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THE INFLUENCE OF OBESITY ON BLOOD MERCURY LEVELS FOR U.S. NON-PREGNANT ADULTS AND CHILDREN: NHANES 2007–2010

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Abstract

Background—In animal studies obesity is associated with higher blood and tissue mercury concentrations; however human studies are lacking. Although the mechanism underlying this association is uncertain, obesity may alter the metabolism and distribution of methylmercury.

Objectives—We determined whether obesity influenced blood mercury levels, the majority of which was methylmercury, for U.S. non-pregnant adults (≥20 years) and children (2–19 years) after controlling for methylmercury intake through fish and shellfish consumption, and other confounders.

Methods—We completed secondary data analysis of the National Health and Nutrition Examination Survey (NHANES) (2007–2010) for participants who consumed fish/shellfish within 24 hours of blood collection for mercury analysis. Weighted least squares regression models related blood mercury levels (the dependent variable) to methylmercury exposure (μg) from fish consumed in the previous 24 hours, body mass index (BMI) (for adults), BMI z-scores (for children), and other confounders. Results: In adjusted models, blood mercury levels were inversely correlated with BMI for adults [β, 95% confidence interval (CI) = −0.54 (−0.90, −0.18)].

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HUMAN SUBJECTS RESEARCH

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For children, blood mercury levels were inversely correlated with BMI z-scores but the trend was not significant [β (95% CI) = −0.016 (−0.066, 0.035)]. When obese adults or children were compared with those who were overweight/normal weight, blood mercury averaged 22% lower for obese adults (95% CI: −33%, −8.2%), while blood mercury did not differ significantly for obese children [β (95% CI) = −1.7% (−31%, +39%)].

Conclusions—After adjusting for the main, if not exclusive, exogenous source of methylmercury exposure (through fish/shellfish intake) and other confounders, our results support potential changes in the metabolism, distribution or excretion of methylmercury with increasing BMI (for adults).

Keywords

obesity; methylmercury; metabolism; diet; fish/shellfish

INTRODUCTION

Mercury (Hg) is a global pollutant and potent neurotoxin. Speciation determines toxicity; methylmercury (MeHg) is one of the most toxic forms of Hg due to its ability to cross the blood-brain and placental barriers (Clarkson and Magos 2006). Fish consumption is the primary human exposure pathway for MeHg (Clarkson and Magos 2006), while rice ingestion is important in regions where rice is a staple food and environmental Hg contamination is substantial (Rothenberg et al. 2014).

Unlike less toxic inorganic Hg, about 95% of MeHg ingested following a fish meal is absorbed into the bloodstream, entering the hepatic portal circulation (Clarkson and Magos 2006). Blood MeHg levels peak ~10 hours after digestion, while clearance of MeHg from blood is biphasic with average half-times of 7.7 hours and 52 days (Kershaw et al. 1980). The long half-time of MeHg is attributed to extensive enterohepatic cycling, which is interrupted when gut microbiota demethylate MeHg, producing inorganic Hg (Clarkson and Magos 2006). This less toxic Hg species is poorly absorbed across the intestine and excreted in feces (Clarkson and Magos 2006). Co-consumption of high fiber foods, including fruit, may decrease Hg accumulation in tissues, presumably due to higher MeHg detoxification by gut microbiota and elimination of inorganic Hg (Passos et al. 2003, Rowland et al. 1986).

There is ample evidence to suggest that inter-individual and inter-population differences in MeHg tissue distribution, metabolism and excretion are important. For example, much of the literature on MeHg health effects relies on hair Hg concentrations as a biomarker for MeHg exposure (Clarkson and Magos 2006), and a conversion factor (250:1) is often used to relate hair Hg and blood Hg [U.S. Environmental Protection Agency (USEPA) 1997]. However there is large variability in the ratio of hair-to-blood Hg, with reported values ranging from 140 to 370 (Bartlett et al., 2000), suggesting variability in the tissue distribution of MeHg. Using the conversion factor between hair and blood (250:1) and other toxico-kinetic parameters, differences were reported between modeled and measured hair Hg concentrations for three Canadian populations, with the greatest difference among the most exposed (the Innu), suggesting MeHg metabolism differed at the population-level and depended on exposure (Canuel et al. 2006). Additionally, the average half-life of MeHg in

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humans varies from 45–70 days (Clarkson and Magos 2006), indicating inter-individual variability in factors related to MeHg metabolism and elimination.

Obesity is an important factor hypothesized to impact inter-individual variability in MeHg metabolism, elimination, tissue distribution, and uptake. Vahter et al. (1995) observed higher accumulation of MeHg in the blood and brains of 3 obese monkeys compared to 24 normal weight monkeys. In the body, MeHg gains entry into cells by forming water-soluble complexes (Clarkson and Magos 2006). The authors suggested higher blood and brain accumulation of MeHg among obese monkeys possibly reflected lower partitioning of MeHg to adipose tissue (Vahter et al. 1995). However, human studies of this topic are lacking. Thus in the present study of a U.S. population-based sample, we hypothesized that higher body mass index (BMI) would result in increased blood MeHg accumulation, after controlling for the primary source of exogenous MeHg exposure, i.e., fish/shellfish consumption.

To investigate the relation of BMI with blood MeHg, we completed secondary data analysis of the U.S. National Health and Examination Survey (NHANES) (2007–2010), including non-pregnant adults (≥20 years) and children (2–19 years), who ingested fish/shellfish within 24 hours of blood collection for Hg analysis. We focused on non-pregnant adults because pregnancy is accompanied by changes in weight and metabolism. The developing fetus is the most vulnerable population for MeHg neurotoxicity (Clarkson and Magos 2006); however, school children are a secondary population of concern (USEPA 1997), and therefore this analysis included both non-pregnant adults and children.

METHODS

Approach

NHANES is a stratified multistage probability sample of the U.S. civilian non-institutionalized population, which is conducted biannually [Centers for Disease Control (CDC) 2014a]. Two consecutive NHANES cycles were employed, utilizing the same sampling strategy (2007–2008–2009–2010) (CDC 2011). NHANES study participants were included if fish or shellfish ingestion was reported on the Day 1 Dietary Interview, reflecting potential MeHg exposure within 24 hours of the medical exam when blood was drawn (n=1888 observations). Fish/shellfish species were identified using the U.S. Department of Agriculture (USDA) food codes (Ahuja et al. 2012; USDA 2012). We did not utilize dietary data for fish/shellfish consumption within the previous 30 days (recorded on the Day 2 Dietary Interview) because some fish types queried differed between the two dietary interviews. Also, the Day 1 Dietary Interview included amount ingested (g), which was used to calculate MeHg exposure (see below). Lastly, inter-individual variability in the timing of fish intake and resultant MeHg metabolism was minimized by focusing on a shorter timeframe (i.e., 24 hours instead of 30 days).

