Archives of Environmental Contamination and Toxicology
https://doi.org/10.1007/s00244-024-01054-0

Hg and Se in Muscle and Liver of Blue Shark (*Prionace glauca*) from the Entrance of the Gulf of California: An Insight to the Potential Risk to Human Health

M. E. Rechimont[1] · J. Ruelas-Inzunza[2] · F. Amezcua[3] · F. Paéz-Osuna[3,4] · J. L. Castillo-Géniz[5]

Received: 18 August 2023 / Accepted: 2 February 2024

Abstract

The blue shark (*Prionace glauca*) is the most commonly caught species of Elasmobranchii at the entrance to the Gulf of California. Although fins are the primary target commodity, the entire organism is consumed. This study examined the concentration of Hg and Se in muscle and liver to understand the antagonistic process that occurs between these two elements within the organism. Twenty-two individuals were captured at the Gulf of California inlet between September 2019 and March 2021. Hg was measured by cold vapor atomic absorption, and Se by atomic absorption spectrophotometry in a graphite furnace. All individuals studied showed higher concentrations (µg g^{-1} wet weight) of Hg (0.69) and Se (2.49) in liver than in muscle (Hg 0.63 and Se 0.08). Although the mean Hg values were below the maximum allowable limits (Hg 1.0 µg g^{-1} wet weight), the molar ratio (< 1.0) and the negative health benefit value of selenium (HBV_{Se}) in muscle show that additional caution should be taken when consuming this species. We recommend a more thorough study of the antagonistic interaction between Hg and Se to accurately assess the health risk for consumers of blue shark.

Interest in food safety has grown over the past two decades worldwide as hazardous compounds are now recognized as a global concern for human health (Cappello et al. 2018). Although seafood is a source of high-quality protein, the presence of highly toxic contaminants in their edible tissues represents a potential risk; in addition, the presence of "obesogens" and "metabolic disruptors" extended the list of chemical components with harmful effects (Maisano et al. 2016). As a pollutant in the aquatic environment, mercury (Hg) has been listed as one of "the ten leading chemicals" (O'Connor et al. 2019). The oceans play a significant role in the biogeochemical cycle of Hg (Kotnik et al. 2007); they can release it to the atmosphere or act as a sink (Mason and Sheu 2002). In addition to an increased risk to fish consumers from pollutants such as Hg, ichthyofauna may also experience harmful impacts as a result of their trophic position. There is a wide range of effects of Hg on fish, but the key impacts involve morphological changes, altered behavior and biochemical, physiological and toxicokinetic modifications (Pereira et al. 2019).

Among the most concerning pollutants present in fish meat consumed by humans is Hg. Consistent findings have indicated that, in sharks, edible muscle tissue becomes the primary target organ for Hg accumulation, mainly in its organic form, and is associated with dietary exposure (Branco et al. 2007). In the case of liver, it has been recognized as an important site for the storage of pollutants, Hg transformation, detoxification and redistribution (Berntssen et al. 2003; Régine et al. 2006; Ung et al. 2010). Once Hg enters the organism, its distribution throughout the various tissues depends on several conditions such as taxa (metabolism) and the way the metallic form interacts (Coelho and Erzini 2008; Mieiro et al. 2012).

Hg enters the marine environment naturally mainly through atmospheric transport and deposition, and it is

✉ J. Ruelas-Inzunza
jorge.ri@mazatlan.tecnm.mx

1 Posgrado en Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México, 04510 Ciudad de Mexico, Mexico

2 Instituto Tecnológico de Mazatlán, 82070 Mazatlán, Sinaloa, Mexico

3 Instituto de Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México, 82040 Mazatlán, Sinaloa, Mexico

4 El Colegio de Sinaloa, 80000 Culiacán, Sinaloa, Mexico

5 Centro Regional de Investigación Pesquera de Ensenada, Instituto Nacional de Pesca y Acuacultura, 22760 Ensenada, Baja California, Mexico

Published online: 21 February 2024

released anthropogenically through industrial and urban waste, mining and agriculture (Harris et al. 2012), causing harmful toxic effects on marine fauna (Eisler 2006). Upon entering the ocean in its inorganic form, its bioavailability increases through methylation by microbial activity (Sunderland et al. 2009), resulting in methylmercury (MeHg), which is incorporated, bioaccumulated and eventually biomagnified (Biton-Porsmoguer et al. 2022; Lavoie et al. 2013; Le Bourg et al. 2019). As a result, large and long-lived predators, including many shark species, exhibit high Hg concentrations (Schartup et al. 2019), predominantly in the methyl mercury (MeHg) form (Carvalho et al. 2014). Alongside these processes, Hg accumulation in marine top predators appears to be also driven by other physiological (e.g., metabolism, ontogeny, detoxification) (Bolea-Fernandez et al. 2019), ecological (e.g., habitat, systems productivity, food web structure, foraging depth) (Senn et al. 2010; Lavoie et al. 2013; Ferriss and Essington 2014; Le Croizier et al. 2019a, b) and physicochemical parameters (e.g., oxygen level, sea temperature) (Le Bourg et al. 2019; Schartup et al. 2019; Houssard et al. 2019). Once in the body, Hg builds up gradually, reaching high concentrations in the tissues of top predators (Frías-Espericueta et al. 2015), while, in contrast, Hg excretion is generally lower than its absorption rate. This process explains the levels of Hg close to, or above, the precautionary limits for human consumption detected in the edible muscle of Pacific predators (Escobar-Sánchez et al. 2011; Lyons and Lowe 2013), which also affects the conservation efforts of these species, especially in the viviparous ones, by the pollutant's transfer from the mother to her embryos (Lyons and Lowe 2013; Mull et al. 2013; Olin et al. 2018). However, recent studies have emphasized the relevant interaction of this metal with selenium (Se), which counteracts the toxicity of Hg in organisms (Raymond and Ralston 2009; Ralston et al. 2016) as it helps to protect the organism against Hg toxicity by balancing the sequestration and loss of Se by Hg (Kaneko and Ralston 2007). Consequently, maintaining optimal Se levels for normal synthesis and activities of essential selenoenzymes is of vital importance, especially for people exposed to MeHg (Ralston 2008). Se is both an essential and a toxic element, depending on the ingested dose (Yang et al. 2008). Either a deficiency or an excess of Se can be linked to adverse health effects depending on its chemical form (Vinceti et al. 2017, 2018). Consequently, Se is considered a vital micronutrient involved in healthy cell function, such as free radical metabolism, reproductive functions, apoptosis and immunity (Kyriakopoulos and Behne 2002; Taylor et al. 2009; Terrazas-López et al. 2019). Natural sources of Se are volcanic activity, marine salt spray and land emissions, while anthropogenic sources are nutritional by-products used in aquaculture and leachates from mining processes that, in some cases, are discharged into water bodies (Blazina et al. 2016). This is how Se, through exposure and diet, is incorporated into marine organisms and biomagnified by humans through seafood consumption (Burridge et al. 2010; Ralston et al. 2016). One of the most commercially important top predators globally is the blue shark (*Prionace glauca*), with estimated catches of ~ 10 million individuals annually worldwide (Clarke et al. 2006), it is also one of the main shark species caught in Mexico (Dulvy et al. 2014; Dent and Clarke 2015; Barreto et al. 2016). Previous studies in the Mexican North Pacific have reported high levels of Hg in muscle tissues of this species, which were above the maximum permissible limit of 1.0 μg g^{-1} wet weight (ww) for human consumption, and a low concentration of Se (Escobar-Sánchez et al. 2011). However, reports from the area near the entrance of the Gulf of California, one of the key fisheries for this species, are non-existent. The monitoring of Hg toxicity in commercial fish is of significant importance as it has a direct impact on public health and economic issues (Beltran-Pedreros et al. 2011). In this study, we assessed the concentration of Hg and Se in blue shark (*P. glauca*), based on the hypothesis that bioaccumulation will occur, and evaluated the risk–benefit trade-offs for consumers by taking into account the antagonistic interactions between Hg and Se.

Materials and Methods

Sampling

The specimens of *P. glauca* were provided by two different sources: from an oceanographic cruise coordinated by INAPESCA (National Institute of Fisheries and Aquaculture of Mexico) in the summer of 2019 (June–September); and from commercial fishing vessels arriving in the Mazatlán (Sinaloa) harbor in winter of 2021 (January–March). The fishing gear used in both cases was longlines settled during the night. The main area where sharks were captured is at the entrance of the Gulf of California (Fig. 1).

