
Special Articles

Assessing and Managing Methylmercury Risks Associated With Power Plant Mercury Emissions in the United States

Gail Charnley, PhD

Medscape General Medicine. 2006;8(1):64. ©2006 Medscape
Posted 03/09/2006

Abstract and Introduction

Abstract

Until the Clean Air Mercury Rule was signed in March 2005, coal-fired electric utilities were the only remaining, unregulated major source of industrial mercury emissions in the United States. Proponents of coal-burning power plants assert that methylmercury is not a hazard at the current environmental levels, that current technologies for limiting emissions are unreliable, and that reducing mercury emissions from power plants in the United States will have little impact on environmental levels. Opponents of coal-burning plants assert that current methylmercury exposures from fish are damaging to the developing nervous system of infants, children, and the fetus; that current technology can significantly limit emissions; and that reducing emissions will reduce exposure and risk. One concern is that local mercury emissions from power plants may contribute to higher local exposure levels, or "hot spots." The impact of the Mercury Rule on potential hot spots is uncertain due to the highly site-specific nature of the relationship between plant emissions and local fish methylmercury levels. The impact on the primary source of exposure in the United States, ocean fish, is likely to be negligible due to the contribution of natural sources and industrial sources outside the United States. Another debate centers on the toxic potency of methylmercury, with the scientific basis of the US Environmental Protection Agency's (EPA's) recommended exposure limit questioned by some and defended by others. It is likely that the EPA's exposure limit may be appropriate for combined exposure to methylmercury and polychlorinated biphenyls (PCBs), but may be lower than the available data suggest is necessary to protect children from methylmercury alone. Mercury

emissions from power plants are a global problem. Without a global approach to developing and implementing clean coal technologies, limiting US power plant emissions alone will have little impact.

Introduction

The extent to which mercury in the environment poses a risk to human health has been under debate for a number of years. Although few would question the toxicity of methylmercury at high exposure levels, such as from poisoning, the debate centers on low environmental exposure levels and the extent to which low levels pose a risk to infants, children, and the developing fetus. This concern has been highlighted because regulations have been promulgated for the first time by the US Environmental Protection Agency (EPA) that would limit mercury emissions from electric power generating plants that burn coal.

Coal-fired electric utilities are the only remaining, unregulated commercial source of mercury emissions in the United States. Proponents of coal-burning plants assert that methylmercury is not a hazard at the current environmental levels, that current technologies for limiting emissions are unreliable, and that reducing mercury emissions from power plants in the United States will have little impact on environmental levels. Opponents of coal-burning plants assert that current methylmercury exposures are damaging to the developing nervous system of infants, children, and the fetus; that current technology can significantly limit emissions; and that reducing emissions will reduce exposure and risk. Also debated is the toxic potency of methylmercury, with the scientific basis of the EPA's recommended exposure limit questioned by some and defended by others. If the exposure limit is correct, some people may be at risk from current environmental levels. If the exposure limit is more stringent than is necessary to protect public health, risk at current exposure levels is less likely.

This article critically evaluates the scientific evidence that is relevant to the assertions of both proponents and opponents of limiting mercury emissions and the impact that such limits are likely to have on public health. This article focuses on the health effects associated with methylmercury -- not all forms of mercury -- and provides comments on the nature and likely effectiveness of the actions proposed to limit mercury emissions from power plants that burn coal. The basis for the EPA's methylmercury exposure limit and the various assertions in regard to the number of people "at risk" for the effects of methylmercury are discussed. This article concludes that until a global approach to limiting mercury emissions and methylmercury exposures is undertaken, limiting power plant emissions in the United States alone may be good public policy as part of the EPA's efforts to improve air quality, but the wider public health benefits should not be oversold. The nature and extent of the anticipated impact, if any, on people who consume locally caught fish are difficult to predict due to the highly site-specific nature of the relationship between plant emissions and local fish methylmercury levels.

Readers are encouraged to respond to George Lundberg, MD, Editor of *MedGenMed*, for the editor's eye only or for possible publication via email: glundberg@medscape.net

Exposure to Mercury From the Environment

Sources of Mercury

Mercury (Hg) is a naturally occurring element that is ubiquitous in the Earth's core, crust, soils, oceans, and atmosphere. Mercury can exist in elemental, inorganic, and organic forms, but almost all of the global mercury pool is elemental.[1] One of the organic forms, methylmercury, is the form of current toxicologic concern. Mercury can and does change its chemical form and move among different environmental media, with the global amount of mercury remaining the same, but our understanding of its environmental behavior is still evolving. Human activity has made substantial amounts of mercury bioavailable that would not be under natural conditions.

Trace amounts of mercury exist naturally in fossil fuels, such as coal and oil. When those fuels are burned to generate electricity, mercury is released from the fuels to the air. Of the approximately 48 tons of mercury released into the air annually as a result of human activity in the United States, electric power generation contributes about 40%.[2] Other sources of airborne mercury that are related to human activities include medical waste incineration, municipal solid waste incineration, mining, pulp and paper milling, and cement manufacturing. Regulation of emissions from waste incineration has reduced airborne mercury emissions from human activities in the United States by more than 45% since 1990.[2] Natural sources of mercury released into the air from its solid form include volcanoes, oceans, forest fires, and soils. Electricity generation contributes about 10% of mercury emissions in the United States when natural sources are included. Globally, all US anthropogenic sources contribute about 2% to 3%, and US electricity generation contributes about 1% of total mercury emissions into the air (see Figure 1).[3,4] Asia accounts for more than half of the mercury emitted globally into the air from human activities, and China's coal-fired power plants alone represent about 22% of those emissions.[3,4]

Figure 1.

Approximate extent to which global atmospheric mercury can be attributed to different sources (based on Pacyna and colleagues[3]).

Mercury is usually released into the environment in its inorganic forms. Mercury vapor can be transported globally, whereas other forms are generally deposited relatively close to their sources. Inorganic mercury deposited in sediment can be converted to organic methylmercury by microorganisms (a conversion that does not take place in the human body).[1] Because mercury in the atmosphere can originate globally, regionally, and locally, the extent to which individual sources contribute to environmental mercury is debated. The EPA estimates that about half of the mercury deposited in the United States from the atmosphere is from US sources, whereas the remainder is from global sources.[5] The Electric Power Research Institute estimates that anywhere from 20% to 80% of the mercury deposited in the United States comes from domestic sources, depending on location, with virtually all of the mercury deposited west of Minnesota and the Mississippi River coming from outside the United States.[6] Seigneur and coworkers[7] estimate that about 70% of the mercury deposited in the United States comes from non-US sources (both natural and anthropogenic).

Dietary Mercury Exposure

When mercury from the atmosphere gets into water bodies and is converted to methylmercury in sediment, it can enter the aquatic food chain, where it bioaccumulates in seafood. Large, predatory saltwater fish contain more methylmercury than smaller fish species due to accumulation effects at each increasing stage of the food chain.[8] Levels in freshwater fish also vary, with higher fish methylmercury concentrations occurring in water with higher levels of methylmercury contamination.

The primary source of human exposure to methylmercury is the consumption of fish, shellfish, and marine mammals. Because different species contain differing concentrations of mercury, exposure varies according to the types of seafood that are consumed. Mercury concentrations in fish vary by about 2 orders of magnitude, with herring containing about 0.01 ppm and shark more than 1 ppm, for example.[9] The EPA estimates that the population as a whole consumes an average of about 1.4 mcg methylmercury daily, whereas the more recent US Food and Drug Administration (FDA) Total Diet Survey data can be used to estimate a mean daily intake of about 0.8 mcg (Table 1).[10] Some ethnic groups and subsistence or sports fishers can have higher dietary intakes of locally caught fish, with concomitantly higher methylmercury exposures than average if those fish are contaminated. More than 75% of the fish consumed in the United States is imported.[11] Farm-raised fish (about one half of US fish consumption) tend to contain very low levels of methylmercury because it is generally not present in their artificial feed.