Dietary MeHg intake

Dietary MeHg intake was calculated as the product between Hg concentration in fish tissue (μg/g) (or MeHg concentration for a few fish species) (see Supplemental Material, Table S1)

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and the amount of fish ingested (g). For participants who ingested more than one fish/shellfish meal within the 24-hour period, MeHg intake was summed across all meals. Two sets of fish tissue Hg concentrations were compared, including those reported by the U.S. Food and Drug Administration (USFDA) (USFDA 2014) and those reported by Karimi et al. (2012). The former is one of the largest existing databases on U.S. commercial fish (USFDA 2014), while the latter includes fish harvested outside the U.S. (Karimi et al. 2012). All statistical analyses were calculated twice, once for MeHg intake estimates using the USFDA database and once for estimates using the Karimi database.

Other covariates

Blood (total) Hg (μg/L) was the dependent variable, reflecting MeHg exposure due to fish/shellfish consumption within the previous 24 hours (Kershaw et al. 1980). For adults (≥20 years), body mass index (BMI, kg/m^2) was used as a crude measure of fatness [World Health Organization (WHO) 2000], while BMI percentiles (or corresponding BMI z-scores), which accounted for age and gender, were more appropriate for children (2–19 years) (CDC 2014b). Weight categories for adults included underweight (BMI: <18.5 kg/m^2), normal weight (BMI: ≥18.5 and <25 kg/m^2), overweight (BMI: ≥25.0 and <30 kg/m^2), and obese (BMI: ≥30 kg/m^2) (WHO, 2000). Weight categories for children included underweight (<5th percentile), healthy weight (≥5th and <85th percentile), overweight (≥85th and <95th percentile) and obese (≥95th percentile) (CDC 2014b).

Other independent variables considered in the analyses were chosen based on a priori considerations including those associated with biomarkers of MeHg exposure in other studies (Mahaffey et al. 2009; Sheehan et al. 2012). Hematocrit was an appropriate covariate because ~80% of MeHg binds to red blood cells (Clarkson and Magos 2006), thus controlling for possible dilution effects and gender differences. The number of fruit/vegetable servings and corresponding fiber content were obtained from the Day 1 Dietary Interview, using USDA food codes for “Fruits and Vegetables” (Ahuja et al. 2012; USDA 2012). The total amount of fiber (g) consumed within the previous 24 hours was also obtained from the Day 1 Dietary Interview. Alcohol consumption (for adults) was determined from the Day 1 Dietary Interview (1=alcohol consumed within the previous 24 hours, 0=not consumed). Smoking status for participants (=12 years) was obtained from the NHANES Questionnaire (1=smoke cigarettes every day or some days, 0=not at all); however smoking status was coded 0 for all children. Demographics included age, gender, ethnicity, education, and income (for adults). Ethnic groups included Mexican-American, Hispanic, White, Black, and other races/ethnicities (the latter included Asian, Pacific and Caribbean Islanders, Native Americans, Alaska Natives, multi-ethnic, and unknown race). Elemental Hg from dental amalgams diffuses into the bloodstream and increases blood Hg levels (Clarkson and Magos 2006); however an estimate of the number of amalgams is not part of the NHANES data.

Participants were excluded from the analysis if fish ingested was unknown or data on Hg content of the fish were not available (n=577), or if confirmed pregnant, or data were missing for BMI, blood Hg or hematocrit (n=155), thereby reducing the number of included participants from 1888 to 1156 (2007–2008: n=510, 2009–2010: n=646), which represented

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5.2% and 6.3% of the total number of examined participants in 2007–2008 and 2009–2010, respectively (CDC 2011). See Table 1 for distribution of blood Hg by categories of all covariates.

Fish/shellfish type ingested

To investigate the association between BMI (or BMI z-scores) and fish/shellfish type consumed, fish/shellfish species were categorized into six groups, including tuna, shrimp, salmon, other shellfish, and other finfish with low Hg levels (i.e., [Hg]<0.2 μg/g) and high Hg levels (i.e., [Hg]>0.2 μg/g) (Mahaffey et al. 2009).

Laboratory analyses

Total Hg concentrations were measured in whole blood samples (μg/L) using inductively coupled plasma mass spectrometry (ICP-MS) (CDC Method # ITB001A) (CDC 2004). Concentrations of total Hg in blood increase following a fish meal (Kershaw et al. 1980), and therefore, blood (total) Hg is an appropriate proxy for blood MeHg. For observations below the limit of detection (0.33 μg/L), the imputed value was the detection limit divided by the square root of two (=0.23 μg/L). The hematocrit (%) is part of the Complete Blood Count, which is determined in duplicate for all NHANES study participants ≥1 year using a Coulter® HMX (CDC 2010).

Statistics

Our primary question concerned the influence of BMI on blood Hg levels, after controlling for dietary MeHg intake and other confounders. Data were analyzed by multivariable weighted least squares regression using weights provided by the National Center for Health Statistics, which accounted for oversampling of population subgroups, noncoverage and nonresponse bias. The $\log_{10}$-transformation was applied to right-skewed variables to improve normality of the residuals. Regression diagnostics included examination of added variable plots, comparison of Cook's distance, and investigation of residual plots to ensure model assumptions were met (mean=0, constant variance). Multicollinearity between covariates was assessed using bivariate analyses and regression diagnostics. For multicollinear covariates, the most predictive of blood Hg remained in the regression model. The percentage of variability in blood Hg concentrations explained by a single variable (i.e., the partial r-squared), was determined after controlling for the contributions of other covariates in the regression model.

Unadjusted oneway analysis of variance (ANOVA) was applied to analyze three or more groups. Two or more groups were assessed using Wilcoxon ranksum test (for skewed variables). An alpha-level of 0.05 was chosen as guide for significance where appropriate. Stata 9.2 (College Station, Texas) and the R-platform were used for all statistical analyses.

RESULTS

Fish/shellfish consumption

Current guidelines emphasize more frequent consumption of fish with low Hg levels and high omega-3 fatty acids (e.g., salmon), and less consumption of fish species with high Hg

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levels (e.g., tuna) (Mahaffey et al. 2011). For adults and children, consumption of tuna and high Hg finfish comprised <10% of fish/shellfish ingested, while salmon and low Hg finfish represented 52% and 40% of fish/shellfish consumed by adults and children, respectively, indicating greater prevalence of healthier fish choices within this NHANES timeframe (2007–2010) (Table 2).

Fish/shellfish consumption differed between weight classes (i.e., underweight, healthy weight, overweight and obese) (Figure 1). Adults in all weight categories ingested all 6 fish/shellfish types, while children in the obese category did not ingest salmon, and underweight children did not ingest salmon, other shellfish, and other finfish with high Hg levels. For those adults who consumed salmon, BMI ($\log_{10}$-transformed) was significantly lower compared to adults who consumed shrimp (ANOVA, $p<0.01$) and low Hg finfish (ANOVA, $p<0.05$). For children, there were no significant differences between BMI z-scores and fish/shellfish types consumed (ANOVA, $p>0.69$ for all comparisons). For adults and children, results did not differ using fish tissue Hg concentrations from the USFDA (USFDA 2014) or Karimi et al. (2012).

