Blood Organic Mercury and Dietary Mercury Intake: National Health and Nutrition Examination Survey, 1999 and 2000

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Blood organic mercury (i.e., methyl mercury) concentrations among 1,709 women who were participants in the National Health and Nutrition Examination Survey (NHANES) in 1999 and 2000 (1999–2000 NHANES) were 0.6 µg/L at the 50th percentile and ranged from concentrations that were nondetectable (5th percentile) to 6.7 µg/L (95th percentile). Blood organic/methyl mercury reflects methyl mercury intake from fish and shellfish as determined from a methyl mercury exposure parameter based on 24-hr dietary recall, 30-day food frequency, and mean concentrations of mercury in the fish/shellfish species reported as consumed (multiple correlation coefficient > 0.5). Blood organic/methyl mercury concentrations were lowest among Mexican Americans and highest among participants who designated themselves in the Other racial/ethnic category, which includes Asians, Native Americans, and Pacific Islanders. Blood organic/methyl mercury concentrations were ~1.5 times higher among women 30–49 years of age than among women 16–29 years of age. Blood mercury (BHg) concentrations were seven times higher among women who reported eating nine or more fish and/or shellfish meals within the past 30 days than among women who reported no fish and/or shellfish consumption in the past 30 days. Blood organic/methyl mercury concentrations ≥ 5.8 µg/L were lowest among Mexican Americans (2.0%) and highest among examinees in the Other racial/ethnic category (21.7%). Based on the distribution of BHg concentrations among the adult female participants in 1999–2000 NHANES and the number of U.S. births in 2000, > 300,000 newborns each year in the United States may have been exposed *in utero* to methyl mercury concentrations higher than those considered to be without increased risk of adverse neurodevelopmental effects associated with methyl mercury exposure. *Key words:* blood, exposure, fish, mercury, methyl mercury, NHANES, population estimates, shellfish, women. *Environ Health Perspect* 112:562–570 (2004). doi:10.1289/ehp.6587 available via *http://dx.doi.org/* [Online 19 November 2003]

Whole blood total mercury (BTHg) concentrations reflect exposure to organic mercury (OHg), predominantly blood methyl mercury (BMHg) from consumption of fish and shellfish (Bjornberg et al. 2003; Sanzo et al. 2001; Svensson et al. 1992). Exposures to inorganic mercury (IHg) are from multiple sources including: dental amalgams (Halbach et al. 2000; Kingman et al. 1998), "folk" or patent medicines (Riley et al. 2001), cosmetic preparations (Al-Saleh and Shinwari 1997; Balluz et al. 1997; Gabrio et al. 2003; Weldon et al. 2000), residential and/or school accidental or deliberate spills, occupational exposures (Mason et al. 2001), and trace quantities in foods of plant origin (Jedrzejczak 2002). High IHg exposures can result in elevated BTHg, whereas blood IHg (BIHg) is usually low. Until IHg exposure is substantially elevated, IHg is excreted in the urine (Mason et al. 2001). By contrast, MHg accumulates in the erythrocyte across a wide range of exposures (Kershaw et al. 1980; Sherlock et al. 1984; Skerfving et al. 1974; Svensson et al. 1992).

Among people who consume fish and do not have a high exposure to IHg, increased BTHg reflects exposure to OHg. For fish consumers, as BTHg rises a greater fraction of BTHg is blood organic mercury (BOHg). Fish-associated exposures producing BTHg in the range of approximately 30 µg/L to > 140 µg/L have been reported in diverse geographic locations in the United States (Burge and Evans 1994; Hightower and Moore 2003; Knobeloch et al. 1995; Smith JG, personal communication). Groups of people with BTHg in this range include recreational anglers, subsistence fishers, members of some Native American Tribes, and others consuming a substantial portion of dietary protein from fish in pursuit of health benefits. The latter group has been reported by Hightower and Moore (2003), who identified seriously elevated BTHg (up to ~ 90 µg/L) in a case series of affluent patients identified through a private medical practice in San Francisco.

Background on Dietary Mercury

Estimated population exposures to dietary Hg can be determined through chemical analyses of total Hg in foods (Gunderson 1995; Larsen et al. 2002; Nakagawa et al. 1997; Sanzo et al. 2001; Urieta et al. 1996; Ysert et al. 2000). Within the diet, fish and shellfish contain the highest Hg concentrations (Larsen et al. 2002; Urieta et al. 1996; Ysert et al. 2000), although trace amounts of total Hg may be detected in other dietary components [e.g., eggs, organ meats such as kidney (Larsen et al. 2002), or offal (Ysert et al. 2000)]. Diets are usually analyzed for total Hg without chemical speciation to differentiate between organic mercury, specifically methyl mercury, and IHg. Based on total diet data for the United States, in which only total Hg is measured, Hg is identified routinely only in the fish and shellfish components of diet. MacIntosh et al. (1996) indicated that dietary Hg exposures at the upper end of the estimated distribution for approximately 120,000 adults were dominated by the consumption of fish products (87%), principally canned tuna (65%), in the Nurses' Health Study and Health Professional Follow-Up Study. The OHg in fish and shellfish has been repeatedly speciated and is MHg (Bloom 1992; Falter and Scholer 1994; Haxton et al. 1979; Kannan et al. 1998). Subsequently, in this report dietary Hg will be referred to as MHg.

Variation in methyl mercury concentrations in fish. MHg concentrations in fish and shellfish species range from < 0.1 ppm for shellfish, such as oysters and mussels, to multiple parts per million reported in high-end predatory fish including ocean fish [such as tuna (Storelli and Marcotrigiano 2001; Storelli et al. 2002), marlin (Schultz et al. 1976), swordfish (Storelli and Marcotrigiano 2000), and shark (Penedo de Pinho et al. 2002)] and freshwater fish [e.g., walleye and northern pike (Gilmour et al. 2000; Jewett et al. 2003)]. Consequently, Hg intake depends on the species of fish consumed as well as the quantity of fish eaten.

Hg present in fish is approximately 85% MHg and higher for fish muscle (e.g., Storelli et al. 2002). In nonmuscle animal tissues (e.g., organs such as kidney or liver), the fraction of

total Hg that is MHg is substantially less than 80–90%, but for the general U.S. population, consumption of these nonmuscle fish tissues is infrequent.

