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Mercury levels in muscle tissue of four common elasmobranch species from the Pacific coast of Costa Rica, Central America

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HIGHLIGHTS

- We measured mercury (Hg) concentration in four elasmobranch species in Costa Rica.
- Electric ray *T. peruana* had the highest Hg concentration.
- Hg concentration was affected by body size, but slopes were different among species.
- No relationship was found between Hg concentration and individual trophic position.
- Hg concentrations were lower than reports for similar species in other regions.

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ABSTRACT

Mercury (Hg) is a non-essential and toxic element that is ubiquitous in the marine environment and biomagnifies through food webs. Given the high trophic position of many elasmobranch species, it is important to quantify potentially harmful trace elements like Hg in their tissues, as this is an indicator of the level of contamination in the ecosystem. This study provides the first examination of total mercury (THg) concentrations in muscle tissue of four common demersal elasmobranchs (*Mustelus henlei, Raja velezi, Torpedo peruana* and *Zapteryx xyster*) from the Pacific coast of Costa Rica. All four species showed a positive relationship between THg concentration and body size, but THg concentration did not vary with trophic position. *Torpedo peruana* showed the highest THg concentration (mean ± SD: 0.52 ± 0.25 mg/kg wet weight) but *Z. xyster* had the highest slope for the THg-size relationship. The THg concentrations found in this study were lower than those reported for similar elasmobranch species in other regions, and only one sample exceeded the concentration limit suggested for human consumption. Our results suggest that THg contamination off the Pacific coast of Costa Rica, and possibly Central America is minimal.

1. Introduction

Pollution is one of the most important threats to marine coastal environments worldwide (Costa et al., 2012). Along with the steady increase in human population of coastal areas, agricultural and industrial activities surrounding watersheds have also impacted these important ecosystems (Seoánez, 2000). One of the most significant pollutants in the marine environment is mercury (Hg) (Manahan, 2001). Most of the Hg released into marine environments is inorganic, a portion of which is subsequently biotransformed into methylmercury (MeHg), a more toxic and

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bioaccumulative derivative. MeHg represents up to 95% of total Hg found in muscle of fishes (Bloom, 1992), which is mainly accumulated from ingested prey, and to a lesser extent through gills (Boening, 2000). At high concentrations, Hg can have negative behavioral, neurochemical, hormonal and reproductive impacts on fish such as emaciation, cerebral lesions, and impaired gonadal development (Leblond and Hontela, 1999; Scheuhammer et al., 2007; Silva et al., 1992; Wiener et al., 2003).

Mercury has a low elimination rate and thus tends to accumulate in a number of fish tissues, including gills, muscle and liver (Jernelöv and Lann, 1971). This is one of the only trace metals that biomagnifies (Kidd and Batchelar, 2012), a process in which concentrations of its organic form increase with each step in the food web, resulting in the highest concentrations in top trophic position organisms (Figuerelo and Dávila, 2004). Given that elasmobranchs often occupy high trophic positions in aquatic food webs, they typically accumulate high Hg concentrations through the process of biomagnification (Cortés, 1999; Ebert and Bizzarro, 2007; Gelsleichter and Walker, 2010; Mull et al., 2012). Accumulation of Hg has also been found to increase with fish body size (Burger and Gochfeld, 2011), and therefore, larger elasmobranches may contain higher Hg concentrations.

Despite the toxic potential and tendency to biomagnify, little is known about Hg concentrations in fish from the Eastern Tropical Pacific (ETP), particularly the Central American region (Costa et al., 2012). Given the high number of active volcanoes and their proximity to the coast, this region is a potential "hot spot" for Hg release to coastal marine environments (Haynes, 2012). Natural Hg emissions are potentially as high as those generated by industrial activities in developed countries, ranging from 5 to 100 g/km^2/yr (Haynes, 2012; Pyle and Mather, 2003). In the ETP, Hg concentrations have only been determined for billfish and a single species of dolphin (*Stenella atenuatta*) (André et al., 1990; Ehrhardt and Fitchett, 2011), but there is limited data on other top marine predators, particularly elasmobranch fishes (Maz-Courrau et al., 2012).

In Costa Rica, 24 elasmobranch species are commonly captured as by-catch in the commercial trawling fishery along the Pacific coast (Clarke et al., 2014; Espinoza et al., 2012, 2013). The velez skate *Raja velezi* (Rajidae), the brown smoothhound *Mustelus henlei* (Triakidae), the southern guitar ray *Zapteryx xyster* (Rhinobatidae) and the Peruvian torpedo *Torpedo peruana* (Torpedinidae) are among the most common species (Clarke et al., 2011, 2014). Recent studies have described the diet, reproduction and distribution patterns of these elasmobranchs (Clarke et al., 2014; Espinoza et al., 2012, 2013). Diet studies revealed that these species are mesopredators that feed primarily on crustaceans (shrimps and stomatopods) as juveniles and demersal teleosts as adults (Espinoza et al., 2012, 2013). While these findings have been important for understanding the biology and ecology of common elasmobranchs associated with trawling fisheries, there is no information available about Hg levels in their tissues.