Sample Analysis

The collected specimens were frozen on board and transported to the laboratory where they were defrosted. Total weight (TW) and total length (TL) were obtained for each specimen. Sexual differentiation was recognized by the presence of claspers in males, and maturity was determined by size. Males are considered juveniles up to 183 cm TL, which is equivalent to an age of 8 years, and as adults, individuals above 184 cm (age > 8 years); and for females, individuals below 195 cm TL (age ≤ 8 years) were considered juveniles, and those above 196 cm TL were considered adults (age > 8 years) (Blanco-Parra 2003; Carrera-Fernández et al. 2010). The specimens were dissected in the laboratory to obtain liver and muscle in 25 g aliquots which were frozen

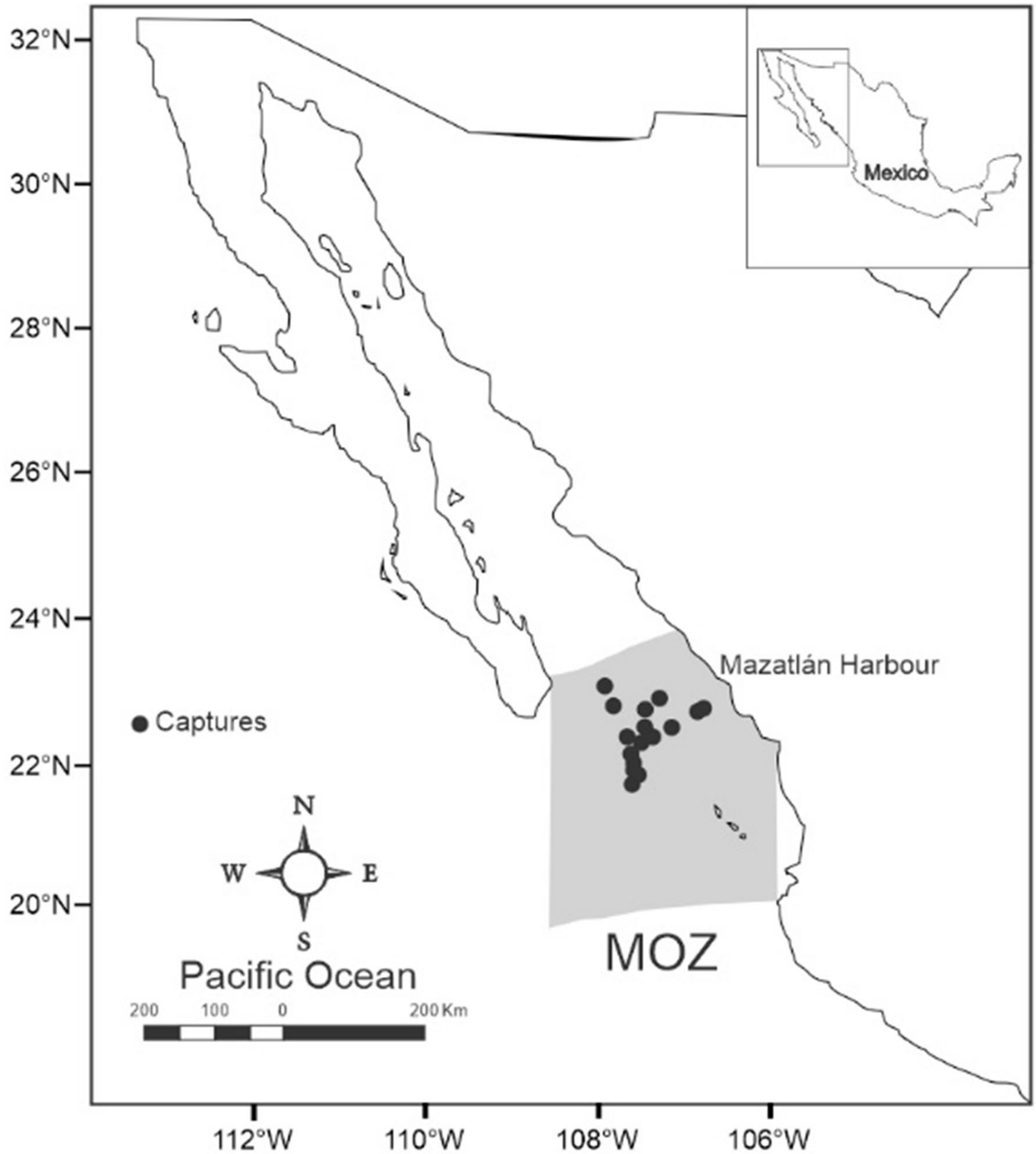


Fig. 1 Position of the site (black dots) where the blue sharks were captured at the entrance of the Gulf of California. The polygon shows the minimum oxygen zone (MOZ) redefined by Álvarez-Rodríguez (2023)

at—20 °C awaiting the analysis process. In order to avoid contamination of samples during handling and processing in the laboratory, glassware and plastic utensils were acid-washed (Moody and Lindstrom 1977). Muscle and liver samples were freeze-dried (−49 °C; 150×10^{-3} mBar; 72 h) and manually ground in an agate mortar. Homogenized powdered samples were digested with concentrated (69%) nitric acid (trace metal grade, J.T. Baker) in capped vials for 3 h at 120 °C (MESL 1997). Se was analyzed by graphite furnace atomic absorption spectrophotometry (GF-AAS) with a Zeeman correction using a model Analyst 800 instrument purchased from Perkin-Elmer (Waltham, MA, USA); the instrument was calibrated using a calibration curve from 0 to 50 ng mL^{-1}, the solution for calibration was prepared from a CertiPUR Merck Se standard solution of 1000 mg L^{-1}. Hg was measured by cold vapor atomic absorption spectrophotometry (CV-AAS) using a model 410 A instrument purchased from Buck Scientific (East Norwalk, CT, USA); the equipment was calibrated with a calibration curve from

0 to 80 ng mL^{-1}, the solution for calibration was prepared by using a Fluka Hg standard solution of 1000 mg L^{-1}.

Quality Assurance and Quality Control

Quality control of elemental analyses included blanks, duplicates, ultrapure water (milli-Q, 18.2 MΩ cm), trace metal grade acids, and reference materials. Measured concentrations of Se (0.27 ± 0.08 µg g^{-1}) and Hg (0.34 ± 0.06 µg g^{-1}) in reference material (dogfish muscle DORM-3) were consistent with the certified mean values of Se (0.346 ± 0.040 µg g^{-1}) and Hg (0.355 ± 0.056 µg g^{-1}). The precision estimated was between 2.5 and 11.6% and 5.0–10.8% for Se and Hg, respectively. The limits of detection (two times the standard deviation of a blank) were 1×10^{-5} µg g^{-1} for Se and 0.02 µg g^{-1} for Hg. Concentration units of Se and Hg are given as µg g^{-1} wet weight.

Estimation of selenium health benefit value (HBV_{Se}) and statistical analysis

Hg concentrations in shark muscle were compared against the maximum allowable limits for fishery products established in national and international legislation. (NOM 2009; Svobodová et al. 1993). The health risk to consumers of shark meat was assessed using the HBV_{Se} proposed by Ralston et al. (2016); HBV_{Se} is a risk assessment criterion based on the molar concentrations of MeHg and Se present in the fish muscle intended for consumption. In order to accurately represent the amount of physiological Se potentially provided or lost relative to sequestration by the associated Hg, the relative amount of available Se is multiplied by the total amount of Hg and Se present in the feed sample. The index is calculated by factoring in the absolute and relative molar amounts of CH3Hg and Se present as follows: HBV_{Se} = [(Se–Hg)/Se] x (Se + Hg) (Ralston et al. 2016). After checking the parameters (muscle Hg-Se and HBV_{Se} concentration) for standardization, we used the nonparametric Mann–Whitney–Wilcoxon test to evaluate the possible significant differences between these variables by sex and maturity stage (R Core Team 2022). Size, represented by TL or TW, which are also correlated with age, was contrasted with Hg and Se concentration in muscle and liver tissue by sex using simple linear models.

