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Selenium and mercury molar ratios in saltwater fish from New Jersey: Individual and species variability complicate use in human health fish consumption advisories[☆]

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Abstract

Balancing risk versus benefits to humans and other organisms from consuming fish is a national concern in the USA, as well as in many other parts of the world. Protecting public health is both a federal and state responsibility, and states respond by issuing fish consumption advisories, particularly for mercury. Recently it has been emphasized that the protective role of selenium against mercury toxicity depends on their molar ratios, which should be evaluated as an indication of selenium's protective capacity, and incorporated in risk assessments for fish consumption. However, there is no single "protective" ratio agreed upon. In this paper we examine the selenium:mercury (Se:Hg) molar ratios in a wide range of saltwater fish caught and eaten by recreational fishers along the New Jersey coast. We were particularly interested in interspecific and intraspecific variability, and whether the molar ratios were consistent within a species, allowing for its use in managing risk. The selenium–mercury molar ratio showed significant variation among and within fish species. The molar ratio decreased with the size of the fish species, decreased with the mercury levels, and within a fish species, the selenium:mercury ratio decreased with fish size. As an essential element, selenium undergoes some homeostatic regulation, but it is also highly toxic. Within species, mercury level tends to increase with size, accounting for the negative relationship between size and ratio. This variability may make it difficult to use the selenium:mercury molar ratio in risk assessment, risk management, and risk communication at this time, and more information is needed on how mercury and selenium actually interact and on the relationship between the molar ratios and health outcomes.

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Keywords

Fish; Mercury; Selenium; Selenium:mercury ratios; Individual variation

1. Introduction

Fish provide an important source of protein, fishmeal and fish oil for human and aquaculture use (Brunner et al., 2009), as well as recreational opportunities and esthetic pleasures (Burger, 2000, 2002). Fish are a low-fat source of protein and omega-3 (n-3) polyunsaturated fatty acids (PUFAs) that are associated with positive pregnancy outcomes (Kris-Etherton et al., 2002; Daviglus et al. 2002), better child cognitive test performances (Oken et al., 2008) and lower incidence of cardiovascular disease (Anderson and Wiener, 1995; Patterson, 2002; Virtanen et al., 2008; Ramel et al., 2010).

Fish consumption is the most significant source of methyl-mercury exposure for the public (Rice et al., 2000), and levels of methylmercury (MeHg) and other contaminants in some fish are high enough to potentially cause toxic effects in the fish themselves, and on top-level predators including humans (WHO, 1989; NRC, 2000). Several reports link methylmercury intake from fish with adverse health effects in people consuming large quantities (IOM, 1991, 2006; Grandjean et al., 1997; Gochfeld, 2003; Hites et al., 2004; Burger et al. 2007a, b). Effects include neurodevelopmental deficits (Crump et al., 1998; Steuerwald et al., 2000; NRC, 2000), postnatal development from prenatal exposure (Stringari et al., 2008), behavioral deficits in infants (JECFA, 2003), and poorer cognitive test performance from fetal (Oken et al., 2008) and childhood exposure (Freire et al., 2010). In adults, methyl-mercury exposure can counteract the cardioprotective effects of fish consumption (Rissanen et al., 2000; Guallar et al., 2002; Stern, 2005), promote development of cardiovascular disease (Choi et al., 2009), and result in neurological and locomotory deficits (Hightower and Moore, 2003). People who consume large amounts of fish are at risk from chronic exposure to methylmercury (Grandjean et al., 1997). There are about 4 million births per year in the United States, and one interpretation of data in the National Health and Nutrition Examination Survey (NHANES) is that in any one year about 250,000 fetuses (6.25%) in the United States may be exposed to levels of methylmercury above the US Environmental Protection Agency (EPA) Reference Dose (Hughner et al. 2008). Trasande et al. (2005) estimate that the proportion of fetuses exposed to excessive mercury is higher (7.8 to 15.7% of all fetuses).

States respond to high mercury levels in fish by issuing consumption advisories. The US Food and Drug Administration (USFDA, 2001; USFDA-EPA, 2004) issued a series of consumption advisories based on methylmercury for saltwater fish. The FDA suggested that pregnant women and women of childbearing age who may become pregnant should limit their fish consumption, should avoid eating four types of marine fish (shark, swordfish, king mackerel, tilefish), should limit their consumption of all other fish to just 12 ounces per week (USFDA, 2001, 2003), and should also limit consumption of canned tuna (USFDA-EPA, 2004). There is some indication that the FDA warnings about fish consumption have resulted in a reduction in the consumption of fish generally, and of canned fish specifically (Shimshack et al., 2007). Groth (2010) recently showed that, with the exception of

swordfish, fish that have high mercury levels make up a small share of seafood consumption in the US.

