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Mercury Content in Commercially Available Finfish in the United States

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ABSTRACT

Seventy-seven finfish species (300 composites of three fish) were obtained from commercial vendors in six regions of the United States: Great Lakes, mid-Atlantic, New England, northwest, southeast, and southwest. Total mercury in fish muscle tissue ranged from 1 ppb (channel catfish) to 1,425 ppb (king mackerel). Of the top 10 most commonly consumed seafoods in the United States, all finfish species, including salmon species (13 to 62 ppb), Alaskan pollock (11 ppb), tilapia (16 ppb), channel catfish (1 ppb), Atlantic cod (82 ppb), and pangasius (swai) (2 ppb), had low total mercury concentrations. However, two large predatory species, king mackerel and swordfish (1,107 ppb), contained mercury concentrations above the current U.S. Food and Drug Administration action level of 1,000 ppb, indicating that consumers may be unaware that species that are high in mercury are being sold in the marketplace.

Mercury is a persistent environmental contaminant from natural sources and the combustion of waste *(19, 21)*. Mercury converts to methylmercury via aquatic microorganisms and bioaccumulates in fish *(7, 18)*. Large predatory species generally have higher tissue mercury concentrations *(8, 24)* because of their increased exposure and the long half-life of methylmercury *(16, 31)*. In humans, methylmercury is efficiently absorbed *(33)* and has a half-life of 45 to 70 days *(7)*.

Excessive exposure to methylmercury can cause injury to the brain and central nervous system *(6, 10, 11, 18)*. These effects were most prominently noted during outbreaks of methylmercury poisoning in Iraq *(2)* and Japan *(14)*. Ten percent of the body burden of methylmercury is found in the brain *(23)*, where the mercury is slowly demethylated to inorganic mercury and can lead to the development of brain lesions *(18)*. This neurotoxicity is especially important for neonates, because the mercury consumed by the mother is passed directly to the infant *(9, 23)*. Fetuses exposed to methylmercury can exhibit delays in language development and deficits in attention, memory, motor skill development, and learning ability *(12, 13, 20)*. These deficits can occur in children exposed to methylmercury, even when their mothers are asymptomatic *(7)*. The U.S. Environmental Protection Agency (EPA) has established a reference dose (RfD) for mercury of 0.1 μg/kg of body weight per day *(27)*. This RfD corresponds to hair mercury concentrations of up to 1,000 ppb, which should not be exceeded by pregnant and nursing women. Fetal neurodevelopmental effects have been observed when maternal hair levels exceeded 1,200 ppb *(20)*.

The primary source of methylmercury exposure is seafood *(7)*. In 2012, Americans consumed an average of 14.4 lb (6.35 kg) of seafood per person *(17)*. To help protect sensitive populations from the harmful effects of methylmercury, in 2004 the U.S. Food and Drug Administration (FDA) and the EPA jointly published guidelines for fish consumption *(28)*. The FDA established an action level of 1,000 ppb of total mercury in commercial fish *(29)*, and the EPA recommends a lower level of 185 ppb, based on the RfD *(25)*. Health Canada has set a limit of 500 ppb of mercury in commercial fish, with the exception of six species (escolar, orange roughy, marlin, tuna, shark, and swordfish), which may have up to 1,000 ppb of mercury *(15)*. The objective of this study was to survey the mercury concentration in a wide variety of commercially available finfish from across the United States.

MATERIALS AND METHODS

Collection protocol. Fish were obtained from commercial vendors in six regions of the United States: Great Lakes (GL), mid-Atlantic (MA), New England (NE), northwest (NW), southeast (SE), and southwest (SW). Three samples of at least 200 g were requested for each species in addition to tracking information (vendor, supplier, wild or farm raised, country and body of water of origin), length, and weight for each fish. Photos were taken by vendors and sent with the samples to ensure positive identification of each species. Samples were collected for each species during two seasons, 4 to 12 months apart, for each region. In total, 77 species (300 composites of three fish) were collected during this study. The tested species and full tracking details, including the date received and region of origin of all samples is available at www.fish4health.net.

