Mercury in Human Hair and Associations with Fish Consumption and other Potential Sources

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Technical Report # 09-196

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Abstract

Hair analysis provides a historical record of an individual's exposure to mercury or methylmercury. In this study analysis of hair mercury was performed on 12,048 samples from self-selected volunteer participants from across the United States. Analysis was performed using digestion and subsequent analysis with cold vapor atomic absorption spectrometer prior to 5/07 and using a direct mercury analyzer thereafter. Slightly over 1/5 of the participants of the study who were women of childbearing age had hair mercury concentrations above the United States reference dose (RFD) for hair mercury concentration of 1.0 µg/g. The results from univariate analyses indicate that total hair mercury concentration is highly associated with overall fish and shellfish consumption as well as consumption of individual fish types and species. In particular, the percent of people with hair mercury concentrations above the United States reference dose for hair mercury concentration of 1.0 µg/g were 2.8 % before 5/2007, when serving size was defined to be 6 oz., and 2.7% after 5/2007, when serving size was defined o be 4 oz., for participants who ate 0-1 servings of fish or shellfish but were 37.7% before 5/2007 and 46.4% after 5/2007 for participants who ate 5 or more servings of fish or shellfish. Hair mercury concentrations were also significantly associated with presence of silver-colored fillings, flu shots in the past year, age, race, gender, and geographic region. However, the fact that in each case the group with higher hair mercury concentration also had the highest fish consumption suggests that those correlations may be artifacts of fish consumption.
Key Words - Mercury, Hair, Seafood, Dental Amalgams

Introduction

Mercury enters the environment naturally from volcanoes, mineral deposits and evaporation from soil and oceans. Anthropogenic sources of mercury include emissions from coal-fired utility boilers (the largest source), municipal waste combustion, commercial/industrial boilers, chlor-alkali plants, cement production, crematoriums, discarded household products, dental waste and medical waste incinerators (USEPA, 1997).

There are three types of mercury: elemental mercury, organic mercury, and inorganic mercury. Elemental or metallic mercury is the familiar metal liquid in thermometers and is one of the most common forms found in the environment. Metallic mercury is also used in silver dental amalgam fillings which contain up to 50% mercury (Agency for Toxic Substances and Disease Registry (ATSDR), 1999). Organic mercury takes several forms as some microorganisms (bacteria and fungi) and natural processes change the mercury in the environment from one form to another; the most common form being methylmercury. (ATSDR, 1999).

In the United States, coal-fired utility boilers are the biggest source (33 percent) of anthropogenic mercury emissions to the atmosphere (USEPA, 1997). Mercury eventually falls from the atmosphere or runs off the ground into water (streams, lakes, rivers) and accumulates in the soil and bottoms of water bodies where microorganisms (bacteria and fungi) convert it to methylmercury. Methylmercury accumulates in the water and is then absorbed by fish and plants near the source. This bioaccumulation process continues with levels of mercury increasing as it moves up the food chain (USEPA, 2001). Mercury builds up through the food

chain until it reaches concentrations in predator animals, such as predatory fish and mammals, that are many times greater than levels in the surrounding water (USEPA, 2001).

The United States Environmental Protection Agency (EPA) has set the Reference Dose (RFD) associated with hair mercury concentration of women at childbearing age at 1.0 µg/g based on its effects on brain and organ development of the fetus (USEPA, 1997). Several studies have explored the relation between mercury and the risk of heart problems in men. While the studies are not completely consistent, they have typically found an odds-ratio of approximately 2 for heart disease when comparing the group with the highest methylmercury levels to the one with the lowest methylmercury levels (Mergler et al., 2007).

Tests for mercury exposure in humans have been performed using analysis of blood, urine, nail clippings, or hair samples, with blood and hair samples the most commonly cited in the literature. Although hair mercury concentrations are approximately 250 times greater than blood mercury concentrations (ATSDR, 1999), total (organic + inorganic) hair mercury concentrations are highly positively correlated with total blood mercury concentrations but inorganic hair concentrations are weakly correlated with inorganic blood concentrations (Berglund et al., 2005; Morrissette et al., 2004, Phelps et al., 1980). This may be because hair has a greater percentage methylmercury relative to inorganic mercury than blood (Mergler et al., 2007). Hair sampling for mercury has the advantages over blood sampling that it is non-invasive and can be self administered, it is less sensitive to large short-term exposures, and can be analyzed with greater relative precision because it is at a higher concentration.

The EPA presumes that hair mercury concentrations reflect blood mercury concentrations at the moment of hair growth (USEPA, 1997). A previous mercury-in-hair study conducted during the 1999-2000 National Health and Nutrition Examination Survey (NHANES) concluded, "Hair Hg [mercury] analysis in national samples of U.S. children and women of childbearing age provide a useful biomarker for long-term Hg exposure" (McDowell et al., 2004). In this U.S. study, samples of hair are analyzed from a nationally distributed self-selected sample. Participants complete a questionnaire about demographic factors and potential exposure to mercury. A statistical analysis is performed to relate mercury concentrations in hair to potential factors such as fish consumption and having dental amalgams.