Association between dietary intake of mercury and blood mercury concentrations. In the initial report of 1999–2000 National Health and Nutrition Examination Survey (NHANES) BTHg data (Schober et al. 2003), fish consumption was defined by a simple "yes/no" response on whether the examinee reported eating fish and/or shellfish within the past 30 days. The purpose of the current report is to describe the association between blood total and calculated organic mercury intake of MHg from fish and shellfish as reported by participants in 1999–2000 NHANES. A second purpose of this article is to estimate the influence of long-term (i.e., 30-day) MHg intake on BMHg.

Methods

Analyses in this article are based on data obtained from participants in 1999–2000 NHANES conducted by the National Center for Health Statistics (NCHS); these data are publicly available on the NCHS website (NCHS 2003). The survey sample was selected through a complex multistage design based on primary sampling units (counties), household segments within the counties, and finally, sample persons from selected households. Blacks (different locations on the NCHS website use both the terms "African American" and "black" to describe the same 370 participants whose data are reported in this article), Mexican Americans, persons in the age group 12–19 years, and persons ≥ 60 years of age were oversampled to obtain reliable estimates of health and nutrition measures for these population subgroups. Low-income whites and pregnant women were also oversampled. There were 280 women with positive pregnancy tests included among the 1999–2000 participants. Twenty-six individual geographic locations were included in the 1999–2000 survey. The survey data were statistically weighted to maintain the representativeness of the sample for the U.S. population as well as the major subpopulations.

Whole-blood samples were analyzed for both BTHg and BIHg for participants in the age groups 1–5 and 16–49 years. Mercury analyses were conducted by cold-vapor atomic absorption spectrophotometry with detection limits of 0.14 μg/L for BTHg and 0.4 μg/L for BIHg. BOHg levels were not analytically quantified in 1999–2000 NHANES. Methodologies and quality control procedures have been described by the NCHS (2003).

Fish and shellfish consumption. Participants completed a 24-hr dietary recall interview as well as an interview in which they were asked about the consumption of fish and/or shellfish during the past 30 days.

Mercury concentrations in fish and shellfish. Mercury concentrations in marine, estuarine, and freshwater fish were obtained from databases maintained by the National Marine Fisheries Service (NMFS) for marine and estuarine fish and shellfish [National Marine Fisheries Service 1978, reported by Hall et al. (1978)] and freshwater fish (Bahnick et al. 1994). Analyses of Hg in fish were based on flameless (cold-vapor) atomic absorption spectrophotometry after chemical digestion of the fish sample (Hall et al. 1978). The mean value for Hg concentrations in the fish or shellfish species was used in calculation of dietary Hg intake. The individual data for 35 species of fish and shellfish have been presented in detail elsewhere (Mercury Study Report to Congress 1997) and are summarized in Table 1.

Calculation of mercury concentrations in fish dishes. The 1999–2000 NHANES participants' Hg intakes from fish were estimated by combining data on Hg concentrations in fish species with the reported quantities and types of fish species consumed. The U.S. Department of Agriculture (USDA) has developed a recipe file identifying the primary components that make up the food or dish reported eaten by a survey respondent (Mercury Study Report to Congress 1997). The total weight of a fish-containing food is typically not 100% fish. The food code specifies a preparation method and gives additional ingredients used in preparation of the dish. For example, in the recipe file, "Fish, floured or breaded, fried" contains 84% fish by weight. Fish dishes contained a wide variety of fish species in varied amounts; from approximately 5% for a frozen "shrimp chow mein dinner with egg roll and peppers" to 100% for fish consumed raw, such as raw tuna.

Using these recipe files available from the USDA (Mercury Study Report to Congress

Table 1. Hg concentrations in fish species (μg Hg/g fresh weight), reported to be consumed by women in NHANES, 1999–2000 .

Fish and shellfish species	Average Hg concentration (μg/g)	Source
Sharks	1.327	Mercury study[a] 1997
Swordfish	0.95	Mercury study[a] 1997
Porgy	0.522	NMFS data (Hall et al. 1978)
Walleye	0.52	Bahnick et al. 1994; U.S. EPA 1992
Bass, freshwater	0.38	Bahnick et al. 1994; U.S. EPA 1992
Northern pike	0.31	Bahnick et al. 1994; U.S. EPA 1992
Halibut	0.25	Mercury study[a] 1997
Snapper	0.25	Mercury study[a] 1997
Lobster	0.232	Mercury study[a] 1997
Tuna (albacore and skipjack)	0.206	Mercury study[a] 1997
Skate	0.176	NMFS data (Hall et al. 1978)
Catfish, channel and flathead	0.16	Bahnick et al. 1994; U.S. EPA 1992
Pollock	0.150	Mercury study[a] 1997
Trout	0.149	Mercury study[a] 1997
Brown trout	0.14	Bahnick et al. 1994; U.S. EPA 1992
Sea bass	0.135	NMFS data (Hall et al. 1978)
Croaker	0.125	Mercury study[a] 1997
Cod	0.121	Mercury study[a] 1997
Crab	0.117	Mercury study[a] 1997
Perch, ocean	0.116	Mercury study[a] 1997
Carp	0.11	Bahnick et al. 1994; U.S. EPA 1992
Perch, white and yellow	0.11	Mercury study[a] 1997
Pompano	0.104	Mercury study[a] 1997
Sardines	0.1	NMFS data (Hall et al. 1978)
Smelt	0.1	Mercury study[a] 1997
Carp, common	0.093	Mercury study[a] 1997
Flounders	0.092	Mercury study[a] 1997
Haddock	0.089	Mercury study[a] 1997
Catfish (channel, large mouth, rock, striped, white)	0.088	Mercury study[a] 1997
Mackerel (not king mackerel)	0.081	Mercury study[a] 1997
Crab, king	0.07	Mercury study[a] 1997
Shrimp	0.047	Mercury study[a] 1997
Scallops	0.042	Mercury study[a] 1997
Whiting (silver hake)	0.041	NMFS data (Hall et al. 1978)
Salmon	0.035	Mercury study[a] 1997
Octopus	0.029	Mercury study[a] 1997
Squid	0.026	Mercury study[a] 1997
Clams	0.023	Mercury study[a] 1997
Oysters	0.023	Mercury study[a] 1997
Herring	0.013	Mercury study[a] 1997
Mullet	0.009	Mercury study[a] 1997

U.S. EPA, U.S. Environmental Protection Agency.
[a]Mercury Study Report to Congress (1997).

