Caracterización del riesgo por exposición a metilmercurio por consumo no intencional de carne de tiburón en mujeres de México

Caracterização do risco de exposição à metilmercurio do consumo não intencional de carne de tubarão em mulheres do México

Characterization of the Risk of Exposure to Methylmercury Due to the Non-intentional Consumption of Shark Meat by Mexican Women

Laura Elizalde-Ramírez, Patricia Ramírez-Romero, Guadalupe Reyes-Victoria, Edson Missael Flores-García

Universidad Autónoma Metropolitana Iztapalapa, México.

Cita: Elizalde-Ramírez L, Ramírez-Romero P, Reyes-Victoria G, Flores-García EM. Risk characterization of exposure to methylmercury due to non-intentional consumption of shark meat in females from Mexico. Rev. salud ambient. 2020; 20(2):167-178.

Recibido: 27 de mayo de 2020. **Aceptado:** 10 de noviembre de 2020. **Publicado:** 15 de diciembre de 2020.

Autor para correspondencia: Patricia Ramírez-Romero.
Correo e: pattdf@gmail.com
Universidad Autónoma Metropolitana, México.

Financiación: Proyecto "Indicadores de integridad ecológica y salud ambiental", de la Universidad Autónoma Metropolitana de México, programa de posgrado en Energía y Medio Ambiente (PEMA) y el Consejo Nacional de Ciencia y Tecnología (CONACYT, México) a través del M. Sc. Beca No. 659582.

Declaración de conflicto de intereses: Los autores declaran que no existen conflictos de intereses que hayan influido en la realización y la preparación de este trabajo.

Declaraciones de autoría: Todos los autores contribuyeron al diseño del estudio y la redacción del artículo. Asimismo todos los autores aprobaron la versión final.

Abstract

Concern about the health risks due to the consumption of shark meat arose in two previous studies in which shark meat with high concentrations of methylmercury (MeHg) and fish meat with up to 60 % substitution with shark meat were documented. In this study, the health risk for women arising from the unintentional consumption of shark meat was calculated. Samples were obtained from the main wholesale market in Mexico City, and consumption habits surveys were given at a variety of markets throughout Mexico City's metropolitan area (MXC-MA). The risk quotient (RQ) for different age groups was calculated using three methylmercury concentrations (lowest, average, and highest), and exposure was calculated using the data collected via the surveys. The RQ was below 1 when calculated with the lowest MeHg concentration but well above 1 with higher Hg concentrations (the average RQ was 1.44). Risk changes with life stage; MeHg concentrations were thus analyzed through numerical and analytic methods, a smooth function being obtained. The stability of this function was highlighted by the analysis of the associated risk vector field, which showed that, even with small data errors (uncertainty), the behavior of the process is the same. The associated risk surface has a non-positive Gaussian curvature, and the points where such curvature is zero determine critical ages of risk: children exhibited the highest risk (5.37 yr.), followed by senior women (74.4 yr.) and adult women in reproductive age (32.64 yr.). Although our results showed there is a widespread risk, this problem could be solved by buying whole fish instead of processed fish in order to avoid involuntary shark meat consumption.

Keywords: methylmercury; health risk; shark meat; women; Mexico; risk smooth function; risk surface; stability; Gaussian curvature.

Resumen

La preocupación por los riesgos a la salud derivados del consumo no intencional de carne de tiburón surgió al encontrar altas concentraciones de metilmercurio (MeHg) y hasta 60 % de substitución de carne de pescado por carne de tiburón en muestras del principal mercado de mayoreo de la Ciudad de México. En este estudio se calculó el riesgo para las mujeres por consumo no intencional de carne de tiburón. El coeficiente de riesgo (RQ) para diferentes edades fue calculado usando tres concentraciones de MeHg y la exposición, de los datos de encuestas realizadas en varios mercados del área metropolitana (MXC-MA). El coeficiente de riesgo para distintos grupos de edad se calculó usando 3 concentraciones de metilmercurio (baja, media, alta) y la exposición se calculó con los datos de investigaciones. El RQ fue menor que 1 cuando se calculó con la concentración más baja de MeHg, pero fue mayor a 1 con mayores concentraciones (RQ promedio = 1,44). Los cambios del riesgo en las diferentes etapas de vida por las concentraciones de MeHg se analizaron usando métodos numéricos y analíticos, obteniendo una función suave estable, lo que se demostró con el análisis de los campos asociados a los vectores del riesgo; así, pequeños errores en los datos (incertidumbre) no cambian el comportamiento del proceso. La superficie de riesgo asociada tiene una curvatura no positiva Gaussiana y los puntos donde la curvatura es cero determinan las edades en las que el riesgo es más alto: niñas (5,37 años) seguidas de mujeres mayores (74,4 años) y aquellas en edad reproductiva (32,64 años). Aunque estos resultados muestran un riesgo generalizado, este problema se puede resolver comprando pescados enteros y evitando carne procesada cuya fuente no se pueda identificar.

Palabras clave: metilmercúrio; risco para a saúde; carne de tubarão; mulheres; México; função suave de risco; superfície de risco; estabilidade; curvatura gaussiana.

Resumo

A preocupação com os riscos para a saúde devido ao consumo de carne de tubarão surgiu em dois estudos anteriores, nos quais a carne de tubarão apresentava altas concentrações de metilmercúrio (MeHg) e até 60 % de substituição de carne de peixe por carne de tubarão em amostras do principal mercado grossista da Cidade do México. Neste estudo foi calculado o risco para a saúde das mulheres pelo consumo não intencional de carne de tubarão. As amostras foram obtidas no principal mercado grossista da Cidade do México e foram realizados inquéritos sobre hábitos de consumo em vários mercados da região metropolitana da Cidade (MXC-MA). O quociente de risco (RQ) para diferentes faixas etárias foi calculado usando três concentrações de metilmercúrio (menor, média e alta) e a exposição foi calculada com os dados dos inquéritos. O RQ foi menor que 1 quando calculado com a menor concentração de MeHg, mas bem acima de 1 com maiores concentrações (média de RQ=1,44). Alterações de risco com o estágio de vida devido à concentração de MeHg foram analisadas por métodos numéricos e analíticos, obtendo-se uma função suave e estável, o que foi demonstrado com a análise dos campos associados aos vetores de risco; assim, pequenos erros nos dados (incerteza) não alteram o comportamento do processo. A superfície de risco associada possui uma curvatura não positiva gaussiana e os pontos em que essa curvatura é zero determinam as idades em que o risco é mais alto: as crianças exibiram o maior (5,37 anos), seguidas pelas idosas (74,4 anos) e mulheres em idade reprodutiva (32,64 anos). Embora esses resultados mostrem um risco generalizado, este problema pode ser resolvido comprando peixes inteiros e evitando carne processada cuja origem não possa ser identificada.

