hg/kg/day on GDs 5–21 (Albores-Garcia et al. 2016). However, no spatial learning or memory impairments were observed in the MWM in Sprague-Dawley rats following exposure to 0.474 mg Hg/kg/day from GD 7 to PND 7 (Rossi et al. 1997) or Wistar rats following gestational exposure to doses up to 0.8 mg Hg/kg/day (Kakita et al. 2000; Sakamoto et al. 2002). Similar to mice, findings in arm-alternation mazes did not show spatial learning deficits in rats following oral methylmercury exposure during development (Cheng et al. 2015; Elsner 1991).

In rats, dose- and duration-dependent motor coordination impairments were observed during rotarod testing. In postnatal-only exposure studies, impairments were reported following exposure to 0.037 mg Hg/kg/day from PNDs 31 to 65 (Oliveira et al. 2018) or doses ≥4 mg Hg/kg/day administered during early neonatal (pre-weaning) periods (Sakamoto et al. 2004, 2020). Impaired motor coordination was

also observed following gestation plus postnatal exposure to doses ≥0.03 mg Hg/kg/day (Cheng et al. 2015; Fagundes et al. 2022; Fujimura et al. 2012; Sakamoto et al. 2002). No changes were observed following a single exposure to 7 mg Hg/kg/day during gestation (Carratu et al. 2006). Findings in the rotarod test were less consistent in mice, with varying findings between different strains and exposure paradigms (Bellum et al. 2007; Dore et al. 2001; Franco et al. 2006; Ghizoni et al. 2018; Goulet et al. 2003; Huang et al. 2011; Montgomery et al. 2008; Rand et al. 2020). Data for other measures of coordination in mice (footprint analysis, vertical pole) are limited (Bellum et al. 2007; Montgomery et al. 2008; Weiss et al. 2005).

One study evaluated auditory function in mice following developmental exposure to 0.02 mg Hg/kg/day throughout gestation and lactation, during GD 1–PND 70, or postnatally only from PND 21–70 (Huang et al. 2011). Observed hearing deficits were similar in the GD 1–PND 21 and PND 21–70 groups, and markedly worse in the group with exposure during GD 1–PND 70.

Pathological changes in the rat brain have been reported following developmental exposure to methylmercury at doses above those associated with neurobehavioral and neurophysiological effects, primarily in regions associated with motor and movement control. An acute-duration gestational exposure study observed dendritic spine abnormalities in the somatosensory cortex in rat offspring at 4 mg Hg/kg/day (Stoltenburg-Didinger and Markwort 1990). Exposure throughout gestation in rats resulted in widespread neuronal degeneration (pyknosis, shrinkage of perikaryon, eosinophilic changes), decreased cell numbers in amygdala and hippocampus, and reactive gliosis at 0.8 mg Hg/kg/day (Kakita et al. 2000). Focal cerebellar dysplasia, including heterotopic location of Purkinje cells and granule cells, and reactive gliosis were observed in rats following exposure to 0.5 mg Hg/kg/day throughout gestation, lactation, and postweaning until PND 55 (Sakamoto et al. 2002). Loss of motor neurons and decreased spinal cord myelination were observed on PND 42 in the offspring of rats exposed to 0.03 mg Hg/kg/day throughout gestation and lactation (da Silva et al. 2022). Widespread neuronal damage in the central nervous system was also observed in rats exposed to 4 mg Hg/kg/day from PND 1 to 30 (Sakamoto et al. 2004). Severe cerebral degeneration was reported in neonatal rats exposed to 6.3 mg Hg/kg/day on PNDs 14–23, including neuronal loss and atrophy, degenerative eosinophilic neurons, and reactive gliosis (Sakamoto et al. 2020).

Pathological changes in regions of the brain associated with motor and movement control have also been observed in mice following developmental exposure to methylmercury at doses above those associated with neurobehavioral and neurophysiological effects. Findings in acute-duration gestational exposure

studies included altered cerebellar development in mouse offspring at ≥1 mg Hg/kg/day (Inouye et al. 1985; Khera and Tabacova 1973) and a reduction in the size of "nucleus caudatus putamen" in mouse offspring at 16 mg Hg/kg/day (Inouye et al. 1985). Additionally, cerebellar inflammation was observed in an autoimmune susceptible mouse strain in offspring following maternal exposure to 0.06 mg Hg/kg/day during gestation and lactation (Zhang et al. 2011). Inflammation was not observed in similarly exposed wild-type mice.

Cerebellar damage has also been observed in hamsters following gestational exposure to methylmercury (no other neurological endpoints evaluated in hamsters). Exposure to 1.6 mg Hg/kg/day on GD 10 or GDs 10–15 resulted in degenerative changes in the cerebellum of hamster offspring examined between PND 1 and 25 (Reuhl et al. 1981a) or PND 275 and 300 (Reuhl et al. 1981b). In neonates, findings were most pronounced from PND 1 to 15, and included accumulation of lysosomes and areas of floccular cytoplasmic degradation in neuroblasts of the granular layer, pyknotic nuclei in the external granular layer, swollen developing dendrites packed with degenerating cytoplasmic material, and large aggregates of irregular debris, lysosomes, and large lipid droplets in astrocytes and perivascular macrophages. In older hamsters, findings included focal astrogliosis in the molecular layer, residual bodies in the perikarya and dendrites of granule and Purkinje neurons (sequalae of neonatal injuries), and degenerative changes of myelinated axons.

Predominant Mercury Form Unknown (General Populations). A large number of studies have been conducted on neurodevelopmental outcomes in general populations (Table 2-50). Most studies of general populations found no associations or inconsistent associations across outcome measures and biomarkers of exposure. These inconsistences may relate to the relatively low exposures in most of these populations (maternal or cord BHg <10 μg Hg/L; HHg <2 μg Hg/g), which may be near or below toxic thresholds, as well as other variables that may have affected outcomes and were not adequately controlled in models of association. These variables include multiple sources of exposure (e.g., diet, mercury amalgam dental restorations), fish consumption rates and related nutritional variables, and exposure to other chemicals (e.g., lead, PCBs).

Table 2-50. Results of Epidemiological Studies Evaluating General Population Exposure to Mercury (Predominant Mercury Form Unknown) and Neurodevelopmental Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result[a]
Al-Saleh et al. 2016 Cross-sectional cohort of 944 mother-infant pairs evaluated at age 3–12 months; Saudi Arabia	BHg median Maternal: 0.635 µg/L HHg median Maternal: 0.118 µg/g Child: 0.101 µg/g HMeHg Maternal: 0.132 µg/g Child: 0.091 µg/g	DDST-II	↓ (HMeHg, maternal) ↔ (HHg, maternal) ↔ (BHg, maternal) ↔ (HMeHg, child) ↔ (HHg, child)
		PEDS	↔ (HMeHg, maternal) ↓ (HHg, maternal) ↔ (BHg, maternal) ↔ (HMeHg, child) ↔ (HHg, child)
Al-Saleh et al. 2019 Cross-sectional cohort of 206 mother-infant pairs evaluated at age 3–12 months; Saudi Arabia	BMeHg median Maternal: 0.455 µg/L BMMeHg Maternal: 1.354 µg/dL	DDST-II	↔ (BMeHg, maternal) ↔ (BMMeHg, maternal)
		PEDS	↔ (BMeHg, maternal) ↔ (BMMeHg, maternal)
Barbone et al. 2019 Prospective cohort of mother-infant pairs, follow-up at 18 months (n=1,308); Mediterranean Europe (Italy, Slovenia, Croatia, Greece)	BHg median Maternal: 0.0024 µg/g Cord: 0.0036 µg/g HHg median Maternal: 0.704 µg/g	BSID cognitive composite score	↔ (BHg, cord) ↔ (BHg, maternal) ↔ (HHg, maternal)
		BSID language composite score	↔ (BHg, cord) ↑ (HHg, maternal)
		BSID motor composite score	↔ (BHg, cord) ↔ (BHg, maternal) ↔ (HHg, maternal)
		BSID receptive communication	↔ (BHg, cord) ↔ (BHg, maternal) ↑ (HHg, maternal)
		BSID expressive communication	↔ (BHg, cord) ↔ (BHg, maternal) ↔ (HHg, maternal)
Calamandrei et al. 2020 Prospective birth cohort, follow-up at age 18 months (n=984); Europe	HHg median Maternal: 0.292 µg/g	BSID (12 months)	↔ (HHg, maternal)
		BSID (24 months)	↔ (HHg, maternal)
Castriotta et al. 2020 Prospective birth cohort, follow-up at age 40 months (n=470); Italy	BHg median Maternal: 3.4 µg/kg Cord: 5.6 µg/kg	BSID	↔ (BHg, cord)

Table 2-50. Results of Epidemiological Studies Evaluating General Population Exposure to Mercury (Predominant Mercury Form Unknown) and Neurodevelopmental Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result[a]
Cheuk and Wong 2006 Case-control study of 52 ADHD cases and 59 controls, age <18 years; Hong Kong	BHg geometric mean Child case: 3.65 µg/L Child control: 2.33 µg/L	ADHD	↑ (BHg, child >5.8 µg/L)
Choi and Park 2017 Cross-sectional study 853 adolescents (mean age 15 years) and 5,187 adults (mean age 45 years) (Republic of Korea; KNHANES 2010–2012)	BHg geometric mean Adults: 3.58 µg/L Adolescents: 2.03 µg/L	Speech-frequency hearing	↔ (BHg)
		High-frequency hearing	↔ (BHg)
Daniels et al. 2004 Prospective cohort of mother-infant pairs, follow-up at age 15–18 months (n=1,054); United Kingdom	Cord tissue mercury median Wet weight: 0.01 µg/g Dry weight: 0.04 µg/g	MSCA	↔ (mercury, cord tissue)
		DDST	↔ (mercury, cord tissue)
Egwunye et al. 2023 Cross-sectional study of children evaluated at age 36 months (n=658); Vietnam	NHg median Child: 0.2 µg/g	BSID cognition	↔ (NHg, child)
		BISD language	↑ (NHg, child)
		BSID motor	↔ (NHg, child)
		BSID social-emotional	↔ (NHg, child)
Farías et al. 2022 Prospective cohort of mother-infant pairs, follow-up at age 1–12 months (n=253); Mexico	BHg median Maternal: 1.79 µg/L	BSID cognition	↔ (BHg, maternal)
		BISD language	↔ (BHg, maternal)
		BSID motor	↔ (BHg, maternal)
Feng et al. 2020 Cross-sectional study of children evaluated at age 8–10 years (n=314); China	HHg mean Child: 1.54 µg/g	WISC IQ	↔ (HHg, child)
		OR IQ<80	↑ (HHg, child)
Freire et al. 2010 Prospective study of mother-child-infant pairs, follow-up at age 4 years (n=72); Spain	HHg mean Child (age 4 years): 0.96 µg/g	MSCA cognitive	↓ (HHg, child≥1 µg/g)
		MSCA quantitative	↔ (HHg, child ≥1 µg/g)
		MSCA memory	↓ (HHg, child ≥1 µg/g)
		MSCA verbal	↓ (HHg, child ≥1 µg/g)
		MSCA performance	↔ (HHg, child ≥1 µg/g)
		MSCA motor	↔ (HHg, child ≥1 µg/g)

Table 2-50. Results of Epidemiological Studies Evaluating General Population Exposure to Mercury (Predominant Mercury Form Unknown) and Neurodevelopmental Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result[a]
Fruh et al. 2021 Prospective birth cohort, follow-up at age 6–11 years (n=1,009); Massachusetts	ErHg (median) Maternal: 3.1 ng/g	BRIEF GEC	↔ (ErHg, maternal)
		SDQ	↔ (ErHg, maternal)
Garí et al. 2022 Prospective birth cohort, follow-up at age 7 years (n=436); Poland	HHg (median) Maternal: 0.18µg/g	IDS	↔ (HHg, maternal)
		SDQ (hyperactivity/ inattention)	↑ (HHg, maternal)
Golding et al. 2016a Prospective birth cohort (ALSPAC) at ages 4–17 years (n=2,776); United Kingdom	BHg median Maternal: 1.86 µg/g	Hyperactivity	↔ (BHg, maternal)
		Conduct problems (SDQ)	↓ (BHg, maternal)
		Emotional problems	↓ (BHg, maternal)
		Peer problems	↓ (BHg, maternal)
		Prosocial	↔ (BHg, maternal)
Golding et al. 2016b Prospective birth cohort (ALSPAC) at ages 6–42 months (n=3,264); United Kingdom	BHg median Maternal: 1.86 µg/g	DDST (6 months)	↑ (BHg, maternal)
		DDST (18 months)	↑ (BHg, maternal)
		DDST (30 months)	↔ (BHg, maternal)
		DDST (42 months)	↑ (BHg, maternal)
Golding et al. 2017 Prospective birth cohort (ALSPAC) at age 8 years (n=4,285); United Kingdom	BHg median Maternal: 1.86 µg/g	WISC-III (verbal)	↔ (BHg, maternal)
		WISC-III (PIQ)	↔ (BHg, maternal)
		WISC-III (FSIQ)	↔ (BHg)
Golding et al. 2018 Prospective birth cohort (ALSPAC) at age 9–11 years (n=2,800); United Kingdom	BHg median Maternal: 1.86 µg/g	Signs of autism	↔ (BHg, maternal)
Guo et al. 2020a, 2020b Prospective birth cohort, follow-up at age 7.4 years (n=326); China	UHg (median) Maternal: 0.41µg/L	Chinese WISC IQ	↔ (UHg, maternal)
Gustin et al. 2017 Cross-sectional cohort of 1,434 children, age 10 years; Bangladesh	HHg median Child: 0.674 µg/g	WISC-IV	↔ (HHg, child)
		SDQ (behavior difficulties)	↓ (HHg, child)

Table 2-50. Results of Epidemiological Studies Evaluating General Population Exposure to Mercury (Predominant Mercury Form Unknown) and Neurodevelopmental Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result[a]
Ha et al. 2009 Cross-sectional cohort of 1,778 children, mean age 7 years; Republic of Korea	BHg geometric mean Child: 2.4 µg/L	ADHD symptoms	↔ (HHg, child)
Hu et al. 2016 Prospective cohort of mother-infant pairs, follow-up at age 12 months (n=410); China	BHg geometric mean Maternal: 0.72 µg/L Cord: 1.2 µg/L	GDS gross motor	↔ (BHg, maternal) ↔ (BHg, cord)
		GDS fine motor	↔ (BHg, maternal) ↔ (BHg, cord)
		GDS adaptive	↔ (BHg, maternal) ↑ (BHg, cord)
		GDS language	↔ (BHg, maternal) ↔ (BHg, cord)
		GDS social	↔ (BHg, maternal) ↑ (BHg, cord)
Hertz-Picciotto et al. 2010 Case-control study of 332 autism cases at ages 2–5 years; California	BHg median Autism: 0.19 µg/L Controls: 0.28 µg/L	Autism	↔ (child BHg)
Hibbeln et al. 2018 Prospective birth cohort (ALSPAC), follow-up at age 7–9 years (n=2,224); United Kingdom	BHg median Maternal: 1.9 µg/L[b]	Scholastic achievement tests	↔ (BHg, maternal)
Jedrychowski et al. 2006 Prospective cohort of mother-infants, follow up at age 12 months (n=233); Poland	BHg geometric mean Maternal: 0.55 µg/L Cord: 0.88 µg/L	BSID PDI or MDI	↓ (BHg, maternal ≥0.5 µg/g) ↓ (BHg, cord ≥0.8 µg/g)
Jedrychowski et al. 2007 Prospective cohort of mother-infant pairs, follow-up at age 12 months (n=374), 24 months (n=353), and 36 months (n=270); Poland	BHg, “high” exposure Cord: >0.90 µg/L (n=177)	BSID PDI or MDI 12 months	↓ (BHg, cord)
		BSID PDI or MDI 24 months	↔ (BHg, cord)
		BSID PDI or MDI 36 months	↔ (BHg, cord)
Jeong et al. 2017 Prospective cohort of mother-infant pairs, follow-up at age 60 months (n=553); Republic of Korea	BHg geometric mean Maternal: 3.14 µg/L	WPPSI-RK (FSIQ)	↓ (BHg, maternal)
		WPPSI-RK (VIQ)	↓ (BHg, maternal)
		WPPSI-RK (PIQ)	↔ (BHg, maternal)

Table 2-50. Results of Epidemiological Studies Evaluating General Population Exposure to Mercury (Predominant Mercury Form Unknown) and Neurodevelopmental Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result[a]
Julvez et al. 2013 Prospective cohort (ALSPAC) of mother-infant pairs, follow-up at age 8 years (n=843); United Kingdom	Cord tissue mercury mean Dry weight: 0.026 µg/g	WISC-III (FSIQ)	↔ (Hg, cord tissue)
		WISC-III (VIQ)	↔ (Hg, cord tissue)
		WISC-III (PIQ)	↔ (Hg, cord tissue)
Julvez et al. 2019 Prospective birth cohort (ALSPAC), follow-up at age 8 years (n=1,051); United Kingdom	Cord tissue mercury mean Dry weight: 0.025 µg/g	WISC-III (FSIQ)	↔ (Hg, cord tissue)
		WISC-III (VIQ)	↔ (Hg, cord tissue)
		WISC-III (PIQ)	↔ (Hg, cord tissue)
Julvez et al. 2021 Prospective birth cohort, follow-up at age 6–11 years (n=1,298); Europe	BHg median Maternal: 1.9 µg/L Child: 0.9 µg/L	RCPM	↑ (BHg, maternal)
Kvestad et al. 2018 Cross-sectional study of children ages 4–6 years (n=210); Norway	HHg mean Fish diet: 0.529 µg/g Meat diet: 0.315 µg/g	WPPSI:	
		Full scale IQ	↔ (HHg, child)
		Verbal IQ	↔ (HHg, child)
		Performance IQ	↔ (HHg, child)
		Processing speed	↔ (HHg, child)
Kim et al. 2018 Prospective cohort of mother-infant pairs, follow-up at age 6 months (n=662), 12 months (n=595), 24 months (n=523), and 36 months (n=438); Republic of Korea	BHg geometric mean Maternal (late pregnancy): 3.0 µg/L Cord: 5.1 µg/L	BSID 6 months	↔ (BHg, maternal) ↔ (BHg, cord)
		BSID 12 months	↔ (BHg, maternal) ↔ (BHg, cord)
		BSID 24 months	↔ (BHg, maternal) ↔ (BHg, cord)
		BSID 36 months	↔ (BHg, maternal) ↔ (BHg, cord)
Kim et al. 2020a Prospective birth cohort, follow-up at age 36 months (n=451); Republic of Korea	BHg median Maternal: 3.15 µg/L Cord: 5.42 µg/L	BSID MDI:	↔ (BHg, maternal)
		MDI low folate	↓ (BHg, maternal) ↓ (BHg, cord)
		MDI high folate	↔ (BHg, maternal) ↔ (BHg, cord)
		PDI low folate	↓ (BHg, maternal) ↓ (BHg, cord)
		PDI high folate	↔ (BHg, maternal) ↔ (BHg, cord)

Table 2-50. Results of Epidemiological Studies Evaluating General Population Exposure to Mercury (Predominant Mercury Form Unknown) and Neurodevelopmental Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result[a]
Kobayashi et al. 2022 Prospective birth cohort, follow-up at ages 6 months to 4 years (n=48,731); Japan	BHg median Maternal: 3.64 µg/kg Cord: 7.56 µg/kg (n=3,083)	ASQ:	
		Communication	↔ (BHg, maternal) ↔ (BHg, cord)
		Gross motor	↔ (BHg, maternal) ↔ (BHg, cord)
		Fine motor	↔ (BHg, maternal) ↔ (BHg, cord)
		Problem solving	↔ (BHg, maternal) ↔ (BHg, cord)
		Social skills	↔ (BHg, maternal) ↔ (BHg, cord)
Lam et al. 2013 Prospective cohort of mother-infant pairs, follow-up at age 8 years (n=608); Hong Kong	BHg median Cord: 9.21 µg/L	WISC-HK (picture arrangement)	↓ (BHg, cord)
		WISC-HK (total)	↔ (BHg, cord)
		HKLLT (recall)	↓ (BHg, cord)
		TEACH	↔ (BHg, cord)
		BNT	↔ (BHg, cord)
		GPB	↔ (BHg, cord)
Lederman et al. 2008 Prospective cohort of mother-infant pairs, follow-up at ages 12, 24, and 36 months (n=280); New York	BHg mean Cord: 7.82 µg/L Maternal: 2.32 µg/L	BSID MDI, 12 months	↔ (BHg, cord)
		BSID PDI, 12 months	↔ (BHg, cord)
		BSID MDI, 24 months	↔ (BHg, cord)
		BSID PDI, 24 months	↔ (BHg, cord)
		BSID MDI, 36 months	↔ (BHg, cord)
		BSID PDI, 36 months	↓ (BHg, cord)
		WPPSI-R IQ, 48 months	↓ (BHg, cord)
Llop et al. 2012 Prospective cohort of mother-infant pairs (n=1,683) follow-up at age 14 months; Spain	BHg geometric mean Cord: 8.4 µg/L	BSID MDI	↔ (BHg, cord)
		BSID PDI	↔ (BHg, cord)

Table 2-50. Results of Epidemiological Studies Evaluating General Population Exposure to Mercury (Predominant Mercury Form Unknown) and Neurodevelopmental Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result[a]
Llop et al. 2012 Prospective cohort of mother-infant pairs (n=1,242) follow-up at age 4–5 years; Spain	HHg geometric mean Child: 0.98 µg/g	MSCA general	↑ (HHg, child)
		MSCA verbal	↑ (HHg, child)
		MSCA memory	↑ (HHg, child)
		MSCA numeric	↔ (HHg, child)
		MSCA motor	↔ (HHg, child)
Lozano et al. 2021 Prospective birth cohort, follow-up at ages 9 years (n=403) and 11 years (n=328); Spain	HHg geometric mean Child: 0.89 µg/g	ANT hit reaction time standard error	↔ (HHg, child)
		CBCL internalizing	↑ (HHg, child)
		CBCL externalizing	↔ (HHg, child)
		CPRS ADHD Index	↔ (HHg, child)
McKean et al. 2015 Case-control study of 164 autism cases at ages 2–5 years; California	BHg median Neonatal autism: 3.41 µg/L Neonatal controls: 3.48 µg/L	Autism	↔ (BHg, child)
Murata et al. 2004b Cross-sectional cohort of 327 mother-child pairs, age 7 years; Japan	HHg mean Maternal: 1.63 µg/g Child: 1.65 µg/g	BAEPL	↔ (HHg, maternal)
Oken et al. 2008 Prospective cohort of mother-infant pairs, follow-up at age 38 months (n=341); Massachusetts	ErHg mean Maternal: 3.8 ng/g	PPVT	↓ (ErHg, maternal)
		WRAVMA	↓ (ErHg, maternal)
Oken et al. 2016 Prospective cohort of mother-infant pairs, follow-up at 8 years (n=872); Massachusetts	ErHg mean Maternal: 4.0 ng/g	KBIT	↔ (ErHg, maternal)
		WRAVMA	↔ (ErHg, maternal)
		WRAML	↔ (ErHg, maternal)
Orenstein et al. 2014 Prospective cohort of mother-infant pairs, follow-up at age 8 years (n=393); Massachusetts	HHg mean Maternal: 0.6 µg/g	WRAML verbal	↔ (HHg, maternal)
		WRAML visual	↓ (HHg, maternal)
		WRAML learning	↔ (HHg, maternal)

Table 2-50. Results of Epidemiological Studies Evaluating General Population Exposure to Mercury (Predominant Mercury Form Unknown) and Neurodevelopmental Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result[a]
Nakamura et al. 2023 Cross-sectional study of children ages 7–8 years (n=134); Japan	Cord tissue (CHg) Gmean 0.11 µg/g HHg Gmean Maternal: 2.65 µg/g (estimated from preserved cord tissue) Child: 2.94 µg/g	WISC full scale IQ	↔ (CHg, maternal) ↔ (CHg, child)
		WISC verbal IQ	↔ (CHg, maternal)
		WISC performance IQ	↔ (CHg, maternal) ↔ (HHg, child)
		BNT	↔ (CHg, maternal) ↔ (HHg, child)
		BAEPL I–V interval	↔ (CHg, maternal, male) ↔ (CHg, maternal, female) ↑ (HHg, child, male) ↔ (HHg, child, female)
		BAEPL III–V interval	↑ (CHg, maternal, male) ↔ (CHg, maternal, female) ↑ (HHg, child, male) ↔ (HHg, child, female)
		VEP N145 latency	↑ (CHg, maternal, male) ↔ (CHg, maternal, female) ↔ (HHg, child, male) ↔ (HHg, child, female)
		Color vision	↔ (CHg, maternal, male) ↔ (CHg, maternal, female) ↔ (HHg, child, male) ↔ (HHg, child, female)

Table 2-50. Results of Epidemiological Studies Evaluating General Population Exposure to Mercury (Predominant Mercury Form Unknown) and Neurodevelopmental Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result[a]
Packull-McCormick et al. 2023 Prospective cohort of mother-infant pairs, follow-up at age 26–47 months (n=527); Canada	BHg median[c] Maternal: 0.68, 0.60 µg/L Cord: 0.91 0.62 µg/L Child: 0.18, 0.20 µg/L	Full-scale IQ	↔ (BHg, maternal; male) ↔ (BHg, maternal; female) ↔ (BHg, cord; male) ↑ (BHg, cord; female) ↔ (BHg, child; male) ↑ (BHg child; female)
		Verbal IQ	↔ (BHg, maternal; male) ↔ (BHg, maternal; female) ↔ (BHg, cord; male) ↔ (BHg, cord; female) ↔ (BHg, child; male) ↑ (BHg child; female)
		Performance IQ	↔ (BHg, maternal; male) ↔ (BHg, maternal; female) ↔ (BHg, cord; male) ↓(BHg, cord, male in lowest maternal fish consumption group) ↑ (BHg, cord; female) ↔ (BHg, child; male) ↔ (BHg child; female)
		Language	↔ (BHg, maternal; male) ↔ (BHg, maternal; female) ↔ (BHg, cord; male) ↔ (BHg, cord; female) ↔ (BHg, child; male) ↑ (BHg child; female)
Patel et al. 2019 Prospective birth cohort, follow-up at ages 2–8 years (n=389); Ohio	BHg median Maternal: 0.67 µg/L	BASC (behavior)	↔ (BHg, maternal)
		SCAS (anxiety)	↔ (BHg, maternal)
Polevoy et al. 2020 Prospective birth cohort, follow-up at age 6.6 months (n=429); Canada	BHg median Maternal: 0.6 µg/L Cord: 0.7µg/L	Visual acuity	↔ (BHg, maternal) ↔ (BHg, cord)

Table 2-50. Results of Epidemiological Studies Evaluating General Population Exposure to Mercury (Predominant Mercury Form Unknown) and Neurodevelopmental Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result[a]
Renzetti et al. 2021 Cross-sectional study of mother-child pairs, evaluation at age 6–11 years (n=299); Italy	HHg median Child: 0.477 µg/g	CBCL	↔ (HHg, child)
		SRS	↔ (HHg, child)
Rodríguez-Carrillo et al. 2022 Prosecutive birth cohort, follow-up at age 15–17 years (n=151); Spain	UHg median Child: 0.76 µg/L	CBCL	
		Withdrawn	↑ (UHg, child)
		Social problems	↑ (UHg, child)
		Internalizing	↔ (UHg, child)
		Externalizing	↔ (UHg, child)
Rothenberg et al. 2016b Prospective cohort of 270 mother-infant pairs, follow-up at age 12 months; China	HHg Gmean Maternal: 0.47 µg/g HMeHg Gmean Maternal: 0.26 µg/g (65%, range 30–108)	BSID MDI	↓ (HHg, maternal)
		BSID PDI	↔ (HHg, maternal)
Rothenberg et al. 2021 Prospective cohort of 190 mother-infant pairs, follow-up at age 36 months; China	HHg median Maternal: 0.42 µg/g	BSID MDI	↔ (HHg, maternal)
		BSID PDI	↔ (HHg, maternal)
Ryu et al. 2017 Prospective cohort of mother-infant pairs, follow-up at 5 years (n=458); Republic of Korea	BHg geometric mean Maternal (late pregnancy): 3.30 µg/L Cord: 5.52 µg/L Child (age 3 years): 2.16 µg/L	SRS (autistic behaviors)	In male children: ↑ (BHg, maternal) ↑ (BHg, cord) ↔ (BHg, child) In female children: ↔ (BHg, maternal) ↔ (BHg, cord) ↔ (BHg, child)
Sagiv et al. 2012 Prospective study of mother-infant pairs, follow-up at age 8 years (n=421); Massachusetts	HHg median Maternal: 0.45 µg/g	CTRS (impulsive/ hyperactive)	↑ (HHg, maternal)
		NES CPT	↔ (HHg, maternal)
		WISC-III (processing speed)	↓ (HHg, maternal)
Shah-Kulkarni et al. 2020 Prospective birth cohort, follow-up at 6 months (n=523); Republic of Korea	BHg geometric mean Early pregnancy; 3.30 µ/L Late pregnancy: 3.13 µg/L Cord: 5.21 µg/L	BSID MDI	↔ (BHg, maternal)
		BSID PDI	↔ (BHg, maternal)

Table 2-50. Results of Epidemiological Studies Evaluating General Population Exposure to Mercury (Predominant Mercury Form Unknown) and Neurodevelopmental Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result[a]
Skogheim et al. 2021 Case-control study of mother-infant pairs, age >2 years (n=705 ADHD cases, 397 ASD cases, 1034 controls); Norway	BHg Gmean Maternal: 1.17	ADHD	↓ (BHg, maternal)
		ASD	↓ (BHg <1 µg/L, maternal)
Snoj Tratnik et al. 2017 Prospective study of mother-infant pairs, follow-up at age 18 months (n=361); Slovenia	BHg Gmean Cord: 2.06 µg/L HHg Gmean Maternal: 0.361 µg/g	BSID III Cognitive	↔ (BHg, cord) ↔ (HHg, maternal)
		Language	↔ (BHg, cord) ↔ (HHg, maternal)
		Motor	↔ (BHg, cord) ↔ (HHg, maternal)
		Fine motor	↓ (BHg, cord) ↔ (HHg, maternal)
		Gross motor	↔ (BHg, cord) ↔ (HHg, maternal)
Stewart et al. 2003 Prospective study of mother-infant pairs, follow-up at age 38 months (n=194) and 54 months (n=197); New York	HHg median Maternal: 0.50 µg/g	MSCA 38 months	↓ (HHg, maternal, prenatal PCB detected)
		MSCA 54 months	↔ (HHg, maternal)
Taylor et al. 2018a Prospective study (ALSPAC) of mother-infant pairs, follow-up at age 7 years (n=1,558); United Kingdom	BHg median Maternal: 2.23 µg/L	ALSPAC CT (5 subtests)	↔ (BHg, maternal)
		DCD	↔ (BHg, maternal)
Valent et al. 2013 Prospective cohort of mother-infant pairs, follow-up at age 18 months (n=606); Italy	BHg median Maternal: 0.00235 µg/g Cord: 0.00397 µg/g HHg median Maternal: 0.788 µg/g	BSID composite scores (cognitive, language, motor, social-emotional, adaptive behavior)	↔ (HHg, maternal) ↔ (BHg, maternal ↔ (BHg, cord)
Vejrup et al. 2016 Prospective cohort (MoBa) of mother-infant pairs, follow-up at age 3 years (n=46,750); Norway	Dietary fish mercury median Maternal: 1.3 µg/day Maternal: 0.14 µg/kg/week	DBGR (speech)	↓ (maternal dietary fish mercury >2.6 µg/day)
		ASQ (language)	↓ (maternal dietary fish mercury >2.6 µg/day)

Table 2-50. Results of Epidemiological Studies Evaluating General Population Exposure to Mercury (Predominant Mercury Form Unknown) and Neurodevelopmental Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result[a]
Vejrup et al. 2018 Prospective cohort (MoBa) of mother-infant pairs, follow-up at age 5 years (n=38,581); Norway	BHg median (n=2,232) Maternal: 1.03 µg/L Dietary fish mercury median Maternal: 0.15 µg/kg/week	ASQ (language)	↔ (BHg, maternal) ↓ (maternal dietary seafood ≤400 g/week) ↔ (maternal dietary seafood >400 g/week)
		SLAS (language)	↔ (BHg, maternal) ↓ (maternal dietary seafood ≤400 g/week) ↔ (maternal dietary seafood >400 g/week)
		Language 20	↔ (BHg, maternal) ↔ (maternal dietary seafood ≤400 g/week) ↔ (maternal dietary seafood >400 g/week)
Vejrup et al. 2022 Prospective cohort (MoBa) of mother-infant pairs, follow-up at age 3 and 5 years (n=51,238); Norway	BHg median (n=2,936) Maternal: 1.02 µg/L Dietary fish mercury median Maternal: 0.15 µg/kg/week	CBCL internalizing behavior	↔ (BHg, maternal) ↓ (maternal dietary)
		CBCL externalizing behavior	↔ (BHg, maternal) ↓ (maternal dietary)
Wang et al. 2019a Prospective birth cohort, follow-up at age 2 days and 18 months (n=286); China	BHg, geometric mean Cord: 2.00 µg/L	NBNA (3 days)	↓ (BHg, cord)
		NBNA (3 days)	↓ (BHg, cord, low DHA)
		NBNA (3 days)	↔ (BHg, cord, high DHA)
		BSID	↔ (BHg, cord)
Wu et al. 2014 Prospective cohort of mother-infant pairs, follow-up at age 3 days (n=418); China	BHg median Maternal: 5.00 µg/L Cord: 7.62 µg/L HHg median Maternal: 1.08 µg/g	NBNA (total)	↑ (BHg, cord)
		NBNA (behavior)	↔ (BHg, cord)
		NBNA (passive muscle tone)	↑ (BHg, cord)
		NBNA (active muscle tone)	↑ (BHg, cord)
Xu et al. 2016 Prospective cohort of mother-infant pairs, follow-up at age 5 weeks (n=344); Ohio	BHg geometric mean Maternal: 0.6 µg/L Cord: 0.72 µg/L	NICU NNS	↔ (HHg, maternal) ↔ (HHg, cord)
Yau et al. 2014 Retrospective cohort of 84 autism cases and 49 developmental delay cases at age 3–4 years; California	SHg geometric mean Maternal autism: 0.48 µg/L Maternal control: 0.32 µg/L	Autism	↔ (maternal serum Hg) ↔ (child BHg)

Table 2-50. Results of Epidemiological Studies Evaluating General Population Exposure to Mercury (Predominant Mercury Form Unknown) and Neurodevelopmental Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result[a]
	BHg geometric mean Neonatal autism: 3.52 µg/L Neonatal control: 2.85 µg/L		

[a]Interpretation of neurobehavioral test scores:
ADHD: higher score = more behavioral problems
ASD: higher score = more behavioral problems
ALSPAC CT: higher score = higher performance
ANT hit reaction time standard error: higher score = lower performance
ASQ: higher score = more behavioral problems
BASC: higher score = more behavioral problems
BNT: higher score = higher performance
BSID: higher score = higher performance
CBCL: higher score = lower performance
CPT: longer response time = lower performance
CTRS: higher score = lower performance
DBGR: higher score = higher performance
DCD: higher score = more behavioral problems
DDST-II: milestones evaluated against a standard; below standard = delayed development
GDS: higher score = higher performance
GPB: higher score = lower performance
HKLLT: higher score = higher performance
IDS: higher score = higher performance
KBIT: higher score = higher performance
Language 20: higher score = higher performance
MSCA: higher score = higher performance
MSCA: higher score = higher performance
NBNA: higher score = higher performance
NICU NNS: higher score = higher performance
PEDS: higher score = higher performance
PPRVT: higher score = higher performance
RCPM: higher score = higher performance
SCAS: higher score = more behavioral problems
SDQ: higher score = more behavioral problems
SLAS: higher score = higher performance
SRS: higher score = more behavioral problems
TEACH: higher score = higher performance
WISC-III: higher score = higher performance
WPPSI-RK: higher score = higher performance
WRAVMA: higher score = higher performance
[b]Weighted mean of age group medians reported in Hibbeln et al. (2018) Appendix A, Table 1,
[c]Values are for pregnancies that resulted in male or female newborns (reported as male, female). Outcomes were assessed for associations with maternal, cord or concurrent child blood Hg concentrations.

↑ = positive association; ↓ = inverse association; ↔ = no association; ADHD = attention deficit/hyperactivity disorder; ALSPAC = Avon Longitudinal Study of Parents and Children; ANT = Attention Network Test; ASD = autism spectrum disorder; ASQ = Ages and Stages Communication Scale; BAEPL = brainstem auditory evoked potential latencies; BASC = Behavioral Assessment System for Children; BHg = blood mercury; BMMeHg = breastmilk mercury; BNT = Boston naming test; BRIEF GEC = Behavior Rating Inventory of Executive Function Global Executive Composite; BSID = Bayley Scales of Infant Development; CBCL = Child Behavior Checklist; CHg = cord mercury; CPRS = Connors' Teacher Rating Scale; CT = Coordination Test; CTRS = Connors' Teacher Rating Scale;

Table 2-50. Results of Epidemiological Studies Evaluating General Population Exposure to Mercury (Predominant Mercury Form Unknown) and Neurodevelopmental Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result[a]

DBGR = Dale and Bishop Grammar Rating; DCD = Development Coordination Disorder; DDST = Denver Developmental Screening Test; DHA = docosahexaenoic acid; ErHg = erythrocyte mercury; FSIQ = full scale intelligence quotient; GDS = Gesell Development Schedules; Gmean = geometric mean; GPB = grooved pegboard; HHg = hair mercury; HKLLT = Hong Kong List Learning Test; HMeHg = hair methylmercury; IDS = Intelligence and Development Scales; IQ = intelligence quotient; KBIT = Kauffman Brief Intelligence Test; KNHANES = Korea National Health and Nutrition Examination Survey; MDI = BSID Mental Development Index; MoBa = Norwegian Mother and Child Cohort Study; MSCA = McCarthy Scales of Children's Abilities; NBNA = Neonatal Behavioral Neurological Assessment; NES CPT = Neurobehavioral Evaluation Systems Continuous Performance Test; NHg = nail mercury; NICU NNS = Neonatal Intensive Care Unit Network Neurobehavioral Scale; OR = odds ratio; PCB = polychlorinated biphenyl; PDI = BSID Psychomotor Development Index; PEDS = Parents Evaluation of Developmental Status; PIQ = Performance Intelligence Quotient; PPVT = Peabody Picture Vocabulary Test; RCPM = Raven Coloured Progressive Matrices; SCAS = Spence Children's Anxiety Scale; SDQ = Strengths and Difficulties Questionnaire; SHg = serum mercury; SLAS = Speech and Language Assessment Scale; SRS = Social Responsiveness Scale; TEACH = Test for Everyday Attention for Children; UHg = urine mercury; VEP = visual evoked potential; VIQ = Verbal Intelligence Quotient; WISC = Wechsler Intelligence Scale; WISC-III = Wechsler Intelligence Scale, 3rd Edition; WISC-IV = Wechsler Intelligence Scale, 4th Edition; WISC-HK = Wechsler Intelligence Scale, Hong Kong; WPPSI = Wechsler Preschool and Primary Scale Intelligence; WPPSI-R = Wechsler Preschool and Primary Scale Intelligence, Revised; WPPSI-RK = Wechsler Preschool and Primary Scale Intelligence, Revised, Korean; WRAML = Wide Range Assessment of Memory and Learning; WRAVMA = Wide Range Assessment of Visual Motor Abilities

In general populations, blood and HHg will be more greatly affected by exposures to other forms of mercury (e.g., mercury from amalgams) than in high fish consuming populations in which methylmercury is the dominant contributor to mercury body burden. Therefore, general population studies that estimated oral intake of methylmercury directly are stronger designs for the purpose of dose-response assessments of methylmercury. One study found associations between methylmercury intake and language proficiency (Vejrup et al. 2016, 2018).

General populations are exposed to a mixture of elemental, inorganic, and organic mercury. The relative contribution from each form of mercury in the studied populations is likely to vary with diet, number and state of mercury amalgam dental restorations, and extent of occupational exposures. Given the uncertainty in the source of exposure to mercury, the biomarkers used to represent exposure (e.g., total HHg, total BHg) cannot be confidently attributed to any specific form of mercury (Section 3.3.1, Biomarkers of exposure).

A possible exception to uncertainty about the mercury form in studies of general population exposures is a large prospective study conducted in Norway (Vejrup et al. 2016, 2018). This study examined a birth cohort consisting of 46,750 mother-infant pairs recruited during the period 1999–2008. Dietary intake of

mercury from fish consumption was estimated in each mother based on outcomes of a food frequency questionnaire (FFQ) completed during pregnancy and a survey of mercury levels in fish consumed by Norwegians (Jenssen et al. 2012). Median mercury intake from fish consumption was estimated to be 0.14 µg Hg/kg/week (range 0.0–1.68 µg Hg/kg/week). The 90th percentile was 0.29 µg Hg/kg/week. (Vejrup et al. 2016). The median intake of fish and seafood was 32 g/day with a range of 0–292 g/day (Vejrup et al. 2016). Since dietary intakes of mercury in fish (which is dominated by methylmercury) were estimated, this study did not use biomarkers for the dose metrics.

The Norwegian study (Vejrup et al. 2016, 2018) evaluated language proficiency and communication skills using parent-administered questionnaires. For the most part, Vejurp et al. (2018) found associations between increasing dietary intake of mercury from fish (µg/kg body weight/week), when maternal seafood consumption was ≤400 g/week, with decreasing performance on language proficiency tests administered at 5 years of age. At 3 years of age, high (>0.29 µg Hg/kg/week) maternal mercury exposure was associated with unintelligible speech (OR 2.22; 95% CI 1.31, 3.72) on the Dale and Bishop Grammar Rating (Vejrup et al. 2016). An association was also observed for high maternal mercury exposure and weak communication skills (OR 1.33; 95% 1.03, 1.70) on the Ages and Stages Communication Scale, ASQ (Vejrup et al. 2016).

Adjustment for known important confounders related to fish consumption, including fish consumption rate (adjustment strengthened the association with mercury), 3-omega LCPUFA consumption, and exposure to PCBs did not affect associations (Vejrup et al. 2016). Maternal mercury exposure (>0.29 µg Hg/kg/week) was associated with weak communication skills when LCPUFA (diet or from supplements) or PCBs were added to the analysis. However, there was a slight reduction in the association of maternal mercury and weak communication (OR 1.29; 95% 1.00, 1.67) when adjusted for exposure to dioxin and PCBs (Vejrup et al. 2016). Estimates of ORs were adjusted for parity, parental education, pre-pregnancy BMI (Vejrup et al. 2016, 2018), bilingual parents, age when child began speaking (Vejrup et al. 2016), maternal age, total energy intake, and two (EPA, DHA) LCPUFAs (Vejrup et al. 2018).

In a follow-up at age 5 years, children were assessed with three outcome tests: ASQ, Speech and Language Assessment Scale, and Twenty Statements about Language-Related Difficulties (Vejrup et al. 2018). No associations were observed with mid-pregnancy maternal BHg concentrations in a subcohort of the main cohort (2,232 subjects) in which BHg levels were measured (median 1.0 µg Hg/L; range 0–14 µg Hg/L). However, in the full cohort (n=38,397) among women who consumed ≤400 g fish/week, both fish consumption and mercury intake were associated with improvement of scores (negative error

scores) in the ASQ (adjusted β -0.16; 95% CI -0.3, -0.02) and Speech and Language Assessment Scale (-0.22; 95% CI -0.4, -.01).

When Vejrup et al. (2018) confined the analyses to matched siblings, dietary fish mercury intake at the 90th percentile level (>3.18 μg Hg/day) was associated with decreasing performance on the Speech and Language Assessment Scale (adjusted β 0.1; 95% CI 0.1, 0.2) but not on the Ages and Stages Communication Scale or Language-Related Difficulties scale. These results suggest that fish intake was a confounding variable in this study (correlation between dietary fish mercury intake and fish intake was 0.88) and may have attenuated associations between dietary methylmercury intake and delays in attainment of language skills. The absence of an association with maternal BHg may represent variance in BHg levels that is unrelated to dietary methylmercury intake (e.g., mercury from amalgam restorations).

Emotional behavior was also examined in the Norwegian birth cohort study (Vejrup et al. 2022). The Child Behavior Checklist was used to assess internalizing behavior (symptoms of anxiety or depression) and externalizing behavior (symptoms of aggressive behavior attention disorder) at age 3 and 5 years. Increasing dietary methylmercury intake (median 0.15 μg MeHg/kg/week) was associated with decreasing internalization and externalization scores (n=46,283). No association was evident between behavior and maternal BHg (median 1.02 μg Hg/L; n=2,744).

Similar to Vejrup et al. (2018), another large prospective study conducted in Japan (n=48,731) found no evidence for an association between maternal BHg levels (median 3.64 μg/kg) and neurodevelopment assessed from scores on the ASQ (Kobayashi et al. 2022). In a subset of the cohort (n=3,083), no association was found when the exposure biomarker was cord BHg (median 7.56 μg/kg).

Results from smaller studies that have examined associations between mercury exposure biomarkers and language proficiency have been inconsistent (Barbone et al. 2019; Freire et al. 2010; Hu et al. 2016; Jeong et al. 2017; Julvez et al. 2013, Kobayashi et al. 2022; Lederman et al. 2008; Orenstein et al. 2014; Rothenberg et al. 2016b; Snoj Tratnik et al. 2017; Valent et al. 2013). For example, Barbone et al. (2019) and Jeong et al. (2017) reported opposite outcomes for the association between BHg and language outcomes and most of the other studies reported no association (Table 2-50) for the same comparators. Further details are provided in the following paragraphs.