In the 1960s, Parízek and Ostádalová (1967) showed that selenium could protect rats against mercury toxicity. This was amplified by studies in the 1970s and 1980s (Ganter et al., 1972; Satoh et al., 1985; Lindh and Johansson, 1987). Mozaffarian (2009) reported that lower levels of nonfatal heart attacks are associated with higher levels of selenium, or conversely, that low levels of selenium are associated with increased coronary heart disease (Seppanen et al., 2004). Recent attention has focused on whether any or most of the toxicity of methylmercury is due to impaired synthesis of selenoenzymes or inhibition of their activity (Watanabe et al., 1999a; Ralston, 2008; Ralston et al., 2008; Ralston, 2009). Mercury binds to selenium with a high affinity, and high maternal exposure to methylmercury in animals inhibits selenium-dependent enzyme activity in the brain while selenium supplementation is protective (Berry and Ralston, 2008). Mercury and methylmercury are irreversible selenoenzyme inhibitors (a, Watanabe et al., 1999b; Carvalho et al., 2008), and they thus impair selenoprotein form and function. Cell culture studies and animal experiments show adverse impacts of high methylmercury exposure on selenoenzymes (particularly glutathione peroxidase and thioredoxin reductase) from the presumably irreversible selenium–mercury interaction. Since selenoenzymes play an important role in anti-oxidant defenses, this interaction may explain the oxidative damage attributable to methylmercury (Beyrouty and Chan, 2006; Cabanero et al., 2007; Stringari et al., 2008; Pinheiro et al., 2009; Ralston, 2009; Ralston and Raymond, 2010). Both the toxicokinetics and toxicodynamics of the selenium and mercury interaction require further extensive study, as the effects differ depending on the forms or species of selenium and of mercury (Dang and Wang, 2011) and how they are administered (Klimstra et al., 2011). Identification and refinement of the protective effect of selenium on mercury toxicity is an important contribution that is needed to interpret molar ratio data. There is at least a theoretic limit to the protection conferred by selenium since it is highly toxic by itself (Klimstra et al. 2011).

Ralston and others (Ralston, 2008; Peterson et al., 2009) have suggested that selenium:mercury molar ratios above 1 protect against mercury toxicity, although the actual ratio that is protective is unclear. Ralston (2008, 2009) and others (Kaneko and Ralston, 2007; Raymond and Ralston, 2004, 2009; Peterson et al., 2009; Ralston and Raymond, 2010) have argued strongly for the molar ratio being an important value for risk assessment, rather than relying only on the level of methylmercury. Still, the practical implications of the modification of mercury toxicity by selenium are unclear (Watanabe, 2002) because of the variability in toxicokinetics. We suggest caution before selenium:mercury ratios become part of risk assessment for mercury toxicity, and that selenium:mercury ratios are not stable for particular species. Ralston (2008) also mentions the desirability of a single scale of Selenium Health Benefit Value (SeHBV) which if fully developed would facilitate risk communication.

In this paper we examine individual and species-specific variations in the selenium:mercury molar ratio among saltwater recreational fish collected in New Jersey. We were particularly interested in whether the intraspecific variation in the selenium:-mercury ratio was

sufficiently low to allow for use in either a regulatory context or in the issuance of consumption advisories. The question thus becomes—are selenium:mercury ratios sufficiently consistent within a species to be useful in advising consumers? And will knowing the selenium:mercury molar ratios help consumers make sound decisions about what fish species to eat, how much to eat, and how often to eat them?

2. Methods

We took edible muscle samples from 19 fish species legally caught from several locations along the New Jersey coast (2003–2009) (Burger and Gochfeld, 2011). Scientific names can be found in Table 1. Fish are an important dietary item of the people living along coastal New Jersey, and people often freeze fish for consumption at all times of the year (Pottern et al., 1989; Burger, 2005; Gobeille et al., 2005). The protocol was approved by the Rutgers University Animal Review Board (Protocol # 97-017). At the time these fish were collected, New Jersey had no fishing license requirement for salt water fishing (currently, registration but not licensure is required to comply with a 2010 federal regulation).