Several studies have evaluated whether the source of methylmercury contamination in ocean fish is more likely to be naturally occurring or associated with human activities. One such study comparing 1971 and 1998 methylmercury concentrations in tuna caught near Hawaii found no differences, although the level of mercury in the atmosphere has almost tripled since 1971 (due to non-US human activities).[12] The study authors concluded that the source of methylmercury in tuna (and probably in other ocean fish) could be primarily natural, not human in origin, originating in deep water or sediment. Similarly, Miller and colleagues[13] found no difference in the mercury concentrations of museum tuna specimens caught between 1878 and 1909 and tuna caught in 1972. Greenfield and colleagues[14] reported no obvious increasing trend for mercury levels in the tissue of striped bass caught off 3 widely dispersed locations throughout the San Francisco Bay area between 1970 and 2000 despite increases in environmental levels during that period. In contrast, during the same period, reductions in pesticide levels were observed in the same fish, paralleling restrictions on pesticide use. Together with the observation that US power plants contribute about 1% of global mercury emissions, these findings suggest that reducing US mercury emissions would have little impact on mercury levels in ocean fish.

Wild freshwater fish comprise about 10% of average US fish consumption, and the extent to which their methylmercury levels are affected by deposition of mercury from nearby coal-fired power plants is debated.[15] Most of the mercury emitted from power plants is elemental mercury or is rapidly degraded to elemental mercury, which tends to remain in the atmosphere and be transported away from the source, entering the global mercury cycle. A much smaller proportion remains in a form that is more likely to be deposited close to the source. Studies show that methylmercury levels in freshwater fish vary considerably, even among fish taken from lakes in the same region with the same sources of mercury. Site-specific factors unrelated to mercury, such as nutrient levels and water chemistry, appear to play a substantial role in determining freshwater fish methylmercury levels.

A study in Florida evaluated the relationship between mercury emissions, deposition, and total mercury accumulation in fish at different locations.[16] No data were collected on mercury speciation. Results showed that between 1991 and 2000, regulation of mercury emissions reduced emissions by 93% and deposition via rain by at least 25%; at 3 of the 12 locations sampled, large-mouth bass showed an approximately 80% decline in mercury levels during that period, whereas bass from the other locations showed no change or increases in mercury content.[16] Although the nature of the sites sampled varied, reasons for the site-specificity of the relationship between declining mercury emissions and fish mercury levels are unknown. In another study, the EPA used the results of a fate and transport model to conclude that, for long-term steady-state conditions, reductions in fish-tissue concentrations are expected to track linearly with reductions in air deposition watershed loads.[17] That conclusion has not been validated by data, however, and the model does not take into account the various ways that site-specific characteristics can alter the relationship between deposition and fish-tissue concentrations. Together, these observations suggest that reducing mercury emissions can reduce fish methylmercury concentrations close to the source in some places but not others.

The potential relationship between power plant mercury emissions and methylmercury concentrations in locally caught fish is complex and poorly understood. Conclusions about the effectiveness of limiting local mercury emissions as a means of reducing local freshwater fish methylmercury levels should be postponed until studies of the impact of current efforts to limit emissions become available.

Body Burdens

Mercury is excreted into and accumulates in human hair, which can therefore be used as an indicator of longitudinal mercury exposure. Most of the mercury in hair is methylmercury.[1] Hair mercury analysis is sensitive to the possibility of mercury contamination both pre- and post collection.[1] Contaminated hair samples would lead to overestimates of exposure, potentially affecting dose-response characterization. The pharmacokinetic behavior of methylmercury and its relationship to toxicity has been reviewed by Clarkson.[18]

The US Centers for Disease Control and Prevention has measured the blood mercury levels of women and children as part of the National Health and Nutrition Examination Survey.[19,20] The most recent results (1999-2002) show that women of childbearing age[16-49] had a geometric mean blood mercury concentration of 0.92 parts per billion, with an upper 95th percentile concentration of 6.04 parts per billion. Children ages 1-5 years had a geometric mean blood mercury concentration of 0.33 parts per billion and an upper 95th percentile concentration of 2.21 parts per billion. Mercury levels have also been measured in umbilical cord blood, and the ratio between cord blood and maternal blood is about 1.7.[8,21] There are few data on methylmercury levels in breast milk, but the concentration of total mercury in human milk appears to correspond to about 8% of the concentration in whole blood.[22]

Health Risks From Methylmercury Exposure

Developmental Neurotoxicity

Methylmercury is a known developmental neurotoxicant when ingested at high levels. During the 1950s-1970s, methylmercury poisoning incidents occurred in Japan and Iraq. In Japan, women who were consuming fish that were heavily contaminated with methylmercury from industrial discharges into Minimata Bay gave birth to children with severe psychomotor retardation. Some adults were also affected.[23] In Iraq, both children and adults experienced toxicity, including neurologic damage, after consuming methylmercury-treated seed grains. More than 6500 people were hospitalized and 459 died.[24] In Japan, the average fish methylmercury concentrations ranged from 9 ppm to 24 ppm, and the amount of fish that was consumed was about 20 times greater than the amount consumed by recreational fishers in the United States.[25] In Iraq, those exhibiting symptoms of neurotoxicity were estimated to have consumed between 200 mg and 1000 mg of methylmercury over a period between 1 and 3 months (about 2-33 mg/day).[26] These poisoning incidents are difficult to extrapolate to the much lower mercury exposure levels commonly associated with fish consumption in the United States (mean, 0.0008 mg/day; see Table 1), and the extent to which mercury is a developmental neurotoxicant at US environmental levels of exposure remains controversial.

Several, recent prospective epidemiologic studies have attempted to characterize the effects of methylmercury at environmental levels of exposure by evaluating subtle neurologic changes among children exposed prenatally and postnatally in societies relying heavily on fish and marine mammals as sources of protein. The results of those studies are conflicting. In the Seychelles Islands, a study involving 711 mother-child pairs found no positive associations between mercury exposure as determined by hair total mercury level and the neurodevelopmental outcomes evaluated at 66 months of age.[27] The study authors concluded that exposure to methylmercury from a diet that is high in ocean fish (maternal average, 12 fish meals per week) posed no neurodevelopmental risks through 66 months of age. A follow-up of the same cohort at 9 years of age also found no support for the hypothesis that there is a neurodevelopmental risk from prenatal methylmercury exposure resulting from ocean fish consumption,[28] although subtle effects that remained undetected cannot be ruled out. The mean prenatal methylmercury exposure was 6.9 parts per billion.

In the Faroe Islands, 917 7-year-old children were tested for their performance on tasks that were associated with the neuropathologic abnormalities seen in the earlier methylmercury poisoning incidents in Japan and Iraq.[29,30] The tests evaluated fine motor tasks, attention measures, executive function tests, language tests, short-term memory tests, and visuospatial tasks. Mercury exposure was characterized by measuring mercury levels in maternal hair when the child was born, the child's hair at 12 months and 7 years of age, the child's cord blood, and the child's blood at 7 years of age. Multiple regression analyses found that cord blood methylmercury concentrations showed the clearest associations with decreased attention, memory, and language.

The Faroe Islands study results have been questioned due to potential confounding by the relatively high levels of polychlorinated biphenyls (PCBs) to which this population is also exposed from consuming pilot whale blubber and to which children were exposed in utero and postnatally via breast milk.[8,31] PCBs are considered developmental neurotoxicants by the EPA. Reanalyses of the data have concluded that the adverse effects observed were not confounded by prenatal PCB

exposure, although postnatal PCB exposure was not evaluated.[8] Steuerwald and coworkers[32] evaluated postnatal exposure to PCBs from breast milk and reported an absence of confounding. However, their analysis evaluated PCB effects only at 2 weeks of age and would have missed any later impacts. Figure 2 compares Faroe and Seychelles adult methylmercury intakes from fish and/or whales, Faroe adult PCB intake, and Faroe child PCB and mercury intakes from breast milk. The level at which PCBs have produced developmental neurotoxicity in infant monkeys fed PCB-contaminated breast milk[33] is also shown. Faroe infant exposure to PCBs from breast milk is almost twice the level that is toxic to infant monkeys and almost 1000 times higher than the EPA limit on exposure that is considered safe. In contrast, the Seychelles study, which reported no impact of methylmercury exposure on neurodevelopment, also detected no exposure to PCBs.[27] Toxicology suggests that the developmental effects seen in Faroe children are more likely to be attributable to PCBs in breast milk than to methylmercury (or to a combination of the 2),[31] but further analysis is needed to support that conclusion.