Regression results for adults

Blood Hg levels were inversely correlated with BMI in unadjusted models, and this result was modestly attenuated in adjusted models (Table 3, Figure 2a). In adjusted models, BMI explained 1.4% and 1.6% of the variability in blood Hg concentrations, when exogenous MeHg exposure was calculated using fish tissue Hg concentrations reported by the USFDA (USFDA 2014) and Karimi et al. (2012), respectively. When BMI was replaced by an indicator variable for obesity (0 = normal weight and overweight, n=611; 1 = obese, n=339), the slope (β) was −0.11 [95% confidence interval (CI): −0.17, −0.037], which was interpreted as a 22% ($=1–10^{-0.11}$) (95% CI: −33%, −8.2%) decrease in blood Hg for obese individuals, holding other factors constant including dietary MeHg intake. As noted above, fish/shellfish consumption for adults differed by weight class, including lower BMI for those who consumed salmon compared to those who consumed shrimp or low Hg finfish. From Table 2, average salmon Hg concentrations were similar or lower than average Hg concentrations for both shrimp and low Hg finfish; therefore the association of lower blood Hg with higher BMI was unlikely to be explained by type of fish/shellfish ingested.

Blood Hg was significantly higher for those classified as “other races/ethnicities,” compared to the other 4 ethnic groups. Results were consistent with other NHANES analyses relating blood Hg and ethnicity, which reported highest blood Hg among “other races/ethnicities” because these populations consumed more fish (Mahaffey et al. 2009; Xue et al. 2012). However, BMI was significantly lower for “other races/ethnicities” (ANOVA, $p<0.0001$ for all groups) and possibly explained the main finding of this analysis (i.e., the association between higher blood Hg and lower BMI). When participants identified as “other races/ethnicities” were excluded from regression analysis, the relationship between BMI and blood Hg remained inverse, but was weaker [Karimi et al. (2012): β (95% CI) = −0.39 (−0.76, −0.0097), n=886; USFDA (USFDA 2014): β (95% CI) = −0.34 (−0.71, 0.040), n=881], while other parameter estimates were similar.

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Increased MeHg exposure due to fish/shellfish consumption within the previous 24 hours corresponded to increased blood Hg concentrations, as expected (Kershaw et al. 1980); however, there was no association between fiber and blood Hg as hypothesized (Passos et al. 2003; Rowland et al. 1986). Although fruit/vegetable consumption was excluded from the regression model due to multicollinearity, blood Hg concentrations did not differ between those consuming fruits/vegetables and those who did not (Wilcoxon ranksum, p=0.42) (Table 1). Alcohol consumption within the previous 24 hours was positively associated with higher blood Hg. In other studies, correlations of blood Hg with alcohol intake have been inverse, positive, or none (Bjermo et al. 2013; Grandjean et al. 1997; Park and Lee 2013), possibly reflecting variability in lifestyle or dietary correlates of fish intake across different populations. For both alcohol and fiber/fruit intake, our analysis was based on intake in the 24 hours prior to blood Hg assessment, and this short time period possibly reflected different information than longer term intake evaluated in other studies. Blood Hg was positively correlated with higher income and college level education, which was consistent with other reports (e.g., Lincoln et al. 2010; Mahaffey et al. 2009); however, only education level was included in the regression model due to multicollinearity.

Regression results for children

For children, blood Hg concentrations were inversely correlated with BMI z-scores but the trend was not significant in unadjusted models or in adjusted models (Table 3, Figure 2b). Inclusion of BMI z-scores in adjusted models increased the r-squared by <0.5% [(when MeHg exposure was based on fish Hg content from Karimi et al. (2012) and the FDA (USFDA 2014)]. The contribution of BMI did not differ when children were subdivided into 2 groups and regression models re-analyzed (2–11 years, n=109, p=0.80 for BMI z-scores; 12–19 years, n=85, p=0.33 for BMI z-scores). When BMI was replaced with an indicator variable for obesity (0 = normal weight and overweight, n=142; 1 = obese, n=44), the slope (β) was −0.0073 (95% CI: −0.16, 0.14), which indicated only a 1.7% ($=1–10^{-0.0073}$) (95% CI: −31%, +39%) decrease in blood Hg for obese children compared with normal/overweight children, holding other factors constant.

Surprisingly MeHg exposure from fish/shellfish consumption did not contribute significantly to blood Hg levels in children, explaining <0.2% of the variability in blood Hg concentrations. This suggested other unmeasured Hg sources increased blood Hg concentrations, e.g. silver-Hg amalgams. Like adults, fiber was not associated with blood Hg, and blood Hg did not differ between those consuming fruits/vegetables and those who did not (Wilcoxon ranksum, p=0.13) (Table 1). In addition, higher blood Hg levels were observed for those identified as “other races/ethnicities” compared to the four other ethnic groups. BMI z-scores were significantly lower for “other races/ethnicities” compared to children categorized as Mexican-American or White (BMI z-score average ± 1 sd: “other races/ethnicities” −0.35 ± 1.3, Mexican-American 0.65 ± 1.2, White: 0.68 ± 1.1; ANOVA, p<0.05). Like adults, when this group was dropped from the analysis, the association between BMI z-scores and blood Hg was somewhat attenuated [Karimi et al. (2012): β [95% CI)] = −0.0078 (−0.067, 0.051), n=178; USFDA (USFDA 2014): β (95% CI) = −0.012 (−0.072, 0.047), n=177], and remained non-significant.

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DISCUSSION

For adults, higher BMI was associated with lower blood Hg after controlling for MeHg exposure through fish/shellfish consumption and other confounders, indicating potential differences in MeHg uptake, metabolism or excretion related to BMI. Alternatively, the observed findings could result if blood Hg was a proxy for dietary differences that are associated with lower BMI. However, the association between BMI and blood Hg persisted, albeit somewhat attenuated, when participants classified as “other race/ethnicity” (who ate more fish and were slimmer) were excluded from the analysis. Although the observed association was significant (for adults), the clinical importance of the modest effect of BMI on blood Hg is uncertain and requires more research. That said, given growing evidence of adverse human health effects of MeHg at low exposure levels (Orenstein et al. 2014), small changes in blood Hg concentrations are likely of interest. Furthermore, modest increases (or decreases) in the mean value of population MeHg levels can reflect substantial increases (or decreases) in the population prevalence of relatively high MeHg levels (Bellinger 2004; Korrick and Bellinger 2007). Inverse associations between blood Hg and BMI z-scores were also observed for children but confidence limits were wide and included the null, consistent with the small sample size (n=194) and limited power to detect modest associations in this age group. Alternatively, there may be differences in MeHg metabolism between adults and children.