1997), the average Hg concentration in the fish species (micrograms per gram) for a particular reported fish-containing dish on a fresh-weight basis (Bahnick et al. 1994; Hall et al. 1978) was used to calculate the quantity of Hg in a gram portion of the food item. Earlier research (Bloom 1992; Falter and Scholer 1994; Morgan et al. 1997; Storelli et al. 2002) indicated that > 90% of Hg present in fish and shellfish is chemically speciated as MHg, which is bound to protein in fish tissue. MHg bound to muscle tissue is not removed during typical cooking processes such as pan frying, baking, boiling, broiling, or deep frying (Chicourel et al. 2001; Morgan et al. 1997; Sherlock et al. 1984). Consequently, the MHg present in the fish tissue in the raw state will remain in the cooked or processed fish. However, moisture is lost when fish is processed or cooked. Mercury concentration data were recalculated to reflect the retention of MHg in the remaining lowered-moisture–content fish dishes. Based on information from the USDA (Mercury Study Report to Congress 1997), the percent moisture lost for baked or broiled fish was 25%; fried fish products lose weight through loss of moisture but increase weight from fat added during frying, for a total weight loss of 12%. The percent moisture in dried, pickled, or smoked fish was identified for individual fish species (e.g., herring, cod, trout) from USDA handbooks of food composition (Mercury Study Report to Congress 1997).

Intake of methyl mercury from fish and shellfish. Projected month-long estimates of fish/shellfish intake and Hg exposure have been developed for individual adult female participants, based on the reported frequency of fish/shellfish consumption data in the preceding 30-day period and the 24-hr recall dietary intake data for the individual as the basis for portion size. The body weight (bw) in kilograms of the individual, measured in the NHANES examination center, was used to calculate Hg exposure on a microgram per kilogram bw basis.

The 24-hr recall data contain a USDA food code and the amount eaten in grams for every food item (identified by a unique 7-digit code) reported eaten by each respondent in the 24 hr immediately preceding the interview. Using the USDA recipe file (Mercury Study Report to Congress 1997) that identifies the primary components of each food or dish reported eaten by a survey respondent, the amount of seafood consumed in each food containing seafood was estimated. Summing these products over all meals reported for the 24-hr recall period gives an estimate of the amount of seafood consumed. These summations can be restricted to particular species or to groups of species such as fish or shellfish.

The 30-day recall data contain estimates of the number of times the respondent has eaten each of 32 types of fish or shellfish in the 30 days immediately preceding the interview. There are no data on the amounts eaten. To estimate the amount of seafood consumed over the course of the 30-day recall period, it is necessary to compute the number of times a seafood type is eaten multiplied by the average amount eaten per meal. The products are summed to determine the amount eaten to get total seafood consumption over the 30-day period. The average amounts of a seafood type eaten in a meal were developed from the NHANES 24-hr recall data by averaging over all respondents and meals the amounts of the seafood type reported by each respondent per meal.

Daily intake of Hg was estimated from the 24-hr recall data and the calculated Hg concentrations in fish. The amount of seafood consumed by a respondent in a dish was calculated as described above. This was multiplied by the Hg concentration calculated for each seafood species in the dish. Aggregations to a respondent's estimated daily intake of Hg or to a group's intake were obtained by adding up the applicable products. To estimate the cumulative amount of Hg ingested over the 30-day recall period, it is necessary to multiply the estimated amount of seafood eaten in 30 days by the Hg concentration in the seafood for each of the 32 seafoods and add the products.

Statistical methods. In the previous sections we describe the procedures used to combine the 1999–2000 NHANES data on seafood consumption and the Bahnick et al. (1994) and NMFS data on Hg concentrations in fish to develop estimates of the amounts of seafood (Hall et al. 1978) consumed and the amount of Hg ingested for each survey respondent. Estimates of the distribution of these amounts, statistically representative of the U.S. population and selected subpopulations, were calculated by applying the statistical weights supplied in the NHANES data sets to the consumption and ingestion data. U.S. population estimates were then calculated using WESVAR, a statistical package designed for use with weighted data from complex surveys such as NHANES [see Westat (2003) for description of WesVar specifications, including the statistical procedures used].

All statistical estimates presented in this paper are weighted estimates. They were calculated using the sampling weights developed by NCHS and included in the data on its website (NCHS 2003). Specifically, following NCHS guidance, the 2-year mobile examination center weights were used for all analyses reported in this paper.

To explore the statistical relationships between the estimated amounts of seafood eaten and the concentrations of Hg in the blood,

several regression models were developed and analyzed. In all of the models, the dependent variable was a function of the BHg concentration. Four dependent variables were employed: BTHg, the logarithm of the BTHg, BMHg, and the logarithm of BMHg. Three sets of independent variables were incorporated in the models: estimated 30-day fish and shellfish consumption; race/ethnicity; and age. Total fish and shellfish consumption was analyzed in four of the models. In the other four models, fish and shellfish consumption was split into four variables; *a)* tuna consumption, *b)* consumption of other fish species, *c)* shrimp consumption, and *d)* consumption of other shellfish species. Logarithms of fish and shellfish consumption were used in the models with the logarithms of the dependent variables. The same race/ethnicity and age variables were used in all eight models. The five race/ethnicity categories require four indicator variables in the regression models, with the fifth category, non-Hispanic white, being the reference category. Thus, the regression coefficients for the other race/ethnic groups are relative to the non-Hispanic white category.

In developing the regression models and following standard statistical practice, the data were reviewed for outliers and other data points that could disproportionately affect the results. This review resulted in the elimination of five data points: three had fish/shellfish consumption between 5,303 and 7,848 g and BTHg < 5 μg/L, and two had BTHg of 30.3 and 38.9 μg/L but seafood consumption < 500 g. These were the extreme cases for both BTHg and fish/shellfish consumption in the data set. In no other cases was fish/shellfish consumption > 4,715 g or BTHg > 22 μg/L. The available data do not allow the determination of the causes of these extreme cases. They may be erroneous data or evidence of different, unidentified contributory factors. It was decided to remove them from the regression analyses.

Presentation of both blood total mercury and calculated blood organic mercury: methodologies. The NHANES data files contain data on BTHg and BIHg, not BOHg. BOHg/methyl mercury (BMHg) was generally calculated as BTHg minus BIHg. This calculation is complicated by the fact that the limit of detection (LOD) for BIHg is larger than the LOD for BTHg (0.4 ppb and 0.14 ppb, respectively). Therefore, negative values for calculated BOHg may result when both are near or below their respective LODs. Approximately one-fourth of the sample (591 participants of 2,386) have negative values (BTHg minus speciated BIHg). To address this difficulty, we calculated BOHg as follows: BOHg = BTHg minus speciated BIHg if the difference is ≥ 0. If the difference is < 0, set BOHg = 0.2 μg/L.