Results and Discussion

Hg and Se Concentration in Muscle and Liver Tissue

Among the sharks studied, adult males were predominant (Table 1), an assumed bias in longline fisheries, due to the more opportunistic diet and deeper feeding area of males, they are more likely to get caught on hooks (Tovar-Ávila et al. 2016). As for Hg concentrations in muscle, no differences were found between males and females (W = 29; $p = 0.1775$), but differences were found between juveniles and adults (W = 102; $p = 0.0004$). In the case of Se, significant differences between sexes or stages were not found (W = 59; $p = 0.4494$ for sex; W = 63; $p = 0.8718$ for stage) (Table 2). Although the mean values of Hg concentrations in age categories (adults and juveniles) and sex (females and males) of sharks (Table 2) did not exceed the international and national limits (1.0 µg g^{-1}) permitted for edible shellfish, we could observe that adults showed a mean value close to the limit (0.8 µg g^{-1}) and several maximum values above the threshold. In addition, Hg concentration values in adults were significantly different from those of juveniles, pointing to the bioaccumulation process, in which older/larger organisms (adults-older in length) exhibited considerably higher concentrations of this metal in muscle (Table 2). Fish, through the biomagnification pathway, are considered some of the most important sources of Se in the human diet (Hu et al. 2021). Although Se studies on sharks are mainly oriented to highlight its antagonism with Hg, most of them also show that the great variability of this element also depends on the combination of geoenvironmental influences and species-specific traits (Wyatt et al. 1996). The size effect may be a function of any one or diverse age-dependent parameters (Phillips 1980). It may depend on differences between the surface/volume ratio, as well as the metabolic and feeding rates of larger (older) and smaller (younger) individuals (Páez-Osuna et al. 1995). Several correlations of Hg and Se with size of specimens were found (Table 3). In the case of Hg, significant positive correlations were found between total length and Hg in muscle of males and females; on the contrary, a negative significant correlation was found between total length and Hg in liver of females. Total weight showed a positive significant correlation with Hg in muscle of males. Given the particular binding that occurs between

Table 1 Sex and stage categories, abundance, mean total weight (± S.D.), and mean total length (± S.D.), of blue shark specimens from the entrance of the Gulf of California

Categories	Number	Total weight (kg)	Total length (cm)
General	22	29.6 ± 11.6	187.8 ± 25.3
Females	6	26.3 ± 13.0	178.1 ± 21.5
Males	16	30.9 ± 11.2	191.5 ± 26.3
Juveniles	10	20.2 ± 6.2	165.6 ± 16.7
Adults	12	36.9 ± 9.7	206.4 ± 12.9
Males (juveniles)	5	19.6 ± 2.6	159.7 ± 15.4
Females (juveniles)	5	22.0 ± 7.8	171.5 ± 14.0
Males (adults)	11	36.0 ± 9.6	205.9 ± 13.5
Females (adults)	1	47.4	211.5

Table 2 Mean concentrations (± S.D.) of Hg and Se (μg g^{-1} wet weight) and Se/Hg molar ratio, in muscle (M) and liver (L) of the blue shark from the entrance of the Gulf of California

Category	n	Tissue	Hg	Se	Se/Hg
General	22	M	0.63 ± 0.34 (0.19–1.47)	0.08 ± 0.06 (0.006–0.15)	0.41 ± 0.29
		L	0.69 ± 0.54 (0.17–1.67)	2.49 ± 1.21 (0.70–4.37)	16.6 ± 11.4
Females	6	M	0.48 ± 0.27 (0.15–0.97)	0.09 ± 0.06 (0.05–1.03)	0.55 ± 0.33
		L	0.43 ± 0.24(0.20–1.11)	2.84 ± 1.21 (0.70–4.29)	16.6 ± 11.4
Males	16	M	0.68 ± 0.35 (0.19–1.47)	0.08 ± 0.05 (0.04–0.25)	0.36 ± 0.27
		L	0.43 ± 0.24 (0.20–1.11)	2.36 ± 1.22 (0.77–4.37)	17.1 ± 11.4
Juveniles	10	M	0.42 ± 0.15 (0.15–0.65)*	0.09 ± 0.07 (0.005–0.25)	0.55 ± 0.37
		L	0.63 ± 0.44 (0.18–1.67)	2.33 ± 1.17 (0.77–4.29)	13.6 ± 10.5
Adults	12	M	0.80 ± 0.36 (0.27–1.47)*	0.09 ± 0.04 (0.009–0.15)	0.30 ± 0.15
		L	0.40 ± 0.24 (0.20–1.11)	2.61 ± 1.27 (0.70–4.37)	19.1 ± 12.0

* Significantly different

the two elements (Se and Hg), most papers on this subject suggest that in muscle tissues a Se/Hg molar ratio (Se/Hg) greater than 1.0 would indicate a low risk to fish consumers (Gerson et al. 2020). However, Manceau et al. (2021) under

Table 3 Results from the linear models adjusted for Hg and Se concentrations against total length (TL) and total weight (TW) by sex in muscle and liver tissue from Blue Sharks

	Correlation	R^2/P-value
Model formula ([Hg] ~ TL)		
Muscle		
Males	+	0.247/0.05*
Females	+	0.733/0.03*
Liver		
Males	+	0.140/0.6
Females	−	0.753/0.02*
Model formula ([Hg] ~ TW)		
Muscle		
Males	+	0.388/0.002*
Females	+	0.698/0.06
Liver		
Males	+	0.191/0.6
Females	−	0.577/0.07
	Correlation	$R^{2/}$ P-value
Model formula ([Se] ~ TL)		
Muscle		
Males	+	0.002/0.38
Females	+	0.733/0.36
Liver		
Males	+	0.331/0.02*
Females	−	0.598/0.07
Model formula ([Se] ~ TW)		
Muscle		
Males	+	0.005/0.79
Females	+	0.282/0.27
Liver		
Males	+	0.342/0.02*
Females	−	0.689/0.04*

*Statistically significant

experimental conditions have pointed out that for the binding process of the selenoprotein P with one MeHg molecule occurs, 4 selenocysteines are needed. This reaction known as demethylation takes place in the animal liver to transform the MeHg into selenide (HgSe) particles. In the bull shark *Carcharhinus leucas* and the tiger shark *Galeocerdo cuvier* from a coastal ecosystem in the western Indian ocean, it was found that they may de-methylate methyl Hg as a pathway for mitigating methyl Hg contamination (Le Croizier et al. 2020). Observing the molar ratio results from muscle samples (Table 2), we deduce that the amount of Se is not enough for the sequestration of the Hg to occur. However, these data alone are not sufficient to make a complete determination as to whether or not consumption of this meat is harmful. As Hg concentration is occasionally above regulation, a more comprehensive approach including HBV_{Se} will be addressed in depth. Overall, while Hg concentration in liver was similar to that in muscle, we could observe the opposite pattern for Se in all target categories (Table 2). For Se, TL and TW were significantly correlated (positive) with Se concentration in liver of males (Table 3). Contrastingly, Se concentration in liver of females was negatively correlated with TW.

The higher concentrations of Se in the liver may be explained by the fact that the liver has the highest propensity for Se accumulation (Escobar-Sánchez et al. 2010; Lara et al. 2020, 2022), mostly due to the presence of selenoproteins and their role in the Hg demethylation/detoxification process (Pantoja-Echevarría et al. 2021). We can remark that the higher Hg accumulation observed in the hepatic tissue of females can be related to the detoxification mechanism of maternal offloading (Adams and McMichael 1999; Cadena-Cárdenas 2004). As this pollutant can potentially be transferred to the embryo, reproductive females may extend Hg retention in the liver so that toxicity through the placenta can be avoided in viviparous species (Frías-Espericueta et al. 2015). Molar ratios of Se/Hg in the liver of blue sharks from Massachusetts (Hauser-Davies et al. 2021) and our study were above 4 (Table 4), which means that the detoxification process through demethylation may be occurring in blue sharks' livers too.