The 19 species are the fish most often caught by N.J. fishermen, and the project was a collaboration with local fishing clubs (Jersey Coast Anglers Association, Jersey Shore Shark Anglers) and others. We obtained either whole fish, or took an approximately 50 g sample plug biopsy from the side of the fish, over the lateral line just anterior to the tail. Most samples were provided by recreational fisher-men (we collected the samples from their fish), but we also obtained small individuals (below the recreational size limits) of some species (bluefish, striped bass) from the N.J. Department of Environmental Protection trawls. For each fish we measured total length, and where applicable, fork length.

Fish or samples were kept in coolers and brought to the Environmental and Occupational Health Sciences Institute (EOHSI) of Rutgers University for element analysis. All fish were analyzed individually for total mercury and selenium. Sample sizes ranged from 5 to 251 fish per species. At EOHSI, a 2 g (wet weight) sample of skinless fish muscle was digested in ultrex ultrapure nitric acid in a microwave (MD 2000 CEM), using a digestion protocol of three stages of 10 min each under 3.5, 7, and 10.6 kg/cm² at 80 × power. Digested samples were subsequently diluted in 100 ml deionized water. All laboratory equipment and containers were washed in 10% HNO₃ solution and deionized water rinse prior to each use (Burger et al., 2001a, b). Mercury was analyzed by the cold vapor technique using the Perkin Elmer FIMS-100 mercury analyzer, with an instrument detection level of 0.2 ng/g, and a matrix level of quantification of 0.002 µg/g. Selenium was analyzed by graphite furnace atomic absorption, with Zeeman correction. All concentrations are expressed in parts per million (ppm=µg/g) on a wet weight basis (1 µg Hg=0.005 µmol; 1 µg Se=0.013 µmol).

Many studies have shown that most of the mercury in most fish tissues is methylmercury, and 90% is a reasonable approximation of this proportion, which does not vary by age of the fish (Lansens et al., 1991; Duffy et al., 1999; Cabanero et al., 2007; Scudder et al., 2009). Bloom (1991) suggested that lower percentages may be biased by analytical and homogeneity variability.

A DORM-2 Certified dogfish tissue was used as the calibration verification standard. Recoveries between 90–110% were accepted to validate the calibration. All specimens were run in batches that included blanks, a standard calibration curve, 2 spiked specimens, and one duplicate. The accepted recoveries for spikes ranged from 85% to 115%; 10% of samples were digested twice and analyzed as blind duplicates (with agreement within 15%). Further methods can be obtained from Burger and Gochfeld (2011).

Mean selenium:mercury molar ratios were calculated from the average selenium and average mercury levels in each fish species (see Table 1). There were very few values below the highly sensitive method detection limits (MDL), and for calculations these were set at half the MDL. For each species we divided the mean selenium concentration ($\mu\text{g/g}$) by 78.96 and the mean mercury concentration ($\mu\text{g/g}$) by 200.59, and calculated the ratio (Se/Hg). Note that some papers report the mercury:selenium ratio rather than the selenium:mercury ratio used in this paper.

We used Kruskal–Wallis non-parametric one way analysis of variance to compare molar ratios among species, and Kendall Rank Correlation yielding a tau statistic to determine associations among variables. We used non-parametric statistics because they are more conservative, less sensitive to distribution, and less likely to make a type I error.

3. Results

Across all individuals of all species ($n=1258$) there was a weak but statistically significant positive correlation between mercury and selenium ($\text{tau}=0.17$; $p<0.0001$). However, only two species had significantly negative mercury–selenium correlations (bluefin tuna, windowpane flounder), and six species had significantly positive correlations ($p<0.05$). Across species the mean selenium and mercury values were not correlated, but the maximum levels for each species were positively correlated ($\text{tau}=0.58$; $p=0.0005$), but the mean.

3.1. Differences among species in selenium:mercury ratios

The selenium:mercury ratio (ratio of mean selenium to mean mercury) varied greatly among fish species from 0.36 for shortfin mako shark (mako), to 61 for menhaden (Table 1). The range in mean mercury levels was greater (mean of 0.01 ppm to 1.83 ppm) than for selenium (mean of 0.18 ppm to 0.48). Although both selenium and mercury contribute to the molar ratio, there was a stronger negative relationship with mercury (across species; see Fig. 1, Kendall $\text{tau}=-0.75$; $p<0.0001$) than there was a positive relationship with selenium (not shown, Kendall tau). Likewise the mean selenium:mercury ratio decreased with the mean length of fish species (Fig. 2), but the relationship was weaker than with mercury ($\text{tau}=-0.41$; $p=0.02$). Some species that were relatively small (mean total length under 40 cm) had comparatively low ratios, while others in this size range had high ratios.