Many elasmobranchs are economically important resources in coastal areas, primarily for human consumption (Vannuccini, 1999). Shark meat is an important protein source for coastal communities in Central America. Moreover, species of the genus *Mustelus* (including *M. henlei*), are some of the most consumed sharks in Costa Rica (Rojas et al., 2000). Since shark meat can contain high concentrations of Hg, regular consumption of this meat can significantly increase the exposure of humans to this trace metal (Castro-González and Méndez-Armenta, 2008). Moreover, Hg is transferred from the mother to the fetus and can act as an endocrine disruptor, potentially altering the early stages of human development (Yang et al., 1997). At low levels, Hg delays the fetus' mental development, while larger amounts can result in severe birth defects (Myers and Davidson, 2000). The serious health risks associated with Hg consumption justifies the need to compare Hg concentrations in sharks and rays with values recommended by the World Health Organization (FAO/WHO, 2011).

This study examined THg concentrations in the muscle tissue of four common demersal elasmobranch species along the Pacific coast of Costa Rica. We also investigated the relationship between Hg concentration and body size, and with nitrogen stable isotope ($^{15}N/^{14}N$ expressed relative to a standard as $\delta^{15}N$) data of muscle tissue. $\delta^{15}N$ provides an estimate of trophic position (TP) (Hussey et al., 2011; Peterson and Fry, 1987; Post, 2002), and has been used extensively to quantify the trophic transfer of Hg through food webs (Lavoie et al., 2013). Therefore, $\delta^{15}N$ can be a good indicator of trophic position among the studied elasmobranch species. Levels of Hg from the present study were also compared with levels recommended by FAO/WHO to assess potential health risks due to elasmobranch consumption.

2. Materials and methods

2.1. Sample collection

Elasmobranch species were collected as by-catch from commercial trawlers (2010–2011) operating at depths between 18 and 350 m along the Pacific coast of Costa Rica (Fig. 1). Each vessel was equipped with two standard epibenthic nets (20.5 m long, 5.35 m × 0.85 m mouth opening, 30 mm mesh-size in the cod-end, and 44 mm mesh-size in the webbing of the rest of the trawl net) (Wehrtmann and Echeverría-Sáenz, 2007). Samples from *R. velezi* and *Z. xyster* were caught in shallower waters (<100 m) whereas samples from *M. henlei* and *T. peruana* were caught throughout the entire depth range. Each collected specimen was stored in ice until further analyses at the Unidad de Investigación Pesquera y Acuicultura of the Centro de Investigación en Ciencias del Mar y Limnología, San José, Costa Rica.

Specimens were sexed, weighed (g) and measured (flexed total length—TL: tip of the snout to posterior tip of the tail, disc width—DW: distance between the wing tips). Hereafter, TL for *M. henlei* and DW for *R. velezi*, *T. peruana* and *Z. xyster* are referred to size. Individuals were classified as mature or immature based on the stage of calcification of the claspers (males) and the macroscopic examination of the oviductal gland, uterus and egg development stages (females) (Clarke et al., 2014; Conrath, 2005).

2.2. Mercury concentration and $\delta^{15}N$

A sample of approximately 5 g of muscle was extracted from the base of the first dorsal fin in sharks, and the left ventral disc side in rays. Dissection tools were thoroughly cleaned between each dissection. Dermal tissue was removed, and the muscle was stored frozen until analysis (−20 °C). Muscle samples were dried in an oven at 60 °C for 48 h until dry, pulverized to a fine powder with a mortar, and stored in sterile vials for subsequent analysis. Dry weight (dw) THg levels were quantified using a Direct Hg Analyzer (DMA-80; Milestone Inc., Shelton, CT, USA) at the Canadian Association for Laboratory Accreditation- (CALA-) accredited Great Lakes Institute for Environmental Research (University of Windsor, Windsor, ON, Canada). Quality control procedures included analysis of blanks (20% of runs), in-house biological tissue reference samples, duplicate shark sample analysis, and National Research Council of Canada certified standards (DORM-3, DOLT-4). Detection limit, three times the blank standard deviation, was 0.005 mg kg^{-1} dw based on a 0.1 g sample weight. Mercury concentration values were obtained on a dry weight basis, which were then transformed to a wet weight (ww) basis using the following formula: $(Hg)_{ww} = C\,(Hg)_{dw} \times (100 - \%H_2O)/100$, where $C(Hg)$ is the Hg concentration, and $\%H_2O$ is the water percentage