The proposed value for BOHg when the difference is negative (0.2 μg/L) is based on the observation that in all but 6 of the 591 cases for which the difference is negative, speciated BIHg ≤ 0.4 μg/L and BTHg ≤ 0.3 μg/L (at or slightly above its LOD). If we assume that BOHg has the same LOD as BIHg, then we can set BOHg equal to one-half the BIHg LOD, or 0.2 μg/L.

Results

Blood total mercury. BTHg contains both BOHg, predominantly BMHg, and BIHg. Previous publication of BTHg data from 1999–2000 NHANES (Schober et al. 2003) has described BTHg. Schober et al. (2003) used SUDAAN software, which is based on jack-knife estimation, whereas the present analyses used WesVar, which is based on balanced repeated replication estimation. The distribution of total BTHg using WesVar is presented in Table 2. These data confirm the distribution of BTHg concentrations presented by Schober et al. (2003). In addition, the current analysis presents separate values for persons in the category of Other among racial/ethnic groups. Participants who designated themselves as Other include Native American Tribal people, individuals of Pacific Island origin, persons of Asian origin, and persons of mixed race who did not designate another category. Women in the Other race category have the highest prevalence of BTHg [the BTHg associated with U.S. Environmental Protection Agency's (EPA) reference dose (RfD) for methyl mercury] at 21.7%. Mexican-American women have the lowest prevalence, at 2.0% (Table 3).

Table 2 indicates that BTHg concentrations are higher among 30- to 49-year-old women than among younger women. This difference is observed across the entire distribution of BTHg over the age range of 16–49 years. At the 90th percentile and the 95th percentile, Mexican Americans have the lowest BTHg levels, Other racial/ethnic groups the highest, and exposures are similar for other Hispanics, non-Hispanic blacks, and non-Hispanic whites.

Treatment of outliers. As previously discussed, the NHANES data on approximately 1,700 women contain a few outliers: the previously described two cases with very large BTHg values and low fish/shellfish consumption, and the three cases with high fish/shellfish consumption and low total BHg. In addition, one woman had BMHg equaling 27.7 μg/L and BIHg equaling 11.2 μg/L, and another woman had BMHg equaling 9.3 μg/L and BIHg equaling 11.0 μg/L. These two unusual cases do not alter the results and conclusions derived from the approximately 1,700 other participants.

Blood organic mercury. Previous research has established that the BOHg compound is MHg (Bjornberg et al. 2003; Sanzo et al. 2001; Svensson et al. 1992). Table 4 presents the distribution of organic (or MHg) among female 1999–2000 NHANES participants 16–49 years of age. Because the detection limit for BIHg was higher than the detection limit for BTHg, the lower percentiles were below the LOD for all age and ethnic groups. The distribution of BMHg parallels the distribution of BTHg for 1,707 women. Table 4 also relates BMHg to the reported 30-day frequency of fish and/or shellfish consumption. BMHg increases with increasing frequency of fish and/or shellfish consumption. Women who eat fish and/or shellfish at least twice a week have average BMHg concentrations seven times greater than women who reported no fish/shellfish consumption in the previous 30 days.

Fish and shellfish consumption. Reported consumption of fish and shellfish (grams per day based on 24-hr recall) was not identified until the 86th percentile of the distribution for any of the race/ethnic categories (Table 5). Fish and shellfish consumption are highest among non-Hispanic black women. Consumption of fish and shellfish is higher among women 30–39 years of age than in any other age group (Table 5). Overall, 14.0% of women reported consumption of fish and/or shellfish in the 24-hr recall.

Methyl mercury consumption. Based on variability in quantity and species of fish and shellfish consumed and using an average mercury concentration for a specific fish/shellfish species, consumption of MHg was estimated and is reported in Tables 6 and 7 for the 24-hr recall data both as total Hg intake and on a microgram per kilogram bw basis. Table 7 shows that all race/ethnic categories and all age categories were ≥ 0.1 μg/kg bw mercury at the 95th percentile.

Table 3. Percentage of women 16–49 years of age with BTHg concentrations (μg/L) above selected thresholds, by age and race/ethnic group, 1999–2000 NHANES.[a,b]

	Sample persons	Percentage ≥ 15.0 μg/L	Percentage ≥ 5.8 μg/L	Percentage ≥ 5.0 μg/L	Percentage ≥ 3.5 μg/L
Total	1,709	0.6	7.8	9.7	15.7
Race/ethnicity					
Mexican American	579	0.3	2.0	2.7	6.1
Other Hispanic	124	2.0	5.8	5.9	16.4
Non-Hispanic white	578	0.1	7.8	10.0	15.3
Non-Hispanic black	364	1.3	7.0	9.5	16.6
Other	64	3.5	21.7	24.8	31.5
Age (years)					
16–19	513	0.5	2.4	2.8	4.9
20–29	437	1.2	7.6	9.6	12.8
30–39	405	0.6	8.8	10.5	15.8
40–49	354	0.2	8.8	11.4	22.1

[a]Data are from NCHS (2003). [b]Sample counts vary because of item missing data; displayed counts are the number of participants with available data for this table.

Table 2. BTHg concentrations (μg/L) for women 16–49 years of age, by age and race/ethnic group, 1999–2000 NHANES.[a,b]

	Sample persons	Geometric mean	95% CI	Percentiles						
				5th	10th	25th	50th	75th	90th	95th
Total	1,709	1.02	0.85–1.20	ND	0.17	0.42	0.94	2.07	4.84	7.13
Race/ethnicity										
Mexican American	579	0.82	0.68–0.96	0.11	0.20	0.38	0.84	1.44	2.50	3.91
Other Hispanic	124	1.16	0.77–1.55	ND	0.15	0.47	1.21	2.52	4.38	8.79
Non-Hispanic white	578	0.96	0.76–1.16	ND	0.16	0.38	0.86	1.83	4.89	7.08
Non-Hispanic black	364	1.35	1.08–1.61	0.16	0.33	0.64	1.34	2.59	4.74	6.55
Other	64	1.32	0.35–2.28	ND	0.25	0.39	1.20	4.86	8.24	10.04
Age (years)										
16–19	513	0.63	0.49–0.76	ND	ND	0.24	0.58	1.33	2.47	3.28
20–29	437	0.87	0.68–1.06	ND	ND	0.34	0.79	1.67	4.79	6.43
30–39	405	1.09	0.84–1.35	0.13	0.19	0.47	0.97	1.97	5.07	8.95
40–49	354	1.32	1.04–1.60	0.18	0.30	0.61	1.24	2.97	5.31	7.13

ND, concentration < LOD (0.14 μg/L).
[a]Data from NCHS (2003). [b]Sample counts vary because of item missing data; displayed counts are the number of participants with available data for this table.