Materials and Methods

Study participants were recruited by Greenpeace, the Sierra Club, and other nonprofit organizations throughout the United States through national internet notices, regional media coverage of the research project, special local awareness events, and other publicity efforts. This report is based on the 12,048 samples obtained from July, 2004 to October, 2009. The study sample is not presumed to be statistically representative of the entire U.S. population, because participants were self-selected, and recruitment of study participants was focused more strongly in some areas of the country than others. Particular geographic areas, individuals who might be more concerned about this particular health issue, individuals with higher-than-average fish consumption, and individuals better able to afford the small fee ($25) to participate in the study are expected to be overrepresented in the sample.

Each volunteer was sent a hair sampling kit by the Environmental Quality Institute of the University of North Carolina Asheville (EQI) consisting of gloves, plastic sample bags, labels, a cardboard weighing balance designed to tip when approximately 0.5 g of hair was added, detailed instructions for cutting, weighing and labeling hair samples, and a return postage-paid mailer. Each volunteer participant was instructed to wash their hair before collecting their hair sample. Each sampling kit also included a detailed research questionnaire which requested information on age, gender, pregnancy status, hair color, occupation, dental amalgams and removal, flu shot history, and, several questions regarding fish consumption habits. Upon receipt at the EQI laboratory, samples were given a laboratory identification number and questionnaire data was transferred to a database.

Hair samples were analyzed using two methods. EPA Method 7470A (cold vapor atomic absorption spectrometry) was used from July, 2004 to April, 2007 and EPA Method 7473 (mercury in solids and solutions by thermal decomposition, amalgamation, and atomic absorption spectrometry) was used from May, 2007 until October, 2009. Hair samples analyzed using EPA Method 7470A were weighed to the nearest 0.0001 gram on an analytical balance and digested using EPA Method 3050B with concentrated nitric acid and 30% hydrogen peroxide in a SCP Science Digiblock^{TM} graphite block digestor. The final volume of the digestate was 50ml. A Thermo Elemental M6 AAS with a VP90 continuous-flow vapor system were used to determine mercury concentration in the digestates. Mercury determinations by EPA Method 7473 were carried out using a Nippon Instruments Corporation Mercury MA-2000© Direct Mercury Analyzer. Each volunteer participant was sent a confidential letter with their individual results along with explanatory information regarding USEPA advisory levels.

The numbers of servings per month for each type of fish and overall fish consumption were categorized into groups. On the questionnaire a serving was defined to be 6 oz prior to May, 2007. In May, 2007 the definition of a serving size was reduced to 4 oz. and a descriptor (about the size of a deck of cards) was added to help people visualize a serving size. The percentage of participants in given food consumption groups that have hair mercury concentrations of 1.0 or greater and 95% z-confidence intervals were calculated for each category. Mantel-Haenzel χ^2 tests were performed to determine if the concentrations were significantly related to amount of fish consumption. Estimated geometric means and confidence intervals for the geometric mean were calculated by first taking the natural log transform of the measured hair mercury concentration after adding 0.05 to make all concentrations positive. The sample mean of the transformed concentrations and 95% t-intervals for the transformed mean were then calculated. The estimated geometric mean and 95% confidence intervals for the geometric mean were then calculated by exponentiating the results and then subtracting 0.05. A similar approach was taken with all of the other predictor or demographic variables with the exception that likelihood-ratio χ^2 tests were performed for those variables because they were categorical as opposed to the ordinal fish-consumption variables.

Results and Discussion

People who eat more fish and shellfish overall have much higher hair mercury concentrations (Tables 1 and 2). The fact that only 2.7% of the participants before May, 2007 and 2.8% of the participants after May, 2007 who reported that they consumed 0-1 servings of fish or shellfish

had hair mercury concentrations at or above the RFD of 1 μg/g while 37.7% of the participants before 5/2007 and 46.4% of the participants after 5/2007 consuming 5 or more servings had hair mercury concentrations at or above the RFD is a strong indication that fish consumption is the predominant source of mercury in human hair. It has been asserted by some authors, for example Nuthall (2006), that analysis of hair to assess exposure to mercury is susceptible to contamination, but the fact that such a low percentage of participants with low fish consumption had elevated hair mercury concentrations suggests that with proper handling, serious contamination is rare.

Table 1. For participants before May 2007 with serving size defined to be 6 ounces, percentage of participants in given fish consumption amount groups based on overall consumption of fish and shellfish that have hair mercury concentrations of 1.0 μg/g or greater with 95% confidence intervals and estimated geometric means with 95% confidence intervals.

Consumption Group	n	Percent ≥ 1 μg/g	95% CI Percent ≥ 1 μg/g	Estimated Geometric Mean (μg/g)	95% CI Est. Geom. Mean (μg/g)
Overall number of fish and shellfish servings per month (χ^2 = 1343.9, p = 0.000)					
0-1 Servings	1981	2.7	(2.0, 3.4)	0.11	(0.10, 0.12)
2-4 Servings	4098	11.8	(10.8, 12.7)	0.33	(0.32, 0.34)
5+ Servings	5462	37.7	(36.4, 39.0)	0.74	(0.72, 0.76)

Table 2. For participants during or after May 2007 with serving size defined to be 4 ounces, percentage of participants in given food consumption amount groups based on overall consumption that have hair mercury concentrations of 1.0 or greater with 95% confidence intervals and estimated geometric means with 95% confidence intervals.