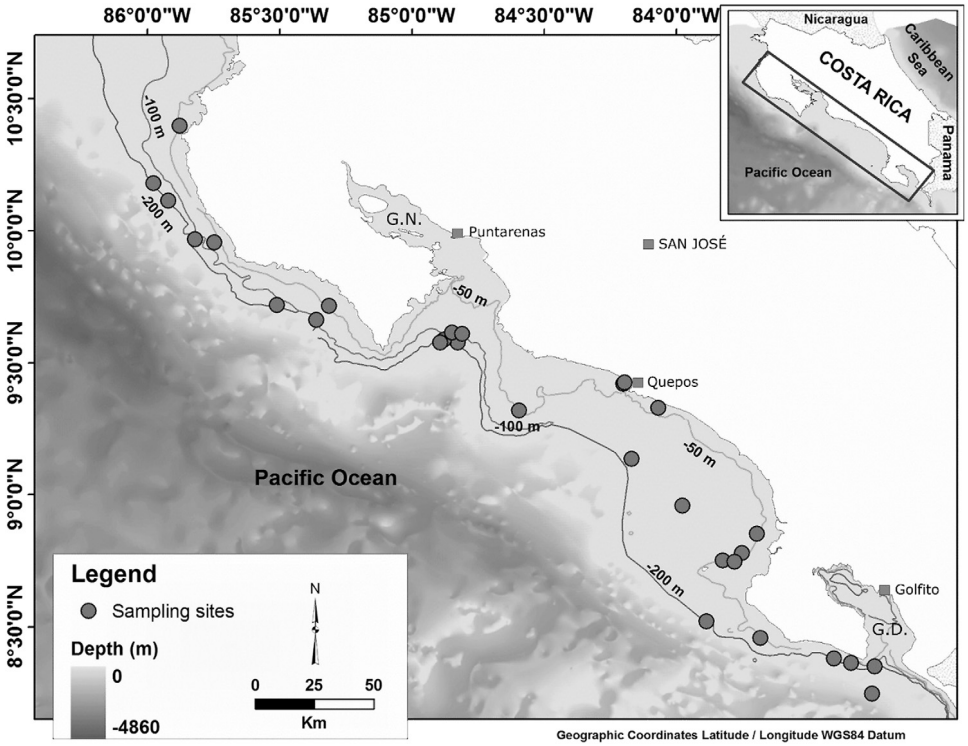

Fig. 1. Location of sampling sites along the Pacific coast of Costa Rica, Central America. G.N. and G.D. show the two main gulfs of Costa Rica: Golfo de Nicoya and Golfo Dulce, respectively.

of the sample. The latter was calculated as following: $\%H_2O$ = ((Wet weigh–Dry weight)/Wet weight) × 100.

Relative abundances of nitrogen ($^{15}N/^{14}N$) isotopes were quantified using ∼0.5 mg muscle tissue sealed in tin capsules and analyzed at the Great Lakes Institute for Environmental Research (Windsor, Ontario, Canada) using a Thermo Finnigan DeltaPlus isotope ratio mass-spectrometer (Thermo Finnigan) coupled with an elemental analyzer (Costech). The ratio of heavy to light isotopes was expressed as δ^{15}N (‰) according to the equation $\delta^{15}N = [(R_{sample}/R_{standard}) - 1] \times 1000$, where R_{sample} is the $^{15}N/^{14}N$ ratio in the sample and $R_{standard}$ was the ratio in the standard reference material (atmospheric nitrogen) (Hussey et al., 2011, 2012). The analytical precision (standard deviation) for NIST standard 1577c (bovine liver, $n = 93$) and an internal laboratory standard (tilapia muscle, $n = 93$) were 0.07‰ and 0.11‰ for δ^{13}C and 0.11‰ and 0.11‰ for δ^{15}N.

2.3. Data analysis

A total of 63 muscle samples from four elasmobranch species were collected and analyzed for THg concentration: 17 *M. henlei*, 19 *R. velezi*, 15 *T. peruana* and 12 *Z. xyster* (see Table 1). Preliminary analyses revealed no difference in THg concentration between males and females (*M. henlei*: $t = 1.14$, $df = 14{,}38$, $p = 0.27$; *R. velezi*: $t = -0.28$, $df = 11{,}01$, $p = 0.79$; *T. peruana*: $t = 0.57$, $df = 12{,}988$, $p = 0.58$; *Z. xyster*: $t = -0.10$, $df = 6.32$, $p = 0.92$), thus sexes were pooled together for further analyses. Differences in THg concentration among species were examined using an analysis of variance (ANOVA, $\alpha = 0.05$) followed by Tukey's post hoc test. Data were log transformed ($\log_{10}(X + 1)$) prior to analyses to achieve normality and equality of variances. Results are presented as mean ± SD. We also compared the THg values with 1.0 mg/kg (wet weight), the suggested maximum concentration for human consumption in predatory fish tissues (FAO/WHO, 2011).

Due to bioaccumulation processes, we expected a positive relationship between body size and THg concentration since in many species individuals are likely to accumulate a higher concentration of mercury in their tissues as they grow (Penedo de Pinho et al., 2002; Pethybridge et al., 2010). The relationship between THg concentration and elasmobranch size was examined using linear regression analysis. Differences in the slope among ray species were examined using an analysis of covariance (ANCOVA). Differences in δ^{15}N between species were determined using an ANOVA, and Tukey post-hoc test. The effect of δ^{15}N (proxy for TP) on log-transformed THg concentration was investigated using linear regression analysis. We pooled all species together to analyze the effect of δ^{15}N on THg concentration.

