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Mercury Levels and Risk Implications Through Fish Consumption on the Sinaloa Coasts (Gulf of California, Northwest Mexico)

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Fish consumption is the major source of mercury to humans. Fetuses and children are the most sensitive groups of populations to the effects of mercury. Consequently, fish consumption by pregnant women, children, and women of childbearing age is of concern because of the effects of mercury exposure on human health. To assess mercury exposure in a population in northwest Mexico, the allowed daily consumption of fish (which indicates the maximum daily amount of fish that can be consumed without causing adverse noncarcinogenic effects) was calculated for the general population (GP) and fishing-related population (FRP). The studied groups for both sectors of the population were children A (3–10 years old), children B (11–15 years old), women of childbearing age (16–40 years old), and the rest of the population (men ≥16 years old, and women ≥41 years old). Mercury content in canned and frozen tuna, smoked marlin, tilapia, Pacific sierra, dolphinfish, and bullseye puffer ranged from 0.01 to 0.23 μg/g wet weight; none of the values were above the limit set by Mexico. Regarding mercury concentrations and rates of fish consumption, the GP consumes 1.7–2.7 times the allowed daily consumption, and the FRP consumes 1.6–3.9 that limit. The risk analysis showed the children A and B groups from the GP and adults of FRP to be the highest percentage of the population at risk (approximately 35%). These results highlight the need for adequate strategies that consider mercury exposure as part of public health policies associated with fish consumption in Mexico.

KEY WORDS: Fish advisory; fish consumption; Hg limits

1. INTRODUCTION

Fish consumption is part of a balanced diet since it provides healthy proteins and nutrients, such as long-chain n-3 polyunsaturated fatty acids; it also helps to lower the risk of coronary heart disease and stroke, and promotes growth and development (Cardoso, Bandarra, Lourenoço, Afonso, & Nunes, 2010; Food and Agriculture Organization of the United Nations [FAO]/World Health Organization [WHO], 2011). However, fish is also a source of contaminants such as mercury (Hg). The increasing attention on neurotoxicity and neurodevelopmental risks among people exposed to low or moderate levels of mercury (Davidson, Myers, & Weiss, 2004) highlights the need for differentiating the benefits and risks of consuming fish (FAO/WHO, 2011); it is also relevant to consider that mercury levels

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vary among different fish species and within the same species from different areas (Storelli et al., 2003). Predator fish can contain higher mercury levels than noncarnivorous species (Ruelas-Inzunza, Patiño-Mejía, Soto-Jiménez, Barba-Quintero, & Spanopoulos-Hernández, 2011) because of biomagnification—that is, fish of elevated trophic positions tend to have high levels of mercury (Ruelas-Inzunza et al., 2014). Hence, for commercially important fish, the bioaccumulation of mercury and other metals can have serious implications for human health, since fish consumption is generally considered as the main pathway of mercury exposure in humans (Cheng & Hu, 2012; U.S. Food and Drug Administration, 2004), with methylmercury (MeHg) being the main contaminant of concern. Methylmercury is considered the most toxic form of mercury; it can constitute 75–100% of the total mercury in fish muscle (Bloom, 1992; Burger & Gochfeld, 2004). Recent studies have shown an annual increase of 3.8% of mercury content in tuna from the Pacific Ocean. This pattern is consistent with a model of anthropogenic emissions of mercury in the North Pacific (Drevnick, Lamborg, & Horgan, 2015).

Diverse factors influence our diet choices (Rideout & Kosatsky, 2017), the risk and health benefits related to certain fish are important; however, other factors related to environmental sustainability, and social, economic, and cultural issues (Meyer & Schwartz, 2000) are also relevant. Previously, anglers and fisherman were considered at high risk of contaminant exposure from fish consumption (Lauber, Connelly, Niederdeppe, & Knuth, 2017) in a comparison with other populations; however, in coastal communities, some sectors of the population that are not engaged in fishing activities can also be exposed through fish consumption. In this context, the estimation of the amount and type of fish consumed are key factors to assess the health benefits and risks (Connelly, Lauber, Niederdeppe, & Knuth, 2017).

Fisheries are economically important in Mexico. The country is ranked 16th in the world for production, with 1,467,790 tons of marine catches (FAO, 2014). Sinaloa state (located in northwest Mexico; Fig. 1) harbors the second largest fishing fleet and the largest tuna industry in Latin America (Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación [SAGARPA], 2013). Of 328,586 tons of fish products caught in the state, 58.3% are destined for direct human consumption. According to the FAO (2004), the offer of edible fish worldwide has increased in the last five decades at an annual average rate of 3.2%. Such figures exceed the growth rate of the world population (1.6%). In 2012, the per capita global fish availability was 19.2 kg (52.6 g/d; SAGARPA, 2013). However, with a per capita fish consumption of 11.4 kg per year (32.2 g/d), Mexico has a lower consumption than the worldwide average.

Within the framework of the Minamata Convention, Mexico plans to evaluate atmospheric transport and human exposure to mercury through air monitoring (Instituto Nacional de Ecología y Cambio Climático [INECC], 2015) and has legislated the maximum permissible limits in diverse fishery products (Norma Oficial Mexicana [NOM], 2009); however, mercury has not been regulated as a product, and it is sold without restriction. In this context, Evers, Keane, Basu, and Buck (2016) suggest the use of "human Hg exposure metrics to evaluate convention effectiveness"; therefore, fish consumption is relevant because it is the main pathway for mercury exposure in humans.