3.2. Differences within species in selenium:mercury ratios

Intraspecific variation in selenium:mercury ratios provides some indication of the reliability of the mean selenium:mercury ratio for each species. We examined individual variation in the molar selenium:mercury molar ratios by plotting them against length, an indication of

size. On these graphs (Figs. 3–7), horizontal lines correspond to molar ratios of one and five. One was chosen because it is a value sometimes given for selenium's protective effects on mercury toxicity (see papers by Ralston given in introduction), and 5 is shown for convenience, and it may well turn out that a higher level is required for protection of some organs or tissues (see Lemire et al., 2010). All individual molar ratios are shown so that values are available for comparison with fish from elsewhere (both marine and freshwater).

Four species (menhaden, ling, winter flounder, croaker) had molar ratios above 10:1 and Mako had a molar ratio below 1:1. The other 14 species had ratios between about 2:1 and 7:1 (Fig. 2). Only one species, shortfin mako, fell in the low ratio group, with almost all individuals below a 1:1 M ratio species (shown on Fig. 3). However, since shark is specifically identified on the FDA fish advisory as a fish to avoid, the utility of the ratio is moot.

Several species (Northern kingfish, striped bass, bluefish, tautog on Fig. 4; summer flounder on Fig. 6) had individual ratios mainly below 10, with many individuals below 5 and some even below 1. Summer flounder (or fluke) is shown in Fig. 6 because it had many ratios above 20, and is related to winter flounder. Correlations with length varied, from close to -0.50 (northern kingfish, bluefish) to intermediate (-0.22 , striped bass), to not significant (-0.02 and -0.07 for Tautog and Summer Flounder), meaning that the ratio had no relationship to size.

An intermediate group (seabass, cunner, southern kingfish on Fig. 5, windowpane flounder, weakfish, winter flounder on Fig. 6) had individual ratios mainly below 20. Inverse correlations with size were high for southern kingfish, yellowfin tuna, and windowpane flounder (over -0.54), or not significant, indicating no relationship between size and ratio. A few fish in these species had molar ratios below 1.

The high molar ratios species had no individual fish with selenium:mercury ratios less than 1. Correlations between length and ratio were all negative, and were significantly negative in 10 species. Mercury was the main contributor to the ratio, and was statistically significant in all species except Menhaden, which was represented by only five individuals. As expected, mercury levels were more variable than selenium (higher coefficient of variation) in all species except bluefin tuna.

Several species of fish had some individuals with ratios below 1, and most species had some individual between 1 and 5. This means that any consumer could encounter several fish with molar ratios below 1. Further, within some species, body length was not predictive of the selenium:mercury molar ratio. Eating short (and therefore small) bluefish or tautog would not ensure exposure to a high selenium:mercury molar ratio.

4. Discussion

4.1. Species-specific differences in selenium:mercury ratios

The saltwater fish in this study showed clear and significant interspecific differences in selenium:mercury ratios. Generally, smaller species that had relatively low levels of mercury had higher selenium:mercury ratios than larger species with high levels of mercury. These

relationships are partly the result of greater variation in mercury levels among species than variation in selenium levels. Selenium is an essential trace element (i.e. a deficiency state has been identified), and it is toxic at high levels. It is regulated in the body (Eisler, 2000). Mercury, on the other hand, has no known essential role. Mercury levels are usually correlated with fish size (weight or length), both within and among species (Penedo de Pinho et al., 2002; Green and Knutzen, 2003; Storelli et al., 2002; Simonin et al., 2008). Thus, species of fish that are large generally have low selenium:mercury ratios (less than 3, Table 1), but small species of fish can have a range of ratios from low (just over 2) to high (over 60). Consumers, equipped with knowledge of the molar ratios could select fish that are low in mercury, and have high selenium:molar ratios.