A large prospective study conducted in Japan (n=48,731) found no evidence for an association between maternal BHg levels (median 3.64 μg/kg) and neurodevelopment assessed from scores on the ASQ (Kobayashi et al. 2022). In a subset of the cohort (n=3,083), no association was found when the exposure biomarker was cord BHg.

A prospective study conducted in the Republic of North Korea (553 mother-infant pairs) found an inverse association between increasing maternal blood mercury (median 3.1 μg Hg/L) and verbal proficiency at age 5 years (Jeong et al. 2017). The effect size was estimated to be a 2.48 verbal IQ points (95% CI 0.72, 4.2) per doubling of maternal blood mercury. The Barbone et al. (2019) meta-analysis of populations in Mediterranean Europe (1,308 mother infant pairs) found an association between increasing prenatal (cord) blood mercury (median 3.6 μg Hg/L) and improved language performance at age 18 months, based on scores on the Bayley Scales of Infant Development. Mercury levels in the Barbone et al. (2019) study were similar to the Jeong et al. (2017) study (described above), which found an association between prenatal blood mercury and declining language proficiency. Other studies found declines in language or verbal performance (Freire et al. 2010) or no association (Hu et al. 2016; Julvez et al. 2013; Orenstein et al. 2014) with mercury exposure biomarkers.

A cross-sectional study examined associations between a short-term increase in exposure to methylmercury and IQ in children (Kvestad et al. 2018). In this study, children (n=210, age 4–6 years) were fed fish or meat lunches for 16 weeks. Mean HHg levels were 0.53 μg Hg/g in children who consumed fish lunches (0.16 μg Hg/g increase from pre-fish lunch diet). The mean HHg was 0.32 μg Hg/g in children who consumed meat lunches (-0.052 μg Hg/g change from pre-meat lunch diet). This study found no differences in scores on tests of IQ (full-scale, verbal, performance, or processing speed) between children who consumed fish or meat lunches and no association between HHg and IQ prior to starting the fish or meat lunch diets.

Several studies measured cognitive performance with the Bayley Scales of Infant Development at various ages, allowing comparison of the same outcomes across studies. Two of these studies found an inverse association with cord BHg (0.9 μg Hg/L) at age 12 months (Jedrychowski et al. 2006; Rothenberg et al. 2016b). One study found a positive association with cord BHg (median 3.6 μg Hg/L) at age 18 months (Barbone et al. 2019). However, an inverse association with cord BHg (mean 7.8 μg Hg/L) was observed at age 36 months, but not at younger ages (Lederman et al. 2008). Ten other studies found no association with cord or maternal BHg of HHg levels (median range >0.9–8.4 μg Hg/L) at ages 12–36 months (Table 2-50) .

When Jedrychowski et al. (2006) did not adjust for fish consumption or exposure to lead or PCBs, an inverse association was observed. When Jedrychowski et al. (2007) did adjust for fish consumption, there was no association. However, this was not the case for Rothenberg et al. (2016b) where the inverse association was strengthened after adjustment for maternal fish and shellfish consumption, rice consumption, and total energy intake. Other studies that found no association adjusted their regression models for fish consumption (Kim et al. 2018; Llop et al. 2012; Valent et al. 2013) and PCB and lead exposure (Llop et al. 2012). The inverse association observed in the Rothenberg et al. (2016b) study was strengthened after adjustment for maternal fish and shellfish consumption, rice consumptions, and total energy intake. Studies that found no association adjusted their regression models for fish consumption (Jedrychowski et al. 2007; Kim et al. 2018; Llop et al. 2012; Valent et al. 2013) and PCB and lead exposure (Llop et al. 2012).

Exposure to PCBs was found to be an important modifier of the association between cognitive performance measured with the McCarthy Scales of Children's Abilities at age 38 months (Stewart et al. 2003). Lederman et al. (2008) found an inverse association between cord BHg (mean 7.8 µg Hg/L) and IQ measured at age 48 months (Wechsler Preschool and Primary Scale Intelligence, Revised), after adjustment for fish and seafood consumption during pregnancy and other potential confounders (maternal age, race, education IQ, income, marital status, exposure to tobacco smoke, and material hardship; child sex, gestational age, and age at testing). The effect size was -3.6 IQ point per ln (µg/L), which corresponds to a 2.5-point decrease in IQ per doubling of cord BHg.

Latency of brainstem auditory evoked potentials was not associated with increasing maternal HHg in a prospective study (327 mother-infant pairs) conducted in Japan (Murata et al. 2004b). This observation is notable because increased latency of auditory evoked potentials was observed in the Faroe Islands and Madeira Portugal studies of high fish consumption populations (Grandjean et al. 1997, 1998, 2003; Murata et al. 1999a, 1999b). Maternal HHg was higher in the Faroe Islands cohort (median 4.3 µg Hg/g) and Madeira cohort (9.4) compared to the Japanese cohort (mean 2 µg Hg/g). A cross-sectional analysis of data from the KNHANES (853 adolescents) found no association between BHg levels in 853 adolescents (mean 2.0 µg Hg/L) or 5,187adults (mean 3.6 µg Hg/L) and speech-frequency or high-frequency hearing loss (Choi and Park 2017).

Several studies have examined associations between mercury exposure biomarkers (blood or urinary mercury) and signs of autism spectrum disorder (Golding et al. 2016a, 2016b, 2017, 2018; Hertz-Picciotto

et al. 2010; McKean et al. 2015; Ryu et al. 2017; Skogheim et al. 2021; Yau et al. 2014). In general, these studies found no associations between behaviors indicative of autism spectrum disorder and exposure to mercury. The largest prospective study reported (approximately 3,000 mother infant pairs) found no associations between maternal BHg levels (median 1.86 µg Hg/L) and signs of autism (Golding et al. 2016a, 2017, 2018). A smaller prospective study (450 mother-infant pairs) found an association between increasing maternal BHg levels (median 3.3 µg Hg/dL) and increasing scores for autistic behaviors on the Social Responsiveness Scales, in male children age 5 years, but not in females (Ryu et al. 2017). Several case-control studies have not found differences in covariate-adjusted BHg concentrations between autism cases and controls (Hertz-Picciotto et al. 2010; McKean et al. 2015; Yau et al. 2014). Skogheim et al. (2021) found an inverse association between maternal BHg concentrations and OR for autism spectrum and ADHD diagnosis, with elevated ORs at maternal BHg levels >1 µg/L. Meta-analyses have found elevated meta-ORs for autism spectrum disorder or ADHD in association with increasing mercury exposure (Nilsen and Tulve 2020; Yoshimasu et al. 2014).

2.16.2 Neurological Effects in Adults

Elemental Mercury—Epidemiological Studies. Studies of neurological function have been conducted in workers in various industries who were exposed to mercury vapor. Studies of neurological outcomes in workers are summarized in Table 2-51. The following populations exposed to elemental mercury were evaluated: chloralkali workers; florescent lamp workers; thermometer production workers; dental workers; workers in other industries; and populations with amalgam fillings. In some studies, work area or breathing zone mercury levels measured in a subset of the study group were reported. The most common biomarker reported was UHg (µg Hg/L or µg Hg/g creatinine). In cross-sectional studies, these were based on measurements made at the time of outcome assessment. In retrospective studies, UHg estimates were derived from historical industrial hygiene monitoring data and, in some studies, were aggregated into metrics of cumulative exposure (e.g., sum of quarterly average values for all exposure years) or exposure intensity (sum/exposure years). Most of the studies included in this discussion compared outcomes measured in exposed workers to a reference group of workers who were not exposed to elemental mercury. Potential selection bias and confounding were addressed by matching (e.g., age, sex, alcohol and smoking history, duration of exposure-related work) or by exclusion (e.g., head injuries, known neurological disease). However, other numerous potential variables that could have affected performance on tests of cognitive function (e.g., nutrition, exposure to other chemicals) were not evaluated (see discussion of characterization of effects on neurodevelopment). Collectively, these studies provide evidence for associations between exposure to mercury vapor and several categories of

neurological effects, including tremor, vision, nerve conduction, and cognitive performance (motor speed and coordination, memory, and integrative function).

Table 2-51. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Neurological Effects

Reference, study type, and population	Biomarker	Outcome evaluated[a]	Result
Chloralkali workers			
Albers et al. 1982 Retrospective cohort of 138 workers; United States	UHg working mean 36-months: normal: 80 µg/L polyneuropathy: 120 µg/L	Motor nerve conduction	↓ UHg
		Sensory nerve conduction	↓ UHg
Bast-Pettersen et al. 2005 Retrospective cohort of 49 former workers and 49 referents; Norway	UHg cumulative work mean: 16.5 µg/g Cr/year UHg mean at testing Workers: 2.93 µg/g Cr Referents: 2.04 µg/g Cr BHg mean at testing Workers: 4.63 µg/L Referents: 3.51 µg/L	Hand tremor	↔ (exposed versus referents)
		Digit span test	↔ (exposed versus referents)
		Digit symbol test	↔ (exposed versus referents)
		Trail making test	↔ (exposed versus referents)
		Visual retention test	↔ (exposed versus referents)
		Finger tapping test	↔ (exposed versus referents)
		NES CPT	↔ (exposed versus referents)
Bluhm et al. 1992 Cross-sectional study of 26 workers and referent population (n=27); United States	UHg mean: 100–200 µg/24 hours BHg mean: 50–100 µg/L	Trail making test	↓ UHg ↓ (exposed versus referents)
		Stroup color-word test	↓ UHg ↓ (exposed versus referents)
		Finger tapping test	↓ UHg ↓ (exposed versus referents)
		Grooved pegboard test	↓ UHg ↓ (exposed versus referents)
Chang et al. 1995 Retrospective cohort of 26 workers; China	UHg mean at testing Workers: 40.5 µg/24 hours Referents: NR UHg mean at testing Workers: 358 µg/g Cr Referents: NR BHg mean at testing	Visual evoked potential N1-P1 interpeak amplitude	↑ (exposed versus referents)
		BAEP latency	↑ (exposed versus referents)

Table 2-51. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Neurological Effects

Reference, study type, and population	Biomarker	Outcome evaluated[a]	Result
	Workers: 28 µg/L Referents: NR		
Ellingsen et al. 2001 Retrospective cohort of 47 former workers and 47 referents; Norway	UHg cumulative work mean: 16.0 µg/g Cr/year UHg mean at testing Workers: 10.5 µg/g Cr Referents: 2.3 µg/g Cr BHg inorganic mean at testing Workers: 4.15 µg/L Referents: 1.1 µg/L	Hand steadiness	↔ (exposed versus referents)
		Digit span test	↔ (exposed versus referents)
		Digit symbol test	↓ (BHg inorganic)
		Trail making test	↔ (exposed versus referents)
		Visual retention test	↓ (BHg inorganic)
		Finger tapping test	↔ (exposed versus referents)
		NES CPT	↔ (exposed versus referents)
Frumkin et al. 2001 Retrospective cohort of 139 former workers and 107 referents; United States	UHg mean at testing Workers: 2.76 µg/g Cr Referents: 2.31 µg/g Cr UHg working mean: 72.1 µg/L Air mercury average: range: 2–106 µg/m^3	Tremor	↑ (exposed versus referents)
		Vibration threshold	↑ (exposed versus referents)
		Finger tapping	↓ (exposed versus referents)
		Nerve conduction composite	↑ (exposed versus referents)
		Motor speed composite	↔ (exposed versus referents)
		Motor coordination composite	↔ (exposed versus referents)
		Memory composite	↔ (exposed versus referents)
		Integrative functions	↔ (exposed versus referents)
Langolf et al. 1978 Retrospective study of 79 workers and 51 referents; United States	UHg working mean Workers: 240 µg/L Referents: 30 µg/L	Forearm tremor	↑ (UHg)
		Forearm EMG bandwidth	↑ (UHg)
		Finger tapping rate	↓ UHg
		Hand-eye coordination	↓ UHg

Table 2-51. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Neurological Effects

Reference, study type, and population	Biomarker	Outcome evaluated[a]	Result
Langworth et al. 1992a Retrospective sectional cohort of 89 workers and 75 referents; Sweden	UHg working median Workers: 25.4 µg/g Cr Referents: 1.9 µg/g Cr BHg working median Workers: 11 µg/L Referents: 3.0 µg/L Air mercury mean: 25 µg/m^3	Forearm tremor	↔ (exposed versus referents)
		Hand-eye coordination	↔ (exposed versus referents)
		Finger tapping	↔ (exposed versus referents)
		Simple reaction time	↔ (exposed versus referents)
		Symbol digit	↔ (exposed versus referents)
		Digit span	↔ (exposed versus referents)
		Sternberg memory task	↔ (exposed versus referents)
Levine et al. 1982 Retrospective cohort of 18 workers; United States	UHg working mean 12-month average: 290 µg/L 24-month average: 210 µg/L	Motor nerve conduction latency	↑ UHg (24-month average)
		Sensory nerve conduction latency	↑ UHg (12- and 24-month average)
Mathiesen et al. 1999 Retrospective cohort of 75 former workers and 52 referents; Norway	UHg cumulative work mean: 108 µg/L/year UHg mean at testing Workers: 0.36 µg/g Cr Referents: 0.24 µg/g Cr BHg mean at testing Workers: 5.24 µg/L Referents: 5.54 µg/L	Visual retention	↓ UHg (cumulative/year)
		Grooved pegboard test	↓ UHg (months of exposure)
		Trail making test	↓ UHg (cumulative/year)
		Digit symbol test	↑ UHg (≥50 µg/g Cr) ↑ BHg (≥10 µg/L UHg (cumulative/year)
Miller et al. 1975 Cross-sectional cohort of 77 workers and 65 referents; United States	UHg group mean range Workers: 129–787 µg/L Referents: 7.11–152 µg/L BHg group mean range Workers: 3.97–17.11 µg/L Referents: 0.90–5.89 µg/L	Forearm tremor	↑ UHg
		Forearm EMG bandwidth	↑ UHg

Table 2-51. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Neurological Effects

Reference, study type, and population	Biomarker	Outcome evaluated[a]	Result
Piikivi et al. 1984 Retrospective cohort of 36 workers and referents; Finland	UHg mean at testing Workers: 58.3 µg/L Referents: NR BHg mean at testing Workers: 20.0 µg/L Referents: NR	Picture similarity test	↓ UHg (TWA >110 µg/L) ↓ UHg (highest >300 µg/L)
		Logical memory	0 UHg (TWA >110 µg/L) ↓ UHg (highest >300 µg/L)
		Santa Ana dexterity test	↓ UHg (TWA <110 µg/L) ↓ UHg (highest <300 µg/L) ↓ (exposed versus referents)
Piikivi and Hänninen 1989 Retrospective cohort of 60 workers and referents; Finland	UHg mean at testing Workers: 17.9 µg/g Cr Referents: 2.1 µg/g Cr BHg mean at testing Workers: 6.78 µg/L Referents: 0.92 µg/L BHg (inorganic) TWA working mean: 5.94 µg/L	Hand-eye coordination	↑ (exposed versus referents)
		Finger tapping	↔ (exposed versus referents)
		Memory and learning	↔ (exposed versus referents)
		Continuous performance test	↔ (exposed versus referents)
Roels et al. 1982 Cross-sectional cohort of 43 chloralkali and mercury battery workers and 47 referents; Belgium	UHg median at testing Workers: 71.0 µg/g Cr Referents: 1.2 µg/g Cr BHg median at testing Workers: 20.6 µg/L Referents: 1.9 µg/L	Hand tremor	↑ UHg (≥50 µg/g Cr) ↑ BHg (≥10 µg/L)
		Hand-eye coordination	↓ UHg (≥50 µg/g Cr) ↓ BHg (≥10 µg/L
Smith et al. 1983 Retrospective cohort of 86 workers; United States	UHg working mean Plants 1 and 2 (n=26) 3 months: 195 µg/L 24 months: 143 µg/L Plants 3 and 4 (n=60) 3 months: 108 µg/L 24 months: 93 µg/L	Short-term memory	↓ UHg
Urban et al. 2003 Cross-sectional cohort of 24 workers and 24 referents; Czech Republic	UHg mean Workers: 20.5 µg/g Cr Referents: 1 µg/L Air mercury 8 hours TWA: 59 µg/m^3	Visual color discrimination	↔ UHg ↓ UHg (DMPS-provoked) ↓ (exposed versus referents)

Table 2-51. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Neurological Effects

Reference, study type, and population	Biomarker	Outcome evaluated[a]	Result
Wastensson et al. 2006, 2008 Retrospective cohort of 43 workers and 22 referents; Sweden	UHg cumulative work mean: 266 µg year/g Cr (mean 15 years), which corresponds to an average of 1.7 µg/g Cr UHg median at testing Workers: 5.9 µg/g Cr Referents: 0.7 µg/g Cr	Postural tremor	↔ UHg at testing ↔ UHg cumulative
		Hand tremor	↓ UHg at testing ↓ UHg cumulative
		Hand-eye coordination	↔ UHg at testing ↔ UHg cumulative
		Hand-eye coordination	↔ UHg at testing ↔ UHg cumulative
Florescent lamp workers			
Barboni et al. 2008 Retrospective cohort of 35 former workers and 34 referents; Brazil	UHg working mean: 41.15 µg/g Cr UHg mean at testing Workers: 2.39 µg/g Cr Referents: NR	Visual field loss	↓ (exposed versus referents)
Fawer et al. 1983 Cross-sectional cohort of 26 workers (12 chloralkali, 7 lamp and 7 acetaldehyde) and 25 referents; Belgium	UHg mean Workers: 20.1 µg/g Cr Referents: 6.0 µg/g Cr Air mercury TWA: 26 µg/m^3	Tremor	↑ (exposed versus referents)
Bagheri Hosseinabadi et al. 2020 Cross-sectional cohort of 50 workers and 50 referents; Iran	BHg mean Workers: 22.59 µg/L Referents: 1.28 µg/L Air mercury mean: 42 µg/m^3	Tremor	↑ (exposed versus referents)
		Fatigue	↑ (exposed versus referents)
		Depression	↑ (exposed versus referents)
Milioni et al. 2017 Cross-sectional cohort of 31 workers and 31 referents; Brazil	NR	Recover of pupil contraction response to light	↓ (exposed versus referents)
Ventura et al. 2005 Retrospective cohort of 39 former workers and 21 referents; Brazil	UHg working mean: 41.09 µg/g Cr	Color vision loss	↓ (exposed versus referents)
Verberk et al. 1986 Retrospective cohort of 20 workers; The Netherlands	UHg mean at testing: 35.7 µg/g Cr	Tremor	↑ UHg

Table 2-51. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Neurological Effects

Reference, study type, and population	Biomarker	Outcome evaluated[a]	Result
Thermometer production workers			
Cavalleri and Gobba 1998 Cross-sectional cohort of 21 workers and 21 referents; Italy	Workers: 114.9 µg/g Cr Referents: NR UHg mean after chelation: 10.0 µg/g Cr	Color discrimination	↓ (exposed versus referents) ↓ UHg
Ehrenberg et al. 1991 Cross-sectional cohort of 83 workers and 79 referents; United States	UHg mean: 73 µg/g Cr Air mercury, 80-hour TWA, range: 9.3–75.6 µg/m^3	Abnormal heal-to-toe walk	↑ (exposed versus referents)
Tang and Li 2006 Cross-sectional cohort of 143 workers; China	UHg mean: 30 µg/L Air workplace mean: 27 µg/m^3	Tremor	↑ UHg (≥50 µg/L versus <10 µg/L)
		Neurasthenic symptoms (self-reported)	↑ UHg (≥50 µg/L versus <10 µg/L)
		Emotional changes (self-reported)	↑ UHg (≥50 µg/L versus <10 µg/L)
		Oral or gum inflammation	↑ UHg (≥50 µg/L versus <10 µg/L)
Dental workers			
Anglen et al. 2015 Retrospective cohort of 13,906 dental workers; United States	UHg mean Year 1976: 20.1 µg/L Year 2012: 2.04 µg/L basis for OR: 4.7 µg/L	Tremor	↑ UHg ↔ Restorations per week
		Multiple sclerosis	↔ UHg ↔ Restorations per week
Bittner et al. 1998 Pooled study cohort of 230 dental workers; United States	UHg: 95% <55 µg/L	Hand steadiness	↓ UHg
		Finger tapping	↔ UHg
		One-hole test	↔ UHg
		Reaction time	↔ UHg
		Hand tremor	↔ UHg
Canto-Pereira et al. 2005 Cross-sectional cohort of 15 dental workers and 13 referents; Brazil	UHg Gmean testing Workers: 1.54 µg/g Cr Referents: 0.66 µg/g Cr	Color contrast sensitivity	↓ (exposed versus referents)
		Color discrimination	↓ (exposed versus referents)
		Color confusion index	↔ (exposed versus referents)

Table 2-51. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Neurological Effects

Reference, study type, and population	Biomarker	Outcome evaluated[a]	Result
Echeverria et al. 1998 Cross-sectional cohort of 49 dental workers (24 dentists, 15 assistants); United States	UHg mean Dentists: 0.89 µg/L Assistants: 1.07 µg/L	Mood symptoms	↑ UHg
		Motor coordination	↓ UHg
		Visual processing performance	↓ UHg
		Verbal processing and attention	↔ UHg
Echeverria et al. 2005 Cross-sectional cohort of 427 male dentists, 233 female dental assistants; United States	UHg mean Females: 1.98 µg/L Males: 3.32 µg/L	Attention	↓ UHg
		Working memory	↓ UHg
		Visual memory	↓ UHg
		Motor performance	↓ UHg
		Hand steadiness	↓ UHg
Franzblau et al. 2012 Longitudinal cohort of 2,767 dental workers, United States	UHg median 2.58 µg/L	Median NCV	↔ UHg
		Ulnar NCV	↔ UHg
Heyer et al. 2004 Cross-sectional cohort of 423 dental workers (193 male dentists, 230 female dental assistants); United States	UHg mean 2.32 µg/L	Mood symptoms	↑ UHg
		Neurologic symptoms	↑ UHg
Ngim et al. 1992 Cross-sectional cohort of 98 dental workers and 54 referents; Singapore	Air mercury Gmean 8-hour TWA: 13.6 µg/m^3 BHg geometric mean Dentists: 9.8 µg/L Referents: NR	Motor coordination	↓ UHg
		Visual processing performance	↓ UHg
		Working memory	↓ UHg
		Visual-motor performance	↓ UHg
Ritchie et al. 2002 Cross-sectional cohort of 170 dental workers and 179 referents; United Kingdom	UHg median Workers: 0.34 µg/g Cr Referents: 0.10 µg/g Cr Air mercury median range: 5.7–21.2 µg/m^3	Attention	↔ UHg
		Reaction time	↔ UHg
		Visual memory	↔ UHg
		Working memory	↔ UHg

Table 2-51. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Neurological Effects

Reference, study type, and population	Biomarker	Outcome evaluated[a]	Result
Sletvold et al. 2012 Cross-sectional cohort of 91 female dental workers; Norway	UHg median 12.0 µg/L	Motor function	↔ UHg
		Short-term memory	↔ UHg
		Working memory	↔ UHg
		Verbal long-term memory	↔ UHg
		Visual long-term memory	↓UHg
		Executive function	↔ UHg
		Mental flexibility	↔ UHg
Wang et al. 2012 Cross-sectional cohort of 513 dental workers (244 dentists and 269 dental assistants and hygienists); United States	UHg Gmean 0.65 µg/L HHg median: 0.28 µg/g	Sural nerve conduction onset latency	↓ UHg ↓ HHg
		Ulnar nerve conduction onset latency	↔ UHg ↓ HHg
Other workers			
Albers et al. 1988 Retrospective cohort of 247 lithium 6 workers and 255 referents; United States	UHg working mean 199.9 µg/L[b]	Tremor	↑ UHg ↑ (exposed versus referents)
Barboni et al. 2009 Cross-sectional cohort of 10 mercury recycling workers and 79 referents (10–20 referents per test); Brazil	UHg mean Workers: 22.3 µg/g Cr Referents: NR	Color discrimination	↓ (exposed versus referents)
		Visual field threshold	↓ (exposed versus referents)
		Visual contrast sensitivity	↓ (exposed versus referents)
Boogaard et al. 1996 Retrospective cohort of 40 natural gas workers and 19 referents; The Netherlands	UHg working median High exposure: 41 µg/L Low exposure: 12 µg/L UHg median at testing High exposure: 17 µg/L Low exposure: 5 µg/L Referents: 2 µg/L UHg median at testing high exposure: 17 µg/L low exposure: 5 µg/L	Tremor	↔ UHg ↔ (exposed versus referents)

Table 2-51. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Neurological Effects

Reference, study type, and population	Biomarker	Outcome evaluated[a]	Result
Cañadas et al. 2021 Cross-sectional cohort of 29 metal manufacture workers and 22 referents; Spain	UHg range (of individual maximums) during exposure Workers: 93.61–245.57 µg/g Cr BHg range (of individual maximums) during exposure Workers: 252.62–507.42 µg/L	Ocular (corneal) surface pathology	
		Sensitivity threshold	↑ (exposed versus referents)
		Nerve density	↓ (exposed versus referents)
		Nerve branching	↓ (exposed versus referents)
Chapman et al. 1990 Cross-sectional cohort of 18 battery workers and 18 referents; United States	UHg mean at testing Workers: 23.1 µg/L Referents: NR	Tremor	↑ (exposed versus referents)
Harari et al. 2012 Cross-sectional cohort of 200 gold miners or processors, 37 gold merchants, and 72 referents; Ecuador	UHg mean at testing Merchants: 36.9 µg/g Cr Miners: 3.3 µg/g Cr Referents: 1.6 µg/g Cr BHg mean at testing Merchants: 30.1 µg/L Miners: 5.3 µg/L Referents: 5.0 µg/L	Postural tremor	↑ UHg
		Postural sway	↑ UHg
		Hand coordination	↔ UHg
Iwata et al. 2007 Cross-sectional cohort 27 cinnabar miners and 52 referents; China	UHg Gmean at testing Workers: 228 µg/g Cr Referents: 2.59 µg/g Cr	Tremor	↔ UHg ↑ (exposed versus referents)
		Postural sway	↑ UHg (transverse sway) ↔ (exposed versus referents)
Letz et al. 2000 Retrospective cohort of 104 lithium 6 workers and 101 referents; United States	UHg working median 180 µg/L	Polyneuropathy (tremor, decreased hand grip strength, slowed peripheral nerve conduction)	↑ UHg ↑ (exposed versus referents)
Mercury amalgam fillings			
Bilak et al. 2019 Cross-sectional cohort of 56 people with amalgam fillings (age range 17–35 years) and 44 referents	BHg mean: Amalgam group: 2.76 µg/L Referents: 2.06 µg/L Mean number of amalgams: 2.77	Retinal abnormalities:	
		Retinal nerve fiber layer thickness	↔ (amalgams versus no amalgams)
		Choroid ganglion layer volume	↓ (amalgams versus no amalgams)

Table 2-51. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Neurological Effects

Reference, study type, and population	Biomarker	Outcome evaluated[a]	Result
		Inner plexiform layer volume	↓ (amalgams versus no amalgams)
Factor-Litvak et al. 2003 Cross-sectional cohort of 550 health center employees not exposed occupationally (mean age 40 years); New York	UHg median: 1.3 µg/g Cr Median number of amalgams: 10 Median number of occlusal amalgam surfaces: 6	SRT (verbal memory)	↔ UHg ↔ number of amalgams ↔ number of occlusal amalgams
		BVRT (nonverbal memory)	↔ UHg ↔ number of amalgams ↔ number of occlusal amalgams
		WAIS trail making	↔ UHg ↔ number of amalgams ↔ number of occlusal amalgams
		WAIS digit symbol	↔ UHg ↔ number of amalgams ↔ number of occlusal amalgams
		Grooved pegboard (fine motor control)	↔ UHg ↔ number of amalgams ↔ number of occlusal amalgams
Hsu et al. 2016 Retrospective cohort of 10,236 people with amalgam restorations matched to referents without amalgam restorations (age >55 years); China	None	Parkinson's Disease at death	↑ (amalgams versus no amalgams)
Parkin Kullmann and Pamphlett 2018 Case-control study (age range 40–89 years) of 262 cases, 338 controls; international	None	ALS	↔ (amalgams versus no amalgams)
Sun et al. 2015 Retrospective cohort of 31,379 people with amalgam restorations and 176,208 without amalgam restorations (age >65 years); Taiwan	None	Alzheimer's disease at death	↑ (amalgams versus no amalgams)

Table 2-51. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Neurological Effects

Reference, study type, and population	Biomarker	Outcome evaluated[a]	Result
Tseng et al. 2020b Case-control study of 3,008 cases, 3,008 controls; China	Amalgams or no amalgams	Tremor	↔ (amalgams versus no amalgams)
Tseng et al. 2020a Case-control study of 612 cases, 612 controls; China	Amalgams or no amalgams	Multiple sclerosis	↔ (amalgams versus no amalgams)

[a]Interpretation of neurobehavioral test scores:
BVRT: higher score = higher performance
CPT: longer response time = lower performance
Digit span: higher score = higher performance
Digit symbol test: higher score = higher performance
Finger tapping: higher score = higher performance
Grooved pegboard: longer time = lower performance
Picture similarity test: higher score = higher performance
RVRT: higher score = higher performance
Sant Ana dexterity test: higher score = higher performance
SRT: higher score = higher performance
Steinberg memory test: higher score = higher performance
Stoop color-word test: higher score = higher performance
Trail making: longer time = lower performance
Visual retention test: higher score = higher performance

[b]The UHg working mean value was not reported by Albers et al. (1988) but was calculated based on data presented in Letz et al. (2000). There is substantial overlap between subjects in this study and the study by Letz et al. (2000); 89 exposed and 83 referents were examined in both studies.

↑ = positive association; ↓ = inverse association; ↔ = no association; ALS = amyotrophic lateral sclerosis BAEP = brainstem auditory evoked potential; BHg = blood mercury; BVRT = Benton Visual Retention Test; Cr = creatinine; DMPS = 2,3-dimercapto-1-propane sulfonate; EMG = Electromyography; Gmean = geometric mean; HHg = hair mercury; NCV = nerve conduction velocity; NES CPT = Neurobehavioral Evaluation Systems Continuous Performance Test; NR = not reported; SRT = Selective Reminder Test; TWA = time-weighted average; UHg = urine mercury; WAIS = Wechsler Adult Intelligence Scale

Chloralkali workers. Chloralkali workers are exposed to mercury vapor during handling, processing, and storage of elemental mercury used in mercury electrolysis cells in the production of sodium hydroxide. These studies have found associations between exposure to mercury vapor or mercury biomarkers (UHg) and tremor, vision, peripheral nerve conduction and sensory evoked potentials, and performance on tests of hand-eye coordination and memory.

Several studies of chloralkali workers have found associations between exposure to mercury vapor and tremor (Chapman et al. 1990; Fawer et al. 1983; Frumkin et al. 2001; Bagheri Hosseinabadi et al. 2020; Langolf et al. 1978; Miller et al. 1975; Roels et al. 1982). UHg levels (mean or median) in these studies

ranged from approximately 20 to 240 µg Hg/g creatinine. The largest of these studies examined 139 former chloralkali workers and found increased tremor and increased threshold for sensing vibration in workers compared to a referent group matched with workers for sex, age, race, educations (Frumkin et al. 2001). The mean UHg level measured at the time of work in the plant was 72 µg Hg/L. Several metrics of cognitive performance were also assessed in this study and were not found to be associated with exposure to mercury. These included tests of motor speed and fine motor and visuomotor coordination, memory, and integrated cognitive function. Bagheri Hosseinabadi et al. (2020) found that scores on a survey of tremor severity were higher among chloralkali workers (mean BHg 23 µg/L, n=50) compared to a reference group (mean BHg 1.3 µg/L, n=50). In this study, the mean air mercury level at the workplace was 42 µg/m^3. Several studies that evaluated tremor in chloralkali workers did not find associations with mercury exposure (Bast-Pettersen et al. 2005; Ellingsen et al. 2001; Langworth et al. 1992a; Wastensson et al. 2006, 2008). UHg levels (mean or median) in these studies ranged from approximately 11 to 18 µg Hg/g creatinine.

A clinical study found decreased visual color discrimination in a group of chloralkali workers (n=24) compared to a sex- and age-matched referent group (n=24; Urban et al. 2003). Color discrimination was not associated with UHg levels (mean 21 µg Hg/g creatinine; range 0.15–62 µg Hg/g creatinine); however, discrimination decreased in association with urinary mercury excretion provoked with administration of 2,3-dimercapto-1-propane sulfonate (DMPS), a metric of mercury body burden. A clinical study found changes in visual evoked potentials and increased brainstem auditory evoked potentials in a group of chloralkali workers (n=26; mean UHg: 358 µg Hg/g creatinine) compared to sex- and age-matched referents (Chang et al. 1995). Increased latency of ulnar nerve conduction was observed in workers (n=18) in association with increasing UHg levels (mean 290 µg Hg/L; Levine et al. 1982).

Several studies of chloralkali workers have found associations between exposure to mercury and various measures of cognitive function (Bluhm et al. 1992; Mathiesen et al. 1999; Piikivi et al. 1984 and Smith et al. 1983). These studies found associations between increasing UHg and performance on various tests of motor coordination, visual memory, and working memory. UHg levels (mean or median) in these studies ranged from 100 to 140 µg Hg/L. A study of former chloralkali workers (n=49) found no differences between cognitive performance of workers and a referent group (Bast-Pettersen et al. 2005). Mean UHg at testing was 2.9 µg Hg/g creatinine (range 0.3–9.2 µg Hg/g creatinine) and the average over the working period was 16.5 µg Hg/g creatinine per year (range 7–45 µg Hg/g creatinine per year).

Cessation of mercury exposure or chelation therapy to lower the mercury body burden resulted in improvement of outcomes (Bluhm et al. 1992; Langolf et al. 1978). A study of workers (n=26) who were exposed to mercury vapor while performing construction work in a chloralkali plant found lower performance on trial making and Stroup color word tests, relative to a reference group (Bluhm et al. 1992). The mean urinary mercury excretion rate measured 20–36 days after cessation of exposure was approximately 100–200 µg Hg/day and mean BHg level was approximately 50–100 µg Hg/L. Scores on trial making tests improved following treatment with DMSA which accelerated excretion of mercury in urine. A study of chloralkali workers (n=79) found increased tremor and lower performance on tests of hand coordination (Langolf et al. 1978). The mean UHg level was 240 µg Hg/L. Follow up of five subjects whose exposures were decreased showed that their neurological outcomes improved after exposures were decreased. UHg levels were 660 µg Hg/L during the high exposure period and 300 µg Hg/L after 6–10 months working in a lower exposure environment.

Mercury battery production workers. Studies of mercury battery production workers are summarized in Table 2-51. Increased prevalence of tremor was observed in workers exposed to mercury vapor in the production of mercury cell batteries (Chapman et al. 1990; Roels et al. 1982). A study of workers (n=43) that included battery production and chloralkali workers, found a higher prevalence (relative to a reference group) of hand tremor in workers who had UHg in the range of 50–100 µg Hg/g creatinine and BHg in the range of 10–20 µg Hg/L (Roels et al. 1982). Another study (n=15) found a shift in the power spectrum of finger tremor to higher tremor frequencies in battery workers compared to a reference group (Chapman et al. 1990). The mean UHg level was 23 µg Hg/L (range <10–121 µg Hg/L). A study of battery production workers (n=8) observed changes in brainstem auditory evoked potential latencies, relative to subjects in a reference group (Discalzi et al. 1993). The mean UHg level was 325 µg Hg/g creatinine.

Studies of fluorescent lamp production workers. Studies of fluorescent lamp production workers are summarized in Table 2-51. These studies compared signs and symptoms in workers and reference groups and found higher prevalence of tremor and impaired vision in workers. Increased prevalence of tremor was observed in workers exposed to mercury vapor in the production of mercury fluorescent lamps (Al-Batanony et al. 2013; Fawer et al. 1983; Verberk et al. 1986). In a study of lamp workers (n=25), hand tremor correlated with UHg level (mean 36 µg Hg/g creatinine; range 9–53 µg Hg/g creatinine) (Verberk et al. 1986). In a study that evaluated a combined cohort of workers in lamp, chloralkali, and acetaldehyde production (n=26); prevalence of hand tremor was higher in workers exposed to mercury vapor compared to a reference group not exposed to mercury vapor (Fawer et al. 1983). Mean UHg in

exposed workers was 20 µg Hg/g creatinine (SD 2.1) compared to the reference group (6.0±1.2 µg Hg/g creatinine). The mean time-weighted average mercury air level of the mercury workers was 26 µg Hg/m^3.

Decreased color discrimination and color vision loss was observed in lamp workers (Barboni et al. 2008; Feitosa-Santana et al. 2010; Ventura et al. 2004, 2005). Studies of former lamp workers (n=30–40) observed, relative to reference groups, lower red-green and blue-yellow discrimination and foveal visual field loss. Mean working urinary levels were 41 µg Hg/g creatinine (SD 1.7) and 2.4 µg Hg/g creatinine at the time of evaluation, approximately 7 years without occupational exposure (Barboni et al. 2008; Ventura et al. 2005). Recovery of pupillary contraction in response to a light flash (a sympathetic nervous system response) was prolonged in former lamp workers (n=31) relative to an age-matched reference group (Milioni et al. 2017). In this same study, mean scores on tests of working memory, spatial memory, and visual memory were lower in the lamp production workers compared to workers in the reference group.

Thermometer production workers. Studies of thermometer production workers are summarized in Table 2-51. Neurological effects have been studied in mercury thermometer production workers (Cavalleri and Gobba 1998; Ehrenberg et al. 1991; Tang and Li 2006). These studies compared signs and symptoms in workers and reference groups and found higher prevalence of tremor, impaired motor coordination, and impaired vision in workers.

The prevalence of neurological symptoms was evaluated in a group of workers (n=122) (Ehrenberg et al. 1991). Prevalence of difficulty in heel-to-toe walk was lower in workers compared to the reference group (relative risk 5.78; 95% CI 1.63, 20.50). Mean urinary mercury level was 73 µg Hg/g creatinine in workers (range 1–344 µg Hg/g creatinine) and 4.2 µg Hg/g creatinine (range: non-detected to 10 µg Hg/g creatinine) on reference workers. Mean 8-hour time-weighted average air mercury levels in the breathing zone ranged from 9.3 to 75.6 µg Hg/m^3.

The prevalence of neurological symptoms was evaluated in a group of workers (n=143) (Tang and Li 2006). Prevalence increased in workers who had urinary mercury levels ≥50 µg Hg/L compared to a group who had urine levels <10 µg Hg/L. The symptoms included tremor and self-reported neurasthenic symptoms (e.g., headache, dizziness, insomnia, memory loss, fatigue, weakness) and emotional changes (mood swings, irritability, nervousness, timidity, loss of confidence). The mean air mercury level measured in workplaces was 27 µg Hg/m^3 (range 11–57 µg Hg/m^3).

Decreased visual color discrimination was observed in a group of workers (n=21) who had a mean UHg of 115 µg Hg/g creatinine (range 34–287 µg Hg/g creatinine) relative to a matched reference group (matched for age, sex, alcohol consumption, and cigarette smoking) with mean UHg of 1.1 µg Hg/g creatinine (SD 0.13) (Cavalleri and Gobba 1998). Color discrimination was not different from the reference group following implementation of improved industrial hygiene procedures which resulted in mean urinary mercury levels of 10 µg Hg/g creatinine.

Dental practitioners. Several studies of dental practitioners have examined possible associations between exposures to mercury vapor and cognitive function and behavior; studies are summarized in Table 2-51. In these studies, exposures included elemental mercury released from during preparation, installation, or removal of mercury amalgam restorations, as well as exposures to methylmercury and inorganic mercury from other sources (e.g., diet). As a result, biomarkers such as urinary or BHg were not specific metrics of exposures to mercury vapor. Few studies reported estimates of exposure concentrations (Decharat et al. 2014; Ngim et al. 1992; Ritchie et al. 2002). Ritchie et al. (2002) measured breathing zone air concentrations in various areas of 180 active dental surgery facilities and reported median time-weighted average concentrations that ranged from 6 to 21 µg Hg/m^3. The median time-weighted average concentration measured in the breathing zones of 124 working dentists was 12 µg Hg/m^3 (range 2–38 µg Hg/m^3) (Decharat et al. 2014). Air mercury vapor concentrations are highly dynamic during some procedures, such as removal drilling of amalgam restorations (Warwick et al. 2019) and, as a result, time-weighted average concentrations may not reflect peak exposures experienced during the procedure.

Most studies of neurological outcomes in dentists have assessed exposure from biomarkers, typically urinary mercury in units of µg Hg/L or µg Hg/g creatinine. The largest study (n=13,905) matched historical records of urinary mercury and health survey data in which subjects self-reported experiencing tremor or diagnosis of multiple sclerosis (Anglen et al. 2015). Urinary mercury levels declined substantially during the survey period from a mean of 20.1 µg Hg/L in 1976 to 2.0 µg Hg/L in 2012. Increasing urinary mercury was associated with an increased OR of tremor per change in cohort mean UHg (OR 1.10 per 4.7 µg Hg/L urine; 95% CI 1.00, 1.22) but not with the number of mercury amalgam restorations placed or removed per week. No association was found with diagnosis of multiple sclerosis. Results of several smaller cross-sectional cohort studies that examined cognitive performance in dental practitioners were inconsistent. Some studies have found age-adjusted associations between increasing urinary mercury and decreasing performance on tests of motor coordination, visual processing, and working memory (Bittner et al. 1998; Echeverria et al. 1998, 2005; Ngim et al. 1992), while other studies have found no associations (Ritchie et al. 2002: Sletvold et al. 2012). Changes in self-reported mood

states or neurological symptoms were associated with increasing urinary mercury (Echeverria et al. 1998; Heyer et al. 2004). Results of studies of nerve conduction have also been inconsistent (Franzblau et al. 2012; Wang et al. 2012). Clinical studies have compared neurosensory or cognitive performance in dental practitioners compared to a reference group (Aydin et al. 2003; Canto-Pereira et al. 2005). Decreased visual color discrimination and contrast sensitivity was observed in a group of 15 dentists (median urinary mercury 1.54 µg Hg/g creatinine) compared to an age-matched reference group (0.66 µg Hg/g creatinine) (Canto-Pereira et al. 2005). Decreased performance on tests of logical memory and retention were found in a clinical study of 43 dental practitioners, compared to a reference group (hospital workers) (Aydin et al. 2003).

Other worker populations. *S*tudies of other worker populations are summarized in Table 2-51. Increased tremor was observed in cinnabar miners (n=27), relative to a referent group (Iwata et al. 2007). The median UHg level in miners was 228 µg Hg/g creatinine (range 23–4,577 µg Hg/g creatinine). Increased UHg was associated with increases in postural sway in workers exposed to mercury vapor during mining (n=200) and processing of gold (n=37) (Harari et al. 2012). The mean UHg in merchants were 36.9 µg Hg/g creatinine (range 3.2–420 µg Hg/g creatinine) and 3.3 µg Hg/g creatinine (range 0.3–170 µg Hg/g creatinine) in miners. Exposures to mercury vapor occurred during handling, processing, and storage of elemental mercury used in the COLEX process of lithium isotope separation. A study of workers exposed to mercury vapor during production of lithium 6 (n=195) found increased tremor, decreased hand grip strength, and changes in peripheral nerve conduction in association with increased UHg (Albers et al. 1988; Letz et al. 2000). The neurological outcomes were prominent when historic peak UHg levels were >600 µg Hg/L (Albers et al. 1988). The median quarterly average UHg in exposed workers was 180 µg Hg/L (range 64–7,000 µg Hg/L) (Letz et al. 2000). Neurologic outcomes were studied in workers (n=40) in natural gas production (Boogaard et al. 1996). Exposures in gas production occurs typically during maintenance and clean-up operations when mercury (from source materials) that has accumulated on equipment surfaces can vaporize. In a comparison to a reference group, no differences were observed in tests of tremor, hand-eye coordination, or peripheral never conduction velocity (Boogaard et al. 1996). Median UHg were 41 µg Hg/L (range 7–72 µg Hg/L) in a high-exposure group and 17 µg Hg/L (range 7–53 µg Hg/L) in a low-exposure group. Median air mercury concentration was 67 µg Hg/m^3 (range 10–1,500 µg Hg/m^3). A study of workers in the mercury recycling industry (n=10) found changes to visual field thresholds and contrast sensitivity color discrimination in workers compared to a reference group (Barboni et al. 2009). Mean UHg at the time of examination was 22 µg Hg/g creatinine (range 9–35 µg Hg/g creatinine). Performance improved after chelation with DMSA. Impaired vision and other ocular disturbances were observed in workers who were exposed to mercury vapor at a metal manufacturing

plant and subsequently diagnosed with mercury intoxication (Cañadas et al. 2021). The maximum observed UHg levels in the patients ranged from 94 to 246 µg/g creatinine and BHg levels ranged from 250 to 500 µg/L.

Mercury released from amalgam dental restorations. Details of studies that examined associations between dental amalgams and neurological effects are summarized in Table 2-51. A cross-sectional study of 530 health center employees who had no known occupational exposure to mercury found no associations between urinary mercury (median 1.3 µg Hg/g creatinine) or number of mercury amalgam restorations and performance on tests of memory or fine motor control (Factor-Litvak et al. 2003). Two large retrospective studies found elevated hazard ratios for diagnosis at death of Parkinson's Disease (hazard ratio 1.58; 95% CI 1.12, 2.23; 20,000 subjects) or Alzheimer's Disease (hazard ratio 1.1; 95% CI 1.01, 1.19; 200,000 subjects) in adults who had mercury amalgam restorations (Hsu et al. 2016; Sun et al. 2015). Results from studies of associations between mercury amalgam restorations and multiple sclerosis have been inconsistent (Aminzadeh and Etminan 2007). A case-control study (143 cases, 128 controls) estimated the OR to be 1.05 (95% CL 1.19, 3.53) (Bangsi et al. 1998); however, other studies have found no association between amalgam restorations and multiple sclerosis (Bates et al. 2004; Casetta et al. 2001; McGrother et al. 1999; Tseng et al. 2020a). A case-control study (3,008 cases, 3,008 controls) found no evidence for an association between dental amalgams and tremor (Tseng et al. 2020b). A case-control study (262 cases, 338 controls) found no evidence for an association between dental amalgams and amyotrophic lateral sclerosis (ALS) (Parkin Kullmann and Pamphlett 2018). A cross-sectional comparison of retina tomography of adults who had dental amalgams (n=56) and 44 age- and sex-matched referents found decreased retinal choroid ganglion layers and inner plexiform layers in the amalgam group compared to referents (Bilak et al. (2019). Mean BHg levels in this study were 2.76 µg/L in the amalgam group and 2.05 µg/L in the referent group.