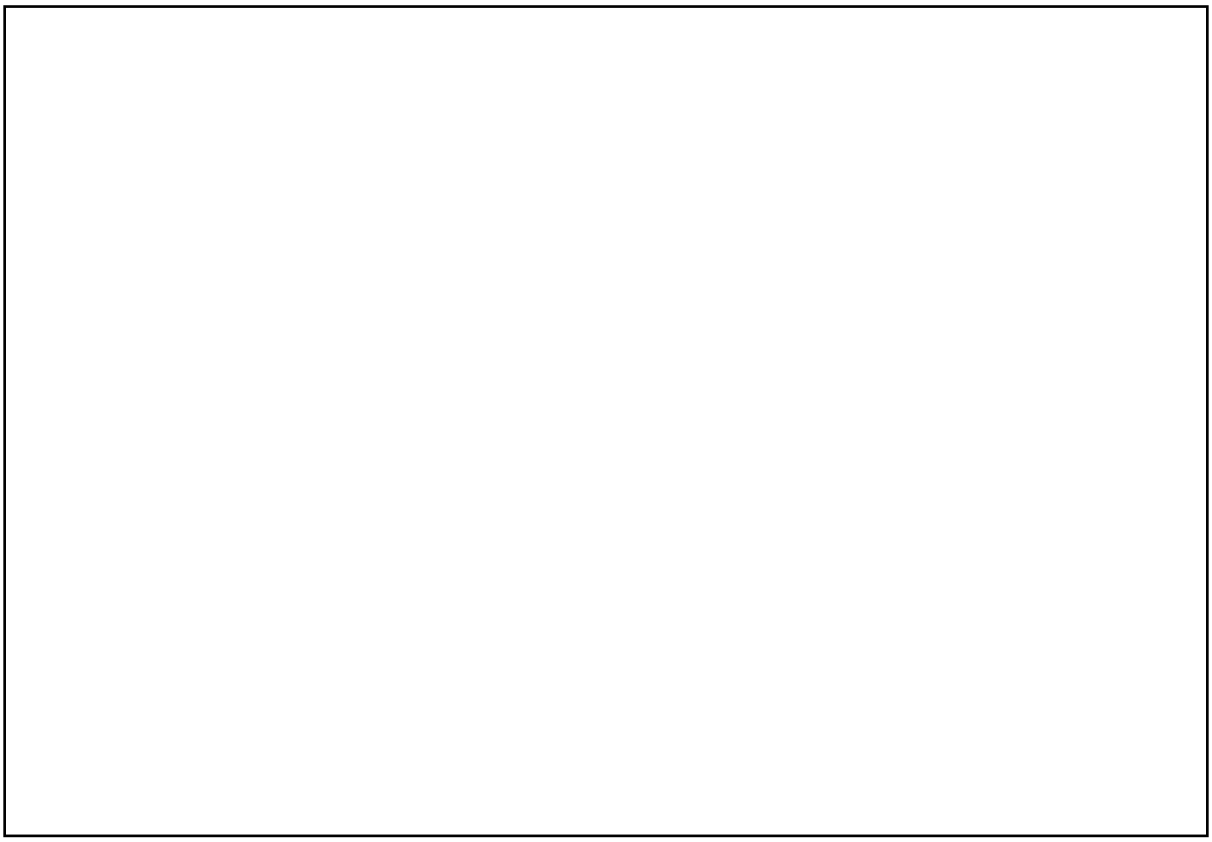

Figure 2.

Contaminant intakes in the Faroe and Seychelles Islands. Polychlorinated biphenyl (PCB) intake from breast milk exceeds the dose that is developmentally neurotoxic in infant monkeys and almost 1000 times higher than the EPA reference dose for PCBs (source: Dourson and coworkers[31]).

In New Zealand, general intelligence, academic attainment, language development, social

adjustment, and fine and gross motor coordination were assessed in a group of 230 6- and 7-year-old children.[34,35] The study authors concluded that there was an "apparent consistent association" between prenatal exposure to high levels of methylmercury (based on either "higher" or "lower" maternal hair mercury levels) and decreased performance on scholastic and psychological tests. Because the New Zealand cohort was small, however, and because of technical problems with the study, it is less reliable than the Seychelles or Faroe Islands cohorts.

All 3 epidemiologic studies of the developmental effects of methylmercury are concerned with effects that are very small compared with normal variation, leading to several problems. First, because the signal-to-noise ratio is very low, it is difficult to detect or measure the size of the effect, which may explain some of the differences between the studies. Second, it is very easy for a secondary correlation to increase or diminish the apparent effect, which is why correlation does not prove causation. In addition to PCBs in the Faroe Islands, other potential confounding factors include urban vs rural upbringing (ie, the children with lower exposures in the Faroe Islands tended to live in town) and the potential negative correlation from beneficial effects from fish consumption, which may have been realized to a lesser extent in the Faroe Islands than in the Seychelles Islands or New Zealand because many of the high methylmercury exposures were from whale consumption, not fish. Because it is not possible to draw any strong conclusions from these studies, the fact that the effects observed in the Iraqi poisoning incident are much larger relative to background variation makes that study worthy of consideration when evaluating risk at environmental exposures despite the data collection problems associated with that study.[36,37]

A recent study evaluated the relationship between blood mercury levels and neurobehavioral function in an aging US population participating in a study of cognitive decline with age. For the 474 participants, aged 50-70 years, no evidence of an association between mercury levels and worse neurobehavioral performance was found.[38]

Coronary Heart Disease

Many studies have demonstrated the clear cardiovascular benefits of regular fish consumption, despite the potential for mercury exposure. For example, among the high fish-consuming native peoples of James Bay in Quebec, Canada, a period of high methylmercury exposure from fish was related to a period of low coronary heart disease risk.[39,40] Eating broiled or baked fish (but not fried), including tuna, has been associated with a lower incidence of irregular heartbeat among the elderly.[41] Eating oily fish, such as salmon, tuna, or bluefish, at least twice a week can prevent sudden cardiac death.[42] The American Heart Association recommends that individuals consume 2 servings of a variety of fish weekly, both for the benefits of omega-3 fatty acids and because fish tends to be low in saturated fats, which contribute to elevated cholesterol levels.

Recently, however, a study of Finnish men found an association among the highest third of hair mercury content and an approximately 60% greater prevalence of coronary heart and cardiovascular diseases compared with men with the lower two thirds of hair mercury content.[43] The men who were least likely to experience heart problems were those who had both low levels of hair mercury and high blood levels of fatty acids found in fish that are known to reduce the risk for heart disease.

Attempts to correlate hair mercury content with fish consumption were tenuous, with one third of the men in the highest hair mercury group reporting higher fish consumption than the other study participants. No information was provided on whether high- or low-mercury-containing types of fish were consumed. Contrary to the large body of epidemiologic evidence showing a negative correlation between fish consumption and heart disease, the population of Eastern Finland has a high rate of heart disease regardless of high fish consumption,[44] suggesting that factors other than methylmercury are responsible for elevated risk.[45] The Finnish results were considered preliminary by the American Heart Association, which has concluded that when consumed according to the established FDA/EPA guidelines, the cardiovascular benefits of eating fish far outweigh the risks for middle-aged and older men and women after menopause.[46]

Numerous other factors may contribute to the discrepancies among studies, such as differences in contaminant levels and in the omega-3 fat content of the fish consumed, the extent of variability in fish consumption in the population, background risk, the nature of the endpoints examined,[47] and differential exposure to inorganic or methylmercury (both of which are reflected in total hair mercury levels).

The mechanisms of mercury cardiotoxicity, if any, are not known. Multiple mechanisms are plausible, however, including altered cardiac sodium handling and modified responses to viral infections.[48] Methylmercury can accumulate in heart tissue.[49] Thus, although the evidence that mercury is associated with coronary heart disease risk is contradictory and there is insufficient evidence to conclude that mercury is associated with risk, the suggestive positive findings and the plausible biological modes of action warrant additional research.