Palavras-chave: metilmercurio; risco à saúde; carne de tubarão; mulheres; México; função suave de risco; superfície de risco; estabilidade; curvatura gaussiana.

INTRODUCTION

Mercury pollution comes from different sources; some are natural but those of anthropogenic origin are the most important. Hg is released by the degassing of the earth's crust, volcanic activity, and the erosion of rocks and soils. On the other hand, anthropogenic sources like mining and smelting, the use of hydrocarbons and coal for energy generation, and the incineration of solid waste have significantly increased the concentration of Hg in the environment.[1] The intake of fish with high concentrations of methylmercury can cause damage to the central nervous system, as seen in Minamata, Japan. Symptoms of this syndrome include impaired equilibrium, paraesthesia, impaired vision and hearing, generalized weakness, and, in extreme cases, paralysis and death.[2]

Furthermore, fish methylmercury concentrations increase with size and trophic level; therefore, predators, such as sharks, are expected to have the highest concentrations.[3] Previous studies in Mexico have reported methylmercury concentrations ranging from 0.27 to 3.33 ppm in commercial sharks and the potential substitution of fish meat with shark meat in edible products.[4] This practice occurs because there are no morphological features that can help to differentiate shark's meat from other products since the former are purchased already processed (without fins or head, filleted, smoked, or minced).

One hundred and four shark species had been reported in Mexico; 55 inhabit the Pacific Ocean, and the others are distributed in the Gulf of Mexico and the Caribbean.[5] Their economic importance is based on their meat and fins. One of the main distribution sites and the biggest wholesale market for these products in Mexico City (CDMX) is the Central de Abasto de Pescados y Mariscos market, where fish meat is sold fresh, minced, dried-salted (like cod), smoked, in pieces, and filleted.

Also, shark fins and other dried products are exported to Asia, where they are sold for making soup.[6]

To find out the frequency of the substitution of fish meat with shark meat, in 2018[7] Elizalde collected 53 fish samples in different presentations (meat for ceviche, for fish broth, for quesadillas, breaded fillet, smoked fillet, and inexpensive steaks of sea bass, Nile white fish, catfish, etc.) at the fish and seafood market of Central de Abasto; their identity was analysed through Polymerase Chain Reaction (PCR) using universal shark oligonucleotides: 60.37% tested positive for the replacement with shark species meat.

When applying the EPA's hazard coefficient power model[8] to the previous study,[7] a high risk for the population of Mexico City's metropolitan area (MXC-MA) was obtained (RQ > 1). A less biased approach to risk assessment uses uncertainty analyses to evaluate the degree of confidence that can be assigned to the risk estimation. Still, mathematically, when studying some natural phenomenon, such as pollution and its effects on the biota and humans, it must be understood that observations are subject to errors. Trying to formalize this phenomenon employing a formula should be understood as an approximation to reality.[9] Therefore, the purpose of this study was to calculate the health risk for women from MXC-MA due to an unintentional exposure to methylmercury through the consumption of shark meat using numerical and qualitative methods.

MATERIALS AND METHODS

1. Survey Design

In order to identify the population's characteristics and consumption habits (quantity and frequency of fish products consumption, non-probabilistic sampling, also known as discretionary sampling,[10] was performed. To this end, a questionnaire was prepared that included the participant's and her family members' age, gender, weight, and dietary habits, such as frequency of fish consumption, portion size (weight in grams), and species presentation. The survey followed the ethical principles of the WMA Declaration of Helsinki in that only adult people responded to the questionnaire—anonymously to protect their privacy; they gave their consent to the data being used for the purpose of this work.

The survey application sites were selected markets in various municipalities of *Estado de México (Ixtapaluca and Nezahualcoyotl*) and Mexico City (*Iztapalapa, Xochimilco, Iztacalco, Coyoacan, and Benito Juarez*), all of which are part of MXC-MA.

2. Dose Modeling

The lifetime average daily dose (LADD) or chronic daily intake (CDI) is a function of the average concentration of pollutants and the intake rate. The parameters used (body weight, age, sex, consumption, and frequency) were obtained from the abovementioned surveys. Additionally, the average life expectancy of Mexican female consumers (78 years) was obtained from national statistics available online.[11]

The total dose and the average daily dose (ADD) were calculated using the following equations[12]:

Total dose = (concentration) (ingestion) (duration) (frequency) (1)

Average daily dose = (total dose) / (bodyweight x life expectancy) (mg/kg-day) (2)

The concentrations of methylmercury in fish were obtained from the report[13] of a study conducted by the Mexican government, which reported the following MeHg concentrations in shark meat samples taken from 2009 to 2012 at 10 fishing ports in the Gulf of Mexico and on the Pacific Ocean coast: minimum = 0.27 mg/kg, average = 2.43 mg/kg, and maximum = 3.33 mg/kg.

The quantitative health risk assessment of non-carcinogenic agents is based on a reference dose that is an estimate (with uncertainty spanning an order of magnitude of 10) of daily exposure, where sensitive human subgroups are included. The chosen level was a lower limit of reference dose of 95% at a 5% effect level obtained by applying a K-power model (K > 1) to dose-response data based on previous studies conducted in the Faroe Islands.[14] The RfD is 0.0001 mg/kg/day for women of reproductive age, children, and older adults and 0.0003 mg/kg/day for the adult population.

3. Calculation of Risk From Unintentional Consumption of Shark Mmeat

To calculate the weekly and monthly consumption of fish (g) in each age group, the following equation of the United States Environmental Protection Agency[8] was used:

$$CR_{mm} = \frac{CR_{\lim} \times T_{ap}}{MS} \quad (3)$$

where:

CR_{mm} = Maximum consumption allowed in fish portion (meals/month)

CR_{lim} = Maximum consumption allowed in fish portion (kg/day)

T_{ap} = Average period (365.25 days / 12 months = 30.44 days/month)

MS = Fish portion weight

On the other hand, in order to determine the maximum consumption of fish portions the sensitive population should be allowed, expressed in kilograms per day we used the following formula and the information on women of reproductive age from the abovementioned survey:

$$CR_{\mathrm{lim}} = \frac{RfD \times BW}{C_{\mathrm{m}}} \quad (4)$$

where:

BW = Body weight of the consumer (kg)

C_m = Concentration of mercury in fish species (mg/kg)

RfD = reference dose-day of 0.0001 mg/kg for the developing fetus and women of childbearing age.[15]

4. Health Risk Characterization

For the health risk analysis, the hazard or risk coefficient was calculated according to the following expression[1]:

$$Risk\ coefficient = \frac{Exposure}{RfD} \quad (5)$$

which is equal to the risk (R).