Several studies have reported improvement in self-reported signs of psychological disturbances following removal of mercury amalgam restorations; however, because placebo treatments are not possible in these types of studies, the association between the observed outcome changes and exposure to mercury is highly uncertain (Weidenhammer et al. 2010; Zwicker et al. 2014).

Other non-occupational exposures. A clinical study was conducted of families who had resided for up to 2 years in a florescent lamp factory that had been converted to apartments (Fiedler et al. (1999). Average air levels ranged from 5 µg/m^3 (adult breathing zone) to 888 µg/m^3 over visible pools of elemental mercury. The study included motor and cognitive testing of 19 adults and 6 children. The median adult

UHg was 19.4 µg/g creatinine. The study did not find significant differences in tremor between subjects who had UHg ≥19 µg/g creatinine, compared to subjects with UHg <19 µg/g creatinine. Hand-eye coordination errors (Neurobehavioral Evaluation System 2) were significantly higher in the higher UHg group. Results of other tests were not different between the high and low UHg groups (finger tapping, grooved pegboard, trail making, symbol-digit substitution, simple reaction time, continuous performance, verbal learning, and memory). Statistical comparison of test outcomes in children were not reported, and results were characterized as "no clinically significant deficits relative to age-adjusted normative values."

Elemental Mercury—Animal Studies. Two inhalation studies evaluated neurological effects in adult animals following acute-duration exposure to metallic mercury vapor. One study observed reduced grip strength in female mice when assessed 4–7 months after a single 4-hour exposure to 0.5 mg Hg/m^3 (Stankovic 2006). Upon necropsy at 7 months, decreased motor axon diameter was observed. The other acute-duration study observed clinical signs of neurotoxicity (mild tremor, lethargy, and unsteady gait) in maternal rats following exposure to 8 mg Hg/m^3 during GDs 6–15 for 2 hours/day (Morgan et al. 2002). These rats were sacrificed moribund on PND 1 based on excessive body weight loss and clinical signs. Similar effects were not observed at ≤4 mg Hg/m^3.

A limited number of intermediate-duration studies found clinical signs of toxicity, impaired learning, and pathological findings in the central nervous system following adult exposure to metallic mercury vapor. Tremors and impaired conditioned response learning (conditioned avoidance and escape response testing) were observed in rats intermittently exposed to 3 mg Hg/m^3 for 12–42 weeks (Kishi et al. 1978). Decreased cerebellar volume and cerebellar damage (gliosis, perineuronal vacuolization, decreased density of Purkinje cells) were observed in rats exposed to 1 mg Hg/m^3 for 9 hours/day for 45 days (Altunkaynak al. 2019). In another study, exaggerated reflexes, clonus, and tremors were observed in rabbits following intermittent exposure to 4 mg Hg/m^3 for 11–13 weeks (Fukuda 1971). Mild to moderate unspecified pathological brain lesions were observed in rabbits exposed to 0.86 mg Hg/m^3 for 2–12 weeks (7 hours/day, 5 days/week) (Ashe et al. 1953).

The size of the myelin sheath of the dorsal nerve root of the spinal cord was decreased in adult male rats intermittently exposed to 0.48 mg Hg/m^3 for 8 weeks (Schiønning et al. 1998b). Findings were not accompanied by clinical signs of neurotoxicity, obvious microscopic lesions, changes in ganglia volume, changes in number or size of motor neurons, or changes in the ventral nerve root. Therefore, the biological relevance of this finding is unclear, and a NOAEL/LOAEL determination for this study could not be made. In a companion study, male rats similarly exposed to 0.5 mg Hg/m^3 for 8 weeks showed

irritability and aggressiveness during the final 2 weeks of exposure (Sørensen et al. 2000). At necropsy, stereological changes in the cerebellum showed a reduction in the number of Purkinje and granular cells and a reduced volume of the granular cell layer. Based on these findings, the study authors concluded that elemental mercury vapor predominantly affects the central nervous system, rather than the peripheral nervous system.

Inorganic Mercury—Animal Studies. Available studies in adult rodents exposed to mercuric chloride indicate that exposure is potentially associated with altered neurobehavior (hyperactivity, impaired coordination, impaired learning and memory), damage to the dorsal root ganglion and cerebellum, and severe clinical signs of neurotoxicity with repeated, high-dose exposure. Neurological effects have also been reported in adult rodents following oral exposure to mercuric sulfide; doses associated with toxicity are much higher for mercuric sulfide compared to mercuric chloride. Available data following inhalation exposure to mercuric oxide are too limited to draw conclusions.

Sun et al. (2018) reported some evidence of altered pain sensitivity in rats following exposure to mercuric chloride; however, findings do not show a clear dose- or time-related pattern. After exposure for 1 week, responses in thermal and mechanical pain stimulation are comparable to control at doses up to 12.6 mg Hg/kg/day. At 2 weeks, increased sensitivity to thermal and mechanical pain were observed at 3.10 and 6.3 mg Hg/kg/day, but not at 12.6 mg Hg/kg/day (Sun et al. 2018). However, after 3 weeks, no changes in behavioral pain sensitivity were observed at doses up to 6.3 mg Hg/kg/day. Similar inconsistencies were observed in findings for the density of intraepidermal nerve fibers in hind paw skin samples, with decreased density at ≥6.3 mg Hg/kg/day at 1 week but only at 3.10 mg Hg/kg/day, but not higher doses, at 2 and 3 weeks (Sun et al. 2018).

A series of studies evaluated neurobehavior in adult male rats following intermediate-duration exposure to mercuric chloride. Rats exposed to 0.277 mg Hg/kg/day showed reduced total, horizontal, and vertical activity in an open field, impaired motor coordination and balance (rotarod, beam walking, inclined plane tests), and impaired spatial learning and memory in the Morris water maze (Bittencourt et al. 2021; Teixeira et al. 2014, 2018, 2019). No changes in social behavior were observed in the social recognition test (Teixeira et al. 2014). Alterations in behavior, not motor coordination, were associated with apoptosis and loss of neurons and astrocytes in the motor cortex and elevated glutamate uptake in the motor cortex and hippocampus (Teixeira et al. 2018, 2019). Impaired spatial learning in the Morris water maze was also reported in adult male rats at all evaluated doses (≥0.4 mg Hg/kg/day) following exposure for 21 days (Behzadfar et al. 2020).

No additional studies were available that were designed to evaluate neurobehavior in adult animals following exposure to mercuric chloride. However, severe clinical signs of neurotoxicity were observed in rats following acute-duration exposure to doses ≥3.10 mg Hg/kg/day or intermediate-duration exposure to doses ≥0.7 mg Hg/kg/day, including hindlimb spread and/or crossing, severe ataxia and abnormal gait, tremor, decreased activity, and partial paralysis (Chang and Hartmann 1972; Goldman and Blackburn 1979; Sun et al. 2018). No clinical signs of toxicity were observed in rats following acute-duration exposure to doses up to 9.24 mg Hg/kg/day (Chang and Hartmann 1972; Lecavalier et al. 1994). No exposure-related clinical signs were observed in mice following intermediate-duration exposure to doses up to 11 mg Hg/kg/day for 7 weeks (Dieter et al. 1983; Khan et al. 2004).

Ultrastructural changes were noted in the dorsal root ganglia (vacuole formation, focal cytoplasmic lesions) and cerebellum (vacuolation, degeneration of granule cells) of male rats following acute- or intermediate-duration exposure to mercuric chloride at doses of 0.7 mg Hg/kg/day (Chang and Hartmann 1972). No changes were observed in anterior horn motoneurons. Decreased cervical, thoracic, and lumbar motor neurons along with axonal damage in the spinal cord were observed in male rats exposed to mercuric chloride at doses of 0.277 mg Hg/kg/day for 45 days via gavage (Corrêa et al. 2020). No exposure-related changes in brain histology were observed in rats exposed to mercuric chloride at acute-duration doses up to 9.24 mg Hg/kg/day (Lecavalier et al. 1994) or intermediate- or chronic-duration doses up to 4 mg Hg/kg/day (Dieter et al. 1992; NTP 1993). No exposure-related changes in brain histology were observed in mice at intermediate-duration doses up to 15 mg Hg/kg/day (Dieter et al. 1983; Khan et al. 2004; NTP 1993) or chronic-duration doses up to 7.4 mg Hg/kg/day (NTP 1993).

A series of studies evaluated neurological function in adult laboratory animals following gavage exposure to mercuric sulfide. In rats, peripheral nerve conduction was altered following a 5- or 14-day exposure to 860 mg Hg/kg/day, specifically suppression and/or incomplete recovery of compound muscle action potentials (CMAPs) after induced tetany (Chuu et al. 2007). No changes in motor equilibrium or nociceptive testing were observed in exposed rats. In mice, increased thresholds for auditory brainstem responses were observed 5 weeks after a 7-day exposure to 860 mg Hg/kg/day, indicative of hearing loss (Chuu et al. 2001a). Thresholds returned to normal by 11 weeks post-exposure. No changes in thresholds were observed at 86 mg Hg/kg/day. In guinea pigs, an abnormal vestibular ocular reflex (VOR) and impaired equilibrium (measured using rotarod test) were observed after acute- or intermediate-duration exposure to mercuric sulfide at ≥86 mg Hg/kg/day (Chuu et al. 2001b). In the acute-duration study, outcomes were persistent 2 weeks after exposure at 860 mg Hg/kg/day and were

accompanied by Purkinje cell loss in the cerebellum (recovery and histopathology were not evaluated in the intermediate-duration study).

The effects of inhaled mercuric oxide on the cerebellum of female rats were evaluated in a single study. Following exposure to 1 mg Hg/m^3 for 45 days (9 hours/day), treated rats showed cerebellar gliosis and perineuronal and perivascular vacuolization, reduced cerebellar volume, and decreased number and density of Purkinje cells (Altunkaynak et al. 2019). Purkinje cells from treated animals showed irregular cellular boundaries, eosinophilic cytoplasm, and heterochromatic nuclei.

Organic Mercury—Epidemiological Studies. Outbreaks of severe neurological effects have occurred in association with ingestion of methylmercury in seafood (Minamata disease) and from ingestion of wheat contaminated with a methylmercury fungicide (Iraq outbreak). Studies of associations between exposure to methylmercury and neurological function in adults have also been conducted in populations that consume large amounts of fish or marine mammals (Table 2-52); these populations include communities from the Amazonian River basin, the St. Lawrence River, coastal Japan (whaling communities), and other fish consuming populations. Collectively, these studies provide evidence for associations between exposure to methylmercury and decreasing performance on tests of fine motor coordination and speed, muscle strength, tactile sensation, color vision and visual contrast sensitivity, and memory and learning.

Table 2-52. Results of Epidemiological Studies Evaluating Exposure to Methylmercury or Ethylmercury and Neurological Effects in Adults

Reference, study type, and population	Biomarker	Outcome evaluated[a]	Result
Amazonian River basin studies			
Feitosa-Santana et al. 2018 Cross-sectional cohort (n=36, age range 18–64 years) and 37 referents; Brazil	HHg median Exposed: 18.6 µg/g Referents: NA	Color vision	
		Lanthony desaturated error score	↑ HHg (exposed versus referents)
		Farnsworth-Munsell error score	↑ HHg (exposed versus referents)
Hoshino et al. 2015 Cross-sectional cohort (n=58, age range 1–47 years); Brazil	HHg median 10.91 µg/g	Tympanometry	↔ HHg
		Acoustic reflexes	↔ HHg
		Pure tone audiometry	↔ HHg
		Transient otoacoustic emissions	↔ HHg

Table 2-52. Results of Epidemiological Studies Evaluating Exposure to Methylmercury or Ethylmercury and Neurological Effects in Adults

Reference, study type, and population	Biomarker	Outcome evaluated[a]	Result
Khoury et al. 2015 Cross-sectional cohort (n=108; age range 13–53 years) and 49 referents; Brazil	HHg mean Exposed: 8.8 µg/g Referent: 0.73 µg/g	Tactile sensation threshold	↑ HHg ↑ (exposed versus referents)
		Vibration sensation duration	↔ HHg ↓ (exposed versus referents)
		2-point tactile discrimination threshold	↔ HHg ↑ (exposed versus referents)
Mergler 2002 (Dolbec et al. 2000, 2001; Lebel et al. 1996, 1998) Cross-sectional cohort (n=233, age >15 years); Brazil	HHg median: 11 µg/g	Fine motor coordination	↓ HHg
		Muscle strength	↓ HHg
		Vision (visual contrast, color vision)	↓ HHg
Oliveira et al. 2021 Cross-sectional cohort (n=110, mean age 28 years); Brazil	HHg median: 7.4 µg/g	Cognitive deficits (BCSB)	↑ (HHg >10 µg/g)
		Verbal fluency deficits	↑ (HHg >10 µg/g)
Yokoo et al. 2003 Cross-sectional cohort (n=129, age rage 17–81 years); Brazil	HHg median 3.7 µg/g	Fine motor speed	↓ HHg
		Memory	↓ HHg
		Learning	↓ HHg
St. Lawrence River studies			
McKeown-Eyssen et al. 1983 Case-control study of 41 cases and 179 controls (age range: adults), Canada	HMeHg mean: Mistassini cases: males: 15.9 µg/g females: 16.7 µg/g Great Whale cases: males: 10.5 µg/g females: 10.1 µg/g	Bilateral coordination, visual field, nystagmus, tremor, sensory loss, or tactile discrimination	↓ HMeHg, males ↓ HMeHg, females
Mergler 2002 Cross-sectional cohort of 63 fish consumers and 63 non-fish-consumers (age range 20–69 years); Canada	BMeHg median Fish consumers: 37.3 µg/L Non-consumers: 29.0 µg/L	Auditory or visual memory	↓ (fish consumers versus non-consumers)
		Cognitive flexibility	↓ (fish consumers versus non-consumers)
		Fine motor coordination	↓ (fish consumers versus non-consumers)
		Reaction time	↓ (fish consumers versus non-consumers)
		Vision (visual color vision)	↔ (fish consumers versus non-consumers)

Table 2-52. Results of Epidemiological Studies Evaluating Exposure to Methylmercury or Ethylmercury and Neurological Effects in Adults

Reference, study type, and population	Biomarker	Outcome evaluated[a]	Result
Coastal Japan whaling communities			
Nakamura et al. 2014 Cross-sectional cohort (n=194, age range: 20–85 years); Japan	HHg geometric mean 14.9 µg/g	Sensorineural hearing loss	↑ HHg (>50 µg/g versus <50 µg/g)
		Gait disturbance	↑ HHg (>50 µg/g versus <50 µg/g)
		Muscular weakness	↔ HHg
		Tremor	↔ HHg
		Rigidity	↔ HHg
		Coordinated movements	↔ HHg
		Tactile, pain, vibration sensation	↔ HHg
Studies of other populations			
Carta et al. 2003 Cross-sectional cohort (n=22, median age 52 years) and 22 referents; Italy	Organic BHg median Exposed (n=10): 41.5 µg/L Referent (n=6): 2.6 µg/L	Digit-symbol reaction time	↑ BHg ↑ (exposed versus referents)
		Motor coordination	↓ BHg ↔ (exposed versus referents)
		Color word reaction time	↑ BHg ↑ (exposed versus referents)
		Finger tapping speed	↔ BHg ↓ (exposed versus referents)
		Digit span	↔ BHg ↔ (exposed versus referents)
		Tremor	↔ BHg ↔ (exposed versus referents)
Hoffman et al. 2021 Case-control study (age range: 50–65 years),165 cases, 330 controls; United States	Mercury consumption from fish mean: Cases: 355 mg/year Controls: 339 mg/year	ALS	↔ (Hg consumption from fish)

Table 2-52. Results of Epidemiological Studies Evaluating Exposure to Methylmercury or Ethylmercury and Neurological Effects in Adults

Reference, study type, and population	Biomarker	Outcome evaluated[a]	Result
Studies of other fish-eating populations or populations for which organic mercury was measured			
Geier et al. 2019 Cross-sectional study of data from NHANES 2011–2012 (n=NA; age range 60–80 years); Unites States	BEtHg mean Cohort: 0.3 µg/L	Digit symbol	↔ (BHg)
			↔ (BEtHg, BMeHg)
		Word fluency test	↓ (BEtHg)
		Word list learning	↓ (BEtHg)
Philibert et al. 2022 Cross-sectional cohort (n=391, median age 54 years); Canada	BHg median Cord: 5 µg/L HHg median Age 10 years: 1.1 µg/g	Symptoms of neurological deficits:	
		Cranial nerve	↑ (HHg, age 10 years)
		Gross motor	↑ (HHg, age 10 years)
		Cognitive	↑ (HHg, age 10 years)
Rossa-Roccor and Karim 2021 Cross-sectional study of data from NHANES 2011–2016 (n=3,930; age >18 years); United States	BMeHg median: 0.36 µg/L	Depression	↔ (BMeHg)

[a]Interpretation of neurobehavioral tests:
Word fluency: higher score = higher performance
BCSB: higher score = lower performance
Color word reaction time: longer reaction time = lower performance
Digit span: higher score = higher performance
Digit-symbol reaction time: longer reaction time = lower performance
Finger tapping speed: higher speed = higher performance
2-Point tactile discrimination threshold: higher threshold = lower performance
Tactile sensation threshold: higher threshold = lower performance
Vibration sensation duration: lower duration = lower performance
Word list learning: higher score = higher performance

↑ = positive association; ↓ = inverse association; ↔ = no association; ALS = amyotrophic lateral sclerosis; BCSB = Brief Cognitive Screening Battery; BHg = blood mercury; BEtHg = blood ethylmercury; BMeHg = blood methylmercury; HHg = hair mercury; HMeHg = hair methylmercury; NA = not available; NHANES = National Health and Nutrition Examination Survey

Poisoning case studies. A lethal dose of dimethylmercury occurred to a 48-year-old female laboratory chemist following accidental contact of the dorsal surface of a latex gloved hand to "a few drops" of liquid dimethylmercury (Nierenberg et al. 1998; Siegler et al. 1999). Approximately 5 months after the exposure, the patient developed severe neurological symptoms that included deterioration of balance, gait and speech, paresthesia, and disturbances of vision and hearing; the patient died 298 days following the exposure (Nierenberg et al. 1998). Autopsy revealed thinning of the cerebral cortex and atrophy of the cerebellum (Siegler et al. 1999). The applied dose was reconstructed based on measurements of BHg made approximately 5 months following the accident and the estimated half-time of 75 days for HHg in

the subject (Nierenberg et al. 1998). The applied dose was estimated to have been approximately 1,344 mg mercury contained in approximately 0.48 mL of liquid dimethylmercury (density 3.2 g dimethylmercury/mL) (Nierenberg et al. 1998).

Minamata, Japan. Discharges of wastewater from an acetaldehyde production facility into the Shiranui Sea located in the Kumamato Prefecture of Japan resulted in exposure to methylmercury ingested in locally contaminated fish and shellfish (Harada 1995). An outbreak of what became known as Minamata disease occurred in the area. Patients diagnosed with Minamata disease showed a common set of signs which included: severe neuromotor (e.g., tremor, dysarthria, rigidity, ataxia), sensory disturbances (visual and auditory; paresthesia) and, in lethal cases, pathological changes in the cerebral cortex, cerebellar cortex, and dorsal root ganglia of the spinal cord (Ekino et al. 2007; Eto et al. 2002; Harada 1995).

Measurements of mercury in blood and hair were not made until several years following the period of most intense exposure and, therefore, do not provide reliable estimates of exposures that may have contributed to Minamata disease. HHg levels in Minamata disease patients measured 4–5 years following onset of Minamata disease ranged from 2 to 700 µg Hg/g (Harada 1995). In a study of fishermen of the Shiranui Sea coastline (n=191) conducted approximately 40 years following onset of Minamata disease, mean total HHg ranged from 1.9 to 3.7 µg Hg/g; the percent methylmercury ranged from 70 to 94% (Harada et al. 1998).

Follow-ups of Minamata disease patients conducted 40–60 years following onset of disease found evidence for persistence of neurological symptoms (Futatsuka et al. 2005; Nakamura et al. 2023; Uchino et al. 2005). Evidence for higher prevalence of neurological disorders in residents of the Minamata area has also been observed in follow-up studies (Yorifuji et al. 2008, 2009, 2011, 2016, 2023). Symptoms observed included paresthesia, ataxia, dysarthria, tremor, and abnormal reflexes (Yorifuji et al. 2008). Odds ratios for these symptoms were elevated in a study conducted 15–20 years following onset of Minamata disease (Yorifuji et al. 2016). Another 15–20-year follow-up study of residents of the Shiranui Sea coast (Minamata and Goshonoura) observed an association between increasing HHg and increasing ORs for perioral sensory loss (Yorifuji et al. 2009). HHg levels in the study group (n=120) ranged from 0 to 10 µg Hg/g (36% of subjects) to >50 µg Hg/g in 10% of subjects. Prevalence ORs were also elevated in Minamata residents (relative to a reference population) for impairment of intelligence and mood and behavior dysfunction (Yorifuji et al. 2011).

Cognitive deficits persisted in 25 Minamata residents who were exposed to methylmercury when evaluated in 2020 (Yorifuji et al. 2023). A study of brain morphology in 30 Minamata Disease patients conducted in 2021 found evidence for decreased gray matter volume of the calcarine, the cerebellum, and the thalamus and decreased white matter volume of the cerebrum and cerebellum, relative to an age- and sex-matched control group (Hirai et al. 2023).

Niigata, Japan. Discharges of wastewater from an acetaldehyde production facility into the mouth of the Agano River located in the Niigata Prefecture of Japan resulted in exposure to methylmercury from ingestion of locally contaminated fish and shellfish (Saito et al. 2020). Following discovery of Minamata Disease among local residents, 690 adults were subsequently diagnosed with methylmercury poisoning. HHg levels in some cases exceeded 50 μg/g (Saito et al. 2020). A follow-up of children of 50 cases (at age 40 years) found self-reported symptoms that included muscle cramps, irritability, headache, dizziness, impaired motor abilities, numbness, disturbed hearing or vision, delayed speech, and delayed walking (Saito et al. 2020). Medical examinations of 17 of these cases confirmed neurological deficits in cases in which maternal HHg at the time of exposure were >50 μg/g and, in some cases, in which maternal HHg ranged from 10 to 24 μg/g (Saito et al. 2020).

Iraq. An outbreak of methylmercury poisoning occurred in Iraq in as a result of widespread consumption of wheat that had been treated with a methylmercuric fungicide (Al-Mufti et al. 1976; Bakir et al. 1973; Clarkson et al. 1976). Approximately 6,500 cases of mercury poisoning occurred, with approximately 459 related deaths (Clarkson et al. 1976). BHg levels in poisoning cases measured approximately 65 days after exposure ranged from 10 to 3,000 μg Hg/L (Clarkson et al. 1976). Cases of poisonings occurred across all age ranges. Neurological symptoms included paresthesia, ataxia, visual disturbances, dysarthria, and hearing defects (Bakir et al. 1973). Prevalence of multiple symptoms increased with increasing BHg levels (Bakir et al. 1973). Based on measurements of methylmercury in flour used to bake contaminated bread and estimates of bread consumption, methylmercury intake was estimated to have ranged from 80 to 1,000 mg over a 3-month period (Al-Mufti et al. 1976).

Amazonian riverine populations. Studies of methylmercury exposure and neurological outcomes have been conducted in populations residing in Amazon River basins (Dolbec et al. 2000, 2001; Feitosa-Santana et al. 2018; Hoshino et al. 2015; Khoury et al. 2015; Lebel et al. 1996, 1998; Mergler 2002; Oliveira et al. 2021; Yokoo et al. 2003). Exposure to methylmercury in these populations derives primarily from methylation of inorganic mercury released to local aquatic ecosystems from alluvial gold mining (Mergler 2002). These studies have found associations between increasing HHg and decreasing

performance on tests of fine motor coordination and speed, muscle strength, tactile sensation, color vision and visual contrast sensitivity, and memory and learning (Feitosa-Santana et al. 2018; Khoury et al. 2015; Mergler 2002; Oliveira et al. 2021; Yokoo et al. 2003). Median HHg in these studies ranged from 4 to 19 µg Hg/g. One of the largest studies evaluated residents of the Tapjós River basin in Brazil (n=233) and found associations between increasing HHg (median 11 µg Hg/g; range <2–150) and decreasing performance on tests of fine motor coordination, muscle strength, color vision, and visual contrast sensitivity (Mergler 2002).

Other high fish or marine mammal consumers. A case-control study of fish and fish-eating mammal consumers (n=41 cases, 179 controls) who resided in Northern Quebec found increased ORs for neurologic symptoms (any of the following: impaired bilateral coordination, visual field, nystagmus, tremor, sensory loss, or tactile discrimination) in association with increasing hair methylmercury levels (McKeown-Eyssen et al. 1983). Adjusted ORs for a 20 µg/g increase in hair methylmercury level were 5.1 (95% CI 1.3, 20.8) in males and 2.9 (95% CI 1.1, 7.3 in females). Mean hair methylmercury levels measured at the time of evaluation were 15.9 and 10.5 µg/g in male cases (from subjects who resided in either of two locations) and 16.7 and 10.1 µg/g in female cases. A study of fish consumers (n=63) who resided in the St. Lawrence River basin found poorer performance on tests of auditory or visual memory, cognitive flexibility, and fine motor coordination among fish consumers compared to people who did not consume fish (Mergler 2002; Mergler et al. 1998). The median blood methylmercury levels were 37 µg Hg/L for fish consumers and 27 µg Hg/L for nonconsumers. A study of a whaling community in Japan (n=194) found associations between increasing HHg (median 19 µg Hg/g, range 1–102 µg Hg/g) and hearing loss and gait disturbances (Nakamura et al. 2014). A study of fish consumers who resided in St Peter Island, Sardinia, Italy (n=22 and 22 referents) found associations between increasing blood organic mercury levels (median 41 µg Hg/L, range 13–85 µg Hg/L) and digit-symbol reaction time and motor coordination (Carta et al. 2003). A study of residents of the Grassy Narrows watershed in western Ontario, Canada (n=391, age >18 years) found symptoms of neurological deficits in association with increasing HHg (median 1.1 µg/g measured at age 10 years) (Philibert et al. 2022).

Several studies have evaluated associations between fish consumption or organic mercury biomarkers in cross-sectional cohorts of adults in the United States. Geier et al. (2019) analyzed data from the 2011–2012 NHANES (U.S. population; age range 60–80 years) and found that increasing blood ethylmercury levels were associated with decreased performance on word learning and word fluency tests. An evaluation of data from the 2011–2016 NHANES (age >18 years) found no evidence for an association between blood methylmercury levels (n=3,930; median 0.36 µg/L) and risk of depression (OR 1.356,

95% CL: 0.85, 1.58) (Rossa-Roccor and Karim 2021). A case-control study of ALS (165 cases, 330 controls) found no evidence for an association between mercury consumption from fish (399 mg Hg/year) and ALS diagnosis (Hoffman et al. 2021).

Organic Mercury—Animal Studies. Methylmercury is neurotoxic to several species of experimental animals following acute-, intermediate-, and chronic-duration oral exposure. The major neurobehavioral effects that are seen across studies include sensorimotor dysfunction, vision and hearing deficits, and impaired learning and memory, with overt signs of neurotoxicity at higher doses. Methylmercury exposure is associated with degenerative brain changes (particularly in the cerebellum), spinal cord degenerations (particularly the sensory regions), and peripheral nerve degeneration. Effects observed in adult rodents following methylmercury exposure are consistent with findings observed in developing animals; however, effects generally occur at exposure levels higher than those associated with neurodevelopmental effects in animals.

Neurological effects have also been observed in adult macaque monkeys following exposure to methylmercury compounds (Table 2-53). Overt clinical signs of neurotoxicity (clumsiness, impaired fine motor coordination, insensitivity to touch), impaired high-frequency hearing function, and increased reactive gliosis in the brain were observed following intermediate- or chronic-duration exposure to 0.05 Hg/kg/day (Charleston et al. 1994, 1995, 1996; Rice 1989c; Rice and Gilbert 1992). No changes in visual function or operant training were observed at 0.05 mg Hg/kg/day (Rice 1998b; Rice and Hayward 1999). Chronic-duration exposure to 0.08 mg Hg/kg/day resulted in slight tremors and decreased sucking responses, followed by claw-like grasp, gross motor incoordination, and apparent blindness in monkeys (Burbacher and Mottet 1988; Burbacher et al. 1984, 2005). Overt signs of neurotoxicity were not observed in adult monkeys at doses ≤0.04 mg Hg/kg/day (Burbacher and Mottet 1988; Petruccioli and Turillazzi 1991); no other neurological endpoints were evaluated at doses <0.05 mg Hg/kg/day. In adult marmoset monkeys, exposure to 0.5 mg Hg/kg/day for 242 days resulted in clinical signs of neurotoxicity (restlessness, irritability, mild ataxia of the hindlimbs) and cortical findings consistent with anoxic-ischemic encephalopathy observed in Minamata disease, including white matter edema and compression near the calcarine fissure and astrogliosis and microcytic changes in the cortex (Eto et al. 2001).

Table 2-53. Neurological Effects[a] in Primates Following Oral Exposure to Methylmercury Compounds

Species (sex); exposure duration	Overt clinical signs	Learning/ memory	Auditory function	Visual function	Neuro-pathology	Reference (compound)
M. fascicularis (F); 150 days	↔ N: 0.04 (NR)[b]	–	–	–	–	Petruccioli and Turillazzi 1991 (MMC)
Marmoset (M); up to 242 days	+ L:0.5 (~10)	–	–	–	+ L:0.5 (~10)	Eto et al. 2001 (MM)
M. fascicularis (F); up to 395 days	+ L: 0.08 (1.56–2.209)	–	–	–	–	Burbacher and Mottet 1988; Burbacher et al. 1984, 2005 (MMH)
M. fascicularis (F); up to 548 days	0 N: 0.05 (1.1–2)	–	–	–	+ L: 0.05 (1.1–2)	Charleston et al. 1994, 1995, 1996; Vahter et al. 1994 (MMH)
M. fascicularis (M, F): up to 2,555 days (from birth)[c]	+ L: 0.05 (0.6–0.9)	↔	↓ L: 0.05 (0.6–0.9)	↔	–	Rice 1998b, 1989c; Rice and Gilbert 1992; Rice and Hayward 1999 (MMC)

[a]Studies with exposure in post-pubertal animals, including macaque monkey studies that include exposures, beginning during early neonatal periods and continuing through puberty (which occurs at ~5 years).
[b]NOAEL (N) or LOAEL (L) for dose administered in mg Hg/kg/day (blood level in mg Hg/L).
[c]Findings in studies with exposure extending from birth through adulthood may be due to developmental exposure, post-pubertal exposure, or both.

↓ = decreased; ↔ = no change; – = not assessed; + = present; F = female; LOAEL = lowest-observed-adverse-effect level; M = male; MM = methylmercury; MMC = methylmercuric chloride; MMH = methylmercury hydroxide; NOAEL = no-observed-adverse-effect level; NR = not reported

Numerous acute- and intermediate-duration studies have reported neurobehavioral and/or neuro-physiological changes in adult rodents following oral exposure to methylmercury, often at or below doses associated with frank neurotoxic signs. Effects observed have including altered motor function, impaired memory, decreased nociception, impaired reflexes, altered sleep patterns, and changes in peripheral and central nervous system electrophysiology (Table 2-54).

Table 2-54. Neurobehavioral and Neurophysiological Effects in Rodents Following Adult Oral Exposure to Methylmercury Compounds

Species; duration	Motor activity, coordination, strength[a]	Learning and memory[a]	Neuro-physiology[a]	Other[a]	Reference (compound)
Acute					
Rat; 1 day	↓ (L: 20)	↓ (L: 20)	–	–	Post et al. 1973 (MMC)
Rat; 2 days	–	–	–	↑ Altered sleep patterns (L: 4)	Arito and Takahashi 1991 (MMC)
Rat; 2 days	↓ (L: 10)	–	↓ PNS (L: 20)	–	Fehling et al. 1975 (MMC)
Rat; 5 or 14 days	↓ (L: 1.9)	–	↓ PNS (L: 1.9)	0 Nociception: ↔ (N: 1.9)	Chuu et al. 2007 (MM)
Mouse; 5 days	↓ (L: 0.9)	–	–	–	Bellum et al. 2013 (MMC)
Mouse; 7 days	–	–	↓ Auditory: (L: 0.2)	–	Chuu et al. 2001a (MM)
Mouse; 7 or 14 days	0 (N: 5.6)	–	–	–	Moreira et al. 2012 (MM)
Mouse; 7 or 14 days	0 (N: 4.6)	–	–	–	Kirkpatrick et al. 2015 (MM)
Mouse; 7 or 14 days	↓ (L: 8.7)	–	–	–	Dietrich et al. 2005 (MMC)
Mouse; 14 days	↓ (L: 3.2)	–	↔ Auditory (N: 3.2)	–	Ishihara et al. 2019 (MMC)
Intermediate					
Rat; 26 days	↓ (L: 1.6)	–	–	–	Tamashiro et al. 1986 (MMC)
Rat; 35 days	↓ (L: 0.5)	–	↓ Auditory, visual, SMS, hippocampal (L: 0.5)	↓ Reflexes (L: 0.5) 0 Pre-pulse inhibition (N: 2.0)	Vezér et al. 2005 (MMC)
Rat; 45 days	↑ (L:0.4)			↑ Anxiety (L:0.4)	Rosa-Silva et al. 2020a, 2020b (MMC)
Rat; 60 days	0 (N: 0.04)	↓ (L: 0.04)	–	↔ Anxiety, sociability: (N: 0.04)	Bittencourt et al. 2019 (MMC)

Table 2-54. Neurobehavioral and Neurophysiological Effects in Rodents Following Adult Oral Exposure to Methylmercury Compounds

Species; duration	Motor activity, coordination, strength[a]	Learning and memory[a]	Neuro-physiology[a]	Other[a]	Reference (compound)
Rat; 60 days	–	↓ (L: 0.04)	–	–	Bittencourt et al. 2019 (MMC)
Rat; 60 days	↓ (L: 0.04)	–	–	–	Bittencourt et al. 2022 (MMC)
Rat; 60 days	↓ (L: 0.03)	–	–	–	Freire et al. 2010
Rat; 60 days	↓ (L: 0.037)	–	–	↔ Anxiety (N: 0.037)	Santana et al. 2019 (MM)
Rat; 91 days	–	↓ (L: 0.09)	–	–	Wu et al. 2023
Mouse; 21 days	↓ (L: 4.7)	–	–	–	Dietrich et al. 2005 (MMC)
Mouse; 21 days	↔ (N: 4.6)	–	–	–	Kirkpatrick et al. 2015 (MM)
Mouse; 21 days	↓ (L: 5.6)	–	–	–	Moreira et al. 2012 (MM)
Mouse; 28 days	↓ (L: 4.6)	–	–	–	Kirkpatrick et al. 2015 (MM)
Mouse; 28 days	↔ (N: 3.2)	–	↓ Auditory (L: 3.2)	–	Ishihara et al. 2019 (MMC)
Mouse; 30 days	↓ (L:0.21)	↓ (L:0.21)	–	↑ Stereotypy (L:0.21)	Nascimento et al. 2022 (MMC)
Mouse; 35–56 days	↓ (L: 3.2)	–	–	–	Ishihara et al. 2019 (MMC)
Mouse; 60 days	–	↓ (L: 0.0073)	–	↔ Anxiety (N: 0.0073)	Bourdineaud et al. 2011 (MM)
Mouse; 60 days	↓ (L: 0.25)	–	–	–	Berthoud et al. 1976 (MMC)
Mouse; 196 days	↓ (L: 0.89)	–	–	–	MacDonald and Harbison 1977 (MMC)

[a]NOAEL (N) or LOAEL (L) dose in mg Hg/kg/day for endpoint category.

↑ = increased; ↓ = decreased; ↔ = no change; – = not assessed; LOAEL = lowest-observed-adverse-effect level; MM = methylmercury; MMC = methylmercuric chloride; NOAEL = no-observed-adverse-effect level; PNS = peripheral nervous system; SMS = somatosensory

Dose- and duration-dependent clinical signs of neurotoxicity have also been observed in adult rats following oral exposure to methylmercury compounds. Transient effects (lethargy, ataxia) were observed following a single exposure to 20 mg Hg/kg (Post et al. 1973). With repeated acute-duration exposure, mild effects (weakness, hindlimb crossing) were observed at ≥4 mg Hg/kg/day progressing to severe and persistent effects (spasms, ataxia, gait disturbances) at ≥6 mg Hg/kg/day for 8–10 days (Fuyuta et al. 1978; Miyakawa et al. 1974; Su et al. 1998; Usuki et al. 1998). In intermediate-duration studies, severe clinical signs of neurotoxicity were observed in rats following exposure to ≥1.6 mg Hg/kg/day for 2–4 weeks or ≥0.8 mg Hg/kg/day for 5–6 weeks, including ataxia, tremor, unsteady/uncoordinated gait, partial paralysis, and hindlimb crossing (Chang and Hartmann 1972; Gandhi et al. 2013; Larsen and Brændgaard 1995; Schiønning et al. 1998a; Sitarek and Gralewicz 2009; Tamashiro et al. 1986; Tonk et al. 2010). No clinical signs of toxicity were observed in rats following chronic-duration exposure to doses up to 0.18 mg Hg/kg/day (Verschuuren et al. 1976).

Overt signs of neurotoxicity (e.g., ataxia, muscular incoordination, intention tremors, partial paralysis) were observed in mice exposed to intermediate-duration doses ≥0.89 mg Hg/kg/day (MacDonald and Harbison 1977; Mitsumori et al. 1981) and in male, but not female, mice chronically exposed to 0.686 mg Hg/kg/day (Mitsumori et al. 1990). However, another study did not report clinical signs of neurotoxicity in mice following intermediate- or chronic-duration exposure to doses up to 0.724 mg Hg/kg/day (Hirano et al. 1986). Severe clinical signs of neurotoxicity (e.g., ataxia, impaired gait, tremors, convulsions) were observed in cats following intermediate-duration exposure to ≥0.012 mg Hg/kg/day (Chang et al. 1974; Charbonneau et al. 1976; Khera et al. 1974) or chronic-duration exposure to ≥0.074 mg Hg/kg/day (Charbonneau et al. 1976). In rabbits, ataxia and intermittent convulsions were observed following intermediate-duration exposure to ≥0.49 mg Hg/kg/day (Koller et al. 1977).

Following acute-duration exposure to methylmercury compounds, the most sensitive effects were observed in mice, including impaired hearing at ≥0.2 mg Hg/kg/day (Chuu et al. 2001a) and decreased motor activity and impaired motor coordination at 0.9 mg Hg/kg/day (Bellum et al. 2013). Additional details on neurobehavioral testing and dose-response information for sensitive effects observed in mice following acute-duration oral exposure can be found in Table 2-55. For hearing impairment findings in mice of an unspecified strain following acute-duration exposure, degree and persistence of hearing impairment were dose-dependent when measured immediately following a 7-day exposure and 5 and 11 weeks post-exposure (Chuu et al. 2001a). However, no hearing impairment was observed in ICR mice following exposure to 3.2 mg Hg/kg/day for 2 weeks (Ishihara et al. 2019). Available data indicate that age and strain may influence exposure-related changes in motor activity and coordination. In C57BL/6

mice, no exposure-related changes in motor activity were observed following exposure to 5.6 mg Hg/kg/day for 7 or 14 days starting at 3 months of age (Moreira et al. 2012); however, when exposure started at 16–20 months of age (aged mice), five daily doses of 0.9 mg Hg/kg/day resulted in decreased motor activity, altered gait, and impaired coordination/balance on the vertical pole test (Bellum et al. 2013). In 2-month-old Swiss mice, dose- and duration-dependent decreases in motor activity and coordination were observed following exposure to 4.7 or 8.7 mg Hg/kg/day for 7 or 14 days (Dietrich et al. 2005).

Table 2-55. Dose-Response Data for Sensitive Neurobehavioral Effects in Mice following Acute-Duration Oral Exposure to Methylmercury

Reference, study duration	Assay/ outcome measured	Dose (mg Hg/kg/day)	Result (% change compared to control)
Auditory function			
Chuu et al. 2001a 7 days	Hearing threshold	0.2	End of exposure: ↔ 5 weeks post-exposure: ↑ (180)[a] 11 weeks post-exposure: ↔
		1.9	End of exposure: ↑ (200)[a] 5 weeks post-exposure: ↑ (520)[a] 11 weeks post-exposure: ↑ (300)[a]
		9.3	End of exposure: ↑ (710)[a] Post-exposure: ND[b]
	ABR absolute latency	0.2	End of exposure: Wave V: ↑ (10)[c] 5 weeks post-exposure: Wave V: ↑ (9)[c] 11 week post-exposure: ↔
		1.9	End of exposure: Wave V: ↑ (23)[c] 5 weeks post-exposure: Wave IV: ↑ (14)[c] Wave V: ↑ (15)[c] 11 weeks post-exposure: Wave IV: ↑ (11)[c] Wave V: ↑ (16)[c]
	ABR interwave latency (Waves I–V)	0.2	End of exposure: ↑ (19)[c] 5 weeks post-exposure: ↔ 11 weeks post-exposure: ↔
		1.9	End of exposure: ↑ (41)[c] 5 weeks post-exposure: ↑ (18)[c] 11 weeks post-exposure: ↑ (21)[c]

Table 2-55. Dose-Response Data for Sensitive Neurobehavioral Effects in Mice following Acute-Duration Oral Exposure to Methylmercury

Reference, study duration	Assay/ outcome measured	Dose (mg Hg/kg/day)	Result (% change compared to control)
Ishihara et al. 2019 2 weeks	Hearing threshold	3.2	End of exposure: ↔
	ABR amplitude	3.2	End of exposure: ↔
	ABR interwave latency (Waves I–V)	3.2	End of exposure: ↔
Motor activity and coordination			
Bellum et al. 2013 5 days; exposure began at 16–20 months; all tests were conducted 6 days post-exposure	Motor activity in open field (30 minutes)	0.9	First 5 minutes: ↓ (25)[a] Total 30 minutes: ↔
	Gait analysis	0.9	Angle of foot placement: ↓ (50)[a] Stride length: ↔ Base length: ↔
	Vertical pole test	0.9	% animals that didn't fall at 90°: ↓ (45)[c] % animals falling between 45 and 90°: ↑ (39)[c]
	Rotarod	0.9	↔
Kirkpatrick et al. 2015, 7 or 14 days	Rotarod	4.6	Latency to fall: ↔
Dietrich et al. 2005, 7 or 14 days; exposure began at 2 months	Motor activity in open field (20 minutes)	4.7	7 days: ↔ 14 days: ↓ (30)[a]
		8.7	7 days: ↓ (25)[a] 14 days: ↓ (45)[a]
	Beam walking (10 mm circle beam)	4.7	7 days: ↔ 14 days: ↑ (150)[a]
		8.7	Latency to cross beam: 7 days: ↔ 14 days: ↑ (500)[a]
Moreira et al. 2012, 7 or 14 days; exposure began at 3 months	Motor activity in open field (5 minutes)	5.6	↔

[a]Estimated from graphically presented data.
[b]All animals died prior to 5-week examination.
[c]Calculated from quantitative data.

↑ = increased; ↓ = decreased; ↔ = no change; ABR = auditory brainstem response; ND = no data

In intermediate-duration studies, mice were again more sensitive than rats, with impaired memory in the Y-maze observed at ≥0.0073 mg Hg/kg/day as the most sensitive effect following intermediate-duration exposure (Bourdineaud et al. 2011). In the Y-maze, the rate of spontaneous alteration was significantly decreased by 14% following exposure to 0.0073 mg Hg/kg/day for 2 months, compared to controls, suggesting that the animals had difficulty remembering which arm was entered last. No adverse effects in the Y-maze were observed in male mice following a shorter 30-day exposure to 0.21 mg Hg/kg/day; however, exposed mice showed impaired spatial learning and memory in the Barnes maze, compared to control (Nascimento et al. 2022). Memory impairments have also been reported in rats. Impaired spatial memory in the Morris water maze and impaired social memory in the social recognition task were observed following exposure to 0.04 mg Hg/kg/day for 60 days (Bittencourt et al. 2019). Open field and rotarod tests also indicated decreased motor activity, balance, and coordination in male rats exposed to 0.04 mg Hg/kg/day for 60 days (Bittencourt et al. 2022). Similarly, impaired spatial memory in the Morris water maze was reported in rats exposed to 0.09 mg Hg/kg/day for 3 months (Wu et al. 2023). Other effects reported in rodents at higher doses included decreased motor activity and exploration, impaired motor coordination and/or strength, impaired reflexes, impaired hearing and vision, and increased anxiety and stereotypical/repetitive behaviors (Table 2-54).