Comparison with other epidemiologic studies

Our findings regarding BMI (for adults) differed from most other epidemiologic studies investigating MeHg exposure, which included BMI as a covariate. In unadjusted models, hair Hg (or hair MeHg) (dependent variable) was not strongly correlated with BMI (independent variable) among fish consumers in southern Italy (n=237 adults) (Diez et al. 2008), or among inhabitants in the Amazon Basin in Brazil (n=50 adults and children) (Barbosa et al. 2001). BMI did not predict toenail Hg values among residents of New Hampshire (n=27 adults) (Rees et al. 2007). Among Louisiana recreational anglers, BMI did not add information to regression models relating fish consumption frequency (independent variable) and hair Hg (dependent variable) (n=534 adults) (Lincoln et al. 2010). In an elderly Korean population, BMI (independent variable) was positively correlated with blood Hg (dependent variable), but the association was non-significant in models adjusted for age, gender, frequency of fish intake, drinking and smoking (You et al. 2011). Among U.S. men and women (n=6045 adults), an inverse, significant trend was observed in unadjusted bivariate analyses between toenail Hg (dependent variable) and BMI (independent variable), but this trend was non-significant in adjusted models (Mozaffarian et al. 2012). Among women of reproductive age who were NHANES study participants, an inverse trend between blood Hg (dependent variable) and BMI (independent variable) was also observed in adjusted models (Sheehan et al. 2012).

Differences in findings between most studies and the present analysis may reflect choice of biomarker. There is a lag between MeHg exposure and accumulation of Hg species in hair or toenails, including 20 days for hair (Clarkson and Magos 2006) and at least 6 months for toenails (Longnecker et al. 1993), while blood Hg represents a shorter time period between

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exposure and accumulation (minutes to hours) (Kershaw et al. 1980). Additionally, MeHg is not re-mobilized once deposited into the hair shaft or toenail, while the blood compartment is more variable due to enterohepatic cycling of MeHg (Clarkson and Magos 2006).

MeHg and adipose tissue

The mechanistic basis for the observed inverse association of BMI (adjusted for fish/shellfish MeHg ingestion) with significantly lower blood Hg concentrations is uncertain. MeHg is not lipophilic; most MeHg in tissues is complexed with hydrophilic compounds containing thiol groups, including L-cysteine, reduced glutathione (GSH), haemoglobin, albumin, and other cysteine-containing polypeptides (Clarkson and Magos 2006; Dutczak and Ballatori 1994; Roos et al. 2010; Simmons-Willis et al. 2002). Simmons-Willis et al. (2002) noted that lipid-soluble compounds of MeHg were never detected in tissues of animals dosed with MeHg. However, in a case-control study, Hg was detected in subcutaneous and visceral fat obtained from women undergoing abdominal surgery for uterine leiomyoma tumors, and in subcutaneous fat of women receiving liposuction for cosmetic reasons (average values: 5.9–13 ng Hg/g fat, Qin et al. 2010). Hg has also been detected in the adipose tissue of rats (<1–5.6 ng/g, Levine et al. 2000) and marine mammals (3–190 ng/g, Wagemann et al. 1998). Adipose tissue contains adipocytes, which are comprised mainly of lipid droplets (~95%), as well as stromal vascular cells with less lipid content (Lee et al. 2013). Like adipocytes, stromal vascular cells increase in size with increasing BMI, and may be a potential reservoir for lipophobic MeHg.

MeHg and the liver

Changes in GSH or other hepatic enzymes could alter the enterohepatic cycling of MeHg, thereby affecting blood Hg concentrations (Cave et al. 2010; Sheehan et al. 2012). In the liver, MeHg forms a complex with GSH, which is secreted into bile using GSH carriers, and may be reabsorbed or demethylated and excreted in the feces (Clarkson and Magos 2006). The level of intracellular GSH is considered a rate-limiting step in MeHg transport from the liver (Dutczak and Ballatori 1994). For example, animal models of reduced MeHg biliary secretion have demonstrated impaired fecal excretion and enhanced retention in the liver but no significant alteration in blood Hg (Ballatori et al. 1995). In humans, obesity is associated with higher risk for nonalcoholic fatty liver disease, which is characterized by changes in some hepatic enzymes, including GSH depletion (Koek et al. 2011; Rolo et al. 2012). Changes in hepatic secretion or retention of MeHg are one hypothesized mechanism whereby BMI-associated alterations in blood Hg- both decreases and increases- might occur.

CONCLUSIONS

For adults, the association of higher BMI with significantly lower blood Hg concentrations after adjustment for fish/shellfish intake is consistent with potential BMI-related differences in MeHg uptake, metabolism or excretion. Possible mechanisms of this observed association and its implication vis-à-vis MeHg health impacts should be further investigated. More definitive inferences from the observed findings are limited by the cross-sectional design of NHANES, which precludes defining the direction of associations, lack of information on non-fish Hg exposure sources (e.g., silver-Hg amalgams), and use of MeHg exposure

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measures based on estimates of fish tissue Hg concentrations rather than measures from the actual fish ingested, which likely contributed to measurement error in our models.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Abbreviations

β	regression slope
BMI	body mass index
CI	confidence interval
NHANES	National Health and Nutrition Examination Survey

Abbreviations

ANOVA	oneway analysis of variance
β	regression slope
BMI	body mass index
CDC	Centers for Disease Control and Prevention
CI	confidence interval
GSH	reduced glutathione
Hg	mercury
ICP-MS	inductively coupled plasma mass spectrometry
MeHg	methylmercury
n	sample size
NA	not applicable
NHANES	National Health and Nutrition Examination Survey
USDA	U.S. Department of Agriculture
USEPA	U.S. Environmental Protection Agency
USFDA	U.S. Food and Drug Administration

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WHO World Health Organization

References

Ahuja, JKA.; Montville, JB.; Omolewa-Tomobi, G.; Heendeniya, KY.; Martin, CL.; Steinfeldt, LC., et al. USDA Food and Nutrient Database for Dietary Studies, 5.0. Beltsville, MD: U.S. Department of Agriculture; 2012.

Ballatori N, Clarkson TW. Developmental changes in the biliary excretion of methylmercury and glutathione. Science. 1982; 216:61–63. [PubMed: 7063871]

Ballatori N, Gatmaitan Z, Truong AT. Impaired biliary excretion and whole body elimination of methylmercury in rats with a congenital defect in biliary glutathione excretion. Hepatol. 1995; 22:1469–1473.