3. Results

3.1. THg concentrations

Mercury concentration in muscle tissue was significantly different among the four elasmobranch species ($F_{3,59} = 15.17$, $p < 0.001$; Fig. 2). The highest THg concentration was observed in *T. peruana*, which was twice as the concentration of *R. velezi*, and more than threefold the concentration found in *Z. xyster* and *M. henlei*. The THg concentration for *T. peruana* was significantly higher than the rest of the species (Tukey HSD: $p < 0.05$), but similar concentrations were observed in *M. henlei*, *R. velezi* and *Z. xyster* (Tukey HSD: all $p > 0.05$). There was only one sample from the 63 individuals analyzed which surpassed the THg concentration threshold value suggested for human consumption (1 mg/kg). This value was obtained for the largest individual of *T. peruana*, a 59.5 cm (DW) and 13.5 kg female.

3.2. Size and Hg bioaccumulation

Torpedo peruana was the largest species, followed by *R. velezi* and *Z. xyster*, *M. henlei* (Table 1). The size–THg relationship differed

Table 1
Mean (± SD) and range of total mercury (THg) concentration by sex and stage for *Mustelus henlei*, *Raja velezi*, *Torpedo peruana* and *Zapteryx xyster*, Pacific Coast of Costa Rica, Central America. Sex: M—males; F—females. Stage: In—immature; Ma—mature. N—number of samples examined.

Species	Sex	Stage	N	Size range (cm)	THg range (mg/kg)	THg concentration (Mean ± SD)
M. henlei	F	In	3	26.8–42.0	0.03–0.13	0.10 ± 0.05
		Ma	4	55.5–63.7	0.09–0.28	0.15 ± 0.09
	M	In	2	28.7–33.6	0.05–0.06	0.05 ± 0.01
		Ma	8	42.5–51.5	0.10–0.36	0.21 ± 0.09
	Total		**17**	**26.8–63.7**	**0.03–0.36**	**0.16 ± 0.09**
R. velezi	F	In	1	42.0	0.09	0.09
		Ma	7	49.0–57.8	0.15–0.42	0.26 ± 0.13
	M	In	2	17.5–18.7	0.01–0.03	0.02 ± 0.01
		Ma	9	46.5–52.5	0.12–0.50	0.30 ± 0.15
	Total		**19**	**17.5–55.4**	**0.01–0.50**	**0.25 ± 0.16**
T. peruana	F	In	8	25.5–41.6	0.32–0.90	0.44 ± 0.07
		Ma	2	45–59.5	0.90–1.24	1.07 ± 0.24
	M	In	3	27.3–29.3	0.32–0.38	0.35 ± 0.03
		Ma	2	38.5–39	0.52–0.59	0.46 ± 0.05
	Total		**15**	**25.5–59.5**	**0.32–1.24**	**0.52 ± 0.25**
Z. xyster	F	In	2	8.6–23.3	0.01–0.04	0.03 ± 0.02
		Ma	6	26.9–32.7	0.05–0.46	0.28 ± 0.17
	M	In	3	20.6–22.7	0.03–0.06	0.05 ± 0.02
		Ma	1	22.7	0.08	0.08
	Total		**12**	**8.6–32.7**	**0.01–0.46**	**0.17 ± 0.17**

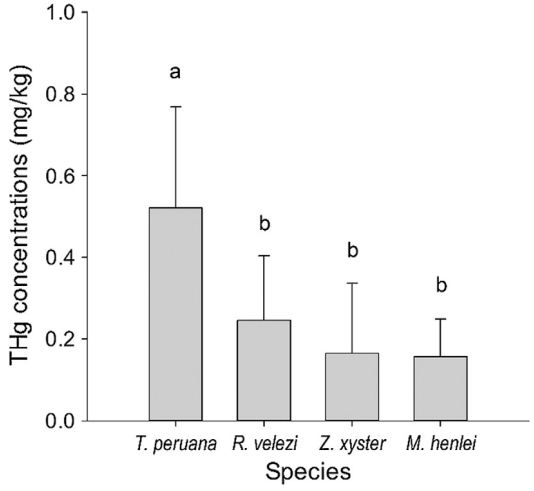

Fig. 2. Mercury concentrations (wet weight) (mean ± SD) found in muscle samples of four elasmobranch species (*Mustelus henlei*, *Raja velezi*, *Torpedo peruana* and *Zapteryx xyster*), Pacific coast of Costa Rica, Central America. Species with different letters have significantly different means (Tukey HSD).

among batoids (ANCOVA: $F_{2,40} = 3.63$, $p = 0.036$). A positive linear relationship between size and log-transformed THg concentration was found for *M. henlei* ($F_{1,15} = 6.38$, $p = 0.023$, $R^2 = 0.30$), *R. velezi* ($F_{1,17} = 8.28$, $p = 0.0029$, $R^2 = 0.33$), *T. peruana* ($F_{1,13} = 55.75$, $p < 0.001$, $R^2 = 0.87$) and *Z. xyster* ($F_{1,10} = 10.24$, $p < 0.0095$, $R^2 = 0.56$), indicating that THg concentration increases exponentially with body size in demersal elasmobranch species (Fig. 3). The steepest slope for the size–THg relationship was observed in *Z. xyster* and *T. peruana* (slope = 0.0067 log(mg/kg)/cm DW and 0.0066 log(mg/kg)/cm DW, respectively), while the slopes for *R. velezi* (0.0029 log(mg/kg)/cm DW) and *M. henlei* (0.0018 log(mg/kg)/cm TL) were considerably lower (Fig. 3).