Risk Management Strategies

As a widely recognized developmental toxicant, mercury has been the target of regulation in the United States since the passage of the Clean Air Act in 1970. Mercury-containing pesticides have been banned; disposal of mercury-containing waste is strictly controlled; mercury mining has ceased; and mercury emissions resulting from municipal, medical, or hazardous waste incineration are significantly restricted. Recently promulgated regulations will restrict mercury emissions from coal-fired power plants in the future, although technologies currently in place to control other pollutants also reduce mercury emissions to varying degrees.

There are 2 basic risk management strategies that have been initiated or are under consideration to reduce potential risks from methylmercury exposure. One approach relies on defining exposure limits that are considered unlikely to be associated with adverse effects and then limiting the consumption of certain fish by children and pregnant women. Such exposure limits are meant to limit exposure once environmental contamination has occurred. Another approach requires the implementation of particular technologies that have been determined to reduce mercury emissions and is thereby meant to prevent contaminant emissions before they occur.

Health-Based Exposure Limits

Regulatory agencies and scientific organizations in the United States and Europe have identified quantitative exposure levels for methylmercury -- based partly on science but mostly on policy -- that are considered to be limits on safety. Such limits are goals that, if exceeded, may warrant actions to reduce exposure, although exceeding a limit does not imply lack of safety. Most exposure limits for methylmercury are advisory levels and not regulatory requirements. Table 2 shows the exposure levels considered protective by different organizations. All of the protective exposure levels identified in Table 2 are based on methylmercury's ability to produce developmental neurotoxicity. Most were based on the data from the Seychelles study described above, although some also considered the Faroe Islands and New Zealand data. Some derived a "benchmark dose" from the dose-response relationships for methylmercury exposure and developmental neurotoxicity, that is, a statistical lower confidence limit on the methylmercury concentration in maternal blood that resulted in a 5% or 10% increased incidence of neuropsychological impairment in infants born of women who had consumed fish and pilot whale meat. In other cases, a no-observed-adverse-effect level (NOAEL) was identified, that is, the median maternal hair concentration from the highest exposure group in the Seychelles Islands study (which, as noted above, found no significant positive association between exposure and abnormality). The benchmark dose or NOAEL, expressed as concentrations of mercury in blood or hair, was then converted to the dose of methylmercury from fish that would produce that blood or hair concentration. Finally, that dose was divided by an "uncertainty factor" to obtain a dose considered to be without deleterious effects by accounting for the possibility that some people may be more sensitive to methylmercury toxicity than others. The resulting dose is considered the amount of methylmercury that can be consumed daily without producing developmental neurotoxicity even in the most sensitive children. The EPA calls such limits reference doses (RfDs); the Agency for Toxic Substances and Disease Registry calls them chronic minimal risk levels (MRLs); and others refer to them as tolerable daily intakes (TDIs).

The fact that the exposure limits calculated by different organizations are similar suggests that the results of the different studies upon which they are based are comparable, but they are not. The Faroe Islands study was probably confounded by PCBs in breast milk and found slightly decreasing performance on neurodevelopmental tests among children correlated with increasing cord blood mercury levels. The Seychelles study found slightly improving performance on neurodevelopmental tests with increasing maternal hair mercury. The results of the Seychelles study do not appear to be confounded by other exposures and are therefore more reliable as the basis for setting an exposure limit than the results of the Faroe Islands study. Because there were no adverse neurodevelopmental effects associated with methylmercury exposure in the Seychelles study, however, the benchmark dose derived from the Seychelles data takes as its 5% or 10% response level the statistical upper bound on zero response, that is, the largest response that could have been missed, had it existed. In other words, to be health-protective, the benchmark dose is based on the assumption that the response occurred but was too small to be detected. That assumption is intentionally biased by the policy need and statutory mandate to protect public health.

Despite the health-protective nature of MRLs, RfDs, and TDIs, their meaning is often misinterpreted. MRLs, RfDs, and TDIs are derived on the basis of the most sensitive type of toxicity; in the case of methylmercury, developmental neurotoxicity is the effect that has been observed at levels of exposure lower than those that cause other health effects. Exposure limits based on developmental neurotoxicity are thus expected to protect the most sensitive individuals, children. Exposure limits incorporate uncertainty factors so that even the *most* sensitive children are protected. Nonetheless,

especially in the case of methylmercury, their meaning has been misrepresented.

For example, Mahaffey and coworkers[50] concluded that more than 300,000 newborns per year in the United States are at increased risk for adverse neurodevelopmental effects from prenatal exposure to methylmercury. That conclusion is based on the fact that 7.8% of 1709 women ages 16-49 surveyed in 1999-2000[51] had mercury levels exceeding 5.8 mcg/L of blood. That concentration is the benchmark dose of 58 mcg methylmercury per liter of maternal blood from the Faroe Islands study divided by an uncertainty factor of 10.[8] There were 4,058,814 births in the United States in 2000; 7.8% of 4,058,814 is 316,587. There are a number of problems with that conclusion. First, mercury body burdens increase with age, and the 40- to 49-year-old women in the survey had twice the blood mercury levels as the younger women. Far fewer women over 40 give birth than do younger women. The average age for giving birth in the United States is 27; more than half of all births occur to women in their 20s.[52] It is therefore likely that far fewer than 7.8% of the women who bore children in 2000 had mercury levels exceeding 5.8 mcg/L of blood. More recent Nano Chemical Systems Holdings (NCSH) data report 5.7% of women ages 16-49 with methylmercury levels exceeding 5.8 mcg/L of blood.[20]

Even more importantly, exceeding 5.8 mcg methylmercury per liter of blood does *not* necessarily mean that a fetus is at increased risk. The derivation of an RfD is based on many policy choices in order to serve regulatory purposes and has little scientific basis. According to the EPA, RfDs incorporate a number of uncertainty factors and are defined as "an estimate of an exposure . . . that is likely to be without an appreciable risk of adverse effects over a lifetime"; therefore, "exceeding the RfD is not a statement of risk.[53]" In other words, although exposures at or below an RfD are unlikely to pose a risk, the converse -- that exposures exceeding an RfD are likely to pose a risk -- is not the case. The number of children "at risk" is determined by the dose-response relationship, not by the number of people whose doses or blood mercury levels exceed the RfD at a single point in time. Meanwhile, none of the US women or children tested in the NCSH study had methylmercury doses exceeding the EPA's benchmark dose for developmental neurotoxicity (58 mcg/L, the lower confidence limit on the dose estimated to produce a 5% response as determined with the Faroe data, assuming no confounding by PCBs).

Other reports claim that more than 600,000 children are at risk on the basis of the estimate of 300,000 described above adjusted upward to account for the approximately 2-fold difference in mercury blood concentrations in the umbilical cord compared with that in the mother. Some argue that the adjustment constitutes double-counting because the EPA's RfD calculation already takes that difference into account implicitly through the use of the uncertainty factor used to account for intraindividual pharmacokinetic differences.[54] EPA scientists who are responsible for determining the RfD state that they did not take the 2-fold difference into account explicitly when choosing the uncertainty factor although future evaluations will do so, and they hope to use probabilistic methods to choose an RfD in the future instead of relying on uncertainty factors.

The US National Academy of Sciences (NAS) report on methylmercury also offers an estimate of the number of children who are at risk for adverse neurodevelopmental effects from prenatal exposure to methylmercury.[8] The study authors assumed that children born to women who consume the most fish would be highly exposed to methylmercury and thus at risk. In 1989/1990, 30.5% of adolescent

girls and women ages 15-44 surveyed reported consuming fish regularly. Those in the 95th percentile of that group (918,172) were thought to have consumed 100 g of fish or more daily. Because the birth rate during that period was 65.6 per 1000, about 60,000 (65.6 x 918) children were considered to have been born to high fish consumers and were therefore at risk. Because fish consumption alone was considered a surrogate for exposure to methylmercury, for which there was no direct measurement, this classification of risk is arbitrary and unreliable. The levels of methylmercury in fish vary by several orders of magnitude; assuming simply that fish consumption is equivalent to methylmercury exposure is not supportable. In response to an FDA request for clarification, the chairman of the NAS Committee on the Toxicological Effects of Mercury stated that the term "at risk" in the NAS report merely meant "above the RfD" and implied neither harm to those exposed above the RfD nor an absence of harm to those exposed below the RfD.[55]

Not all limits on methylmercury exposure involve identifying specific concentrations in food that are considered safe (or unsafe). The FDA has worked with EPA to develop advice for consumers in regard to methylmercury and fish consumption. That advice warns pregnant women not to eat shark, swordfish, king mackerel, or tilefish because they may contain high levels of methylmercury.[56] To avoid losing the benefits of consuming fish, however, pregnant women are advised to eat up to 12 oz (2 average meals) a week of a variety of fish and shellfish that are lower in mercury, such as shrimp, canned light tuna, salmon, pollock, and catfish.