Association between dietary mercury intake and blood total mercury and blood organic mercury. The adjusted multiple correlation coefficient (R) for the association between quantity of fish and shellfish eaten per kilogram bw and BHg was 0.54 for BTHg and 0.55 for BOHg (i.e., BMHg) (Table 8). Log transformation of the BTHg consumed variable yielded a lower R for both BTHg (R = 0.47) and for BMHg (R = 0.48) compared with the untransformed variable.

Separating Hg intake of tuna (0.206 ppm) and shrimp (0.047 ppm), the two most commonly consumed fish/shellfish products, from other species of fish/shellfish species increased the strength of the association between BTHg, BOHg, and fish consumption slightly. All fish/shellfish consumption is a significant predictor of BTHg and BOHg. Each gram of fish/shellfish consumed per kilogram bw was associated with an increase of 0.2–0.5 µg/L MHg in blood for each gram of fish/shellfish consumed per kilogram bw. If fish/shellfish species are subdivided, tuna consumption and other fish consumption are both very highly significant predictors (i.e., $p < 0.05$), each predicting a BHg increase of 0.2–0.5 µg/L for each gram of fish/shellfish consumed per kilogram bw. In two of the models, log (other shellfish) has a negative coefficient with a very large p-value. That is, the effect on BTHg and BOHg is essentially zero. Age is also significant in all but one of the models, with a consistent coefficient, approximately 0.02. Finally, the coefficients for the race/ethnicity variables estimate the differences between the respective race/ethnic groups and the non-Hispanic white group. In most of the models, non-Hispanic blacks and other Hispanics (not Mexican Americans) are significantly different from non-Hispanic whites in BTHg and BOHg when recent (30-day) fish/shellfish consumption and age are held constant.

Discussion

As BTHg concentrations increase, the fraction of BTHg that is BMHg increases (Figure 1). The top 10% of women in the Other race/ethnic category had BMHg concentrations approximately twice that of women in the other racial/ethnic categories (Table 4). More than 20% of women in the Other category had BTHg values > 5.8 µg/L (Table 3). The top 10% of women in the 20- to 49-year-old categories had BMHg values more than twice that of women in the 16- to 19-year-old category (Table 4).

Two of the women who were outliers had BIHg > 5.8 µg/L and also had BMHg > 5.8 µg/L. Although the organic fraction of Hg in blood was not speciated for blood samples from the 1999–2000 NHANES participants, exposures of adult women to organic mercurials other than MHg in fish and shellfish have not been documented except for unusual situations after occupational exposure (Nierenberg et al. 1998). Except for exposures of young children to an organic mercurial (Thimerosal) used as a preservative in vaccines (CDC 2000) and the potential for a rare occupational exposure to organic mercurials, BOHg is predominantly MHg from fish and shellfish consumption.

Table 5. Total fish/shellfish consumed per day (g) by women 16–49 years of age, by age and race/ethnic group, 24-hr recall data from NHANES, 1999–2000.[a,b]

	Sample persons	Geometric mean	95% CI	Percentage reporting no consumption	Percentiles 75th	90th	95th
Total	1,735	1.8	1.51–2.04	86.0	0.0	42.8	86.9
Race/ethnicity							
Mexican American	587	1.6	1.37–1.77	88.8	0.0	12.0	87.7
Other Hispanic	127	1.9	1.25–2.45	85.2	0.0	56.5	108.7
Non-Hispanic white	582	1.7	1.34–2.02	86.6	0.0	32.6	85.3
Non-Hispanic black	372	2.4	1.73–3.1	79.2	0.0	73.8	142.1
Other	67	1.8	0.99–2.66	85.2	0.0	33.5	75.5
Age (years)							
16–19	523	1.5	1.19–1.81	89.3	0.0	2.1	56.5
20–29	448	1.8	1.44–2.1	85.8	0.0	49.5	85.1
30–39	402	2.0	1.51–2.48	82.7	0.0	54.0	95.0
40–49	362	1.7	1.34–1.96	87.5	0.0	28.0	85.8

[a]Data are from NCHS (2003). [b]Sample counts vary because of item missing data; displayed counts are the number of participants with available data for this table.

Table 4. Blood organic (MHg) concentrations (µg/L) for women 16–49 years of age, by age and race/ethnic group, 1999–2000 NHANES.[a,b]

	Sample persons	Geometric mean	95% CI	Percentiles 5th	10th	25th	50th	75th	90th	95th
Total	1,707	0.80	0.66–0.34	ND	ND	ND	0.60	1.70	4.44	6.73
Race/ethnicity										
Mexican American	578	0.57	0.48–0.67	ND	ND	ND	0.44	1.03	2.09	3.42
Other Hispanic	123	0.97	0.65–1.29	ND	ND	ND	0.90	2.14	4.09	8.44
Non-Hispanic white	578	0.75	0.59–0.90	ND	ND	ND	0.48	1.44	4.40	6.68
Non-Hispanic black	364	1.01	0.78–1.24	ND	ND	ND	1.01	2.29	4.34	6.19
Other	64	1.06	0.18–1.34	ND	ND	ND	0.80	4.59	7.94	9.64
Age (years)										
16–19	513	0.49	0.4–0.58	ND	ND	ND	ND	1.00	2.03	2.88
20–29	436	0.70	0.54–0.87	ND	ND	ND	0.44	1.33	4.50	6.10
30–39	405	0.83	0.61–1.04	ND	ND	ND	0.61	1.60	4.65	8.62
40–49	353	1.02	0.79–1.24	ND	ND	ND	0.90	2.56	4.93	6.73
Fish and/or shellfish consumption frequency										
0 times in 30 days (never)	480	0.39	0.34–0.44	ND	ND	ND	ND	0.44	1.1	1.6
1–4 times (< once a week)	780	0.70	0.59–0.82	ND	ND	ND	0.60	1.29	2.9	4.7
5–8 times (≥ 1, < 2 times per week)	230	1.33	1.05–1.60	ND	ND	0.43	1.29	3.29	6.1	9.9
≥ 9 times (≥ 2 times per week)	153	2.46	1.82–3.11	ND	0.44	1.15	2.75	5.20	11.1	12.1
Fish consumption (no shellfish consumed) frequency										
0 times in 30 days (never)	729	0.43	0.37–0.49	ND	ND	ND	ND	0.60	1.4	2.1
1–4 times (< once a week)	733	0.93	0.76–1.11	ND	ND	ND	0.82	1.80	4.4	6.4
5–8 times (≥ 1, < 2 times per week)	118	2.04	1.44–2.63	ND	ND	0.83	2.56	4.54	8.8	11.6
≥ 9 times (≥ 2 times per week)	63	2.70	1.51–3.89	0.39	0.71	1.12	3.02	6.68	12.0	13.4

ND, concentration < LOD (0.4 µg/L).
[a]Data are from NCHS (2003). [b]Sample counts vary because of item missing data; displayed counts are the number of participants with available data for this table.