Fish species were divided into three categories for collection. The top 10 species category included finfish species from the

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TABLE 1. *Calibration equations used for each of the catalyst tubes*[a]

	Cell 1		Cell 2	
Catalyst	Calibration equation	R^2	Calibration equation	R^2
1	$A = 0.05641C - 8.943e{-}4C^2$	0.9998	$A = 0.001025C - 2.8e{-}7C^2$	1.0000
2	$A = 0.03586C - 3.049e{-}4C^2$	0.9999	$A = 0.001021C - 2.1e{-}7C^2$	0.9998
3	$A = 0.04893C - 0.001012C^2 + 1.352e{-}5C^3$	0.9991	$A = 0.001076C - 3.1e{-}7C^2$	1.0000

[a] Each catalyst tube was conditioned and then calibrated with liquid mercury standards. Calibration equations and correlation coefficients were determined by Milestone software included with the DMA-80. *A*, absorbance; *C*, concentration.

National Marine Fisheries Service *(17)* list of the most commonly consumed seafoods in the United States. The other popular species category included fish higher in n-3 fatty acids or mercury that are commonly consumed across the United States. To include species that are popular in different parts of the country, experts in each region were consulted in the development of a list of regionally popular species. All regions except MA were asked to provide lists of top 10, other popular, and regionally popular species. For the MA region, only swordfish and striped bass from the other popular species category were requested in addition to the regionally popular species.

The top 10 species were Atlantic salmon (*Salmo salar*), Chinook salmon (*Oncorhynchus tshawytscha*), coho salmon (*Oncorhynchus kisutch*), sockeye salmon (*Oncorhynchus nerka*), Alaskan pollock (*Theragra chalcogramma*), tilapia (*Tilapiini* spp.), channel catfish (*Ictalurus punctatus*), Atlantic cod (*Gadus morhua*), and pangasius or swai (*Pangasius hypophthalmus*). The other popular species were striped bass (*Morone saxatilis*), swordfish (*Xiphias gladius*), Alaskan halibut (*Hippoglossus stenolepis*), rainbow trout (*Oncorhynchus mykiss*), monkfish (*Lophius* spp.), red snapper (*Lutjanus campechanus*), grouper (*Epiniphelus* spp.) or red grouper (*Epinephelus morio*), black sea bass (*Centropristis striata*), mahi mahi (*Coryphaena hippurus*), and orange roughy (*Hoplostethus atlanticus*).

Regionally popular species differed by region. GL vendors provided the following species: summer flounder (*Paralichthys dentatus*), bluefin tuna (*Thunnus thynnus*), lake trout (*Salvelinus namaycush*), walleye (*Sander vitreus*), yellow perch (*Perca flavescens*), lake whitefish (*Coregonus clupeaformis*), and rainbow smelt (*Osmerus mordax*). MA vendors provided the following species: striped bass, swordfish, Atlantic croaker (*Micropogonias undulatus*), bluefish (*Pomatomus saltatrix*), spot (*Leiostomus xanthurus*), summer flounder, white perch (*Morone americana*), scup (*Stenotomus chrysops*), spiny dogfish (*Squalus acanthias*), and skate (*Rajidae* spp.). NE vendors provided the following species: yellowtail flounder (*Limanda ferruginea*), winter flounder (*Pseudopleuronectes americanus*), Atlantic pollock (*Pollachius pollachius*), yellowfin tuna (*Thunnus albacares*), haddock (*Melanogrammus aeglefinus*), gray sole (*Glyptocephalus cynoglossus*), silver hake (*Merluccius bilinearis*), tilefish from the north Atlantic population (*Lopholatilus chamaeleonticeps*), American plaice (*Hippoglossoides platessoides*), and American shad (*Alosa sapidissima*). A NW vendor provided the following species: lingcod (*Ophiodon elongates*), sablefish (*Anoplopoma fimbria*), Pacific cod (*Gadus macrocephalus*), Pacific Dover sole (*Microstomus pacificus*), English sole (*Parophrys vetulus*), petrale sole (*Eopsetta jordani*), Rex sole (*Glyptocephalus zachirus*), white sturgeon (*Acipenser transmontanus*), green sturgeon (*Acipenser medirostris*), albacore tuna (*Thunnus alalunga*), brown rockfish (*Sebastes auriculatus*), widow rockfish (*Sebastes entomelas*), Pacific ocean perch (*Sebastes alutus*), Pacific whiting (*Merluccius productus*), and Chilean sea bass (*Dissostichus eleginoides*). SE vendors provided the following species: king mackerel (*Scomberomorus cavalla*), tilefish from the Gulf of Mexico population, Spanish mackerel (*Scomberomorus maculatus*), Atlantic croaker, greater amberjack (*Seriola dumerili*), striped mullet (*Mugil cephalus*), yellowfin tuna, gag grouper (*Mycteroperca microlepis*), yellowedge grouper (*Hyporthodus flavolimbatus*), yellowtail snapper (*Ocyurus chrysurus*), vermilion snapper (*Rhomboplites aurorubens*), Florida pompano (*Trachinotus carolinus*), spotted seatrout (*Cynoscion nebulosus*), Gulf flounder (*Paralichthys albigutta*), and southern flounder (*Paralichthys lethostigma*). A SW vendor provided the following species: Pacific Dover sole, petrale sole, common thresher shark (*Alopias vulpinus*), white sea bass (*Atractoscion nobilis*), California halibut (*Paralichthys californicus*), yellowtail amberjack (*Seriola lalandi*), sablefish, albacore tuna, wahoo (*Acanthocybium solandri*), lingcod, and Chilean sea bass.