The exposure (E) was obtained with the following equation[16]:

$$E = \frac{C \times IR \times EF}{BW} \quad (6)$$

where:

C= Concentration of the pollutant in fish (mg/kg/day)

IR= Intake rate (mg)

EF= Exposure factor (unitless)

BW= Body weight (kg)

The exposure factor allowed us to calculate the dose of pollutant ingested. However, we compared it with the administered dose used in experimental animal studies designed to obtain the dose-response relationship. We calculated the exposure factor using Equation 7 below for the different groups divided by age.[16] According to Elizalde,[7] the genetics analyses showed a 60.37% average substitution of fish meat with shark meat.

$$FE = \frac{(exposure \in days/weeks)(52\,weeks/year)(exposureyears)}{(yearsexposure)(365\,days/years)} \quad (7)$$

According to Evans et al.[12], a value of R < 1 represents an acceptable risk.

5. Numerical and Qualitative Risk Analysis

Life stages were conveniently reparameterized to adapt them to a [1, 5] interval. It should be noted that according to[17] fish consumption begins after the first year of life. Therefore, women were divided into four life stages according to their age: 1-6 (babies), 6-12 (girls), 12-60 (women), and 60-90 (senior).

We devised a global function $R(t, c)$ with the stage and concentration variables (t, c) that estimates the risk in the domain D = [1,5] x [0.2,3.5]. We obtained the following:

$$R(t, c) = -0.3377c + 0.0017t^4 + (4.3781c - 0.0335)t^3 + (-20.047c + 0.1489)t^2 + (37.49c - 2706)t + (-21.483c + 0.1516)$$

For any fixed given concentration value c, the function $R_c(t)$ has a corresponding graph in the (t, R) plane, as will be shown in the results section. The associated *Risk Surface* is a Hadamard two-dimensional surface embedded in the three-dimensional Euclidean space. The points where the Gaussian curvature vanishes determine the critical ages of the process. A standard analysis[18] was applied to look for equilibrium points and closed orbits of the associated Risk vector field in the domain D considered.

RESULTS

1. Survey

Seven hundred and seventy-seven people responded to the survey, which provided information about a total of 1,976 subjects. The results showed that men eat fish more frequently and in greater quantity (262.60 g/month), followed by women and seniors (194 and 193 g/month respectively) (Table 1). Moreover, the most preferred products were fish fillets followed by fish nuggets and other presentation options (Table 2).

Table 1. Surveyed population (Mexico City´s Metropolitan Area) characteristics and consumption habits

Group	Number surveyed	Age (years)	Average Bodyweight (kg)	Average Intake rate (g)	Average Fish portions consumed per month
Children	421	1-12	34.94	188.17	1.3
Women	613	12-60	61.04	194.30	2.3
Men	546	12-60	73.44	262.60	2.6
Senior	396	60-100	68.85	193.38	2.1

Table 2. Fish product preferences of people from different municipalities of Mexico City´s Metropolitan Area

Product	Adult population preference	Sensitive population preference
Fish fillet (g)	56%	31%
Fish Meat for ceviche (g)	12%	16%
Fish Meat for fish broth (g)	10%	17%
Smoked fish (g)	8%	18%
Fish nuggets	14%	18%

2. Dose Modeling

Girls were the age group at highest risk since their calculated ADDs (0.003 to 0.032 mg/kg) were above the RfD regardless of the MeHg concentration considered. Women of reproductive age exposed to the minimum MeHg dose did not exceed the RfD. However, at the average and maximum MeHg concentrations (2.3 and 3.33 mg/kg respectively) the daily dose increased enough to exceed the RfD by 14 and 19 times respectively.

For senior women, the ADD had a similar behavior to that of women: an ADD equal to the RfD when the lowest MeHg concentration was considered, but 12 to 17 times higher when the average and maximum MeHg concentrations respectively were taken into account.

The above results show that people are exposed to MeHg due to their daily fish consumption habits, which means that women are at risk from the unintentional consumption of shark meat, even when low concentrations of methylmercury are considered.

3. Maximum Consumption Allowed of Shark Meat

Considering the results of the genetic analysis published by[7], where a 60.37% substitution of fish meat for shark meat was recorded, the maximum consumption allowed for all population groups was recalculated with regard to the minimum, average, and maximum concentrations of methylmercury in shark meat. On average, for the sensitive population and for all products, it amounted to 0.3 servings/month (Table 4), i.e. one serving every three months.

Table 4. Allowed portion of fish for the sensitive population (food/month)

Fishing product	Fish portion (g)
Fish fillet	0.286
Smoked fish	0.392
Fish broth	0.256
Ceviche	0.248
Nuggets	0.267

4. Risk Coefficient

With the low methylmercury concentration and the 60.37% substitution of fish for shark meat, the risk coefficient is below 1, which means that, in general, the unintentional consumption of shark meat is acceptable. However, for 1-to-6–year-old children, the calculated value (0.785) approaches 1, which may be of concern since the lowest MeHg concentration is easily exceeded. The risk coefficient for medium and high MeHg concentrations was always well above 1, which means that fish consumption habits may increase the health risks for the entire population.

If people cannot avoid consuming shark meat, the alternative for lowering this health risk would be to reduce the portion size and the frequency of consumption.

5. The Scalar Field of Risk

As previously discussed, life stages were conveniently reparameterized to a [1, 5] interval.