Barbosa AC, Jardim W, Dorea JG, Fosberg B, Souza J. Hair mercury speciation as a function of gender, age, and body mass index in inhabitants of the Negro RIver Basin, Amazon, Brazil. Arch Environ Contam Toxicol. 2001; 40:439–444. [PubMed: 11443378]

Bartlett SM, Ponce RA, Sanga RN, Faustman EM. Human variability in mercury toxicokinetics and steady state biomarkers ratios. Environ Res. 2000; 84:127–132. [PubMed: 11068925]

Bellinger DC. What is an adverse effect? A possible resolution of clinical and epidemiological perspectives on neurobehavioral toxicity. Environ Res. 2004; 95:394–405. [PubMed: 15220073]

Bjermo H, Sand S, Nalsen C, Lundh T, Barbieri HE, Pearson M, Lindroos AK, Jonsson BAG, Barregard L, Darnerud PO. Lead, mercury, and cadmium in blood and their relation to diet among Swedish adults. Food Chem Toxicol. 2013; 57:161–169. [PubMed: 23537601]

Canuel R, de Grosbois SB, Atikesse L, Lucotte M, Arp P, Ritchie C, et al. New evidence on variations of human body burden of methylmercury from fish consumption. Environ Health Perspect. 2006; 114:302–306. [PubMed: 16451872]

Cave M, Appana S, Patel M, Falkner KM, McCain CJ, Brock G. Polychlorinated biphenyls, lead, and mercury are associated with liver disease in American Adults: NHANES 2003–2004. Environ Health Perspect. 2010; 118:1735–1742. [PubMed: 21126940]

CDC (Centers for Disease Control and Prevention). [accessed 26 December 2014] Laboratory procedure manual, Method no. ITB001A. 2004. Available: http://www.cdc.gov/nchs/data/nhanes/nhanes_07_08/PbCd_E_met_lead_cadmium.pdf

CDC (Centers for Disease Control and Prevention). [accessed 26 December 2014] Laboratory procedure manual for Complete Blood Count. 2010. Available: http://www.cdc.gov/nchs/data/nhanes/nhanes_07_08/cbc_e_met.pdf

CDC (Centers for Disease Control and Prevention). [accessed 26 December 2014] Note on 2007–2010 Sampling Methodology. 2011. Available: http://www.cdc.gov/nchs/nhanes/nhanes2007-2008/sampling_0708.htm/

CDC (Centers for Disease Control and Prevention). [accessed 26 December 2014] National Center for Health Statistics (NCHS), National Health and Nutrition Examination, Questionnaires, Datasets and Related Documentation. 2014a. Available: http://www.cdc.gov/nchs/nhanes/nhanes_questionnaires.htm

CDC (Centers for Disease Control and Prevention). [accessed 26 December 2014] About BMI for Children and Teens. 2014b. Available: http://www.cdc.gov/healthyweight/assessing/bmi/childrens_bmi/about_childrens_bmi.html

Clarkson TW, Magos L. The toxicology of mercury and its chemical compounds. Crit Rev Toxicol. 2006; 36:609–662. [PubMed: 16973445]

Diez S, Montuori P, Pagano A, Sarnacchiaro P, Bayona JM, Triassi M. Hair mercury levels in an urban population from southern Italy: fish consumption as a determinant of exposure. Environ Int. 2008; 34:162–167. [PubMed: 17904222]

Dutczak WJ, Ballatori N. Transport of the glutathione–methylmercury complex across liver canalicular membranes on reduced glutathione carriers. J Biol Chem. 1994; 269:9746–9751. [PubMed: 8144567]

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Grandjean P, Weihe P, White RF, Debes F, Araki A, Yokoyama K, Murata K, Sorensen N, Dahl R, Jorgensen PJ. Cognitive deficit in 7-year-old children with prenatal exposure to methylmercury. Neurotoxicol Teratol. 19:417–428. [PubMed: 9392777]

Ishihara N. Excretion of methyl mercury in human feces. Arch Environ Health. 2000; 55:44–47. [PubMed: 10735519]

Karimi R, Fitzgerald TP, Fisher NS. A quantitative synthesis of mercury in commercial seafood and implications for exposure in the United States. Environ Health Perspect. 2012; 120:1512–1519. [PubMed: 22732656]

Kershaw TG, Dhahir PH, Clarkson TW. The relationship between blood levels and dose of methylmercury in man. Arch Environ Health. 1980; 35:28–36. [PubMed: 7189107]

Koek GH, Liedorp PR, Bast A. The role of oxidative stress in non-alcoholic steatohepatitis. Clin Chim Acta. 2011; 412:1297–1305. [PubMed: 21514287]

Korrick SA, Bellinger DC. Invited commentary: persistent organic pollutants and childhood learning and behavioural disorders. J Epidemiol Community Health. 2007; 61:564–565. [PubMed: 17568044]

Lee MJ, Wu Y, Fried SK. Adipose tissue heterogeneity: implication of depot differences in adipose tissue for obesity complications. Mol Aspects Med. 2013; 34:1–11. [PubMed: 23068073]

Levine KE, Fernando RA, Lang M, Essader A, Handy RW, Collins BJ. Development of a method for the determination of ultra-trace level mercury in adipose tissue by cold vapour atomic fluorescence spectrometry. J Autom Methods Manag Chem. 2000; 22:103–108. [PubMed: 18924864]

Lincoln RA, Shine JP, Chesney EJ, Vorhees DJ, Grandjean P, Senn DB. Fish consumption and mercury exposure among Louisiana recreational anglers. Environ Health Perspect. 2010; 119:245–251. [PubMed: 20980220]

Longnecker MP, Stampfer MJ, Morris JS, Spate V, Baskett C, Mason M, et al. A 1-y trial of the effect of high-selenium bread on selenium concentrations in blood and toenails. Am J Clin Nutr. 1993; 57:408–413. [PubMed: 8438776]

Mahaffey KR, Clickner RP, Jeffries RA. Adult women's blood mercury concentrations vary regionally in the United States: association with patterns of fish consumption (NHANES 1999–2004). Environ Health Perspect. 2009; 117:47–53. [PubMed: 19165386]

Mahaffey KR, Sunderland EM, Chan HM, Choi AL, Grandjean P, Marien K, et al. Balancing the benefits of n-3 polyunsaturated fatty acids and the risks of methylmercury exposure from fish consumption. Nutr Rev. 2011; 69:493–508. [PubMed: 21884130]

Mozaffarian D, Shi P, Morris S, Grandjean P, Siscovick DS, Spiegelman D, et al. Mercury exposure and risk of hypertension in US men and women in 2 prospective cohorts. Hypertension. 2012; 60:645–652. [PubMed: 22868395]

NRC (National Research Council). Toxicological Effects of Methylmercury. Washington, DC: National Academies Press; 2000.