In the above context, with the aim of generating information concerning mercury risk assessment in the Mexican population, mercury exposure in a coastal population was estimated by Zamora-Arellano, Ruelas-Inzunza, García-Hernández, Ilizaliturri-Hernández, and Betancourt-Lozano (2017) using fish consumption data in children, women, and men, and published data regarding mercury in local fishery products. The results indicated that the percentage of risk reached 97% in some population sectors. In addition, eight items reached around 50% of the total consumption of fishery products in some population groups. Considering that mercury levels in fish from the Pacific have increased around 3% per year (Drevnick et al., 2015), we hypothesized that mercury levels in the most consumed fish would be higher than previously reported and will increase with respect to the trophic level. In addition, elevated fish consumption in some sectors of the population will represent a potential risk for consumers. In that context, the current study represents the second part of an investigation related to health risk assessment in different sectors of a population in northwest Mexico (Zamora-Arellano et al., 2017). The aims of this work are (1) to evaluate mercury levels in the edible portion of the most consumed fish by a coastal population in northwestern Mexico, (2) to evaluate the risk in the studied population, and (3) to recommend maximum fish consumption based on dietary preferences and mercury levels in fish.

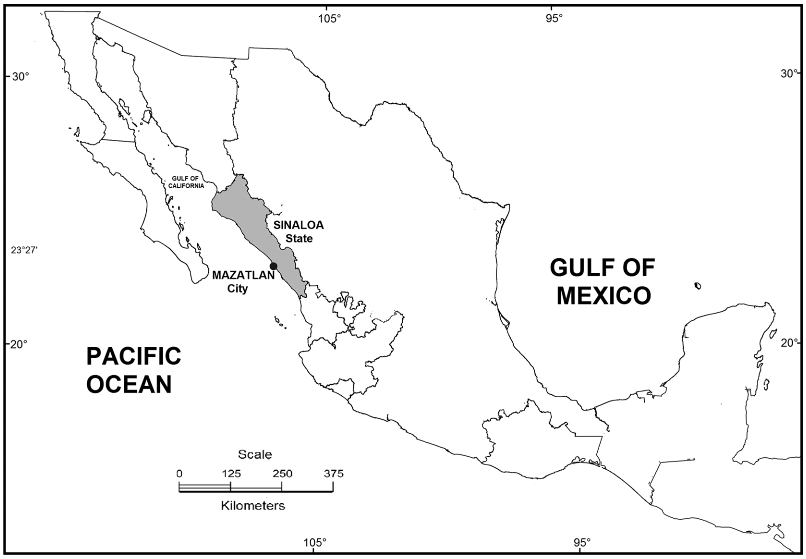

Fig. 1. Location of Mazatlán city (northwest Mexico).

2. MATERIALS AND METHODS

2.1. Field and Laboratory Work

Fish consumption was evaluated in Mazatlán, Sinaloa, in 2014 (Fig. 1), and the results were detailed by Zamora-Arellano et al. (2017). The survey was made using the protocol described by García-Hernández et al. (2013) for the Mexican population. Two populations were considered: the general population (GP) and the fishing-related population (FRP). In both populations, the subgroups were children A (3–10 years old), children B (11–15 years old), women of childbearing age (16–40 years old), and the rest of the population (men >16 years old, and women >41 years old). Gender and age were registered for each surveyed person.

Of 34 fish listed in the survey, the eight most consumed fish were selected to determine mercury content in the edible portion: tuna (canned in oil or water and frozen presentations), striped marlin, tilapia, dolphinfish, Pacific sierra, and bullseye puffer. The fish products were locally acquired ($n = 15$ per fish product) in fish markets in the summer of 2014. Except for striped marlin, a complete organism of each species was obtained for taxonomic identification. Trophic level for each species was obtained from Fish Base (2017). Samples were freeze dried for 72 hours (–49 °C and 133×10^{-3} Mbar) and then ground in an agate mortar. Powdered samples were acid digested (5 mL HNO_3 trace metal grade) on a hot plate (120 °C) in capped vials for three hours (Marine Environmental Studies Laboratory [MESL], 1997) and stored in polyethylene containers. Analysis of mercury in duplicate samples was made by cold vapor atomic absorption spectrophotometry; blanks were included in every batch of samples.

2.2. Risk Assessment and Consumption Limits

A model of no carcinogens was considered according to the U.S. Environmental Protection Agency (EPA, 2000). The individual risk was based on the evaluation of exposure limits and consumption of a single metal from all sources, following the fish advisory guidelines. To assess mercury exposure, the following equation was used (EPA, 2000):

$$E_{m,j} = \frac{\sum (C_{m,j} \cdot CR_j \cdot P_j)}{BW},$$

where $E_{m,j}$ is the individual exposure to a chemical contaminant m from ingesting fish species j (μg/kg body weight per day), $C_{m,j}$ is the concentration of mercury (m) in the edible portion of fish species j (μg/kg wet weight basis), CR_j is the consumption rate of fish species j (kg/d; the same CR_j was used for canned tuna in oil and water presentations), P_j is the proportion of a given fish species in an individual's diet (unitless), and BW is the body weight (kg) of a consumer.

The individual risk ratio was estimated considering mercury exposure through fish consumption ($E_{m,j}$) and the oral reference dose (RfD) for mercury in its methylated form, methylmercury—0.1 μg MeHg per kg/d (National Academy Press, 1991).