Babies and 1-6 year olds in the [1, 2] interval

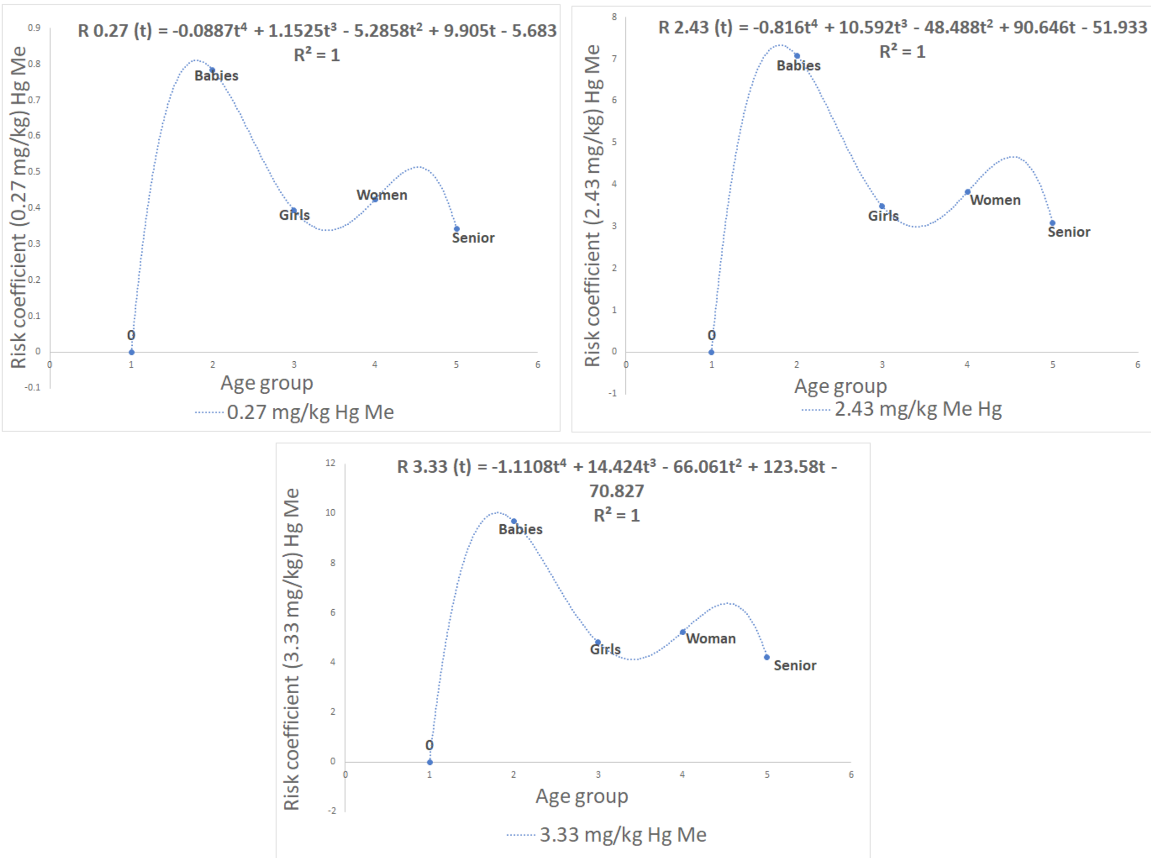
Girls 6 to 12 years of age in the [2, 3] interval

Women 12 to 60 years of age in the [3, 4] interval

Senior women 60 to 90] years of age in the [4, 5] interval

With these conditions, three fourth-degree polynomials were obtained for the stage and Risk variables using the Interpolation method[9], which soften the polygonal graphs of given life stage intervals for each methylmercury concentration: 0.3, 2.7, 3.7 mg / kg respectively (Fig. 1).

Figure 1. Risk coefficients for women in different life stages according to three methylmercury concentrations



That is, if we define the main variables as the stage variable and as the concentration variable, we can obtain the following particular polynomials:

Concentration	Associated fourth-degree polynomials of the variable t
[0.27] MeHg	R0.27 (t) = - 0.0887t4 + 1.1525t3 - 5.2858t2 + 9.905t - 5.683
[2.43] MeHg	R2.43 (t) = - 0.816t4 + 10.592t3 - 48.489t2 + 90.646t - 51.933
[3.33] MeHg	R3.33 (t) = - 1.1108t4 + 14.424t3 - 66.061t2 + 123.58t - 70.827

As a global function $R(t,c)$ of the life stage and concentration variables (t,c) for estimating the risk in the $D = [1,5] \times [0.2,3.5]$ domain, where for each concentration value c there is a polynomial relationship that only depends on the life-stage variable t, we propose the following:

$$R(t,c) = f_4(c)\, t^4 + f_3(c)\, t^3 + f_2(c)\, t^2 + f_1(c)\, t + f_0(c)$$

where the functions $f_k(c)$ were obtained by the linear regression method according to the conditions of the obtained polynomials:

$f_4(0.27) = -0.08887, f_4(2.43) = -0.816, f_4(3.33) = -1.1108$

$f_3(0.27) = 1.1525, f_3(2.43) = 10.592, f_3(3.33) = 14.424$

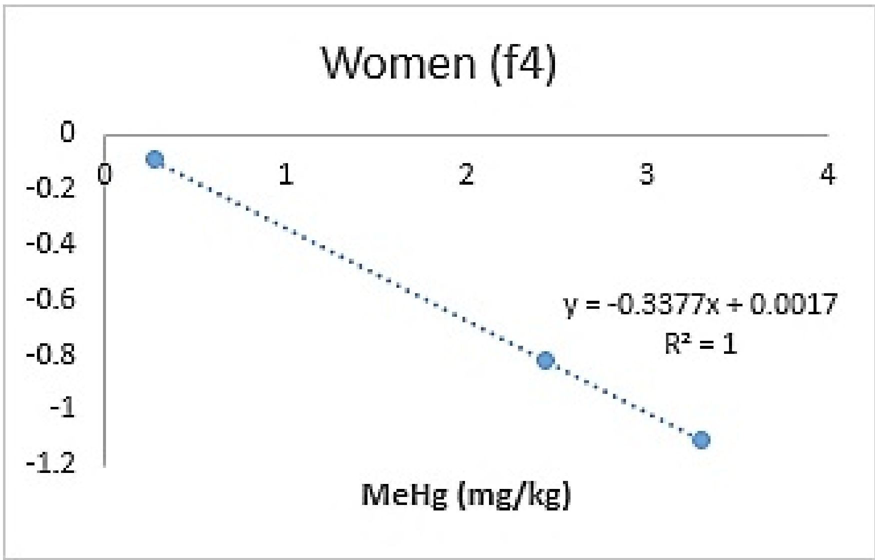
$f_2(0.27) = -5.2858, f_2(2.43) = -48.489, f_2(3.33) = -66.061...$

The first function $f_4(c)$ was obtained using variables x = c and y in Excel, as shown in figure 2.

Therefore, for the variable c we have the following linear relationship:

$$f_4(c) = -0.3377c + 0.0017$$

Figure 2. First coefficient function for the Risk polynomial



The other linear functions were obtained similarly for the universal variables x and.