Data on neurobehavior following chronic-duration exposure is limited to a single study in cats, rats, and mice. The most sensitive finding was decreased nociception in cats exposed to dietary levels of 0.046 mg Hg/kg/day for 2 years; additional effects observed at 0.074 mg Hg/kg/day included muscle weakness, impaired balance and coordination (during beam walking), and impaired reflexes (righting, hopping, placing, optical, patellar) (Charbonneau et al. 1976). No adverse neurobehavioral effects were observed in cats at chronic-duration doses up to 0.02 mg Hg/kg/day. In the rat study, no changes in motor activity were observed following exposure to dietary doses up to 0.18 mg Hg/kg/day for 2 years (Verschuuren et al. 1976). In the mouse study, lifetime exposure to methylmercury (including gestation and lactation via dam) resulted in impaired spatial learning in the delayed alternation task and altered gait (increased hindlimb splay) at 5, 15, and/or 26 months of age at drinking water doses ≥0.2 mg Hg/kg/day (lowest dose tested); impaired operant training was observed at 0.6 mg Hg/kg/day (Weiss et al. 2005).

Histopathological changes in the brain have been reported in rats and mice following oral exposure to methylmercury; similar to neurodevelopmental studies, lesions were primarily in regions involved in motor and movement control. Ultrastructural changes were noted in the rat cerebellum (vacuolation, degeneration of granule cells) following acute- or intermediate-duration exposure to doses ≥0.8 mg Hg/kg/day (Chang and Hartmann 1972).

In acute-duration rat studies, degeneration of cortical and cerebellar neurons was observed in rats exposed to 8 mg Hg/kg/day for 10 days (Su et al. 1998). Other studies observed no histopathological damage in the brain at doses up to 20 mg/kg/day for 1 or 2 days or 7 mg Hg/kg/day for 10 days (Fehling et al. 1975; Miyakawa et al. 1974; Post et al. 1973).

In intermediate-duration rat studies, no exposure-related histopathological changes were observed at doses up to 9.72 mg Hg/kg/day for up to 35 days (Larsen and Brændgaard 1995; Sakamoto et al. 2017; Schiønning et al. 1998a). However, a reduction in cellular number or density has been reported in several brain regions of rats exposed to ≥0.03 mg Hg/kg/day for 60 days, including the motor cortex (neurons, astrocytes), visual cortex (astrocytes), cerebellum (Purkinje cells, mature neurons, astrocytes, microglia, oligodendrocytes), and hippocampus (neurons, mature neurons, astrocytes) (Bittencourt et al. 2019, 2022; Freire et al. 2020; Santana et al. 2019). Reduced neuronal number in the pyramidal layer of the hippocampus, resulting in thinning of the CA1 and CA3 regions, was also reported in rats following exposure to 0.09 mg Hg/kg/day for 3 months (Wu et al. 2023). In mice, histopathological brain lesions were observed following intermediate-duration exposures ≥0.89 mg Hg/kg/day, including neuronal degeneration and microgliocytosis in subcortical regions (e.g., the putamen and corpus striatum, and to a lesser extent, the thalamus, hypothalamus, and amygdala) and degenerative changes in Purkinje cells and loss of granular cells in the cerebellum (Berthoud et al. 1976; MacDonald and Harbison 1977). The number of reactive astrocytes was increased in the inferior colliculus of the midbrain in mice exposed to 3.2 mg Hg/kg/day for 2 or 4 weeks (Ishihara et al. 2019). Ventricular enlargement of the inferior colliculus was also observed after 4 weeks of exposure.

No histopathological changes were observed in the mouse brain following intermediate- or chronic-duration exposure to doses up to 0.724 mg Hg/kg/day (Hirano et al. 1986; Mitsumori et al. 1990). No histopathological brain lesions were observed in rats at chronic-duration doses up to 0.18 mg Hg/kg/day (Verschuuren et al. 1976).

Several studies have reported damage and degeneration of sensory regions of the spinal cord in rats (e.g., dorsal nerve root and ganglia, posterior column) following oral exposure to methylmercury at doses of 20 mg Hg/kg/day for 2 days (Fehling et al. 1975), 5.4 mg Hg/kg/day for 2 weeks (Shinoda et al. 2019), or intermediate-duration doses ≥1.4 mg Hg/kg/day (Larsen and Brændgaard 1995; Sakamoto et al. 2017; Schiønning et al. 1998a; Yip and Chang 1981). Ultrastructural changes were also noted in the dorsal root ganglia (vacuole formation, focal cytoplasmic lesions) of rats following acute- or intermediate-duration

exposure to doses ≥0.8 mg Hg/kg/day (Chang and Hartmann 1972; Yip and Chang 1981). No changes were observed in anterior horn motor neurons in these studies. However, degeneration of the large motor neurons in spinal cord and myelinated fibers of spinal anterior roots was observed in rats exposed to 8 mg Hg/kg/day for 10 days (Su et al. 1998). No exposure-related histopathological changes in the spinal cord were observed in rats following chronic-duration exposure to 0.18 mg Hg/kg/day (Verschuuren et al. 1976) or in mice at intermediate- or chronic-duration doses up to 9.5 or 0.724 mg Hg/kg/day, respectively (Hirano et al. 1986; MacDonald and Harbison 1977; Mitsumori et al. 1990).

A few studies have reported damage to peripheral nerves in rats and mice exposed to methylmercury. Degeneration of peripheral nerves was also observed in rats following a 2-day exposure to 20 mg Hg/kg/day (Fehling et al. 1975) or a 10-day exposure to 7 mg Hg/kg/day (Miyakawa et al. 1974). No histopathological changes in peripheral nerves were observed in rats following chronic-duration exposure to doses up to 0.18 mg Hg/kg/day (Verschuuren et al. 1976). In mice, no histopathological changes in peripheral nerves were observed at intermediate-duration doses up to 0.724 mg Hg/kg/day for 26 weeks (Hirano et al. 1986). In chronic-duration studies, one study observed degeneration and fibrosis of the sciatic nerve in female mice at 0.627 mg Hg/kg/day, but not in males at doses up to 0.724 mg Hg/kg/day (Hirano et al. 1986). A second study observed peripheral nerve damage in males at 0.686 mg Hg/kg/day, but not females at doses up to 0.601 mg Hg/kg/day (Mitsumori et al. 1990).

Neuropathological data are limited for other laboratory animal species. Degeneration and/or necrosis of cerebellar granule and Purkinje cells and cortical neurons were observed in cats following intermediate-duration exposure to ≥0.012 mg Hg/kg/day (Chang et al. 1974; Khera et al. 1974). Degeneration of the cerebral cortex, cerebellum, and dorsal root ganglia was also observed in cats following intermediate- or chronic-duration exposure to 0.176 or 0.074 mg Hg/kg/day, respectively (Charbonneau et al. 1976). In rabbits, cerebellar degeneration was observed following intermediate-duration exposure to doses ≥1.0 mg Hg/kg/day (Koller et al. 1977).

Predominant Mercury Form Unknown (General Populations). An analysis of data from the 2011–2014 NHANES (n=6,199, age range 20–79 years) found no evidence for an association between BHg levels (median 0.8 µg/L) and grip strength (Gbemavo and Bouchard 2021) (Table 2-56). An analysis of data from the 2011–2014 NHANES restricted to age >60 years (n=2,002) found no evidence for an association between BHg levels and scores of tests for cognition (Lu et al. 2023). Kim et al. (2020b) analyzed data from the 2008–2013 Korean NHANES (n=11,754, age >19 years) and found an association between increasing BHg levels (5.01–168 µg/L) and symptoms of depression in adult females, but not in males. A

follow-up study of data from the 2009–2017 Korean NHANES (n=16,371, mean age 43 years) found no association between BHg levels and depression in females or males (Nguyen 2023). A cross-sectional study of adults in Korea (n=172; age range 20–65 years) found decreasing finger tapping speed in association with increasing UHg (median 1.2 μg/g creatinine; range 0–33 μg/g creatinine) (Kim et al. 2013a). Takeuchi et al. (2022a, 2022b) examined various metrics of cognitive function in a cross-sectional study of young adults (n=920, age range 18–27 years). In this study, increasing HHg (means: males 2.01 μg/g; females 1.85 μg/g) was associated with decreasing performance (lower score) on the Tanaka B-type intelligence test (total and perception score), color-word task, and Beck Depression Inventory Score (three of these measure processing speed). HHg was not associated with performance on other tests of general intelligence (e.g., Raven's Advanced Progressive Matrices) or on tasks that evaluated arithmetic, reading comprehension, inhibition or impulsivity, or creativity. A cross-sectional study of adults (n=436, mean age 59 years) found that increasing BHg levels (geometric mean 6.31 μg/L) were associated with decreasing performance on tests of attention, visual-spatial and executive function, and language based on the Montreal Cognitive Assessment (Sirivarasai et al. 2021). A cross-sectional study of adults (n=200, mean age 34 years) found that increasing HHg (median 8.5 μg/L) was associated with decreasing performance on the tests of visuomotor function or executive function (trail making test) (Rafiee et al. 2020).

Table 2-56. Results of Epidemiological Studies Evaluating General Population Exposure to Mercury (Predominant Mercury Form Unknown) and Neurological Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result[a]
Andrew et al. 2020 Case-control study (females age range 35–66 years), 70 cases, 210 controls; United States	NHg mean Cases 0.093 μg/g Controls: 0.074 μg/g	ALS	↔ (NHg, ≤0.21 μg/g) ↑ (NHg, ≥0.21 μg/g)
Gbemavo and Bouchard 2021 Cross-sectional study of data from NHANES 2011–2014 (n=6,199; mean age 46 years); United States	BHg median Female: 0.82 μg/L Male: 0.84 μg/L	Grip strength	↔ (BHg)
Kim et al. 2020b Cross-sectional study of data from KNHANES 2008–2013 (n=11,754; median age 44 years); Republic of Korea	BHg 5th quintile range: 5.01–168 μg/L	Depression	↑ (BHg, females) ↔ (BHg, males)

Table 2-56. Results of Epidemiological Studies Evaluating General Population Exposure to Mercury (Predominant Mercury Form Unknown) and Neurological Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result[a]
Lu et al. 2023 Cross-sectional study of data from NHANES 2011–2014 (n=2,002; age >60 years); United States	BHg median 0.94 µg/L	Animal fluency test	↔ (BHg)
		CERAD DSST	↔ (BHg)
		WAIS DSST	↔ (BHg)
Nguyen 2023 Cross-sectional study of data from KNHANES 2009–2017 (n=16,371; mean age 43 years); Republic of Korea	SHg mean: 4.06 µg/L	Depression	↔ (BHg, females) ↔ (BHg, males)
Peters et al. 2021 Prospective case-control study, 107 cases, 319 controls (median age 60 years); Europe	ErHg geometric mean Cases: 2.82 µg/kg Controls: 2.75 µg/kg	ALS	↔ (ErHg)
Rafiee et al. 2020 Cross-sectional cohort (n=200; mean age 34 years); Iran	HHg median: 8.5 µg/g	Trail making time (visuomotor function)	↑ HHg
		Trail making time (executive function)	↑ HHg
Sirivarasai et al. 2021 Cross-sectional cohort (n=436; mean age 59 years); Thailand	BHg geometric mean: 6.31 µg/L	Montreal Cognitive Assessment	↓ BHg
Takeuchi et al. 2022a, 2022b Cross-sectional cohort (n=920, age range 18–27 years); Japan	HHg mean: males: 2.01 µg/g females 1.85 µg/g	RAPM	↔ (HHg)
		TBIT total intelligence score	↓ (HHg)
		TBIT perception score	↓ (HHg)
		Arithmetic	↔ (HHg)
		Word-color task	↓ (HHg)
		Stroop	↔ (HHg)
		Reading comprehension	↔ (HHg)
		SA creativity task	↔ (HHg)
		Digit span	↔ (HHg)
		Beck Depression Inventory	↓ (HHg)

Table 2-56. Results of Epidemiological Studies Evaluating General Population Exposure to Mercury (Predominant Mercury Form Unknown) and Neurological Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result[a]
Xiong et al. 2022 Cross-sectional cohort (n=1,154, age >80 years); China	BHg Gmean 1.02 μg/L	Depression symptoms	↑ BHg (≥1.83 μg/L)

[a]Interpretation of neurobehavioral test scores:
Animal Fluency Test: higher score = higher performance
Beck Depression Inventory: higher score = more severe depression
Digit symbol substitution test: higher score = higher performance
Montreal Cognitive Assessment: higher score = higher performance
TBIT: higher score = higher performance
Trail-making: higher score = lower performance
Word-color task: higher score = higher performance
Word learning: higher score = higher performance

↑ = positive association; ↓ = inverse association; ↔ = no association; ALS = amyotrophic lateral sclerosis; BHg = blood mercury; CERAD = Consortium to Establish a Registry for Alzheimer's Disease; DSST = digit symbol substitution test; ErHg = erythrocyte mercury; HHg = hair mercury; KNHANES = Korean National Health and Nutrition Examination Survey; NHANES = National Health and Nutrition Examination Survey; NHg = toenail mercury; RAPM = Raven's Advance Progressive Matrices; RAVPM = Raven's Advanced Progressive Matrices; SHg = serum mercury; TBIT = Tanaka B-type Intelligence Test; WAIS = Wechsler Adult Intelligence Scale

Associations between mercury biomarkers and diagnosis of ALS have been examined in case-control studies of general population cohorts. A prospective case-control study (107 cases, 319 controls, median age 60 years) found no association between erythrocyte mercury levels (cases 2.82 μg/kg, controls 21.75 μg/g) and ALS diagnosis (Peters et al. (2021). Another case-control study (70 cases, 210 controls, age range 35–66 years) found an association between increasing NHg levels and ALS diagnosis when the analysis was restricted to comparing 0.38 to 0.21 μg/g (Andrew et al. 2020). In this study, no association was found for lower NHg strata (0.041–0.21 μg/g).

Mechanisms of Action. General mechanisms of toxicity of mercury (Section 2.21) are likely involved in adverse neurodevelopmental and neurological effects of mercury. Mercury is distributed to the fetus and has been measured in fetal tissues (Section 3.1.2, Distribution), providing a toxicokinetic mechanism for direct exposure of the placental tissues and fetus. Transfer of methylmercury across the placenta may be facilitated by amino acid or organic anion transporters that recognize CH_3Hg^{2+}-thiol conjugates of amino acids (Bridges and Zalups 2017). Amino acid transporters also participate in transfer of CH_3Hg^{2+}-S-cysteine conjugate across the blood brain barrier (Bridges and Zalups 2017).

A variety of toxicodynamic mechanisms contributing to neurological effects of methylmercury have been proposed. These include alteration or disruption in regulation of intracellular calcium homeostasis, the cytoskeleton, mitochondrial function, oxidative stress, neurotransmitter release, and DNA methylation (Aaseth et al. 2020; Cardenas et al. 2016, 2017a; Cediel Ulloa et al. 2021; Culbreth and Aschner 2016; Johansson et al. 2007; Patel and Reynolds 2013; dos Santos et al. 2016). Studies in humans, animals, and *in vitro* models have revealed that several potential mechanisms may contribute to neurological effects of methylmercury. Neurodegenerative mechanisms include tau hyperphosphorylation in the cerebral cortex, (Fujimura et al. 2009), neurite membrane disassembly, and neuron growth rate suppression (Leong et al. 2001). Methylmercury exposure has been shown to inhibit Na^+,K^+-ATPase and to decrease update of norepinephrine and dopamine in brain tissue (Rajanna and Hobson 1985). Song and Choi (2013) observed accumulation of amyloid beta protein through increased production of amyloid precursor protein and reduction of neprilysin and suggested it as a mechanism of mercury toxicity. Disruption of brain-derived neurotrophic factor mediation of growth and differentiation of nerve tissue may also contribute to neurological effects of methylmercury (Rodríguez-Carrillo et al. 2022; Zhou et al. 2021).

The vulnerability of the nervous system to mercury vapor is related to its pronounced distribution to the brain following inhalation. This is attributed, in part, to the high solubility of Hg^0 in lipid, its affinity for proteins such as hemoglobin, and its extracellular and intracellular oxidation, which can favor absorption from the lung and delivery to the brain (Hursh 1985; Magos 1967; Magos et al. 1978; U.S. Atomic Energy Commission 1961).

2.17 REPRODUCTIVE

Overview. The database for reproductive effects associated with exposure to mercury includes epidemiological studies and studies in laboratory animals. Epidemiological studies are available for workers exposed to elemental mercury, populations with high fish diets, and general populations. Few studies meeting inclusion criteria were identified for workers and populations with high fish diets, whereas the database for general populations was more robust (inclusion criteria summarized in Section 2.1). Few studies examined the same reproductive endpoints, and those that did often reported conflicting results. The available epidemiological studies do not provide convincing evidence that the reproductive system is a sensitive target of mercury exposure in males or females.

Studies evaluating reproductive function in animals (mating, fertility, pregnancy, and live birth indices) are available for inhalation exposure to elemental mercury or oral exposure to mercuric chloride or

methylmercury. Overall, oral studies indicate dose-dependent decreases in fertility in female monkeys exposed to methylmercury, in male rodents exposed to mercuric chloride and methylmercury, and in female rodents exposed to mercuric chloride. Data are inconsistent and/or inadequate to determine fertility effects in male monkeys and female rodents exposed to methylmercury. Supporting studies suggest that alterations in sperm parameters and/or estrous cyclicity may contribute to observed decreases in fertility. Evidence from inhalation studies are too limited to draw conclusions.

The following summarizes results of epidemiological and animal studies on reproductive outcomes.

- ***Elemental mercury***
  - *Epidemiology studies*
    - It is not possible to determine if there are associations between elemental mercury exposure and adverse reproductive outcomes in males or females; few studies have been conducted, with most reporting no effects.
    - Studies in males show no effects on testosterone levels or increased risk of spontaneous abortion in their partners.
    - One study in females reported increased spontaneous abortion. This finding has not been corroborated.
  - *Animal studies*
    - Few studies investigated effects on reproductive function; data are insufficient to draw conclusions.
- ***Inorganic mercury salts***
  - *Epidemiology studies*
    - No epidemiological studies evaluating associations between exposure to inorganic mercury salts and reproductive effects were identified.
  - *Animal studies*
    - Reproductive studies consistently reported dose-related impairments in fertility in male and female rodents following oral exposure.
    - Oral studies showed multiphasic changes in testosterone levels with respect to dose and duration, with initial decreases, followed by increases, followed by return to baseline/control levels. Few studies investigated effects of other male or female reproductive hormones. Data are insufficient to draw conclusions about effects on reproductive hormones other than testosterone.
    - Two oral studies have shown dose-related decreases in sperm motility and/or number in male rats.

- Evidence for histopathological lesions in testes is inconsistent in acute- and intermediate-duration oral studies, and reports are generally qualitative; no histopathological lesions were identified in male reproductive tissue following chronic-duration oral exposure.
- No histopathological lesions were identified in female reproductive tissue following acute-, intermediate-, or chronic-duration oral exposure.
- Few studies investigated effects of inhalation exposure on reproductive function; data are insufficient to draw conclusions.

- ***Organic mercury***
  - *Epidemiology studies*
    - Few epidemiology studies in populations with high fish diets have evaluated reproductive endpoints. Available data are not adequate to determine if methylmercury from high fish diets is associated with adverse reproductive effects.
    - In males, there were no adverse effects on sperm quality or serum levels of reproductive hormones; however, only one study was identified.
    - In females, results of two studies reported conflicting results for duration of gestation.
  - Animal studies
    - Reproductive studies consistently reported dose-related impairments in fertility in male rats and female monkeys following oral exposure; male monkeys were not assessed for fertility but showed alterations in sperm parameters.
    - Alterations in sperm parameters were observed in male rats following acute- or intermediate-duration exposure, but there is no clear evidence of increased magnitude of effect with dose or duration.
    - Evidence for exposure-related impairments in female rodent fertility following oral exposure is inconsistent.
    - Evidence for histopathological lesions in male reproductive organs in rodents is inconsistent; no histopathological lesions were identified in male reproductive organs in monkeys following intermediate-duration exposure.
    - No histopathological lesions were identified in female reproductive organs following intermediate- or chronic-duration oral exposure.
- ***Predominant mercury form unknown (general populations)***
    - No adverse effects of mercury exposure on sperm quality or serum levels of reproductive hormones were observed in males. Mercury exposure in general populations does not appear to adversely affect the male reproductive system.

- In nonpregnant women without known infertility, the female reproductive system does not appear to be a sensitive target for mercury. Most studies showed no associations between mercury biomarkers and serum levels of reproductive hormones. Other outcomes (e.g, menstrual cycle length, risk of endometriosis) were only assessed in a few studies, without compelling evidence of adverse effects.
- In pregnant women, most studies did not find associations between preterm birth, gestational age, or pre-eclampsia. No consistent effects were observed between mercury biomarkers and gestational diabetes or elevated blood glucose.

Confounding Factors. Numerous factors may add uncertainty in the interpretation of studies examining associations between mercury and reproductive effects, including overall health, body weight, nutrition, and SES. Exposures to other substances, including recreational drugs, alcohol, therapeutic agents, industrial chemicals, insecticides, and pesticides, also may affect fertility (Foster and Gray 2008). Failure to account for these factors may attenuate or strengthen the apparent associations between mercury exposure and the outcome, depending on the direction of the effect of the variable on the outcome.

Elemental Mercury—Epidemiological Studies. The effects of occupational exposure to elemental mercury have not been well-studied. Studies, summarized in Table 2-57, have been conducted in small populations (n≤147) of males and females exposed at chloralkali plants and dental offices. Small population sizes limit the power to detect effects. All studies quantified elemental mercury exposure using UHg, with or without adjustment for urine creatinine.

Table 2-57. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Reproductive Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Males			
Barregard et al. 1994a Cross-sectional; 41 male chloralkali workers and 41 matched controls (Sweden)	UHg mean Workers: 27 µg/g Cr Controls: 3.3 µg/g Cr	Testosterone	↔ (UHg, workers versus controls)
		Free testosterone	↔ (UHg, workers versus controls)
		Prolactin	↔ (workers versus controls)
Cordier et al. 1991 Cross-sectional; 152 male chloralkali workers (France)	UHg quartiles Q1: 0 (reference) Q2: 1–19 µg/L Q3: 20–49 µg/L Q4: ≥50 µg/L	Spontaneous abortion	↔ (UHg, Q4)

Table 2-57. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Reproductive Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Erfurth et al. 1990 Cross-sectional; 9 male dentists 11 controls and 11 chloralkali workers and 10 controls (Sweden)	UHg mean, dentists Dentists: 2.3 µg/g Cr Controls: 0.71 µg/g Cr UHg mean, workers Workers: 46 µg/g Cr Controls: 1.1 µg/g Cr	Testosterone	↔ (UHg, workers or dentists versus respective controls)
Females			
El-Badry et al. 2018 Prospective; 64 pregnant dental workers and 60 pregnant controls (Egypt)	UHg mean, workers 1st trimester: 42.2 µg/g Cr 2nd trimester: 41.8 µg/g Cr 3rd trimester: 42.8 µg/g Cr UHg mean, control: 1st trimester: 6.2 µg/g Cr 2nd trimester: 6.3 µg/g Cr 3rd trimester: 7.1 µg/g Cr	Spontaneous abortion	↑ (UHg, relative to control)
		Pre-eclampsia	↑ (UHg, relative to control)
Louopou et al. 2020 Prospective cohort; 1,817 pregnant women with 1, 1–4, or ≥5 amalgam fillings (Canada)	BHg median, 1st trimester 0 amalgams: 0.58 µg/L 1–4 amalgams: 0.74 µg/L ≥5 amalgam: 0.90 µg/L BHg median, 3rd trimester 0 amalgams: 0.60 µg/L 1–4 amalgams:0.74 µg/L ≥5 amalgam: 0.90 µg/L	Gestational hypertension	↔ (BHg)
Males and females			
Frumkin et al. 2001 Retrospective cohort; 147 chloralkali workers (137 males and 10 females) and 132 controls (117 males and 15 females) (Brunswick, Georgia)	UHg mean Workers: 2.76 µg/g Cr Controls: 2.31 µg/g Cr	Spontaneous abortion	↔ (UHg)
		Preterm birth	↔ (UHg)

↑ = positive association or increased compared to controls; ↔ = no association or no increase compared to controls; BHg = blood mercury; Cr = creatinine; Q = quartile; UHg = urine mercury

Studies in male workers did not identify effects on reproductive hormones including testosterone and prolactin (Barregard et al. 1994a; Erfurth et al. 1990). In addition, exposure of males was not associated with risk of spontaneous abortion in their partners (Cordier et al. 1991). In females, a prospective study of dental workers found an increased risk of spontaneous abortion and pre-eclampsia, relative to controls (El-Badry et al. 2018). However, no increases in spontaneous abortion or preterm birth were observed in partners of males or in female chloralkali workers compared to controls. Given the small number of

studies, data are not adequate to determine if elemental mercury adversely affects reproductive function in males or females.

Elemental Mercury—Animal Studies. The effects of exposure to elemental mercury have not been well-studied in animals. A single study found significant testicular damage in male rats exposed to 1 mg/m^3 for 6 weeks (7 days/week, 9 hours/day), including seminiferous tubule atrophy; damage to spermatogenic cells; decreased volume of the testicles; decreased diameter and volume of the seminiferous tubules; and decreased Sertoli cells, spermatogonia, spermatocytes, and spermatids (Altunkaynak et al. 2015). In a series of experiments in female rats, Davis et al. (2001) found estrous cycle abnormalities following nose-only exposure to mercury vapor at concentrations ≥2 mg Hg/m^3 for 6–11 days (2 hours/day), including a concentration-related increase in the number of females with prolonged estrous cycles (≥5 days) and evidence of immature corpora lutea during estrus and metestrus phases. Significant alterations in reproductive hormone levels (decreased estradiol, increased progesterone) were observed at 4 mg Hg/m^3. However, no evidence of impaired fertility was observed when females were exposed to concentrations up to 2 mg Hg/$m^3$for 8 days (2 hours/day) prior to mating to unexposed males; fertility was not assessed at 4 mg Hg/m^3 (Davis et al. 2001).

Inorganic Mercury Salts—Animal Studies. Studies in laboratory animals have evaluated effects of inorganic mercuric mercury (e.g., mercuric chloride) on reproductive function following intermediate-duration inhalation exposure and intermediate- and chronic-duration oral exposure. Additional data regarding reproductive endpoints (e.g., histology, organ weights, hormone levels, sperm parameters) are available from acute-, intermediate-, and chronic-duration oral studies. Available inhalation data are too limited to draw conclusions; however, results from oral studies indicate that exposure to mercuric chloride can impair male and female fertility in rodents.

The effects of inhaled mercuric oxide on the female rat reproductive system were evaluated in a single study. Following continuous exposure to 0.9 mg Hg/m^3 for 45 days, treated rats showed reduced ovary volume, decreased number of ovarian follicles, and various histopathological changes in the ovaries, including thickened tunica albuginea, increased fibrils within connective tissue, congested capillaries and blood vessels, thinned walls of large and dilated veins, fibrin deposits in veins, edema and maldeveloped follicles in the stroma, and irregular oocyte borders within follicles (Altunkaynak et al. 2016).

Reproductive capacity was reduced in a dose- and duration-related manner in generational studies in rats and mice following oral exposure to mercuric chloride (Table 2-58). In rats, exposure to both males and

females in a 2-generation study resulted in dose-related decreases in fertility index, live birth index, implantation efficiency, and number of live pups/litter in the F0 generation at all tested doses (≥0.37 Hg/kg/day in males; ≥0.55 Hg/kg/day in females); no significant impairments were observed in the F1 generation at doses up to 1.31 mg Hg/kg/day in males and 1.98 mg Hg/kg/day in females (Atkinson et al. 2001). In mice, premating exposure to mercuric chloride in a 1-generation study in males and females (40 and 16 days, respectively) resulted in a decreased fertility index at ≥0.18 mg Hg/kg/day and a decreased live birth index at 0.74 mg Hg/kg/day. Collectively, these studies indicate that mercuric chloride can impair rodent reproductive function; however, it is unclear if impaired fertility observed in generational studies was attributable to reproductive effects in males, females, or both. Findings from single-sex studies suggest that oral mercuric chloride exposure can alter reproductive function in both male and female rodents (Tables 2-59 and 2-60, respectively). Studies in male rats indicate dose-related impairments in reproductive function, including increased time to impregnate and decreased fertility at 1.5 mg Hg/kg/day, decreased viable embryos at ≥3 mg Hg/kg/day, and decreased mating index at 6 mg Hg/kg/day (Boujbiha et al. 2009, 2011; Heath et al. 2012). In females, decreased number of implantations and increased resorptions were observed in rats exposed to 1.5 mg Hg/kg/day prior to mating (Heath et al. 2012), decreased fetuses/litter by 58% in female rats exposed to 3 mg Hg/kg/day from GD 1 to 21 (Ismail and El-Meligy 2021), and decreased live pups per litter was observed in mice exposed to 0.4 mg Hg/kg/day prior to mating through lactation (Huang et al. 2011). No evidence of impaired fertility was observed in male or female rats exposed to ≤0.7 mg Hg/kg/day when mated to untreated animals (Heath et al. 2012; Szász et al. 2002).

Table 2-58. Reproductive Function in Rodents Orally Exposed to Mercuric Chloride when Both Sexes are Exposed

Species; duration	Dose (mg Hg/kg/day)	FI[a,b]	LBI[a,c]	IE[a,d]	Live pups/ litter[a]	Reference (study type)
Rat; 80 days	0.46[e]	F0: ↓ (32) F1: ↔	F0: ↓ (12) F1: ↔	F0: ↓ (38) F1: ↔	F0: ↓ (38) F1: ↔	Atkinson et al. 2001 (2-generation)
Rat; 80 days	0.93[e]	F0: ↓ (58) F1: ↔	F0: ↓ (10) F1: ↓ (6)	F0: ↓ (49) F1: ↓ (34)	F0: ↓ (49) F1: ↔	Atkinson et al. 2001 (2-generation)
Rat; 80 days	1.65[e]	F0 ↓ (83) F1: –	F0 ↓ (22) F1: –	F0 ↓ (56) F1: –	F0 ↓ (56) F1: –	Atkinson et al. 2001 (2-generation)
Mouse; 61–79 days	0.18	↓ (30)	↔	↔	↔	Khan et al. 2004 (1-generation)
Mouse; 61–79 days	0.37	↓ (30)	↔	↔	↔	Khan et al. 2004 (1-generation)

Table 2-58. Reproductive Function in Rodents Orally Exposed to Mercuric Chloride when Both Sexes are Exposed

Species; duration	Dose (mg Hg/kg/day)	FI[a,b]	LBI[a,c]	IE[a,d]	Live pups/ litter[a]	Reference (study type)
Mouse; 61–79 days	0.74	↓ (30)	↓ (81)	↔	↔	Khan et al. 2004 (1-generation)

[a]Numbers in ( ) are percent change compared to control, calculated from quantitative data.
[b]Fertility index = number of dams delivering/number of dams cohabited.
[c]Live birth index = number of live pups/total number of pups.
[d]Implantation efficiency = number of pups born/number of implants.
[e]Doses are the midpoint of estimated male and female doses for the F0 generation. Estimated F0 male doses were 0.37, 0.74, and 1.31 mg Hg/kg/day, respectively, and estimated F0 female doses were 0.55, 1.11, and 1.98 mg Hg/kg/day, respectively.

↓ = decreased; ↔ = no change; – = not assessed; FI = fertility index; IE = implantation efficiency; LBI = live birth index

Table 2-59. Reproductive Function in Male Rodents Orally Exposed to Mercuric Chloride Prior to Mating to Unexposed Females

Species; duration	Dose (mg Hg/kg/day)	MI[a,b]	Time-to-pregnant[a]	FI[a,c]	Live pups/ litter[a]	Reference
Rat; 60 days	0.7	–	↔	↔	–	Heath et al. 2012
Rat; 60 days	1.5	–	↑ (53[c])	↓ (30)	–	Heath et al. 2012
Rat; 90 days	3	↔	–	–	↓ (36)	Boujbiha et al. 2009, 2011
Rat; 90 days	6	↓ (50)	–	–	↓ (76)	Boujbiha et al. 2009, 2011

[a]Numbers in ( ) are percent change compared to control, calculated from quantitative data.
[b]Mating index = number of confirmed matings/number of pairs cohabited.
[c]Fertility index = number of dams delivering/number of dams cohabited.

↑ = increased; ↓ = decreased; ↔ = no change; – = not assessed; FI = fertility index; MI = mating index

Table 2-60. Reproductive Function in Female Rodents Orally Exposed to Mercuric Chloride Prior to Mating to Unexposed Males

Species duration	Dose (mg Hg/kg/day)	FI[a]	Live pups/ litter	Number of implants	Number of resorptions	Reference
Rat; 60 days	0.7	–	–	↔	↔	Heath et al. 2012
Rat; 60 days	1.5	–	–	↓ (15[b])	↑ (1,900[b])	Heath et al. 2012
Rat; 70–77 days	0.6	↔	↔	–	–	Szász et al. 2002

Table 2-60. Reproductive Function in Female Rodents Orally Exposed to Mercuric Chloride Prior to Mating to Unexposed Males

Species duration	Dose (mg Hg/kg/day)	FI[a]	Live pups/ litter	Number of implants	Number of resorptions	Reference
Mouse; 70 days	0.4	–	↓ (14[c])	–	–	Huang et al. 2011

[a]Fertility index = number of dams delivering/number of dams cohabited.
[b]Percent change compared to control, calculated from quantitative data.
[c]Percent change compared to control, estimated from graphically presented data.

↑ = increased; ↓ = decreased; ↔ = no change; – = not assessed; FI = fertility index

A 3-generation study in male and female rats with continuous breeding reported a decrease in the number of F3 litters and litter size (Lukacinova et al. 2012); however, reporting of the study design and results were inadequate for independent review and analysis of the results. Therefore, this study was not included in Table 2-60 or the LSE tables.

Alterations in sperm parameters and male reproductive hormones have also been reported following oral exposure to mercuric chloride (Table 2-61). Dose-related decreases in sperm number and mobility have been reported in rats following oral exposure to mercuric chloride at drinking water doses ≥3 Hg/kg/day for 3–90 days or gavage doses ≥0.7 Hg/kg/day for 60 days (Boujbiha et al. 2009, 2011; Heath et al. 2012); findings were generally duration-dependent, although there is some variation in the effect of exposure duration. In rats, alterations in serum testosterone levels show a multiphasic response with respect to dose and duration. Significant decreases in serum testosterone were observed after exposure to 3 mg Hg/kg/day for 3–15 days, 6 mg Hg/kg/day for 3 days, and 0.7 or 1.5 mg Hg/kg/day for 30 days. Similarly, significant increases were observed after exposure to 3 mg Hg/kg/day for 30 or 60 days or 6 mg Hg/kg/day for 7 days. However, no significant changes were observed after exposure to 3 mg Hg/kg/day for 90 days, 6 mg Hg/kg/day for 15–90 days, or 0.7 or 1.5 mg Hg/kg/day for 60 days (Boujbiha et al. 2009, 2011; Heath et al. 2012; Ramalingam et al. 2003). At 0.3 mg Hg/kg/day for 7 days, Albasher et al. (2020) also observed a significant decrease in serum testosterone in male rats. Similarly, testicular testosterone was significantly elevated following exposure to 0.7 or 1.5 mg Hg/kg/day for 60 days (Heath et al. 2012), but significantly decreased following exposure to ≥3 mg Hg/kg/day for 90 days (Boujbiha et al. 2009, 2011). Data on other male reproductive hormones is limited. Significant decreases in serum luteinizing hormone (LH) were observed in male rats following exposure to 0.7 mg Hg/kg/day for 30 days; serum prolactin and follicle-stimulating hormone (FSH) were also decreased at 1.5 mg Hg/kg/day (Ramalingam et al. 2003). Both serum and testicular estradiol (E2) levels were

significantly decreased in male rats after exposure to ≥3 mg/kg/day for 90 days (Boujbiha et al. 2009, 2011). Interpretation of observed serum hormone changes at higher doses is complicated based on known renal toxicity in animals (acute-duration exposures ≥7.4 mg Hg/kg/day, intermediate-duration exposures ≥0.923 mg Hg/kg/day; Section 2.11, Renal) because impaired renal function can alter testosterone production in humans and animals (e.g., Iglesias et al. 2012; Nakada and Adachi 1999) and the kidney participates in the metabolism and excretion of steroids (Schiffer et al. 2019).

Table 2-61. Sperm Parameters and Male Reproductive Hormones in Male Rodents Orally Exposed to Mercuric Chloride

Species; duration	Dose (mg Hg/kg/day)	Sperm No.	Sperm mobility	Serum T	Other hormone levels	Reference
Rat; 3 days	3	↓ (10[a])	↓ (10[a])	↓ (13[a])	–	Boujbiha et al. 2009
Rat; 3 days	6	↓ (35[a])	↓ (30[a])	↓ (22[a])	–	Boujbiha et al. 2009
Rat; 7 days	0.3	–	–	↓ (24[a])	–	Albasher et al. 2020
Rat; 7 days	3	↓ (24[a])	↓ (30[a])	↓ (40[a])	–	Boujbiha et al. 2009
Rat; 7 days	6	↓ (44[a])	↓ (38[a])	↑ (52[a])	–	Boujbiha et al. 2009
Rat; 15 days	3	↓ (27[a])	↓ (31[a])	↓ (52[a])	–	Boujbiha et al. 2009
Rat; 15 days	6	↓ (33[a])	↓ (34[a])	↔	–	Boujbiha et al. 2009
Rat; 30 days	0.7	–	–	↓ (35[a])	FSH: ↔ LH: ↓ (47[a]) PRL: ↔	Ramalingam et al. 2003
Rat; 30 days	1.5	–	–	↓ (63[a])	FSH: ↓ (15[a]) LH: ↓ (65[a]) PRL: ↓ (33[a])	Ramalingam et al. 2003
Rat; 30 days	3	↓ (16[a])	↔	↑ (93[a])	–	Boujbiha et al. 2009, 2011
Rat; 30 days	6	↓ (29[a])	↔	↔	–	Boujbiha et al. 2009, 2011
Rat; 60 days	0.7	↓ (10[b])	–	↔	TT: ↓ (30[b])	Heath et al. 2012
Rat; 60 days	1.5	↓ (10[b])	–	↔	TT: ↓ (30[b])	Heath et al. 2012
Rat; 60 days	3	↓ (9[a])	↓ (17[a])	↑ (103[a])	–	Boujbiha et al. 2009, 2011

Table 2-61. Sperm Parameters and Male Reproductive Hormones in Male Rodents Orally Exposed to Mercuric Chloride

Species; duration	Dose (mg Hg/kg/day)	Sperm No.	Sperm mobility	Serum T	Other hormone levels	Reference
Rat; 60 days	6	↓ (21[a])	↓ (34[a])	↔	–	Boujbiha et al. 2009, 2011
Rat 90 days	3	↓ (31[a])	↓ (16[a])	↔	TT: ↑ (23[a]) E2: ↓ (19[a]) TE2: ↓ (15[a])	Boujbiha et al. 2009, 2011
Rat; 90 days	6	↓ (38[a])	↓ (23[a])	↔	TT: ↑ (35[a]) E2: ↓ (37[a]) TE2: ↓ (26[a])	Boujbiha et al. 2009, 2011

[a]Percent change compared to control, calculated from quantitative data.
[b]Percent change compared to control, estimated from graphically reported data.

↑ = increased; ↓ = decreased; ↔ = no change; – = not assessed; E2 = serum estradiol; FSH = serum follicle-stimulating hormone; LH = serum luteinizing hormone; PRL = serum prolactin; T = testosterone; TE2 = testicular estradiol; TT = testicular testosterone

Evidence for histopathological damage to male reproductive organs is inconsistent in rats and mice following oral exposure to mercuric chloride. One study reported alterations to the seminiferous tubules that included vacuolation and degeneration of the spermatogenic cells and detachment of spermatogenic cells from the basement membrane in Wistar rats exposed to 0.3 Hg mg/kg/day for 7 days (Albasher et al. 2020). Boujbiha et al. (2009, 2011) reported changes in the histoarchitecture of the testes and seminiferous tubules in Wistar rats following drinking water exposure to mercuric chloride at doses of 3 or 6 mg Hg/kg/day for 3–90 days; the study authors reported that findings were "prominent" at the higher dose, but do not provide incidence data or additional dose- or time-specific details. Changes included interstitial effusion, increased space between seminiferous tubules, enlarged tubule lumen, degenerative and detachment of lining cells, reduced number of round spermatids, and an absence of mature spermatozoa in 48–70% of tubules. The only dose-specific quantitative data reported were increased degree of testicular edema (3.18 and 13.42% of tissue weight) and a 14 and 27% reduction in thickness of the germinative layer of the seminiferous tubules at 3 and 6 mg Hg/kg/day, respectively, after exposure for 90 days. In contrast, no exposure-related lesions were observed in male reproductive organs in F344 rats following intermediate- or chronic-duration gavage doses up to 4 mg Hg/kg/day (NTP 1993), in C57Bl/6 mice at intermediate-duration gavage doses up to 0.74 mg Hg/kg/day (Khan et al. 2004; NTP 1993), or in B6C3F1 mice at intermediate- or chronic-duration gavage doses up to 15 or 7.4 mg Hg/kg/day, respectively (NTP 1993).

Two additional studies in rodents qualitatively reported histopathological changes in the testes following acute- or intermediate-duration exposure to low doses of mercuric chloride; however, these studies were not included in the LSE tables due to reporting deficiencies that precluded independent evaluation of the data. Penna et al. (2009) reported time- and dose-related increases in testicular histopathology in male Sprague-Dawley rats exposed to mercuric chloride via drinking water for up to 90 days, with "mild" lesions in ≤10% of seminiferous tubules in <50% of animals (n=5) after exposure to 0.0133 mg Hg/kg/day for 30 days or 0.0011 mg Hg/kg/day for 60 days, and "moderate" lesions in 20–50% of seminiferous tubules in >50% of animals after exposure to ≥0.0059 mg Hg/kg/day for 60 days or ≥0.0011 mg Hg/kg/day for 90 days. Histopathological findings for control animals were not explicitly reported. Nagar and Bhattacharya (2001) reported various histopathological changes in the testes (detached tunica albuginea, hypertrophied and/or vacuolized spermatogenic and interstitial cells, luminal dilation) following gavage exposure to 0.006 mg Hg/kg/day (as mercuric chloride) for 7–21 days; incidence data were not reported, but effects reportedly became more pronounced with longer exposure duration (Nagar and Bhattacharya 2001). Control testes were "normal." Decreased diameter of seminiferous tubules, germ cells (spermatogonia, spermatocytes, spermatids, and/or sperm), Sertoli cells, and interstitial cells were also observed. The study authors also reported elevated testosterone; however, no measures of variance or statistics were reported.

A series of oral dosing studies in Wistar rats showed dose- and time-related 12–24% increases in relative testes weight following exposure to doses of 3 or 6 mg Hg/kg/day (as mercuric chloride) for 30, 60, or 90 days; no changes were observed in testes weight in rats similarly exposed for 3, 7, or 15 days (Boujbiha et al. 2009, 2011). In other studies, no exposure-related changes in testes weight were observed in Sprague-Dawley rats at intermediate-duration doses up to 1.31 mg Hg/kg/day (Atkinson et al. 2001) or F344 rats at intermediate- or chronic-duration doses up to 4 mg Hg/kg/day (NTP 1993). Significant, dose-related 15–20% decreases in seminal vesicle weight were reported in F0 male Sprague-Dawley rats exposed to ≥0.74 mg Hg/kg/day in a 2-generation study; no changes were observed in F1 males at doses up to 1.31 mg Hg/kg/day (Atkinson et al. 2001). No exposure-related changes were noted in epididymides or prostate weight in Sprague-Dawley rats exposed to intermediate-duration doses up to 1.31 mg Hg/kg/day (Atkinson et al. 2001). In mice, no exposure-related changes were noted in testes weight at intermediate-duration doses up to 15 mg Hg/kg/day (Khan et al. 2004; NTP 1993). Khan et al. (2004) also reported a lack of exposure-related changes in seminal vesicles, epididymides, and prostate weight in mice at intermediate-duration doses up to 0.74 mg Hg/kg/day.

Studies in female laboratory animals orally exposed to mercuric chloride provide no evidence of alterations to reproductive organs and minimal evidence of alterations in reproductive hormones. Histopathological lesions in female reproductive organs have not been reported following gavage exposure to mercuric chloride at acute-duration doses up to 9.24 mg Hg/kg/day in rats (Lecavalier et al. 1994), intermediate-duration doses up to 4 mg Hg/kg/day in rats or 15 mg Hg/kg/day in mice (Khan et al. 2004; NTP 1993), or chronic-duration doses up to 4 mg Hg/kg/day in rats or 7.4 mg Hg/kg/day in mice (NTP 1993). No changes in ovary or uterus weight were observed in F0 or F1 rats exposed to gavage doses up to 1.98 mg Hg/kg/day in a 2-generation study (Atkinson et al. 2001), and no changes in ovary weight were observed in mice exposed to gavage doses up to 0.74 mg Hg/kg/day for 79 days during premating, gestation, and lactation (Khan et al. 2004). Female reproductive hormone data are limited to a 60-day gavage study reporting an 18% decrease in serum progesterone and a 19% increase in pituitary LH levels at 1.5 mg Hg/kg/day, compared to control; these hormones were not altered at 0.7 mg Hg/kg/day and pituitary FSH was not altered at doses up to 1.5 mg Hg/kg/day (Heath et al. 2009).

One study reported reduced maternal care (increased latency to retrieve a pup removed from the nest) in dams exposed to mercuric chloride on GDs 1–21 at drinking water concentrations ≥6.1 mg Hg/kg/day (Chehimi et al. 2012). This may be secondary to altered pup behavior (e.g., decreased pup vocalizations), because foster dams also showed reduced maternal care; however, pup vocalizations were not measured.