Comparison of Hg and Se Concentration with other Studies

Globally, concerns about the toxicity of Hg in sharks for human consumption have sparked a considerable amount of research data on the subject. Although most of the data originated in Asia, because of the larger consumer market, we were able to select representative papers from the main blue shark fishing areas to compare with our results (Dell'apa et al. 2014) (Table 4). Since muscle is the most commonly studied as it is the most commonly consumed part of the animal, a comparison with liver tissue was not possible in the majority of cases. Allowing for this, the Hg concentrations in muscle found in our investigation were similar to those reported in the Mediterranean, and particularly low compared to those reported in Mexico, close to the study area. Notwithstanding the smaller amount of papers reporting Se concentration in muscle, we can again point out a similarity with the Mediterranean values reported for the coast of Italy (Storelli et al. 2022). Looking at a broader picture and taking into account the antagonism effect and the importance of this element for nutritional purposes, not only for sharks but also for consumers, we identified the lowest concentrations reported in the literature compared to those found in the muscle of blue sharks (Escobar-Sánchez et al. 2011; Barrera-García et al. 2013; Hauser-Davis et al. 2021; Lara et al 2022). The recent work of Amezcua et al. (2022) set a reference baseline for Hg and Se in a comprehensive evaluation of the work published to date for any shark species in general, whereas in a global evaluation, they estimated a level of 0.90 ± 0.59 (μg g^{-1} ww) mean ± (SD) for Hg in blue shark muscle and 0.54 (0.44) in liver and found 0.25 (0.12) for Se in muscle and 1.77 (0.12) in liver. Comparing our results with this baseline, we can conclude that, although for muscle the mean Hg concentration is lower, the maximum value observed was similar, while the liver results are very similar to the mean obtained by Amezcua et al. (2022). In contrast, Se was considerably lower in muscle and higher in liver.

Particularly striking about this similarity to the Hg and Se values found by Storelli et al. (2022) is that the atmospheric deposition of Hg for our study area is lower than that reported for the Mediterranean (Table 4). So, in addition, the bioaccumulation observed in our results (Table 2) indicates that MeHg availability to sharks is relatively high at the entrance to the Gulf of California. So we can attribute this phenomenon that methylation of inorganic Hg by bacterial transformation is enhanced in low-oxygen waters (Blum 2013; Le Croizier et al. 2019a, b). The study area is indeed located in the northern region of the Pacific ocean oxygen minimum zone (OMZ) off Mexico, already well documented (Sánchez-Pérez et al. 2021). This is one of the largest naturally occurring shallow OMZ and is located in the Tropical Pacific off Mexico in the subsurface layer of the region, emerging up to 60 m depth near the shore (Fiedler and Talley 2006; Prince et al. 2006; Gilly et al. 2012). The OMZ is present in the Gulf of California, particularly, in the central and southern portions, with concentrations < 5 mL/L at depths of 150 m, being undetectable (< 0.1 mL/L) at depths between 500 and 1100 m (Páez-Osuna et al. 2017). Recently, Álvarez-Rodríguez (2023) redefined the oxycline limit for the entrance of the Gulf of California in the water column with the OMZ intersects the points where the blue sharks for this study were captured (Fig. 1). In these areas with hypoxic and anoxic conditions, Hg methylation may occur and potentially be dispersed to the surrounding ecosystems (Fitzgerald et al. 2007).

Table 4 Concentration of Hg and Se (μg g^{-1} ww), HBV_{Se}, and [Se]/[Hg] molar ratio (mean ± SD) in muscle and liver of blue sharks from Mexico and other parts of the world. Approximated Hg atmospheric deposition for the region reported by Amezcua et al. (2022)

Hg Muscle/Liver	Se Muscle/Liver	Stage	Molar ratio Muscle/Liver	HBV_{Se} Muscle/Liver	Atmospheric deposition of Hg (μg m^{-2} y^{-1})	Region	References
0.014 ± 0.09/ 0.104 ± 0.03	NA	Adults	NA	NA	10	South Pacific (Chile)	Lopez et al. (2013)
1.12 ± 0.57/NA				NA	8	Atlantic Ocean (Brazil)	Carvalho et al (2010)
1.3 ± 0.22/0.96 ± 0.032	0.30 ± 0.084/3 ± 0.47		41.5 ± 31/NA	NA	5	Atlantic Ocean (Azores-Africa)	Branco et al (2007)
2.257 ± 0.71/NA	0.30 ± 0.05/NA		3.08 ± 1.08/ NA	33.58 ± 21.24	25	Northeast Atlantic (Lisbon area, Portugal	Matos et al (2015)
0.42 ± 0.16/ 0.12 ± 0.030		Adults		NA	> 30	East China Sea (China)	Kazama et al (2020)
1.27 ± 0.53/0.27 ± 0.22	3.09 ± 2.54/1.26 ± 0.37		1.5/12	NA	30	North Atlantic (Massachusetts-USA)	Hauser-Davis et al (2021)
0.63 ± 0.01/NA	0.20 ± 0.04/NA			− 1.36	> 30	Mediterranean Sea (Italy)	Storelli et al (2022)
1.39 ± 1.58/NA	0.10 ± 0.05/NA	Juveniles-Adults	0.2/NA	NA	< 5	NW Pacific (Baja California-Mexico)	Escobar-Sanchez et al. (2011)
1.96 ± 1.48/NA	NA	Adults	NA	NA	5	Gulf of California (Baja California-Mexico)	Maz-Corrau et al (2012)
1.03 ± 0.08/ 0.22 ± 0.35	0.22 ± 0.02/ 1.67 ± 0.58	Juveniles-Adults	NA	NA	5	SW Pacific (Baja California-Mexico)	Barrera-García et al (2013)
0.44 ± 0.35/0.02 ± 0.02	0.51 ± 0.43/1.54 ± 1.14	Juveniles	NA	NA	5	Bahía Tortugas (Baja California sur-Mexico)	[66]
0.63 ± .0.34/0.50 ± 0.37	0.08 ± 0.06/2.49 ± 1.21	Juveniles-Adults	0.41/16.59	-51.18/35.05	10	Entrance Gulf of California (Sinaloa)	Present study

NA- not available

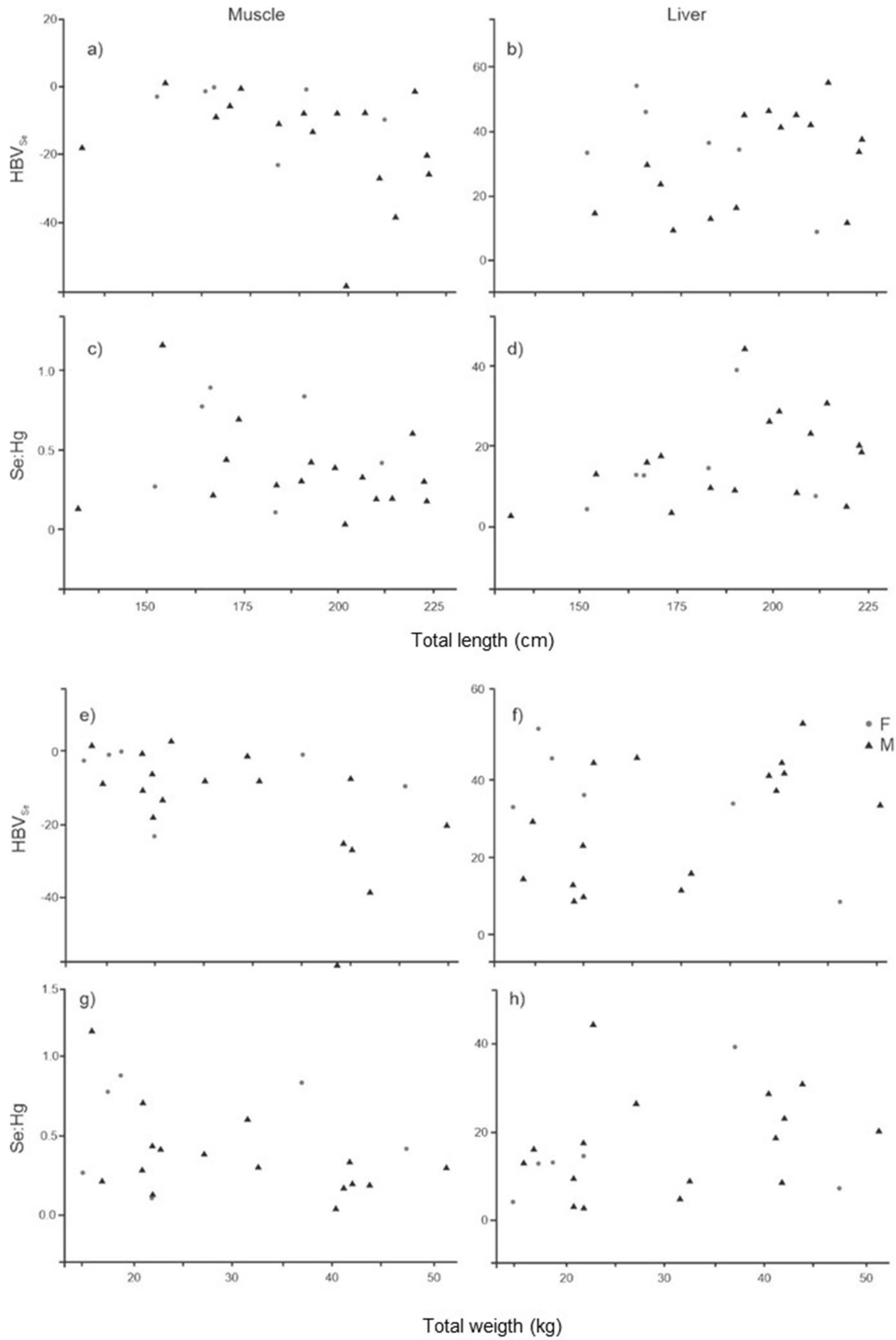
Table 5 An improved criterion for selenium health benefit value (HBV_{Se}) means and standard deviation, for muscle and liver of *P. glauca,* separated into five categories