Thus, the searched-for scalar field for estimating the risk of methylmercury intake in region D becomes:

$$R(t,c) = -0.3377c + 0.0017t^4 + (4.3781c - 0.0335)t^3 + (-20.047c + 0.1489)t^2 + (37.49c - 2706)t + (-21.483c+0.1516)$$

The associated so-called Risk Surface is the graph corresponding to $R(t,c)$ and it is a two-dimensional surface embedded in the three-dimensional Euclidean space, as shown in Figure 3A.

For any given fixed concentration value c, the corresponding function $R(t,c)$ generates a graph in the (t, R) plane, as shown by means of the interpolation process (Fig. 3B).

We calculated the risk gradient vector field of the risk function and obtained the following:

$$\nabla R(t,c) = (-21.483 + 37.49t - 20.047t^2 + 4.3781t^3 - 0.3377t^4, -0.27 + 37.49c + 2(0.1439-20.047c)t + 3(-0.0335+4.3781c)t^2 + 4(0.0017 - 0.3377c)t^3)$$

Standard analysis[18] shows that the risk vector field does not have either equilibrium points or closed orbits in region D, as shown in Figure 4. Therefore, the risk function does not have critical points in the considered domain. The same figure shows horizontal bands in the flow of the risk vector field:, these bands are understood to represent the ages where the risk is significant. These ages were calculated later using geometric methods.

Consequently, the risk field $R(t,c)$ is a *Morse function* in the compact set D since the whole set is regular and, according to,[19] it is a stable function. That is, under small soft deformations of the risk function R (t, c) in D, the

Figure 3A. Women´s risk surface; Figure 3B. Graph of function R_c (t) representing the unintentional exposure to methylmercury

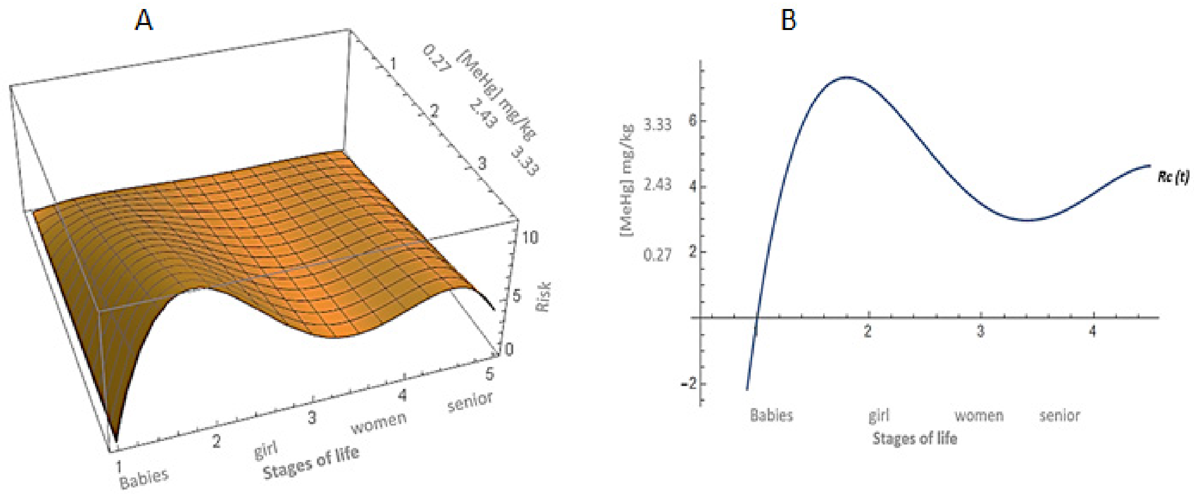
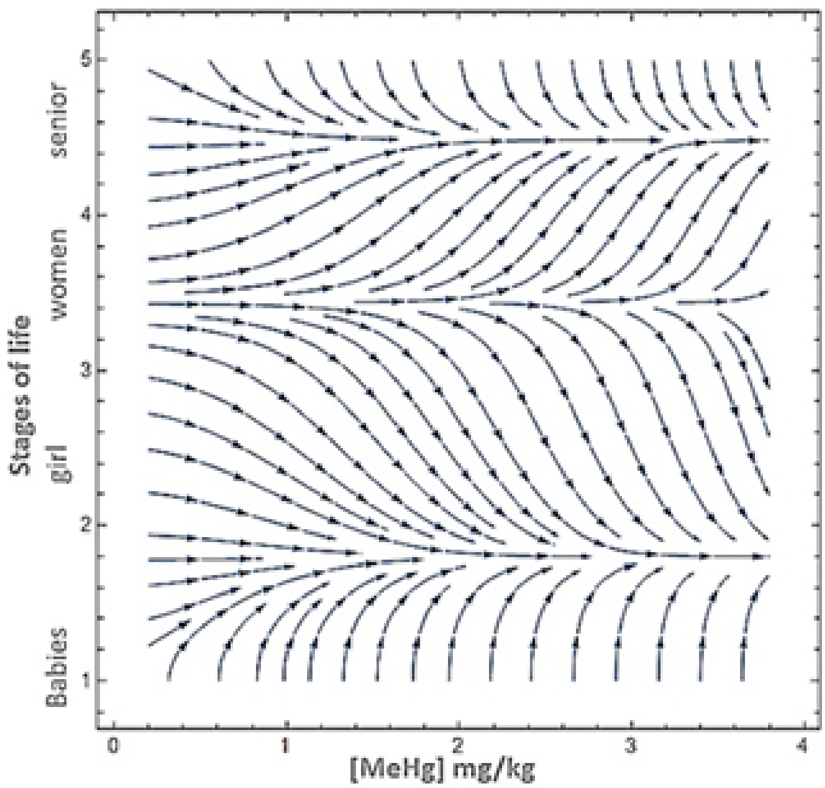


Figure 4. Risk vector field for the unintentional consumption of shark meat in the case of women



deformed function obtained has the same qualitative behavior. In other words, any small error in obtaining the data would lead to a new risk relationship with the same characteristics.