Organic Mercury—Epidemiological Studies. Few epidemiological studies on male and female reproductive effects have been conducted in populations with high fish diets, with one study in males and two studies in females. Studies are summarized in Table 2-62. A study of male Inuit adults from Greenland examined comprehensive endpoints to evaluate male reproductive function (Mocevic et al. 2013). This study did not find adverse associations between BHg and sperm quality or serum levels of male reproductive hormones. The increase in serum levels of inhibin B, which reflects high Sertoli cell activity and high sperm counts, is not considered to be adverse. The single outcome evaluated for female reproductive function was duration of gestation, with studies reporting conflicting results (Dallaire et al. 2013; Murcia et al. 2016). A prospective study in Quebec Inuit mother-infant pairs reported an inverse association between umbilical cord BHg and the duration of gestation (Dallaire et al. 2013). In contrast, a cohort study of mother-infant pairs with high maternal fish consumption did not find an association (Murcia et al. 2016). Several factors may have contributed to these different observations: (1) differences may be due to differences in the types of fish consumed and corresponding intakes of methylmercury; (2) differences may exist in genetic predispositions between study populations; (3) mean cord BHg was higher in the Dallaire et al. (2013) study compared to the Murcia et al. (2016) study (21.3 versus

8.2 µg/L), although the Murcia study did not find an association between cord BHg and duration of gestation for the highest cord BHg tertile (≥15.0 µg/L); (4) sample size in the Murcia study was approximately 7 times larger than in the Dallaire et al. (2013) study; and (5) the Dallaire et al. (2013) study considered additional confounding factors (exposure to PCBs and fatty acids from fish). Given these conflicting data, it is unclear if methylmercury exposure from high fish diets is associated with decreased gestational length.

Table 2-62. Epidemiological Studies Evaluating Associations between Mercury and Reproductive Effects in Populations with High Fish Diets

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Males			
Ai et al. 2019 Cross-sectional; 84 men (Taiwan)	BHg mean: 9.0 µg/L Tertiles: T1: <5.5 µg/L T2: 5.5–8.9 µg/L T3: >8.9 µg/L	Total sperm count	↔ (BHg)
		Normal sperm morphology	↓ (BHg, T2)
Mocevic et al. 2013 Cross-sectional; 194 male Inuits (Greenland)	BHg median: 9.2 µg/L	Semen volume	↔ (BHg)
		Sperm concentration	↔ (BHg)
		Total sperm count	↔ (BHg)
		Sperm motility	↔ (BHg)
		Normal sperm morphology	↔ (BHg)
		LH	↔ (BHg)
		FSH	↔ (BHg)
		Testosterone	↔ (BHg)
		Free androgen index	↔ (BHg)
		Inhibin B[a]	↑ (BHg)
Females			
Dallaire et al. 2013 Prospective longitudinal; 248 mother-infant pairs; Inuit (Arctic Quebec) (adjustments included PCBs and DHA acid from fish and seafood intake)	Cord BHg mean: 21.3 µg/L	Duration of gestation	↓ (BHg)
Murcia et al. 2016 Cohort; 1,756 mother-infant pairs with high maternal fish consumption (Spain)	Cord BHg Gmean: 8.2 µg/L Tertiles T1: 5.0–<8.5 µg/L T2: 8.5–<15.0 µg/L T3: ≥15.0 µg/L	Duration of gestation	↔ (BHg, T3)

Table 2-62. Epidemiological Studies Evaluating Associations between Mercury and Reproductive Effects in Populations with High Fish Diets

Reference, study type, and population	Biomarker	Outcome evaluated	Result

[a]Increased serum levels of inhibin B, which reflects high Sertoli cell activity and high sperm counts, is not considered to be adverse.

↑ = positive association; ↓ = inverse association; ↔ = no association; BHg = blood mercury; DHA = docosahexaenoic acid; FSH = follicle-stimulating hormone; Gmean = geometric mean; LH = luteinizing hormone; PCB = poly-chlorinated biphenyl; T = tertile

Organic Mercury—Animal Studies. Studies in laboratory animals have evaluated effects of methylmercury compounds on reproductive function following acute-, intermediate-, and chronic-duration oral exposure. Additional data regarding reproductive endpoints (e.g., histology, organ weights, hormone levels, sperm parameters) are available from acute-, intermediate-, and chronic-duration oral studies. Available oral data suggest that organic mercury can impair male and female fertility in monkeys and male fertility in rats. Data in male mice are too limited to draw conclusions. Available data in rodents do not provide consistent evidence of impaired female rodent fertility following oral exposure to organic mercury.

Studies in male rats found that acute- or intermediate-duration gavage exposure to methylmercury prior to mating with untreated females resulted in dose- and duration-dependent decreases in reproductive performance; no evidence of impaired fertility was observed in male mice following acute-duration gavage exposure (Table 2-63). In Wistar rats, decreased male fertility was observed after acute-duration exposure to 5 mg Hg/kg/day or intermediate-duration exposure to 1 mg Hg/kg/day (Khera 1973). Additionally, the number of viable embryos per litter (embryos/litter) was significantly decreased after acute-duration exposure to 5 mg Hg/kg/day or intermediate-duration exposure to ≥0.05 mg Hg/kg/day (Khera 1973). In male Brown Norway rats dosed 22 times over an 11-week period prior to mating, fertility rates were 36, 22, 11, and 0% at 0, 0.0008, 0.008, and 0.08 mg Hg/kg/day, respectively (Friedmann et al. 1998). No viable fetuses were observed in the single litter produced at 0.008 mg Hg/kg/day. In mice, no exposure-related changes in fertility indices or viable embryos/litter were observed following acute-duration exposure to doses up to 5 mg Hg/kg/day prior to mating (Khera 1973).

Table 2-63. Reproductive Function in Male Rodents Orally Exposed to Methylmercuric Chloride via Gavage Prior to Mating to Unexposed Females

Species; duration	Dose (mg Hg/kg/day)	FI[a]	Live fetuses/ embryos per litter	Reference
Rat; 7 days	1	↔	↔	Khera 1973
Rat; 7 days	2.5	↔	↔	Khera 1973
Rat; 7 days	5	↓ (8–15[b])	↓ (12–13[b])	Khera 1973
Rat; 77 days[c]	0.0008	↔	↔	Friedmann et al. 1998
Rat; 77 days[c]	0.008	↔	↓ (100[b])	Friedmann et al. 1998
Rat; 77 days	0.08	↓ (36[b])	NA	Friedmann et al. 1998
Rat; 95–125 days	0.1	↔	↔	Khera 1973
Rat; 95–125 days	0.5	↔	↓ (30[d])	Khera 1973
Rat; 95–125 days	1	↓ (>60[d])	↓ (70[d])	Khera 1973
Mouse; 7 days	1	↔	↔	Khera 1973
Mouse; 7 days	2.5	↔	↔	Khera 1973
Mouse; 7 days	5	↔	↔	Khera 1973

[a]Fertility index = number of dams confirmed pregnant/number of dams with successful matings.
[b]Percent change compared to control, calculated from quantitative data.
[c]Rats only dosed 2 times/week.
[d]Percent change compared to control, estimated from graphically reported data.

↓ = decreased; ↔ = no change; – = not assessed; FI = fertility index

There is no evidence for impaired ability to become pregnant in female monkeys or mice orally exposed to methylmercury prior to mating untreated males: however, there is evidence for dose-related decreases in the ability for exposed monkeys to bring a pregnancy to term and decreased live pups/litter in mice exposed via gavage (Table 2-64). In monkeys, no exposure-related changes in fertility, menstrual cyclicity, or gestation length were observed following exposure to methylmercury in apple juice over one or two breeding cycles at doses up to 0.08 mg Hg/kg/day; however, a 50–54% decrease in the number of viable pregnancies occurred following exposure to ≥0.06 mg Hg/kg/day (Burbacher and Mottet 1988; Burbacher et al. 1984, 2005). In rats, no changes in female fertility, live birth index, or number of live pups/litter were observed following intermediate-duration exposure to methylmercury at drinking water

doses up to 0.6 mg Hg/kg/day (Elsner 1991; Newland and Reile 1999; Newland and Rasmussen 2000; Newland et al. 2004; Szász et al. 2002) or dietary doses up to 0.25 mg Hg/kg/day over 2 generations (Khera and Tabacova 1973). There were also no exposure-related changes in the number of implantations, resorptions, or corpora lutea in a 2-generation study of female rats (Khera and Tabacova 1973). In mice, the number of live pups/litter were significantly decreased by 16% following exposure to methylmercury at a dose of 0.4 mg Hg/kg/day via gavage before mating and through gestation and lactation (Huang et al. 2011); however, no exposure-related changes in the number of live pups/litter were observed in mice similarly exposed to methylmercury at drinking water doses up to 0.6 mg Hg/kg/day (Weiss et al. 2005) or dietary doses up to 0.98 mg Hg/kg/day (Thuvander et al. 1996). Studies in mice did not evaluate any additional reproductive function parameters.

Table 2-64. Reproductive Function in Female Laboratory Animals Orally Exposed to Methylmercury Compounds

Species; duration	Dose (mg Hg/kg/day)	Viable pregnancies/LBI[a,b]	Live pups/ litter[a]	Reference (compound)
Exposure prior to mating with unexposed males and through gestation and lactation				
Monkey; 395 days	0.04	↔	–	Burbacher et al. 1984 (MMH)
Monkey; 395 days	0.08	↓ (50)	–	Burbacher et al. 1984 (MMH)
Monkey; 1,456 days	0.04	↔	–	Burbacher and Mottet 1988; Burbacher et al. 2005 (MMH)
Monkey; 1,456 days	0.06	↓ (54)	–	Burbacher and Mottet 1988; Burbacher et al. 2005 (MMH)
Monkey; 1,456 days	0.08	↓ (54)	–	Burbacher and Mottet 1988; Burbacher et al. 2005 (MMH)
Rat; 60 days	0.19	–	↔	Elsner 1991 (MMC)
Rat; 60 days	0.74	–	↔	Elsner 1991 (MMC)
Rat; 70–77 days	0.6	–	↔	Szász et al. 2002 (MMC)
Rat; 70–91 days	0.045–0.6	↔	↔	Newland and Reile 1999; Newland and Rasmussen 2000; Newland et al. 2004 (MMC)
Rat; 122 days	0.002–0.25	↔	↔	Khera and Tabacova 1973 (MMC)

Table 2-64. Reproductive Function in Female Laboratory Animals Orally Exposed to Methylmercury Compounds

Species; duration	Dose (mg Hg/kg/day)	Viable pregnancies/LBI[a,b]	Live pups/ litter[a]	Reference (compound)
Mouse; 70 days	0.2	–	↔	Weiss et al. 2005 (MM)
Mouse; 70 days	0.4	–	↓ (16)	Huang et al. 2011 (MMC)
Mouse; 70 days	0.6	–	↔	Weiss et al. 2005 (MM)
Mouse; 105–112 days	0.098–0.98	–	↔	Thuvander et al. 1996 (MMC)
Exposure throughout gestation and lactation only (GD 1–PND 21)				
Rat; 42 days	0.05–0.23	↔	↔	Fujimura et al. 2012 (MM)
Rat; 42 days	0.5	↓ (100)	↓ (100)	Fujimura et al. 2012 (MM)
Rat; 42 days	0.7	↔	↔	Chang et al. 2015 (MM)
Mouse; 42 days	0.9–1.3	–	↔	Goulet et al. 2003 (MMH)
Mouse; 42 days	1.7	–	↓ (18)	Goulet et al. 2003 (MMH)

[a]Numbers in ( ) are percent change compared to control, calculated from quantitative data.
[b]Viable pregnancies (monkeys) or Live birth index (rodents = number of live pups/number of pups).

↓ = decreased; ↔ = no change; – = not assessed; GD = gestation day; LBI = live birth index; MM = methylmercury; MMC = methylmercuric chloride; MMH = methylmercury hydroxide; PND = postnatal day

Evidence for reproductive effects in rodents following exposure to methylmercury throughout gestation and lactation (GD 1 to PND 21) is mixed (Table 2-64). In one gestational/lactational rat study, no viable litters were produced at a drinking water dose of 0.5 mg Hg/kg/day; no changes in live birth index or litter size were observed at drinking water doses ≤0.23 mg Hg/kg/day (Fujimura et al. 2012). However, in a second gestational/lactation study in rats, no exposure-related changes were observed in live birth index or litter size at drinking water doses up to 0.7 mg Hg/kg/day (Chang et al. 2015). In mice, exposure to methylmercury at a drinking water dose of 1.7 mg Hg/kg/day resulted in an 18% decrease in the number of live pups/litter (Goulet et al. 2003).

Alterations in sperm parameters have been reported in monkeys, rats, and mice following oral exposure to methylmercury (Table 2-65). In monkeys, morphological examination of semen smears indicated an increased incidence of tail defects (primarily bent and kinked tails) following intermediate-duration

exposure to methylmercury in apple juice at doses ≥0.046 mg Hg/kg/day; at 0.065 mg Hg/kg/day, additional sperm effects included a decrease in the mean percentage of motile spermatozoa and the mean sperm speed (Mohamed et al. 1987). No changes in the sperm count in monkey semen were observed at doses up to 0.065 mg Hg/kg/day.

Table 2-65. Sperm Parameters in Male Laboratory Animals Orally Exposed to Methylmercury Compounds

Species; duration	Dose (mg Hg/kg/day)	Number	Mobility	Percent immobile	Speed	Percent abnormal	Reference
Monkey; 140 days	0.046	↔	↔	–	↔	↑ (17[a])	Mohamed et al. 1987 (MM)
Monkey; 140 days	0.065	↔	↔	–	↓ (33[a])	↑ (16[a])	Mohamed et al. 1987 (MM)
Rat; 5 days	9	↓ (17–45[b,c])	–	↑ (11–32[b,c])	–	–	Chen et al. 2019a (MMC)
Rat; 14 days	0.5	↓ (17[b])	↓ (50[a])	↑ (30[a])	–	↑ (350[b])	Fossato da Silva et al. 2011 (MM)
Rat; 14 days	0.93	↓ (18[b])	↓ (43[a])	↑ (20[a])	–	0	Fossato da Silva et al. 2011 (MM)
Rat; 14 days	2.8	↓ (16[b])	↓ (36[a])	↔	–	↔	Fossato da Silva et al. 2011 (MM)
Rat; 56 days	3.2	↔	–	–	–	–	Moussa et al. 2010 (M)
Rat; 133 days[d]	0.0008–0.008	↔	–	–	–	–	Friedmann et al. 1998 (MMC)
Rat; 133 days[d]	0.08	↓ (17[a])	–	–	–	–	Friedmann et al. 1998 (MMC)
Mouse; 728 days	0.03–0.15	↔	–	–	–	–	Hirano et al. 1986 (MMC)
Mouse; 728 days	0.724	↓ (NR[e])	–	–	–	–	Hirano et al. 1986 (MMC)

[a]Percent change compared to control, estimated from graphically reported data.
[b]Percent change compared to control, calculated from quantitative data.
[c]Alterations in sperm parameters observed 19–26 days after initial exposure.
[d]Rats only dosed 2 times/week.
[e]"Decreased spermatogenesis" reported in the testes; no quantitative data reported.

↑ = increased; ↓ = decreased; ↔ = no change; – = not assessed; MM = methylmercury; MMC = methylmercuric chloride; NR = not reported

In rats, decreased sperm number (in the cauda epididymides) and/or decreased sperm mobility were observed following acute-duration exposure to doses ≥0.5 mg Hg/kg/day (Fossato da Silva et al. 2011; Chen et al. 2019a) or intermediate-duration exposure to 0.08 mg Hg/kg/day (Friedmann et al. 1998). Acute-duration findings do not appear to be strongly dose-related; however, effects persisted and worsened post-exposure following higher exposure levels (9 mg Hg/kg/day) (Chen et al. 2019a). Fossato da Silva et al. (2011) also reported an increase in the proportion of sperm with head abnormalities following acute-duration gavage exposure to 0.5 mg Hg/kg/day, but not at higher doses (≥0.93 mg Hg/kg/day). In mice, decreased spermatogenesis was qualitatively reported in the testes of mice exposed to methylmercury at a dietary dose of 0.724 mg Hg/kg/day for 2 years (Hirano et al. 1986).

No exposure-related changes in serum testosterone levels or Leydig cell testosterone secretion were observed in monkeys following intermediate-duration exposure to methylmercury in apple juice at doses up to 0.065 mg Hg/kg/day (Mohamed et al. 1987). In rats, a limited number of studies reported dose- and duration-related decreases in serum testosterone following acute- or intermediate-duration exposures to methylmercury. Acute-duration gavage exposure to 2.8 mg Hg/kg/day resulted in a 65% decrease in serum testosterone (Fossato da Silva et al. 2011) and intermediate-duration drinking water exposure to 3.2 mg Hg/kg/day resulted in a 98% decrease in serum testosterone (Moussa et al. 2010). No exposure-related changes were observed for serum testosterone following gavage exposure to methylmercury at acute-duration doses up to 0.93 mg Hg/kg/day (Fossato da Silva et al. 2011) or intermediate-duration doses up to 0.08 mg Hg/kg/day (Friedmann et al. 1998). Decreased testicular (interstitial) testosterone levels were also reported following intermediate-duration exposure to methylmercury at a drinking water dose of 3.2 mg Hg/kg/day (-74%) (Moussa et al. 2010) or a gavage dose of 0.08 mg Hg/kg/day (-44%) (Friedmann et al. 1998). No changes in serum FSH or LH were reported in rats following acute-duration gavage exposure to methylmercury at doses up to 2.8 mg Hg/kg/day (Fossato da Silva et al. 2011).

No exposure-related changes in testicular histology were observed in monkeys following intermediate-duration exposure to methylmercury in apple juice at doses up to 0.065 mg Hg/kg/day (Mohamed et al. 1987). In rats, the only reported damage to the testes was reported 26 days after the start of a 5-day exposure to 9 mg Hg/kg/day via gavage as methylmercury (Chen et al. 2019a). Treatment-related findings included significant disruption of the germinal epithelium of the seminiferous tubules and few spermatozoa; these findings were not evident 12 or 19 days after the start of exposure. In other rat studies, no histopathological changes in the testes were observed following oral exposure to methylmercury at acute-duration doses up to 2.8 mg Hg/kg/day (Fossato da Silva et al. 2011), intermediate-duration doses up to 3.2 mg Hg/kg/day (Moussa et al. 2010), or chronic-duration exposure to

doses up to 0.16 mg Hg/kg/day (Verschuuren et al. 1976). In B6C3F1 mice, chronic-duration exposure to methylmercury at a dietary dose of 0.686 mg Hg/kg/day resulted in increased incidence of tubular atrophy of the testes; this increase was not observed at doses up to 0.139 mg Hg/kg/day (Mitsumori et al. 1990). However, no exposure-related testicular lesions were observed in ICR mice similarly exposed to intermediate- or chronic-duration dietary doses up to 0.724 mg Hg/kg/day (Hirano et al. 1986).

A single study in rats reported numerous histopathological lesions in the prostate following 14-day gavage exposure to methylmercury (Fossato da Silva et al. 2012). Alterations in prostate histology included increased incidence of inflammatory foci in 6/10 at 0.5 mg Hg/kg/day, periacinar connective tissue causing epithelial folds at 0.93 mg Hg/kg/day, and apparent thinning of the glandular epithelium, dilation of glandular acini, and higher nuclear-to-cytoplasmic ratio at 2.8 mg Hg/kg/day. Stereological measurements showed 40 and 34% increases in the epithelial component of the prostate at 0.5 and 0.93 mg Hg/kg/day, respectively; 46 and 56% decreases in the stromal component at 0.93 and 2.8 mg Hg/kg/day, respectively; and a 25% increase in the size of the lumen at 2.8 mg Hg/kg/day. In other studies, no evidence of pathological lesions in the prostate were observed following dietary exposure to methylmercury for up to 2 years at doses up to 0.16 mg Hg/kg/day in rats (Verschuuren et al. 1976) or 0.724 mg Hg/kg/day in mice (Hirano et al. 1986; Mitsumori et al. 1990).

There is no consistent evidence for alterations in male reproductive organ weights in rats following exposure to methylmercury. One study reported a significant 8% decrease in absolute testes weight following exposure to methylmercury at a gavage dose of 0.08 mg; relative testes weight was not reported, but no body weight effects were noted in the study (Friedmann et al. 1998). However, other studies reported no exposure-related changes in testes weight at acute-duration doses up to 2.8 mg Hg/kg/day (Fossato da Silva et al. 2011), intermediate-duration doses up to 3.2 mg Hg/kg/day (Moussa et al. 2010), or chronic-duration doses up to 0.16 mg Hg/kg/day (Verschuuren et al. 1976). A significant 28% decrease in relative seminal vesicle weight was reported in rats following acute-duration gavage exposure to 2.8 mg Hg/kg/day, but not ≤0.93 mg Hg/kg/day (Fossato da Silva et al. 2011); no other available studies evaluated seminal vesicle weight. No dose-related changes in prostate weight were observed at acute-duration doses up to 2.8 mg Hg/kg/day (Fossato da Silva et al. 2012) or chronic-duration doses up to 0.16 mg Hg/kg/day (Verschuuren et al. 1976), and no dose-related changes in epididymides weights were observed at acute-duration doses up to 2.8 mg Hg/kg/day (Fossato da Silva et al. 2011) or intermediate-duration doses up to 0.08 mg Hg/kg/day (Friedmann et al. 1998).

Studies in female laboratory animals provide no evidence of alterations to reproductive organ weight and/or histology following dietary exposure to methylmercury for up to 2 years at doses up to 0.18 mg Hg/kg/day in rats (Verschuuren et al. 1976) or 0.627 mg Hg/kg/day in mice (Hirano et al. 1986; Mitsumori et al. 1990).

Predominant Mercury Form Unknown (General Populations). Studies evaluating reproductive effects of mercury in general populations are summarized in Table 2-66. Studies of male reproductive effects used cross-sectional designs and evaluated sperm quality and serum reproductive hormones. Most studies had small study populations (n=30–394), although two studies examined larger populations (n=1,940–2,763) (Lee et al. 2019; Liu et al. 2023). One study evaluating serum hormone levels was conducted in adolescent males (Castiello et al. 2020). Studies were also conducted in male partners of infertile couples for which other causes for decreased fertility may have been effect modifiers. The most common biomarker was BHg. In males, a large range for mean or median BHg was reported (0.72–14.3 µg/L). In women, several study designs were used to evaluate reproductive effects, including several prospective studies. Reproductive effects were primarily assessed by measurement of serum levels of reproductive hormones and incidence of preterm birth, with some studies evaluating other reproductive effects (e.g., endometriosis, pre-eclampsia) and effects on ovarian stimulation in sub- or infertile women. Studies evaluating reproductive effects in females were generally larger (n=30–77,341) than in males. The most common biomarkers were BHg or HHg, with a range of BHg of 0.24–5.3 µg/L. In addition, a few studies evaluated reproductive success in couples. Two studies evaluated reproductive endpoints based on maternal and cord biomarkers (Sarzo et al. 2022; Wang et al. 2021a).

Table 2-66. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Reproductive Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Male reproductive effects			
Calogero et al. 2021 Cross-sectional; 179 men (Italy)	BHg median: 5.42 µg/L	Sperm concentration	↔ (BHg)
		Sperm count	↑ (BHg)
		Progressive motility	↔ (BHg)
		Normal sperm	↑ (BHg)
Castiello et al. 2020 Cross-sectional; 133 male adolescents (ages 15–17 years) (Spain)	UHg Gmean: 0.03 µg/g creatinine	Total testosterone	↔ (UHg)
		FSH	↔ (UHg)
		LH	↑ (UHg)

Table 2-66. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Reproductive Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Choy et al. 2002 Cross-sectional; 111 subfertile men (Hong Kong)	BHg mean: 8.3 µg/L	Sperm concentration	↔ (BHg)
		% motile sperm	↔ (BHg)
Lee et al. 2019 Cross sectional; 2,763 men (KoNEHS)	BHg median: 3.80 µg/L	FSH	↔ (BHg)
Liu et al. 2023 Cross-sectional; 1,940 men males (NHANES 2013–2016)	BHg Gmean: 0.81 mg/L	Total testosterone	↔ (BHg)
		Estradiol	↔ (BHg)
		SHBG	↔ (BHg)
		Free androgen index	↔ (BHg)
		Total testosterone/ estradiol ratio	↔ (BHg)
Leung et al. 2001 Cross-sectional; 51 male partners of infertile couples (Hong Kong)	BHg median Low mercury: 6.32 µg/L High mercury: 14.3 µg/L	Sperm concentration	↔ (BHg, low versus high BHg)
		Normal sperm morphology	↔ (BHg, low versus high BHg)
		Sperm velocity	↔ (BHg, low versus high BHg)
		FSH	↔ (BHg, low versus high BHg)
		LH	↔ (BHg, low versus high BHg)
		Testosterone	↔ (BHg, low versus high BHg)
		Prolactin	↔ (BHg, low versus high BHg)
Meeker et al. 2008 Cross-sectional; 219 men (Michigan)	BHg median: 1.10 µg/L	Sperm concentration	↔ (BHg)
		Sperm motility	↔ (BHg)
		Sperm morphology	↔ (BHg)
Mendiola et al. 2011 Case-control; 30 infertile men and 31 controls (Spain)	BHg mean Cases: 5.8 µg/L Control: 6.2 µg/L	FSH	↔ (BHg)
		LH	↔ (BHg)
		Testosterone	↔ (BHg)
		Sperm concentration	↔ (BHg)
		Sperm motility	↔ (BHg)
		Sperm morphology	↔ (BHg)

Table 2-66. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Reproductive Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Mínguez-Alarcón et al. 2018 Cross-sectional; 129 men enrolled in a study for infertile couples (Massachusetts)	HHg median: 0.72 µg/g Quartiles Q1: 0.03–0.37 µg/g Q2: 0.38–0.67 µg/g Q3: 0.70–1.25 µg/g Q4: 1.26–8.01 µg/g	Semen volume	↔ (HHg, Q1 versus Q4) ↔ (HHg, continuous)
		Sperm concentration	↔ (HHg, Q1 versus Q4) ↑ (HHg, continuous)
		Total sperm count	↔ (HHg, Q1 versus Q4) ↑ (HHg, continuous)
		Sperm motility	↔ (HHg, Q1 versus Q4) ↑ (HHg, continuous)
		Normal sperm morphology	↔ (HHg, Q1 versus Q4) ↔ (HHg, continuous)
Shi et al. 2021 Cross-sectional; 288 men, 28–57 years of age (Hong Kong)	BHg quartiles Q1: ≤3.85 µg/L Q2: >3.85–5.36 µg/L Q3: >5.37–7.22 µg/L Q4: >7.22 µg/L	Semen volume	↔ (BHg, Q4)
		Sperm concentration	↔ (BHg, Q4)
		Sperm count	↔ (BHg, Q4)
		Sperm motility	↔ (BHg, Q4)
		Motile sperm count	↔ (BHg, Q4)
		Sperm morphology	↔ (BHg, Q4)
		Sperm vitality	↔ (BHg, Q4)
Sukhn et al. 2018 Cross-sectional; 116 male partners of infertile couples (Lebanon)	BHg quartiles Q1: ≤4.35 µg/L Q2: 4.36–11.05 µg/L Q3: 11.06–21.47 µg/L Q4: ≥21.48 µg/L	Semen volume	↔ (BHg, Q4)
		Sperm concentration	↔ (BHg, Q4)
		Sperm count	↔ (BHg, Q4)
		Sperm motility	↔ (BHg, Q4)
		Sperm motility	↔ (BHg, Q4)
		Sperm viability	↔ (BHg, Q4)
		Sperm morphology	↔ (BHg, Q4)
Zeng et al. 2013 Cross-sectional; 118 men from an infertility clinic (China)	UHg median: 1.98 µg/L Cr	Testosterone	↔ (UHg)
Zeng et al. 2015 Cross-sectional; 394 men from an infertility clinic (China)	UHg median: 1.21 µg/L Cr	Sperm concentration	↔ (UHg)
		Sperm count	↔ (UHg)
		Sperm motility	↔ (UHg)
		Sperm morphology	↔ (UHg)

Table 2-66. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Reproductive Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Female reproductive effects			
An et al. 2021 Nested case-control; 126 cases, 348 controls (China)	BHg median Cases: 0.46 µg/L Controls: 0.43 µg/L SHg median Cases: 0.26 µg/L Controls: 0.24 µg/L ErHg median Cases: 0.64 Controls: 0.66	Preterm birth	↔ BHg ↔ SHg ↑ (ratio of SHg:ErHg, first trimester only)
Arakawa et al. 2006 Retrospective; 198 women (Japan)	HHg Gmean: 2.01 µg/g	TTP	↔ (HHg)
Ashrap et al. 2020 Prospective cohort; 731 pregnant women (Puerto Rico)	BHg median: 1.3 µg/L	Preterm birth	↔ (BHg)
Borghese et al. 2023 Cohort; 1,560 pregnant women (Canada)	BHg median (µg/L) Normotensive: 7.2 Gestational hypertension: 6.4 Pre-eclampsia: 6.6	Gestational hypertension	↔ (BHg)
		Pre-eclampsia	↔ (BHg)
Bloom et al. 2015 Prospective longitudinal; 253 couples with singleton deliveries (Michigan and Texas)	BHg Maternal tertiles T1 (33%): 0.66 µg/L T2 (median): 0.94 µg/L T3 (67%): 1.38 µg/L Paternal tertiles T1 (33%): 0.76 µg/L T2 (median): 1.11 µg/L T3 (67%): 1.76 µg/L	Gestational age	↑ (BHg, maternal T3; paternal T3)
Dickerson et al. 2011 Prospective; 30 subfertile women undergoing IVF (United Kingdom)	HHg mean: 0.89 µg/g	Oocyte yield after ovarian stimulation	↓ (HHg)
		Follicle number after ovarian stimulation	↓ (HHg)
		IVF fertilization rate	↔ (HHg)
Garcia-Fortea et al. 2018 Prospective; 194 subfertile women undergoing IVF (Spain)	HHg mean: 1.145 µg/g	Probability of mature oocytes	↓ (HHg)

Table 2-66. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Reproductive Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Gerald et al. 2023 Cross-sectional; 1,618 women, age, mean age 43.43 years (NHANES 2013–2016)	BHg median: 0.73 µg/L	Estrogen	↔ (BHg)
Gokoel et al. 2020 Cross-sectional; 1,143 pregnant women (Suriname)	HHg median: 0.826 µg/g Low HHg: < 1.1 µg/g High HHg: ≥1.1 µg/g	Preterm birth	↑ (HHg, high)
Jackson et al. 2008 Cross-sectional; 1,425 premenopausal women (NHANES)	BHg mean: 1.00 µg/L	Endometriosis	↔ (BHg)
		Uterine fibroids	↔ (BHg)
Jackson et al. 2011; Pollack et al. 2011 Cross-sectional; 252 premenopausal women (Buffalo, New York)	BHg median: 1.10 µg/L	Menstrual cycle length	↔ (BHg)
		FSH	↔ (BHg)
		LH	↔ (BHg)
		Estradiol	↔ (BHg)
		Progesterone	↔ (BHg)
Lee et al. 2019 Cross sectional; 1,926 postmenopausal women (KoNEHS)	BHg median: 2.81 µg/L	FSH	↔ (BHg)
Liu et al. 2019 Birth cohort; 1,274 women 24–72 hours post-partum (Boston)	ErHg quintiles Qi1: 0.58–1.56 mg/L Qi2: 1.57–2.10 mg/L Qi3: 2.12–2.80 mg/L Qi4: 2.81–4.28 mg/L Qi5: 4.40–24.80 mg/L	Pre-eclampsia	↔ (BHg, Qu5)
Liu et al. 2023 Cross-sectional; 1,559 females (NHANES 2013–2016)	BHg Gmean: 0.79 mg/L	Total testosterone	↔ (BHg)
		Estradiol	↔ (BHg)
		SHBG	↔ (BHg)
		Free androgen index	↔ (BHg)
		Total testosterone/ estradiol ratio	↔ (BHg)

Table 2-66. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Reproductive Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Ma et al. 2022 Nested case control; 146 cases with pre-eclampsia or gestational hypertension and 292 controls (China)	SHg median Cases: 0.33 µg/L Controls: 0.28 µg/L	Pre-eclampsia or gestational hypertension	↑ (SHg)
Maeda et al. 2019 Case-control; 98 infertile women and 43 controls (Japan)	BHg mean Infertile: 5.3 µg/L Control: 5.0 µg/L	Infertility	↑ (BHg)
		DHRA-S	↔ (BHg)
		Testosterone	↔ (BHg)
		Estradiol	↔ (BHg)
		Prolactin	↔ (BHg)
McClam et al. 2023 Cross-sectional; 1,919 women (amenorrhea), 1,900 (infertility) (NHANES 2013–2018)	BHg median: 0.61 µg/L	Amenorrhea	↔ (BHg)
		Infertility	↔ (BHg)
Mínguez-Alarcón et al. 2021 Prospective cohort; 353 women attending a fertility center (Massachusetts)	HHg tertiles T1: 0.001–0.39 µg/g T2: 0.40–0.99 µg/g T3: 1.00–8.60 µg/g	Antral follicle count (measure of ovarian reserve)	↑ (HHg, T2), only in the high n3PUFA group
Nyanza et al. 2020 Prospective longitudinal; 961 pregnant women (Tanzania)	BHg median: 1.2 µg/L	Spontaneous abortion	↔ (BHg)
		Preterm birth	↑ (BHg)
Ren et al. 2022 Prospective nested case-control; 82 cases of preterm birth and 415 controls (China)	HHg median Cases: 0.397 µg/g Controls: 0.410 µg/g	Preterm birth	↔ (HHg)
Rezaei et al. 2021 Cross-sectional; 102 pregnant women (60 with gestational diabetes and 42 without gestational diabetes) (Iran)	BHg mean With GDM: 2.60 µg/L No GDM 0.90 µg/L	GDM	↑ (BHg)
Shen et al. 2023 Case-control; 451 women, 217 controls and 234 cases (China)	BHg tertiles: T1: 0.010–1,207 µg/L T2: 1.208–1.893 µg/L T3: 1.894–5.205 µg/L	Risk of endometriosis	↑ (BHg, T2)

Table 2-66. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Reproductive Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Tatsuta et al. 2022 Cross-sectional; 78,964 pregnant women (1,624 with GDM and 77,341 without GDM) participating in JECS (Japan)	BHg median: 3.6 µg/L Quintiles Qi1: 0.18–2.31 Qi2: 2.32–3.16 µg/L Qi3: 3.17–4.12 µg/L Qi4: 4.13–5.62 µg/L Qi5: 5.63–58.8 µg/L	GDM	↑ (BHg, Qi4)
Tsuji et al. 2018 Cohort; 18,847 pregnant women (Japan)	BHg quartiles Q1: ≤2.57 µg/L Q2: 2.58–3.65 µg/L Q3: 3.66–5.16 µg/L Q4: ≥5.17 µg/L	Preterm birth	↔ (BHg, Q4)
Tsuji et al. 2019 Cross-sectional; 16,019 pregnant women (Japan)	BHg median: 3.65 µg/L BHg quartiles: Q1: ≤2.56 µg/L Q2: 2.57–3.64 µg/L Q3: 3.65–5.15 µg/L Q4: ≥5.16 µg/L	Placenta previa	↔ (BHg, Q4)
		Placenta accreta	↔ (BHg, Q4)
Wang et al. 2019b Nested case-control; 776 women with GDM and 776 without GDM	BHg median: All: 1.339 µg/L With GDM: 1.370 µg/L Without GDM: 1.300 µg/L Tertiles (all) T1: <0.99 T2: 0.99–1,73 T3: ≥1,73	GDM	↑ (BHg, T3)
Wang et al. 2020 Case-control; 427 women with pre-eclampsia and 427 controls (China)	BHg tertiles T1: <1,01 µg/L T2: 1.01–1.89 µg/L T3: ≥1.89 µg/L	Pre-eclampsia	↑ (BHg, T3)
Wang et al. 2023c Prospective cohort; 1,355 women, ages 45–56 years (United States)	UHg mean: 1.22 µg/L	Estradiol	↓ (UHg)
		FSH	↔ (UHg)
		SHBG	↔ (UHg)
Wells et al. 2016 Cross-sectional; 271 mother-infant pairs (Baltimore, Maryland)	Cord BMeHg Gmean: 0.94 µg/L	Gestational age	↔ (BMeHg)

Table 2-66. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Reproductive Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Wright et al. 2015 Prospective; 205 subfertile women undergoing IVF (Massachusetts)	HHg median: 0.62 µg/g	Oocyte yield after ovarian stimulation	↔ (HHg)
		IVF fertilization rate	↔ (HHg)
		Successful implantation	↔ (HHg)
		Live birth	↔ (HHg)
Xue et al. 2007 Prospective, 1,024 pregnant women (Michigan)	Maternal HHg median: 0.23 µg/g ≥90th percentile: 0.55–2.50 µg/g	Preterm birth (<35 weeks)	↑ (HHg, ≥90th percentile)
Yildirim et al. 2019 Case-control; 30 preterm delivery women and 20 term delivery women (Turkey)	Maternal BHg mean Preterm: 2.60 µg/L Term: 2.41 µg/L	Preterm birth	↔ (BHg)
Xu et al. 2022a Nested case-control; 74 cases of preterm birth and 74 controls (China)	SHg median Cases: 0.33 µg/L Controls: 0.25 µg/L Q4 range: 0.58–1.13 µg/L	Preterm birth	↑ (SHg, Q4)
Xu et al. 2022b Cross-sectional; 696 women at parturition (Argentina)	BHg Gmean: 0.52 µg/L	Preterm birth	↔ (BHg)
Yu et al. 2019 Nested case-control; 147 cases of preterm birth and 381 controls (China)	SHg mean Cases: 0.275 µg/L Controls: 0.242 µg/L	Preterm birth	↔ (SHg)
Zhang et al. 2023a Cross-sectional; 614 women (NHANES 2013–2016)	BHg median: 0.74 µg/L	Estradiol	↔ (BHg)
		Free estradiol	↔ (BHg)
		Total testosterone	↔ (BHg)
		Free testosterone	↔ (BHg)
		SHBG	↔ (BHg)
		Total testosterone/ estradiol ratio	↔ (BHg)
Zhao et al. 2023 Prospective cohort; 292 mother-infant pairs (China)	SHg mean (maternal in 2nd trimester): 0.69 µg/L	Gestational age	↑ (SHg)

Table 2-66. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Reproductive Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Zheng et al. 2021 Prospective; 1,311 pregnant women (Boston, Massachusetts)	ErHg median: 3.25 ng/g	Gestational glucose concentration	↔ (ErHg)
Zhu et al. 2020 Cross-sectional; 1,592 fertile and 204 ever infertile women (NHANES)	BHg mean: Infertile: 1.00 µg/L Fertile: 1.32 µg/L Stratified as <5.278 and >5.278 µg/L	Infertility	↔ (BHg, all BHg) ↑ (BHg, >5.278 µg/L)
Reproductive effects in couples			
Buck Louis et al. 2012 Prospective; 401 couples (United States)	BHg Gmean Males: 1.81 µg/L Females: 1.40 µg/L	Fecundity	↔ (BHg, males) ↔ (BHg, females) ↔ (BHg, couple)
Buck Louis et al. 2017 Cohort; 344 couples (United States)	BHg median Men: 1.18 µg/L Women: 0.98 µg/L	Pregnancy loss	↔ (BHg, men and women)
Cole et al. 2006 Cross-sectional; 41 couples (Canada)	BHg quartiles, women Q1: 0.4–0.6 µg/L Q2: 0.7–1.0 µg/L Q3: 1.1–1.2 µg/L Q4: 1.3–3.6 µg/L BHg quartiles, men Q1: 0–0.6 µg/L Q2: 0.7–1.0 µg/L Q3: 1.1–1.8 µg/L Q4: 1.9–4.8 µg/L	TTP	↑ (BHg, women Q4) ↔ (BHg, men Q4)
Reproductive effects following gestational exposure			
Sarzo et al. 2022 Prospective; 412 children, 9 years of age (Spain)	Males (medians) Cord BHg: 2.3 µg/L HHg Age 4 years: 2.8 µg/g Age 9 years: 2.9 µg/g Females (medians) Cord BHg: 2.2 µg/L HHg Age 4 years: 2.5 µg/g Age 9 years: 2.3 µg/g	Estradiol	↔ (BHg, cord, males and females) ↔ (HHg, males and females at 4 and 9 years)
		Testosterone	↔ (BHg, cord, males and females) ↔ (HHg, males 4 years, and females at 4 and 9 years) ↓ (HHg, males at 9 years)

Table 2-66. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Reproductive Effects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
		Tanner evaluation	↔ (BHg, cord female) ↓ (BHg, cord males) ↔ (HHg, males and females at 4 and 6 years)
Wang et al. 2021a Prospective birth cohort; 1,512 mother-child pairs (Boston)	Maternal ErHg tertiles T1: 0.30–1.37 µg/L T2: 1.38–3.06 µg/L T3: 3.08–27.8 µg/L	Precocious puberty	↑ (ErHg, maternal, T3)

↑ = positive association; ↓ = inverse association; ↔ = no association; BHg = blood mercury; Cr = creatinine; DHRA-S = dehydroepiandrosterone sulfate; ErHg = erythrocyte mercury; FSH = follicle-stimulating hormone; GDM = gestational diabetes mellitus; Gmean = geometric mean; HHg = hair mercury; IVF = *in vitro* fertilization; JECS = Japan Environment and Children's Study national birth cohort; KoNEHS = Korean National Environmental Health Survey; LH = luteinizing hormone; n3PUFA = long chain omega-3 polyunsaturated fatty acids; NHANES = National Health and Nutrition Examination Survey; Q = quartile; Qi = quintile; SHBG = sex hormone binding globulin; SHg = serum mercury; T = tertile; TTP = time to pregnancy; UHg = urine mercury

Male reproductive effects. Several studies on male reproductive function have been conducted in general populations. Study populations include men with no known pre-existing reproductive system abnormalities (Calogero et al. 2021; Lee et al. 2019; Liu et al. 2023; Meeker et al. 2008; Shi et al. 2021), sub- or infertile males (Choy et al. 2002; Mendiola et al. 2011; Zeng et al. 2013, 2015), and male partners of infertile couples (Leung et al. 2001; Mínguez-Alarcón et al. 2018; Sukhn et al. 2018). Results show no inverse associations between mercury and sperm quality. One study showed a positive association between BHg and sperm count and normal sperm (Calogero et al. 2021). Similarly, no associations between mercury biomarkers and serum levels of reproductive hormones in males were observed, except for one study in adolescent males that showed an inverse association between UHg and LH, but not total testosterone or LSH (Castiello et al. 2020). In male partners of infertile couples, the only association that was observed was positive associations between HHg and sperm concentration, total sperm count, and sperm motility (Mínguez-Alarcón et al. 2018); these effects are not adverse. Based on these findings, mercury exposure in general populations did not appear to adversely affect the male reproductive system in the populations studied.

Female reproductive effects. Epidemiological studies on female reproductive function have been conducted in different subpopulations: women with no known fertility issues (Arakawa et al. 2006;

Jackson et al. 2008, 2011; Pollack et al. 2011); sub- or infertile women (Dickerson et al. 2011; Garcia-Fortea et al. 2018; Maeda et al. 2019; Wright et al. 2015); and pregnant women (Tsuji et al. 2018; Wells et al. 2016; Yildirim et al. 2019). Outcomes assessed in nonpregnant women with no fertility issues include serum reproductive hormone levels, menstrual cycle length, and reproductive disorders (e.g., amenorrhea, endometriosis, uterine fibroids). In sub- or infertile women, serum reproductive hormones and other reproductive parameters to assess fertility were evaluated. Assessments in pregnant women included spontaneous abortion, preterm birth, and other pregnancy associated disorders (e.g., pre-eclampsia, gestational diabetes). Several study types were used to evaluate reproductive effects, including prospective, case-control, retrospective, cohort, and cross-sectional designs. As discussed below, taken together, epidemiological studies on females provide conflicting results, with no clear evidence of adverse reproductive effects.

Results of studies in nonpregnant women with no known fertility issues indicate that the female reproductive system is not a sensitive target for mercury. No associations between mercury biomarkers and serum reproductive hormones (e.g., estradiol, FSH, LH, progesterone, testosterone) were observed in available studies (Gerald et al. 2023; Jackson et al. 2011; Liu et al. 2023; Wang et al. 2023c; Zhang et al. 2023a), except for one prospective study showing an inverse association between UHg and estradiol (Wang et al. 2023c). No associations have been observed between BHg and menstrual cycle length (Jackson et al. 2011; Pollack et al. 2011), amenorrhea (McClam et al. 2023), or uterine fibroids (Jackson et al. 2008). Results of two studies on endometriosis were conflicting, with one study finding no association between BHg (0.61 μg/L) and endometriosis (Jackson et al. 2008), and another study showing an increased risk of endometriosis at a BHg range of 1.2–5.2 μg/L (Shen et al. 2023). No associations were observed between HHg and time to pregnancy (Arakawa et al. 2006) or infertility (McClam et al. 2023). However, in a study of combined fertile and “ever infertile” women, the risk of infertility was increased at BHg levels >5.278 μg/L (Zhu et al. 2020).