When the obtained ratio is equal to or greater than 1 (i.e., when exposure exceeds the *RfD*), the exposed populations may be at risk. According to the EPA (2000), when the *RfD* is exceeded, the possible health effects include liver, kidney, neurologic, muscular, ocular, reproductive, respiratory, circulatory, or other organ toxicities and adverse neurodevelopmental and reproductive effects from acute and chronic exposure. To avoid possible health effects, the allowed daily consumption (CR_{lim}) was calculated; it represents the maximum lifetime daily consumption rate (in grams of fish) that would be expected not to cause adverse noncarcinogenic health effects (EPA, 2000). We used the following equation to calculate CR_{lim} (EPA, 2000):

$$CR_{lim} = \frac{RfD \cdot BW}{\sum (C_{m,\,j} \cdot P_j)},$$

where CR_{lim} is the maximum allowable fish consumption rate (kg/d), *RfD* is the reference dose for MeHg (μg/kg body weight per day), *BW* is the consumer body weight (kg), C_{mj} is the measured concentration of mercury *m* in fish species *j* (μg/kg wet weight basis), and P*j* is the proportion of a given species in the diet (unitless). The following equation was used to convert (CR_{lim}) to monthly fish meal limits (C_{mm}) (EPA, 2000):

$$C_{mm} = \frac{CR_{lim} \cdot 30.44\ d/mo}{0.080\ kg/meal},$$

where C_{mm} is the monthly meal consumption limit (meals per month), 30.44 is the average number of days in a month, and 0.080 kg is the size of a fish meal in the Mexican population (Ortega, Quizán, Morales, & Preciado, 1999).

2.3. Reference Material and Statistical Analysis

Precision and accuracy of the analytical methods were assessed by using a certified reference material of fish muscle (DORM-3). Recovery percentages of mercury were acceptable (98–102%), and the limit of detection was 0.01 μg/g. Concentration of mercury was given as micrograms per gram on a dry weight basis; results were expressed as mean ± standard deviation (*SD*). Significant differences ($p < 0.05$) of mercury concentrations among species were defined with a Kruskal–Wallis nonparametric analysis of variance using Graph Pad Prism version 7.0 (GraphPad Software, San Diego, CA). To estimate the range of exposure in the different groups, a probabilistic approach was used for a Monte Carlo

Table I. Description of Parameters for Health Risk Assessment, According to the U.S. Environmental Protection Agency Noncarcinogenic Model

Population Groups	Age (Years)[a]	Body Weight (kg)[a]	Consumption Rate (g/d)[a]	Proportion of Fish in Diet (0.00–1.00)	MeHg Exposure (μg MeHg per kg/d)	Risk Ratio	Allowed Fish Consumption (g/d)	Monthly Fish Consumption (Meals per Month)
Distribution	Normal	Normal	Log normal		Log normal	Log normal	Log normal	Log normal
General population								
Children A	7 ± 2	31 ± 15	84 ± 79	0.01–0.25	0.107 ± 1.468	1.07 ± 14.68	66 ± 64	25 ± 24
Children B	13 ± 2	52 ± 10	105 ± 108	0.03–0.20	0.093 ± 0.144	0.93 ± 1.44	43 ± 34	16 ± 13
Women of childbearing age	24 ± 7	61 ± 10	90 ± 109	>0.01–0.13	0.044 ± 0.037	0.44 ± 0.37	89 ± 44	33 ± 6
Rest of population	37 ± 16	74 ± 13	134 ± 174	0.01–0.30	0.014 ± 0.006	0.14 ± 0.60	79 ± 43	30 ± 16
Fishing-related population								
Children A	7 ± 3	31 ± 12	42 ± 26	0.03–0.27	0.004 ± 0.285	0.44 ± 2.85	50 ± 27	19 ± 10
Children B	13 ± 1	51 ± 9	90 ± 59	0.01–0.22	0.058 ± 0.039	0.58 ± 0.39	54 ± 24	20 ± 9
Women of childbearing age	25 ± 7	61 ± 12	91 ± 85	0.01–0.20	0.056 ± 0.006	0.56 ± 0.06	77 ± 52	29 ± 20
Rest of population	39 ± 14	81 ± 12	228 ± 283	0.06–0.26	0.124 ± 0.290	1.24 ± 2.90	115 ± 57	44 ± 22

[a]Rate of consumption based on data for eight fish products (Zamora-Arellano et al., 2017). Calculation of $E_{m,j}$, CR_{lim}, and C_{mm} at a mercury concentration of 0.13 ± 0.10 μg/g wet weight was used as shown in Table II. Reference dose used for MeHg was 0.1 μg MeHg per kg bodyweight per day (EPA, 2000). The data are expressed as mean ± *SD*.

analysis with 10,000 iterations, performed with Oracle Crystal Ball version 11.1.2.3.500 software (Oracle, Redwood Shores, CA; EPA, 2001). This type of analysis reduces uncertainty, using the natural fluctuations and the variability of the data caused by differences in body weight, fish consumption rates, chemical concentration fluctuations, and frequency of exposure (Dong et al., 2015). Data are provided in Table I.

3. RESULTS AND DISCUSSION

3.1. Mercury Concentration in Edible Portion of Fish

Fifteen samples of each product were analyzed: canned yellowfin tuna (light and oil presentation), frozen yellowfin tuna (*Thunnus albacares)*, smoked striped marlin (*Tetrapturus audax*—smoked yellowfin tuna is frequently sold as smoked striped marlin and vice versa), fresh Pacific sierra (*Scomberomorus sierra*), fresh dolphinfish (*Coryphaena hippurus*), fresh tilapia (*Gerres cinereus*), and bullseye puffer (*Sphoeroides annulatus*). Levels of mercury ranged from 0.04 μg/g (dolphinfish) to 0.93 μg/g (bullseye puffer), with an average of 0.5 μg/g (Table II). Levels of mercury were significantly lower ($p < 0.001$) in dolphinfish than in the rest of the fish products; however, mercury concentrations in bullseye puffer were significantly higher ($p < 0.001$) than in dolphinfish, tilapia, sierra, and canned yellowfin tuna (oil presentation). In general, the species with higher trophic levels accumulated more mercury; however, bullseye puffer, with a trophic level of 3.1 (Chávez-Sánchez, Álvarez-Lajonchère, de la Parra, Isabel, & García-Aguilar, 2008), accumulated more mercury than dolphinfish did, which has a trophic level of 4.4. This finding could be explained by the rapid growth of dolphinfish with a life span of less than two years (Oxenford & Hunte, 1999), which could have a diluting effect on mercury concentrations (Karimi, Chen, Pickhardt, Fisher, & Folt, 2007). In contrast, bullseye puffer, similar to other puffer fish, can live 10 years or longer and have slow growing rates; therefore, they have a longer exposure period to contaminants (Chávez-Sánchez et al., 2008), compared with dolphinfish (Adams, 2009). In addition, bullseye puffer live in shallow waters of sandy coastal areas, near lagoon–estuarine systems (Chávez-Sánchez et al., 2008) that could be subject to mercury contamination. Regarding mercury levels in fish from Mexico and elsewhere,