Sample preparation. Samples were packed on ice and sent via overnight shipping to Purdue University, where testing was completed. Upon arrival, the temperature of each sample was measured to ensure it was 7°C or lower. All fish were immediately filleted, with skin and pin bones removed. Homogeneous composites of the three fillets of each species were created by grinding in a food processor (Robot Coupe R2 Ultra, Robot Coupe, Ridgeland, MS). Samples were packed in airtight, sterile sampling bags (Fisher Scientific, Pittsburgh, PA) and frozen at −20°C until analysis.

Mercury measurement. Total mercury concentration was determined using a thermal decomposition (gold) amalgamation, atomic absorption spectrophotometer direct mercury analyzer (DMA-80, Milestone Inc., Sheldon, CT) with the following operating conditions. Samples were dried at 300°C for 60 s and thermally decomposed at 850°C for 180 s. Oxygen (commercial grade, 99.5% pure; Indiana Oxygen Company, Indianapolis, IN) was used to purge the system for 60 s and remove interferences. The amalgamator was rapidly heated to 900°C for 12 s to vaporize the mercury and pass it to the detector, where the absorbance was measured at 253.65 nm for 30 s.

Calibration of the DMA-80 was achieved using a 1,000-ppm mercury standard solution (AccuStandard, New Haven, CT). Three dilute mercury solutions (0.100, 1.0, and 10.0 ppm of mercury in 5% hydrochloric acid) were made and used for calibration. Two calibration curves were developed for the two catalyst cells (0 to 25 and 25 to 600 ng of Hg), yielding a working range of 0.02 (limit of detection) to 600 ng of Hg. Because of the large number of samples analyzed and the need to repeat the analysis of many samples, the catalyst was changed three times during this study. The amalgamator was changed with the first and third catalyst changes, yielding higher absorbencies and a longer catalyst life. Table 1 shows the calibration curves used for each of the three catalyst tubes and the correlation coefficients.

Some uncertainty exists as to whether solid standards (e.g., TORT-3, DORM-4, DOLT-4) or liquid standards are better for calibration of the DMA-80 *(4, 5)*, although both are accepted for