Categories	$HBV_{SeMuscle}$	$HBV_{SeLiver}$
General	−13.29 ± 14.6	31.18 ± 15.44
Females	−6.29 ± 8.84	35.5 ± 15.34
Males	−15.92 ± 15.67	29.55 ± 15.66
Adults	−19.27 ± 16.33*	32.96 ± 16.2
Juveniles	−6.13 ± 8.19*	29.05 ± 15.05

*Significantly different

Selenium Health Benefit Value

Broadly speaking, in the last decade, most studies addressing the negative effects of Hg in seafood intended for human consumption acknowledge that Se:Hg is a more suitable tool for estimating the risks of Hg than Hg concentrations alone. These findings confirm that an excess of Se (Se: Hg > 1; $HBV_{Se} > 0$) can protect the body against the danger of Hg. This approach for investigating the Se: Hg interaction through HBV_{Se} proposed and improved by Ralston et al. (2016) is a highly proficient human health assessment criterion for determining risks from Hg and Se concentrations in marine fish (Kaneko and Ralston 2007). This index analyzes the molar ratio between the two elements and if it is negative


Muscle
Liver
a)
b)
c)
d)
e)
f)
g)
h)
HBV_Se
Se:Hg
Total length (cm)
Total weigth (kg)
F
M

◂**Fig. 2** HBV_{Se} and Se:Hg molar ratio variation between sexes (circle: female; triangle: male) versus total length (top) and total weight (bottom) in the liver (right) and muscle (left) tissue of blue shark collected from the entrance of Gulf of California

it will indicate a potential risk whereas if it is positive, it will show significant benefits from the consumption of that particular seafood product (Ralston et al. 2016). In the case of muscle, we obtained all negative values (Table 5), indicating that the risk of ingesting this meat is greater than the benefit, while liver shows high and positive values. Consistent with other studies, our results indicate that blue sharks, due to various conditions such as size/age, diet and feeding areas (pollutant exposure), show negative values of this index, suggesting that sequestration or inhibition of Hg by Se might be less likely in muscle (Storelli et al. 2022), which is similar to Mediterranean blue shark muscle (Table 5). Matos et al. (2015) in the Northeast Atlantic (Portugal), also reported high negative values of this index for *P. glauca*, concluded after risk/benefit assessment, a recommended consumption of a maximum of one meal per year of raw or cooked blue shark meat. Considering the above scenario, ingestion of blue shark meat could have the potential to produce harmful Hg effects in the consumer (Cuvin-Aralar and Furness 1991). As HBV_{Se} varies by sex and life stage for muscle, the index shows the same pattern as Hg concentration, with no differences between sexes ($W=68$; $p=0.1545$), and significantly different according to stages, with adults being more harmful for consumption than juveniles ($W=21$; $p=0.008957$).

While shark meat is mainly consumed directly in different forms in a large number of countries (Cardeñosa 2019), shark liver is mainly processed as oil, for its high medicinal value in the treatment of several diseases such as cancer (Hajimoradi et al. 2009). Liver oil medicinal properties stem from its high levels of fatty acids and fat-soluble vitamins (Santos et al. 2020). Although HBV_{Se} in liver tissue did not show significant differences between any of the categories (sex and stage) ($W=55$, $p=0.6407$; $W=72$, $p=0.4562$), and its positive values, it is worth noting that this part of the shark might not pose a risk to the consumption of shark meat ($W=72$, $p=0.4562$). HBV_{Se} and the molar ratio did not present a significant result with TL except for the HBV_{Se} in the liver, while in the females the index decreased with size, indicating that a bigger risk of consumption in males is the opposite (Fig. 2b). With respect to the weight of the individuals, there were negative significant correlations with HBV_{Se} and Se/Hg in the muscle of males (Fig. 2e, g), i.e., edible muscle of heavier specimens may be hazardous for consumers.

Conclusions

The results of this study confirm the hypothesis that bioaccumulation of Hg and Se occurs in blue sharks, with higher Hg concentrations in the muscle of adult sharks than in juveniles. While Hg concentrations were comparable in the muscle and liver of sharks (overall, by sex and maturity). Se was always higher in liver than in muscle. Finally, the HBV_{Se} was negative in both juveniles and adults and females and males, indicating a potential risk from the consumption of this meat. The shark fleet of the Mexican Pacific is the principal supplier of blue shark meat in different forms to the domestic consumer market, so we can recommend that blue shark meat caught along the entrance to the Gulf of California be eaten with caution. Although the liver can be a valuable resource according to the results of this and other studies, its benefits appear to outweigh the risks for those who consume it. This study confirms previous findings on this shark species and serves as a basis for recommending a moderate to low consumption of its meat.

Acknowledgements We thank C. Suárez-Gutiérrez for software technical support, R. Cruz for data processing, P. Spanopoulos-Zarco and H. Bojórquez-Leyva for mercury and selenium analyses. The data provided in this study were taken from the Ph.D. project in Marine Sciences and Limnology (Marine Biology) of M. E. Rechimont. The authors of this study gratefully acknowledge to the Institute of Marine Sciences and Limnology (ICMyL), from The National Autonomous University of Mexico (UNAM).

Author Contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by FA, JR-I, FP-O and MER. The first draft of the manuscript was written by MER, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This work was supported by the Dirección General de Asuntos del Personal Académico (DGAPA), Programa de Apoyo a Proyectos de Investigación e Innovación Tecnológica (PAPIIT) and the Universidad Nacional Autónoma de México (UNAM) grant number IN203922 titled "Metales, metaloides y microplásticos en organismos de importancia ecológica y comercial de la eco-región del Golfo de California." The National Fisheries and Aquaculture Institute of Mexico (INAPESCA) funded the research surveys. The National Autonomous University of México (UNAM) through the Institute of Marine Sciences and Limnology (ICMyL), funded the laboratory research and analyses. Author M. E. Rechimont has received research support by The National Council of Science and Technology of Mexico (CONACYT) through grant 512466.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

References

Adams DH, McMichael RH (1999) Mercury levels in four species of sharks from the Atlantic coast of Florida. Fish Bull 97:372–379

Álvarez Rodríguez N (2023) Relación entre la profundidad de la oxiclina y la actividad de mesoescala en la Entrada al Golfo de California. Dissertation, Centro de Investigación Científica y de Educación Superior de Ensenada. URL: https://cicese.repositorioinstitucional.mx/jspui/handle/1007/3879

Amezcua F, Ruelas-Inzunza J, Coiraton C, Spanopoulos-Zarco P, Páez-Osuna F (2022) A global review of cadmium, mercury, and selenium in sharks: geographical patterns, baseline levels and human health implications. Rev Environ Contam Toxicol 260:4. https://doi.org/10.1007/s44169-021-00006-2

Barrera-García A, O'hara T, Galván-Magaña F, Méndez-Rodríguez LC, Castellini JM, Zenteno-Savín T (2013) Trace elements and oxidative stress indicators in the liver and kidney of the blue shark (*Prionace glauca*). Comp Biochem Physiol 165(4):483–490. https://doi.org/10.1016/j.cbpa.2013.01.024

Barreto R, Ferretti F, Flemming JM, Amorim A, Andrade H, Worm B, Lessa R (2016) Trends in the exploitation of south Atlantic shark populations. Conserv Biol 30:792–804. https://doi.org/10.1111/cobi.12663

Beltran-Pedreros S, Zuanon J, Leite RG, Peleja JRP, Mendonça AB, Forsberg BR (2011) Mercury bioaccumulation in fish of commercial importance from different trophic categories in an Amazon floodplain lake. Neotrop Ichthyol 9:901–908. https://doi.org/10.1590/S1679-62252011000400022