Table II. Mercury Levels (μg/g Dry Weight) in the Edible Portion (Muscle) of Different Fish Products Available in Local Markets in Mazatlán, Mexico

Scientific Name	Common Name	Presentation	*N*	% Humidity	Mercury	Maximum	Minimum	Trophic Level[a]
Scombridae								
Thunnus albacares	Yellowfin tuna	Canned in oil	15	72.7 ± 1.6	0.43 ± 0.44^{b}	1.45	0.03	4.4 ± 0.4
		Canned in water	15	75.6 ± 1.8	0.52 ± 0.29^{bc}	1.20	0.17	
		Frozen	15	75.4 ± 0.8	0.79 ± 0.29^{bc}	1.48	0.36	
		Smoked	15	67.8 ± 2.5	0.48 ± 0.12^{bc}	0.75	0.29	
Scomberomorus sierra	Pacific sierra	Fresh	15	73.9 ± 0.9	0.27 ± 0.06^{b}	0.36	0.19	4.5 ± 0.8
Istiophoridae								
Tetrapturus audax	Striped marlin	Smoked	15	67.8 ± 2.5	0.48 ± 0.12^{bc}	0.75	0.29	4.5 ± 0.76
Coryphaenidae								
Coryphaena hippurus	Dolphinfish	Fresh	15	69.7 ± 2.2	0.04 ± 0.03^{a}	0.11	0.01	4.4 ± 0.0
Gerreidae								
Gerres cinereus	Yellowfin mojarra	Fresh	15	73.2 ± 0.8	0.54 ± 0.48^{b}	1.61	0.08	3.5 ± 0.2
Tetraodontidae								
Sphoeroides annulatus	Bullseye puffer	Fresh	15	77.4 ± 0.6	0.93 ± 0.46^{c}	1.67	0.50	3.1 ± 0.44

[a]Fish Base, 2017. Smoked tuna and marlin were considered the same product. Different letters denote significant differences ($p < 0.05$) of mercury in fish products. The data are expressed as mean ± *SD*.

Table III. Mean Mercury Levels (μg/g Wet Weight) in Muscle of Some Fish Species Worldwide

Species	Presentation	Localization	*N*	Mercury	Reference
Thunnus albacares	Fresh	New Zealand	1	0.04	Sadhu, Kim, Furrel, and Bostock (2015)
		Gulf of California	—	0.15	Ordiano-Flores, Rosíles-Martínez, and Galván-Magaña (2012)
		South Africa	14[a]	0.87	Bosh, O'Neill, Sigge, Kerwath, and Hoffman (2016)
			14[b]	0.73	
		Florida coast	56	0.25	Adams (2004)
	Frozen	Northwest Mexico	15	0.20	Current study
	Canned (light)	Northwest Mexico	42	0.36	Ruelas-Inzunza et al. (2011)
	Canned (oil)	Northwest Mexico	43	0.26	Ruelas-Inzunza et al. (2011)
		Northwest Mexico	15	0.12	Current study
	Canned (water)	Northwest Mexico	15	0.13	Current study
Coryphaena hippurus	Fresh	Southeast United States	385	0.10	Adams (2009)
		Gulf of Mexico	57	0.07	Cai, Rooker, Gill, and Turner (2007)
		Hawaiian Islands	30	0.13	Kaneko and Ralston (2007)
		Brazil	20	0.053	Sellanes et al. (2002)
		Southeastern Africa	6	0.17	Kojadinovic, Potier, Le Corre, Cosson, and Bustamante (2007)
		Mozambique Channel	42	0.01	
		Taiwan	31	0.12	Hsu (2001)
		Northwest Mexico	15	0.01	Current study
Gerres cinereus	Fresh	Gulf of Mexico	18	0.04	Ruelas-Inzunza, Páez-Osuna, Zamora-Arellano, Amezcua-Martínez, and Bojorquez-Leyva (2009)
		Northwest Mexico	N/A	0.25	Ruelas-Inzunza, Meza-López, and Páez-Osuna (2008)
		Sinaloa coast	N/A	0.05	Jara-Marini, Soto-Jiménez, and Páez-Osuna (2010)
		Northwest Mexico	15	0.15	Current study
Scomberomorus sierra	Fresh	Southeast Gulf of California	N/A	0.20	Ruelas-Inzunza et al. (2008)
		Northwest Mexico	15	0.07	Current study
Sphoeroides annulatus	Fresh	Northwest Mexico	15	0.23	Current study
Tetrapturus audax	Smoked	Northwest Mexico	15	0.15	Current study

[a]Dark muscle.
[b]White muscle.
Note: N/A = number of sample not available or used in pulls.

the concentrations reported in the present study are in general lower than those reported in other studies, and they are comparable with the values reported in fish from the Gulf of California (Table III).