On the other hand, we defined the *Critical Risk Region* inside domain D as the subset

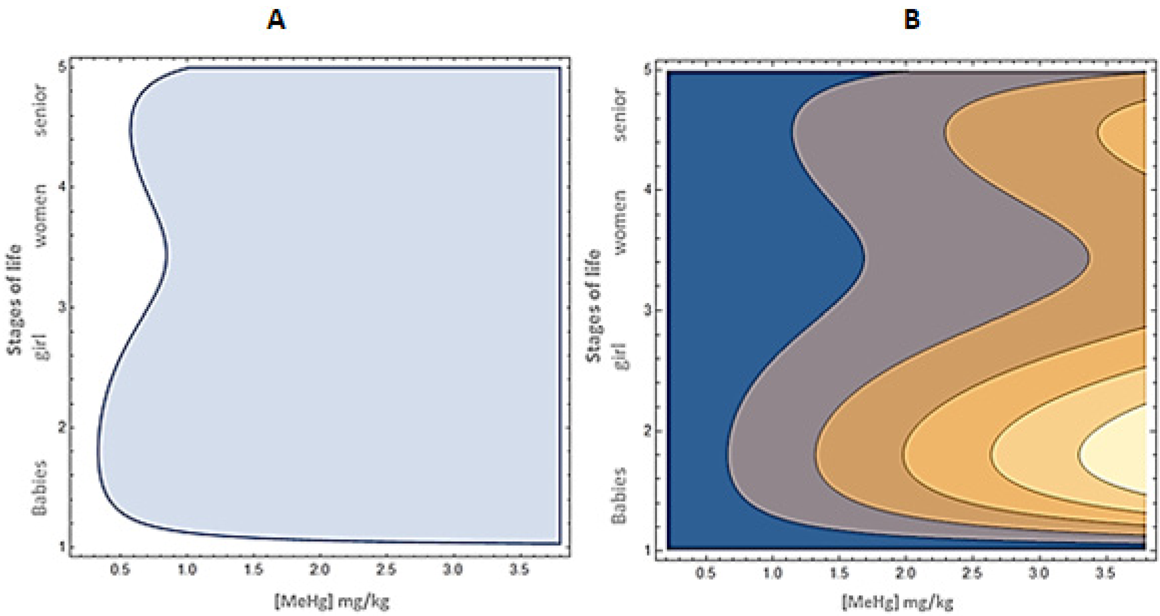
$$R(D) = \{(t,c) \vee - 0.3377c + 0.0017t^4 + (4.3781c - 0.0335)t^3 + (-20.047c + 0.1489)t^2 + (37.49c - 2706)t + (-21.483c + 0.1516) \geq 1\}$$

represented as a colored contour in Figure 5A, which shows a big risk region, as expected from the data in Table 3.

Table 3. Average daily methylmercury (MeHg) dose and reference dose for different age groups

Age group	Average daily dose			Reference dose
	[0.27 mg/kg] MeHg	[2.43 mg/kg] MeHg	[3.33 mg/kg] MeHg	[mg/kg] MeHg
Women	0.0001	0.0014	0.0019	0.0001
Girls	0.0003	0.0023	0.0032	0.0001
Senior Women	0.0001	0.0012	0.0017	0.0001

Figure 5A. Women´s critical risk region R(D); Figure 5B. Risk level curves due to unintentional shark meat consumption. Color represents the magnitude of the risk; the darker the color, the lower the risk



The contour lines of the scalar risk field $R(t,c)$ are displayed in domain D in Figure 5B. The darker region indicates less risk, while the lighter region indicates higher risk.

The average value of the risk in domain D is calculated by applying the following formula[20], which represents a big risk in the whole set D.

$$R^* = \frac{1}{Area(D)} \int_1^5 dc \int_{0.2}^{3.5} [(-0.3377c + 0.0017)t^4 + (4.3781c - 0.0335)t^3$$

$$+ (-20.047c + 0.1439)t^2 + (37.49c - 0.27)t + (-21.483c + 0.1516)]dt$$

$$= \frac{18.99}{13.2} = 1.4389$$

We used the Gaussian curvature function K(t, c)[21] of the *Risk Surface* to determine the critical ages of the global risk function. A straightforward calculation shows the sign of such a curvature function is entirely determined by the reduced function:

$$k(t,c) = -(37.49 - 40.094t + 13.1343t^2 - 1.3508t^3)^2$$

which means that the *Risk Surface* is a non-positive Gaussian curvature surface (Hadamard surface). The points where the Gaussian curvature is zero determine the critical ages of the risk function and are obtained by solving the following equation:

$$0 = -(37.49 - 40.094t + 13.1343t^2 - 1.3508t^3)^2$$

The solutions are all real numbers:

$$t = 1.79 \text{ (5.37 years)}$$

$$t = 3.43 \text{ (32.64 years)}$$

$$t = 4.48 \text{ (74.4 years)}$$

and they correspond to the horizontal lines -integral solutions- of the risk vector field.

DISCUSSION

The sensitive population prefers to consume processed fish products like fish fillets (31%), fish nuggets (18%), ceviche (17%), fish broth, and smoked fish (16%). A processed fish product that is difficult to identify and that can be easily substituted with shark meat increases the risk of MeHg contamination, hence the importance of this study.

To analyze the health risk due to the unintentional consumption of shark meat, it is essential to point out that sharks tend to accumulate more mercury because they are top predators[22] and have a slow growth rate, Therefore, they have a long period of exposure to pollutants,[23] hence the need to conduct more risk studies.

The average risk calculated for women using the EPA's MeHg reference dose (RfD) and critical risk region (Figure 5A) was 1.4329, which represents an unacceptable health risk (> 1) and a high probability that some toxic or adverse health effect will ensue. The analyses also showed that the age of maximum risk in females is 5.37 years for any concentration of MeHg, followed by a second stage of risk during a reproductive age of 32.66 years, and a third stage at 74.4 years of age, which is close to the average life expectancy of Mexican women (78 years). These results match those of another study[24] showing that women are at higher risk when they consume products such as shark meat as part of their diet, mainly during childhood, the reproductive age period, and in the latter part of their life.

Another study[25] recommended that pregnant women, infants, and children under three years old should avoid eating shark meat, and Clarkson and Magos[26] mentioned that the susceptibility to neurotoxicity due to MeHg is related to gender—-this however has not been widely studied and the results available are inconclusive. In the poisoning event that occurred in Iraq as a result of the consumption of grain contaminated with a mercurial fungicide, women were affected more than men when those exposed were adults.

The results obtained by Rainmann et al.[27] match the risk curves of this study, where the exposure interval is higher in women—- mainly in the reproductive age period and during infancy. Consequently, children require special care since their nervous system is the main target of MeHg effects. As a precautionary measure, USEPA[8] set an acceptable level of 0.5 mg/kg of methylmercury for fish products.