Berntssen MHG, Aatland A, Handy RD (2003) Chronic dietary mercury exposure causes oxidative stress, brain lesions, and altered behaviour in Atlantic salmon (*Salmo salar*) parr. Aquat Toxicol 65:55–72. https://doi.org/10.1016/S0166-445X(03)00104-8

Biton-Porsmoguer S, Bănaru D, Harmelin-Vivien M, Béarez P, Bouchoucha M, Marco-Miralles F, Marquès M, Lloret J (2022) A study of trophic structure, physiological condition and mercury biomagnification in swordfish (*Xiphias gladius*): evidence of unfavourable conditions for the swordfish population in the Western Mediterranean. Mar Pollut Bull 176:113411. https://doi.org/10.1016/J.MARPOLBUL.2022.113411

Blanco-Parra MP (2003) Edad y crecimiento del tiburón azul, *Prionace glauca* (Linnaeus 1758), en la costa occidental de Baja California Sur, México. Dissertation, Universidad Nacional Autónoma de México, México. URL: https://repositorio.unam.mx/contenidos/78838

Blazina T, Lä A, Jones GD, Sodemann H, Wernli H, Kirchner JW, Winkel LHE (2016) Marine primary productivity as a potential indirect source of selenium and other trace elements in atmospheric deposition. Environ Sci Technol 51(1):108–118. https://doi.org/10.1021/acs.est.6b03063

Blum JD (2013) Mesmerized by Mercury. Nature Chem 5:1066. https://doi.org/10.1038/nchem.1803

Bolea-Fernandez E, Rua-Ibarz A, Krupp EM, Feldmann J, Vanhaecke F (2019) High-Precision isotopic analysis sheds new light on mercury metabolism in long-finned pilot whales (*Globicephala melas*). Sci Rep 9:7262. https://doi.org/10.1038/s41598-019-43825-z

Branco V, Vale C, Canário J, Dos Santos MN (2007) Mercury and selenium in blue shark (*Prionace glauca*, L. 1758) and swordfish (*Xiphias gladius*, L. 1758) from two areas of the Atlantic Ocean. Environ Pollut 150:373–380. https://doi.org/10.1016/J.ENVPOL.2007.01.040

Burridge L, Weis JS, Cabello F, Pizarro J, Bostick K (2010) Chemical use in salmon aquaculture: a review of current practices and possible environmental effects. Aquaculture 306:7–23. https://doi.org/10.1016/J.AQUACULTURE.2010.05.020

Cadena-Cárdenas L (2004) Mercurio total en peces elasmobranquios y teleósteos del Golfo de California. Dissertation, Instituto Tecnológico Mar, México.

Cappello T, Giannetto A, Parrino V, De Marco G, Mauceri A, Maisano M (2018) Food safety using NMR-based metabolomics: assessment of the atlantic bluefin tuna, *Thunnus thynnus*, from the mediterranean sea. Food Chem Toxicol 115:391–397. https://doi.org/10.1016/j.fct.2018.03.038

Cardeñosa D (2019) Genetic identification of threatened shark species in pet food and beauty care products. Conserv Gen 20:1383–1387. https://doi.org/10.1007/s10592-019-01221-0

Carrera-Fernández M, Galván-Magaña F, Ceballos-Vázquez BP (2010) Reproductive biology of the blue shark *Prionace glauca* (Chondrichthyes: Carcharhinidae) off Baja California Sur, Mexico. Aqua, Int J Ichthyol 16(3):101–110

Carvalho FC, Murie DJ, Hazin FHV, Hazin HG, Leite-Mourato B, Travassos P, Burgess GH (2010) Aquatic living resources catch rates and size composition of blue sharks (*Prionace glauca*) caught by the Brazilian pelagic longline fleet in the southwestern Atlantic ocean. Aquat Living Resour 23:373–385. https://doi.org/10.1051/alr/2011005

Carvalho F, Ahrens R, Murie D, Ponciano JM, Aires-da-Silva A, Maunder MN, Hazin F (2014) Incorporating specific change points in catchability in fisheries stock assessment models: an alternative approach applied to the blue shark (*Prionace glauca*) stock in the South Atlantic Ocean. Fish Res 154:135–146. https://doi.org/10.1016/J.FISHRES.2014.01.022

Clarke SC, McAllister MK, Milner-Gulland EJ, Kirkwood GP, Michielsens CGJ, Agnew DJ, Pikitch EK, Nakano H, Shivji MS (2006) Global estimates of shark catches using trade records from commercial markets. Ecol Lett 9:1115–1126. https://doi.org/10.1111/j.1461-0248.2006.00968.x

Coelho R, Erzini K (2008) Effects of fishing methods on deep water shark species caught as by-catch off southern Portugal. Hydrobiol 606:187–193. https://doi.org/10.1007/s10750-008-9335-y

Cuvin-Aralar MLA, Furness RW (1991) Mercury and selenium interaction: a review. Ecotoxicol Environ Saf 21:348–364. https://doi.org/10.1016/0147-6513(91)90074-y

Dell'apa A, Chad M, Mahealani S, Kaneshiro-Pineiro Y (2014) The influence of culture on the international management of shark finning. Environ Manag 54:151–161. https://doi.org/10.1007/s00267-014-0291-1

Dent F, Clarke S (2015) State of the global market for shark products. FAO Fish Aquac Tech Pap 590:1–187

Dulvy NK, Fowler SL, Musick JA, Cavanagh RD, Kyne PM, Harrison LR, Carlson JK, Davidson LNK, Fordham SV, Francis MP, Pollock CM, Simpfendorfer CA, Burgess GH, Carpenter KE, Compagno LJV, Ebert DA, Gibson C, Heupel MR, Livingstone SR, Sanciangco JC, Stevens JD, Valenti S, White WT (2014) Extinction risk and conservation of the world's sharks and rays. eLife 2014:1–34. https://doi.org/10.7554/eLife.00590

Eisler R (2006) Mercury hazards to living organisms. CRC Press, Boca Raton

Escobar-Sánchez O, Galván-Magaña F, Rosíles-Martínez R (2010) Mercury and selenium bioaccumulation in the smooth hammerhead shark, *Sphyrna zygaena* Linnaeus, from the Mexican Pacific Ocean. Bull Environ Contam Toxicol 84(4):488–491. https://doi.org/10.1007/s00128-010-9966-3

Escobar-Sánchez O, Galván-Magaña F, Rosíles-Martínez R (2011) Biomagnification of mercury and selenium in blue shark *Prionace glauca* from the Pacific Ocean off Mexico. Biol Trace Elem Res 144:550–559. https://doi.org/10.1007/s12011-011-9040-y

Ferriss BE, Essington TE (2014) Does trophic structure dictate mercury concentrations in top predators? A comparative analysis of pelagic food webs in the Pacific Ocean. Ecol Model 278:18–28. https://doi.org/10.1016/J.ECOLMODEL.2014.01.029

Fiedler PC, Talley LD (2006) Hydrography of the eastern tropical Pacific: a review. Prog Oceanogr 69:143–180. https://doi.org/10.1016/J.POCEAN.2006.03.008

Fitzgerald WF, Lamborg CH, Hammerschmidt CR (2007) Marine biogeochemical cycling of mercury. Chem Rev 107(2):641–662. https://doi.org/10.1021/cr050353m

Frías-Espericueta MG, Zamora-Sarabia FKG, Márquez-Farías JF, Osuna-López JI, Ruelas-Inzunza J, Voltolina D (2015) Total mercury in female Pacific sharpnose sharks *Rhizoprionodon longurio* and their embryos. Lat Am J Aquat Res 43:534–538. https://doi.org/10.3856/vol43-issue3-fulltext-14

Gerson JR, Walters DM, Eagles-Smith CA, Bernhardt ES, Brandt JE (2020) Do two wrongs make a right? Persistent uncertainties regarding environmental selenium-mercury interactions. Environ Sci Technol 54:9228–9234. https://doi.org/10.1021/acs.est.0c01894

Gilly WF, Beman JM, Litvin SY, Robison BH (2012) Oceanographic and biological effects of shoaling of the oxygen minimum zone. Annual Rev Mar Sci 5:393–420. https://doi.org/10.1146/annurev-marine-120710-100849