The Codex Alimentarius Guidelines (FAO/WHO, 1993) indicate a maximum mercury limit of 0.5 mg/kg (wet weight) for fish and seafood, except for predatory fish (e.g., shark, tuna, swordfish), which have a limit of 1.0 mg/kg. Legislation in Mexico (NOM, 2009) sets a limit of 1.0 mg/kg of MeHg for tuna, marlin, mero, and bonito and 0.5 mg/kg for remaining fishery products (equivalent to 4 and 2 mg/kg dry weight, respectively). In the present study, all fish products contained less mercury than the current legislation limit (Fig. 2), although differences between species or product presentations were found (Table II). For example, in the case of canned tuna, there was a significant difference ($p < 0.05$) between the frozen (0.79 $\pm$ 0.29 μg/g) and canned in oil (0.43 $\pm$ 0.44 μg/g) presentations. This difference can be attributed to the possibility that larger tuna with higher mercury content could be used in frozen presentations, compared with smaller tuna used for canning. Differences in mercury concentration among tuna presentations have been previously reported by Ruelas-Inzunza et al. (2011), in which higher mercury

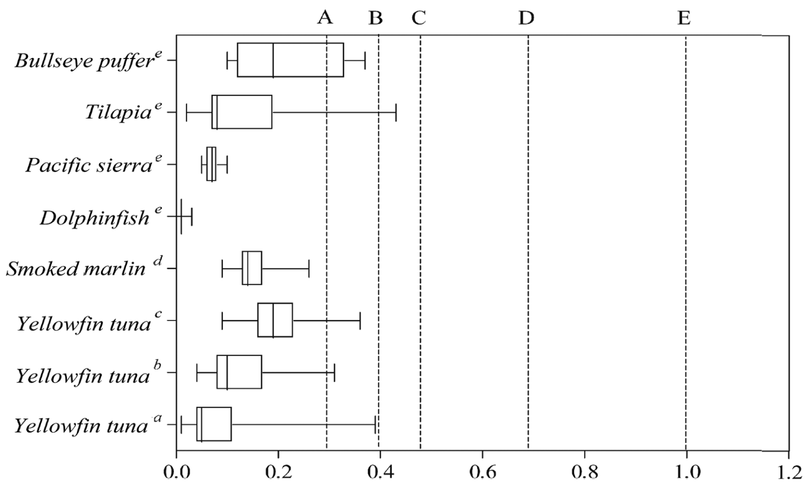

Fig. 2. Mercury levels (μg/g wet weight) in different fish products compared with the limits set in Mexican legislation. Lines A and B set the methylmercury and total mercury limits in Japan. Line C sets the methylmercury limit in shark, tuna, and swordfish in Mexico. Line D sets the total mercury limit in Italy. Line E sets the methylmercury limit in the remaining fish (other than shark, tuna, and swordfish) and seafood in Mexico; it also represents the total mercury limit in the United States of America. [a]Canned in oil; [b]canned in water; [c]frozen; [d]smoked; [e]fresh (NOM, 2009; Nauen, 1983).

concentrations in presentations of canned tuna in water (0.36 μg/g) versus canned tuna in oil (0.26 μg/g) were found. The same tendency was observed in our study between water presentation (0.52 $\pm$ 0.29 μg/g) and oil presentation (0.43 $\pm$ 0.44 μg/g). It is important to note that mercury concentrations in tuna were higher than levels reported by Ruelas-Inzunza et al. (2011), indicating an increment of mercury bioaccumulation as suggested by Drevnick et al. (2015).

3.2. Consumption Rate (CR_j) and Multiple Species Exposure ($E_{m,j}$)

Based on the information from the survey of 2014, the interviewed sector of the population was divided in two groups: the FRP (n = 161) and the GP (n = 209). Every group was separated as children A (3–10 years old), children B (11–15 years old), women of childbearing age (16–40 years old), and rest of the population (>16 years old men and >41 years old women). In comparison to the average national consumption of 32 g/d (SAGARPA, 2013), the CR_j in the Mazatlán population was higher (Table IV). Children A of FRP had the lowest CR_j (42 $\pm$ 26 g/d), while the rest of the population of FRP had the highest values (228 $\pm$ 283 g/d). The rate of consumption in women in the present study was comparable to women from an urban coastal community in the United States (Hollman & Newman, 2012) with an average consumption of 137 g/d. It is worth mentioning that sample sizes for children were small (<26); this could mean a limitation for this study, and results should be interpreted with caution. Similarly, in a study in Japan (Zhang, Nakai, & Masunaga, 2009) with children, women, and men, the average fish consumption was 97 $\pm$ 85 g/d, which is comparable to the overall average in the present study (108 g/d).

Comparisons of MeHg exposures among the studied populations were made with the calculation of $E_{m,j}$ (Table V), which exhibited a considerable variability that could be explained by the differences in individual consumption rates in the different groups. The groups with the highest exposures were children A and B from the GP (0.107 $\pm$ 1.468 and 0.093 $\pm$ 0.144 μg Hg/kg/d, respectively) and the rest of the population of FRP (0.124 $\pm$ 0.290 μg Hg/kg/d). These results were comparable to MeHg exposures in other regions, such as children (0.18 μg Hg/kg/d) and adults (0.14 μg Hg/kg/d) from Japan (Zhang et al., 2009) and 1- to 5-year-old children (0.11 μg Hg/kg/d) from the United States (Tran, Barraj, Smith, Javier, & Burke, 2004). In contrast, in a study considering the consumption of eight fish species in Colombia (López-Barrera et al., 2016), a low $E_{m,j}$ (0.01 μg/kg/d) associated with low consumption rates (74 g/d) and low mercury concentrations (0.016–0.0933 μg/g) was reported.