In sub- or infertile women, a case-control study reported a positive association between BHg and infertility, but no associations were observed between BHg and reproductive hormones (Maeda et al. 2019). Three prospective studies evaluated associations between mercury and ovarian response to stimulation in sub- or infertile women, with studies reporting conflicting results (Dickerson et al. 2011; Garcia-Fortea et al. 2018; Wright et al. 2015). Inverse associations were observed between HHg and oocyte yield, follicle number and probability of mature oocytes (Dickerson et al. 2011; Garcia-Fortea et al. 2018), whereas Wright et al. (2015) did not find an association between HHg and oocyte yield. A prospective study of women attending a fertility clinic found a positive association between HHg (range

0.04–8.6 µg/g) and antral follicle count (a measure of ovarian reserve); however, these associations were only observed in the group of women with higher long-chain omega-3 polyunsaturated fatty acids (n3PUFA) levels than the median, suggesting that the positive association may be due to the beneficial effects of n-3 PUFA rather than mercury (Mínguez-Alarcón et al. 2021). No associations were observed for *in vitro* fertilization (IVF) rate or successful implantation (Garcia-Fortea et al. 2018; Wright et al. 2015).

Several studies in pregnant women examined associations between mercury and preterm birth (<35 weeks of gestation) or gestational age; results are conflicting. Three prospective studies observed positive associations between mercury biomarkers and preterm birth (Nyanza et al. 2020; Xue et al. 2007; Zhao et al. 2023). A prospective study in a U.S. population observed a positive association for HHg and preterm birth (Xue et al. 2007) and a prospective study in a small Chinese population showed a positive association between SHg and gestational age (Zhao et al. 2023). Nyanza et al. (2020) also reported a positive association between BHg and preterm birth, but no association for spontaneous abortion. In contrast, other prospective studies did not find associations between BHg or HHg and preterm birth (Ashrap et al. 2020; Ren et al. 2022). Other case-control, cohort, and cross-sectional studies did not show associations between biomarkers and preterm birth or gestational age, except for a small, nested case-control study showing a positive association for the highest quartile of SHg (0.058–1.13 µg/L) (Xu et al. 2022a).

Studies also assessed associations between mercury biomarkers and other disorders during pregnancy, including pre-eclampsia and gestational hypertension, gestational diabetes, and placenta previa or accreta. One case-control study (427 cases and 427 controls) showed an association between BHg and pre-eclampsia at the highest exposure tertile (≥1.89 µg/L) (Wang et al. 2020). However, other studies of larger populations (1,274–1,560) did not find associations (Borghese et al. 2023; Liu et al. 2019). Three cross-sectional studies and one case-control study showed positive associations between BHg and gestational diabetes (Rezaei et al. 2021; Tatsuta et al. 2022; Wang et al. 2019b), although a prospective study of an NHANES population did not find an association between erythrocyte mercury and gestational glucose concentration. A larger cross-sectional study of a Japanese population did not observed associations between BHg and placenta previa or accreta (Tsuji et al. 2019). Given the conflicting results of studies in pregnant women, inadequate data were identified to determine if mercury exposure in general populations adversely affects the female reproductive system.

Reproductive effects in couples. Studies evaluating reproductive effects in couples show no associations between fecundity or pregnancy loss (Buck Louis et al. 2012, 2017), although an association was observed for time to pregnancy based on BHg in women, but not in men. Data are inadequate to determine if exposure to mercury adversely affects reproductive success.

Reproductive effects in offspring following gestational exposure. Two studies evaluated reproductive effects using biomarkers that reflect gestational exposure (Sarzo et al. 2022; Wang et al. 2021a). Sarzo et al. (2022) did not find associations between cord BHg and serum estradiol or testosterone measured at 9 years of age. However, tanner evaluation showed an inverse association between cord BHg in males, but not females. Wang et al. (2021a) observed a positive association between maternal erythrocyte mercury and precocious puberty at the highest exposure tertile. However, findings of these studies have not been corroborated.

Mechanisms of Action. General mechanisms of toxicity of mercury, including oxidative stress and inflammation are likely involved in the toxicity to male and female reproductive systems (Section 2.21). Several mechanisms may be involved in the toxicity of mercury compounds to the reproductive system (Ferguson and Chin 2017; Lu et al. 2018; Schuurs 1999; Tan et al. 2009; Wirth and Mijal 2010). Proposed mechanisms include the following: (1) altered hormonal regulation of the hypothalamic-pituitary-gonadal axis; (2) disruption of steroidogenesis; (3) enzyme inhibition; (4) inhibition of DNA, RNA, and protein synthesis; (5) decreased mitochondrial energy production and alterations of microtubule assembly in sperm tails; (6) altered estrogen production resulting in decreased numbers, size, and quality of ova; (7) agonist activity at estrogen receptors; (8) genetic polymorphisms; and (9) DNA methylation in sperm. In addition, mercury has been shown to accumulate in the hypothalamic-pituitary-gonadal axis.

2.18 DEVELOPMENTAL

A large body of literature addresses the potential for mercury exposure to produce neurological effects following exposure during early development. Similarly, several animal studies address the potential for mercury exposure to produce immunological effects following exposure during early development. Studies that have evaluated neurodevelopmental outcomes in humans and animal models are discussed in Section 2.16 (Neurological) and studies that have evaluated altered immune system development in animal models are discussed in Section 2.15 (Immunological) to facilitate comparison with effects observed following adult exposure. This section discusses developmental effects of mercury other than

neurodevelopmental and immunodevelopmental effects. The term "developmental" used in the discussion that follows refers to effects other than neurodevelopmental and immunodevelopmental.

Overview. Data on developmental effects of mercury are available from epidemiology studies and studies in animals. Epidemiological studies have assessed effects in workers exposed to elemental mercury, populations with high fish diets, and general populations. These studies examined possible associations between mercury exposure and anthropometric measures in newborns (e.g., birth weight and size) and postnatal growth in children. The studies reported conflicting results, with no strong evidence of associations between mercury exposure and *in utero* or postnatal growth.

Studies evaluating developmental toxicity in animals are available for inhalation exposure to elemental mercury or oral exposure to mercuric chloride, mercuric acetate, or methylmercury. Overall, oral studies indicate dose- and duration-dependent developmental toxicity (increased offspring mortality, increased malformations and variations, decreased body weight) in rodents exposed to methylmercury, predominantly at maternally toxic doses. Oral studies with exposure to inorganic mercury salts are limited but suggest potential decreases in postnatal growth and survival following exposure to mercuric chloride, primarily at maternally toxic doses. Evidence from inhalation studies are too limited to draw conclusions.

The following summarizes results of epidemiological and animal studies on developmental outcomes.

- ***Elemental mercury***
  - *Epidemiology studies*
    - Few studies have evaluated effects of exposure to elemental mercury and developmental outcomes.
    - One study reported an increased risk of small for gestational age (SGA) infants in dental workers versus controls; this outcome was not evaluated in other studies.
    - No associations were observed between exposure and anthropometric measures in neonates, neonatal mortality, or congenital malformations.
    - Available data are not sufficient to determine if exposure to elemental mercury is associated with adverse developmental outcomes.
  - *Animal studies*
    - Few studies investigated effects on developmental toxicity; one study reported developmental toxicity in rats (increased resorptions, decreased birth weight) following exposure to maternally toxic exposure levels.

- ***Inorganic mercury salts***
  - *Epidemiology studies*
    - No epidemiological studies evaluating associations between exposure to inorganic mercury salts and developmental effects were identified.
  - *Animal studies*
    - Developmental endpoints evaluated in available studies are primarily limited to survival and growth parameters.
    - Decreased postnatal growth and survival have been reported in two multigenerational studies at doses associated with maternal toxicity; a few additional studies have reported decreased body weight in offspring following gestational exposure.
    - Available data are not sufficient to determine if exposure is associated with adverse developmental outcomes at oral exposures below those associated with maternal toxicity.
- ***Organic mercury***
  - *Epidemiology studies*
    - In the Minamata population, congenital defects were observed in infants.
    - Results of studies evaluating birth size and postnatal growth in populations with high maternal fish diets were inconsistent, with most results reporting no associations.
    - Available studies do not provide evidence of adverse effects on *in utero* or postnatal growth.
  - *Animal studies*
    - Developmental studies consistently reported dose- and duration-dependent decreases in offspring survival and increases in malformations and variations in rats and mice. Common malformations observed in both rats and mice at high doses include cleft palate, skeletal malformations (ribs, sternebrae), and hydronephrosis.
    - Developmental studies in mice consistently reported dose- and duration-dependent decreases in offspring body weight; findings in rat were less consistent.
    - The majority of effects were noted at maternally toxic doses, but some effects were observed below doses associated with maternal toxicity.
- ***Predominant mercury form unknown (general populations)***
    - Evidence for effects on mercury exposure on birth size in general populations is inconclusive, with studies reporting inconsistent results. Most studies did not observe associations between mercury biomarkers and birth size.

- Few studies have evaluated effects of mercury exposure on postnatal growth in general populations. The study results were inconsistent and do not provide clear evidence that mercury exposure in general populations is associated with decreased postnatal growth.

Confounding Factors. Numerous complicating factors may add uncertainty in the interpretation of studies examining associations between mercury exposure and developmental effects if not homogenously distributed in the study population. These factors include nutrition during pregnancy, prenatal care, adequate nutrition during infancy and childhood, socio-economic factors, intercurrent diseases, alcohol consumption, smoking status, and potential exposure to other chemicals. Failure to account for these factors may attenuate or strengthen the apparent associations between mercury exposure and the outcome, depending on the direction of the effect of the variable on the outcome.

Elemental Mercury—Epidemiological Studies. Few studies have evaluated effects of occupational exposure and developmental effects; studies are summarized in Table 2-67. Developmental outcomes evaluated were birth size, congenital malformations, and mortality. Two prospective studies examined small populations of females exposed through dental work or amalgam fillings (Bedir Findik et al. 2016; El-Badry et al. 2018) and one retrospective study evaluated neonates of male and female chloralkali workers (Frumkin et al. 2001). The only adverse effect observed was an increased risk (risk ratio 6.2; 95% CI 2.3, 16.4) of SGA infants in dental workers versus controls (El-Badry et al. 2018). SGA was not evaluated in the other studies. No other adverse associations between biomarkers (cord BHg or UHg) were observed for anthropometric measures, congenital malformations, or neonatal mortality. Data are not adequate to determine if exposure to elemental mercury is associated with adverse developmental outcomes.

Table 2-67. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Developmental Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Bedir Findik et al. 2016 Prospective case-control; 28 pregnant women with amalgam fillings and 32 pregnant women with no amalgam fillings (Turkey)	BHg mean, cord Amalgam: 0.5 µg/L No amalgam: 0.3 µg/L BHg mean, maternal Amalgam: 0.50 µg/L No amalgam: 0.27 µg/L	Weight	↔ (BHg amalgam versus no amalgam)
		Length	↔ (BHg, amalgam versus no amalgam)
		Head circumference	↔ (BHg, amalgam versus no amalgam)
		Gender	↔ (BHg, amalgam versus no amalgam)

Table 2-67. Results of Epidemiological Studies Evaluating Exposure to Elemental Mercury (Hg^0) and Developmental Effects

Reference, study type, and population	Biomarker	Outcome evaluated	Result
		Neonatal mortality	↔ (BHg, amalgam versus no amalgam)
El-Badry et al. 2018 Prospective; 64 pregnant dental workers and 60 pregnant controls (Egypt)	UHg mean, workers 1st trimester: 42.2 µg/g Cr 2nd trimester: 41.8 µg/g Cr 3rd trimester: 42.8 µg/g Cr UHg mean, control: 1st trimester: 6.2 µg/g Cr 2nd trimester: 6.3 µg/g Cr 3rd trimester: 7.1 µg/g Cr	SGA	↑ (UHg, workers versus controls)
		Congenital malformations	↔ (UHg, workers versus controls)
Frumkin et al. 2001 Retrospective cohort; 147 chloralkali workers and 132 controls (Brunswick, Georgia)	UHg mean Workers: 2.76 µg/g Cr Controls: 2.31 µg/g Cr	Birth weight	↔ (UHg)
		Fetal malformation	↔ (UHg)

↑ = positive association or increased compared to controls; ↔ = no association; BHg = blood mercury; Cr = creatinine; SGA = small for gestational age; UHg = urine mercury

Elemental Mercury—Animal Studies. The developmental effects of exposure to elemental mercury have not been well-studied in animals. An increase in the number of resorptions, decreased litter size, and decreased pup weight on PND 1 was observed in rats following inhalation exposure to 8 mg Hg/m^3 for 2 hours/day on GDs 6–15; maternal toxicity (body weight loss) was observed in this group (Morgan et al. 2002). These effects were not observed in groups similarly exposed to ≤4 mg Hg/m^3 on GDs 6–15 or ≤8 mg Hg/m^3 on GD 6 or GDs 6–10 (Morgan et al. 2002). In other acute-duration inhalation studies, no exposure-related changes in litter size or birth weight were observed in rats following exposure to 1.8 mg Hg/m^3 for 1 or 3 hours/day on GDs 11–14 plus GDs 17–20 or 1–5 hours/per day on GDs 14–19 (Danielsson et al. 1993; Fredriksson et al. 1996). No changes in postnatal growth were observed in rats following direct postnatal inhalation exposure to 0.05 mg Hg/m^3 for 1 or 4 hours/day on PNDs 11–17 (Fredriksson et al. 1992). In mice, no changes in PND 10 body weight were observed following gestational exposure to 0.03 mg Hg/m^3 for 6 hours/day on GDs 0–18 (Yoshida et al. 2011). In squirrel monkeys, no exposure-related differences in birth weight, weight gain, or body weight through 4 years of age were observed in offspring following exposure to 0.5 or 1 mg Hg/m^3 for 4 or 7 hours/day, 5 days/week during the last two-thirds of gestation (Newland et al. 1996).

No exposure-related changes in emergence of developmental landmarks (e.g., pinna unfolding, tooth eruption) or reflex ontogeny (e.g., surface righting, negative geotaxis) were observed in rats following acute-duration gestational inhalation exposure to 1.8 mg Hg/m^3 for 1–5 hours per day (Danielsson et al. 1993; Fredriksson et al. 1996).

Inorganic Mercury Salts—Animal Studies. A limited number of developmental endpoints have been evaluated in laboratory animals exposed to mercuric chloride in multigenerational, gestational, gestational plus lactational, and early postnatal exposure studies. Most available studies were focused on neurological or immune development, which are discussed in Section 2.16 (Neurological) or Section 2.15 (Immunological), respectively, with limited information on systemic developmental toxicity (e.g., body weight). No comprehensive developmental toxicity evaluations were available (e.g., examinations for skeletal or visceral malformations); therefore, oral data are too limited to draw conclusions. However, some studies indicate that growth and survival of offspring may be impacted following developmental exposure to mercuric chloride, generally at oral doses associated with maternal toxicity in rodents.

Reduced postnatal survival has been reported in rats following developmental exposure to mercuric chloride at high oral doses. In a 2-generation gavage study in rats, neonatal survival to PND 4 decreased by 59% in F1 offspring at 1.98 mg Hg/kg/day and 19% in F2 offspring at 1.11 mg Hg/kg/day (F1 dams were not mated at 1.98 mg Hg/kg/day due to low F1 birth and survival rates); maternal toxicity (decreased body weight, decreased survival) were observed in F0 dams at ≥1.11 mg Hg/kg/day (Atkinson et al. 2001). In a gestation-only study, pup mortality was increased by 16% following maternal drinking water exposure to 9.6 mg Hg/kg/day on GDs 1–21; no maternal toxicity was observed (Chehimi et al. 2012). In mice, no exposure-related changes in postnatal survival were observed following exposure to gavage doses up to 0.74 mg Hg/kg/day in a 1-generation study (Khan et al. 2004) or drinking water exposure to 1.5 mg Hg/kg/day on GDs 0–21 (Pilones et al. 2009).

No gross malformations were seen in rat offspring following gestational exposure to gavage doses up to 1.6 mg Hg/kg/day on GDs 5–15 (Papp et al. 2005). No changes in reflex ontogeny were observed in rat offspring following drinking water exposure to doses up to 3.8 mg Hg/kg/day from GD 0 to PND 21 (Oliveira et al. 2016). No other identified studies specifically evaluated malformations or reflex ontogeny following developmental exposure to mercuric chloride.

Body weight effects in rat offspring have been reported following gestational and/or postnatal exposure to mercuric chloride; findings were often associated with maternal toxicity. In a 2-generation gavage study,

birth weight was decreased by 30% in F1 offspring at 1.98 mg Hg/kg/day and dose-related decreases in body weight were observed at all doses by PND 21 (20, 30, and 35% reductions at 0.55, 1.11, and 1.98 mg Hg/kg/day, respectively); F0 dam body weights were decreased at ≥1.11 mg Hg/kg/day (Atkinson et al. 2001). No exposure-related decreases were observed in F2 offspring at doses up to 1.11 mg Hg/kg/day (no F2 litters at 1.98 mg Hg/kg/day). A gavage study in rats exposed to 3 mg Hg/kg/day on GDs 1–21 reported a 17% decreased birth weight of offspring (Ismail and El-Meligy 2021). A non-specified "slight" decrease in birth weight was reported in female rat pups following gestational exposure to gavage doses ≥0.8 mg Hg/kg/day on GDs 5–15; no exposure-related changes were observed in male birth weight and no exposure-related changes were observed in body weights of either sex at 12 weeks of age at gestational doses up to 1.6 mg Hg/kg/day (Papp et al. 2005). Similarly, no body weight effects at 12 weeks of age were observed in similarly treated rats with continued postnatal exposure on PNDs 2–28 (via dam) or PNDs 2–28 (via dam) plus direct exposure on PNDs 29–84 (Papp et al. 2005). In a drinking water study, no changes in fetal body weight on GD 20 were observed in rats following exposure doses up to 0.0301 mg Hg/kg/day on GDs 0–20 (Oliveira et al. 2012). However, maternal exposure to higher drinking water doses of 6.1 or 9.6 mg Hg/kg/day on GDs 1–21 resulted in offspring body weight decreases of approximately 10–15 and 20–30%, respectively, through PND 17 (Chehimi et al. 2012). No postnatal body weight effects were noted in rats following maternal exposure to doses up to 0.094 mg Hg/kg/day throughout gestation and lactation; body weights were monitored through PND 40 (Galiciolli et al. (2022).

Developmental body weight data in mice exposed to mercuric chloride are limited and inconsistent. In ICR mice, a 6% decrease in birth weights and a 12% decrease in PND 70 body weights were observed in offspring following gavage exposure to 0.4 mg Hg/kg/day during gestation plus lactation (GD 0 to PND 21); body weight decreases were slightly more (15%) if direct exposure continued postweaning through PND 70 (Huang et al. 2011). No changes were observed in birth weights of SfvF1 or FvSF1 (autoimmune-susceptible) mice following drinking water exposure to 2.7 mg Hg/kg/day from GD 8 to PND 21 (Zhang et al. 2013). In a gestation-only study, no changes in birth weight were noted in DBF1 mouse offspring following drinking water exposure to 1.5 mg Hg/kg/day on GDs 0–21 (Pilones et al. 2009).

One study evaluated developmental toxicity in hamster offspring on GD 12 or 14 following a single maternal exposure to oral mercuric acetate on GD 8 (Gale 1974). The number of resorptions was increased in a dose-related manner at doses ≥22.1 mg Hg/kg/day, with 99% resorption at 63 mg Hg/kg/day. Additionally, the percentage of "malformed" embryos was increased at ≥15.8 mg Hg/kg/day,

and the crown-rump length was decreased at ≥5 mg Hg/kg/day. Maternal toxicity (weight loss, diarrhea, tremor, somnolence, liver and kidney damage) was qualitatively reported; however, the dose(s) associated with effects were not reported. While no malformations were reported, one study reported ultrastructural changes in fetal lungs that included collapsed alveoli and cellular degeneration in the offspring of dams exposed to 3 mg Hg/kg/day on GDs 1–21 (Ismail and El-Meligy 2021).

Organic Mercury—Epidemiological Studies. Congenital malformations were reported in infants of Minamata mothers who consumed fish contaminated with very high levels of methylmercury (Harada 1995; Rice et al. 2014). Malformations included polydactyly, syndactyly, craniofacial malformations, microcornea, undescended testicles, enlarged colon, and protrusion of the coccyx.

Epidemiological studies investigating effects of mercury exposure on developmental outcomes in populations with high fish diets are summarized in Table 2-68. Studies include populations from the Faroe Islands and Seychelles Islands, an Inuit population, and other populations with high maternal fish consumption. Most studies evaluated populations with <300 participants, although a few studies evaluated larger populations (1,756–2,152 participants). Most studies used prospective designs and one study was a pooled analysis of prospective studies (Timmermann et al. 2017). Outcomes evaluated included anthropometric measures at birth (weight, length, head circumference), and postnatal growth, sex ratio, and heart rate variability. Most studies assessed mercury exposure using maternal and/or umbilical cord BHg. Collectively, these studies do not provide strong evidence for associations between maternal mercury exposure and birth weight or length; however, some studies found associations with head circumference and postnatal growth.

Table 2-68. Epidemiological Studies Evaluating Associations between Mercury and Developmental Effects in Populations with High Maternal Fish Diets

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Faroe Islands			
Grandjean et al. 2001 Prospective birth cohort; 182 pregnant women (Faroe Islands)	Cord BHg tertiles T1: <14 µg/L T2: 14–33 µg/L T3: >33 µg/L	Birth weight	↔ (BHg, T3)

Table 2-68. Epidemiological Studies Evaluating Associations between Mercury and Developmental Effects in Populations with High Maternal Fish Diets

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Grandjean et al. 2003 Prospective birth cohort; 171 children evaluated at 18 months and 154 evaluated at 42 months (Faroe Islands)	Cord BHg mean: 20.4 µg/L	Postnatal weight	↓ (BHg, 18 months) ↔ (BHg, 42 months)
		Postnatal height	↔ (BHg, 18 months) ↔ (BHg, 42 months
Timmermann et al. 2017 Pooled data from 3 prospective birth cohorts; 2,152 mother-child pairs (Faroe Islands)	Maternal HHg median Cohort 1: 4.49 µg/g Cohort 3: 2.20 µg/g Cohort 5: 0.71 µg/g	Sex ratio (male:female)[a]	↑ (HHg, combined cohorts) ↔ (HHg, cohort 1) ↔ (HHg, cohort 3) ↑ (HHg, cohort 5)
Seychelles Islands			
van Wijngaarden et al. 2014 Prospective birth cohort; 230 mother-infant pairs (Seychelles Islands)	Maternal HHg mean: 5.9 µg/g	Birth weight	↔ (HHg)
Yeates et al. 2020 Prospective birth cohort; 1,236 mother-infant pairs (Seychelles Islands)	Maternal HHg mean (prenatal) Mothers of males: 3.96 µg/g Mothers of females: 3.90 µg/g	Birth weight	↔ (HHg)
		Birth length	↔ (HHg)
		Head circumference	↔ (HHg)
Zareba et al. 2019 Prospective birth cohort; 514 mother-child pairs participating; assessments made in offspring at 19 years of age (Sechelles)	Maternal HHg mean: 6.92 µg/g Offspring HHg mean at age 19 years: 10.21 µg/g	Heart rate variability	↔ (HHg, maternal) ↔ (HHg, offspring age 19 years)
Inuit populations			
Dallaire et al. 2013 Prospective longitudinal; 248 mother-infant pairs; Inuit (Arctic Quebec) (adjusted for DHA fatty acids from fish)	Cord BHg mean: 21.3 µg/L	Birth weight	↔ (BHg)
		Birth length	↔ (BHg)
		Head circumference	↔ (BHg)
Other populations			
Murcia et al. 2016 Prospective birth cohort; 1,756 mother-infant pairs with high maternal fish consumption (Spain)	Cord BHg Gmean: 8.2 µg/L Tertiles T1: 5.0–<8.5 µg/L T2: 8.5–<15.0 µg/L T3: ≥15.0 µg/L	Birth weight	↔ (BHg, T3)
		Birth length	↔ (BHg, T3)
		Head circumference	↓ (BHg, T3)

Table 2-68. Epidemiological Studies Evaluating Associations between Mercury and Developmental Effects in Populations with High Maternal Fish Diets

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Tang et al. 2016 Cross-sectional; 103 mother-infant pairs with high maternal fish consumption (China)	Cord BHg median: 21.94 µg/L	Birth weight	↔ (BHg)
		Birth length	↔ (BHg)
		Head circumference	↔ (BHg)
Tatsuta et al. 2017 Prospective birth cohort; 289 mother-infant pairs (252 male newborns and 237 female newborns) with high maternal fish consumption (Japan)	Cord BHg mean: 10.1 µg/L	Birth weight	↑ (BHg, males) ↔ (BHg, females) ↔ (BHg, males and females)

[a]The toxicological significance of a positive association between HHg and male:female sex ratio is not established.

↑ = positive association, indicating an increase in the measured parameter; ↓ = inverse association, indicating a decrease in the measured parameter; ↔ = no association; BHg = blood mercury; DHA = docosahexaenoic acid; Gmean = geometric mean; HHg = hair mercury; T = tertile

Results of studies evaluating anthropometric measures in populations with high maternal fish diets do not provide evidence of adverse effects. The largest prospective study (n=1,236) from the Seychelle Islands (Nutrition cohort 2) found that maternal HHg was not associated with birth weight, length, or head circumference (Yeates et al. 2020). This outcome is consistent with results from the smaller (n=230) main Seychelle Islands cohort (van Wijngaarden et al. 2014) and from the Faroe Islands prospective cohort (Grandjean et al. 2001). Another large prospective study conducted in Spain (n=1,756) also did not find an association between mercury exposure (cord BHg) and birth weight or birth length (Murcia et al. 2016). However, this study did find an association with decreasing head circumference at birth (-0.052 cm per doubling of total BHg; 95% CI 0.109, 0.005)). Other smaller prospective studies did not find associations between increasing with birth weight and/or birth length (Dallaire et al. 2013; Tatsuta et al. 2017). One prospective study of a Faroe Islands birth cohort evaluated postnatal growth in children from birth to 18 and 42 months of age (Grandjean et al. 2003). Results showed an inverse association between umbilical cord BHg and postnatal weight at 18 months, with a 0.8 kg (95% CI -1.56, -0.04) decrease per 10-fold increase in umbilical cord BHg. However, no association was observed at 42 months, and no associations were observed for postnatal height at 18 or 42 months.

A large pooled analysis of data from three prospective birth cohorts in the Faroe Islands, found a positive association between maternal HHg and male:female sex ratio (Timmermann et al. 2017). Examination of individual cohorts showed that this association only occurred in the cohort with the lowest HHg. One prospective study evaluated heart rate variability in children (age 19 years) from the Seychelle Islands cohort and found no association with maternal HHg (Zareba et al. 2019).

Organic Mercury—Animal Studies. Decreased offspring survival and increased malformations and variations are associated with developmental exposure to methylmercury compounds in rats and mice in a dose- and duration-dependent manner. Offspring body weight decreases in mice are also dose- and duration-dependent, while body weight findings in rats are less consistent. While the majority of effects are noted at maternally toxic doses, some effects were observed below doses associated with maternal toxicity, indicating that the developing organism may be susceptible to methylmercury toxicity.

Several studies have reported increased fetal death/resorption, decreased litter size, and/or decreased neonatal survival in rats following gestational exposure to methylmercury, predominantly at doses associated with maternal toxicity (Table 2-69). Increased fetal death and decreased live litter size were observed in rats in a dose- and duration-dependent manner following gestational exposure to a single dose ≥8 mg Hg/kg/day, repeat acute-duration doses ≥6 mg Hg/kg/day, or an intermediate-duration dose of 1.9 mg Hg/kg/day; these findings were associated with maternal toxicity (decreased body weight, clinical signs of toxicity) (Fuyuta et al. 1978; Gandhi et al. 2013; Lee and Han 1995). Decreased postnatal survival to weaning was observed following gestational exposure to 7 mg Hg/kg/day on GD 8 or 15, with increased mortality following exposure on GD 15, compared to GD 8; no maternal toxicity was noted (Carratu et al. 2006). No change in postnatal survival was observed in rats exposed to 6.4 mg Hg/kg/day on GD 15 (Cagiano et al. 1990), 1.9 mg Hg/kg/day on GDs 6–9 (Fredriksson et al. 1996), or doses up to 0.9 mg Hg/kg/day on GDs 5–21 (Gandhi et al. 2013).

Table 2-69. Pre- and Postnatal Survival in Rats Following Gestation-Only Exposure to Methylmercury Compounds

Duration; dose (mg Hg/kg/day)	Dead/ resorbed[a]	Live litter size[a]	Postnatal survival[a]	Reference (compound)
1 day, GD 15; dose: 6.4	–	–	↔ PND 21	Cagiano et al. 1990 (MMC)
1 day, GD 8; dose: 7	–	↔	↓ PND 21 (8)	Carratu et al. 2006 (MM)

Table 2-69. Pre- and Postnatal Survival in Rats Following Gestation-Only Exposure to Methylmercury Compounds

Duration; dose (mg Hg/kg/day)	Dead/ resorbed[a]	Live litter size[a]	Postnatal survival[a]	Reference (compound)
1 day, GD 15; dose: 7	–	↔	↓ PND 21 (16)	Carratu et al. 2006 (MM)
1 day GD 7; dose: 8[b]	↑ (17)	↓ (19)	–	Lee and Han 1995 (MMC)
1 day, GD 7; dose: 16[b]	↑ (19)	↓ (41)	–	Lee and Han 1995 (MMC)
1 day, GD 7; dose: 24[b]	↑ (41)	↓ (91)	–	Lee and Han 1995 (MMC)
4 day, GDs 6–9; dose: 0.02–0.4	–	↔	–	Stoltenburg-Didinger and Markwort 1990 (MMC)
4 days, GDs 6–9; dose: 1.9	–	–	↔	Fredriksson et al. 1996 (MM)
4 days, GDs 6–9; dose: 4	–	↔	–	Stoltenburg-Didinger and Markwort 1990 (MMC)
8 days, GDs 7–14; dose: 2[b] or 4[b]	↔	↔	–	Fuyuta et al. 1978 (MMC)
8 days, GDs 7–14; dose: 6[b]	↑ (38)	↓ (45)	–	Fuyuta et al. 1978 (MMC)
9 days, GDs 6–14; dose: 0.024–4.6[b]	↔	↔	–	Nolen et al. 1972 (MMC)
17 days, GDs 5–21; dose: 0.5–0.9	↔	↔	↔	Gandhi et al. 2013 (MM)
17 days, GDs 5–21; dose: 1.9[b]	↑ (100)	↓ (100)	NA	Gandhi et al. 2013 (MM)

[a]Numbers in ( ) are percent change compared to control, calculated from quantitative data.
[b]Dose associated with maternal toxicity (e.g., decreased body weight, clinical signs).

↑ = increased; ↓ = decreased; ↔ = no change; – = not assessed; GD = gestation day; MM = methylmercury; MMC = methylmercuric chloride; NA = not applicable; PND = postnatal day

In gestation plus lactation studies in rats, one study reported an unspecified increase in the number of stillbirths and decreased postnatal survival following gavage exposure to methylmercury at 1.6 mg Hg/kg/day from GD 6 to PND 6, a dose associated with maternal toxicity (Tonk et al. 2010). Exposure to methylmercury at gavage doses up to 1.2 mg Hg/kg/day or drinking water doses up to 1.9 mg Hg/kg/day during gestation and lactation did not result in exposure-related changes in live litter size or postnatal survival (Albores-Garcia et al. 2016; Cheng et al. 2015; Fujimura et al. 2012; Giménez-Llort et al. 2001; Rossi et al. 1997; Sitarek and Gralewicz 2009; Tonk et al. 2010). Additionally, no exposure-related

changes in live litter size or postnatal survival were observed in 1- or 2-generational studies in rats at doses up to 0.9 mg Hg/kg/day (Beyrouty et al. 2006; Elsner 1991; Khera and Tabacova 1973; Newland and Reile 1999; Szász et al. 2002).

In mice, increased fetal death/resorption, decreased litter size, and/or decreased neonatal survival have also been observed following gestation or gestation plus lactation exposure to methylmercury at doses below those associated with maternal toxicity (Table 2-70). Increased fetal death was observed in mice following repeat acute-duration exposures ≥4.8 mg Hg/kg/day and following an intermediate-duration dose of 5 mg Hg/kg/day; in both studies, fetal effects were observed (Fuyuta et al. 1978; Khera and Tabacova 1973). No changes in fetal death/resorption were observed in mice following single gestational methylmercury exposure to doses up to 20 mg Hg/kg/day (Fuyuta et al. 1979; Belles et al. 2002; Yasuda et al. 1985).

Table 2-70. Pre- and Postnatal Survival in Mice Following Gestation-Only or Gestation plus Lactation Exposure to Methylmercury Compounds

Duration; dose (mg Hg/kg/day)	Dead/resorbed[a]	Live litter size[a]	Neonatal survival[a]	Reference (compound)
1 day, GD 8; dose: 1–2	–	↔	–	Hughes and Annau 1976 (MMH)
1 day, GD 8; dose: 3[b]	–	↓ (35)	–	Hughes and Annau 1976 (MMH)
1 day, GD 8; dose: 5[b]	–	↓ (40)	–	Hughes and Annau 1976 (MMH)
1 day, GD 10; dose: 8	↔	↓ (13)	–	Fuyuta et al. 1979 (MMC)
1 day, GD 10; dose: 9.99	↔	–	–	Belles et al. 2002 (MMC)
1 day, GD 8; dose: 10	–	↓ (73)	–	Hughes and Annau 1976 (MMH)
1 day, GD 10; dose: 12–16	↔	↔	–	Fuyuta et al. 1979 (MMC)
1 day, GD 13, 14, 15, 16, or 17; dose: 16[b]	–	↔	PND 56: ↓ (67–94%)	Inouye et al. 1985 (MMC)
1 day, GD 10 or 12; dose: 10–20	↔	↔	–	Yasuda et al. 1985 (MMC)
1 day, GD 10; dose: 20[c]	↔	↓ (15)	–	Fuyuta et al. 1979 (MMC)
3 days, GDs 7–9 or 12–14; dose: 3	–	↔	↔	Dore et al. 2001 (MMC)
3 days, GDs 7–9; dose: 5[b]	–	↔	PND 35: ↓ (28)	Dore et al. 2001 (MMC)

Table 2-70. Pre- and Postnatal Survival in Mice Following Gestation-Only or Gestation plus Lactation Exposure to Methylmercury Compounds

Duration; dose (mg Hg/kg/day)	Dead/resorbed[a]	Live litter size[a]	Neonatal survival[a]	Reference (compound)
3 days, GDs 12–14; dose: 5[b]	—	↔	PND 35: ↓ (26)	Dore et al. 2001 (MMC)
8 days, GDs 6–13; dose: 2–4	↔	↔	—	Fuyuta et al. 1978 (MMC)
8 days, GDs 6–13; dose: 4.8	↑ (25)	↔	—	Fuyuta et al. 1978 (MMC)
8 days, GDs 6–13; dose: 6[c]	↑ (89)	↔	—	Fuyuta et al. 1978 (MMC)
12 days, GDs 6–17; dose: 0.0001–1	↔	↔	↔	Khera and Tabacova 1973 (MMC)
12 days, GDs 6–17; dose: 5	↑ (100)	NA	NA	Khera and Tabacova 1973 (MMC)
41 days, GD 2–PND 21; dose: 0.9–1.3	–		↔	Goulet et al. 2003 (MMC)
41 days, GD 2–PND 21; dose: 1.7[b]	–	↓ (18)	↓ (14)	Goulet et al. 2003 (MMC)
63–70 days, premating through PND 13; dose: 0.2–6	–	↔	↔	Weiss et al. 2005 (MMC)
112 days, premating through PND 15; dose: 0.098–0.98	–	↔	↔	Thuvander et al. 1996 (MMC)
119 days, premating through PND 70; dose: 0.02	–	↓ (16)	↔	Huang et al. 2011 (MM)

[a]Numbers in ( ) are percent change compared to control, calculated from quantitative data.
[b]Maternal health not reported.
[c]Dose associated with maternal toxicity (e.g., decreased body weight, clinical signs).

↑ = increased; ↓ = decreased; ↔ = no change; – = not assessed; GD = gestation day; MM = methylmercury; MMC = methylmercuric chloride; MMH = methylmercury hydroxide; NA = not applicable; PND = postnatal day

Decreased postnatal survival to PND 56 was observed following gestational exposure to 16 mg Hg/kg/day on GD 13, 14, 15, 16, or 17, with the highest mortality after exposure on GD 15 or 16 (Inouye et al. 1985). Decreased postnatal survival to PND 35 was also observed in mice exposed to 5 mg Hg/kg/day on GDs 7–9 or 12–14, but not 3 mg Hg/kg/day; mortality was comparable for both exposure paradigms (Dore et al. 2001). No change in postnatal survival was observed in mice exposed to doses up to 1 mg Hg/kg/day on GDs 6–17 (Khera and Tabacova 1973). No exposure-related changes in postnatal

survival were observed in the 1-generation studies (Huang et al. 2011; Thuvander et al. 1996; Weiss et al. 2005).

There is inconsistent evidence for decreased live litter size following single exposures to methylmercury during gestation. No changes were observed in litter sizes following repeated gestational exposure to methylmercury at doses below those associated with 100% fetal death (12-day exposure to 5 mg Hg/kg/day; Khera and Tabacova 1973). In a mouse study with gestational plus lactational exposure, live litter size and postnatal survival were both decreased at 1.7 mg Hg/kg/day, but not at doses ≤1.3 mg Hg/kg/day (Goulet et al. 2003). A 1-generation study in mice reported decreased live litter size following exposure to 0.02 mg Hg/kg/day (Huang et al. 2011); however, no change in live litter size was reported in two other 1-generation studies at doses up to 6 mg Hg/kg/day (Thuvander et al. 1996; Weiss et al. 2005).

A single study in guinea pigs reported 100% fetal death in 20, 50, 67, 50, and 20% of dams following exposure to 11.5 mg Hg/kg/day once on GD 21, 28, 35, 42, or 49, respectively, compared to 0% of control dams (Inouye and Kajiwara 1988). Exposed dams showed clinical signs of toxicity.

Dose- and duration-related increases in malformations and variations have been observed in rats and mice following gestational exposure to methylmercury compounds; some findings were observed at doses below those associated with maternal toxicity and/or offspring lethality (Tables 2-71 and 2-72, respectively). In rats, total gross malformations, including cleft palate and generalized edema were observed after repeated oral exposures to doses ≥4 mg Hg/kg/day during gestation (Fuyuta et al. 1978; Nolen et al. 1972). Cleft palate was also observed in mice following repeated oral exposures to doses ≥4 mg Hg/kg/day during gestation (Fuyuta et al. 1978) or single gestational exposures ≥9.99 mg Hg/kg/day (Belles et al. 2002; Fuyuta et al. 1979; Yasuda et al. 1985). Observed skeletal malformations and variations in rats included spinal curvature, sternal absence or defects, wavy ribs, absent or bilobed vertebral centra, and delayed ossification at single doses ≥8 mg Hg/kg/day and repeat doses ≥0.024 mg Hg/kg/day (Abd El-Aziz et al. 2012; Fuyuta et al. 1978; Lee and Han 1995; Nolen et al. 1972). Similar effects (delayed ossification, sternal and vertebral defects) were observed in mice following single doses ≥8 mg Hg/kg/day and repeat doses ≥2 mg Hg/kg/day (Belles et al. 2002; Fuyuta et al. 1978, 1979; Yasuda et al. 1985). Visceral malformations in rats included hydrocephaly following exposure to ≥4 mg Hg/kg/day on GDs 7–14 (Fuyuta et al. 1978) and defects in the urinary system (bladder defects, hydronephrosis, and/or hydroureter) following exposure to ≥0.024 mg Hg/kg/day on GDs 6–14 (Nolen et al. 1972). Hydronephrosis and/or dilatation of the renal pelvis were observed in mice following single

doses ≥16 mg Hg/kg/day; hydronephrosis was also observed following repeat doses of 4.8 mg Hg/kg/day (Belles et al. 2002; Fuyuta et al. 1978, 1979; Yasuda et al. 1985).

Table 2-71. Malformations and Variations in Rats Following Gestation-Only Exposure to Methylmercury Compounds

Duration; dose (mg Hg/kg/day)	Gross malformations	Skeletal malformation/ variation	Visceral malformation/ variation	Reference (compound)
1 day, GD 7; dose: 8[a,b]	↔	Decreased ossification centers ↓ (9–12[c]) Spinal curvature ↑ (NR)	↔	Lee and Han 1995 (MMC)
1 day, GD 7; dose: 16[a,b]	↔	Decreased ossification centers ↓ (25–63[c]) Spinal curvature ↑ (NR)	↔	Lee and Han 1995 (MMC)
1 day, GD 7; dose: 24[a,b]	↔	Decreased ossification centers ↓ (55–100[c]) Spinal curvature ↑ (NR)	↔	Lee and Han 1995 (MMC)
8 days, GDs 7–14; dose: 2[a]	↔	↔	↔	Fuyuta et al. 1978 (MMC)
8, GDs 7–14; dose: 4[a]	Total malformations ↑ (7[d])	Wavy ribs ↑ (7[d])	Hydrocephaly ↑ (6[d])	Fuyuta et al. 1978 (MMC)
8 days, GDs 7–14; dose: 6[a,b]	Total malformations ↑ (80[d]) Cleft palate ↑ (18[d]) General edema ↑ (79[d])	Wavy ribs ↑ (27[d]) Sternal defects/ absence ↑ (20–61[d]) Absence or bilobed vertebral centra ↑ (6–13[d])	Hydrocephaly ↑ (67[d])	Fuyuta et al. 1978 (MMC)
9 days, GDs 6–14; dose: 0.024	↔	Missing 5th sternebra ↑ (7[c]) Incomplete calcification ↑ (15[c])	Bladder defect ↑ (8[c])	Nolen et al. 1972 (MMC)
9 days, GDs 6–14; dose: 0.23	↔	Missing 5th sternebra ↑ (8[c])	Bladder defect ↑ (16[c]) Hydronephrosis ↑ (11[c])	Nolen et al. 1972 (MMC)

Table 2-71. Malformations and Variations in Rats Following Gestation-Only Exposure to Methylmercury Compounds

Duration; dose (mg Hg/kg/day)	Gross malformations	Skeletal malformation/ variation	Visceral malformation/ variation	Reference (compound)
9 days, GDs 6–14; dose: 4.6[a]	Total malformations ↑ (61[c])	Missing 5th sternebra ↑ (22[c])	Bladder defect ↑ (54[c]) Hydronephrosis ↑ (36[c]) Hydroureter ↑ (9[c])	Nolen et al. 1972 (MMC)
21 days, GDs 0–20; dose: 0.9	–	Delayed ossification ↑ (12[d])	–	Abd El-Aziz et al. 2012 (MMC)
21 days, GDs 0–20; dose: 1.8[e]	–	Delayed ossification ↑ (18[d])	–	Abd El-Aziz et al. 2012 (MMC)

[a]Dose associated with maternal toxicity (e.g., decreased body weight, clinical signs).
[b]Dose associated with increased fetal/neonatal death.
[c]Percent change compared to control, calculated from quantitative data.
[d]Percent difference in fetal incidence, compared to control.
[e]Maternal health not reported.

↑ = increased; ↓ = decreased; ↔ = no change; – = not assessed; GD = gestation day; MMC = methylmercuric chloride; NR = not reported

Table 2-72. Malformations and Variations in Mice Following Gestation-Only Exposure to Methylmercury Compounds

Duration; dose (mg Hg/kg/day)	Gross malformations[a]	Skeletal malformation/ variation[a]	Visceral malformation/ variation[a]	Reference (compound)
1 day, GD 10; dose: 8	↔	Incomplete fusion sternebrae ↑ (5)	↔	Fuyuta et al. 1979 (MMC)
1 day, GD 10; dose: 9.99	Cleft palate ↑ (61)	Delayed ossification ↑ (69)	↔	Belles et al. 2002 (MMC)
1 day, GD 10 or 12; dose: 10–12	↔	↔	–	Yasuda et al. 1985 (MMC)
1 day, GD 10; dose: 12	Total malformations ↑ (29) Cleft palate ↑ (28)	Incomplete fusion sternebrae ↑ (65)	↔	Fuyuta et al. 1979 (MMC)
1 day, GD 10; dose: 16	Total malformations ↑ (61) Cleft palate ↑ (59)	Incomplete fusion sternebrae ↑ (74)	Hydronephrosis ↑ (19)	Fuyuta et al. 1979 (MMC)

Table 2-72. Malformations and Variations in Mice Following Gestation-Only Exposure to Methylmercury Compounds

Duration; dose (mg Hg/kg/day)	Gross malformations[a]	Skeletal malformation/ variation[a]	Visceral malformation/ variation[a]	Reference (compound)
1 day, GD 13, 14, 15, 16, or 17; dose: 16[b]	↔	–	–	Inouye et al. 1985 (MMC)
1 day, GD 10 or 12; dose: 16	Cleft palate GD 10: ↑ (70) GD 12: (81)	↔	Dilatation of renal pelvis GD 10: ↑ (22) GD 12: (25)	Yasuda et al. 1985 (MMC)
1 day, GD 10 or 12; dose: 20	Cleft palate GD 10: ↑ (99.9) GD 12: (98)	↔	Dilatation of renal pelvis GD 10: ↑ (41) GD 12: (36)	Yasuda et al. 1985 (MMC)
1 day, GD 10; dose: 20[c]	Total malformations ↑ (97) Cleft palate ↑ (100)	Incomplete fusion sternebrae ↑ (88)	Hydronephrosis ↑ (24)	Fuyuta et al. 1979 (MMC)
8 days, GDs 6–13; dose: 2	Total malformations ↑ (11)	Delayed ossification ↑ (36) Absent sternebra ↑ (18)	↔	Fuyuta et al. 1978 (MMC)
8 days, GDs 6–13; dose: 4	Total malformations ↑ (76) Cleft palate ↑ (57)	Fused thoracic vertebra ↑ (63) Delayed ossification ↑ (72) Absent sternebra ↑ (80)	↔	Fuyuta et al. 1978 (MMC)
8 days, GDs 6–13; dose: 4.8[a]	Total malformations ↑ (98) Cleft palate ↑ (98)	Fused thoracic vertebra ↑ (61) Delayed ossification ↑ (80) Absent sternebra ↑ (91)	Hydronephrosis ↑ (24)	Fuyuta et al. 1978 (MMC)
8 days, GDs 6–13; dose: 6[b,c]	Total malformations[d] ↑ (100) Cleft palate[d] ↑ (100)	↔[d]	↔[d]	Fuyuta et al. 1978 (MMC)

[a]Numbers in ( ) are percent difference in fetal incidence, compared to control.
[b]Dose associated with increased fetal/neonatal death.
[c]Dose associated with maternal toxicity (e.g., decreased body weight, clinical signs).
[d]Based on a single live fetus.