3.3. Stable isotopes analysis

Values of δ^{13}C in elasmobranchs muscle ranged between −17.64‰ and −14.62‰, which represent typical values from a coastal marine food web (Fig. 4). *Torpedo peruana* showed the highest average δ^{13}C value (−15.30 ± 0.41‰) followed by *Z. xyster* (−15.98 ± 0.57‰), *M. henlei* (−16.41 ± 0.48‰) and *R. velezi* (−16.42 ± 0.46‰). Significant differences were observed between δ^{13}C values of the four elasmobranch species ($F_{3,59} = 19.46$; $p < 0.001$). The δ^{13}C values of *T. peruana* were significantly higher than the rest of the species, but were similar among them.

Values of δ^{15}N varied significantly among species ($F_{3,59} = 8.19$, $p < 0.001$). The highest δ^{15}N values were found in *M. henlei* (15.49 ± 0.45‰), followed by *Z. xyster* (15.16 ±0.66‰), *R. velezi* (14.81 ± 0.44‰) and *T. peruana* (14.76 ± 0.42‰). *Mustelus henlei* also had higher δ^{15}N values than *R. velezi* and *T. peruana* (Tukey HSD tests $p < 0.05$), but did not differ from *Z. xyster*. Similar δ^{15}N values were found in *R. velezi*, *T. peruana* and *Z. xyster*. There was no effect of δ^{15}N on THg concentration for the four species pooled ($F_{1,61} = 0.47$, $p = 0.49$; $R^2 = 0.0077$) (Fig. 5). However, a separate analysis revealed a positive relationship between δ^{15}N and THg concentration in *M. henlei* ($F_{1,15} = 5.92$, $p = 0.028$).

4. Discussion

4.1. Previous studies on Hg content in elasmobranchs

This study provides the first quantification of THg levels of common demersal elasmobranchs in Costa Rica, and the Central American region. The THg concentration for *M. henlei* found in this study was approximately 70% lower than previously reported for other *Mustelus* species in the Southwestern Atlantic (De Marco et al., 2006; Marcovecchio et al., 1988; Penedo de Pinho et al., 2002; Scapini et al., 1993) (Table 2), with the exception of *M. higmani* in Brazil, which had a Hg concentration 10 times lower than our study (Lacerda et al., 2000). In Costa Rica, *M. henlei* also had a Hg concentration 74% lower than values reported for *Mustelus* spp. in Australia (Bloom and Ayling, 1977; Glover, 1979), and 54% lower than values reported in the Mediterranean Sea (Kousteni et al., 2006; Storelli et al., 2002a). Lacerda et al. (2000) found Hg concentrations one order of magnitude lower in *Mustelus higmani* (13.4 ng/g) than other elasmobranch species in the Southwestern Atlantic. Such a large difference cannot be attributed exclusively to size and dietary habits as these studies suggested. Our study showed that *M. henlei* has one of the lowest Hg concentrations in muscle reported so far for a species of this genus, suggesting that

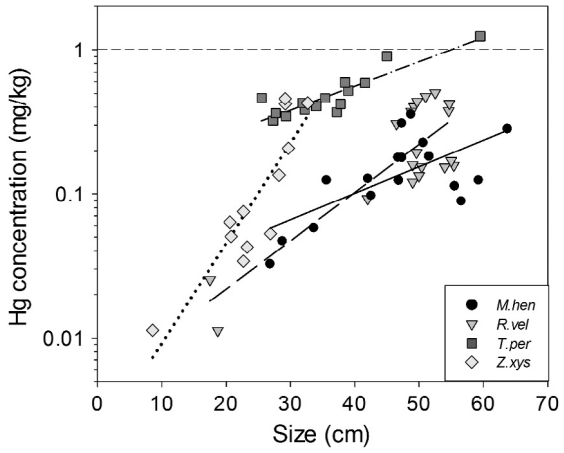

Fig. 3. Relationship between THg concentration (wet weight) in muscle tissue and body length of four elasmobranch species, Pacific off Costa Rica, Central America. The short-dashed line represents the limit suggested by the WHO for human consumption (1 mg/kg). Regression lines correspond to the linear model of log transformed THg concentration vs. size (see results section): solid line: *M. henlei*, dashed line: *Raja velezi*, dash-dotted line: *Torpedo peruana,* dotted line: *Zapteryx xyster*.