One difficulty with examining selenium:mercury ratios relates to method detection limits. While it is analytically unlikely to obtain selenium levels below the detection limit of the instrumentation, mercury levels can be below detection limits. This problem occurs much less frequently today than thirty years ago because more sensitive instruments have pushed detection limits downward toward the “vanishing zero” (Zarbl et al. 2010). The error involved in using half the detection level is currently relatively small since detection levels in the present study were low (0.0002 ppm in this study), and very few fish were below detection limits for mercury or selenium.

4.2. Within species variations in selenium:mercury ratios

Our primary objective was to examine interspecific and intraspecific difference in selenium:mercury ratios to consider whether these ratios in commonly-eaten fish might be useful in considering potential toxicity of mercury from fish consumption. There was substantial variation in the molar ratios within individual fish species. Although there was a clear negative relationship between ratios and size for most species, this was not the case for some species (i.e. tautog, seabass, cunner, summer and winter flounder, weakfish, scup). A fish eater could not predict their selenium:mercury ratio exposure from only knowing the species of fish, and would need a combination of species and size to make an educated guess about the methylmercury level.

Reasons for the variability in selenium:molar ratios within a species include: (1) selenium is a trace element that is homeostatically regulated (Eisler, 2000), but still varies somewhat, (2) mercury levels are not regulated; levels reflect bioaccumulation with age, and biomagnification up the food chain (Montiero et al., 1996; Downs et al., 1998; Swanson et al., 2003), (3) mercury levels increase with size and age, while selenium levels usually do not (Storelli et al., 2002; McIntyre and Beauchamp, 2007; Burger and Gochfeld, 2011), (4) differences in trophic level affect mercury uptake (Power et al., 2002), (5) prey foods can differ in mercury levels even if the prey are at the same trophic level or even if the same prey species feeds in different habitats (Watras et al., 1998; Snodgrass et al., 2000), and (6) different migratory paths (and time in residence) can affect mercury levels within and among species. Different migratory paths can result in different levels of mercury in fish in a bay in the spring and fall (Burger, 2009).

The variability in selenium:mercury ratios within a species suggests that mercury toxicity may vary for the fish themselves, that the selenium:mercury ratios in muscle tissue reflect

storage and are not related to relevant levels in fish brains, and that exposure and the selenium:mercury ratios vary in the muscle tissue eaten by eco-receptors such as predatory birds, fish and mammals, as well as humans. This variation has implications for the use of selenium:mercury ratios in risk assessment, risk management, and the issuance of fish consumption advisories.

An unexpected finding was the high correlation between the maximum selenium and maximum mercury concentrations across species ($\tau=0.58$, $p=0.0005$). Information on fish with high levels of mercury is important because it is at the high levels that toxicity is greatest. This is consistent with the suggestion that mercury sequesters selenium (Ralston et al. 2008), and we suggest that some of the mercury and selenium in fish may not be readily bioavailable. Indeed the ability of mercury and selenium to interact in the first place depends on their joint bioavailability to each other in different body compartments.

4.3. Selenium:mercury ratios and risk decisions

It has long been known that selenium confers some protection against mercury toxicity in some organisms, but it is less well appreciated that mercury may likewise reduce selenium toxicity (Klimstra et al. 2011). While data is accumulating on selenium:mercury ratios there is no consensus as to how much selenium is needed to reduce the risk of mercury toxicity, nor is it clear whether there is a linear relationship between the hypothesized protective ratio and mercury levels. The intraspecific variability in selenium and mercury concentrations complicates the process of developing fish advisories. Since selenium varies less than mercury, the admonition to avoid fish that are high in mercury is still more useful to the consumer and risk manager than information about the ratio. Most papers on mercury levels in fish report means, ignoring size and location, and until recently few papers have reported selenium levels. We suggest that computing selenium:mercury molar ratios without also providing information on the variance within fish species does not provide a complete picture.

Risk assessors generally examine risk using means, assuming that the fish consumption of a person who eats fish almost daily would converge on the mean concentration for that species. That is, a person with high fish consumption would be expected over time to be eating fish with mercury levels at the mean. A meal of fish might have an above-average mercury content one day or week and low content the next. The same reasoning should apply to selenium:mercury ratios—over time frequent fish consumers would be consuming fish with the average ratios. Therefore we agree that it is important to obtain extensive data on selenium as well as mercury, however, our data indicate the more data are needed before meaningful ratios can be inferred for many species.