Another example of nonquantitative exposure limits are fish advisories targeted at specific bodies of water. Each state, tribe, or territory establishes its own criteria for issuing fish advisories. An advisory may completely ban eating fish or shellfish or it may recommend consumption limits that are considered safe (eg, numbers of fish meals per specified time period). It is typically more restrictive toward pregnant women, nursing mothers, and young children. In 2003, 21 states had issued statewide advisories for mercury in freshwater lakes and/or rivers; 11 states had statewide advisories for mercury in their coastal waters; and Hawaii had a statewide advisory for mercury in marine fish.[57] There were also 2 tribal statewide advisories put into effect for mercury in freshwater and marine fish (including lobster) by the Micmac Tribe of Maine.

Some advocates of mercury control point to the increasing numbers of fish consumption advisories due to mercury contamination as evidence that mercury from power plants has local impacts.[58] The acreage of freshwater lakes under fish consumption advisories for mercury increased 4 times between 1993 and 2002, although that increase is likely to be due to greater awareness, more extensive testing, and a decrease in the mercury RfD, not to an actual increase in mercury contamination,[59] and no relationship to the proximity of power plants has been investigated.

Technology-Based Exposure Limits

The Clean Air Act Amendments of 1990 required the EPA to investigate by 1993 the emissions of hazardous air pollutants from power plants relying on fossil fuel-fired steam generation for the purpose of deciding whether regulating those emissions was necessary or appropriate. The EPA was also required to investigate specifically mercury emissions from a variety of sources by 1994, in terms of their impact on health and the environment and the availability and cost of control technologies. In 1998, the EPA released a report finding that mercury was the hazardous air pollutant

of greatest public health concern emitted from fossil fuel-fired power plants, but did not address whether such power plants should be regulated. Environmental groups then sued the EPA, which ultimately agreed to investigate mercury emissions and control technologies further, to make a decision about the need for regulation, and if needed, to promulgate such regulation (see *Natural Resources Defense Council, Inc. v Environmental Protection Agency*, No. 92-1415 [D.C. Cir. Jan. 13,1999]). In December 2000, the EPA announced that regulating mercury emissions from oil- and coal-fired electric power plants was indeed necessary and appropriate but did not issue a regulation.

One of the first steps in regulating a source of hazardous air pollutants is to identify an effective technology to control emissions from a category of pollutant sources, in this case, coal-fired electric utilities. The type of technology and extent of emissions control required depend on identifying the maximum achievable control technology (MACT), which in turn cannot be less stringent than the average emissions limitation achieved by the best performing, top 12% of existing sources for which information is available. In the case of coal combustion, identifying MACT is complicated and, therefore, contentious. One approach, based on a limited number of emissions tests from 80 plants, suggests that a 90% reduction in mercury emissions is achievable at some facilities. However, because basing regulation on the best performing 12% of sources does not account for the wide variety of processes and coal types in use, another approach divides plants into categories according to process and to coal type and chemistry, proposing different MACT standards for different categories on the basis of the amount of mercury released per unit of energy created. The effectiveness of control devices at removing mercury depends, to a large extent, on the levels of chlorine in the coal, which vary substantially depending on its source and control the types of mercury compounds in the flue gas.[60] Some mercury compounds are captured more effectively than others.

According to the EPA and the courts, MACT requirements are expected to be "achievable under the most adverse circumstances which can reasonably be expected to recur" (64 Fed. Reg. 31898, 31915 [June 14, 1999]]. As yet, there is no single technology that can reliably control mercury emissions from all types of coal-fired power plants.[61] Mercury reductions at all existing coal-fired power plants, including the "best" performing units, result from control equipment that was installed to reduce the emissions of other pollutants. New coal-fired power plants are subject to stringent regulation under a number of Clean Air Act provisions, including new source performance standards. These requirements cause new plants to install high-efficiency particulate removal devices, scrubbing systems, and devices that reduce nitrogen oxides. Additional control strategies that specifically address mercury, such as activated carbon injection, are under development and not yet commercially available.

In December 2003, the EPA proposed the first rule to control mercury emissions from power plants. The rule proposed 2 approaches to limiting mercury emissions, one based on MACT and the other setting a cap on mercury emissions to be achieved with market-based emissions trading. The Clean Air Mercury Rule was finalized in March 2005 and derives its authority from section 111(d) of the Clean Air Act, so is based on the trading approach and not the MACT approach. The rule involves a first phase reflecting the mercury reductions expected as cobenefits to limiting sulfur dioxide and nitrogen oxides, with a cap of 38 tons per year starting in 2010, and a second phase with an additional emissions cap of 15 tons per year starting in 2018. The rule is predicted to achieve a 70% reduction in mercury emissions when fully implemented. The emissions trading or "cap-and-trade"

system for controlling mercury and other pollutants is based on the EPA's successful Acid Rain Program. The Acid Rain Program produced reductions in air pollutants faster and at far lower costs than anticipated, achieving more than 50% of the air-pollution reduction attained by the entire EPA with less than one tenth of 1% of agency staff.[62] The EPA's experience indicates that trading programs, such as the one proposed for mercury, can be cost-effective and health-protective.

Mercury control has also been pursued through legislation. The Bush Administration proposed Clear Skies legislation that would control mercury through emissions trading. The EPA predicted that Clear Skies legislation would lead to a 15% to 60% reduction in mercury deposition in many areas of the United States. Congress has taken no action on Clear Skies legislation to date. Both the regulatory and legislative approaches are intended to limit nitrogen oxides and sulfur dioxide in addition to mercury.

Under the new cap-and-trade approach, the EPA would allocate to each state a mercury budget, or specified amounts of emission "allowances" for mercury. The states decide how to meet the emissions cap (subject to EPA approval), and if a cap-and-trade approach is chosen, those allowances would be allocated to utilities, which would trade them. A utility must hold sufficient allowances to cover its emissions each year, so the limited number of allowances ensures that the required reductions are achieved. The mandatory emissions caps, coupled with significant automatic penalties for noncompliance and stringent emissions monitoring and reporting requirements, are meant to ensure that regulatory goals are achieved and sustained. The flexibility of allowance trading creates financial incentives for utilities to look for new and low-cost ways to reduce emissions and improve the effectiveness of pollution control equipment.

One of the criticisms of the emissions trading approach is that, by using each state as the unit within which trading is made, "hot spot" issues are not addressed, that is, special circumstances involving local mercury deposition from a power plant into nearby water bodies, from which people may catch and eat fish, are ignored. Whether the hot spots criticism is valid is as yet unclear, given the evidence discussed earlier suggesting that connections between local emissions, local deposition, and freshwater fish contamination are poorly understood and appear to be highly site-specific. A recent analysis by the Environmental Law Institute concluded that data from the current major air-pollution emissions trading programs indicate that trading has *not* created hot spots and, in promoting reductions at the largest power plants, has actually smoothed out pollution emissions instead of concentrating them.[63] In any case, the Rule is being litigated and its future is uncertain.

Effectiveness

Various proposals to limit mercury emissions from US coal-fired power plants have been made, each of which will reduce emissions. The proposed approaches, timing, cost, and extent of reductions differ, but all would eventually reduce emissions in some way. Whether those reductions in mercury emissions ultimately will have an impact on fish contamination, human exposure, and public health is far less certain, although such uncertainty should not be used as an excuse to avoid reducing emissions cost-effectively.