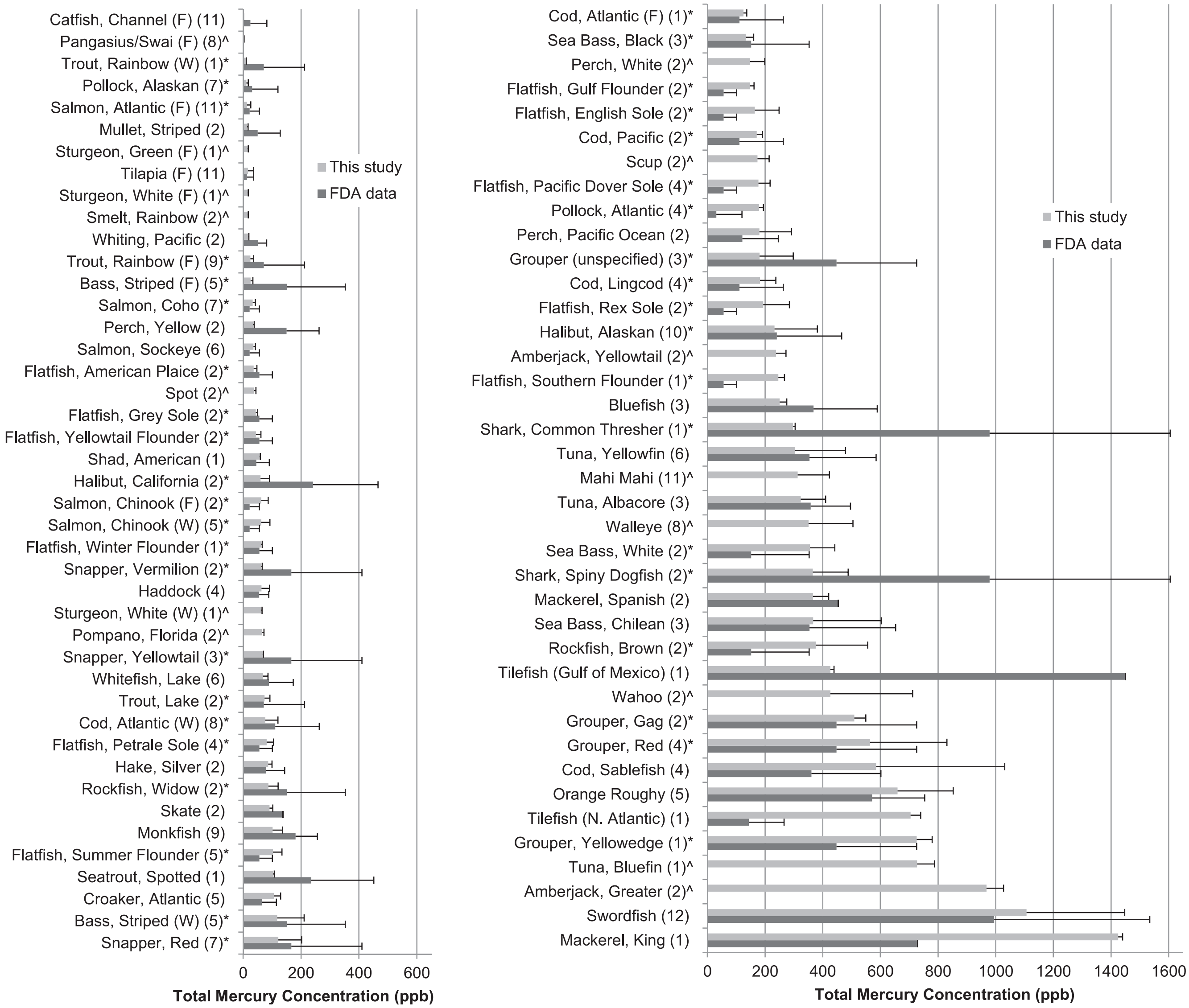

FIGURE 1. *Mercury concentration in commercially available U.S. finfish. Shaded bars represent data from the current study, and solid bars represent data from the FDA (30). Numbers in parentheses represent the number of composites (three fish each) collected for each species. F, Farmed samples; W, wild samples (unlabeled species are wild); ^, no data available on the FDA Web site; *, FDA data are not specific to the species but are the closest approximation. For example, all flatfish species are grouped together as ''flounder, plaice, or sole'' on the FDA Web site. The current study differentiates between all species.*

use with EPA method 7473 *(26)*. Liquid samples were chosen for this analysis to achieve higher accuracy *(4)*.

Each composited fish sample (100 mg wet weight) was analyzed in triplicate. Samples were randomized; however, samples with lower mercury concentrations were run first to minimize errors resulting from carryover effects *(5)*. At the beginning of each run, a blank, a 50-mg sample of TORT-2, and a 100-mg sample of TORT-2 (Institute for National Measurement Standards, National Research Council of Canada, Ottawa, Ontario) as a standard reference material were run to validate the performance of the full working range of the instrument. Additional samples of TORT-2 were run every 20 replicates to continually monitor and validate proper performance. To limit carryover or memory effects in the instrument, blanks were run between each fish species, i.e., after every set of triplicates. Matrix effects with oily fish can increase carryover effects *(22)*. To eliminate these effects, one boat with flour and one boat with 5 to 10% nitric acid were run every 10 to 15 replicates when running samples with high fat content *(22)*.