Consumption Group	n	Percent ≥ 1 μg/g	95% CI Percent ≥ 1 μg/g	Estimated Geometric Mean (μg/g)	95% CI Est. Geom. Mean (μg/g)
Overall number of fish and shellfish servings per month (χ^2 = 113.4, p = 0.000)					
0-1 Servings	323	2.8	(1.0, 4.6)	0.12	(0.11, 0.14)
2-4 Servings	615	14.1	(11.4, 16.9)	0.38	(0.35, 0.41)
5+ Servings	1069	46.4	(43.4, 49.4)	0.91	(0.85, 0.96)

There is a similar pattern for store fish and shellfish servings per month, tuna servings per month, and locally caught fish or shellfish servings per month, which were only categorized as such in samples sent out prior to May, 2007 (Table 3). For each of these variables, the percent of people with hair mercury concentrations of 1 μg/g or more increases significantly as the number of servings increases. The percentages of people with hair mercury concentrations of 1 μg/g or more and estimated geometric mean hair mercury concentrations for people with 0 servings per month in each of those categories are not as low as that of the people who eat 0-1 servings overall of fish and shellfish. This is not surprising because many people who don't consume many fish of one of those types do consume more fish of the other types. Similarly, people who eat 5 or more servings of fish in one of these categories have higher percentages of people with hair mercury concentrations of 1 μg/g or more and estimated geometric mean hair mercury

concentrations than people with 5 or more servings of fish or shellfish overall, probably because they eat some fish in the other categories as well.

Table 3. Percentage of participants of samples sent out before May, 2007 in food consumption amount groups for general types of consumption that have hair mercury concentrations of 1.0 or greater with 95% confidence intervals and estimated geometric means along with 95% confidence intervals.

Consumption Group	n	Percent ≥ 1 µg/g	95% CI Percent ≥ 1 µg/g	Estimated Geometric Mean (µg/g)	95% CI Est. Geom. Mean (µg/g)
Store fish and shellfish servings per month (excluding tuna) (χ^2 = 1330.1, p = 0.000)					
0 Servings	3311	8.7	(7.7, 9.6)	0.19	(0.18, 0.20)
1-2 Servings	3731	16.0	(14.9, 17.2)	0.38	(0.37, 0.39)
3-4 Servings	2465	26.7	(25.0, 28.5)	0.55	(0.53, 0.58)
5+ Servings	2509	48.3	(46.3, 50.2)	0.96	(0.93, 1.00)
Tuna servings per month (χ^2 = 326.8 , p = 0.000)					
0 Servings	4482	17.1	(16.0, 18.2)	0.28	(0.27, 0.29)
1-2 Servings	4101	20.9	(19.7, 22.2)	0.44	(0.42, 0.45)
3-4 Servings	1877	27.3	(25.3, 29.3)	0.56	(0.54, 0.59)
5+ Servings	1699	38.4	(36.1, 40.7)	0.76	(0.72, 0.79)
Locally caught fish or shellfish servings per month (χ^2 = 461.0, p = 0.000)					
0 Servings	9561	19.2	(18.4, 20.0)	0.36	(0.35, 0.37)
1-2 Servings	2032	26.8	(24.9, 28.7)	0.54	(0.52, 0.56)
3-4 Servings	675	37.6	(34.0, 41.3)	0.71	(0.66, 0.77)
5+ Servings	617	52.0	(48.1, 56.0)	1.07	(0.99, 1.16)

Because general categories of consumption such as store or restaurant fish include fish of many species, it is difficult to see from Table 3 which species have the greatest effect on mercury in hair. Therefore in May, 2007 the questionnaire was changed to ask participants how many servings of specific varieties they consumed. In some cases similar species were grouped together in the questionnaire in an attempt to increase the number of participants who eat species in that group regularly enough to be able to measure the effect of eating from that group. Only types of fish that have more than 100 participants who ate 2 or more servings per month are reported here.

Increased consumption of almost every species or group of species is highly significantly related to an increased risk of having mercury in hair above the RFD. The one exception is pollock (FDA fish median=non-detect), commonly used for fish sticks and seafood salad and listed by the United States Food and Drug Administration (FDA) as being low in mercury (2006), which was not quite statistically significant (p=0.083). It is surprising that increased consumption of other types of fish that are listed by the FDA as being low in mercury such as salmon (FDA fish median=non-detect, χ^2 = 124.9, p=0.000), shellfish (FDA fish median=non-detect for each species measured, χ^2 = 105.1, p=0.000), tilapia (FDA fish median=non-detect, χ^2 = 19.9, p=0.000), and canned chunk light tuna (FDA fish median=0.075 µg/g, χ^2 = 8.4, p=0.003) are all positively associated with increased hair mercury concentrations (Table 4). It may be that eating