↑ = increased; ↔ = no change; – = not assessed; GD = gestation day; MMC = methylmercuric chloride

In a 2-generation study in rats, delayed eye opening, suborbital edema, and corneal opacity were observed in offspring following exposure to 0.25 mg Hg/kg/day, but not ≤0.05 mg Hg/kg/day. Delays in developmental landmark acquisitions were not observed at gestation-only doses up to 1.9 mg Hg/kg/day (Fredriksson et al. 1996; Gandhi et al. 2013) or at doses up to 0.6 mg Hg/kg/day in a 1-generation study in rats (Newland and Reile 1999). Decreased pup vocalization was reported in rat offspring in a 1-generation study at doses ≥0.19 mg Hg/kg/day (Elsner 1991). No other available study examined this endpoint.

No changes in postnatal body weight were observed in monkey offspring following exposure to methylmercury in a 1-generation study (premating through gestation) at a dose of 0.04 mg Hg/kg/day (Burbacher et al. 1984).

Body weight effects in rats following developmental exposure to methylmercury are inconsistent; observed effects were often associated with maternal toxicity (Table 2-73). Rat fetal body weight and length on GD 20 were decreased in a dose-related manner following gestational exposure to methylmercury at doses ≥8 and 16 mg Hg/kg/day, respectively, on GD 7 (Lee and Han 1995). However, findings from repeat-dose gestational exposure studies in rats do not show consistent dose- or duration-dependent effects for fetal/birth weight (Table 2-73). Postnatal body weight on PND 21 was decreased following exposure to 7 mg Hg/kg/day on GD 15, but not on GD 8 (Carratu et al. 2006), and no change in postnatal weight was observed in another study following exposure to 6.4 mg Hg/kg/day on GD 15 (Cagiano et al. 1990). No exposure-related changes in postnatal weight were observed following repeated gestation-only exposures up to 1.9 mg Hg/kg/day (Abd El-Aziz et al. 2012; Fredriksson et al. 1996). When exposure continued during lactation, dose-related decreases were observed in postnatal weight during lactation at doses ≥0.8 mg Hg/kg/day (Sitarek and Gralewicz 2009; Tonk et al. 2010).

Table 2-73. Body Weight and Length Effects in Rats Following Gestation or Gestation Plus Lactation Exposure to Methylmercury Compounds

Duration; dose (mg Hg/kg/day)	Fetal/birth weight	Fetal length	Postnatal birth weight	Reference (compound)
1 day, GD 15; dose: 6.4	↔	–	↔	Cagiano et al. 1990 (MMC)
1 day, GD 8; dose: 7[a]	↔	–	↔	Carratu et al. 2006 (MM)
1 day, GD 15; dose: 7[a]	↔	–	PND 21: ↓ (18)[b]	Carratu et al. 2006 (MM)

Table 2-73. Body Weight and Length Effects in Rats Following Gestation or Gestation Plus Lactation Exposure to Methylmercury Compounds

Duration; dose (mg Hg/kg/day)	Fetal/birth weight	Fetal length	Postnatal birth weight	Reference (compound)
1 day, GD 7; dose: 8[a,c]	GD 20: ↓ (12)[b]	↔	–	Lee and Han 1995 (MMC)
1 day, GD 7; dose: 16[a,c]	GD 20: ↓ (24)[b]	GD 20: ↓ (22)[b]	–	Lee and Han 1995 (MMC)
1 day, GD 7; dose: 24[a,c]	GD 20: ↓ (49)[b]	GD 20: ↓ (37)[b]	–	Lee and Han 1995 (MMC)
4 days, GDs 6–9; dose: 1.9	↔	–	↔	Fredriksson et al. 1996 (MM)
8 days, GDs 7–14; dose: 2[c]	↔	–	–	Fuyuta et al. 1978 (MMC)
8 days, GDs 7–14; dose: 4[c]	M: ↓ (9)[b] F: ↓ (8)[b]	–	–	Fuyuta et al. 1978 (MMC)
8 days, GDs 7–14; dose: 6[a,c]	↔	–	–	Fuyuta et al. 1978 (MMC)
9 days, GDs 6–14; dose: 0.024–4.6[c]	↔	–	–	Nolen et al. 1972 (MMC)
17 days, GDs 5–21; dose: 0.5	PND 1: ↓ (12)[b]	–	↔	Gandhi et al. 2013 (MM)
17 days, GDs 5–21; dose: 0.9	PND 1: ↓ (14)[b]	–	↔	Gandhi et al. 2013 (MM)
21 days, GDs 0–20; dose: 0.9	↔	↔	–	Abd El-Aziz et al. 2012 (MMC)
21 days, GDs 0–20; dose: 1.8[d]	GD 20: ↓ (14)[b]	GD 20: ↓ (14)[b]	–	Abd El-Aziz et al. 2012 (MMC)
22 days, GD 7–PND 7; dose: 0.5	↔	–	↔	Giménez-Llort et al. 2001; Rossi et al. 1997 (MMH)
26 days, GD 6–PND 10; dose: 0.08–0.6	–	–	↔	Tonk et al. 2010 (MMC)
26 days, GD 6–PND 10; dose: 0.8	–	–	PND 10: M: ↓ (7)[e] F: 0	Tonk et al. 2010 (MMC)
26 days, GD 6–PND 10; dose: 1.2	–	–	PND 10: M: ↓ (9)[e] F: 0	Tonk et al. 2010 (MMC)
26 days, GD 6–PND 10; dose: 1.6[a,c]	–	–	PND 10: M: ↓ (10)[e] F: ↓ (15)[e]	Tonk et al. 2010 (MMC)
36 days, GD 7–PND 21; dose: 0.5	↔	–	↔	Sitarek and Gralewicz 2009 (MMC)
36 days, GD 7–PND 21; dose: 1.9[c]	↔	–	PND 21: ↓ (23)[e]	Sitarek and Gralewicz 2009 (MMC)

Table 2-73. Body Weight and Length Effects in Rats Following Gestation or Gestation Plus Lactation Exposure to Methylmercury Compounds

Duration; dose (mg Hg/kg/day)	Fetal/birth weight	Fetal length	Postnatal birth weight	Reference (compound)
38 days, GD 5–PND 21 dose: 0.2–0.4	↔	–	↔	Albores-Garcia et al. 2016 (MMC)
42 days, GD 1–PND 21; dose: 0.05–0.23	↔	–	↔	Cheng et al. 2015; Fujimura et al. 2012 (MM)

[a]Dose associated with increased fetal/neonatal death.
[b]Percent change compared to control, calculated from quantitative data.
[c]Dose associated with maternal toxicity (e.g., decreased body weight, clinical signs).
[d]Maternal health not reported.
[e]Percent change compared to control, estimated from graphically reported data.

↓ = decreased; ↔ = no change; – = not assessed; F = female; GD = gestation day; M = male; MM = methylmercury; MMC = methylmercuric chloride; MMH = methylmercury hydroxide; PND = postnatal day

Findings regarding alterations in birth and postnatal weight following methylmercury exposure in 1-generation rat studies are inconsistent. One study reported an 11% decrease in birth weight at a drinking water dose of 0.3 mg Hg/kg/day (Szász et al. 2002), but no changes in birth weight were observed in other studies at drinking water doses up to 0.74 mg Hg/kg/day or gavage doses up to 0.9 mg Hg/kg/day (Beyrouty et al. 2006: Elsner 1991; Newland and Reile 1999). No decreases in offspring postnatal body weight were observed at drinking water doses up to 0.74 mg Hg/kg/day (Elsner 1991; Newland and Reile 1999; Szász et al. 2002). One study reported a >20% increase in body weight at postnatal week 6 in offspring following F0 drinking water exposure to doses ≥0.0006 mg Hg/kg/day; this finding was no longer observed at postnatal week 12 (Wild et al. 1997). The adversity of this transient increase in offspring body weight is unclear; therefore, it is not included in the LSE tables or Table 2-73. In gavage and dietary studies, 6–12% decreases in postnatal body weight were observed at 0.9 and 0.37 mg Hg/kg/day, respectively (Beyrouty et al. 2006; Ilback et al. 1991). No changes in birth or postnatal weight were observed in a 2-generation study in rats at dietary doses up to 0.25 mg Hg/kg/day (Khera and Tabacova 1973).

Observed decreases in late gestation or birth weight in mice were generally dose- and duration-dependent following gestational exposure to methylmercury and occurred below maternally toxic doses (Table 2-74). Decreased weights were consistently observed following single exposures to ≥9.99 mg Hg/kg/day or repeat exposures ≥4 mg Hg/kg/day (Belles et al. 2002; Fuyuta et al. 1979; Hughes and Annau 1976), although one study did not report body weight effects on GD 18 following exposure until doses ≥16 mg Hg/kg/day were administered on GD 10 or 12 (Yasuda et al. 1985). Decreased postnatal

weight or decreased weight gain was reported during lactation following single gestational exposures to doses ≥5 mg Hg/kg/day (Hughes and Annau 1976; Inouye et al. 1985). No changes in postnatal weight were observed following repeated exposure to methylmercury during gestation at doses up to 1 mg Hg/kg/day (Khera and Tabacova 1973; Yoshida et al. 2011).

Table 2-74. Body Weight Effects in Mice Following Gestation-Only Exposure to Methylmercury Compounds

Duration; dose (mg Hg/kg/day)	Fetal/birth weight[a]	Postnatal body weight[a]	Reference (compound)
1 day, GD 8; dose: 1–2	↔	↔	Hughes and Annau 1976 (MMH)
1 day, GD 8; dose: 3[b,c]	↔	PND 21: ↓ (13)[c]	Hughes and Annau 1976 (MMH)
1 day, GD 8; dose: 5[b,c]	↔	PND 21: ↓ (17)	Hughes and Annau 1976 (MMH)
1 day, GD 10; dose: 8[c]	↔	–	Fuyuta et al. 1979 (MMC)
1 day, GD 10; dose: 9.99	GD 18: ↓ (17)	–	Belles et al. 2002 (MMC)
1 day, GD 10 or 12; dose: 10–12	↔	–	Yasuda et al. 1985 (MMC)
1 day, GD 8; dose: 10	PND 1: ↓ (6)	PND 21: ↓ (16)	Hughes and Annau 1976 (MMH)
1 day, GD 10; dose: 12	GD 18: ↓ (M) (9) ↓ (F) (11)	–	Fuyuta et al. 1979 (MMC)
1 day, GD 10; dose: 16	GD 18: ↓ (M) (9) ↓ (F) (11)	–	Fuyuta et al. 1979 (MMC)
1 day, GD 10 or 12; dose: 16	GD 18: ↓ (10–16)	–	Yasuda et al. 1985 (MMC)
1 day, GD 13, 14, 15, 16, or 17; dose: 16[b,c]	–	PND 14: ↓ (NR)	Inouye et al. 1985 (MMC)
1 day, GD 10; dose: 20[c,d]	GD 18: ↓ (M) (16) ↓ (F) (19)	–	Fuyuta et al. 1979 (MMC)
1 day, GD 10 or 12; dose: 20	GD 18: ↓ (21–27)	–	Yasuda et al. 1985 (MMC)
8 days, GDs 6–13; dose: 2	↔	–	Fuyuta et al. 1978 (MMC)
8 days, GDs 6–13; dose: 4	GD 18: ↓ (M) (18) ↓ (F) (20)	–	Fuyuta et al. 1978 (MMC)

Table 2-74. Body Weight Effects in Mice Following Gestation-Only Exposure to Methylmercury Compounds

Duration; dose (mg Hg/kg/day)	Fetal/birth weight[a]	Postnatal body weight[a]	Reference (compound)
8 days, GDs 6–13; dose: 4.8[c]	GD 18: ↓ (M) (21) ↔ (F)	–	Fuyuta et al. 1978 (MMC)
12 days, GDs 6–17; dose: 0.0001–1	↔	↔	Khera and Tabacova 1973 (MMC)
19 days, GDs 0–18; dose: 0.9	–	↔	Yoshida et al. 2011 (MM)

[a]Numbers in ( ) are percent change compared to control, calculated from quantitative data.
[b]Maternal health not reported.
[c]Dose associated with increased fetal/neonatal death.
[d]Dose associated with maternal toxicity (e.g., decreased body weight, clinical signs).

↓ = decreased; ↔ = no change; – = not assessed; GD = gestation day; F = female; M = male; MM = methylmercury; MMC = methylmercuric chloride; MMH = methylmercury hydroxide; NR = not reported; PND = postnatal day

A single study in guinea pigs reported 12, 23, and 30% decreases in GD 63 fetal body weight following methylmercury exposure at 11.5 mg Hg/kg/day once on GD 35, 42, or 49, respectively, compared to controls (Inouye and Kajiwara 1988). No effects on fetal body weight were observed in fetuses following similar exposures on GD 21 or 28. Exposed dams showed clinical signs of toxicity.

A few studies reported body weight effects in laboratory animals following postnatal-only exposure to methylmercury. In monkeys, an approximate 13% decrease in body weight was observed at PND 45 following exposure to 0.5 mg Hg/kg/day from PND 0 to 29 (Willes et al. 1978); no body weight effects were observed in monkeys exposed to 0.05 mg Hg/kg/day for the first 4 years of life (Rice and Gilbert 1982). Inconsistent findings were observed in rats, with a 7% decrease in body weight at PND 15 following exposure to 0.37 mg Hg/kg/day on PNDs 1–15 (Ilback et al. 1991) and by an unspecified amount at PND 33 following exposure to 4 mg Hg/kg/day on PNDs 1–30, but not doses up to 2 mg Hg/kg/day (Sakamoto et al. 2004). No changes in postnatal weight were observed in rats exposed to 0.6 mg Hg/kg/day on PNDs 14–23 (Coluccia et al. 2007). No effects on postnatal weight were observed in mice following acute- or intermediate-duration postnatal exposure to doses up to 3.7 or 4.7 mg Hg/kg/day, respectively (Bellum et al. 2007; Fischer et al. 2008; Franco et al. 2006; Huang et al. 2011).

Predominant Mercury Form Unknown (General Populations). Several studies have evaluated relationships between mercury exposure and neonatal anthropometric measures and postnatal growth. The main outcomes assessed in newborns were birth weight, height, and head circumference; for

postnatal growth, main outcomes were weight and height for age. Study designs include prospective and cross-sectional studies. Several different biomarkers were used to assess exposure, with BHg as the most common biomarker. Studies have also assessed congenital defects, although little information is available.

Anthropometric measures at birth. Studies evaluating effects of *in utero* exposure on anthropometric measures in newborns are summarized in Table 2-75. Evidence for effects of mercury exposure on birth size in general populations is inconclusive, with studies reporting inconsistent results. Several prospective and cross-sectional studies did not observe associations between mercury biomarkers and birth weight, birth length, head circumference, and/or SGA. Two large prospective studies evaluated birth size in cohorts consisting of >70,000 births (Okubo and Nakayama 2023; Takatani et al. 2022). The Takatani et al. (2022) study found an association between increasing maternal BHg (median BHg 3.63 µg/L) and head circumference, with a doubling of maternal BHg associated with a 0.02-cm decrease in head circumference. No associations were observed for SGA, birth weight, birth length, or chest circumference. The Okubo and Nakayama (2023) study found an association between maternal BHg >3.63 µg/L and risk of low birth weight. Another large prospective study (n=15,444) did not find an association between maternal BHg and birth weight or SGA (highest quartile BHg 5.18– 30.1 µg/L). Twelve other smaller prospective studies (n<1,000) did not find associations between maternal mercury exposure and birth size metrics or found mixed results for these outcomes (associations with length but not weight or head circumference, Table 2-75). Collectively, results from larger prospective studies and conflicting results from smaller prospective studies and cross-sectional studies do not provide conclusive evidence that birth size is adversely affected by mercury exposure in general populations.

Table 2-75. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Anthropometric Measures in Newborns in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Al-Saleh et al. 2014 Cross-sectional; 1,578 pregnant women (Saudi Arabia)	BHg (mean) Maternal: 3.005 µg/L Cord: 3.354 µg/L	Birth weight	↔ (BHg, maternal and cord)
		Birth length	↔ (BHg, maternal and cord)
		SGA	↔ (BHg, maternal and cord)
		Head circumference	↔ (BHg, maternal and cord)

Table 2-75. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Anthropometric Measures in Newborns in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Ashrap et al. 2020 Prospective cohort; 731 pregnant women (Puerto Rico)	Maternal BHg median: 1.3 µg/L	Gestational age	↔ (BHg)
		Z-score birth weight	↔ (BHg)
		SGA	↔ (BHg)
		LGA	↔ (BHg)
Bloom et al. 2015 Prospective longitudinal; 253 couples with singleton deliveries (Michigan and Texas)	BHg Maternal tertiles T1 (33%): 0.66 µg/L T2 (median): 0.94 µg/L T3 (67%): 1.38 µg/L Paternal tertiles T1 (33%): 0.76 µg/L T2 (median): 1.11 µg/L T3 (67%): 1.76 µg/L	Birth weight	↔ (BHg, maternal T3; paternal T3)
		Birth length	↑ (BHg, maternal T3; paternal T3)
		Head circumference	↔ (BHg, maternal T3; paternal T3)
		Ponderal index	↔ (BHg, maternal T3; paternal T3)
		Sex	↔ (BHg, maternal T3; paternal, T3)
Chang et al. 2015 Cross-sectional; 252 infants (Korea)	Infant BHg mean: 0.94 µg/L Infant HHg: 0.22 µg/g	Z-score birth weight	↔ (BHg, HHg)
		Z-score weight for age	↔ (BHg, HHg)
		Z-score height for age	↔ (BHg, HHg)
		Weight percentiles difference between body weight and weight at time of study	↔ (BHg) ↓ (HHg)
Choi et al. 2022 Cross-sectional; 182 pregnant women (South Korea)	Maternal UHg median: 1.80 µg/g Cr	Birth weight	↔ (UHg)
		Birth length	↑ (UHg)
		Head circumference	↔ (UHg)
		Ponderal index	↓ (UHg)
Dack et al. 2023 Birth cohort; 544 mother-child pairs; child weight assessed at ages 4–61 months (United Kingdom)	Maternal BHg median: 1.88 µg/L	Birth weight	↔ (BHg)
Ding et al. 2013 Prospective birth cohort; 258 mother-infant pairs (China)	BHg Gmean Cord: 1.46 µg/L Maternal: 0.84 µg/L	Birth weight	↔ (BHg, maternal and cord)
		Birth length	↔ (BHg, maternal and cord)
		Head circumference	↔ (maternal and cord BHg)

Table 2-75. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Anthropometric Measures in Newborns in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Dou et al. 2022 Prospective; pregnant women, 1,030 at GW 22–24, 1,082 at GWs 30–32, and 860 at GWs 34–36 (China)	Maternal UHg median: 0.36 µg/L	Estimated fetal weight	↔ (UHg, GW 22–24 and 30–32 ↓ (UHg, GW 34–36)
Gokoel et al. 2020 Cross-sectional; 1,143 pregnant women (Suriname)	Maternal HHg median: 0.826 µg/g Low HHg: < 1.1 µg/g High HHg: ≥1.1 µg/g	Birth weight	↔ (HHg, high HHg)
		Apgar score	↔ (HHg, high HHg)
Gao et al. 2018 Cross-sectional; 14,202 children ages 0–6 years (China)	Child BHg mean: 1.39 µg/L	Weight	↔ (BHg)
		Z-height	↔ (BHg)
		Height	↔ (BHg)
		Z-weight	↔ (BHg)
		BMI	↑ (BHg)
		Z-BMI	↑ (BHg)
Govarts et al. 2016 Cohort; 248 mother-child pairs (Belgium)	Maternal HMeHg Gmean: 0.255 µg/g	Birth weight	↔ (HMeHg)
Guo et al. 2013 Prospective cohort; 213 mother-infant pairs (China)	Gmean Cord BHg: 1.54 µg/L Maternal HHg: 0.497 µg/kg Fetal HHg: 0.234 µg/g	Birth weight	↔ (BHg, HHg)
		Birth length	↔ (BHg, HHg)
		Head circumference	↔ (BHg, HHg)
Gustin et al. 2020 Prospective cohort; 584 pregnant women (Sweden)	Maternal ErHg median: 1.5 µg/g stratified as <1.0 and >1.0 µg/g	Birth weight	↑ (ErHg, <1.0 µg/g) ↓ (ErHg, >1.0 µg/g)
		Birth length	↑ (ErHg, <1.0 µg/g) ↓ (ErHg, >1.0 µg/g)
		Head circumference	↔ (ErHg, <1.0 µg/g) ↔ (ErHg, >1.0 µg/g)
Howe et al. 2022 Prospective pooled analysis; 1,002 pregnant women (California, New Hampshire, Puerto Rico)	Maternal UHg mean: 1.22 µg/L	Birthweight for gestational age	↔ (UHg)

Table 2-75. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Anthropometric Measures in Newborns in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Kim et al. 2017 Pooled analysis (2 prospective birth cohorts); 1,147 mother-infant pairs (Taiwan and Korea)	BHg median Cord: 5.75 µg/L Maternal: 3.27 µg/L BHg 25th percentile Cord: 4.18 µg/L Maternal: 2.29 µg/L	Birth weight	↔ (BHg, median) ↓ (BHg, >25th percentile)
Kim et al. 2020c Prospective cohort; 390 pregnant women (Boston, Massachusetts)	Maternal UHg median (at ~GW 26): 0.27 µg/L	Estimated fetal weight	↔ (UHg)
		Fetal head circumference	↔ (UHg)
		Fetal abdominal circumference	↔ (UHg)
Kobayashi et al. 2019 Prospective birth cohort; 15,444 pregnant women for birth weight assessment, 12,632 pregnant women for SGA assessment	Maternal BHg quartiles Q1: 0.334–<2.59 Q2: 2.58–<3.66 Q3: 3.66–<5.18 Q4: 5.18–30.1	Birth weight	↔ (BHg)
		SGA	↔ (BHg)
Lee et al. 2010 Prospective cohort; 417 mother-infant pairs (South Korea)	BHg Gmean Maternal: 3.30 µg/L Cord: 5.53 µg/L	Birth weight	↔ (maternal and cord BHg)
Lee et al. 2020b Prospective birth cohort; 719 mother-infant pairs (466 with BHg at <20 GW and 542 with BHg at >20 weeks) (South Korea)	Maternal BHg mean <20 GW: 3.15 µg/L >20 GW: 2.96 µg/L	Birth weight	↔ (BHg, <20 GW and >20 GW)
Nyanza et al. 2020 Prospective longitudinal; 961 pregnant women (Tanzania)	Maternal BHg median: 1.2 µg/L	Low birth weight	↔ (BHg)
Okubo and Nakayama 2023 Birth cohort; 72,317 mother-child pairs (Japan)	Maternal BHg quartiles: Q1: 0.25–2.54 Q2: 2.55–3.63 Q3: 3.64–5.18 Q4: 5.19–43.7	Risk of low birth weight	↑ (BHg, Q3)

Table 2-75. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Anthropometric Measures in Newborns in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Ou et al. 2015 Prospective; 50 mother-infant pairs (China)	Total BHg mean Cord: 2.93 µg/L Maternal: 2.36 µg/L BMeHg mean Cord: 2.11 µg/L Maternal: 1.11 µg/L BIHg mean Cord: 0.84 µg/L Maternal: 1.22 µg/L Maternal UIHg mean: 0.76 µg/g Cr	Birth weight	↓ (BHg, BIHg, maternal) ↔ (BMeHg, UIHg, maternal) ↔ (BHg, BMeHg, BIHg, cord)
		Birth length	↓ (BHg, UIHg, maternal) ↔ (BMeHg BIHg, maternal) ↔ (BHg, BMeHg, BIHg, cord)
Takatani et al. 2022 Prospective birth cohort; 91,739 pregnant women (Japan)	Maternal BHg median: 3.63 µg/L	Birth weight	↔ (BHg)
		Small for gestational age	↔ (BHg)
		Birth length	↔ (BHg)
		Head circumference	↓ (BHg)
		Chest circumference	↔ (BHg)
Taylor et al. 2016 Prospective; 4,044 mother-infant pairs (United Kingdom)	Maternal BHg: 2.07 µg/L	Birth weight	↔ (BHg)
		Crown-heel length	↔ (BHg)
		Head circumference	↔ (BHg)
Vigeh et al. 2018 Prospective birth cohort; 334 mother-infant pairs (Japan)	Maternal BHg mean 1st trimester: 6.06 µg/L 2nd trimester: 4.99 µg/L 3rd trimester: 4.97 µg/L	Birth weight	↓ (BHg, log_{10}, 1st trimester) ↓ (BHg, log_{10}, 2nd trimester) ↔ (BHg, log_{10}, 3rd trimester)
Wells et al. 2016 Cross-sectional; 271 newborns (Baltimore, Maryland)	Cord BHg Gmean BIHg: 0.13 µg/L BMeHg: 0.94 µg/L	Birth weight	↔ (BMeHg)
		Birth length	↔ (BMeHg)
		Head circumference	↔ (BMeHg)
		Ponderal index	↓ (BMeHg)
Zhao et al. 2023 Prospective cohort; 292 mother-infant pairs (China)	Maternal SHg mean (in 2nd trimester): 0.69 µg/L	Birth weight	↑ (SHg)

Table 2-75. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Anthropometric Measures in Newborns in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Zhang et al. 2023b Prospective cohort 919 mother-infant pairs (China)	Maternal BHg median: 2.80 µg/L	Z-score weight	↔ (BHg, maternal)
		Z-score length	↔ (BHg, maternal)
		Z-score BMI	↔ (BHg, maternal)
		Z-score head circumference	↔ (BHg, maternal)

↑ = positive association; ↓ = inverse association; ↔ = no association; BHg = blood mercury; BIHg = blood inorganic mercury; BMeHg = blood methylmercury; BMI = body mass index; Cr = creatinine; ErHg = erythrocyte mercury; Gmean = geometric mean; GW = gestational week; HHg = hair mercury; HMeHg = hair methylmercury; calculated as [(birth weight; g)/(birth length; cm)3] × 100; LGA = large for gestational age; Q = quartile; SGA = small for gestational age; T = tertile; UHg = urine mercury; UIHg = urine inorganic mercury

Postnatal growth. Few studies have evaluated effects of mercury exposure on postnatal growth in general populations; studies are summarized in Table 2-76. Results of studies on postnatal growth are inconsistent. The largest prospective study (n=2,227) prospective study assessed associations between maternal BHg and BMI in children from 1 month through 8 years of age (Papadopoulou et al. 2021). No associations were observed between maternal BHg in the top 10th percentile and BMI in girls ages 1 month through 3 years. However, inverse associations were observed between maternal BHg in the top 10th percentile and BMI in girls at ages 4, 5, 6, 7, and 8 years of age. Another large prospective study (n=921) found an association between increasing maternal or cord BHg and growth measured at age 24 months, although this effect was not observed at 12 months (Kim et al. 2011). A much smaller prospective study (n=50) did not observe an association between maternal or cord BHg and weight for age (Ou et al. 2015); however, this study did find that increasing maternal or cord BHg was associated decreased height for age. A prospective study of mother-child pairs found an association between maternal erythrocyte mercury and overweight or obesity in children aged 2–15 years (Wang et al. 2019c). Cross-sectional studies did not find associations between BHg and/or HHg and measures of postnatal growth (weight, height) in infants or children ages 6 months to 6 years (Chang et al. 2015; Gao et al. 2018). Chang et al. (2015) observed an inverse association between child HHg and postnatal growth measured as the difference between body weight z-score at birth and at age of postnatal observation (6–20 months). However, the weight z-score difference was also independently inversely associated with duration of breastfeeding, and was no longer associated with child HHg when adjusted for duration of breastfeeding. Gao et al. (2018) observed a positive association between child BHg and BMI; however, other studies did not assess this endpoint. Results of these studies do not provide clear evidence that

mercury exposure in general populations is associated with decreased postnatal growth. Collectively, results from larger prospective studies and conflicting results from smaller prospective studies and cross-sectional studies do not provide conclusive evidence that postnatal growth is adversely affected by mercury exposure in general populations.

Table 2-76. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Postnatal Growth in General Populations

Reference, study type, and population	Biomarker	Weight for age	Weight percent difference[a]	Height for age	BMI
Chang et al. 2015 Cross-sectional; 252 infants (age: 6–24 months) (Korea)	Infant Gmean BHg: 0.94 µg/L HHg: 0.22 µg/g	↔ (BHg) ↔ (HHg)	↔ (BHg ↓ (HHg)	↔ (BHg ↔ (HHg)	−
Gao et al. 2018 Cross-sectional; 14,202 children (age: 0–6 years) (China)	Child BHg mean: 1.39 µg/L	↔ (BHg)	−	↔ (BHg)	↑ (BHg)
Kim et al. 2011 Prospective; 921 mother-infant pairs (South Korea)	Gmean Maternal BHg: 3.1 µg/L Cord BHg Gmean: 5.2 µg/L	12 months: ↔ (BHg, M, C) 24 months: ↓ (BHg, M, C)	−	−	−
Ou et al. 2015 Prospective; 50 mother-infant pairs (age: 12 months) (China)	Maternal mean BHg: 2.36 µg/L BIHg: 1.25 µg/L BMeHg: 1.11 µg/L UIHg: 0.76 µg/g Cr Cord mean BHg: 2.93 µg/L BIHg: 0.82 µg/L BMeHg: 2.11 µg/L	↔ (BHg, M) ↔ (BIHg, M) ↔ (BMeHg, M) ↔ (UIHg, M) ↔ (BHg, C) ↔ BIHg, C) ↔ (BMeHg, C)	–	↓ (BHg, M) ↓ (BIHg, M) ↔ (BMeHg, M) ↔ (UIHg, M) ↔ (BHg, C) ↓ (BIHg, C) ↔ (BMeHg, C)	−

Table 2-76. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Postnatal Growth in General Populations

Reference, study type, and population	Biomarker	Weight for age	Weight percent difference[a]	Height for age	BMI
Papadopoulou et al. 2021 Prospective study; 2,277 mother-child pairs (n=227 in the 90th percentile maternal BHg), assessed from 1 month to 8 years of age (Norway)	Maternal BHg Median: 1.03 µg/L 90th percentile: 2.23 µg/L	–	−	−	BMI trajectory ↓ (BHg, 90th percentile, females) ↔ (BHg, 90th percentile, males) ↔ (BHg, 90th percentile, males and females combined)
Signes-Pastor et al. 2021 Cross-sectional; 1,634 children, ages 6–11 years of age (NHANES)	Child BHg median: 0.3 µg/L	−	−	−	↔ (BHg)
Wang et al. 2019c Prospective, longitudinal birth cohort; 1,442 mother-child pairs; children assessed at 2–15 years of age	Maternal ErHg quartiles (measured at parturition) Q1: 0.39–1.04 µg/L Q2: 1.04–2.10 µg/L Q3: 2.12–3.68 µg/L Q4: 3.70–27.8 µg/L	Overweight or obesity ↑ (ErHg, maternal, Q4)	−	−	−

[a]Weight percentiles difference between birth weight and postnatal birth weight at time of study.

↑ = positive association; ↓ = inverse association; ↔ = no association; – = not assessed; BHg = blood mercury; BIHg = blood inorganic mercury; BMeHg = blood methylmercury; C = umbilical cord; Cr = creatinine; ErHg = erythrocyte mercury; Gmean = geometric mean; HHg = hair mercury; M = maternal; NHANES = National Health and Nutrition Examination Survey; Q = quartile; UIHg = urine inorganic mercury

Congenital defects. The effects of gestational exposure on congenital defects in general populations have not been well-studied. Available studies are summarized in Table 2-77. A very large prospective cohort study (n=89,273) did not find associations between maternal BHg and abdominal congenital malformations (Miyashita et al. 2021). Other smaller case-control studies did not find associations between gestational exposure and neural tube defect (Tian et al. 2021; n=273 cases) or cleft palate

(Takeuchi et al. 2022c; n=192 cases). A small case-control study found an association between increasing maternal SHg and congenital heart defects (specific heart defects were not reported) (Wang et al. 2022c). The results from these studies are mixed and have not been sufficiently corroborated to conclude whether or not gestational exposure to mercury is associated with congenital defects.

Table 2-77. Overview of Epidemiological Studies Evaluating Associations between Mercury (Predominant Mercury Form Unknown) and Congenital Defects in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Miyashita et al. 2021 Prospective cohort; 89,273 mother-infant pairs (139 with abdominal congenital malformations)	Maternal BHg median: 3.64 µg/L	Abdominal congenital malformations	↔ (BHg, maternal)
Tian et al. 2021 Case-control; 273 women with neural tube defect-affected pregnancies and 477 controls (China)	Maternal SHg median Cases: 0.25 µg/L Controls: 0.23 µg/L	Neural tube defect	↔ (SHg, maternal)
Takeuchi et al. 2022c Nested case-control; maternal-infant pairs; 192 offspring with cleft palate and 1,920 controls (Japan)	Maternal BHg median Cases: 3.64 µg/L Controls: 3.54 µg/L	Cleft palate	↔ (BHg, maternal)
Wang et al. 2022c Case-control; maternal-infant pairs; 303 with congenital heart defect and 303 controls (China)	Maternal SHg median CHD Cases: 4.92 µg/L Controls: 3.03 µg/L	Congenital heart defect	↑ (SHg, maternal)

↑ = positive association; ↔ = no association; BHg = blood mercury; SHg = serum mercury

Mechanisms of Action. Specific mechanisms for developmental effects of mercury exposure have not been established. Kim et al. (2013b) have shown that BHg is inversely associated with serum folate levels. Folate has an important role in preventing neural tube defects and intrauterine growth restriction; therefore, decreased folate levels could contribute to developmental effects, including neurotoxicity and decreased anthropometric measures. Prenatal exposure to mercury has been shown to alter DNA methylation in pregnant women and infants (Cardenas et al. 2017b; Weyde et al. 2021). General

mechanisms of toxicity of mercury (reviewed in Section 2.21) are also likely involved in adverse developmental effects. Mercury is distributed to the fetus and has been measured in fetal tissues (Section 3.1.2, Distribution), providing a toxicokinetic mechanism for direct exposure of the placenta and fetus.

2.19 CANCER

Cancer Classifications of Mercury and Mercury Compounds. The U.S. Department of Health and Human Services (NTP 2016) has not categorized the carcinogenicity of mercury and mercury compounds. IARC (1993) has developed cancer classifications for metallic and inorganic mercury compounds and methylmercury compounds as follows.

- Metallic and inorganic mercury compounds: "not classifiable as to their carcinogenicity to humans (Group 3)," based on inadequate evidence in humans, inadequate evidence for elemental mercury in experimental animals, and limited evidence for mercuric chloride in experimental animals.
- Methylmercury compounds: "possibly carcinogenic to humans (Group 2B)," based on inadequate evidence in humans and sufficient evidence in experimental animals.

IRIS (1995a, 1995b, 2001) classified the carcinogenicity of mercury and mercury compounds as follows:

- Elemental mercury: not classifiable as to human carcinogenicity (Group D), "based on inadequate human and animal data."
- Mercuric chloride: possible human carcinogen (Group C), "based on the absence of data in humans and limited evidence in rats and mice."
- Methylmercury: possible human carcinogen (Group C), "based on inadequate data in humans and limited evidence of carcinogenicity in animals."

Overview. A limited number of epidemiological studies have evaluated the potential carcinogenicity of mercury exposure. Consistent with the IARC (1993) and IRIS (1995a, 1995b, 2001) classifications noted above, available epidemiological data do not provide adequate evidence that mercury exposure is associated with cancer in humans.

Carcinogenicity has been assessed in rats and mice following chronic-duration oral exposure to mercuric chloride, methylmercury, and phenylmercuric acetate. Mercuric chloride induced forestomach and thyroid tumors in male rats and methylmercury induced renal tumors in male mice. There is limited

evidence of renal tumors in male rats exposed to phenylmercuric acetate. There are no animal inhalation cancer data available.

The following summarizes results of epidemiological and animal studies on cancer outcomes.

- ***Elemental mercury***
  - *Epidemiology studies*
    - No epidemiology studies on cancer outcomes associated with exposure to elemental mercury reporting data on mercury biomarkers were identified.
  - *Animal studies*
    - No studies evaluating cancer following exposure to elemental mercury were identified.
- ***Inorganic mercury salts***
  - *Epidemiology studies*
    - No epidemiological studies evaluating associations between exposure to inorganic mercury salts and cancer outcomes were identified.
  - *Animal studies*
    - Mercuric chloride showed some evidence of carcinogenicity in male rats (forestomach and thyroid tumors), equivocal evidence of carcinogenicity in female rats and male mice (low incidence of forestomach and renal tumors, respectively), and no evidence of carcinogenicity in female mice in an NTP (1993) bioassay.
- ***Organic mercury***
  - *Epidemiology studies*
    - Two studies on the Minamata population found elevated SMRs for liver cancer. However, results were not adjusted for alcohol consumption or other confounding factors, and mercury biomarkers were not reported.
    - One cross-sectional study reported a positive association between blood methylmercury levels in the general population and increased prevalence of non-melanoma skin cancer after adjustment for several confounders.
  - *Animal studies*
    - Methylmercury is associated with induction of renal tumors in male mice.
    - Methylmercury did not induce tumors in female mice or male or female rats.
    - There are limited data that phenylmercuric mercury induces renal tumors in male rats.
- ***Predominant mercury form unknown (general populations)***
    - One prospective cohort study reported a positive association between NHg levels and incidence of various skin cancers.

- Findings from four case-control studies are mixed regarding potential associations between urinary mercury levels and risk of thyroid cancer.
- Additional epidemiological studies did not find an association between mercury biomarkers and death due to cancer, prevalence of breast cancer, or risk of glioma.

Confounding Factors. Numerous factors can influence results of epidemiological studies evaluating associations between mercury exposure and cancer if they are not homogenously distributed in the study population. These factors include age, smoking status, family history of cancer, and co-exposure to other carcinogens that are also risk factors for cancer but may not be homogenous between exposure groups in the study population. Some of the studies reviewed in this section did not adjust for some or all of these factors.

Elemental Mercury—Epidemiological Studies. Studies that evaluated associations between occupational exposure to elemental mercury and cancer did not report quantitative mercury biomarker data.

Elemental Mercury—Animal Studies. No studies were located regarding cancer in animals after exposure to elemental mercury.

Inorganic Mercury Salts—Animal Studies. The carcinogenicity of mercuric chloride was investigated in a 2-year gavage study in rats and mice (NTP 1993). In rats, statistically significant increases in the incidence of forestomach squamous cell papillomas in males (12/50 versus 0/50 in control) and thyroid follicular cell carcinomas in male rats (6/50 versus 0.50 control) were observed at 4 mg Hg/kg/day. Forestomach squamous cell papillomas were also observed in 3/50 males at 1.8 mg Hg/kg/day and in 2/50 females at 4 mg Hg/kg/day. In mice, potentially exposure-related tumors were limited to low incidence renal tumors in males at 7.4 mg Hg/kg/day, including renal tubule adenoma (2/50) and adenocarcinoma (1/50). NTP (1993) concluded that there was some evidence for carcinogenicity in male rats (increased forestomach tumors, marginally increased thyroid follicular cell tumors); equivocal evidence of carcinogenic activity in female rats (low incidence of forestomach tumors) and male mice (low incidence of renal tumors); and no evidence of carcinogenic activity in female mice.

Organic Mercury—Epidemiological Studies. No studies evaluating cancer in populations with high fish diets and reporting exposures based on mercury biomarkers were identified. Two studies evaluating cancer outcomes in the Minamata population found elevated SMRs for liver cancer (Futatsuka et al. 2005; Tamashiro et al. 1986). However, these studies are of limited usefulness as results were not adjusted for alcohol consumption or other confounding factors, and mercury biomarkers were not reported.

A large cross-sectional study in NHANES adults found a positive association between blood methylmercury levels and increased prevalence of non-melanoma skin cancer after adjusting for age, sex, ethnicity, BMI, smoking history, income status, and survey year (Rhee et al. 2020). Individuals included in the study population were exposed to both inorganic and organic forms of mercury; however, based on blood biomarker levels, the predominant exposure was organic mercury (BHg means: 0.3 µg/L inorganic mercury and 1.3 µg/L methylmercury).

Organic Mercury—Animal Studies. Renal cell adenomas were increased in male rats exposed to phenylmercuric acetate at drinking water doses of 3.7 mg Hg/kg/day for 2 years (Solecki et al. 1991). The report is limited because the assay was not intended as a carcinogenicity assay and utilized small animal groups; however, renal tumors were observed in 10/20 treated males compared to 0/18 controls. In a 2-year methylmercury study, no increase in tumor incidence was observed in rats exposed to dietary doses as high as 0.18 mg Hg/kg/day (Verschuuren et al. 1976).

Chronic-duration dietary exposure to methylmercury has resulted in significant increases in renal epithelial cell tumors in male mice in three cancer bioassays (Hirano et al. 1986; Mitsumori et al. 1981, 1990). In B6C3F1 mice, significant increases in renal epithelial cell adenomas and carcinomas were observed in males exposed to 0.686 mg Hg/kg/day for 2 years (Mitsumori et al. 1990). In ICR mice, a significant increase in the incidence of renal epithelial cell adenocarcinomas was observed in males exposed to 0.724 mg Hg/kg/day for 2 years (Hirano et al. 1986) and an increase in kidney adenomas and adenocarcinomas were observed in males exposed to 2.1 mg/kg/day for 78 weeks (Mitsumori et al. 1981). No exposure-related tumors were observed in similarly exposed female mice (Hirano et al. 1986; Mitsumori et al. 1981, 1990).

Predominant Mercury Form Unknown (General Populations). Studies of general populations have examined associations between mercury biomarkers and general mortality associated with cancer as well as specific forms of cancer (Table 2-78). A large population-based cohort in the United States did not observe an association between cancer mortality and BHg (Duan et al. 2020). Similarly, an excess of

cancer deaths was not associated with SHg in a prospective study in Swedish women with amalgam fillings (Ahlqwist et al. 1999). In a prospective cohort, positive associations between NHg and different types of skin cancer were observed (Matthews et al. 2019). Positive associations were observed between NHg and basal cell carcinoma incidence in men and women, squamous cell carcinoma in women only, and melanoma in men only. A cross-sectional study in NHANES adult women did not observe an association between UHg levels and breast cancer prevalence (Bell et al. 2023).

Table 2-78. Results of Epidemiological Studies Evaluating Exposure to Mercury (Predominant Mercury Form Unknown) and Cancer in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Ahlqwist et al. 1999 Prospective cohort; 1,462 women with amalgam fillings, enrolled in 1968–1969, and followed through 1980–1981(n=135 at follow-up) (Sweden)	SHg mean: 17 µg/L	Cancer deaths	↔ (SHg)
Bell et al. 2023 Cross-sectional with nested case-control; 3,352 women, including 106 cases of breast cancer and 3,246 without (United States; NHANES 2007–2016)	UHg quartiles (µg/g Cr): Q1: <0.20 Q2: 0.20–<0.40 Q3: 0.40–<0.79 Q4: ≥0.79 Cases (Gmean): 0.53 Controls (Gmean): 0.41	Breast cancer prevalence	↔ (UHg; case versus control, Q4 versus Q1)
Creed et al. 2019 Case-control; 300 cases of glioma and 300 matched controls (Southeastern United States)	NHg quintiles (µg/g) Qi1: <0.030 Qi2: 0.031–0.055 Qi3: 0.056–0.084 Qi4: 0.084–0.161 Qi5: >0.162 Cases (median): 0.066 Controls (median): 0.069	Glioma risk	↔ (NHg; case versus control, Qi5 versus Qi1)
Duan et al. 2020 Population-based cohort; 12,129 men and 13,927 women (United States[a])	BHg median: 0.90 µg/L	Cancer mortality	↔ (BHg)

Table 2-78. Results of Epidemiological Studies Evaluating Exposure to Mercury (Predominant Mercury Form Unknown) and Cancer in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Liu et al. 2021b Case-control; 197 patients with papillary thyroid microcarcinoma, papillary thyroid carcinoma, and nodular goiter and 197 matched controls (China)	UHg median Cases: 0.27 µg/L Controls: 0.38 µg/L	Thyroid tumor risk	↔ (UHg)
Matthews et al. 2019 Prospective cohort; 3,730 males (HPFS cohort) and 6,708 women (NHS cohort) (United States)	NHg mean Men: 0.54 µg/g Women: 0.31 µg/g	Basal cell carcinoma incidence	M: ↑ (NHg) F: ↑ (NHg)
		Squamous cell carcinoma incidence	M: ↔ (NHg) F: ↑ (NHg)
		Melanoma incidence	M: ↑ (NHg) F: ↔ (NHg)
Rezaei et al. 2019 Case-control; 11 cases (3 men, 8 women) of thyroid cancer and 33 healthy controls (22 men, 11 women) (Iran)	SHg mean Case: 37.7 µg/g Control: 18.9 µg/g	Thyroid cancer risk	↔ (SHg)
Zhang et al. 2019 Case-control; 262 cases of papillary thyroid cancer and 262 matched controls (China)	UHg median Cases: 21.38 µg/g Cr Controls: 14.89 µg/g Cr UHg, by quartile (µg/g Cr) Q1: ≤2.67 Q2: 2.67–14.89 Q3: 14.89–34.81 Q4>34.81	Thyroid cancer risk	↑ (UHg, Q2, Q3, or Q4 versus Q1; trend; case versus control)

Table 2-78. Results of Epidemiological Studies Evaluating Exposure to Mercury (Predominant Mercury Form Unknown) and Cancer in General Populations

Reference, study type, and population	Biomarker	Outcome evaluated	Result
Zhang et al. 2021d Case-control; 308 cases of thyroid cancer and 308 matched controls (China)	UHg median Cases: 29.75 µg/g Cr Controls: 15.73 µg/g Cr UHg, exposure groups (µg/g Cr) low: <2.44 moderate: 2.44–34.97 high: >34.97	Thyroid cancer risk	↑ (UHg, high versus low; trend; case versus control)

[a]Exposure information obtained from historical NHANES data.