There are three problems with using molar ratios at present: (1) it remains unclear what the protective molar ratio is for either individual people or populations overall, and it is unclear whether the same ratio is protective for all organs or endpoints or even from all species of fish, (2) sensitive or susceptible populations (such as fetuses and neonates) may suffer ill effects from only one meal with high mercury (Ginsberg and Toal, 2000) due to a peak exposure exceeding some threshold, and (3) fish with different characteristics are not evenly distributed in time and space. By this we mean that several factors make it unlikely that on

any given day or week a fisherman will obtain fish of the same species with the full range of mercury and selenium levels. Many species of fish travel in schools of the same size and age classes (e.g. bluefish, striped bass), and on a given day, an angler is likely to catch several individuals of the same size (and thus the same mercury levels and molar ratios). If the fish are large, then mercury levels could be high, and selenium:mercury molar ratios low. Since anglers will take these fish home, their exposure may be high for mercury (and low for the protective effects of selenium), and they may eat those fish over several days. In this manner, pregnant women may be exposed for several days to fish with higher mercury levels and low selenium. Anglers often target the largest fish available and some legal size limits (i.e. for striped bass) force anglers to retain the largest fish. These practices can also result in a several days of consumption of fish high in mercury, with a relatively low selenium:mercury ratio.

Fish of the same species that are different sizes may be foraging in the same habitat, leading to similar mercury exposure, regardless of their size. Since fishermen generally do not know the fish migratory paths, foraging areas, and residency times in different places, it is difficult to predict either the levels of mercury or the selenium:mercury ratios (within the variability found in that species). Selecting species known to be low in mercury, and selecting the smallest individuals within the legal size limit, remains the best method of ensuring low mercury levels and high selenium:mercury ratios. Consuming fish is a matter of risk balancing: health benefits versus costs from contaminants, red meat vs fish, depleting fish populations vs eating fish, availability and cost, pleasure and esthetics of fishing, and personal preferences (Burger et al., 2005; Conover et al., 2009).

4.4. Risk management and communication

The US FDA (2001, 2003) warnings about mercury have the potential to reduce fish consumption in the US overall, and there is some indication that fish (especially canned fish) consumption has decreased (Shimshack et al., 2007). Groth (2010) recently showed that, with the exception of swordfish, relatively high mercury fish made up a small share of fish and shellfish consumption in the US. These two facts might suggest cause for concern about the advisories since fish are a good source of protein that provide omega-3 fatty acids, associated with health benefits (see introduction, Gochfeld and Burger, 2005). A clear framework for public health action about fish consumption seems appropriate for the general public (Frieden, 2010).

However, both Shimshack et al. (2007) and Groth (2010) considered that the general public in the US eats primarily commercial fish. As Sunderland (2007) has suggested, publicized differences in mercury concentration for specific commercial fish can significantly affect per capita mercury intake. We suggest that differences in the relative contribution of commercial vs. self-caught fish that a person consumes can also affect mercury intake. Many N.J. fishermen consume large quantities of flounder (low mercury concentrations), and less of shark (high mercury content), for example. For many coastal states, self-caught saltwater fish play a significant role in total fish consumption (Sechena et al., 2003; Harris et al., 2009; Buchanan et al., 2010; Burger and Gochfeld, 2011). Thus, fish consumers who obtain a significant proportion of their fish from self-caught marine fish may represent the high end

of the fish consumption curve with respect to mercury exposure. It is the high end exposure that concerns risk assessors and managers, not consumers at the 50th percentile of exposure (Mahaffey and Schoeny, 2007).

Even for anglers there is great variation in their preference for fishing, and for consuming, particular fish species. In a study of anglers from coastal New Jersey, the area where fish were collected, we (Burger et al., 2011) found differences in the percent of people that consume different species of fish (Fig. 8). The greatest percentage of the over 400 anglers interviewed ate summer flounder (with high selenium:mercury molar ratio), striped bass (with a lower ratio), yellowfin tuna (higher ratio), and bluefin tuna (lower ratio). Thus their preferences do not include only fish with high ratios. While the mean ratios provide useful information for these anglers, it is clear that many individuals in fish species with high molar ratios had some individuals with ratios below 5 or even 1 (Fig. 8).