Results were rejected and the analysis repeated on all samples that had a relative standard deviation (RSD) greater than 10% among the three replicates. Exceptions were made for samples with low mercury concentrations ($\leq$20 ppb), because the RSD increases rapidly at low concentrations. This criterion was based upon the manufacturer's certification that five replicates of 100 mg of a 100-ppb Hg liquid standard will yield an RSD of $<$5% when the instrument is functioning properly *(22)*. Thus, to accommodate the use of composited muscle tissue samples, the RSD was doubled to 10% as the acceptance criterion among the replicates of fish tissue. Applying this criterion, 10.3% of samples failed and had to be retested.

RESULTS

Total mercury concentration of all species obtained in this study and a comparison with current FDA data *(30)* are shown in Figure 1. Total mercury ranged from 1 ppb (channel catfish) to 1,425 ppb (king mackerel). The top 10 species are all low in mercury; all except farmed Atlantic cod have <80 ppb of total mercury. The other popular species and regionally popular species were variable in mercury concentration.

All but two species (swordfish and king mackerel) contained average mercury concentrations below 1,000 ppb, the FDA's current action level for fish sold in U.S. markets *(29)*. However, based on the more conservative Health Canada limit of 500 ppb in all species except escolar, orange roughy, marlin, fresh and frozen tuna, shark, and swordfish, which may have up to 1,000 ppb *(15)*, six additional species (gag grouper, red grouper, sablefish, north Atlantic tilefish, yellowedge grouper, and greater amberjack) exceeded the limit. The most conservative recommendations have been established by the EPA, which advises against consumption of fish with more than 185 ppb, calculated from the RfD of 0.1 μg/kg of body weight per day *(25)*. Based on this criterion, 27 species in this study should be avoided: Alaskan halibut, albacore tuna, greater amberjack, bluefin tuna, bluefish, brown rockfish, Chilean sea bass, common thresher shark, gag grouper, king mackerel, mahi mahi, orange roughy, red grouper, Rex sole, sablefish, Spanish mackerel, spiny dogfish, southern flounder, swordfish, tilefish (north Atlantic and Gulf of Mexico populations), wahoo, walleye, white sea bass, yellowedge grouper, yellowfin tuna, and yellowtail amberjack.

DISCUSSION

Mercury in popular U.S. finfish. Agreement between the data obtained in this study and the FDA data *(30)* was generally close (Fig. 1). The most noticeable feature in both data sets is the large standard deviations in nearly all species. This feature has been noted by others and can be attributed to the age and size of the fish and fish exposure levels *(3)*. Wente *(32)* modeled mercury concentration differences in 11 species, using fish length as the primary factor in estimating mercury. All 11 species produced different length-mercury curves, illustrating the role of fish size in mercury concentration.

One important aspect of the data presented here is the difference between species within a genus or family. For example, the average mercury concentration of groupers in this study ranged from 181 to 726 ppb, whereas the FDA established the average mercury concentration for grouper (all species) as 448 ppb *(30)*. This approach does not take into account the large variability between species within a genus or family, which is exceedingly important for the creation of effective seafood advisories, especially for fish with relatively high levels of mercury. Species in several other genera or families, including cod, flatfish, trout, sea bass, and shark, also differ in their mercury concentrations and should be analyzed and reported separately. Because the FDA database is the most comprehensive and complete source of mercury data for fish and shellfish, small changes in the categorization of various species would help expand the impact of the database and allow consumers to obtain specific advice for each species in the marketplace.

TABLE 2. *Fish consumption categories for sensitive populations*

Recommended weekly intake	Mercury concn (ppb)
Up to 12 oz (340 g)	<123
Up to 8 oz (227 g)	123–185
Up to 4 oz (113 g)[a]	185–370
0[a]	>370

[a] Consumption of fish with >185 ppb of mercury is not recommended for sensitive populations because large doses of mercury may have toxic effects.

The average mercury concentrations in swordfish (1,107 ppb) and king mackerel (1,425 ppb) exceeded the FDA action level of 1,000 ppb in commercial fish. The presence of these high mercury species in commercial markets may expose consumers to unsafe levels of mercury and indicates that consumers are not being adequately protected or informed.

Consumption advice. The neurotoxic effects of methylmercury have been well documented, and special care has been urged for sensitive populations, including pregnant and nursing women, women who may become pregnant, and young children *(1)*. However, because fish portions vary in the modern diet, advisories on fish consumption should recommend exact amounts of fish that should be consumed (e.g., 12 oz [340 g] per week) rather than meal frequency (e.g., up to three meals per week) to maximize the usefulness of the results to consumers.