About 40% of the mercury in the global environment comes from natural sources, such as oceans

and volcanoes, and another 40% comes from non-US human activities. US electric utilities that burn coal are estimated to produce about 40% of the mercury emitted in the United States from human activities, but account for only 1% of the global mercury attributable to human sources. Asia accounts for nearly half of the mercury emitted globally from human activities, and China's coal-fired power plants alone represent about 22% of those emissions.[3,4] Asia's emissions are expected to continue to increase substantially as its need for electricity and its reliance on coal in the absence of environmental controls continue to increase. China alone currently plans to build coal-fired power plants at the rate of *1 per month*.[64]

Meanwhile, limited studies discussed above suggest that the source of methylmercury in tuna and other predatory ocean fish is likely to be primarily natural, not human in origin. Ocean fish account for almost all of most people's exposure to methylmercury. Some studies predict that reducing mercury emissions from US power plants by 50% could reduce methylmercury levels in ocean fish by about 1.5%. On the other hand, preliminary studies suggest that reducing mercury emissions from US power plants may reduce mercury contamination in locally caught fish, depending on a variety of circumstances, which would reduce exposure to people for whom locally caught fish comprise a significant proportion of their diets. A multiscale deposition modeling analysis conducted by the Electric Power Research Institute suggests that any potential local impacts of mercury control would be limited, however.[65,66] That study characterized mercury deposition both with and without contributions from coal-fired electric utilities and found that for 0.4% of US land area, utilities contribute more than 50% of mercury deposition ("utility-dominated"), whereas for 99.6% of US land area they contribute less than 50% ("non-utility-dominated"). More research is needed to clarify the local impact of mercury emissions.

According to a recent report by the Northeast States for Coordinated Air Use Management (NESCAUM),[67] a nonprofit association of state air-quality regulators, "Given the global nature of the problem, a significant reduction in US power sector mercury will be insufficient by itself to adequately address mercury contamination of fish and the resulting adverse health impacts." In the absence of international efforts to control mercury emissions, further mercury controls in the United States alone will have only a minor impact on our methylmercury exposure.

Conclusions and Recommendations

Conclusions

There is little doubt that methylmercury can produce developmental neurotoxicity, but, like all other substances, its toxicity depends on the dose and on the circumstances of exposure. If exposure occurs to doses that are sufficiently high, particularly during pregnancy or early childhood, toxicity may result.

The dose of methylmercury that is required to produce developmental toxicity is still being debated. Studies of children in the Faroe Islands who were exposed to relatively high doses of methylmercury during pregnancy, from breast milk, and in their diets showed signs of developmental neurotoxicity only when they were also exposed to high levels of PCBs from breast milk. Analyses concluding that

PCBs did not interfere with study results were performed after only 2 weeks of exposure, so would not have detected the later responses. The doses of PCBs that the children received were about twice as high as the dose that produces developmental neurotoxicity in infant monkeys exposed through breast milk, and nearly 1000 times higher than the dose of PCBs that the EPA considers safe. It appears likely that the neurotoxicity seen in children was due to PCB exposure or to the mixture of PCBs and methylmercury, and not solely to methylmercury. Therefore, it is possible that the current reference dose established by the EPA for methylmercury alone is lower than is needed to provide adequate public health protection. If PCB exposure were taken into account, the acceptable dose of methylmercury would be higher, similar to that found by other organizations based on the Seychelles data.

Recent evidence suggests a potential relationship between high mercury exposure and adverse cardiovascular effects, although many studies have demonstrated the clear cardiovascular benefits of regular fish consumption. The nature and likelihood of a potential relationship between mercury and cardiovascular toxicity should be explored with further research.

There is likely to be little relationship between US power plant emissions and methylmercury levels in ocean fish, which comprise most of the fish that people in the United States eat and are the source of most methylmercury exposure. For freshwater fish caught in the vicinity of coal-fired power plants, available data neither support nor rule out a relationship between fish methylmercury levels and plant emissions; such relationships appear to be site-specific. The evidence suggests that reducing power plant mercury emissions may have little impact on most US exposure to methylmercury but may affect exposure among those who frequently consume freshwater fish caught near coal-fired power plants where coal chemistry, emissions characteristics, atmospheric characteristics, mercury deposition, and water chemistry are consistent with a relationship between mercury emissions and uptake by fish.

Recommendations

The potential relationship between PCB exposure through breast milk and developmental neurotoxicity requires more careful analysis. If that relationship is supported, the EPA's current RfD for methylmercury should be reclassified as an RfD for a mixture of PCBs and methylmercury, and a different RfD for methylmercury should be developed on the basis of data from the Seychelles Islands, where PCB contamination was absent. Limiting methylmercury exposures to an unnecessarily stringent level would be a poor use of societal resources and send inappropriate risk messages that potentially limit the many benefits of fish consumption.

Pregnant women and children should follow the advice of the EPA and FDA and limit their consumption of high-mercury-containing fish while maintaining the health benefits of fish consumption by eating a variety of other fish.

Although it is clear from the EPA's acid rain trading program that market-based, cap-and-trade approaches to limiting air pollutant emissions can be both successful and cost-effective, whether a similar plan for limiting mercury emissions can address the hot spots issue, in which local mercury deposition and methylmercury contamination are attributable to individual power plants, requires

more research. Characterization of the nature and likelihood of mercury hot spot formation and the relationship to power plant emissions should be performed. If mercury hot spots prove to be important contributors to risk in some locations, local concentration-based limits on mercury emissions should be explored so that specific plants can be targeted where needed. However, because there appears to be little relationship overall between mercury emissions from coal-fired power plants in much of the United States and methylmercury exposure from eating fish, reductions in US power plant mercury emissions should not be oversold as a universal means of reducing methylmercury risks to pregnant women and children. On the other hand, a suspicion that the public health benefits may be small should not be used to avoid reducing mercury emissions if doing so can be accomplished cost-effectively.

Because most global mercury emissions that result from human activities come from sources outside the United States and because coal-fired power plant emissions of many pollutants are likely to continue to increase globally without intervention, the United States should lead international efforts to develop and implement effective and affordable clean-coal technologies that limit emissions.

Table 1. Mean Daily Dietary Methylmercury Intake Estimates

Population	Mean Methylmercury Intake (mcg/day)	
	US EPA[9]	FDA TDS Data‡
Whole	1.4	0.8
Women of childbearing age*	0.6	0.8
Children†	Not determined	0.2

*US Environmental Protection Agency (EPA), 15-45 years old; US Food and Drug Administration (FDA), 25-30 years old
†FDA, 2 years old
‡TDS = total diet survey[10]

Table 2. Exposure Limits for Methylmercury

	Organization				
	ATSDR	EPA	RIVM	WHO	ICF/TERA

Exposure limit*,†	0.3 chronic MRL	0.1 RfD	0.1 TDI	0.23 TDI	0.3-1 RfD
Study	Seychelles Islands	Faroe Islands (primarily)	Seychelles Islands	Seychelles, Faroes Islands	Seychelles Islands
Study dose*	1.3	0.9-1.5	1.3	1.5	0.9-3
Uncertainty factor‡	4.5	10	10	3.2	3
Year	1999	2001	2000	2003	1998

Abbreviations for organizations: ATSDR = Agency for Toxic Substances and Disease Registry; EPA = US Environmental Protection Agency; RIVM = National Institute for Public Health and the Environment, The Netherlands; WHO = World Health Organization; ICF = ICF Inc.; TERA = Toxicology Excellence for Risk Assessment

*Exposures expressed in units of micrograms methylmercury per kilogram body weight per day

†Abbreviations for exposure limits: MRL = minimal risk level; RfD = reference dose; TDI = tolerable daily intake

‡Uncertainty factors are used to lower the acceptable exposure level to the extent considered protective of nearly all people.