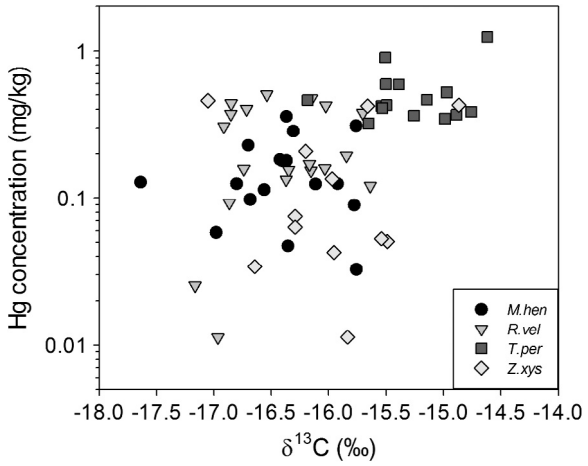

Fig. 4. Relationship between THg concentration (wet weight) in muscle tissue and carbon stable isotope ratio (δ^{13}C) of the four elasmobranch species, *Mustelus henlei*, *Raja velezi*, *Torpedo peruana* and *Zapteryx xyster* in the Pacific off Costa Rica, Central America.

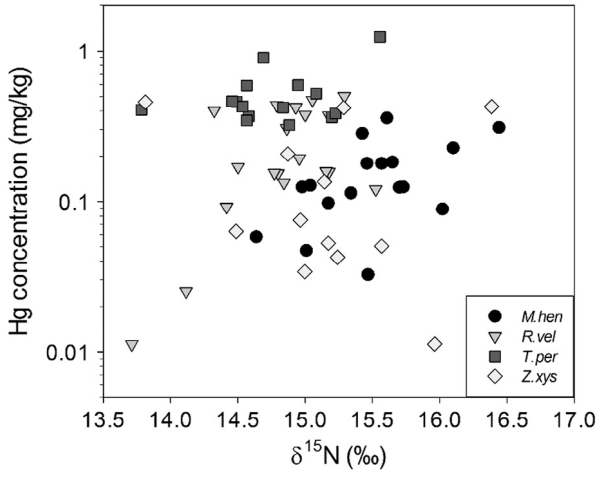

Fig. 5. Relationship between THg concentration (wet weight) in muscle tissue and nitrogen stable isotope ratio (δ^{15}N) of the four elasmobranch species, *Mustelus henlei*, *Raja velezi*, *Torpedo peruana* and *Zapteryx xyster* in the Pacific off Costa Rica, Central America.

Hg levels for the Pacific coast of Costa Rica may be lower than in other coastal regions.

Mercury concentrations in muscle tissue has only been analyzed for another species in the genus *Torpedo*: *T. nobiliana* in the Adriatic Sea (Storelli et al., 2002b). This species had Hg concentrations four times higher than those reported for *T. peruana* in this study. Differences in Hg concentration among *T. peruana* and *T. nobiliana* may be due to differences in habitat and/or depth. Along the Pacific coast of Costa Rica *T. peruana* is mostly distributed between 50–250 m (Clarke et al., 2011), and *T. nobiliana* in the Mediterranean Sea has been found mainly between 200–500 m (Baino et al., 2001). Deep-water fishes generally have higher Hg levels (Koenig et al., 2013), which has been attributed to higher abundance of bacteria that bio-transform Hg into Me–Hg in deep hypoxic waters, in addition to the photochemical degradation of Me–Hg in shallow waters (Blum et al., 2013). A deeper range distribution in *T. nobiliana* could therefore explain the higher Hg concentration reported for this species compared to *T. peruana*.

The Hg concentration in *R. velezi* was 75% lower than values reported for other skates in the Mediterranean (Storelli et al., 1998, 2003) and 32% lower than in *R. radiata* in the Barents Sea (Joiris et al., 1997). However, Baeyens et al. (2003) found lower values than the ones reported in this study for *R. clavata* in the North Sea. There are no previous studies of Hg concentration for *Zapteryx xyster* or any other rhinobatid species, which limits any comparisons between Costa Rica and other populations and/or other species.

The low THg concentrations found in this study may be attributed to the availability and release of Hg in nearshore environments. The study region lacks activities that favor Hg release into the environment (e.g. gold/silver mining and coal burning). In contrast, Hg has been extensively used in South America for silver and gold recovery since the colonization by European settlers in America, over 450 years ago, and has continued to be emitted at a rate of about 150 tons per year (Malm, 1998; UNEP, 2013). This substantial anthropogenic release can explain the high Hg content for a wide range of fishes found in Brazil and Argentina (Penedo de Pinho et al., 2002; De Marco et al., 2006). Conversely, high volcanic gas emissions in the Central American region is likely to be the main source of Hg, although these are not comparable to Hg emissions in highly industrialized regions (Haynes, 2012). Elasmobranchs are free-ranging species, so Hg concentration in their tissues does not necessarily reflect local Hg deposition. Our findings suggest either that these species are not moving long distances, or that they are not spending significant periods in regions where pollution by Hg could be significant.