Orenstein STC, Thurston SW, Bellinger DC, Schwartz JD, Amarasiriwardena CJ, Altshul LM, Korrick SA. Prenatal organochlorine and methylmercury exposure and memory and learning in school-age children in communities near the New Bedford Harbor Superfund Site, Massachusetts. Environ Health Perspect. 2014; 122:1253–1259. [PubMed: 25062363]

Park S, Lee BK. Strong positive associations between seafood, vegetables, and alcohol with blood mercury and urinary arsenic levels in the Korean adult population. Arch Environ Contam Toxicol. 2013; 64:160–170. [PubMed: 23011092]

Parks JM, Johs A, Podar M, Bridou R, Hurt RA, Smith SD, et al. The genetic basis for bacterial mercury methylation. Science. 2013; 339:1332–1335. [PubMed: 23393089]

Passos CJ, Mergler D, Gaspar E, Morais S, Lucotte M, Larribe F, et al. Eating tropical fruit reduces mercury exposure from fish consumption in the Brazilian Amazon. Environ Res. 2003; 93:123–130. [PubMed: 12963396]

Qin Y, Leung CKM, Leung AOW, Wu S, Zheng J, Wong M. Persistent organic pollutants and heavy metals in adipose tissues of patients with uterine leiomyomas and the association of these pollutants with seafood diet, BMI, and age. Environ Sci Pollut Res Int. 2010; 17:229–240.

Rees JR, Sturup S, Chen C, Folt C, Karagas MR. Toenail mercury and dietary fish consumption. J Expo Sci Environ Epidemiol. 2007; 17:25–30. [PubMed: 16912698]

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Rolo AP, Teodoro JS, Palmeira CM. Role of oxidative stress in the pathogenesis of nonalcoholic steatohepatitis. Free Radic Biol Med. 2012; 52:59–69. [PubMed: 22064361]

Roos DH, Puntel RL, Lugokenski TH, Ineu RP, Bohrer D, Burger ME, et al. Complex methylmercury-cysteine alters mercury accumulation in different tissues of mice. Basic Clin Pharmacol Toxicol. 2010; 107:789–792. [PubMed: 20486922]

Rothenberg SE, Windham-Myers L, Creswell JE. Rice methylmercury exposure and mitigation: a comprehensive review. Environ Res. 2014; 133:407–423. [PubMed: 24972509]

Rowland IR, Mallett AK, Flynn J, Hargreaves RJ. The effect of various dietary fibres on tissue concentration and chemical form of mercury after methylmercury exposure in mice. Arch Toxicol. 1986; 59:94–98. [PubMed: 3019277]

Sheehan MC, Burke TA, Breysse PN, Navas-Acien A, McGeady J, Fox MA. Association of markers of chronic viral hepatitis and blood mercury levels in US reproductive-age women from NHANES 2001–2008: a cross-sectional study. Environ Health. 2012; 11:62.10.1186/1476-069X-11-62 [PubMed: 22970929]

Simmons-Willis TA, Koh AS, Clarkson TW, Ballatori N. Transport of a neurotoxicant by molecular mimicry: the methylmercury-L-cysteine complex is a substrate for human L-type large neutral amino acid transporter (LAT) 1 and LAT2. Biochem J. 2002; 367:239–246. [PubMed: 12117417]

USDA (U.S. Department of Agriculture). [accessed 26 December 2014] TABLE. Food categories, by US Department of Agriculture Food and Nutrient Database for Dietary Studies (FNDDS) version 4.1 food codes — What We Eat in America, National Health and Nutrition Examination Survey, 2007–2008. 2012. Available: http://www.cdc.gov/mmwr/preview/mmwrhtml/mm6105-table.htm

USEPA (U.S. Environmental Protection Agency). [accessed 26 December 2014] Integrated Risk Information System (IRIS): Reference Dose (RfD): Description and Use in Health Risk Assessments. 1993. Available: http://www.epa.gov/iris/rfd.htm

USEPA (U.S. Environmental Protection Agency). Mercury Study for Congress. Volume VII: Characterization of Human Health and Wildlife Risks from Mercury Exposure in the United States. EPA-452/R-97-009. Washington, DC: U.S. Environmental Protection Agency; 1997.

USFDA (U.S. Food and Drug Administration). [accessed 26 December 2014] Mercury Levels in Commercial Fish and Shellfish (1990–2010). 2014. Available: http://www.fda.gov/food/foodborneillnesscontaminants/metals/ucm115644.htm

Vahter ME, Mottet NK, Friberg LT, Lind SB, Charleston JS, Burbacher TM. Demethylation of methyl mercury in different barain sites of Macaca fascicularis monkeys during long-term subclinical methyl mercury exposure. Toxicol Appl Pharmacol. 1995; 134:273–284. [PubMed: 7570604]

Wagemann R, Trebacz E, Boila G, Lockhart WL. Methylmercury and total mercury in tissues of arctic marine mammals. Sci Total Environ. 1998; 218:19–31. [PubMed: 9718742]

WHO (World Health Organization). WHO Technical Report Series. Vol. 894. Geneva: World Health Organization; 2000. Obesity: preventing and managing the global epidemic.

Xue J, Zartarian VG, Liu SV, Geller AM. Methyl mercury exposure from fish consumption in vulnerable racial/ethnic populations: probabilistic SHEDS-Dietary model analyses using 1999–2006 NHANES and 1990–2002 TDS data. Sci Total Environ. 2012; 414:373–379. [PubMed: 22119327]

You CH, Kim BG, Kim JM, Yu SD, Kim YM, Kim RB, Hong YS. Relationship between blood mercury concentration and waist-to-hip ratio in elderly Korean individuals living in coastal areas. J Prev Med Public Health. 2011; 44:218–225. [PubMed: 22020187]

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Highlights

- Blood mercury was inversely related to body mass index (for non-pregnant adults)
- Blood mercury was 22% lower for obese compared to overweight/normal weight adults
- Methylmercury metabolism possibly differed between adults and children
- Obesity may contribute to inter-individual variability in mercury metabolism

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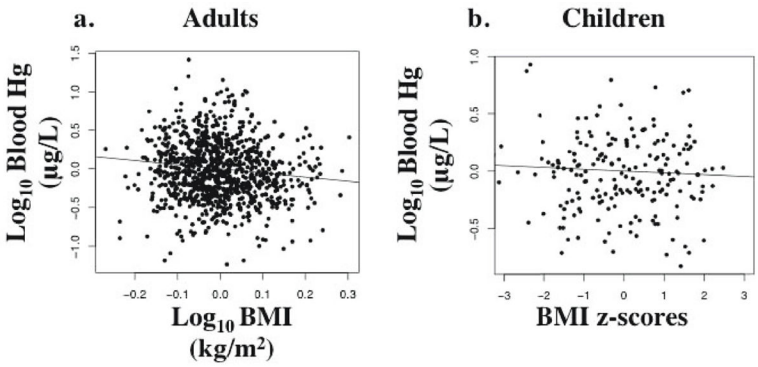

Figure 1.

Fish/shellfish consumed within the previous 24 hours by weight class for NHANES a) adults (≥ 20 years) and b) children (2–19 years), including the number of fish meals consumed for each weight class.