↑ = positive association; ↔ = no association; BHg = blood mercury; Cr = creatinine; Gmean = geometric mean; HPFS = Health Professionals Follow-up Study; NHANES = United States National Health and Nutrition Examination Survey; NHg = toenail mercury; NHS = Nurses' Health Study; Q = quartile; Qi = quintile; SHg = serum mercury; UHg = urine mercury

Four case-control studies present mixed results regarding potential associations between mercury biomarkers and thyroid tumors. Two studies from China observed a positive association between the risk of thyroid cancer and UHg (Zhang et al. 2019, 2021d); however, one observed the association at UHg levels ≥2.67 µg/g Cr (Zhang et al. 2019) while the other only observed an association at levels >34.97 µg/g Cr (Zhang et al. 2021d). A third case-control study from China did not observe an association between the risk of thyroid tumors and UHg levels (Liu et al. 2021b). A small case-control study from Iran did not observe an association between the risk of thyroid cancer and SHg levels (Rezaei et al. 2019).

A case-control study of glioma did not observe an association between NHg levels and risk of glioma in the Southeastern United States (Creed et al. 2019).

Mechanisms of Action. As reviewed in Section 2.20 (Genotoxicity), elemental mercury has been shown to produce oxidative damage to DNA. There is limited evidence that inorganic and organic mercury are mutagenic. These findings provide a plausible mechanism for carcinogenesis. In addition, a recent review proposed that mercury may act as an epigenetic tumor promoter (Zefferino et al. 2017).

Mechanisms of Action. As reviewed in Section 2.20 (Genotoxicity), elemental mercury has been shown to produce oxidative damage to DNA. There is limited evidence that inorganic and organic mercury are

mutagenic. These findings provide a plausible mechanism for carcinogenesis. In addition, a recent review proposed that mercury may act as an epigenetic tumor promoter (Zefferino et al. 2017).

2.20 GENOTOXICITY

Overview. Available data indicate that elemental mercury may cause oxidative DNA damage; findings regarding chromosomal effects are inconclusive. There is limited evidence that inorganic and organic mercury are mutagenic. Inorganic and organic mercury are consistently clastogenic and DNA damaging in mammalian cells.

The following summarizes results of *in vitro* and *in vivo* studies on genotoxic effects.

- ***Elemental mercury (in vivo studies only)***
    - Inconclusive evidence for chromosome aberrations in exposed workers.
    - Limited evidence of oxidative DNA damage in the general population.
- ***Inorganic mercury salts***
    - *In vitro* studies
        - Limited evidence of mutagenicity in mammalian cells.
        - Consistent evidence of clastogenicity in mammalian cells.
        - Consistent evidence of DNA binding and damage in mammalian cells.
    - *In vivo* studies
        - Induced dominant lethal mutations in rats with oral exposure.
        - Inconclusive evidence for chromosome aberrations in exposed workers.
        - Oral, but not intraperitoneal, exposure is associated with chromosome aberrations and micronuclei in rodents.
        - Consistent evidence of DNA binding and damage in rodents following oral exposure.
- ***Organic mercury***
    - *In vitro* studies
        - Limited evidence of mutagenicity in mammalian cells.
        - Consistent evidence of clastogenicity in human, hamster, and rat cells; no evidence in mouse cells.
        - Consistent evidence of DNA damage in bacteria and mammalian cells.
    - *In vivo* studies
        - Induced dominant lethal mutations in one mouse strain with oral exposure.

- Inconclusive evidence for chromosome aberrations from occupational and general population studies in humans and *in vivo* studies in animals.
- Consistent evidence of DNA damage in mammals and chicken embryos.

Elemental Mercury. There is inconclusive evidence that occupational inhalation exposure to metallic mercury causes structural and numerical chromosome aberrations in human lymphocytes. However, most human studies have significant limitations, precluding clear conclusions. There is limited evidence that exposure to elemental mercury causes oxidative DNA damage. Available genotoxicity studies are reviewed in Table 2-79.

Table 2-79. Genotoxicity of Elemental Mercury in Epidemiological Studies

Species (exposure route)	Mercury compound	Endpoint	Results	Reference
Human (occupational exposure)	Metallic mercury	Aneuploidy in peripheral lymphocytes	–	Popescu et al. 1979
Human (occupational exposure)	Metallic mercury	Aneuploidy in peripheral lymphocytes	(+)	Verschaeve et al. 1976
Human (occupational exposure)	Metallic mercury	Aneuploidy in peripheral lymphocytes	–	Verschaeve et al. 1979
Human (occupational exposure)	Metallic mercury	Chromosome aberrations in peripheral lymphocytes	(+)	Popescu et al. 1979
Human (occupational exposure)	Metallic mercury	Chromosome aberrations in peripheral lymphocytes	(+)	Verschaeve et al. 1976
Human (occupational exposure)	Metallic mercury	Chromosome aberrations in peripheral lymphocytes	–	Verschaeve et al. 1979
Human (occupational exposure)	Amalgams	Chromosome aberrations in peripheral lymphocytes	(+)	Verschaeve et al. 1976
Human (occupational exposure)	Mercury amalgamated with zinc	Chromosome aberrations in peripheral lymphocytes	–	Mabille et al. 1984
Human (occupational exposure)	Mercury	Micronuclei induction in peripheral lymphocytes	+[a]	Barregard et al. 1991
Human (general population exposure)	Unspecified mercury	Oxidative DNA damage (urine 8-OHdG)	+	Al-Saleh et al. 2017
Human (oral)	Amalgams	Oxidative DNA damage (urine 8-OHdG)	+	Al-Saleh et al. 2012

[a]Positive response only in stimulated T-lymphocytes.

+ = positive result; – = negative result; (+) = reported as positive but study was either seriously compromised or findings did not provide valid evidence of a positive response; 8-OHdG = 8-hydroxydeoxyguanosine; DNA = deoxyribonucleic acid

One study reported increased aneuploidy in peripheral lymphocytes of 28 subjects exposed to various types of mercury (including 14 exposed to metallic mercury vapor and 3 exposed via amalgams), compared to 7 unexposed controls (Verschaeve et al. 1976). However, the study was not well controlled (i.e., not matched for sex, smoking habits, or sample size). Additionally, these data should be interpreted with caution since age has an influence on aneuploidy, and in this study, there was a general trend toward a higher incidence of aneuploidy in the older exposed workers (ages 36–63 years). It is noteworthy that in a subsequent study performed by these investigators (Verschaeve et al. 1979), no adverse effect on the number of chromosomes was demonstrated in 28 workers exposed to moderate levels of metallic mercury (mean urine levels of 35 µg/L; range 7–175 µg/L), compared to 8 unexposed controls from the plant (e.g., clerks; urine level range <5–11 µg/L) and 12 general population controls (UHg levels not reported). The study authors concluded that the results from their 1976 study suggesting a potential association between increased chromosomal aberrations and occupational exposure to mercury may have been affected by factors other than exposure to mercury compounds. No evidence of aneuploidy was observed in four workers exposed to high concentrations of metallic mercury (range 0.15–0.44 mg/m^3) (Popescu et al. 1979).

The study described above by Verschaeve et al. (1976) also reported an increase in structural chromosomal aberrations in mercury-exposed workers; as discussed above, data should be interpreted with caution. As with aneuploidy, no adverse effect on the structure of chromosomes was demonstrated in the subsequent study by Verschaeve et al. (1979) in 28 workers exposed to moderate levels of metallic mercury. Another study reported significant increases in the frequency of acentric fragments (chromosome breaks) in four workers exposed to high concentrations of metallic mercury (range 0.15–0.44 mg/m^3); the urinary excretion level of mercury for both exposed groups was 0.890 µg/L (Popescu et al. 1979). However, the findings of this study are suspect because the control group was not matched for sex, smoking habits, or sample size. Additionally, one of the four exposed individuals had a history of benzene poisoning, which was reflected in the unusually high frequency of abnormal chromosome morphology seen in this individual. Chromosomal aberrations were not observed in peripheral lymphocytes of 22 workers exposed to mercury amalgamated with zinc; the mean urine and blood mercury levels in the exposed group were 117 µg/g creatinine and 0.031 µg/mL, respectively (Mabille et al. 1984). Another study evaluated micronuclei induction in peripheral lymphocytes from 26 workers exposed to mercury vapors (25–50 µg/m^3) for a mean exposure time of 10 years, compared to 26 unexposed controls (Barregard et al. 1991). Groups were matched for age (within 7 years) and smoking habits; plasma, erythrocyte, and UHg levels were determined. Parallel lymphocyte cultures from each donor group were incubated in the presence of pokeweed mitogen, which stimulates both B- and

T-lymphocytes, and phytohemagglutinin, which primarily activates T-cells. The analysis showed no significant increase in the frequency or the size of micronuclei in the exposed versus the control group. Nor was there a correlation between micronuclei induction and plasma, erythrocyte, or urine levels of mercury. Within the exposed group, however, there was a significant correlation between micronuclei induction in phytohemagglutinin in stimulated lymphocytes and cumulative exposure (whole-blood mercury level over employment time); the response was independent of age or smoking habits. These results, suggesting a genotoxic effect on T-lymphocytes, are unusual since there is evidence that B-lymphocytes may be more sensitive indicators of chemically induced clastogenesis than T-lymphocytes (Högstedt et al. 1988). Barregard et al. (1991) stated that the evidence of a genotoxic response confined to T-lymphocytes could have been a random finding but hypothesized that long-term exposure to mercury may cause an accumulation of cytogenetic effects.

Oxidative DNA damage was significantly associated with the UHg levels in children aged 5–15.5 years with dental amalgam fillings (Al-Saleh et al. 2017). Oxidative DNA damage was also significantly associated with increased UHg levels in mothers and young children; however, environmental mercury exposure source(s) and form(s) are unknown in this study population (Al-Saleh et al. 2017).

Inorganic Mercury Salts. There is limited evidence that inorganic mercury salts are mutagenic in mammalian cells. *In vitro* data in mammalian cells and *in vivo* oral data in rodents show clear, consistent evidence of clastogenicity and DNA damage associated with inorganic mercury exposure. Available *in vitro* and *in vivo* genotoxicity studies for inorganic mercury salts are reviewed in Tables 2-80 and 2-81, respectively.

Table 2-80. Genotoxicity of Inorganic Mercury Salts *In Vitro* Studies

Species (test system)	Mercury compound	Endpoint	Results		Reference
			With activation	Without activation	
Prokaryotic organisms					
Salmonella typhimurium (TA1535, TA1537, TA98, TA102)	Mercuric chloride	Gene mutation	–	–	Wong 1988
Bacillus subtilis (H17, M45)	Mercuric chloride	DNA damage	NT	+	Kanematsu et al. 1980
Mammalian cells					
Mouse lymphoma cells L5178Y	Mercuric chloride	Gene mutation	+/–	–	Oberly et al. 1982
NIH 3T3 cells	Mercuric chloride	Gene mutation	NT	+	Schurz et al. 2000

Table 2-80. Genotoxicity of Inorganic Mercury Salts *In Vitro* Studies

Species (test system)	Mercury compound	Endpoint	Results		Reference
			With activation	Without activation	
Human (peripheral lymphocytes)	Mercuric chloride	Aneuploidy	NT	+	Patel and Rao 2018
Human (peripheral lymphocytes)	Mercuric chloride	Chromosome aberrations	NT	–	Rao et al. 2001
Human (peripheral lymphocytes)	Mercuric chloride	Chromosome aberrations	NT	+	Patel and Rao 2018
CHO cells	Mercuric chloride	Chromosome aberrations	NT	+	Howard et al. 1991
Human (peripheral lymphocytes)	Mercury nitrate	Sister chromatid exchange	NT	–	Lee et al. 1997
Human (peripheral lymphocytes)	Mercuric chloride	Sister chromatid exchange	NT	+	Patel and Rao 2015
Human (peripheral lymphocytes)	Mercuric chloride	Sister chromatid exchange	NT	+	Purohit and Rao 2014
Human (peripheral lymphocytes)	Mercuric chloride	Sister chromatid exchange	NT	+	Rao et al. 2001
CHO cells	Mercuric chloride	Sister chromatid exchange	NT	+	Howard et al. 1991
Human (peripheral lymphocytes)	Mercuric chloride	Micronuclei induction	NT	+	Patel and Rao 2018
Chinese hamster V79 cells	Mercuric chloride	Micronuclei induction	NT	+	Stoiber et al. 2004
Rat embryo fibroblasts	Mercuric chloride	DNA binding	NT	+	Rozalski and Wierzbicki 1983
CHO cells	Mercuric chloride	DNA binding	NT	+	Cantoni et al. 1984a
Human (U-937 monocyte-like cells)	Mercuric chloride	DNA damage	NT	+	Ben-Ozer et al. 2000
Human (WRL-68 hepatocytes)	Mercuric chloride	DNA damage	NT	+	Bucio et al. 1999
Human (TK6 lymphoblastoid cells)	Mercuric chloride	DNA damage	NT	+	Guillamet et al. 2008
Human (peripheral lymphocytes)	Mercuric chloride	DNA damage	NT	+	Patel and Rao 2018
Human (salivary gland tissue cells)	Mercuric chloride	DNA damage	NT	+	Schmid et al. 2007
Human (lymphocytes)	Mercuric chloride	DNA damage	NT	+	Schmid et al. 2007
Human KB cells	Mercuric acetate	DNA damage	NT	+	Williams et al. 1987
Rat embryo fibroblasts	Mercuric chloride	DNA damage	NT	+	Zasukhina et al. 1983

Table 2-80. Genotoxicity of Inorganic Mercury Salts *In Vitro* Studies

Species (test system)	Mercury compound	Endpoint	Results		Reference
			With activation	Without activation	
Mouse embryo fibroblasts	Mercuric chloride	DNA damage	NT	+	Zasukhina et al. 1983
CHO cells	Mercuric chloride	DNA damage	NT	+	Cantoni and Costa 1983
CHO cells	Mercuric chloride	DNA damage	NT	+	Cantoni et al. 1982, 1984a, 1984b
CHO cells	Mercuric chloride	DNA damage	NT	+	Christie et al. 1984, 1986

+ = positive result; – = negative result; +/– = weakly positive (2- to 3-fold increase in mutations); CHO = Chinese hamster ovary; DNA = deoxyribonucleic acid; NT = not tested

Table 2-81. Genotoxicity of Inorganic Mercury Salts *In Vivo* Animal Studies

Species (exposure route)	Mercury compound	Endpoint	Results	Reference
Mammals				
(101xC3H)F1 mouse (intraperitoneal)	Mercuric chloride	Dominant lethal mutations in oocytes	+/–	Suter 1975
Rat (oral)	Mercuric chloride	Dominant lethal mutations in spermatogonia	+	Zasukhina et al. 1983
Human (occupational exposure)	Mixture of mercuric chloride, methylmercuric chloride, and ethylmercuric chloride	Aneuploidy in peripheral lymphocytes	–	Popescu et al. 1979
Swiss mouse (intraperitoneal)	Mercuric chloride	Aneuploidy in spermatogonia	–	Poma et al. 1981
Swiss mouse (intraperitoneal)	Mercuric acetate	Aneuploidy in oocytes	–	Jagiello and Lin 1973
Human (occupational exposure)	Mixture of mercuric chloride, methylmercuric chloride, and ethylmercuric chloride	Chromosome aberrations in peripheral lymphocytes	(+)	Popescu et al. 1979
Rat (gavage)	Mercuric chloride	Chromosome aberrations in bone marrow cells	+	Bhowmik and Patra 2015
Rat (drinking water)	Mercuric chloride	Chromosome aberrations in bone marrow cells	+	Boujbiha et al. 2012

Table 2-81. Genotoxicity of Inorganic Mercury Salts *In Vivo* Animal Studies

Species (exposure route)	Mercury compound	Endpoint	Results	Reference
Swiss mouse (intraperitoneal)	Mercuric chloride	Chromosome aberrations in bone marrow cells	–	Poma et al. 1981
Swiss mouse (gavage)	Mercuric chloride	Chromosome aberrations in bone marrow cells	+	Ghosh et al. 1991
Rat (gavage)	Mercuric chloride	Micronuclei induction in reticulocytes	+	Rozgaj et al. 2005
Golden Syrian hamsters (intraperitoneal)	Mercurous chloride	Micronuclei induction in bone marrow cells	–	Cortés-Gutiérrez et al. 2004
Swiss mouse (drinking water)	Mercuric chloride	DNA binding in liver	+	Bryan et al. 1974
Rat (gavage)	Mercuric chloride	DNA damage in lymphocytes	+	Bhowmik and Patra 2015
Rat (gavage)	Mercuric chloride	DNA damage in lymphocytes	+	Rozgaj et al. 2005
Rat (oral intubation)	Mercuric chloride	DNA damage in peripheral leukocytes	+	Grover et al. 2001
Non-mammalian eukaryotic organisms				
Drosophila melanogaster (diet)	Mercuric chloride	Somatic mutation and recombination	–	Carmona et al. 2008

+ = positive result; – = negative result; +/– = inconclusive; (+) = reported as positive but study was either seriously compromised or findings did not provide valid evidence of a positive response; DNA = deoxyribonucleic acid

Mercuric chloride is not mutagenic in bacteria (Wong 1988). In mammalian cells, mercuric chloride was weakly mutagenic with activation in mouse lymphoma cells (Oberly et al. 1982) and mutagenic without activation in mouse fibroblasts (Schurz et al. 2000). An *in vivo* study in rats showed dominant lethal mutations in spermatogonia following oral exposure to mercuric chloride (Zasukhina et al. 1983). Evidence for dominant lethal mutations in oocytes was inconclusive following intraperitoneal exposure to mercuric chloride in mice (Suter 1975). There is no evidence for somatic mutation or recombination in *Drosophila melanogaster* following dietary exposure to mercuric chloride (Carmona et al. 2008).

Several studies have reported clastogenic effects in human peripheral lymphocytes following exposure to mercuric chloride (without metabolic activation). One study reported aneuploidy (Patel and Rao 2018), one reported chromosomal aberrations (Patel and Rao 2018), three reported sister chromatid exchanges (Patel and Rao 2015; Purohit and Rao 2014; Rao et al. 2001), and one reported micronuclei induction (Patel and Rao 2018). However, one study reported a lack of chromosomal aberrations in human peripheral lymphocytes exposed to mercuric chloride (Rao et al. 2001) and another reported a lack of sister chromatid exchanges in human peripheral lymphocytes exposed to mercuric nitrate (Lee et al.

1997). In hamster cells, chromosome aberrations, sister chromatid exchanges, and micronuclei were induced following exposure to mercuric chloride in the absence of metabolic activation (Howard et al. 1991; Stoiber et al. 2004).

Evidence for clastogenicity of mercuric chloride is less consistent *in vivo*. In humans, one study reported significant increases in the frequency of acentric fragments (chromosome breaks) in 18 workers exposed to a mixture of mercuric chloride, methylmercuric chloride, and ethylmercuric chloride (Popescu et al. 1979). The urinary excretion level of mercury for the exposed group was 0.890 μg/L. The findings of this study should be interpreted with caution because the control group was not matched for sex, smoking habits, or sample size. No difference in the incidence of aneuploidy was found between the exposed workers and the controls. In rodents, there is no evidence of aneuploidy in spermatogonia or oocytes following intraperitoneal exposure to mercuric chloride or acetate, respectively (Jagiello and Lin 1973; Poma et al. 1981). Chromosomal aberrations in bone marrow were reported in rats and mice following oral exposure to mercuric chloride (Bhowmik and Patra 2015; Boujbiha et al. 2012; Ghosh et al. 1991), but not in mice following intraperitoneal exposure (Poma et al. 1981). Oral exposure to mercuric chloride also induced micronuclei in rat reticulocytes (Rozgaj et al. 2005), but intraperitoneal exposure to mercurous chloride did not induce micronuclei in hamster bone marrow (Cortés-Gutiérrez et al. 2004).

Mercuric chloride does not cause DNA damage in bacteria (Kanematsu et al. 1980). However, numerous studies consistently reported DNA damage in human, rat, mouse, and hamster cells exposed to mercuric chloride (Table 2-80 for citations), and mercuric chloride binds to rat and hamster DNA (Cantoni et al. 1984a; Rozalski and Wierzbicki 1983). Mercuric acetate also induced DNA damage in human cells (Williams et al. 1987). *In vivo* studies in rodents show DNA damage in rat lymphocytes and leukocytes and DNA binding in mouse liver following oral exposure to mercuric chloride (Bhowmik and Patra 2105; Bryan et al. 1974; Grover et al. 2001; Rozgaj et al. 2005).

Organic Mercury. There is limited evidence that exposure to organic mercury is mutagenic in mammalian cells. Evidence for clastogenicity is inconclusive in mammals following *in vivo* exposure; *in vitro* data in mammalian cells generally show evidence of clastogenicity associated with organic mercury exposure. DNA damage is consistently observed in both *in vivo* and *in vitro* studies in mammals; there is limited evidence for DNA damage in bacteria and chicken embryos. Available *in vitro* and *in vivo* genotoxicity studies for organic mercury are reviewed in Tables 2-82 and 2-83, respectively.

Table 2-82. Genotoxicity of Organic Mercury *In Vitro*

Species (test system)	Mercury compound	Endpoint	Results		Reference
			With activation	Without activation	
Prokaryotic organisms					
Bacillus subtilis (H17, M45)	Methylmercury chloride	DNA damage	NT	+	Kanematsu et al. 1980
B. subtilis (H17, M45)	Phenylmercuric acetate	DNA damage	NT	+	Kanematsu et al. 1980
Non-mammalian eukaryotic organisms					
Saccharomyces cerevisiae	Methylmercury chloride	Gene mutation	NT	–	Nakai and Machida 1973
S. cerevisiae	Methylmercury chloride	Chromosome nondisjunction	NT	(+)	Nakai and Machida 1973
S. cerevisiae	Methylmercury chloride	Recombination	NT	–	Nakai and Machida 1973
Mammalian cells					
Chinese hamster V79 cells	Methylmercury chloride	Gene mutation	NT	+/–	Fiskesjo 1979
Chinese hamster V79 cells	Methoxyethyl mercury chloride	Gene mutation	NT	+/–	Fiskesjo 1979
Human peripheral lymphocytes	Methylmercury chloride	Aneuploidy	NT	+	Betti et al. 1992
Human peripheral lymphocytes	Dimethyl mercury	Aneuploidy	NT	+	Betti et al. 1992
Human peripheral lymphocytes	Methylmercury chloride	Chromosome aberrations	NT	+	Betti et al. 1992
Human peripheral lymphocytes	Dimethyl mercury	Chromosome aberrations	NT	+	Betti et al. 1992
CHO cells	Methylmercury chloride	Chromosome aberrations	NT	+	Ehrenstein et al. 2002
Human lymphocytes	Phenylmercury acetate	Sister chromatid exchange	NT	+	Lee et al. 1997
Human lymphocytes	Methylmercury chloride	Sister chromatid exchange	NT	+	Lee et al. 1997
Early mouse embryos (blastocysts)	Methylmercury	Sister chromatid exchange	NT	-	Matsumoto and Spindle 1982
CHO cells	Methylmercury chloride	Sister chromatid exchange	NT	+	Ehrenstein et al. 2002
Human glioblastoma cell line	Methylmercury	Micronuclei induction	NT	+	Crespo-López et al. 2007
Human neuroblastoma cell line	Methylmercury	Micronuclei induction	NT	+	Crespo-López et al. 2007
Human lymphocytes	Methylmercury chloride	Micronuclei induction	NT	+	Migliore et al. 1999

Table 2-82. Genotoxicity of Organic Mercury *In Vitro*

Species (test system)	Mercury compound	Endpoint	Results		Reference
			With activation	Without activation	
Rat glioma C6 cells	Methylmercury	Micronuclei induction	NT	+	Crespo-Lopez et al. 2016
Human nerve cells	Methylmercury chloride	DNA damage	NT	+	Costa et al. 1991
Human lung cells	Methylmercury chloride	DNA damage	NT	+	Costa et al. 1991
Human leukocytes	Methylmercury chloride	DNA damage	NT	+	Frenzilli et al. 2000
Human TK6 lymphoblastoid cells	Methylmercury chloride	DNA damage	NT	+	Guillamet et al. 2008
Rat glioblastoma cells	Methylmercury chloride	DNA damage	NT	+	Costa et al. 1991
Rat glioma C6 cells	Methylmercury	DNA damage	NT	+	Crespo-Lopez et al. 2016
Mouse wild-type and OGG1-null ($Ogg1^{-/-}$) embryonic fibroblasts	Methylmercury	DNA damage	NT	+	Ondovcik et al. 2012
Chinese hamster V79 cells	Methylmercury chloride	DNA damage	NT	+	Costa et al. 1991

+ = positive result; – = negative result; +/– = weakly positive at concentrations with >50% survival (2–3-fold increase in mutations); (+) = reported as slightly increased, but quantitative data were not reported; CHO = Chinese hamster ovary; DNA = deoxyribonucleic acid; NT = not tested

Table 2-83. Genotoxicity of Organic Mercury Following *In Vivo* Exposure

Species (exposure route)	Mercury compound	Endpoint	Results	Reference
Mammals				
(101xC3H)F1 mouse (intraperitoneal)	Methylmercuric hydroxide	Dominant lethal mutations in spermatogonia	–	Suter 1975
(101xC3H)F1 mouse (intraperitoneal)	Mercuric chloride	Dominant lethal mutations in oocytes	–	Suter 1975
(SECxC57BL)F1 mouse (intraperitoneal)	Methylmercuric hydroxide	Dominant lethal mutations in spermatogonia	+	Suter 1975
Human (occupational exposure)	Mixture of mercuric chloride, methylmercuric chloride, and ethylmercuric chloride	Aneuploidy in peripheral lymphocytes	–	Popescu et al. 1979

Table 2-83. Genotoxicity of Organic Mercury Following *In Vivo* Exposure

Species (exposure route)	Mercury compound	Endpoint	Results	Reference
Human (diet, fish consumption)	Methylmercury	Aneuploidy in peripheral lymphocytes	(+)	Skerfving et al. 1970
Human (diet, fish consumption)	Methylmercury	Aneuploidy in peripheral lymphocytes	(+)	Skerfving et al. 1974
Human (occupational exposure)	Ethylmercury	Aneuploidy in peripheral lymphocytes	(+)	Verschaeve et al. 1976
Human (occupational exposure)	Phenylmercury	Aneuploidy in peripheral lymphocytes	(+)	Verschaeve et al. 1976
Human (occupational exposure)	Mercury fulminate	Aneuploidy in peripheral lymphocytes	–	Anwar and Gabal 1991
Swiss mouse (intraperitoneal)	Dimethyl-mercury	Aneuploidy in oocytes	–	Jagiello and Lin 1973
Swiss mouse (intraperitoneal)	Mercaptomerin (as Thiomerin)	Aneuploidy in oocytes	–	Jagiello and Lin 1973
Syrian hamsters (intraperitoneal)	Methylmercury	Aneuploidy in oocytes	+	Mailhes 1983
Human (occupational exposure)	Mixture of mercuric chloride, methylmercuric chloride, and ethylmercuric chloride	Chromosome aberrations in peripheral lymphocytes	(+)	Popescu et al. 1979
Human (diet, fish consumption)	Methylmercury	Chromosome aberrations in peripheral lymphocytes	(+)	Skerfving et al. 1970
Human (diet, fish consumption)	Methylmercury	Chromosome aberrations in peripheral lymphocytes	(+)	Skerfving et al. 1974
Human (occupational exposure)	Ethylmercury	Chromosome aberrations in peripheral lymphocytes	(+)	Verschaeve et al. 1976
Human (occupational exposure)	Phenylmercury	Chromosome aberrations in peripheral lymphocytes	(+)	Verschaeve et al. 1976
Human (occupational exposure)	Mercury fulminate	Chromosome aberrations in peripheral lymphocytes	+[a]	Anwar and Gabal 1991
Cat (diet)	Methylmercury	Chromosome aberrations in bone marrow cells	+/-	Miller et al. 1979
Syrian hamsters (intraperitoneal)	Methylmercury	Chromosome aberrations in oocytes	–	Mailhes 1983
Human (diet, seal consumption)	Mercury	Sister chromatid exchange in peripheral lymphocytes	(+)	Wulf et al. 1986
Human (occupational exposure)	Mercury fulminate	Micronuclei induction in peripheral lymphocytes	+[a]	Anwar and Gabal 1991
Cat (diet)	Methylmercury	Micronuclei induction in bone marrow cells	–	Miller et al. 1979
CBA mouse (intraperitoneal)	Methylmercury hydroxide	Micronuclei induction in bone marrow cells	–	Jenssen and Ramel 1980

Table 2-83. Genotoxicity of Organic Mercury Following *In Vivo* Exposure

Species (exposure route)	Mercury compound	Endpoint	Results	Reference
Human (diet, fish consumption)	Methylmercury	Mitochondrial DNA copy number and damage in white blood cells	–	Berky et al. 2019 (all regions)
Human (diet, fish consumption)	Methylmercury	Mitochondrial DNA copy number and damage in white blood cells	+	Berky et al. 2019 (outside capital region)
Cat (diet)	Methylmercury	UDS in peripheral leukocytes	–	Miller et al. 1979
Rat (gavage)	Methylmercury	DNA damage in peripheral leukocytes	+	Barcelos et al. 2011
Rat (gavage)	Methylmercury	DNA damage in hepatocytes	+	Barcelos et al. 2011
Rat (gavage)	Methylmercury	DNA damage in peripheral leukocytes	+	Barcelos et al. 2012
Rat (gavage)	Methylmercury	DNA damage in hepatocytes	+	Barcelos et al. 2012
Rat (oral)	Methylmercury	DNA damage in testes	+	Chen et al. 2019a
Rat (gavage)	Methylmercury	DNA damage in whole blood	+	de Oliveira Lopes et al. 2021
Rat (gavage)	Methylmercury	DNA damage in whole blood	+	Grotto et al. 2009b
Rat (gavage)	Methylmercury	DNA damage in liver and kidneys	+	Jin et al. 2008
Rat (oral via intragastric catheter)	Methylmercury	DNA damage in liver, kidneys, and brain	+	Joshi et al. 2014
Rat (stereotaxic injection)	Methylmercury	DNA damage in frontal cortex	+	Juárez et al. 2005
Rat (gavage)	Methylmercury	DNA damage in leukocytes	+	Manzolli et al. 2015
Rat (gavage)	Methylmercury	DNA damage in hepatocytes	+	Manzolli et al. 2015
Mice (gavage)	Methylmercury	DNA damage in hepatocytes	+	Maqbool et al. 2019
Non-mammalian eukaryotic organisms				
Drosophila melanogaster (diet)	Methylmercury chloride	Somatic mutation and recombination	–	Carmona et al. 2008
Chicken embryos (injection)	Methylmercury	DNA damage	+	Ferreira et al. 2015

[a]Positive response but no correlation to urine mercury levels or duration of exposure.

+ = positive result; – = negative result; +/– = weakly positive or marginal result; (+) = reported as positive but study was either seriously compromised or findings did not provide valid evidence of a positive response;
DNA = deoxyribonucleic acid; UDS = unscheduled DNA synthesis

Methylmercury is not mutagenic in yeast cells (Nakai and Machida 1973). In hamster cells, both methylmercury and methoxyethyl mercury chloride are weakly mutagenic without metabolic activation (Fiskesjo 1979). An *in vivo* study in (SEC × C57BL)F1 mice showed dominant lethal mutations in spermatogonia following intraperitoneal exposure to methylmercury; dominant lethal mutations were not

induced in spermatogonia or oocytes in similarly exposed (101 × C3H)F1 mice (Suter 1975). There is no evidence for somatic mutation or recombination in *D. melanogaster* following dietary exposure to methylmercury (Carmona et al. 2008).

In yeast, methylmercury exposure is a weak inducer of chromosome nondisjunction, but does not cause recombination (Nakai and Machida 1973). *In vitro* studies show consistent evidence of clastogenicity (aneuploidy, chromosome aberrations, sister chromatid exchanges, and micronuclei) in human, rat, and hamster cell lines exposed to various organic mercury compounds in the absence of metabolic activation (Betti et al. 1992; Crespo-López et al. 2007; Ehrenstein et al. 2002; Lee et al. 1997; Migliore et al. 1999). Sister chromatid exchanges were not observed in early mouse embryos (blastocysts) exposed to methylmercury in the absence of metabolic activation (Matsumoto and Spindle 1982).

The overall findings from cytogenetic monitoring studies of workers occupationally exposed to organic mercury compounds (Anwar and Gabal 1991; Popescu et al. 1979; Verschaeve et al. 1976) or the general population exposed via diet (Skerfving et al. 1970; Wulf et al. 1986) provided no convincing evidence that mercury adversely affects the number or structure of chromosomes in human somatic cells. Studies reporting a positive result (Anwar and Gabal 1991; Popescu et al. 1979; Skerfving et al. 1970, 1974; Verschaeve et al. 1976; Wulf et al. 1986) were compromised either by technical problems, a lack of consideration of confounding factors, or a failure to demonstrate a relationship between mercury exposure and induced aberrations. Therefore, none of these studies can be used to predict the potential genetic hazard to humans associated with exposure to mercury or mercury compounds. In hamsters, the number of aneuploid oocytes was significantly increased following intraperitoneal exposure to methylmercury, but not to dimethylmercury or mercaptomerin; structural chromosomal alterations were not induced (Jagiello and Lin 1973; Mailhes 1983). The number of chromosomal alterations was increased in cat bone marrow following oral exposure to methylmercury; however, findings were not clearly dose-related (Miller et al. 1979). Micronuclei were not induced in mouse bone marrow cells following intraperitoneal exposure to methylmercury (Mailhes 1983) or in cat bone marrow cells following oral exposure to methylmercury (Miller et al. 1979).

Methylmercury and phenylmercuric acetate both induced DNA damage in bacteria (Kanematsu et al. 1980). Various organic mercury compounds consistently induced DNA damage in human, rat, mouse, and hamster cells lines *in vitro* in the absence of metabolic activation (Costa et al. 1991; Crespo-Lopez et al. 2016; Frenzilli et al. 2000; Guillamet et al. 2008; Ondovcik et al. 2012). Oral exposure to organic mercury compounds consistently induced DNA damage in various tissues in rats (Barcelos et al. 2011,

2012; Chen et al. 2019a; Grotto et al. 2009b; Jin et al. 2008; Joshi et al. 2014; Juárez et al. 2005; Manzolli et al. 2015). DNA damage was also observed in chicken embryos injected with methylmercury (Ferreira et al. 2015). Unscheduled DNA synthesis was not induced in cats following oral exposure to methylmercury (Miller et al. 1979).

The potential association between exposure to mercury and mitochondrial DNA copy number or damage in WBCs was assessed in Peruvian subjects living various distances from artisanal and small-scale gold mining operations outside the capital city of Puerto Maldonado (Berky et al. 2019). Exposure to mercury in these populations was attributed to consumption of methylmercury contaminated fish. Overall, HHg were similar across regions and no associations were observed between HHg and mitochondrial DNA copy number or damage. Additionally, no associations were found when the data were stratified by relationship to mining operations (upriver, near Puerto Maldonado, downriver). However, when evaluated just in individuals who lived >20 miles outside of the capital city, HHg levels were significantly associated with increased mitochondrial DNA damage.

2.21 GENERAL MECHANISMS OF ACTION

A diverse list of toxic mechanisms for mercury compounds has been described. This includes alteration or disruption of the regulation of intracellular calcium homeostasis, cytoskeleton, mitochondrial function, oxidative stress, neurotransmitter release, and DNA methylation. Mercury is a soft electrophile and will interact with soft nucleophiles, including thiols (R-SH) and selenols (R-Se) in proteins (Carty and Malone 1979). A contributor to the diversity of activity of mercury in biological systems is the high affinity of Hg^{2+} and CH_3Hg^{2+} for thiolate ($R\text{-}S^-$) and selenolate ($R\text{-}Se^-$) groups in proteins (Carty and Malone 1979; Parks and Smith 2016; Ralston and Raymond 2018). This enables mercury to bind to and disrupt structure and activity of enzymes, transporters, and other proteins whose activity is dependent on functional thiol or selenol groups. These include a diverse set of important transporters and enzymes that participate in the regulation of cell structure and function such as ATPases; hemoglobin and myoglobin; tubulin; numerous oxidoreductases, transferases, hydrolases and isomerases; and selenoenzymes (Khan and Wang 2009; Nagahara 2011). Low molecular weight thiols also serve as important ligands for mercury transport in and out of cells. Conjugates of Hg^{2+} and CH_3Hg^{2+} with extracellular thiols (e.g., cysteine, glycinyl-cysteine, glutathione) are recognized by physiological transport systems for amino acids (e.g., molecular mimicry) and, once in cells, mercury can distribute to other critical intracellular thiol and selenol groups. Transport of mercury S-conjugates has been shown to be important in a variety of tissues, including, brain, intestines, kidneys, liver, placenta, and RBCs (Ballatori 2002; Bridges and

Zalups 2010, 2017; Clarkson et al. 2007; Lohren et al. 2015). Molecular mimicry may contribute to tissue target specificity of methylmercury and inorganic mercuric mercury, primarily to brain, fetus, and kidneys (Bridges and Zalups 2017). General mechanisms by mercury form (elemental, inorganic, organic) are discussed in more detail below.

Elemental Mercury. Toxic actions of elemental mercury are related to mercury levels in the target tissues, primarily (e.g., brain). The relatively high lipid solubility of Hg^0 contributes to the partitioning of inhaled mercury vapor into blood and delivery of Hg^0 and Hg^{2+}-thiol conjugates to the central nervous system. Vascular proximity of the brain, coupled with a limiting oxidation rate of Hg^0 in blood, contributes to a first-pass effect on uptake of mercury into the brain following inhalation of Hg^0 (Magos et al. 1989). Transfer of inhaled Hg^0 into the brain results from several processes: (1) diffusion of Hg^0 vapor into blood; (2) physical partitioning (dissolving) of Hg^0 into plasma, RBCs, and other tissues; (3) extracellular and intracellular oxidation of Hg^0 to Hg^{2+}; (4) formation of Hg^{2+} complexes with proteins and non-protein species (primarily with sulfhydryls, including sulfhydryl amino acids); and (5) transport and distribution of Hg^{2+} complexes. Toxicity of absorbed Hg^0 in target tissues is related to inorganic mercury (primarily mercuric) levels in the target tissues (see discussion of mechanisms of toxicity of inorganic mercuric mercury below).

Inorganic Mercuric Mercury. Toxic actions of inorganic mercuric mercury are related to mercury levels in the target tissues (e.g., brain, kidneys, red blood cells). Delivery of inorganic mercuric mercury to target tissues is facilitated by membrane transporters that recognize S-conjugates of Hg^2. The Hg^{2+} ion has a strong tendency to form conjugates with two sulfur ligands (e.g., R-S-Hg-S-R′) (Carty and Malone 1979; Parks and Smith 2016). This distinguishes S-conjugates of inorganic Hg^{2+} from those formed by CH_3Hg^{2+} (CH_3Hg-S-R). Transporters implicated in the uptake of Hg^{2+}-S conjugates in the mammalian renal proximal tubule include the organic anion transporter, OAT1, located in the basolateral membrane of the proximal tubule and amino acid transporter system, $b^{0,+}$, located in the luminal membrane (Bridges and Zalups 2005; Bridges et al. 2004; Wei et al. 1999; Zalups and Ahmad 2004; Zalups et al. 2004). Both systems transport thiol conjugates of Hg^{2+} with the amino acid cysteine (Cys-S-Hg-S-Cys). On the luminal side of the proximal tubule, formation of the cysteine S-conjugate is facilitated by the catabolism of a glutathione S-conjugate (GluGlyCys-S-Hg-S-CysGlyGlu), which is catalyzed by the luminal membrane enzymes, GGT and cysteinylglycinase (Berndt et al. 1985; de Ceaurriz et al. 1994; Tanaka et al. 1990; Tanaka-Kagawa et al. 1993; Zalups 1995; Zalups and Lash 1997). Kinetics of reversible binding of Hg^{2+} to thiols is sufficiently fast enough to allow the Hg^{2+} in transported S-conjugates of Hg^{2+}

to exchange with other thiol or selenol ligands, including thiolate or selenolate groups in proteins (Carty and Malone 1979; Parks and Smith 2016; Ralston and Raymond 2018).

Interactions of mercury with transporters, enzymes, and other proteins are thought to be the primary mechanisms by which inorganic mercuric mercury disrupts cell function. Several specific systems have been identified as targets of inorganic mercuric mercury. Mercuric mercury binds to and inhibits selenoenzymes, including thioredoxin reductases, enzymes that function in regulation of the oxidation state of protein thiols (Branco and Carvalho 2019). Inhibition of thioredoxin reductases is considered to be an important mechanism by which inorganic mercuric mercury impairs cellular antioxidant systems and produces oxidative damage to cells (Branco et al. 2012). Disruption of antioxidant systems leads to formation of ROS, lipid peroxidation, necrosis, and apoptosis, and in RBCs, promotes the formation of methemoglobin (Ahmad and Mahmood 2019; dos Santos et al. 2016; Branco et al. 2012). Mercuric mercury binds to thiol groups in heme-thiolate proteins, which include cytochrome P450 and nitric oxide synthase (Ynalvez et al. 2016). Inhibition of nitric oxide synthase is thought to be an important mechanism by which mercuric chloride disrupts regulation of vascular resistance (Omanwar et al. 2014; Vassallo et al. 2011; Wiggers et al. 2008). Altered expression of cytochrome P450 in cardiac tissue is thought to be a contributing mechanism to mercuric chloride-induced cardiotoxicity (Amara et al. 2014).

The Hg^{2+} ion can displace cationic metals (copper, zinc) from binding sites on metallothionein (and other metalloproteins) and induces the synthesis of metallothionine (Aschner et al. 2006; Kagi et al. 1984, Yasutake and Nakamura 2011).

Methylmercury. Toxic actions of methylmercury are related to mercury levels in the target tissues, which primarily include the brain and kidneys. Delivery of methylmercury to target tissues is facilitated by membrane transporters that recognize S-conjugates of methylmercury with cysteine and other thiols (Ballatori 2002; Bridges and Zalups 2010, 2017; Clarkson et al. 2007; Lohren et al. 2015). The high affinity of CH_3Hg^{2+} for thiols enables mercury to bind to and perturb the function of a wide variety of proteins. These include ATPases; globins (e.g., hemoglobin, myoglobin); tubulin; and numerous oxidoreductases, transferases, hydrolases, and isomerases (Nagahara 2011). Methylmercury also forms stable complexes with selenols (R-Se) (Khan and Wang 2009). Formation of complexes with selenocysteine residues can alter the function of selenoenzymes (e.g., GPX and thioreductase). Direct complexation of selenium with methylmercury may also sequester selenium, making it unavailable for incorporation into protein or other selenium-dependent physiological processes (Ralston and Raymond 2018).

Interactions of mercury with transporters and enzymes are thought to be the primary mechanisms by which methylmercury disrupts cell differentiation and function. Several specific systems have been identified as targets of methylmercury. Methylmercury disrupts cellular antioxidant systems and promotes generation of ROS (Aaseth et al. 2020; Farina and Aschner 2017; Garza-Lombo et al. 2018). Several mechanisms contribute to the pro-oxidative action of mercury, including direct binding to cysteine and glutathione, depletion of glutathione, and inhibition of selenoenzymes that function in maintaining cell redox potential (Farina and Aschner 2017; Ralston and Raymond 2018; Spiller 2018). These include the selenoenzymes, GPX and thioreductase. In mitochondria, disruption of antioxidant systems leads to loss of mitochondrial membrane integrity, apoptotic cell cytokine cascade, and cell death (Ceccatelli et al. 2010; Roos et al. 2012). Methylmercury stimulates neuronal excitatory N-methyl-D-aspartate (NMDA) glutamate receptors (Aaseth et al. 2020; Colon-Rodriguez et al. 2017; Farina and Aschner 2017). This can lead to dysregulation of intracellular calcium levels and production of ROS (Aschner et al. 2007). Methylmercury binds to thiols on neuronal gamma-aminobutyric acid (GABA) receptors and inhibits GABA signaling (Basu et al. 2010; Fonfria et al. 2001). Methylmercury disrupts cell signaling pathways, including phospholipase C, calcium, and phosphatidylinosito-3-kinases/protein kinases (Fretham et al. 2012; Kang et al. 2006). Disruption of cell signaling is thought to contribute to increased production of ROS and inflammatory responses to methylmercury in neuronal tissues (Chang 2011; Hwang et al. 2011). Methylmercury forms complexes with thiols in microtubule-associated proteins, disrupting tubulin organization, and cellular architecture dependent on microtubules (Aaseth et al. 2020, Sager et al. 1983; Vogel et al. 1985). Methylmercury changes expression and post-translational modification of genes involved in neuronal cell differentiation, antioxidant responses, and inflammation (Fujimura and Usuki 2014; Hwang et al. 2011; Ke et al. 2019; Onishchenko et al. 2008; Robinson et al. 2011; Theunissen et al. 2011).