enough fish even if it is relatively low in mercury can raise hair levels or that people who eat one kind of fish are more likely to eat other kinds of fish. The participants who ate 2 or more servings per month of tuna other than canned albacore or chunk light tuna had a geometric mean hair mercury concentration of 1.47 and 70.3% of them were above the RFD. This may include many people who eat tuna in sushi, which is commonly made of bluefin tuna. Another group of fish whose consumers had a geometric mean above the RFD was flounder, grouper, or snapper (estimated participants geometric hair mean=1.23 µg/g, with 60.5% of participants above RFD). In the latest sampling from the FDA the median fish mercury concentration in flounder was 0.045 µg/g, in grouper was 0.465 µg/g, and in snapper was 0.189 µg/g. The three types of fish that are listed as high in mercury in the FDA sampling are swordfish, shark and tilefish. Because only 19 participants ate 2 or more servings of any of those fish, the results were not reported in Table 4 but those people had a geometric mean hair mercury concentration of 2.42, which provides some evidence of elevated mercury levels despite the very small sample. Either the FDA warning has been effective at discouraging consumers from eating these fish or they were rarely consumed to begin with.

An earlier (1994) study conducted by Schweinsberg in Germany, of the relationship between fish consumption and mercury concentration in Germany, found that subjects who consumed 0-400 g, 400-1,000 g, or more than 1,000 g per month had mean hair mercury concentrations of 0.56 ug/g, 0.94 ug/g, and 1.60 ug/g (Schweinsburg, 1994). Converting to 6-ounce servings, the consumption groups would be 0-2.4 servings, 2.4-5.8 servings, and more than 5.8, servings respectively. Because the mean of the positively skewed hair mercury concentrations would be expected to be larger than the median or geometric mean, these results are consistent with the current study.

Overall fish consumption appears to have increased from 2004 to 2006 and decreased in 2009 (Table 5). Hair mercury concentrations have tracked closely with fish consumption with the possible exception of the latter half of 2007 for which there appears to be a jump in hair mercury concentrations. This may be due to the change to a more accurate methodology for measuring hair mercury concentrations implemented in May, 2007. There are no apparent trends up or down in the hair mercury concentrations relative to fish consumption from this data. Because the data is based on a self selected sample, it is possible that any trends or lack of trends could be partially a result of which people were finding out about and choosing to participate in the study.

Participants were asked if they have exposure to mercury at work. Surprisingly, participants who thought they had exposure to mercury at work had slightly lower, but not statistically significantly lower concentrations of mercury in their hair (Table 6) ($\chi^2 = 1.5$, $p = 0.228$). Dentists had slightly higher concentrations of mercury in their hair but the difference was not statistically significant (Table 6) ($\chi^2 = 1.5$, $p = 0.228$). Dentists ate higher amounts of fish which could account for any differences in hair mercury concentrations (Table 6). However, the small number of dentists in our survey limited the power in finding statistically significant differences and it is possible that dentists who would want to have their hair tested might be more careful in avoiding mercury exposure than those who do not.

Table 4. Percentage of participants of samples sent out during or after May, 2007 in food consumption amount groups for consumption of specific species of fish that have hair mercury concentrations of 1.0 or greater with 95% confidence intervals and estimated geometric means along with 95% confidence intervals.

Consumption Group	n	Percent ≥ 1 µg/g	95% CI Percent ≥ 1 µg/g	Est. Geom. Mean (µg/g)	95% CI Est. Geom. Mean (µg/g)
Total shellfish servings per month (χ^2 = 105.1, p = 0.000)					
0 Servings	765	17.8	(15.1, 20.5)	0.31	(0.28, 0.34)
1 Servings	342	32.5	(27.5, 37.4)	0.60	(0.54, 0.67)
2+ Servings	756	41.9	(38.4, 45.4)	0.81	(0.75, 0.87)
Canned albacore tuna servings per month (χ^2 = 40.8, p = 0.000)					
0 Servings	1068	24.1	(21.5, 26.6)	0.43	(0.40, 0.46)
1 Servings	174	29.3	(22.5, 36.1)	0.60	(0.52, 0.69)
2+ Servings	166	48.8	(41.2, 56.4)	0.90	(0.76, 1.06)
Canned chunk light tuna servings per month (χ^2 = 8.4, p = 0.003)					
0 Servings	1108	26.4	(23.8, 28.9)	0.46	(0.43, 0.50)
1 Servings	144	25.7	(18.6, 32.8)	0.51	(0.43, 0.62)
2+ Servings	161	39.1	(31.6, 46.7)	0.69	(0.58, 0.82)
Other tuna servings per month (χ^2 = 266.7, p = 0.000)					
0 Servings	1035	16.8	(14.5, 19.1)	0.35	(0.33, 0.38)
1 Servings	130	32.3	(24.3, 40.3)	0.70	(0.60, 0.82)
2+ Servings	229	70.3	(64.4, 76.2)	1.47	(1.31, 1.65)
Salmon servings per month (χ^2 = 124.9, p = 0.000)					
0 Servings	586	12.8	(10.1, 15.5)	0.27	(0.24, 0.29)
1 Servings	220	28.2	(22.2, 34.1)	0.55	(0.48, 0.63)
2+ Servings	578	42.0	(38.0, 46.1)	0.84	(0.78, 0.91)
Pollock servings per month (χ^2 = 3.0, p = 0.083)					
0 Servings	1194	26.3	(23.8, 28.8)	0.47	(0.44, 0.50)
1 Servings	102	29.4	(20.6, 38.3)	0.57	(0.47, 0.70)
2+ Servings	120	33.3	(24.9, 41.8)	0.62	(0.50, 0.76)
Flounder, grouper or snapper servings per month (χ^2 = 83.9, p = 0.000)					
0 Servings	1196	22.7	(20.4, 25.1)	0.42	(0.39, 0.45)
1 Servings	124	38.7	(30.1, 47.3)	0.82	(0.68, 0.98)
2+ Servings	114	60.5	(51.6, 69.5)	1.23	(1.01, 1.50)
Other saltwater fish servings per month (χ^2 = 89.9, p = 0.000)					
0 Servings	1121	21.5	(19.1, 23.9)	0.40	(0.37, 0.43)
1 Servings	111	35.1	(26.3, 44.0)	0.72	(0.60, 0.85)
2+ Servings	197	53.3	(46.3, 60.3)	1.15	(1.00, 1.32)
Tilapia servings per month (χ^2 = 19.9, p = 0.000)					
0 Servings	1123	24.8	(22.2, 27.3)	0.44	(0.41, 0.48)
1 Servings	157	33.8	(26.4, 41.2)	0.62	(0.53, 0.73)
2+ Servings	145	40.7	(32.7, 48.7)	0.81	(0.68, 0.96)