To determine appropriate levels of fish consumption for sensitive populations, various factors must be considered, including an individual's body weight and current regulatory guidelines. For the current study, exposure calculations were performed to determine appropriate consumption levels based on the EPA RfD for mercury of 0.1 μg/kg of body weight per day *(27)* and a body weight of 60 kg (132 lb). For sensitive populations, no more than 42 μg of mercury per week should be consumed (60 kg of body weight × 0.1 μg/kg of body weight per day × 7 days per week). To translate these figures into intake values, four consumption categories were created: safe to eat up to 12 oz/week (340 g/week), 8 oz/week (227 g/week), or 4 oz/week (113 g/week), and not safe to eat. For example, sensitive populations may safely consume up to 12 oz/week (340 g/week) of fish with <0.123 ppm of mercury (42 μg/week × 1 week/12 oz × 1 oz/28.375 g). Table 2 outlines the categories for sensitive populations.

By adopting these proposed categories for finfish fillets, sensitive populations will have more well established guidelines to follow when consuming seafood. Table 3 lists the species in this study that can be safely consumed within each of the categories. Even in the most restrictive category (<0.123 ppm of mercury), over half of the evaluated species are safe to eat. This flexibility is important for consumers, because individual preferences for fish vary.

This study provides a broad overview of the myriad species of finfish available to U.S. consumers through commercial markets. The results are more specific within

TABLE 3. *Consumption advice for sensitive populations, based on results from this study*[a]

Up to 12 oz (340 g)/wk	Up to 8 oz (227 g)/wk	Up to 4 oz (113 g)/wk	Do not eat
Bass, striped (F)	Cod, Atlantic (F)	Amberjack, yellowtail	Amberjack, greater
Bass, striped (W)	Cod, lingcod	Bluefish	Cod, sablefish
Catfish, channel (F)	Cod, Pacific	Flatfish, Rex sole	Grouper, gag
Cod, Atlantic (W)	Flatfish, English sole	Flatfish, southern flounder	Grouper, red
Croaker, Atlantic	Flatfish, Gulf flounder	Halibut, Alaskan	Grouper, yellowedge
Flatfish, American plaice	Flatfish, Pacific Dover sole	Mackerel, Spanish	Mackerel, king
Flatfish, gray sole	Grouper (unspecified)	Mahi mahi	Roughy, orange
Flatfish, petrale sole	Perch, Pacific ocean	Rockfish, Brown	Swordfish
Flatfish, summer flounder	Perch, white	Sea Bass, Chilean	Tilefish (Mexico)
Flatfish, winter flounder	Pollock, Atlantic	Sea Bass, white	Tilefish (North Atlantic)
Flatfish, yellowtail flounder	Scup	Shark, common thresher	Tuna, bluefin
Haddock	Sea bass, black	Shark, spiny dogfish	Wahoo
Hake, silver	Snapper, red	Tuna, albacore	
Halibut, California		Tuna, yellowfin	
Monkfish		Walleye	
Mullet, striped			
Pangasius or swai (F)			
Perch, yellow			
Pollock, Alaskan			
Pompano, Florida			
Rockfish, widow			
Salmon, Atlantic (F)			
Salmon, Chinook (F)			
Salmon, Chinook (W)			
Salmon, coho			
Salmon, sockeye			
Seatrout, spotted			
Shad, American			
Skate			
Smelt, rainbow			
Snapper, vermilion			
Snapper, yellowtail			
Spot			
Sturgeon, green (F)			
Sturgeon, white (F)			
Sturgeon, white (W)			
Tilapia (F)			
Trout, lake			
Trout, rainbow (F)			
Trout, rainbow (W)			
Whitefish, lake			
Whiting, Pacific			

[a] F, farmed; W, wild; unlabeled species are wild.

certain species (e.g., groupers) and confirm the large differences in mercury concentration within and between species. Overall, results were similar to FDA data and expand the number of species for which data are available. One key finding in this study is that consumers are not being protected from high mercury fish; two species (swordfish and king mackerel) sold commercially had average mercury concentrations above the FDA action level. This work also provides information that will help protect sensitive populations by establishing more definitive consumption advice for a larger number of species commonly consumed in the United States. Monitoring mercury in fish is necessary to continually update and expand the information available to consumers so they can make informed decisions regarding seafood consumption.