Source: Based in part on International Toxicity Estimates for Risk Database (ITER)[68]

References

1. Agency for Toxic Substances and Diseases Registry (ATSDR). Toxicological Profile for Mercury. Atlanta, Ga: US Department of Health and Human Services, Public Health Service; 1999. Available at: http://www.atsdr.cdc.gov/toxprofiles/tp46.html Accessed January 25, 2006.
2. US Environmental Protection Agency (EPA). 1999 National Emission Inventory Documentation and Data. Final Version 3.0. Research Triangle Park, NC: US Environmental Protection Agency (EPA), Office of Air Quality Planning and Standards. Available at: http://www.epa.gov/ttn/chief/net/1999inventory.html#final3haps Accessed January 25, 2006.
3. Pacyna JM, Pacyna EG, Steenhuisen F, Wilson S. Mapping 1995 global anthropogenic emissions of mercury. Atmospheric Environment. 2003;37(suppl1):S109-117.
4. United Nations Environment Programme (UNEP). Global Mercury Assessment. Geneva, Switzerland. 2002. Available at: http://www.unep.org/GC/GC22/Document/UNEP-GC22-INF3.pdf Accessed January 25, 2006.
5. US Environmental Protection Agency (EPA). Mercury Emissions: The Global Context. Washington, DC: US Environmental Protection Agency (EPA); 2005. Available at: http://www.

epa.gov/mercury/control_emissions/global.htm Accessed January 25, 2006.
6. Levin L. Mercury science: an update. Presentation to the Edison Electric Institute on behalf of the Electric Power Research Institute. Cited in: Northeast States for Coordinated Air Use Management. Mercury emissions from coal-fired power plants: the case for regulatory action. Boston, Mass: Northeast States for Coordinated Air Use Management. October 2003. Available at: http://bronze.nescaum.org/airtopics/mercury/rpt031104mercury.pdf Accessed January 25, 2006.
7. Seigneur C, Vijayaraghavan K, Lohman K, Karamchandani P, Scott C. Global source attribution for mercury deposition in the United States. Sci Technol. 2004;38:555-569.
8. National Academy of Sciences (NAS). Toxicological Effects of Methylmercury. National Academy Press. Washington, DC: National Academy Press; 2000.
9. US Environmental Protection Agency (EPA). Mercury Study Report to Congress. Volume III: Fate and Transport of Mercury in the Environment. December 1997. Available at: http://www.epa.gov/ttn/oarpg/t3/reports/volume3.pdf Accessed January 25, 2006.
10. US Food and Drug Administration (FDA). Total Diet Study. Washington, DC: Center for Food Safety and Applied Nutrition. Available at: http://vm.cfsan.fda.gov/~comm/tds-toc.html Accessed January 25, 2006.
11. National Marine Fisheries Service (NMFS). Fisheries of the United States, 2003. Per Capita Consumption. National Oceanic and Atmospheric Administration. Washington, DC: US Department of Commerce. 2003. Available at: http://www.st.nmfs.gov/st1/fus/fus03/08_perita2003.pdf Accessed January 25, 2006.
12. Kraepiel AML, Keller K, Chin HB, Malcolm EG, Morel FMM. Sources and variations of mercury in tuna. Environ Sci Technol. 2003;37:5551-5558. Abstract
13. Miller GE, Rowland FS, Steinkru FJ, Grant PM, Guinn VP, Kishore R. Science. 1972;175:1121-1122. Abstract
14. Greenfield BK, Davis JA, Fairey R, Roberts C, Crane D, Ichikawa G. Seasonal, interannual, and long-term variation in sport fish contamination, San Francisco Bay. Sci Total Environment. Available at: http://www.sfei.org/rmp/reports/fish_contamination/Interannualvar_sportfish_BG.pdf Accessed January 26, 2006.
15. Annapolis Center for Science-Based Public Policy. Mercury in the environment: the problems, the risks, and the consequences. Annapolis, Md. Available at: http://www.annapoliscenter.org/skins/default/display.aspx?moduleid=8cde2e88-3052-448c-893d-d0b4b14b31c4&mode=User&action=display_page&ObjectID=c69722a1-5eca-41ba-a492-757235a0218f#environment Accessed February 2, 2006.
16. Florida Department of Environmental Protection. Integrating Atmospheric Mercury Deposition With Aquatic Cycling in South Florida: An Approach for Conducting a Total Maximum Daily Load Analysis for an Atmospherically Derived Pollutant. Tallahassee, Fla: Florida Department of Environmental Protection; 2003. Available at: www.floridadep.org/labs/mercury/index.htm Accessed January 26, 2006.
17. US Environmental Protection Agency (EPA). Mercury maps. A quantitative spatial link between air deposition and fish tissue. Washington, DC: Office of Water, US Environmental Protection Agency (EPA); 2001. EPA-823-R-01-009. Available at: http://www.epa.gov/waterscience/maps/report.pdf Accessed February 2, 2006.
18. Clarkson TW. The three modern faces of mercury. Environ Health Perspect. 2002;110 (suppl1):11-23.
19. US Centers for Disease Control and Prevention (CDC). National Report on Human Exposure

to Environmental Chemicals. Washington, DC: Department of Health and Human Services; 2004. Available at: http://www.cdc.gov/exposurereport/ Accessed January 26, 2006.
20. Jones RL, Sinks T, Schober SE, Pickett M. Blood mercury levels in young children and childbearing-aged women -- United States, 1999-2002. MMWR Morb Mortal Wkly Rep. 2004;53:1018-1020. Abstract
21. Stern AH, Smith AE. An assessment of the cord blood:maternal blood methylmercury ratio: implications for risk assessment. Environ Health Perspect. 2003;111:1465-1470. Abstract
22. Grandjean P, Jorgensen PJ, Weihe P. Human milk as a source of methylmercury exposure in infants. Environ Health Perspect. 1994;102:74-77. Abstract
23. Tsubaki T, Takahashi H. Recent Advances in Minamata Disease Studies. Tokyo, Japan: Kodansha, Ltd.; 1986.
24. Bakir F, Damluji SF, Min-Zaki L, et al. Methylmercury poisoning in Iraq. Science. 1973;181:230-241. Abstract
25. Wheeler M. Measuring mercury. Environ Health Perspect. 1996;104:826-830. Abstract
26. Al-Mufti AW, Copplestone JF, Kazanitzis G, Mahmoud RM, Majid MA. Epidemiology of organomercury poisoning in Iraq: I. Incidence in a defined area and relationship to the eating of contaminated bread. Bull World Health Organ. 1976;53(suppl):23-36. Abstract
27. Davidson PW, Myers GJ, Cox C, et al. Effects of prenatal and postnatal methylmercury exposure from fish consumption on neurodevelopment: outcomes at 66 months of age in the Seychelles child development study. JAMA. 1998;280:701-707. Abstract
28. Myers GJ, Davidson PW, Cox C, et al. Prenatal methylmercury exposure from ocean fish consumption in the Seychelles child development study. Lancet. 2003;361:1686-1692. Abstract
29. Grandjean P, Weihe P, White RF, et al Cognitive deficit in 7-year-old children with prenatal exposure to methylmercury. Neurotoxicol Teratol. 1997;19:417-428. Abstract
30. Grandjean P, Weihe P, White RF, Debes F. Cognitive performance of children prenatally exposed to "safe" levels of methylmercury. Environ Res. 1998;77:165-172. Abstract
31. Dourson ML, Wullenweber AE, Poirier KA. Uncertainties in the reference dose for methylmercury. Neurotoxicology. 2001;22:677-689. Abstract
32. Steuerwald U, Weihe P, Jorgensen P, et al. Maternal seafood diet, methylmercury exposure, and neonatal neurological function. J Pediatr. 2000;136:599-605. Abstract
33. Rice DC. Effects of postnatal exposure of monkeys to a PCB mixture on spatial discrimination reversal and DRL performance. Neurotoxicol Teratol. 1998;20:391-400. Abstract
34. Kjellstrom T, Kennedy P, Wallis S, Mantell C. Physical and Mental Development of Children with Prenatal Exposure to Mercury from Fish. Stage 1: Preliminary Tests at Age 4. Solna, Sweden: National Swedish Environmental Board; 1986. Report #3080.
35. Kjellstrom T, Kennedy P, Wallis S, et al. Physical and Mental Development of Children with Prenatal Exposure to Mercury from Fish. Stage 2: Interviews and Psychological Tests at Age 6. Solna, Sweden: National Swedish Environmental Board; 1989. Report #3642.
36. World Health Organization (WHO). Environmental Health Criteria 101: Methylmercury. Geneva, Switzerland: International Programme on Chemical Safety, WHO; 1990.
37. Carrington CD, Bolger PM. A pooled analysis of the Iraqi and Seychelles methylmercury studies. Hum Ecol Risk Assess. 2000;6:323-340.
38. Weil M, Bressler J, Parsons P, Bolla K, Glass T, Schwartz B. Blood mercury levels and neurobehavioral function. JAMA. 2005;293:1875-1882. Abstract