Table 5. Trends in overall fish and shellfish consumption and hair mercury concentrations over time. (The definition of serving size was reduced from 6 oz. before 5/2007 to 4 oz. thereafter.)

Year	n	% Consuming ≥ 5 Serv. Fish and Shellfish	% Hair Hg ≥ 1.0 μg/g	Geom. Mean Hair Hg (μg/g)
2004	2862	41.2	21.1	0.39
2005	5299	46.3	21.7	0.42
2006	2926	54.2	25.2	0.43
2007(<May)	454	53.5	21.8	0.40
2007(≥May)	681	57.7	35.2	0.61
2008	831	55.6	25.6	0.47
2009	495	43.2	23.9	0.41

Participants who had silver-colored fillings (amalgams) had significantly higher concentrations of mercury in their hair than those who didn't (Table 6) ($\chi^2 = 23.7$, $p = 0.000$). However the difference in the percent above the RFD was less than 4% and the difference in geometric means was 0.1μg/g, which are small compared to the differences related to fish consumption (Table 6). Also participants with silver-colored fillings consumed more fish which may be the reason for the difference in hair mercury concentrations (Table 6). It is possible that the fact that people with large numbers of amalgams are lumped together with those having only one amalgam dilutes the differences due to amalgams. Participants who had amalgams removed in the past year had slightly higher concentrations of mercury in their hair but the difference was not statistically significant (Table 6) ($\chi^2 = 2.7$, $p = 0.103$). Overall, it may be possible that there is some exposure from amalgams but it is clear that fish consumption has a much greater effect on hair mercury concentrations. In the 1994 study by Schweinsberg it was found that among individuals who had no fish consumption, individuals with no amalgams had mean blood mercury concentrations of approximately 0.3 μg/L, while individuals with more than six amalgams had mean blood mercury concentration of approximately 1.0 μg/L. In a summary of several studies, ADSTR estimated the exposure contributions from those with dental amalgams to range from 3-17 μg/day (ATSDR, 1999). One possible explanation for the difference in the results between the current study and other studies is that the inorganic mercury obtained from dental amalgams accumulates less in hair and other tissues than the methylmercury obtained from consuming fish.

Participants who have had flu shots in the past year had significantly higher mercury concentrations than those who did not ($\chi^2 = 11.9$, $p = 0.003$), although the differences were relatively very small (difference in percent above the RFD = 2.5%, difference in geometric mean=0.05 μg/g) (Table 6). Participants who have had flu shots in the past year consumed slightly more fish than those that did not (Table 6), which may account for the slight differences in hair mercury concentrations. Vaccines using thimerosal as a preservative typically include about 25 μg of mercury in ethylmercury (Marques et al., 2007), a different form of organic mercury from the methylmercury that is the predominant form in fish. It would take one 6 oz serving of fish at a concentration of approximately 0.15 μg/g to create a similar amount of mercury in methylmercury so it is not surprising that the effect of flu shots is quite small when

compared to fish consumption. However, the body metabolizes ethylmercury slightly differently than methylmercury. Also, if only participants who had a thimerosal vaccine recently as opposed to the previous year were included, there might have been a greater effect seen in the data.

Table 6. Percentage of participants that have hair mercury concentrations of 1.0 or greater with 95% confidence intervals and estimated geometric means along with 95% confidence intervals for factors that might cause increased mercury concentrations.