Fish and shellfish as sources of methyl mercury. Analyses of total diet by the U.S. Food and Drug Administration (U.S. FDA) indicate that fish and shellfish are almost exclusively the source of Hg (specifically MHg) in the U.S. diet (Gunderson 1995; U.S. FDA 2000). The Total Diet Study data from the U.S. FDA (2000) report an occasional (i.e., about 4% of samples) trace Hg value (i.e., greater than the detection limit but less than the quantification limit) in beef liver, spinach, oatmeal, and chicken. Except for one of 26 samples of chicken, which contained 1 μg Hg/g chicken, the other nonfish foods had nondetectable levels. Similar findings were seen in Spain (Sanzo et al. 2001), Japan (Nakagawa et al. 1997), United Kingdom (Ysert et al. 2000), Germany (Wilhelm et al. 1995), and Denmark (Larsen et al. 2002).

Surveys on a regional level and national level indicate BHg is associated with the overall level of fish consumed (Sanzo et al. 2001; Urieta et al. 1996). Urieta et al. (1996) determined that adults (25–60 years of age) ingested an average of 18 μg Hg/day, with 80–90% coming from fish and shellfish. Sanzo et al. (2001) confirmed an increase in erythrocyte Hg as fish consumption increased and reported that 30% of the variance in erythrocyte Hg was explained by recent consumption of fish. Ikarashi et al. (1996) reported most Hg in the diet is found in the fish and shellfish component. At higher intakes of Hg from diet, the contribution from fish/shellfish is over 95% of dietary intake (Haxton et al. 1979).

National data on the association between dietary fish intake and blood mercury. When Hg intake is consistent and prolonged, there is a well-defined association between Hg in blood and Hg in diet. The R for 1999–2000 NHANES indicated the association between BMHg and estimated MHg intake from fish/shellfish was approximately 0.5. There are several factors that influence the magnitude of this association. The first and most commonly assumed limitation is a person's ability to recall what they have eaten. In the United States, approximately 9% of women consume fish at least once a week. Because fish and shellfish are generally easily identifiable components of diet,

Table 6. Estimated amount of Hg ingested in 1 day (μg) through fish/seafood consumption for women 16–49 years of age, by age and race/ethnic group, 1999–2000 NHANES.[a,b]

	Sample persons	Geometric mean	95% CI	75th	90th	95th
Total	1,735	1.22	1.15–1.29	0.0	2.6	8.5
Race/ethnicity						
Mexican American	587	1.2	1.09–1.25	0.0	0.3	5.9
Other Hispanic	127	1.3	1.09–1.56	0.0	2.3	15.5
Non-Hispanic white	582	1.2	1.09–1.26	0.0	1.9	7.4
Non-Hispanic black	372	1.4	1.13–1.64	0.0	5.9	16.4
Other	67	1.3	0.9–1.67	0.0	1.1	7.7
Age (years)						
16–19	523	1.2	1.05–1.26	0.0	0.6	4.5
20–29	448	1.3	1.15–1.41	0.0	2.7	13.0
30–39	402	1.2	1.11–1.35	0.0	3.3	9.9
40–49	362	1.2	1.07–1.29	0.0	1.4	8.3

[a]Data are from NCHS (2003). [b]Sample counts vary because of item missing data; displayed counts are the number of participants with available data for this table.

Table 7. Estimated amount of Hg ingested in 1 day (μg/kg bw) through fish/shellfish consumption by women 16–49 years of age, by age and race/ethnic group, 1999–2000 NHANES.[a,b]

	Sample persons	Geometric mean	95% CI	75th	90th	95th
Total	1,727	0.02	0.02–0.03	0.00	0.04	0.13
Race/ethnicity						
Mexican American	584	0.02	0.01–0.03	0.00	0.01	0.09
Other Hispanic	127	0.03	0.01–0.04	0.00	0.04	0.22
Non-Hispanic white	579	0.02	0.01–0.02	0.00	0.03	0.11
Non-Hispanic black	370	0.05	0.01–0.09	0.00	0.06	0.28
Other	67	0.05	0.00–0.11	0.00	0.02	0.10
Age (years)						
16–19	522	0.02	0.01–0.02	0.00	0.01	0.09
20–29	447	0.03	0.02–0.04	0.00	0.04	0.19
30–39	399	0.02	0.01–0.03	0.00	0.05	0.12
40–49	359	0.02	0.01–0.05	0.00	0.02	0.12

[a]Data are from NCHS (2003). [b]Sample counts vary because of item missing data; displayed counts are the number of participants with available data for this table.

Table 8. Summaries of regressions of BHg on fish/shellfish consumption, race/ethnic group,[a] and age for women 16–49 years of age, 1999–2000 NHANES.[b,c]

Dependent variable	Sample size	Model fit statistics R	Model fit statistics R²	Independent variable measurement scale	Total fish and shellfish	Tuna	Other fish	Shrimp	Other shellfish	Non-Hispanic black	Mexican American	Other Hispanic	Other	Age
BTHg	1,636	0.54	29%	Original	0.258 (< 0.0001)	—	—	—	—	0.343 (0.011)	–0.002 (0.985)	0.545 (0.006)	0.290 (0.278)	0.022 (< 0.0001)
Log BTHg	1,093	0.47	22%	Logarithm	0.452 (< 0.0001)	—	—	—	—	0.227 (0.003)	0.081 (0.250)	0.456 (< 0.0001)	0.302 (0.047)	0.017 (< 0.0001)
BOHg	1,634	0.55	30%	Original	0.249 (< 0.0001)	—	—	—	—	0.307 (0.017)	–0.094 (0.409)	0.550 (0.004)	0.274 (0.279)	0.020 (< 0.0001)
Log BOHg	1,092	0.48	23%	Logarithm	0.508 (< 0.0001)	—	—	—	—	0.250 (0.005)	–0.007 (0.928)	0.557 (< 0.0001)	0.388 (0.028)	0.020 (< 0.0001)
BTHg	1,636	0.54	30%	Original	—	0.240 (< 0.0001)	0.322 (< 0.0001)	0.081 (0.242)	0.224 (< 0.0001)	0.294 (0.031)	0.013 (0.915)	0.562 (0.005)	0.300 (0.270)	0.021 (< 0.0001)
Log BTHg	76	0.64	40%	Logarithm	—	0.273 (0.018)	0.422 (0.003)	0.386 (0.028)	–0.300 (0.820)	–0.349 (0.184)	0.424 (0.235)	0.314 (0.335)	0.617 (0.084)	0.022 (0.057)
BOHg	1,634	0.55	31%	Original	—	0.236 (< 0.0001)	0.307 (< 0.0001)	0.067 (0.305)	0.223 (< 0.0001)	0.266 (0.040)	–0.076 (0.505)	0.569 (0.003)	0.288 (0.257)	0.020 (< 0.0001)
Log BOHg	76	0.63	40%	Logarithm	—	0.360 (0.018)	0.561 (0.003)	0.481 (0.039)	–0.072 (0.677)	–0.306 (0.377)	0.669 (0.158)	0.607 (0.162)	0.902 (0.057)	0.031 (0.046)