In a previous study in Mazatlán using historical mercury data in fish (Zamora-Arellano et al., 2017), children presented the highest risk (97%). In the current study, the probabilistic analysis indicated that all groups were at risk (Table V, Fig. 3), ranging from 1.4% to 35.5% for GP and from 9.2% to 35.1% for FRP. However, the groups with greater MeHg exposure (~35%) were children in the GP (coinciding with the previous study) and the rest of the population in the FRP. Children in the GP (A and B) are similarly exposed because of their consumption habits (higher proportion of tuna and

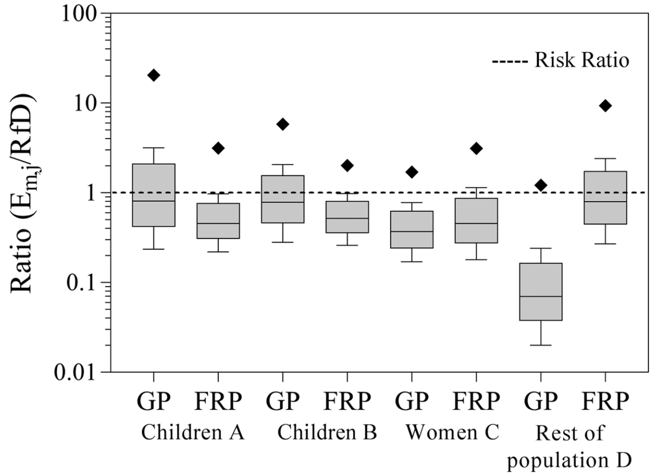

Fig. 3. Box plots of risk based on fish consumption and oral reference dose of methylmercury (MeHg) for the studied groups. The dotted line represents the risk threshold for the studied population. Filled diamonds represent outliers. Risk ratio was calculated using a reference dose of 0.1 μg MeHg per kg/d (EPA, 2000). FRP = fishing-related population; GP = general population; E_{mj} = individual exposure to a chemical contaminant m from ingesting fish species j (μg/kg body weight per day); RfD = reference dose.

marlin in their diet), while exposure in the rest of the population of FRP could be explained by their high fish consumption rate (228 ± 283 g/d). Our results are a matter of concern, indicating that further risk assessments should be conducted, particularly to determine actual exposure and effects in sensitive groups. For instance, female exposure could be measured using maternal hair MeHg concentration as an exposure biomarker to determine whether levels could be associated with teratogenic and neurodevelopment effects in fetuses (Axelrad, Bellinger, Ryan, & Woodruff, 2007; WHO, 2008). Similarly, neurodevelopmental tests are desirable in children to assess cognitive disorders (FAO/WHO, 2011).

3.3. Allowed Fish Consumption (CR_{lim})

The type and amount of consumed fish are the main factors influencing mercury exposure (EPA, 2000). This is particularly important for coastal communities, such as Mazatlán, where fish consumption is at least greater than twofold higher than the average national consumption, depending on the group under consideration. Therefore, to protect these populations, fish advisories must be implemented according to the fish consumption patterns. In that context, the allowed daily consumption (CR_{lim}) for each population group is presented in Table VI. In general, it can be observed that body weight influences CR_{lim}. For instance, body weight explains why children A in both populations had a lower CR_{lim} than the rest of the groups. Similarly, mercury content of some fish products lowers the CR_{lim}. In all cases, the CR_j (Table IV) were higher than CR_{lim}, indicating that the choice and rate of fish consumption could be a matter of concern regarding MeHg exposure.

Considering all the fish products, the monthly consumption limit (C_{mm}) in the GP ranged from 16 to 33 meals per month (1.3–2.6 kg); for the FRP, it ranged from 19 to 44 meals (1.5–3.5 kg) per month (Table VI). This variability in meal consumption shows differences in fish eating habits, although the preference for some products is clear.

In general, tuna products (canned in oil, canned in water, fresh, and smoked) and smoked marlin are the main mercury contributors; they represent 22–89% of the total MeHg exposure (Table VII). In children A in the GP, tilapia contributed 63% of the MeHg exposure. In contrast, dolphinfish, with P_j between 0.02 and 0.14, contributed to less than 1% of MeHg exposure in all cases, suggesting that this fish could be a good alternative to reduce tuna and marlin consumption. Sierra fish could also be a possible substitute because of their relatively low mercury levels, although its MeHg contribution ranges from 4% to 23%.

An additional matter of concern could be related to bolus dosing (i.e., "consuming a few large meals over a very short period"), which is similar to an acute exposure; this issue is not usually considered in the developing of fish advisories (EPA, 2000). This constitutes a nonestimated risk to people with special susceptibilities, such as children, older people, pregnant or lactating women, and people taking medication. Therefore, future research is necessary to assess the effects caused by short-term exposure that might be substantially different from long-term exposure at low levels (EPA, 2000; Zahir, Rizwi, Haq, & Khan, 2005).