Factor Group	n	Percent ≥ 1 μg/g	95% CI Percent ≥ 1 μg/g	Geom. Mean (μg/g)	95% CI Geom. Mean (μg/g)	% Consuming ≥ 5 Servings Fish or Shellfish
Work exposure to mercury (χ^2 = 1.5, p = 0.228)						
Yes	201	19.9	(14.4, 25.4)	0.40	(0.34, 0.47)	47.0
No	13920	23.5	(22.8, 24.2)	0.43	(0.42, 0.44)	48.2
Dentist (χ^2 = 1.5, p = 0.228)						
Yes	84	28.6	(18.9, 38.2)	0.48	(0.38, 0.61)	53.8
No	12828	22.9	(22.2, 23.6)	0.42	(0.41, 0.43)	47.7
Have any silver-colored fillings (χ^2 = 23.7, p = 0.000)						
Yes	8947	24.6	(23.7, 25.5)	0.46	(0.45, 0.47)	50.5
No	4436	20.8	(19.6, 22.0)	0.36	(0.35, 0.38)	42.8
Have any silver-colored fillings removed in past year (χ^2 = 2.7, p = 0.103)						
Yes	1650	24.7	(22.6, 26.7)	0.47	(0.44, 0.49)	48.9
No	10658	22.8	(22.0, 23.6)	0.42	(0.41, 0.43)	47.5
Flu shot in the last 12 months (χ^2 = 7.7, p = 0.005)						
Yes	2735	25.0	(23.4, 26.7)	0.46	(0.44, 0.48)	51.4
No	9846	22.5	(21.7, 23.3)	0.41	(0.40, 0.42)	47.8

Males had greater hair mercury concentrations than females (Table 7) (χ^2 = 55.3, p = 0.000). They had slightly greater fish consumption, but probably not enough different to account for the difference in hair mercury unless males have a different idea of serving size than females. Overall, slightly more than 1/5 of the participants of the study who were women of childbearing age had hair mercury concentrations above the United States reference dose (RFD) for hair mercury concentration of 1.0 μg/g. There is no evidence of a difference between pregnant women and other women of childbearing age (Table 7) (χ^2 = 0.0, p = 0.871). There are great differences in hair mercury concentrations between the different age groups (χ^2 = 325.4, p = 0.000), but those differences seem to track closely with fish consumption (Table 7). Hair mercury concentrations for Asians were considerably higher than for the other races, while African-Americans had the lowest concentrations (Table 7) (χ^2 = 112.0, p = 0.000). The hair mercury concentrations for different races also track closely with differences in fish consumption (Table 7). The Midwest region had the lowest median Hg value, while the West region had the highest median mercury (Region χ^2 = 320.7, p = 0.000) (Table 7). The Northeast and Southeast regions medians were similar (Table 7). The hair mercury concentrations for different races also track closely with differences in fish consumption with the exception that the Northeast has slightly higher hair mercury concentrations but slightly lower consumption of fish than the

Southeast (Table 7). This may be natural variation but it is also possible that fish available in the Northeast has higher mercury concentrations or that people in the Northeast choose to eat fish species that have higher mercury concentrations than in the Southeast. It may also be caused by other sources to mercury in the Northeast. However, a very small percentage of people overall who eat 0-1 servings of fish monthly have elevated mercury levels so that is unlikely.

Table 7. Percentage of participants that have hair mercury concentrations of 1.0 or greater with 95% confidence intervals and estimated geometric means along with 95% confidence intervals for demographic variables.

Factor Group	n	Percent ≥ 1 µg/g	95% CI Percent ≥ 1 µg/g	Geom. Mean (µg/g)	95% CI Geom. Mean (µg/g)	% Consuming ≥ 5 Servings Fish or Shellfish
Gender (χ^2 = 55.3, p = 0.000)						
Female	9231	21.4	(20.6, 22.3)	0.41	(0.40, 0.42)	47.6
Male	5063	27.0	(25.7, 28.2)	0.46	(0.45, 0.48)	49.3
Pregnant (Females Aged 16-49 Years Only) (χ^2 = 0.0, p = 0.871)						
Yes	325	21.5	(17.1, 26.0)	0.45	(0.41, 0.51)	43.6
No	5515	21.9	(20.8, 23.0)	0.41	(0.40, 0.42)	47.4
Age in Years (χ^2 = 325.4, p = 0.000)						
0-1	63	7.9	(1.3, 14.6)	0.22	(0.16, 0.29)	14.0
2-5	534	4.9	(3.0, 6.7)	0.15	(0.13, 0.16)	19.6
6-15	704	6.3	(4.5, 8.0)	0.18	(0.16, 0.19)	24.8
16-49	8071	24.5	(23.6, 25.5)	0.44	(0.43, 0.45)	48.5
50+	4712	26.2	(25.0, 27.5)	0.51	(0.49, 0.52)	55.3
Race (χ^2 = 112.0, p = 0.000)						
African Am.	130	10.8	(5.4, 16.1)	0.24	(0.19, 0.29)	35.2
Asian	344	47.1	(41.8, 52.4)	0.85	(0.76, 0.95)	59.9
Caucasian	9471	22.4	(21.6, 23.3)	0.42	(0.41, 0.43)	48.0
Hispanic	264	20.5	(15.6, 25.3)	0.37	(0.32, 0.43)	48.5
Mixed	221	20.8	(15.5, 26.2)	0.37	(0.32, 0.44)	48.1
Region (χ^2 = 320.7, p = 0.000)						
MW	2766	12.4	(11.2, 13.6)	0.27	(0.26, 0.28)	42.2
NE	3170	25.6	(24.1, 27.2)	0.45	(0.43, 0.47)	45.9
SE	3721	22.4	(21.0, 23.7)	0.42	(0.40, 0.43)	49.4
W	4576	29.7	(28.4, 31.0)	0.55	(0.53, 0.57)	52.5