Another study[22] reached the same conclusion as this work since it considered that fetuses and young children are especially susceptible to exposure to MeHg; therefore, fertile women and pregnant women are a group of interest given the potential of transfer of MeHg to the fetus. Also, a study carried out in Mazatlán—a Mexican coastal city—-concluded that, in general, children had the highest risk of exposure to MeHg, and that 97% of the population was at risk due to their consumption habits.[28] Children who eat greater quantities of fish products than adults relative to their body weight may have a greater susceptibility to pollutants combined with less ability to detoxify them. In a study of French children, the authors found a negative weight correlation.[29] In this context, portions greater than 100 g and the number of days of consumption are the most critical factors in MeHg exposure; even if the MeHg content is low in fishery products (e.g., below the Mexican regulatory level), there is a risk if the frequency and the quantity of ingested fishery products are considerable.

It should be mentioned that this risk depends on the consumption habits (frequency of ingestion and food preparation), age and size of the consumer, and the product itself. Additionally, the magnitude of heavy metal bioaccumulation in fish tissues is influenced by biotic and abiotic factors, such as fish habitat, chemical form of the metal, water temperature, pH, concentration of dissolved oxygen, water transparency, and fish age, sex body mass, and physiological conditions.[30] Therefore, a more precise risk assessment must consider all these factors.

Mexican legislation sets the limit of MeHg in fishery products, including shark meat, at 0.5 mg/kg wet weight.[31] This limit, however, does not necessarily provide a dietary advice to reduce exposure to MeHg, which highlights the need for risk characterization studies.

An additional issue of concern is the consumption of large portions of shark meat during a short period, which is similar to an acute exposure. This problem is not usually contemplated when preparing fishing notices,[14] and poses an unestimated risk to particularly susceptible people such as children, older adults, pregnant women, and lactating women.[22] Hence, future research is needed to assess the effects caused by short-term exposure and which could be substantially different from those of long-term exposure at low levels.[32,33]

Based on the results of the risk coefficient, the consumption of fish-substituting shark meat results in an unacceptable risk at the average and maximum MeHg concentrations for all age groups, and acceptable risk at the low MeHg concentration for all age groups except babies (0.785). Therefore, in the analyzed sample there is a high probability of suffering deleterious health effects. Hence, if women want to consume fish products, they should buy whole fish to avoid this substitution.

The most significant uncertainty in the risk estimation of this work is the lack of a direct quantification of MeHg concentrations in the same fish samples that were genetically analyzed. However, this is an acceptable approximation for making decision in the field of health risk prevention since the data used was obtained from samples taken during three years in 10 of the most important fishing ports in Mexico, which provides a reasonable estimate of the concentrations of MeHg in fish muscle sold in Mexico City's Metropolitan Area.

The mathematical analysis in this study was carried out using the classical interpolation method[9] to analyze the uncertainties and to obtain a risk function. The result was a stable function[19] that suggests that any error in obtaining the data (uncertainties) will lead to a risk correlation with the same characteristics (similar results). Thus, we can conclude that the results of the risk coefficient have a high degree of truthfulness.

This study analyzed the consumption habits of a sample of the population in Mexico City's Metropolitan Area, and showed that with a 60.3% substitution of fish meat with shark meat, the overall risk coefficient for women was 1.4389. From this value it can be inferred that women are chronically exposed—even though the population as a whole does not often eat fish. Futhermore, this risk coefficient implies there is a health risk for consumers. Therefore, in order to avoid consuming shark meat with large concentrations of methylmercury, we suggest restricting the consumption of fish products to smaller portions and at a lower frequency and, more importantly, to buy fish in whole to facilitate the correct identification of the product.

ACKNOWLEDGMENTS

This work was supported by the Universidad Autónoma Metropolitana through the Research Project "Indicadores de integridad ecológica y salud ambiental" and the Energy and Environment postgraduate program (PEMA), and by the Consejo Nacional de Ciencia y Tecnología (CONACYT, Mexico) through M. Sc. Scholarship No. 659582.

REFERENCES

1. Lu X, Li L, Wang L, Lei K, Huamg J, Zhai Y. Contamination assessment of mercury and arsenic in roadway dust from Baoji, China. Atmospheric Environment. 2009; 43(15), 2489-2496.

2. Takeuchi TMH. A Pathological Study of Minamata Disease in Japan. Acta Neuropathologica; 1962.

3. Maz-Courrau A, López-Vera C, Galván-Magaña F, Escobar-Sánchez O, Rosíles-Martínez R, Sanjuán-Muñoz A. Bioaccumulation and biomagnification of total mercury in four exploited shark species in the Baja California Peninsula, Mexico. Bull Environ Contam Toxicol. 88:129–134; 2012.

4. Ramírez-Romero P, Ramírez-Islas Padilla-Torres JE, Trejo JG, Arellano-López I. Evaluación del riesgo a la salud por exposición a mercurio debido al consumo de peces marinos en comunidades de pescadores. Informe final de proyecto. UAMI/INE; 2012. [Citado el 27 de octubre de 2019] Disponible en: https://www.researchgate.net/publication/344549536_Evaluacion_del_riesgo_a_la_salud_por_exposicion_a_mercurio_debido_al_consumo_de_peces_marinos_en_comunidades_de_pescadores.

5. Espinosa-Pérez H, JL Castro-Aguirre, and L Huidobro Campos. "Listados faunísticos de México." *IX. Catálogo sistemático de tiburones (Elasmobranchii: Selachimorpha). Instituto de Biología UNAM. DF, México*; 2004. [consultado el 8 de octubre de 2020] Disponible en: https://biblat.unam.mx/es/revista/listados-faunisticos-de-mexico.

6. Castellanos-Betancourt JC, Ramírez-Santiago CE, Castillo-Géniz JL. Catálogo de aletas, tronchos y cabezas de tiburones en el Pacífico Mexicano. *INAPESCA. Primera edición*. Distrito Federal, México; 2013. [Citado el 5 de abril de 2018] Disponible en: https://www.inapesca.gob.mx/portal/Publicaciones/Catalogos/2013-Castellanos-Betancourt-etalCatalogo_Tiburones.pdf?download.

7. Elizalde-Ramírez LG. Identificación genética de tiburones comercializados en la ciudad de México como carne de pescado y evaluación del riesgo a la salud por su consumo. Tesis de Maestría en Ciencias (Energía y Medio Ambiente). Universidad Autónoma Metropolitana-Iztapalapa (UAMI); 2018. [Citado el 10 de enero de2019] Disponible en: https://www.researchgate.net/publication/345036186_UNIVERSIDAD_AUTONOMA_METROPOLITANA_-IZTAPALAPA_DIVISION_DE_CIENCIAS_BASICAS_E_INGENIERIA_Tesis_que_presenta.