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REFERENCES

1. Agency for Toxic Substances and Disease Registry. 2012. Sensitive populations and chemical exposure. Available at: www.atsdr.cdc.gov/emes/public/docs/Sensitive%20Populations%20FS.pdf. Accessed 26 February 2014.
2. Bakir, F., S. F. Damluji, L. Amin-Zaki, M. Murtadha, A. Khalidi, N. Y. Al-Rawi, S. Tikriti, H. I. Dhahir, T. W. Clarkson, J. C. Smith, and R. A. Doherty. 1973. Methylmercury poisoning in Iraq. *Science* 181:230–241.

3. Burger, J., and M. Gochfeld. 2011. Mercury and selenium levels in 19 species of saltwater fish from New Jersey as a function of species, size, and season. *Sci. Total Environ.* 409:1418–1429.
4. Butala, S. J. M., L. P. Scanlan, and S. N. Chaudhuri. 2006. A detailed study of thermal decomposition, amalgamation/atomic absorption spectrophotometry methodology for the quantitative analysis of mercury in fish and hair. *J. Food Prot.* 69:2720–2728.
5. Butala, S. J. M., L. P. Scanlan, S. N. Chaudhuri, D. D. Perry, and R. J. Taylor. 2007. Interlaboratory bias in the determination of mercury concentrations in commercially available fish utilizing thermal decomposition/amalgamation atomic absorption spectrophotometry. *J. Food Prot.* 70:2422–2425.
6. Ceccatelli, S., and M. Aschner (ed.). 2012. Methylmercury and neurotoxicity. Springer, New York.
7. Clarkson, T. W., and L. Magos. 2006. The toxicology of mercury and its chemical compounds. *Crit. Rev. Toxicol.* 36:609–662.
8. Depew, D. C., N. M. Burgess, M. R. Anderson, R. Baker, S. P. Bhavsar, R. A. Bodaly, C. S. Eckley, M. S. Evans, N. Gantner, J. A. Graydon, K. Jacobs, J. E. LeBlanc, V. L. St. Louis, and L. M. Campbell. 2013. An overview of mercury concentrations in freshwater fish species: a national fish mercury dataset for Canada. *Can. J. Fish. Aquat. Sci.* 70:436–451.
9. Diez, S., S. Delgado, I. Aguilera, J. Astray, B. Perez-Gomez, M. Torrent, J. Sunyer, and J. M. Bayona. 2009. Prenatal and early childhood exposure to mercury and methylmercury in Spain, a high-fish-consumer country. *Arch. Environ. Contam. Toxicol.* 56:615–622.
10. Farina, M., J. B. T. Rocha, and M. Aschner. 2011. Mechanisms of methylmercury-induced neurotoxicity: evidence from experimental studies. *Life Sci.* 89:555–563.
11. Ferraro, L., M. C. Tomasini, S. Tanganelli, R. Mazza, A. Coluccia, M. R. Carratu, S. Gaetani, V. Cuomo, and T. Antonelli. 2009. Developmental exposure to methylmercury elicits early cell death in the cerebral cortex and long-term memory deficits in the rat. *Int. J. Dev. Neurosci.* 27:165–174.
12. Gilbert, S. G., and K. S. Grant-Webster. 1995. Neurobehavioral effects of developmental methylmercury exposure. *Environ. Health Perspect.* 103:135–142.
13. Grandjean, P., P. Weihe, R. F. White, F. Debes, S. Arake, K. Yokoyama, K. Murata, N. Sorensen, R. Dahl, and P. J. Jorgensen. 1997. Cognitive deficit in 7-year-old children with prenatal exposure to methylmercury. *Neurotoxicol. Teratol.* 19:417–428.
14. Harada, M. 1995. Minamata disease: methylmercury poisoning in Japan caused by environmental pollution. *Crit. Rev. Toxicol.* 25:1–24.
15. Health Canada. 2012. Canadian standards (maximum levels) for various chemical contaminants in foods. Available at: http://www.hc-sc.gc.ca/fn-an/securit/chem-chim/contaminants-guidelines-directives-eng.php. Accessed 26 February 2014.
16. Lieske, C. L., S. K. Moses, J. M. Castellin, J. Klejka, K. Hueffer, and T. M. O'Hara. 2011. Toxicokinetics of mercury in blood compartments and hair of fish-fed sled dogs. *Acta Vet. Scand.* 53:66–74.