—, the respective independent (column) variable is not in the model (row variable).
[a]The race/ethnic group variables are all relative to the non-Hispanic white race/ethnic group. [b]Data are from NCHS (2003). [c]Sample counts vary because of item missing data; displayed counts are the number of participants with available data for this table.

fish and shellfish consumption is more readily recalled than are ingredients of multiple products such as corn oil or wheat flour. In a previous analysis of data from an earlier NHANES, the largest source of error was uncertainty of participants about foods consumed on the recall day (Youland and Engle 1976). Karvetti and Knuts (1985) observed the actual intake of 140 participants and later interviewed them by 24-hr recall. They found that fish was omitted from the dietary recall < 5% of the time and erroneously recalled approximately 7% of the time. The validity of the 24-hr recalls for fish consumption was greater than all other food groups. Supporting results have been reported by others. For example, MacIntosh et al. (1996) determined that based on dietary data from approximately 120,000 U.S. adults, the upper end of the estimated distribution of Hg exposures was dominated by consumption of fish products, principally canned tuna. Within the 1999–2000 NHANES data reported in Table 4, half of the women who consumed fish at least twice a week had BMHg of 3.0 μg/L or greater, whereas < 5% of the women who reported eating no fish reached this threshold.

Another source of uncertainty is the ability to accurately know the species of fish consumed. Many products such as frozen breaded fish are recognized generically by the method of preparation (e.g., fried fish) rather than associated with a specific fish species. Additional uncertainty relates to deliberate misbranding or mislabeling of fish, because some fish species have greater commercial value than other. For example, based on protein banding patterns, less than half the fish labeled as red snapper were red snapper (Anonymous 2001). This problem is also present internationally. For example, in Japan, dolphin has been sold as whale meat (Anonymous Japan Today 2003).

The R statistic for 1999–2000 NHANES participants (~R = 0.5–0.6) is comparable with associations reported from other studies in which Hg concentrations were chemically analyzed in duplicates of the foods consumed by participants. For example, Sherlock et al. (1982) and Haxton et al. (1979) reported R statistics comparable with those observed in the NHANES data (for Sherlock et al., R = 0.54 with 942 participants and dietary Hg intakes between 68 and 1,145 μg/week; for Haxton et al., R = 0.46 with 174 participants). In this report the 95th percentile Hg consumption was 33 μg/week.

At exposures more comparable with those in the current report, Sanzo et al. (2001) determined fish intakes based on 25 days of diet recall distributed throughout the year (dietary recall approximately every 15 days). The association between Hg intake from fish and erythrocyte total Hg for 120 individuals was statistically significant (R = 0.3, p < 0.001) in erythrocyte Hg as fish intake increased over the range of < 30 g/day to > 115 g/day. Sanzo et al. (2001) reported that fish and shellfish consumption at the 95th percentile was 917 g over 30 days, or 30.6 g of fish and shellfish per day.

Limitations on the strength of the association between blood mercury and mercury intake in the past 30 days. There is a physiological basis that limits the strength of the association between current BMHg and past 30-day fish consumption. Data from metabolic studies evaluating change in BTHg with different amounts of THg in diet indicate that as intake of THg from fish and shellfish increases, BTHg will increase. Constant consumption patterns will result in a more predictable relationship between THg intake and whole blood or erythrocyte MHg. Half-lives of BTHg in human adults are generally given as

~70 days; however, individual values as long as 250 days have been reported by Birke et al. (1972). Based on data from 48 patients, al-Shahristani and Shihab (1974) reported that biological half-times of BHg varied between 37 and 189 days, with an average of 72 days. Based on a half-life of ~70 days, roughly three-quarters of the BHg is attributable to intake of MHg from fish/shellfish consumed > 30 days previously. Consequently, MHg intake based on an estimate of dietary MHg intake covering only the preceding 30 days will include MHg consumed in an earlier time period and still present in blood because of the length of the half-time for MHg in humans. Half-times for children have not been reported.

An example of the influence of long-term Hg intake can be seen in the results from Sherlock et al. (1984). Groups of adults consumed fish in varying amounts to achieve dietary intakes of THg at 226, 101, 77, and 42 μg/day, and their BTHg and calculated BMHg concentrations were monitored. BMHg rose during the 96-day period of fish consumption to concentrations proportional to dose. Over the dose range of 42–226 μg/day, there was a close to linear relationship between dietary intake of MHg and BMHg concentration. After dosing with MHg stopped, BMHg declined. After 100 days, BMHg concentrations of the subjects remained elevated above baseline values. The lowest dose evaluated by Sherlock et al. was 0.55 μg/kg bw/day. Among the five subjects on this dose (prestudy BMHg concentrations averaged < 3.2 μg/L), BMHg averaged ~27 μg/L after 96 days of dosing and declined to ~5 μg/L, which was above baseline concentrations.

Whether these relationships can be extrapolated to lower MHg exposures of current concern is not established by data. Sherlock et al. (1982), in reviewing reported data on the relationship between BMHg and MHg intakes, noted that there is a tendency for regression lines with higher slopes to be associated with studies having higher intakes of Hg (Sherlock et al. 1982).