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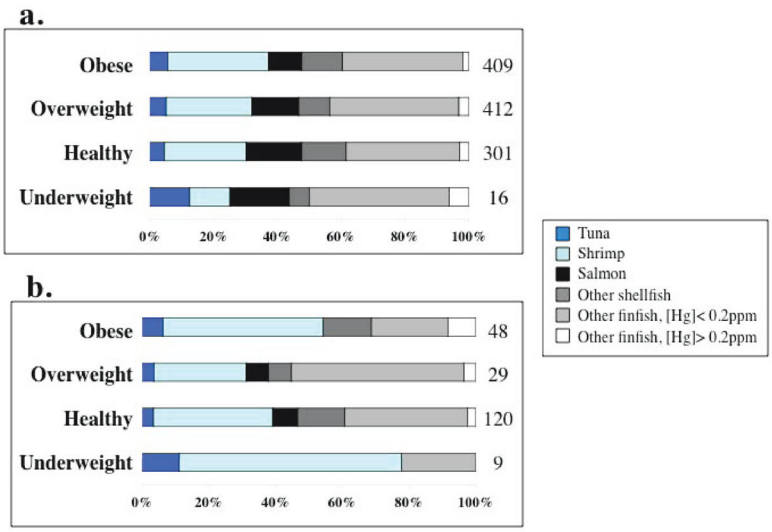

Figure 2.

Partial regression plots from the fully adjusted regression model relating $\log_{10}$blood mercury (Hg) (μg/L) versus $\log_{10}$body mass index ($\log_{10}$BMI) (or BMI z-scores) for NHANES a) adults (≥20 years) and b) children (2–19 years) (Table 3). Figures are from models using fish Hg content from Karimi et al. (2012); figures from models using fish Hg content from the USFDA (USFDA, 2014) were similar.

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Table 1

Blood mercury (μg/L), sample size (n), geometric mean, range and percentiles by categories of covariates for NHANES a) adults (≥20 years) b) children (2–19 years).

a. Adults									
		n (%)	**Geometric Mean**	**Range**	**50th**	**75th**	**90th**	**95th**	**99th**
	All	962	1.7	0.20–44	1.5	3.2	6.1	9.7	20
Weight status	**Underweight**	12 (1.2)	2.0	0.23–6.8	2.6	3.8	6.2	6.8	6.8
	Normal weight	256 (27)	1.9	0.20–44	1.9	3.9	7.3	9.9	20
	Overweight	355 (37)	1.8	0.20–39	1.5	3.2	7.1	11	30
	Obese	339 (35)	1.4	0.20–33	1.3	2.4	4.7	8.0	19
Gender	**Male**	471 (49)	1.8	0.20–44	1.5	3.5	7.6	11	34
	Female	491 (51)	1.6	0.20–20	1.5	2.7	4.8	7.8	14
Age	**20–29**	118 (12)	1.2	0.20–19	1.0	2.2	3.9	5.7	18
	30–39	165 (17)	1.5	0.20–44	1.3	3.2	6.3	9.2	28
	40–49	148 (15)	1.8	0.20–39	1.7	3.1	6.1	10	27
	50–59	184 (19)	2.0	0.20–24	1.7	3.9	7.5	11	20
	60–69	183 (19)	1.9	0.20–33	1.6	3.7	7.0	11	27
	≥70	164 (17)	1.7	0.20–38	1.6	3.0	5.7	11	38
Ethnicity	**Mexican-American**	146 (15)	1.1	0.23–26	1.0	1.9	3.8	4.9	19
	Hispanic	90 (9.4)	1.9	0.20–39	1.8	3.4	5.3	9.7	39
	White	438 (46)	1.7	0.20–44	1.5	3.2	6.1	10	19
	Black	212 (22)	1.6	0.20–38	1.4	2.6	4.1	7.2	19
	Other/multi-racial	76 (7.9)	4.0	0.20–38	4.6	8.0	12	20	38
Education	**<HS**	227 (24)	1.4	0.20–44	1.2	2.4	5.4	8.0	38
	HS	181 (19)	1.4	0.20–19	1.3	2.6	5.2	9.7	15
	Some college	271 (28)	1.6	0.20–22	1.4	2.8	4.9	7.7	16
	College graduate	283 (29)	2.3	0.20–39	2.3	4.5	8.3	13	27
Household Annual Income	**<$35,000**	437 (45)	1.3	0.20–44	1.2	2.2	4.5	7.3	18
	$35,000–$74,999	193 (20)	1.7	0.20–38	1.5	3.4	4.7	9.3	27
	≥$75,000	295 (31)	2.4	0.20–39	2.3	4.7	8.1	12	20

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a. Adults

		n (%)	Geometric Mean	Range	50th	75th	90th	95th	99th
	Refused, don't know, or missing	37 (3.8)	1.6	0.20–24	1.4	2.4	9.2	11	24
Smoking status	**Yes**	145 (15)	1.4	0.20–24	1.3	2.4	4.6	6.6	22
	No	817 (85)	1.7	0.20–44	1.6	3.3	6.9	9.8	20
Alcohol consumed previous 24 hr	**Yes**	309 (32)	2.2	0.20–44	2.2	4.5	9.1	13	32
	No	653 (68)	1.5	0.20–38	1.3	2.6	4.7	7.5	16
Total Fiber previous 24 hr[a] (g)	**<14.8**	484 (50)	1.5	0.20–44	1.4	2.7	4.7	8.0	19
	≥14.8	478 (50)	1.9	0.20–39	1.7	3.7	7.6	11	24
Fruits/Vegetables previous 24 hr	**Yes**	855 (89)	1.7	0.20–44	1.5	3.1	6.4	10	21
	No	107 (11)	1.5	0.20–18	1.4	3.3	5.6	8.1	17
Hematocrit[a] (%)	**<41.4**	480 (50)	1.5	0.20–20	1.5	2.8	4.9	7.8	14
	≥41.4	482 (50)	1.8	0.20–44	1.5	3.7	7.8	12	33

b. Children

		n (%)	Geometric Mean	Range	50th	75th	90th	95th	99th
	All	194	0.76	0.20–6.3	0.70	1.3	2.3	3.5	5.4
Weight status	**Underweight**	8 (4.1)	0.99	0.23–3.8	1.1	1.9	3.8	3.8	3.9
	Normal weight	113 (58)	0.78	0.20–6.3	0.68	1.3	3.1	3.7	6.2
	Overweight	29 (15)	0.71	0.20–1.7	0.80	1.2	1.6	1.7	1.7
	Obese	44 (23)	0.71	0.20–4.3	0.69	1.2	1.6	2.9	4.3
Gender	**Male**	102 (53)	0.68	0.20–6.3	0.62	1.3	2.1	3.3	6.3
	Female	92 (47)	0.84	0.20–5.4	0.76	1.3	2.6	3.6	5.4
Age	**2–11**	109 (56)	0.68	0.20–5.4	0.64	1.1	2.1	3.9	5.3
	12–19	85 (44)	0.86	0.20–6.3	0.91	1.4	2.7	3.4	6.3
Ethnicity	**Mexican-American**	52 (27)	0.58	0.20–4.9	0.57	0.89	1.3	1.5	4.9
	Hispanic	19 (9.8)	1.0	0.23–3.6	0.57	1.3	2.2	2.8	3.5
	White	46 (0.24)	0.74	0.20–6.3	0.80	1.3	1.8	4.7	6.3
	Black	61 (0.31)	0.72	0.20–4.3	0.69	0.96	1.7	3.2	4.3
	Other multi-racial	16 (8.2)	1.6	0.23–4.5	1.2	1.9	3.1	3.5	4.2
Education	**<9th grade**	147 (76)	0.70	0.20–5.4	0.66	1.2	1.9	3.3	5.1