17. National Marine Fisheries Service. 2013. Fisheries of the United States 2012: current fishery statistics. Available at: http://www.st.nmfs.noaa.gov/commercial-fisheries/fus/fus12/index. Accessed 26 February 2014.
18. National Research Council. 2000. Toxicological effects of methylmercury. National Academies Press, Washington, DC.
19. Nordberg, G. F., B. A. Fowler, M. Nordberg, and L. T. Friberg (ed.). 2007. Handbook on the toxicology of metals. Academic Press, Burlington, MA.
20. Oken, E., J. S. Radesky, R. O. Wright, D. C. Bellinger, C. J. Amarasiriwardena, K. P. Kleinman, H. Hu, and M. W. Gillman. 2008. Maternal fish intake during pregnancy, blood mercury levels, and child cognition at age 3 years in a U.S. cohort. *Am. J. Epidemiol.* 167:1171–1181.
21. Pacyna, E. G., J. M. Pacyna, K. Sundseth, J. Munthe, K. Kindbom, S. Wilson, F. Steenhuisen, and P. Maxson. 2010. Global emission of mercury to the atmosphere from anthropogenic sources in 2005 and projections to 2020. *Atmos. Environ.* 44:2487–2499.
22. Randi, M. 2013. Personal communication.
23. Silbernagel, S. M., D. O. Carpenter, S. G. Gilbert, M. Gochfeld, E. Groth III, J. M. Hightower, and F. M. Schiavone. 2011. Recognizing and preventing overexposure to methylmercury from fish and seafood consumption: information for physicians. *J. Toxicol.* 2011:1–7.
24. Tremain, D. M., and D. H. Adams. 2012. Mercury in groupers and sea basses from the Gulf of Mexico: relationships with size, age, and feeding ecology. *Trans. Am. Fish. Soc.* 141:1274–1286.
25. U.S. Environmental Protection Agency. 2001. Human health criteria—methylmercury fish tissue criterion. Available at: http://water.epa.gov/scitech/swguidance/standards/criteria/aqlife/methylmercury/factsheet.cfm. Accessed 26 February 2014.
26. U.S. Environmental Protection Agency. 2007. EPA method 7473: mercury in solids and solutions by thermal decomposition, amalgamation, and atomic absorption spectrophotometry. Available at: http://www.epa.gov/osw/hazard/testmethods/sw846/pdfs/7473.pdf. Accessed 26 February 2014.
27. U.S. Environmental Protection Agency, Integrated Risk Information System. 2001. Methylmercury (MeHg) (CASRN 22967-92-6). Available at: http://www.epa.gov/iris/subst/0073.htm. Accessed 26 February 2014.
28. U.S. Environmental Protection Agency and U.S. Food and Drug Administration. 2004. What you need to know about mercury in fish and shellfish. Available at: http://www.fda.gov/Food/FoodborneIllnessContaminants/BuyStoreServeSafeFood/ucm110591.htm. Accessed 26 February 2014.
29. U.S. Food Drug and Administration. 2007. Compliance policy guidelines section 540.600: fish, shellfish, crustaceans and other aquatic animals—fresh, frozen or processed—methyl mercury. Available at: http://www.fda.gov/ICECI/ComplianceManuals/CompliancePolicyGuidanceManual/ucm074510.htm. Accessed 26 February 2014.
30. U.S. Food and Drug Administration. 2013. Mercury levels in commercial fish and shellfish (1990–2010). Available at: http://www.fda.gov/food/foodborneillnesscontaminants/metals/ucm115644.htm. Accessed 26 February 2014.
31. Van Walleghem, J. L. A., P. J. Blanchfield, L. E. Hrenchuk, and H. Hintelmann. 2013. Mercury elimination by a top predator, *Esox lucius*. *Environ. Sci. Technol.* 47:4147–4154.
32. Wente, S. P. 2004. A statistical model and national data set for partitioning fish-tissue mercury concentration variation between spatiotemporal and sample characteristic effects. Scientific investigation report 2004-5199. U.S. Geological Survey, Minnesota Water Science Center, Mounds View.
33. World Health Organization, International Program on Chemical Safety. 1990. Environmental health criteria 101: methylmercury. Available at: http://www.inchem.org/documents/ehc/ehc/ehc101.htm. Accessed 26 February 2014.