Summaries of the results for states and cities with at least 50 participants are provided in Table 8 and Table 9, respectively. For the most part, these states and cities have similar hair mercury concentrations to their regions. Hawaii had very high hair mercury concentrations with 62.9% of participants above the RFD and a geometric mean hair concentration of 1.15 µg/g. The other states with more than 30% of hair mercury concentrations above the RFD were Alaska, California, Connecticut, Florida, Massachusetts, and New York, which are all coastal states. The states with less than 10% of participants with hair mercury concentrations above the RFD were Indiana, Nebraska and Wisconsin, which are all located in the Midwest. The city with the highest hair mercury concentrations was Los Angeles, which had 50.3% of participants above

Table 8. Percentage of participants of states with more than 50 participants that have hair mercury concentrations of 1.0 or greater with 95% confidence intervals and estimated geometric means along with 95% confidence intervals.

State	n	Percent ≥ 1 µg/g	95% CI Percent ≥ 1 µg/g	Geom. Mean (µg/g)	95% CI Geom. Mean (µg/g)
AK	60	35.0	(22.9, 47.1)	0.78	(0.63, 0.96)
AL	185	15.7	(10.4, 20.9)	0.26	(0.22, 0.31)
AZ	151	23.8	(17.0, 30.6)	0.45	(0.37, 0.53)
CA	2658	33.1	(31.4, 34.9)	0.60	(0.57, 0.62)
CO	298	24.2	(19.3, 29.0)	0.46	(0.41, 0.53)
CT	204	40.2	(33.5, 46.9)	0.67	(0.58, 0.79)
DC	133	30.8	(23.0, 38.7)	0.53	(0.42, 0.65)
FL	796	36.6	(33.2, 39.9)	0.62	(0.57, 0.67)
GA	300	19.3	(14.9, 23.8)	0.41	(0.36, 0.46)
HI	132	62.9	(54.6, 71.1)	1.15	(0.97, 1.37)
IL	698	17.2	(14.4, 20.0)	0.31	(0.29, 0.34)
IN	190	6.8	(3.3, 10.4)	0.17	(0.14, 0.21)
KY	81	12.3	(5.2, 19.5)	0.30	(0.23, 0.38)
LA	84	20.2	(11.6, 28.8)	0.47	(0.38, 0.59)
MA	395	30.4	(25.8, 34.9)	0.55	(0.49, 0.62)
MD	384	21.1	(17.0, 25.2)	0.48	(0.43, 0.53)
ME	110	24.5	(16.5, 32.6)	0.46	(0.37, 0.57)
MI	344	15.7	(11.9, 19.5)	0.30	(0.26, 0.34)
MN	373	10.2	(7.1, 13.3)	0.27	(0.24, 0.31)
MO	114	14.0	(7.7, 20.4)	0.31	(0.25, 0.38)
MT	140	11.4	(6.2, 16.7)	0.35	(0.30, 0.41)
NC	408	13.2	(9.9, 16.5)	0.33	(0.30, 0.37)
NE	73	9.6	(2.8, 16.3)	0.21	(0.16, 0.28)
NH	168	16.7	(11.0, 22.3)	0.45	(0.38, 0.52)
NJ	431	26.7	(22.5, 30.9)	0.48	(0.43, 0.54)
NM	99	17.2	(9.7, 24.6)	0.41	(0.33, 0.51)
NV	86	22.1	(13.3, 30.9)	0.52	(0.42, 0.64)
NY	830	34.2	(31.0, 37.4)	0.58	(0.53, 0.63)
OH	515	12.0	(9.2, 14.8)	0.26	(0.23, 0.29)
OR	258	21.7	(16.7, 26.7)	0.49	(0.43, 0.56)
PA	912	14.0	(11.8, 16.3)	0.28	(0.26, 0.31)
SC	162	24.1	(17.5, 30.7)	0.43	(0.35, 0.53)
TN	95	20.0	(12.0, 28.0)	0.36	(0.28, 0.45)
TX	472	15.7	(12.4, 19.0)	0.32	(0.28, 0.35)
UT	228	14.9	(10.3, 19.5)	0.38	(0.33, 0.44)
VA	442	20.4	(16.6, 24.1)	0.40	(0.36, 0.44)
VT	85	22.4	(13.5, 31.2)	0.41	(0.32, 0.52)
WA	410	27.8	(23.5, 32.1)	0.51	(0.46, 0.57)
WI	327	7.3	(4.5, 10.2)	0.24	(0.21, 0.27)