Hajimoradi M, Hassan ZM, Pourfathollah AA, Daneshmandi S, Pakravan N (2009) The effect of shark liver oil on the tumor infiltrating lymphocytes and cytokine pattern in mice. J Ethnopharmacol 126:565–570. https://doi.org/10.1016/J.JEP.2009.05.033

Harris R, Pollman C, Hutchinson D, Landing W, Axelrad D, Morey SL, Dukhovskoy D, Vijayaraghavan K (2012) A screening model analysis of mercury sources, fate and bioaccumulation in the Gulf of Mexico. Environ Res 119:53–63. https://doi.org/10.1016/j.envres.2012.08.013

Hauser-Davis RA, Rocha RCC, Saintpierre TD, Adams DH (2021) Metal concentrations and metallothionein metal detoxification in blue sharks, Prionace glauca L from the western North Atlantic Ocean. J Trace Elem Med Biol 68:126813. https://doi.org/10.1016/J.JTEMB.2021.126813

Houssard P, Point D, Tremblay-Boyer L, Valérie A, Pethybridge H, Masbou J, Ferriss BE, Baya PA, Lagane C, Menkes CE, Letourneur Y, Lorrain A (2019) A model of mercury distribution in tuna from the Western and Central Pacific Ocean: influence of physiology, ecology and environmental factors. Environ Sci Technol 53(3):1422–1431. https://doi.org/10.1021/acs.est.8b06058

Hu W, Zhao C, Hu H, Yin S, Schomburg L (2021) Food sources of selenium and its relationship with chronic diseases. Nutrients 13(5):1739. https://doi.org/10.3390/nu13051739

Kaneko JJ, Ralston NVC (2007) Selenium and mercury in pelagic fish in the central North Pacific near Hawaii. Biol Trace Elem Res 119:242–254. https://doi.org/10.1007/s12011-007-8004-8

Kazama H, Yamaguchi Y, Harada Y, Kaneko N, Mizushima H, Tsuchiya K, Nemoto M, Takaku Y, Sahoo YV, Tanaka M (2020) Mercury concentrations in the tissues of blue shark (*Prionace glauca*) from Sagami Bay and cephalopods from East China Sea. Environ Pollut 266:115192. https://doi.org/10.1016/j.envpol.2020.115192

Kotnik J, Horvat M, Tessier E, Ogrinc N, Monperrus M, Amouroux D, Fajon V, Gibičar D, Žižek S, Sprovieri F, Pirrone N (2007) Mercury speciation in surface and deep waters of the Mediterranean Sea. Mar Chem 107(1):13–30. https://doi.org/10.1016/j.marchem.2007.02.012

Kyriakopoulos A, Behne D (2002) Selenium-containing proteins in mammals and other forms of life. Rev Physiol Biochem Pharmacol 145:1–46. https://doi.org/10.1007/bfb0116430

Lara A, Galván-Magaña F, Elorriaga-Verplancken F, Marmolejo-Rodríguez AJ, Gonzalez-Armas R, Arreola-Mendoza L, Sujitha SB, Jonathan MP (2020) Bioaccumulation and trophic transfer of potentially toxic elements in the pelagic thresher shark *Alopias pelagicus* in Baja California Sur, Mexico. Mar Pollut Bull 156:1–9. https://doi.org/10.1016/j.marpolbul.2020.111192

Lara A, Galván-Magaña F, Elorriaga-Verplancken FR, Marmolejo-Rodríguez AJ, González-Armas R, Arreola-Mendoza L, Sujitha SB, Jonathan MP, Pantoja-Echevarría LM (2022) Mercury, selenium and cadmium in juvenile blue (*Prionace glauca*) and smooth hammerhead (*Sphyrna zygaena*) sharks from the northwest Mexican Pacific coast. Mar Pollut Bull 175:113311. https://doi.org/10.1016/J.MARPOLBUL.2021.113311

Lavoie RA, Jardine TD, Chumchal MM, Kidd KA, Campbell LM (2013) Biomagnification of mercury in aquatic food webs: a worldwide meta-analysis. Environ Sci Technol 47:13385–13394. https://doi.org/10.1021/es403103t

Le Bourg B, Kiszka JJ, Bustamante P, Heithaus MR, Jaquemet S, Humber F (2019) Effect of body length, trophic position and habitat use on mercury concentrations of sharks from contrasted ecosystems in the Southwestern Indian Ocean. Environ Res 169:387–395. https://doi.org/10.1016/j.envres.2018.11.024

Le Croizier G, Lacroix C, Artigaud S, Le Floch S, Munaron JM, Raffray J, Penicaud V, Rouget ML, Laë R, De Morais LT (2019a) Metal subcellular partitioning determines excretion pathways and sensitivity to cadmium toxicity in two marine fish species. Chemosphere 217:754–762. https://doi.org/10.1016/J.CHEMOSPHERE.2018.10.212

Le CG, Schaal G, Point D, Le LF, Machu E, Fall M, Munaron JM, Boyé A, Walter P, Laë R, De Morais LT (2019) Stable isotope analyses revealed the influence of foraging habitat on mercury accumulation in tropical coastal marine fish. Sci Total Environ 650:2129–2140. https://doi.org/10.1016/J.SCITOTENV.2018.09.330

Lopez SA, Abarca NL, Meléndez RC (2013) Heavy metal concentrations of two highly migratory sharks (*Prionace glauca* and *Isurus oxyrinchus*) in the southeastern pacific waters: comments on public health and conservation. Trop Conserv Sci 6(1):126–137. https://doi.org/10.1177/194008291300600103

Lyons K, Lowe CG (2013) Mechanisms of maternal transfer of organochlorine contaminants and mercury in the common thresher shark (*Alopias vulpinus*). Can J Fish Aquat Sci 70:1667–1672. https://doi.org/10.1139/cjfas-2013-0222

Maisano M, Cappello T, Oliva S, Natalotto A, Giannetto A, Parrino V, Battaglia P, Romeo T, Salvo A, Spano N, Mauceri A (2016) PCB and OCP accumulation and evidence of hepatic alteration in the Atlantic bluefin tuna, *T. thynnus*, from the Mediterranean Sea. Mar Environ Res. https://doi.org/10.1016/j.marenvres.2016.03.003

Manceau A, Gaillot AC, Glatzel P, Cherel Y, Bustamante P (2021) In vivo formation of HgSe nanoparticles and Hg-tetraselenolate complex from methylmercury in seabirds-implications for the Hg-Se antagonism. Environ Sci Technol 55:1515–1526. https://doi.org/10.1021/acs.est.0c06269

Mason RP, Sheu GR (2002) Role of the ocean in the global mercury cycle. Global Biogeoch Cycles 16(4):1093. https://doi.org/10.1029/2001GB001440

Matos J, Lourenço HM, Brito P, Maulvault AL, Martins LL, Afonso C (2015) Influence of bioaccessibility of total mercury, methyl-mercury and selenium on the risk/benefit associated to the consumption of raw and cooked blue shark (*Prionace glauca*). Environ Res 143:123–129. https://doi.org/10.1016/J.ENVRES.2015.09.015

Maz-Corrau A, López-Vera C, Galván-Magaña F, Escobar-Sánchez O, Rosíles-Martínez R, Sanjuán-Muñoz A (2012) Bioaccumulation and biomagnification of total mercury in four exploited shark species in the Baja California Peninsula, Mexico. Bull Environ Contam Toxicol 88:129–134. https://doi.org/10.1007/s00128-011-0499-1

Mieiro CL, Coelho JP, Pacheco M, Duarte AC, Pereira ME (2012) Evaluation of species-specific dissimilarities in two marine fish species: mercury accumulation as a function of metal levels in consumed prey. Arch Environ Contam Toxicol 63(1):125–136. https://doi.org/10.1007/s00244-011-9740-5

Moody JR, Lindstrom RM (1977) Selection and cleaning of plastic containers for storage of trace element samples. Anal Chem 49:2264–2267. https://doi.org/10.1021/ac50022a039

Mull CG, Lyons K, Blasius ME, Winkler C, Sullivan O (2013) Evidence of maternal offloading of organic contaminants in white sharks (*Carcharodon carcharias*). PLoS ONE 8:62886. https://doi.org/10.1371/journal.pone.0062886

NOM (2009) Productos y Servicios. Productos de la Pesca Frescos Refrigerados y Congelados. Especificaciones sanitarias. NOM-242-SSA1–2009. México: Norma Oficial Mexicana. URL: https://www.dof.gob.mx/normasOficiales/4295/salud2a/salud2a.htm