4.2. Size influence on Hg concentrations

Mercury concentrations were positively influenced by body size in all of the study species, a trend which has been previously documented in other elasmobranchs (Adams and McMichael, 1999; Pethybridge et al., 2010). In fact, size has been found to be the best predictor of Hg concentrations found in teleosts (Burger and Gochfeld, 2011). Being a non-essential metal, there are few homeostatic mechanisms that regulate Hg concentration (Kidd and Batchelar, 2012; Ratner et al., 2006). The large body of research on Hg bioaccumulation has demonstrated that the excretion rate is slower than the accumulation rate, resulting in bioaccumulation and biomagnification (Kidd and Batchelar, 2012).

While all the studied species accumulate Hg throughout their lifespan, they present different relationships between Hg concentration in their tissues and body size. *Zapteryx xyster* and *T. peruana*, for example, had higher THg to size ratio than the remaining species, which may reflect differences in life histories. Bioenergetic models predict an inverse relationship between growth

Table 2
Summary of studies that reported Hg concentrations in muscle tissue of elasmobranch species. Samples: DW—dry weight; WW: wet weight.

Species	Range (mg/kg)	Mean ± SD (mg/kg)	Location	Samples	Source
Mustelus asterias	1.7–3.1	2.2 ± 0.5	Celtic Sea	DW	Domi et al., 2005
Mustelus antarcticus		0.5	Australia	WW	Bloom and Ayling, 1977
Mustelus antarcticus	0.3–1.4	0.73 ± 0.35	Australia	WW	Glover, 1979
Mustelus canis		0.41 ± 0.35	Brazil	WW	Penedo de Pinho et al., 2002
Mustelus canis	0.15–1.47	0.53	France	WW	Cumont et al., 1975
Mustelus higmani	0.013–0.163	0.013	Brazil	WW	Lacerda et al., 2000
Mustelus henlei	0.19–3.29	1.15 ± 1.00	Costa Rica	DW	Present study
Mustelus henlei	0.033–0.36	0.16 ± 0.093	Costa Rica	WW	Present study
Mustelus mustelus	0.22–1.83	0.39 ± 0.37	Greece	WW	Kousteni et al., 2006
Mustelus mustelus	0.23–0.37	0.31 ± 0.06	Italy	WW	Storelli et al., 2002a
Mustelus norrisi		0.36 ± 0.28	Brazil	WW	Penedo de Pinho et al., 2002
Mustelus schmitti		0.33 ± 0.20	Argentina	WW	De Marco et al., 2006
Mustelus schmitti		0.09 ± 0.01	Argentina	WW	De Marco et al., 2006
Mustelus schmitti		0.89 ± 0.29	Argentina	WW	Marcovecchio et al., 1988
Mustelus schmitti		0.45 ± 0.30	Argentina	WW	Scapini et al., 1993
Rajidae	0.18–1.85	1.00	Mediterranean	WW	Storelli et al., 2003
Raja spp.	0.05–2.65	1.02	Italy	WW	Storelli et al., 1998
Raja clavata		0.039 ± 0.021	North Sea	WW	Baeyens et al., 2003
Raja radiata	0.20–0.40	0.37	Barents Sea	DW	Joiris et al., 1997
Raja velezi	0.11–4.26	1.24 ± 0.96	Costa Rica	DW	Present study
Raja velezi	0.011–0.505	0.25 ± 0.16	Costa Rica	WW	Present study
Torpedo nobiliana	1.65–3.59	2.42 ± 0.86	Mediterranean	WW	Storelli et al., 2002b
Torpedo peruana	1.66–5.75	2.78 ± 1.15	Costa Rica	DW	Present study
Torpedo peruana	0.32–1.24	0.52 ± 0.24	Costa Rica	WW	Present study
Zapteryx xyster	0.06–2.22	0.77 ± 0.82	Costa Rica	DW	Present study
Zapteryx xyster	0.011–0.46	0.17 ± 0.17	Costa Rica	WW	Present study

rate and Hg concentration in fish: fish that grow faster spend less time metabolizing Hg-containing food, so they accumulate less Hg in their tissues than slower growing species or individuals of the same species (the growth dilution hypothesis) (Harris and Bodaly, 1998; Simoneau et al., 2005; Trudel and Rasmussen, 2006; Lepak et al., 2012). Growth rate is also expected to be an important factor explaining differences in bioaccumulation rate in elasmobranchs (Forrester et al., 1972), but there is limited information available in the Central American Region. Further studies are needed to understand the effect of growth on mercury bioaccumulation of common elasmobranchs in this region.

4.3. Influence of trophic position and sex on THg concentrations

Given that Hg increases at each trophic level in aquatic food webs (biomagnification), the trophic position of a species is often a key variable determining Hg concentration. We used δ^{15}N as an indicator of trophic position, but no relationship between δ^{15}N and THg concentration was found. The absence of a relationship between THg–δ^{15}N is likely due to the fact that these mesopredators had similar trophic positions, and thus may be feeding on prey with similar Hg concentration. This does not mean that trophic position is not a key variable in Hg bioaccumulation, but rather that a clear pattern could not be easily identified from the small range of δ^{15}N values measured in our study. The expected tendency should be evident with a wider δ^{15}N range, for instance when comparing prey and predators from a longer food chain (Jones et al., 2014). The Hg-δ^{15}N relationship may also be compromised if the species being examined feed in different habitats (e.g., different food webs with different Hg and δ^{15}N), which Espinoza et al. (2015) provided evidence for.