the RFD and a geometric mean hair concentration of 0.88 μg/g. The other cities with more than 30% of hair mercury concentrations above the RFD were Atlanta, Miami, Miami Beach, New York, Oakland, San Diego and San Francisco. Of these, all but Atlanta are coastal cities. However, there were several coastal cities with less than 30% of participants above the RFD. The cities with less than 10% of participants with hair mercury concentrations above the RFD were Albany NY, Indianapolis IN, Masontown PA, Minneapolis MN, Pittsburgh PA, none of which are on the coast.

Table 9. Percentage of participants of cities with more than 50 participants that have hair mercury concentrations of 1.0 or greater with 95% confidence intervals and estimated geometric means along with 95% confidence intervals.

City	n	Percent ≥ 1 μg/g	95% CI Percent ≥ 1 μg/g	Geom. Mean (μg/g)	95% CI Geom. Mean (μg/g)
Albany	71	8.5	(2.0, 14.9)	0.29	(0.23, 0.37)
Arlington	50	30.0	(17.3, 42.7)	0.64	(0.44, 0.91)
Atlanta	90	33.3	(23.6, 43.1)	0.64	(0.53, 0.78)
Austin	123	19.5	(12.5, 26.5)	0.33	(0.27, 0.41)
Baltimore	63	17.5	(8.1, 26.8)	0.39	(0.29, 0.52)
Berkeley	107	22.4	(14.5, 30.3)	0.60	(0.50, 0.72)
Bozeman	63	12.7	(4.5, 20.9)	0.38	(0.30, 0.48)
Charlotte	51	21.6	(10.3, 32.9)	0.43	(0.31, 0.60)
Chicago	189	27.5	(21.1, 33.9)	0.45	(0.38, 0.54)
Denver	57	29.8	(17.9, 41.7)	0.51	(0.37, 0.69)
Houston	68	26.5	(16.0, 37.0)	0.48	(0.34, 0.66)
Indianapolis	78	6.4	(1.0, 11.8)	0.17	(0.12, 0.22)
Los Angeles	155	50.3	(42.5, 58.2)	0.88	(0.74, 1.04)
Madison	55	14.5	(5.2, 23.9)	0.33	(0.23, 0.46)
Masontown	64	3.1	(0.0, 7.4)	0.11	(0.08, 0.14)
Miami	85	36.5	(26.2, 46.7)	0.53	(0.40, 0.71)
Miami Beach	51	37.3	(24.0, 50.5)	0.68	(0.49, 0.95)
Minneapolis	129	9.3	(4.3, 14.3)	0.26	(0.21, 0.32)
New York	356	47.8	(42.6, 52.9)	0.81	(0.72, 0.92)
Oakland	78	34.6	(24.1, 45.2)	0.66	(0.53, 0.82)
Omaha	50	12.0	(3.0, 21.0)	0.26	(0.19, 0.35)
Philadelphia	92	22.8	(14.2, 31.4)	0.40	(0.32, 0.51)
Pittsburgh	110	8.2	(3.1, 13.3)	0.29	(0.23, 0.35)
Portland	102	26.5	(17.9, 35.0)	0.56	(0.46, 0.68)
Richmond	67	11.9	(4.2, 19.7)	0.29	(0.22, 0.37)
Salt Lake	121	12.4	(6.5, 18.3)	0.37	(0.31, 0.44)
San Diego	73	30.1	(19.6, 40.7)	0.62	(0.46, 0.81)
San Francisco	269	36.4	(30.7, 42.2)	0.67	(0.59, 0.75)
Seattle	145	31.7	(24.1, 39.3)	0.58	(0.49, 0.70)
Washington	144	28.5	(21.1, 35.8)	0.48	(0.39, 0.59)

Summary and Conclusions.

There exists a strong relationship between mercury concentration in hair and seafood consumption. The fact that the percent of people with hair mercury concentrations above the RFD of 1.0 µg/g was 2.8 % before 5/2007 and 2.7% after 5/2007 for participants who ate 0-1 servings of fish or shellfish but were 37.7% before 5/2007 and 46.8% after 5/2007 for participants who ate 5 or more servings of fish or shellfish makes it clear that fish consumption is the primary cause of elevated hair mercury concentrations in the US. Also consumption of almost every general type or specific species of fish, even some deemed by the FDA to be low in mercury, was significantly and strongly related to hair mercury concentrations. Participants with silver-colored fillings or flu shots had significantly higher percentages above the RFD but those differences were only 3.8% and 2.5%, respectively and in both cases the group with the higher percentage above the RFD also had higher fish consumption as well. Similarly, several demographic variables were associated with increased hair mercury concentrations but in every case, the group with the highest hair mercury concentrations also had the highest fish or shellfish consumption. Therefore it is clear that consumption of fish is the one variable that is strongly associated with hair mercury concentrations.

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