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b. Children									
		n (%)	**Geometric Mean**	**Range**	**50th**	**75th**	**90th**	**95th**	**99th**
	<High School Diploma	35 (18)	0.87	0.23–3.5	0.80	1.3	2.9	3.5	3.5
	≥High School Diploma	12 (6.2)	1.3	0.37–6.3	1.1	2.5	5.5	6.3	6.3
Total fiber previous 24 hr[a] (g)	**<11.95**	97 (50)	0.73	0.20–5.4	0.69	1.1	1.8	3.6	5.4
	≥11.95	97 (50)	0.78	0.20–6.3	0.74	1.3	2.8	3.5	6.3
Fruits/vegetables previous 24 hr	**Yes**	157	0.72	0.20–5.4	0.61	1.2	2.0	3.5	5.1
	No	37	0.92	0.20–6.3	0.85	1.6	3.2	3.9	6.3
Hematocrit [a] (%)	**<38.3**	101 (52)	0.74	0.20–5.4	0.68	1.2	3.1	3.5	5.4
	≥38.3	93 (48)	0.77	0.20–6.3	0.74	1.4	1.9	3.5	6.3
Smoking status	**Yes**	0							
	No	194							

[a]Continuous variables were dichotomized at the median.

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Table 2

Fish/shellfish types consumed by NHANES adults (≥20 years) and children (2–19 years), including average fish tissue mercury (Hg) concentrations and fish/shellfish tissue sample size (n).

	Adults	Children	Fish tissue average [Hg]	
Fish type	**Frequency (%)**	**Frequency (%)**	**USFDA (2014) (μg/g) (n)**	**Karimi et al. (2012) (μg/g) (n)**
Finfish ([Hg] >0.2 μg/g)	31 (2.7)	8 (3.9)	0.59 (4)	0.62 (5)
Tuna	59 (5.2)	9 (4.4)	0.32 (2)	0.32 (2)
Other Shellfish	135 (12)	26 (13)	0.038 (7)	0.056 (8)
Salmon	160 (14)	11 (5.3)	0.015 (2)	0.042 (2)
Shrimp	319 (28)	80 (39)	0.0090 (1)	0.053 (1)
Finfish ([Hg] <0.2 μg/g)	434 (38)	72 (35)	0.078 (15)	0.10 (17)
Total	1,138	206		

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Table 3

Weighted least squares regression models of the relation between $\log_{10}$ blood Hg and $\log_{10}$BMI (or BMI z-scores) for NHANES adults (≥20 years) and children (2–19 years), including the confidence interval (CI). NA indicates not applicable.

	Covariates	Adults		Children	
		β (95% CI)[a]	r-squared	β (95% CI)[a]	r-squared
Unadjusted	**Adults: Log_{10}BMI (kg/m^2) Children: BMI z-scores**	−0.80 (−1.2, −0.43)***	0.032	−0.038 (−0.087, 0.010)	0.020
Karimi et al. (2012)	**Adults: Log_{10}BMI (kg/m^2) Children: BMI z-scores**	−0.54 (−0.90, −0.18)**	0.21	−0.016 (−0.066, 0.035)	0.21
	Log_{10}MeHg intake from fish/shellfish (μg)	0.12 (0.060, 0.18)***		0.022 (−0.074, 0.12)	
	Age (years)	0.0033 (0.0013, 0.0052)**		NA	
	Hematocrit (%)	0.0082 (0.00031, 0.016)*		0.018 (0.0031, 0.032)*	
	Log_{10}Fiber (g)	0.10 (−0.026, 0.23)		0.074 (−0.14, 0.29)	
	Ethnicity				
	Other race/ethnicity	Referent		Referent	
	Mexican American	−0.33 (−0.46, −0.19)***		−0.45 (−0.63, −0.26)***	
	Hispanic	−0.19 (−0.34, −0.046)*		−0.16 (−0.45, 0.13)	
	White	−0.30 (−0.42, −0.18)**		−0.34 (−0.51, −0.16)***	
	Black	−0.24 (−0.36, −0.10)**		−0.33 (−0.50, −0.15)***	
	Alcohol			NA	
	No	Referent			
	Yes	0.18 (0.11, 0.25)***			
	Smoking			NA	
	No	Referent			
	Yes	−0.094 (−0.18, −0.0099)*			
	Education			NA	
	< High School	Referent			
	High School	0.038 (−0.067, 0.14)			
	Some college	0.035 (−0.055, 0.12)			
	College graduate	0.15 (0.056, 0.25)***			

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	Covariates	Adults		Children	
		β (95% CI)[a]	r-squared	β (95% CI)[a]	r-squared
USFDA (2014)	**Adults: Log_{10}BMI (kg/m^2)** **Children: BMI z-scores−**	−0.50 (−0.86, −0.14)**	0.23	−0.021 (−0.072, 0.029)	0.21
	Log_{10}MeHg intake from fish/shellfish (μg)	0.11 (0.060, 0.16)***		0.036 (−0.041, 0.11)	
	Age (years)	0.0032 (0.0012, 0.0051)**		NA	
	Hematocrit (%)	0.0072 (−0.00060, 0.015)		0.017 (0.0023, 0.032)*	
	Log_{10}Fiber (g)	0.11 (−0.016, 0.24)		0.092 (−0.12, 0.31)	
	Ethnicity				
	Other race/ethnicity	Referent		Referent	
	Mexican American	−0.33 (−0.47, −0.19)***		−0.44 (−0.62, −0.26)***	
	Hispanic	−0.22 (−0.37, −0.074)**		−0.15 (−0.44, 0.13)	
	White	−0.30 (−0.42, −0.17)***		−0.34 (−0.50, −0.15)***	
	Black	−0.24 (−0.38, −0.11)**		−0.33 (−0.50, −0.15)***	
	Alcohol			NA	
	No	Referent			
	Yes	0.18 (0.12, 0.25)***			
	Smoking			NA	
	No	Referent			
	Yes	−0.087 (−0.17, −0.0045)*			
	Education			NA	
	< High School	Referent			
	High School	0.041 (−0.063, 0.14)			
	Some college	0.037 (−0.052, 0.13)			
	College graduate	0.16 (0.066, 0.26)**			

[a]* $p<0.05$,

** $p<0.01$,

*** $p<0.001$