Even though there was no relationship between Hg–δ^{15}N for all species pooled, when analyzed separately *M. henlei* did show a positive relationship. An increase in Hg concentration in individuals with higher δ^{15}N values may be evidence of ontogenetic dietary shifts. Such changes in diet have been previously reported for all of our study species (Espinoza et al., 2012, 2013, 2015). However, the fact that we analyzed samples from a wider range of sizes in *M. henlei* relative to the other species, may have enhanced the relationship between Hg–δ^{15}N. Therefore, further studies with samples covering the entire size range of a species are needed to better understand how trophic position influences Hg concentration at the species level.

The diet of a species should also be considered in trophic level comparisons. Considering that Hg biomagnifies up the food web, piscivorous species can have Hg concentrations up to 15 times higher than those of their prey (Wiener et al., 2003). Bioaccumulation of Hg in animal tissues is attributed mainly to dietary intake, consequently, Hg in elasmobranchs' tissues should reflect local food resources consumed by a species or individual (Bisi et al., 2012; Domi et al., 2005; Morel et al., 1998). While the diet of *T. peruana* has been previously described as mainly piscivorous based on stomach contents, stable isotopes revealed that this species actually had a lower trophic position than the other species examined in this study (Espinoza et al., 2015). The diet of *M. henlei*, *R. velezi* and *Z. xyster* consist primarily of crustaceans (e.g., decapods and stomatopods) and to a lesser extent teleosts (Navia et al., 2007; Espinoza et al., 2012, 2013), yet these species had higher trophic levels than *T. peruana* based on δ^{15}N. Based on these findings, Espinoza et al. (2015) suggested that stomach content data for *T. peruana* did not reflect the full extent of its diet, which may consist of a more diverse range of prey.

Our study showed that *T. peruana* had significantly higher δ^{13}C values, indicating that they were feeding in a more nearshore or benthic habitat relative to the other species, a pattern that was also reported by Espinoza et al. (2015). Mercury intake can be highly influenced by a species' feeding ground. Environmental factors such us latitude, depth, temperature and productivity, in addition to prey availability often change between local food webs, which indeed can affect Hg dynamics (Lavoie et al., 2013). Our results suggest that *T. peruana* may be feeding from a different food web, which may explain why this species showed a significant higher Hg concentration.

A final variable to consider is gender, which has been reported to influence Hg concentration in some elasmobranchs (Penedo de Pinho et al., 2002). This effect is attributed to physiological and size differences between sexes. Female demersal sharks are usually larger and have higher growth rates than males (up to 40%) (Daley et al., 2002). Also, in some shark species Hg can be transferred from the female to the eggs, or directly to the embryo in matrotrophic species (Lyons et al., 2013). According

to these life history characteristics, adult females are expected to have lower Hg concentration than adult males. Differences in Hg concentration between males and females were not observed for the individuals examined in this study. Moreover, sex influence on Hg accumulation should be evaluated taking into account other important factors such as maturity and reproductive strategies. These characteristics were not considered in this study due to limited sample size. Although it is possible that sex and stage of maturity have no effect on Hg uptake on this particular system, further studies should investigate the role of these drivers.

4.4. Hg concentrations compared with consumption guidelines

Muscle Hg concentrations reported in this study were lower than maximum levels proposed for human consumption. Our results suggest that consumption of meat (i.e. muscle tissue) from the elasmobranch species examined in this study do not represent a risk for human health. However, to better assess the individual Hg intake and exposure from shark meat consumption, information of portion size, frequency of consumption and body weight are needed. In Costa Rica, shark meat is one of the least consumed fish meats, average consumption is less than 0.2 kg/person/year, contrary to 1.21 kg/person/year of sea bass and 0.92 kg/person/year of tuna fish (PIMA, 2013). Shark muscle tissue fillets, however, are often "mislabeled" and sold under different names in the national market, meaning that the current data (PIMA, 2013) might represent an underestimation of the actual consumption. Additional (household) studies may be carried out to obtain detailed information on consumption of shark and ray muscle tissue, such as portion size and frequency of consumption. This data should be complemented with consumer information such as gender, age and body weight, in order to get a better assessment of health risks. Further analysis of Hg concentration in commonly consumed teleost species will also be important to get better estimates of Hg exposure from fish consumption in the Costa Rican population. In addition, the risks of Hg bioaccumulation for these elasmobranch species should be studied, including accumulation rate in other tissues such as liver and blood.

5. Conclusions

This study provides the first examination of THg muscle tissue concentrations in marine fishes, specifically for elasmobranchs in the Central American region. The variations in Hg concentrations among species were likely influenced by their feeding ecology, physiological differences in Hg assimilation and metabolic capacity in processing Hg. In spite of important natural sources of Hg (e.g. volcanic activity) in Costa Rica, we found low Hg concentrations – relative to similar species in other regions of the world – in muscle of demersal elasmobranchs. Our findings suggest that natural emissions in the region might not be comparable with emissions from industrial activity in other regions of the world.

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