O'Connor D, Hou D, Ok YS, Mulder J, Duan L, Wu Q, Wang S, Tack FMG, Rinklebe J (2019) Mercury speciation, transformation, and transportation in soils, atmospheric flux, and implications for risk management: a critical review. Environ Int 126:747–761. https://doi.org/10.1016/j.envint.2019.03.019

Olin JA, Shipley ON, Mcmeans BC (2018) Stable isotope fractionation between maternal and embryo tissues in the bonnethead shark (*Sphyrna tiburo*). Environ Biol Fish 101:489–499. https://doi.org/10.1007/s10641-018-0715-5

Páez-Osuna F, Pérez-González R, Izaguirre-Fierro G, Zazueta-Padilla HM, Flores-Campaña LM (1995) Trace metal concentrations and their distribution in the lobster *Panulirus inflatus* (Bouvier, 1895) from the Mexican Pacific coast. Environ Pollut 90:163–170. https://doi.org/10.1016/0269-7491(94)00103-K

Páez-Osuna F, Álvarez-Borrego S, Ruiz-Fernández AC, García-Hernández J, Jara-Marini ME, Bergés-Tiznado ME, Piñón-Gimate A, Alonso-Rodríguez R, Soto-Jiménez MF, Frías-Espericueta MG, Ruelas-Inzunza J, Green-Ruiz CR, Osuna-Martínez CC, Sanchez-Cabeza JA (2017) Environmental status of the Gulf of California: a pollution review. Earth-Sci Rev 166:181–205. https://doi.org/10.1016/j.earscirev.2017.01.014

Pantoja-Echevarría LM, Marmolejo-Rodríguez AJ, Galván-Magaña F, Elorriaga-Verplancken FR, Tripp-Valdez A, Tamburin E, Lara A, Jonathan MP, Sujitha SB, Arreola-Mendoza L (2021) Mercury and selenium concentrations in different tissues of brown smooth-hound shark (*Mustelus henlei*) from the western coast of Baja California Sur. Mexico Mar Pollut Bull 170:112609. https://doi.org/10.1016/J.MARPOLBUL.2021.112609

Pereira P, Korbas M, Pereira V, Cappello T, Maisano M, Canário J, Almeid A, Pacheco M (2019) A multidimensional concept for mercury neuronal and sensory toxicity in fish - from toxicokinetics and biochemistry to morphometry and behavior. BBA-General Sub 1863:129298. https://doi.org/10.1016/j.bbagen.2019.01.020

Phillips DJH (1980) Quantitative aquatic biological indicators: their use to monitor trace metal and organochlorine pollution. Applied Science Publishers, Barking, England

Prince ED, Luo J, Goodyear CP, Hoolihan JP, Snodgrass D, Orbesen ES, Serafy JE, Ortiz M, Schirripa MJ (2006) Ocean scale hypoxia-based habitat compression of Atlantic istiophorid billfishes. Fish Oceanog 19(6):448–462. https://doi.org/10.1111/j.1365-2419.2010.00556.x

R Core Team (2022) R: a language and environment for statistical computing.

Ralston NVC (2008) Selenium health benefit values as seafood safety criteria. EcoHealth 5:442–455. https://doi.org/10.1007/S10393-008-0202-0

Ralston NVC, Ralston CR, Raymond LJ (2016) Selenium health benefit values: updated criteria for mercury risk assessments. Biol Trace Elem Res 171:262–269. https://doi.org/10.1007/s12011-015-0516-z

Raymond LJ, Ralston NVC (2009) Selenium's importance in regulatory issues regarding mercury. Fuel Process Technol 90(11):1333–1338. https://doi.org/10.1016/j.fuproc.2009.07.012

Régine MB, Gilles D, Yannick D, Alain B (2006) Mercury distribution in fish organs and food regimes: significant relationships from twelve species collected in French Guiana (Amazonian Basin). Sci Tot Environ 368:262–270. https://doi.org/10.1016/J.SCITOTENV.2005.09.077

Sánchez-Pérez ED, Sánchez-Velasco L, Ruvalcaba-Aroche ED, Ornelas-Vargas A, Beier E, Barton ED, Peña MA, Godínez VM, Contreras-Catala F (2021) Temperature and dissolved oxygen concentration in the Pacific Ocean at the northern region of the oxygen minimum zone off Mexico between the last two PDO cool phases. J Mar Syst 222:103607. https://doi.org/10.1016/J.JMARSYS.2021.103607

Santos DN, Silva FS, Verde AB, Bittencourt GM, de Oliveira AL (2020) Determination of functional compounds in blue shark (*Prionace glauca*) liver oil obtained by green technology. Grasas Aceites 71(2):e354. https://doi.org/10.3989/gya.0450191

Schartup AT, Thackray CP, Qureshi A, Dassuncao C, Gillespie K, Hanke A, Sunderland EM (2019) Climate change and overfishing increase neurotoxicant in marine predators. Nature 572(771):1–3. https://doi.org/10.1038/s41586-019-1468-9

Senn DB, Chesney EJ, Blum JD, Bank MS, Maage A, Shine JP (2010) Stable isotope (N, C, Hg) study of methylmercury sources and trophic transfer in the Northern Gulf of Mexico. Environ Sci Technol 44:1630–1637. https://doi.org/10.1021/es902361j

Storelli A, Barone G, Garofalo R, Busco A, Storelli MM (2022) Determination of mercury, methylmercury and selenium concentrations in elasmobranch meat: fish consumption safety. Int J Environ Res Public Health 19(2):788. https://doi.org/10.3390/ijerph19020788

Sunderland EM, Krabbenhoft DP, Moreau JW, Strode SA, Landing WM (2009) Mercury sources, distribution, and bioavailability in the North Pacific Ocean: insights from data and models. Global Biochem Cycles. https://doi.org/10.1029/2008GB003425

Svobodová Z, Lloyd R, Machová J, Vykusová B (1993) Water quality and fish health. Food and agriculture organization, Rome URL: https://www.fao.org/fishery/docs/CDrom/aquaculture/a0844t/docrep/009/T1623E/T1623E00.htm

Taylor D, Dalton C, Hall A, Woodroofe MN, Gardiner PHE (2009) Recent developments in selenium research. Br J Biomed Sci 66:107–116. https://doi.org/10.1080/09674845.2009.11730256

Terrazas-López R, Arreola-Mendoza L, Galván-Magaña F, Sujitha SB, Jonathan MP (2019) Understanding the antagonism of Hg and Se in two shark species from Baja California Sur, Mexico. Sci Total Environ 650:202–209. https://doi.org/10.1016/J.SCITOTENV.2018.08.261

Tovar-Ávila J, Furlong-Estrada E, Castillo-Géniz JL (2016) Evaluación de riesgo ecológico por efectos de las pesquerías de tiburón mexicanas para las especies incluidas en el Apéndice II de la CITES. In: Tovar-Ávila J (ed) Castillo-Géniz JL. Tiburones mexicanos de importancia pesquera en la CITES, Instituto Nacional de Pesca, México pp, pp 17–28

Ung CY, Lam SH, Hlaing MM, Winata CL, Korzh S, Mathavan S, Gong Z (2010) Mercury-induced hepatotoxicity in zebrafish: in vivo mechanistic insights from transcriptome analysis, phenotype anchoring and targeted gene expression validation. BMC Genomics 11:212. https://doi.org/10.1186/1471-2164-11-212

Vinceti M, Filippini T, Cilloni S, Bargellini A, Vergoni AV, Tsatsakis A, Ferrante M (2017) Health risk assessment of environmental selenium: emerging evidence and challenges. Mol Med Rep 15:3323–3335. https://doi.org/10.3892/mmr.2017.6377

Vinceti M, Filippini T, Wise LA (2018) Environmental selenium and human health: an update. Curr Environ Health Rep 5:464–485. https://doi.org/10.1007/s40572-018-0213-0

Wyatt CJ, Meléndez JM, Acuña N, Rascon A (1996) Selenium (Se) in foods in northern Mexico, their contribution to the daily Se intake and the relationship of Se plasma levels and glutathione

peroxidase activity. Nutr Res 16(6):949–960. https://doi.org/10.1016/0271-5317(96)00094-2
Yang DY, Chen YW, Gunn JM, Belzile N (2008) Selenium and mercury in organisms: interactions and mechanisms. Environ Rev 16:71–92. https://doi.org/10.1139/A08-001