Table IV. Daily Consumption Rate (CR_j, in g/d) of Fish Products in a Population of Northwest Mexico

Fish Product	Children A		Children B		Women of Childbearing Age		Rest of Population	
	GP ($n = 11$)	FRP ($n = 9$)	GP ($n = 26$)	FRP ($n = 13$)	GP ($n = 55$)	FRP ($n = 45$)	GP ($n = 117$)	FRP ($n = 94$)
Canned tuna[a]	20.8 ± 29.7	9.7 ± 9.3	47.52 ± 66.3	18.9 ± 10.6	25.56 ± 22.0	36.7 ± 58.8	47.0 ± 81.6	49.6 ± 59.6
Fresh tuna	16.4 ± 4.6	6.2 ± 1.7	—	5.6	37.3 ± 51.9	9.7 ± 14.7	6.6 ± 0.00	97.1 ± 181.3
Smoked tuna	7.8 ± 10.2	14.79	—	—	7.7 ± 3.0	7.5 ± 5.2	60.8 ± 76.4	37.5 ± 26.9
Bullseye puffer	9.5 ± 12.8	10 ± 3.7	16.8 ± 30.9	19.3 ± 19.8	19.7 ± 51.3	6.1 ± 6.3	21.4 ± 43.6	24.1 ± 41.9
Dolphinfish	32.2 ± 25.8	5.6 ± 3.6	—	7.3 ± 7.9	23.0 ± 26.2	7.3 ± 7.8	21.8 ± 41.8	44.1 ± 107.4
Smoked marlín	7.6 ± 5.9	12.5 ± 7.7	40.6 ± 65.0	21.7 ± 28.7	18.5 ± 19.3	26.3 ± 29.9	32.3 ± 35.2	38.6 ± 49.0
Tilapia	55.7 ± 101.1	12.4 ± 3.5	7.47 ± 9.7	24.0 ± 13.8	13.9 ± 23.7	13.3 ± 13.8	21.2 ± 4.4	77.3 ± 118.5
Pacific sierra	19.0 ± 27.0	8.5 ± 3.7	23.9 ± 28.2	27.4 ± 21.0	27.3 ± 40.3	13.7 ± 12.0	46.2 ± 111.7	67.7 ± 102.3
Total CR_j[b]	83.9 ± 78.8	41.7 ± 25.6	104.6 ± 107.7	90.4 ± 58.7	89.9 ± 108.89	91.3 ± 85.4	133.8 ± 174.0	227.9 ± 282.6

[a]Includes oil and water presentations.
[b]Average of individual CR_j. Children A (3–10 years old), children B (11–15 years old), women of childbearing age (16–40 years old), and the rest of the population (men >16 years old and women >41 years old). Data are expressed as mean ± *SD*.
Note: FRP = fishing-related population; GP = general population.

Table V. Multiple Species Exposure ($E_{m,j}$) in a Population of Northwest Mexico

	Children A[a]		Children B		Women of Childbearing Age		Rest of Population	
Parameter	GP	FRP	GP	FRP	GP	FRP	GP	FRP
Number of subjects	11	9	26	13	55	45	117	94
Body weight (kg)	31 ± 15	31 ± 12	52 ± 10	51 ± 9	61 ± 10	61 ± 12	74 ± 13	81 ± 12
$E_{m,j}$ (μg MeHg per kg/d)	0.107 ± 1.468	0.044 ± 0.285	0.093 ± 0.144	0.058 ± 0.039	0.044 ± 0.037	0.056 ± 0.0060	0.014 ± 0.056	0.124 ± 0.290
Ratio ($E_{m,j}$/RFD)	1.07 ± 14.68	0.44 ± 2.85	0.93 ± 1.44	0.58 ± 0.49	0.44 ± 0.37	0.56 ± 0.60	0.14 ± 0.56	1.24 ± 2.90
Population at risk (%)	35.5	9.2	33.2	9.4	5.2	12.3	1.4	35.1

[a]Children A (3–10 years old), children B (11–15 years old), women of childbearing age (16–40 years old), and the rest of the population (men >16 years old and women >41 years old). The data are expressed as mean ± *SD*.
Note: $E_{m,j}$ = individual exposure to multiple species; FRP = fishing-related population; GP = general population; RfD = reference dose (0.1 μg methylmercury per kg/d).

Table VI. Fish Consumption Limits (Daily and Monthly) for Noncarcinogenic Health Endpoint: Methylmercury

	Risk-Based Consumption Limit							
	General Population				Fishing-Related Population			
Fish Product	Children A	Children B	Women of Childbearing Age	Rest of Population	Children A	Children B	Women of Childbearing Age	Rest of Population
Body weight (kg)	16–46	42–62	51–71	61–87	18–44	42–60	52–74	69–93
CR_{lim} (g/d)	66 ± 64	43 ± 34	89 ± 44	79 ± 43	50 ± 27	54 ± 24	77 ± 52	115 ± 57
C_{mm} (meals per month)								
Dolphinfish	16 ± 18	—	13 ± 11	4 ± 1	10 ± 4	4 ± 3	11 ± 9	20 ± 17
Pacific sierra	3 ± 2	6 ± 2	10 ± 3	12 ± 3	3 ± 1	8 ± 2	5 ± 1	10 ± 3
Tuna canned in oil	1 ± 5	3 ± 13	3 ± 10	4 ± 14	1 ± 5	1 ± 5	4 ± 15	2 ± 6
Tuna canned in water	2 ± 1	3 ± 3	2 ± 2	3 ± 3	1 ± 1	1 ± 1	4 ± 3	1 ± 1
Smoked tuna	<0.5	—	<0.5	<0.5	<0.5	—	>0.5	1 ± 0
Smoked marlin	1 ± 0	4 ± 1	3 ± 1	4 ± 1	2 ± 1	3 ± 1	4 ± 1	2 ± 1
Mojarra	2 ± 4	<0.5	1 ± 2	1 ± 2	1 ± 2	2 ± 4	1 ± 3	5 ± 9
Fresh tuna	<0.5	—	<0.5	<0.5	<0.5	<0.5	<0.5	2 ± 1
Bullseye puffer	<0.5	<0.5	1 ± 0	1 ± 0	<0.5	1 ± 1	<0.5	1 ± 1
Total C_{mm}	25 ± 24	16 ± 13	33 ± 16	30 ± 16	19 ± 10	20 ± 9	29 ± 20	44 ± 22

CR_{lim} = allowed daily consumption; C_{mm} = monthly meal consumption limit, assuming a portion of meal of 80 g (0.08 kg; Ortega et al., 1999) for children and adults. Children A (3–10 years old), children B (11–15 years old), women of childbearing age (16–40 years old), and the rest of the population (men >16 years old and women >41 years old). Data are expressed as mean ± *SD*.