Stern and Korn (2011) proposed a method for assessing the joint benefit-harm of methylmercury and omega-3 fatty acids in fish where the action of each is confounded by the other. The same thinking should be applied to mercury and selenium, which interact directly in complex chemical ways. Even where selenium may have a measurable benefit on an endpoint (i.e. cataracts in the Amazon), mercury may exert independent harm when selenium level is controlled for (Lemire et al., 2010). Klimstra et al. (2011) reported that selenomethionine and methylmercury each cause hatching failure when injected into duck eggs, and that simultaneous injection showed higher hatching success, but also increased deformities. Likewise combined exposure of breeding females increased the rate of chick deformities (Heinz and Hoffman 1998).

For the people who consume fish frequently (almost daily), considerations of the potential ameliorating effects of selenium intake on mercury toxicity might be important in risk communication, and in risk management (both by agencies and individuals). However, the message is (1) fish high in mercury have lower selenium:mercury molar ratios than fish generally low in mercury, (2) as fish of a given species increase in size, the selenium:mercury molar ratio decreases as mercury increases, and (3) larger fish species higher on the food chain tend to have lower molar ratios.

It may be difficult to provide a message about the molar ratios to the general public, given that it is not merely a matter of knowing both the mercury and selenium levels, but of knowing the molar relationships in specific fish as a function of species and size, and establishing the molar ratio that is protective for different populations (e.g. pregnant women, adults) and for different tissues (especially the brain). Further, the US FDA provides information only on mercury levels (see their most recent website), but not on selenium levels. We suggest that using selenium:mercury ratios at this time in risk assessment, risk management or risk communication is premature because recent evidence suggests that there is no apparent threshold for the adverse effects of methylmercury exposure (Groth, 2010), the ratio of selenium to mercury that would be protective might vary among individuals and tissues (see Lemire et al., 2010), and very little is known about either the blood brain barrier with respect to these issues, or the ratio in the brain that might be protective. The emphasis on understanding selenium–mercury interaction and molar ratios has been a valuable

stimulant for research and discussion, and there is an urgent need for more data on how these molar ratios vary and on the protectiveness of different ratios for different organs and endpoints. However, we suggest that consumers should be very cautious in consuming high mercury fish, regardless of selenium concentrations, and advisories should be written accordingly.

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Fig. 1. Relationship of mean selenium:mercury molar ratios to mean level of total mercury in saltwater fish from New Jersey. The horizontal lines have been arbitrarily placed at ratios of 1 and 5.

Fig. 2.
Relationship of mean selenium:mercury molar ratios to mean length of fish for saltwater fish from New Jersey. The horizontal lines have been arbitrarily placed at ratios of 1 and 5.

Fig. 3. Individual variation in selenium:mercury ratios for shortfin mako shark as a function of length.

Fig. 4. Individual variation in selenium:mercury ratios for northern kingfish, striped bass, bluefish, and tautog as a function of length.

Fig. 5. Individual variation in selenium:mercury ratios for black seabass, yellowfin tuna, cunner, and southern kingfish as a function of length.

Fig. 6. Individual variation in selenium:mercury ratios for windowpane flounder, weakfish, summer flounder and winter flounder as a function of length.

Fig. 7.
Individual variation in selenium:mercury ratios for dolphin, ling, Atlantic croaker and scup (= porgy) as a function of length.

Fig. 8. Percent of people interviewed along NJ shore who reported eating each of the 19 species. Percent of each species with selenium:mercury level below 5.0 and below 1.0, and mean molar ratio for the 19 species (arranged from lowest to highest).

Table 1

Total Mercury and Selenium levels (ppm, wet weight)($\mu\text{g/g}$) in fish species collected from New Jersey. Given are arithmetic means $\pm$ SE, standard deviation and Kendall Tau correlation coefficients.