8. Food and Drug Administration. Fish and fishery products hazards and controls guidance. US Department of Health and Human Services Food and Drug Administration Center for Food Safety and Applied Nutrition, 2011. [Citado el 3 de octubre de 2019] Disponible en: https://www.fda.gov/media/80637/download.

9. Reyes-Victoria J G. Cálculo Diferencial para las Ciencias naturales. México: Trillas; 1996.

10. Méndez A. Metodologías y Técnicas de Investigación aplicadas a la Comunicación. Maracaibo, Venezuela: Colección Textos Universitarios de la Universidad del Zulia; 2007. [Citado el 12 de mayo de 2018] Disponible en: https://metodouces.files.wordpress.com/2015/09/comunicacion_mendez.pdf.

11. Instituto Nacional de Estadística y Geografía (INEGI). Cuéntame. Obtenido de Esperanza de vida. [Citado el 13 de septiembre de 2018] Disponible en: http://cuentame.inegi.org.mx/poblacion/esperanza.aspx?tema=P.

12. Evans JF, Fernández-Bremauntz A, Gavilán-García A, Ize-Lema I, Martínez CMA, Ramirez-Romero P, Zuk M. Introducción al análisis de riesgos ambientales. Primera edición, México: INE-SEMARNAT; 2003.

13. Ramírez RP, Ramírez-Islas M, Padilla-Torres JE, Trejo Ramírez JG, Solórzano Ochoa G, de la Rosa Pérez A et ál. Selección y muestreo en peces de alto consumo humano en México con el objeto de determinar el contenido de mercurio (Hg). México: UAM/INE. 2012.

14. United States Environmental Protection Agency (USEPA). Risk Assessment Guidance for Superfund: Volume III – Part A, Process for Conducting Probabilistic Risk Assessment. Chapter 3 Using Probabilistic Analysis in Human Health Assessment. US Environmental Protection Agency, Washinton DC, USA; 2001.

15. United States Environmental Protection Agency (USEPA). Water quality criterion for the protection of human health: Methylmercury. Office of Science and Technology, Office of Water, United States Environmental Protection Agency. Methylmercury (MeHg). Washinton DC, USA; 2001.

16. Sardiñas-Peña O, Trujillo C, García-Melián M, Fernández-Novo M. Evaluación de riesgos para la salud por exposición a residuos peligrosos. Rev. Cubana Hig. Epidemiol. 2001; 39(2): 144-146.

17. Penny ME, Creed-Kanashiro HM, Robert RC, Narro MR, Caulfield LE, Black RE. Effectiveness of an educational intervention delivered through the health services to improve nutrition in young children: a cluster-randomized controlled trial. Lancet. 2005; 365 (9474):1863-72.

18. Guckenheimer J, Holmes PJ. Nonlinear Oscillations Dynamical Systems and Bifurcations of Vector Fields. Applied Mathematical Sciences 42, Springer-Verlag, USA; 1983.

19. Golubitsky M, Guillemin V. Stable Mappings and Their Singularities. Graduate Texts in Mathematics 14, Springer-Verlag, USA; 1974.

20. Rudin W. Principles of Mathematical Analysis, McGraw-Hill Education, USA; 1976.

21. Dubrovin B, Novikov S, Fomenko A. Modern Geometry Methods and Applications: Part I: The Geometry of Surfaces, Transformation Groups, and Fields (Graduate Texts in Mathematics) (Pt. 1), Springer-Verlag, USA; 1984.

22. Zamora-Arellano NY, Betancourt-Lozano M, Ilizaliturri-Hernández C, García-Hernández J, Jara-Marini M, Chávez-Sánchez C et ál. Mercury Levels and Risk Implications Through Fish Consumption on the Sinaloa Coasts (Gulf of California, Northwest Mexico). Risk Analysis. 2018; 38(12):2646-2658.

23. Chavez-Sánchez MC, Álvarez-Lajonchére L, de la Parra A, Isabel M, García-Aguilar N. Advances in the culture of the Mexican bullseye puffer fish *Sphoeroides annulatus*, Jenyns (1842). Aquaculture Research. 2008; 39(7):718–730.

24. Arellano-López I. Análisis de Riesgos a la Salud por Consumo de Peces. Tesis de Licenciatura. Ingeniería ambiental: Tecnológico de Estudios Superiores del Oriente del Estado de México; 2012. [Citado 08/10/2020] Available at: https://www.researchgate.net/publication/344622849_ANALISIS_DE_RIESGOS_A_LA_SALUD_POR_CONSUMO_DE_PECES_CONTAMINADOS_CON_MERCURIO.

25. Llop S, Ibarlucea J, Sunyer J, Ballester F. Estado actual sobre la exposición alimentaria al mercurio durante el embarazo y la infancia y recomendaciones en salud pública. Gaceta Sanitaria, España, Valencia. 2013; 27(3):273–278.

26. Clarkson TW, Magos L. The toxicology of mercury and its chemical compounds. Crit Rev Toxicol. 2006; 36:609-62.

27. Rimann XL. Mercurio en pescados y su importancia en la salud. Médica de Chile. 2014; 1174-1180.

28. Zamora-Arellano N, Ruelas-Inzunza J, García-Hernández J, Ilizaliturri-Hernández CA, Betancourt-Lozano M. Linking fish consumption patterns and health risk assessment of mercury exposure in a coastal community of NW Mexico. Human and Ecological Risk Assessment. An International Journal 2017; 23(6):1505-1521.

29. Morriset T, Ramírez-Martínez A, Wesolek N, Roudot AC. Probabilistic mercury multimedia exposure assessment in small children and risk assessment. Environ Int 2013; 59:431-41.

30. Has-Schön E, Bogut I, Strelec I. Heavy metal profile in five fish species included in human diet, domiciled in the end flow of River Neretva (Croatia). Arch. Environ. Contam. Toxicol 2006; 50:545-551.

31. Diario Oficial de la Federación (DOF) Norma Oficial Mexicana NOM-242-SSA1-2009). Productos y servicios. Productos de la pesca frescos, refrigerados, congelados y procesados. Especificaciones sanitarias y métodos de prueba. [Citado el 21 de abril de 2018] Disponible en: http://extwprlegs1.fao.org/docs/pdf/mex118793.pdf 9.

32. United States Environmental Protection Agency (USEPA). Handbook for Non-cancer Health Effects Evaluation. Washinton DC, USA. 2000.

33. Zahir F, Rizwi SJ, Haq SK, Khan RH. Low dose mercury toxicity and human health. Environmental Toxicology and Pharmacology 2005; 20(2):351–360.