Comparison of distribution of blood mercury with health-based recommendations. In 2000, a National Research Council Committee (NRC 2000) recommended a benchmark dose level of 58 μg/L Hg in cord blood based on developmental effects in young children following *in utero* exposure to MHg and the use of an uncertainty factor (UF) of 10. The benchmark dose is the lower 95% confidence interval (CI) on an estimated dose that doubles the prevalence of children with scores on a test of intellectual development that would fall into the clinically subnormal range (NRC 2000). The U.S. EPA subsequently adopted these recommendations and expanded consideration to multiple studies on the impact of
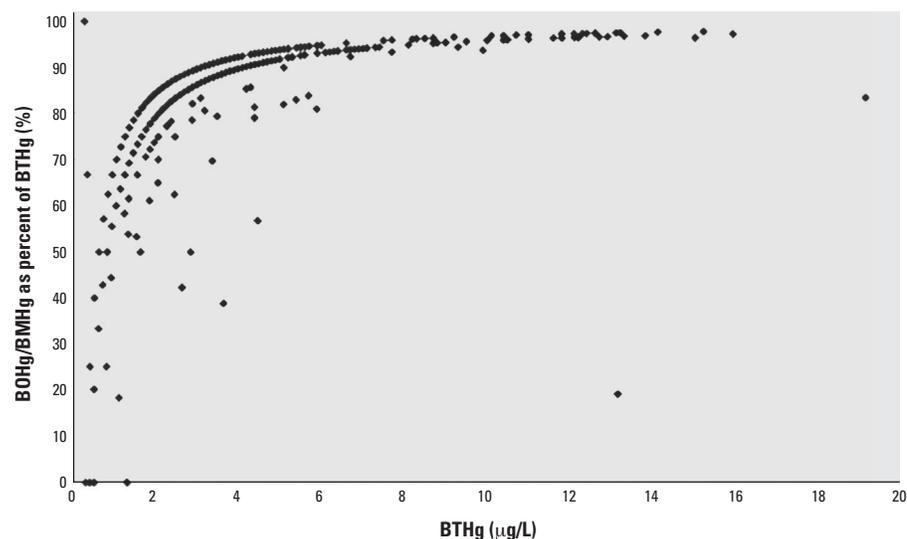
Figure 1. Organic/methyl mercury as percentage of BTHg versus BTHg. Data are from NCHS (2003). This plot is based on 1,733 data points; in many cases, multiple data points have the same values and appear as a single point.

in utero MHg exposure on multiple tests of child development from the Faroese, New Zealand, and Seychelles cohorts (Rice et al. 2003). The NRC committee recommended and the U.S. EPA adopted the use of a UF of 10 to calculate an RfD corresponding to a concentration of 5.8 µg/L Hg in cord blood. At the time of these recommendations, the UF of 10 had been based on the assumption of a 1:1 ratio of cord BHg to maternal BHg. In 1999–2000 NHANES, 7.8% (95% CI, 5.0–10.5) of women 16–49 years of age had BTHg levels at 5.8 µg/L or higher. Based on National Vital Statistics Reports (Ventura et al. 2003), in 2000 the number of births in the U.S. population was 4,058,814. Applying the overall population estimate for adult women of 7.8% having BTHg ≥ 5.8 µg/L (Schober et al. 2003) to the number of newborns in 2000 (Ventura et al. 2003) suggests that > 300,000 newborns per year may have had increased risk of adverse neurodevelopmental effects as a result of *in utero* MHg exposure if a 1:1 ratio of cord BHg to maternal BHg is assumed.

More recent evaluation (Stern and Smith 2003) of the ratio between cord to maternal BHg concentrations indicates that cord blood is, on average, 70% higher in Hg concentration than is maternal blood. Assuming the ratio of 1.7:1.0 and calculating the average BTHg associated with the benchmark dose lower limit and RfD (using the same UF of 10) suggests that a BTHg ≥ 3.5 µg/L may be associated with increased risk to the developing fetal nervous system. The RfD established in 2000 was based on use of a UF of 10 and the assumption that the cord to maternal blood mercury ratio was 1:1 (Rice et al. 2003). An additional possible consideration is that the hemoglobin and hematocrit changes during pregnancy should be considered if comparing BTHg or BMHg of pregnant and nonpregnant women. To that end, comparison of the data for the 280 pregnant women among the 1999–2000 NHANES participants with the 1,941 nonpregnant participants indicates that hemoglobin and hematocrit values at the mean for the pregnant subjects were 10% lower among the 1999–2000 NHANES participants than among the nonpregnant 1999–2000 NHANES adult female participants. (The number of adult female participants having hemoglobin and hematocrit values differs from the number of adult female participants who had BHg analyses.) If the view is taken that the ligands for MHg on hemoglobin are fully saturated at BTHg < 10 µg/L, then the ratio of cord blood to adult nonpregnant women's blood may be more likely to be 1.7:1.1 (BTHg$_{cord}$:BTHg$_{adult female}$) rather than 1.7:1.0, and thus associated with BTHg concentrations of 5.8 to ~ 3.8 µg/L rather than 5.8 to ~ 3.5 µg/L. The percentages of women by race/ethnicity and age categories having BTHg

≥ 5.8 µg/L and 3.5 µg/L are provided in Table 3. Overall, 15.7% of women's BTHg concentrations were ≥ 3.5 µg/L, rising to 31.5% for women in the Other race/ethnicity group.

Comparison with health standards of other countries. The German Kommission "Human-Biomonitoring" des Umweltbundesamtes (Human Biomonitoring Commission of the Federal Environmental Office) developed reference values for Hg that are essentially the upper limits for "safe" exposure (Kommission "Human-Biomonitoring" des Umweltbundesamtes 1999). The commission determined that adverse effects in children are judged to occur if during pregnancy the mother's blood contains more than 15 µg/L Hg, roughly equivalent to 4–5 ppm Hg in hair. To provide additional protection, the commission recommended that if a woman of childbearing age has a BTHg level > 5 µg/L or a hair level of approximately 1.5 ppm Hg, a history should be taken to establish whether the woman consumed fish containing organic Hg or used Hg-containing "medicines." If the woman consumed a lot of fish species high in Hg, reduction of fish consumption was advised. If a woman's BTHg level exceeded 15 µg/L, additional medical intervention was recommended by the commission.

Geographic variability in Hg exposure demonstrated by biomarkers of exposure, including hair Hg and BHg level, is well documented. Other nationally based data describing Hg exposure come from the German Environmental Surveys, of which three have been completed, in 1986, 1992, and 1998 (Becker et al. 2002). Overall, BTHg concentrations were lower in the German population compared with the 1999–2000 U.S. female population. Similar trends were observed in both the U.S. and German data, in that as fish consumption increased, BHg also increased. People who reported consuming fish once a week or more had BHg concentrations 2–3 times greater than those of people who reported no fish consumption (Becker et al. 2002).

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