Common name	Scientific name	n	Mercury mean $\pm$ SE	Selenium mean $\pm$ SE	Hg nmol/g wet wt.	Se nmol/g wet wt.	Se:Hg ^a tau (p)	Se:Hg ratio correlation with Hg tau (p)	Se:Hg ratio correlation with length tau (p)	Hg:Se ^b
Shortfin mako	<i>Isurus oxyrinchus</i>	51	1.96 $\pm$ 0.152	0.26 $\pm$ 0.014	9.77	3.28	0.34	-0.56(<0.0001)	-0.37(0.0001)	2.98
Bluefin tuna	<i>Thunnus thynnus</i>	23	0.52 $\pm$ 0.034	0.43 $\pm$ 0.038	2.61	5.41	2.07	-0.66(<0.0001)	-0.01(NS)	0.48
Striped bass	<i>Morone saxatilis</i>	178	0.39 $\pm$ 0.02	0.30 $\pm$ 0.010	1.96	3.75	1.91	-0.60(<0.0001)	-0.22(<0.0001)	0.52
Bluefish	<i>Pomatomus saltatrix</i>	206	0.35 $\pm$ 0.021	0.37 $\pm$ 0.009	1.75	4.64	2.65	-0.70(<0.0001)	-0.47(<0.0001)	0.38
Tautog	<i>Tautoga onitis</i>	47	0.20 $\pm$ 0.015	0.19 $\pm$ 0.013	0.99	2.44	2.46	-0.46(<0.0001)	-0.12(NS)	0.41
Yellowfin tuna	<i>Thunnus albacares</i>	45 ^b	0.20 $\pm$ 0.025	0.47 $\pm$ 0.027	0.98	6.00	6.11	-0.75(<0.0001)	-0.55(0.007)	0.16
Windowpane	<i>Scophthalmus aquosus</i>	48	0.18 $\pm$ 0.015	0.36 $\pm$ 0.019	0.91	4.55	4.98	-0.74(<0.0001)	-0.59(<0.0001)	0.20
Dolphin	<i>Coryphaena hippurus</i>	27	0.17 $\pm$ 0.038	0.37 $\pm$ 0.024	0.86	4.74	5.52	-0.87(<0.0001)	-0.53(0.0002)	0.18
Southern kingfish	<i>Menticirrhus americanus</i>	23	0.17 $\pm$ 0.017	0.22 $\pm$ 0.021	0.86	2.75	3.21	-0.49(0.001)	-0.54(0.0005)	0.31
Black sea bass	<i>Centropristis striata</i>	19	0.16 $\pm$ 0.017	0.20 $\pm$ 0.018	0.82	2.56	3.13	-0.68(<0.0001)	-0.21(NS)	0.32
Weakfish	<i>Cynoscion regalis</i>	60	0.15 $\pm$ 0.014	0.23 $\pm$ 0.015	0.76	2.87	3.77	-0.54(<0.0001)	-0.03(NS)	0.27
Cunner	<i>Tautoglabrus adspersus</i>	7	0.15 $\pm$ 0.031	0.22 $\pm$ 0.028	0.76	2.81	3.71	-0.62(0.05)	-0.21(NS)	0.27
Northern kingfish	<i>Menticirrhus saxatilis</i>	72	0.15 $\pm$ 0.021	0.28 $\pm$ 0.013	0.76	3.58	4.73	-0.71(<0.0001)	-0.46(<0.0001)	0.21
Summer flounder (fluke)	<i>Paralichthys dentatus</i>	260	0.14 $\pm$ 0.005	0.35 $\pm$ 0.008	0.69	4.42	6.38	-0.67(<0.0001)	-0.07(NS)	0.16
Atlantic croaker	<i>Micropogonias undulatus</i>	63	0.12 $\pm$ 0.009	0.48 $\pm$ 0.023	0.58	6.13	10.5	-0.69(<0.0001)	-0.46(<0.0001)	0.10
Porgy	<i>Stenotomus chrysops</i>	27	0.09 $\pm$ 0.015	0.26 $\pm$ 0.022	0.45	3.24	7.15	-0.77(<0.0001)	-0.02(NS)	0.14
Winter flounder	<i>Pseudopleuronectes americanus</i>	58	0.06 $\pm$ 0.004	0.25 $\pm$ 0.014	0.29	3.14	10.9	-0.64(<0.0001)	-0.09(NS)	0.09
Ling	<i>Molva molva</i>	39	0.04 $\pm$ 0.006	0.18 $\pm$ 0.015	0.18	2.33	12.6	-0.38(0.0008)	-0.33(0.004)	0.08
Menhaden (bunker)	<i>Brevoortia tyrannus</i>	5	0.01 $\pm$ 0.005	0.24 $\pm$ 0.031	0.05	3.04	61.0	-0.32(NS)	0.00(NS)	0.02
Kruskal-Wallis χ^2 (p)			537(<0.0001)	322(<0.0001)		497(<0.0001)				

^aThe Se/Hg molar ratios are calculated on unrounded mean Hg and Se values.

^bThe correlations for Hg:Se ratio with mercury and length are the same as Se:Hg ratio correlations with mercury and length, only positive.