3.4. Perspectives on Fish Advisories

Our results indicate that although mercury concentrations in the edible portions of fish are below the limits set in the Mexican legislation (NOM, 2009) this does not necessarily imply that the products can be consumed without restriction. In most cases, those limits are just a way to determine whether they can be commercialized or exported to other countries. However, if rates of consumption are not considered, permissible levels of contaminants could represent a risk for the consumers. To achieve these objectives, fish advisories should consider the rate of fish consumption (CR_j) and the proportion of the fish of interest in the diet (P_j) within the population sectors of concern (e.g., common, subsistence fishers, anglers), the reliability and availability of mercury data in the local fish products, and a risk estimation of multiple species exposure. The U.S. Food and Drug Administration (FDA) and EPA (2017) recommendations to support fetal growth and development indicate that children and women who are pregnant or might become pregnant should have a weekly consumption of 8–12 ounces (equivalent to 2–3 servings using an adult meal size of 0.112 kg or 4 ounces) of varied fishery products with mercury concentrations less than 0.23 mg/kg (EPA/FDA, 2014). This is particularly important for children because they have different sensitivity (toxicodynamics) and less capacity to detoxify and eliminate chemicals (toxicokinetics) from the body compared with adults (Benford, 2000). Nevertheless, fish is an important source of protein, essential nutrients, and omega-3 fish oils that deliver many health benefits (Mahaffey et al., 2011). In addition, selenium levels in fish should also be considered; the co-occurrence of mercury and selenium is of toxicologic relevance given their antagonistic behavior. Thus, contradictory information reaches the consumers, making it difficult to decide which fish to eat because commonly only one perspective (risk or benefit) is considered (Oken et al., 2012). This risk–benefit scenario poses a challenge to fish advisories communication; therefore, it is desirable to increase awareness within the population to encourage informed dietary choices (Engelberth et al., 2013; Nunes, Cavaco, & Carvalho, 2014) because evidence of neurodevelopmental effects of prenatal MeHg exposure less than the RfD have been found (Karagas et al., 2012). However, the effects of the advisories communicated to the public could lead to a reduction of MeHg exposure, but also of long-chain n-3 polyunsaturated fatty acids (Shimshack & Ward,

Table VII. Proportion of a Given Fish Product in an Individual's Diet and the Corresponding Percentage of MeHg

Population Fish Consumption	Children A[a]		Children B		Women of Childbearing Age		Rest of Population	
	P_j	$\%E_{m,j}$	P_j	$\%E_{m,j}$	P_j	$\%E_{m,j}$	P_j	$\%E_{m,j}$
General population								
Dolphinfish	0.14	<1	—	—	0.06	<1	0.02	<1
Pacific sierra	0.21	8	0.19	7	0.31	23	0.31	12
Tuna canned in oil	0.12	9	0.2	24	0.13	14	0.16	19
Tuna canned in water	0.12	10	0.2	26	0.13	15	0.16	22
Smoked tuna	0.01	<1	—	—	<0.01	<1	0.01	3
Smoked marlin	0.07	2	0.31	39	0.18	18	0.20	25
Tilapia	0.25	63	0.03	1	0.08	14	0.08	6
Fresh tuna	0.01	1	—	—	0.02	4	>0.01	<1
Bullseye puffer	0.07	5	0.06	5	0.08	10	0.07	14
Fishing-related population								
Dolphinfish	0.09	<1	0.02	<1	0.05	<1	0.06	<1
Pacific sierra	0.16	7	0.28	19	0.14	4	0.21	11
Tuna canned in oil	0.11	10	0.09	7	0.20	26	0.06	3
Tuna canned in water	0.11	11	0.09	8	0.20	29	0.06	3
Smoked tuna	0.04	6	—	—	0.01	<1	0.03	2
Smoked marlin	0.27	37	0.22	25	0.25	30	0.11	8
Tilapia	0.13	18	0.18	23	0.10	7	0.25	31
Fresh tuna	0.03	3	<0.01	<1	0.02	1	0.13	37
Bullseye puffer	0.07	8	0.06	18	0.08	2	0.07	5

[a]Children A (3–10 years old), children B (11–15 years old), women of childbearing age (16–40 years old), and rest of population (men > 16 years old and women >41 years old).
Note: P_j = fish product in an individual's diet; $\%E_{m,j}$ = corresponding percentage of methylmercury ($\%E_{m,j}$).

2010). In Mexico, one of the national goals for the period of 2012–2018 (SAGARPA, 2013) is to increase the annual fish and shellfish consumption to 12 kg per capita (32.8 g/d), with a special emphasis on children. This goal highlights the importance of implementing a comprehensive and focused strategy to communicate and influence healthy habits of fish consumption to accomplish responsible national food safety policies.

4. CONCLUSION

The results indicate that although mercury levels in fishery products are within limits set by Mexican legislation, the high consumption of predatory species could be associated with risk in some sectors of the population, where pediatric exposure is a particular matter of concern. To promote the health benefits of fish consumption, risk could be reduced by incorporating fish species with low mercury content, such as dolphinfish or Pacific sierra, in the diet. Our results highlight the need for new research, including the risk–benefit analyses for Mexican fishery products based on fatty acids content and the selenium health benefit value, and the determination of MeHg exposure (using blood or hair) to evaluate potential public health problems.

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