39. Robinson E. The health of the James Bay Cree. Can Fam Physician. 1988;34:1606-1613.
40. Plante M, Babo S. Mercury and the risk of myocardial infarction. N Engl J Med. 2003;348:2151-2152.
41. Mozaffarian D, Psaty BM, Rimm EB, et al. Fish intake and risk of incident atrial fibrillation. Circulation. 2004;110:368-373. Abstract
42. Leaf A, Kang JX, Xiao YF, Billman GE. Clinical prevention of sudden cardiac death by n-3 polyunsaturated fatty acids and mechanism of prevention of arrhythmias by n-3 fish oils. Circulation. 2003;107:2646-2652. Abstract
43. Virtanen JK, Voutilainen S, Rissanen TH, et al. Mercury, fish oils, and risk of acute coronary events and cardiovascular disease, coronary heart disease, and all-cause mortality in men in Eastern Finland. Arterioscl, Thromb, Vascular Biol. 2005;25:222-227.
44. Salonen JT, Seppanen K, Nyyssonen K, et al. Intake of mercury from fish, lipid peroxidation, and the risk of myocardial infarction and coronary, cardiovascular, and any death in Eastern Finnish men. Circulation. 1995;91:645-655. Abstract
45. Smith KM, Sahyoun NR. Fish consumption: recommendations versus advisories, can they be reconciled? Nutr Rev. 2005;63:39-46.
46. American Heart Association (AHA). Fish, levels of mercury and omega-3 fatty acids. 2005. Available at: http://www.americanheart.org/presenter.jhtml?identifier=3013797 Accessed January 26, 2006.
47. Kris-Etherton PM, Harris WS, Appel LJ. Fish consumption, fish oil, omega-3 fatty acids, and cardiovascular disease. Circulation. 2002;106:2747-2757. Abstract
48. Chan HM, Egeland GM. Fish consumption, mercury exposure, and heart diseases. Nutr Rev. 2004;62:68-72. Abstract
49. Matsuo N, Suzuki T, Akagi H. Mercury concentration in organs of contemporary Japanese. Arch Environ Health. 1989;44:298-303. Abstract
50. Mahaffey KR, Clickner RP, Bodurow CC. Blood organic mercury and dietary mercury intake: National Health and Nutrition Examination Survey, 1999 and 2000. Environ Health Perspect. 2004;112:562-570. Abstract
51. National Center for Health Statistics (NCHS). National Health and Nutrition Examination Survey. Hyattsville, Md: National Center for Health Statistics (NCHS); 2003. Available at: http://www.cdc.gov/nchs/nhanes.htm Accessed January 26, 2006.
52. Matthews TJ, Hamilton BE. Mean Age of Mother, 1970-2000. National Vital Statistics Reports 51,1-16. Hyattsville, Md: US Centers for Disease Control and Prevention, National Center for Health Statistics; 2002. Available at: http://www.cdc.gov/nchs/data/nvsr/nvsr51/nvsr51_01.pdf Accessed January 26, 2006.
53. US Environmental Protection Agency (EPA). Exposure and Human Health Reassessment of 2,3,7,8-Tetrachlorodibenzo-p-Dioxin (TCDD) and Related Compounds National Academy Sciences (NAS) Review Draft. Washington, DC: US Environmental Protection Agency (EPA), National Center for Environmental Assessment; 2004. Available at: http://www.epa.gov/ncea/pdfs/dioxin/nas-review/ Accessed February 2, 2006.
54. US Environmental Protection Agency (EPA). Integrated Risk Information System (IRIS). Washington, DC: National Center for Environmental Assessment; 2001. Available at: http://www.epa.gov/iris/subst/0073.htm Accessed February 2, 2006.
55. Goyer R. Letter to Joseph A. Levitt. December 1, 2000. Available at: http://www.cfsan.fda.gov/~acrobat/hgstak32.pdf Accessed January 26, 2006.
56. US Department of Health and Human Services and Environmental Protection Agency (DHHS/

EPA). What You Need to Know About Mercury in Fish and Shellfish. US Department of Health and Human Services, US Food and Drug Administration; March 2004. Available at: http://www.cfsan.fda.gov/~dms/admehg3.html Accessed January 26, 2006.
57. US Environmental Protection Agency (EPA). National Listing of Fish Advisories. Fact Sheet. EPA-823-F-04-016. Washington, DC: US Environmental Protection Agency (EPA), Office of Water; 2003. Available at: http://www.epa.gov/waterscience/fish/advisories/factsheet.pdf Accessed January 26, 2006.
58. Environmental Defense (ED). Out of Control and Close to Home. Mercury Pollution From Power Plants. New York: Environmental Defense (ED); 2003. Available at: www.environmentaldefense.org/go/mercurypowerplants Accessed January 26, 2006.
59. US Environmental Protection Agency (EPA). Fish advisories. 2004. Available at: www.epa.gov/ost/fish Accessed January 26, 2006.
60. US Environmental Protection Agency (EPA). Control of Mercury Emissions from Coal-Fired Electric Utility Boilers: Interim Report Including Errata. EPA-600/R-01-109. Prepared for the EPA Office of Air Quality Planning and Standards by the National Risk Management Research Laboratory. Research Triangle Park, NC. 2003. Available at: http://www.epa.gov/ORD/NRMRL/pubs/600r01109/600R01109.pdf Accessed January 26, 2006.
61. US Department of Energy (DOE). A Review of DOE/NETL's Mercury Control Technology R&D Program for Coal-Fired Power Plants. Washington, DC: National Energy Technology Laboratory, US Department of Energy (DOE); 2003.
62. Executive Office of the President (EOP). Executive Summary -- The Clear Skies Initiative. February 14, 2002. Washington, DC. Available at: http://www.whitehouse.gov/news/releases/2002/02/clearskies.html Accessed January 26, 2006.
63. Swift B. Emissions trading and hot spots: a review of the major programs. Environment Reporter (BNA). 2004;35:1-16.
64. International Energy Agency (IEA). World Energy Outlook 2002. Paris, France: IEA; 2002.
65. Levin L. Mercury science update. Presentation to the State of Pennsylvania on behalf of the Electric Power Research Institute; November 16, 2004; Harrisburg, Pennsylvania.
66. Vijayaraghavan K, Lohman K, Chen S-Y, et al. Sensitivity of mercury atmospheric deposition to anthropogenic emissions in the United States. Paper presented at: 7th International Conference on Mercury as a Global Pollutant; 2004; Ljubljana, Slovenia.
67. Northeast States for Coordinated Air Use Management (NESCAUM). Mercury Emissions from Coal-Fired Power Plants. The Case for Regulatory Action. Boston, Mass: Northeast States for Coordinated Air Use Management (NESCAUM); October 2003. Available at: http://bronze.nescaum.org/airtopics/mercury/rpt031104mercury.pdf Accessed January 26, 2006.
68. International Toxicity Estimates for Risk Database (ITER). Entry for methylmercury. Cincinnati, Ohio: Toxicology Excellence for Risk Assessment (TERA); 2005. Available at: http://iter.ctcnet.net/publicurl/pub_view_list.cfm?crn=22967%2D92%2D6 Accessed February 2, 2006.

Acknowledgements

The author thanks the following individuals for their valuable reviews and helpful comments: Michael Dourson, James D. Wilson, Jay Lehr, Robert Brent, Floy Lilley, S. Fred Singer, David Seidermann, Charles Santerre, and William Robertson.

Funding Information

Preparation of this manuscript was supported in part by a grant from the American Council on Science and Health, which had no control over its content.

Reprint Address

Gail Charnley, E-mail: charnley@healthriskstrategies.com

Gail Charnley, PhD, President, HealthRisk Strategies, Washington, DC

Disclosure: Gail Charnley, PhD, has disclosed no relevant financial relationships.
