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Mercury contamination in the recently described Brazilian white-tail dogfish *Squalus albicaudus* (Squalidae, Chondrichthyes)

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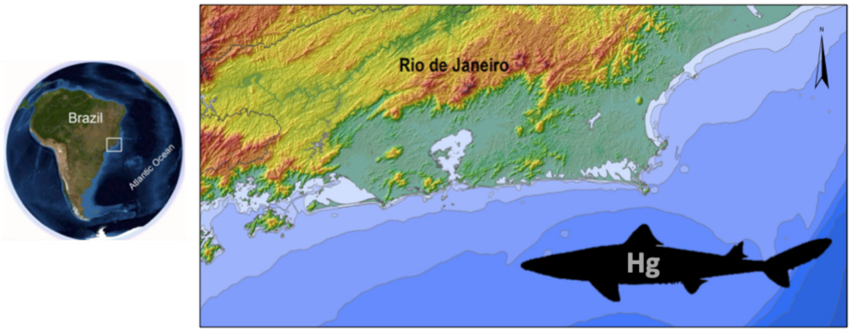
HIGHLIGHTS

- This study reports the first ecotoxicological report for *S. albicaudus*.
- Total Hg in 32 specimens sampled off the coast of Rio de Janeiro were determined.
- Hg levels in muscle, liver, gonads and brain were above toxic thresholds for fish.
- Maternal THg offloading was noted, and embryo Hg was above toxic thresholds for fish.
- THg in males and embryos were higher compared to other *Squalus* species worldwide.

GRAPHICAL ABSTRACT



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ABSTRACT

The recently described *Squalus albicaudus* is a mesopredator shark and, as such, exposed to mercury biomagnification processes. Therefore, this study aimed to assess total Hg (THg) concentrations in *S. albicaudus*, a deep-water species, sampled off Southeastern Brazil and discuss ecological, reproductive, human consumption and conservation implications. Thirty-two individuals were sampled off the coast of Rio de Janeiro, including 13 gravid females carrying 34 embryos. Muscle THg concentrations were higher in all sex classes compared to liver, gonads and brain. The last three, in turn, presented THg concentrations above toxic biota thresholds. Significant correlations were observed between muscle and brain and liver, indicating systemic Hg contamination and inter-organ transport and distribution. In addition, correlations observed between organs strongly support efficient Hg blood-brain barrier crossing and maternal transfer. Maternal THg transfer was observed, with embryo THg also above toxic thresholds for fish. THg levels in muscle and liver, as well as embryos, were higher compared to other *Squalus* species

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Public health risks
Food safety

worldwide. Hg contamination off the coast of Rio de Janeiro is of significant concern and should be further assessed. Potential human consumption risks are noted, as muscle THg concentrations were above maximum permissible levels set by regulatory agencies.

1. Introduction

Environmental aquatic contamination by pollutants that result in toxic and cumulative biota effects, such as metals, has reached global proportions due to the persistence and mobility of these contaminants (Ali et al., 2019). Among toxic metals, mercury (Hg) is of significant concern, as this compound is highly toxic and tends to bioaccumulate and biomagnify throughout trophic webs (Harding et al., 2018). In aquatic ecosystems, this element is found, mainly, in its inorganic form, associated with the sediment or distributed throughout the water column. The interaction of inorganic Hg with different biotic and abiotic factors can favor mercury methylation, where conversion to organic Hg, methylmercury, occurs mainly through bacterial methylation (de Lacerda and Malm, 2008). Methylmercury is the most toxic form of this element, as it is easily absorbed and assimilated by organisms and displays a high affinity for the sulfhydryl groups present in proteins, capable of crossing both the blood brain and placental barriers (Zahir et al., 2005).

Alarming mercury concentrations have been detected in several Brazilian regions, including the highly anthropogenic Guanabara Bay. Over 6000 industries are located around the bay's drainage basin, contributing to the discharge of a wide range of industrial chemicals, such as halogenated hydrocarbons and metals, into the surrounding aquatic environments (Hauser-Davis et al., 2019; Kjerfve et al., 1997; Rosenfelder et al., 2012). Studies, however, are mostly available for the interior Guanabara Bay, and assessments off the Rio de Janeiro coast are scarce.

Approximately 30% of all elasmobranchs are threatened with extinction (Dulvy et al., 2014) and 47% of all elasmobranch species are classified by the International Union for Conservation of Nature (IUCN) as data deficient (Dulvy et al., 2014; Mace et al., 2008). In Brazil, about 33% of all elasmobranchs are categorized as threatened, while 36% are considered data deficient (Silveira, Luis Fábio (Departamento de Zoologia, Instituto de Biociências and Straube, 2009). In this scenario, most Brazilian shark populations are currently depleted, and data on coastal species is very poor (Bornatowski et al., 2018). Shark species are particularly vulnerable to fishing. Their life history is characterized by slow growth, late sexual maturation, long life expectancy and low fecundity (Cortés, 2004). These attributes result in low population growth rates and limited capacity to withstand fishing pressures, leading to rapid population declines (Dulvy et al., 2014).

Shark species belonging to the *Squalus* genus present a global distribution, from continental shelves to submarine crevices in the Atlantic, Pacific and Indian Oceans. These sharks are distributed near the coast in temperate regions and far from the coast, in deeper waters, in the tropics (Edwards, 1986). A recent taxonomic revision performed for the *Squalus* genus in the southwest Atlantic has led to the redescription of the former *Squalus cubensis* (Howell-Rivero, 1936) or *Squalus cubensis/megalops* (Gadig, 2001) now reassigned as *Squalus albicaudus* (Viana et al., 2016), popularly called the Brazilian white-tailed dogfish. This small shark, reaching up to 75 cm in total length, is demersal, occurring between 50 and 400 m in depth, with a geographic range extending from southern Bahia to the state of São Paulo. This species is a mesopredator, feeding on benthic invertebrates and small bony fish (Viana et al., 2016), and is, thus, exposed to mercury biomagnification processes, although ecotoxicological data is lacking for this still biologically unknown species. As this species has been recently described, no data is available on its biology. Although not of great commercial importance in Brazil, the species is caught by industrial bottom longline fishing and landed by the name *cação-bagre* or *cação-gato*.

In this context, the present study aimed to assess total Hg (THg) concentrations in *Squalus albicaudus* specimens sampled off the coast of Rio de Janeiro, Southeastern Brazil and discuss ecological, reproductive, human consumption and conservation implications.

2. Material and methods

2.1. *Squalus albicaudus* sampling and processing

The *Squalus albicaudus* specimens analyzed herein were obtained through sport fishing with a bottom line and donated for research by a member of the Rio de Janeiro Yacht Club (ICRJ). Captures took place from November 2015 to October 2017, at four points along the coast of the state of Rio de Janeiro, at a distance of about 50–70 nautical miles from Guanabara Bay, at depths ranging from 150 to 300 m (Fig. 1). The specimens were frozen right after being fished and maintained in the ICRJ cold room until taken to the Federal University of Rio de Janeiro Fisheries Biology and Technology Laboratory. Individuals were identified at the species level, according to specialized literature (Viana et al., 2016).

At the laboratory, the specimens were measured (total length, in centimeters), weighed (total weight, in grams) and sexed. Maturation stages were determined from the macroscopic analysis of the reproductive tract and gonad aspect (Andrade et al., 2008). Muscle, liver, brain and gonad (ovaries or testes) samples were removed. Embryos when present were also analyzed, whole, as, in some cases, organs were not yet formed. After dissection, each sample was weighed (g), identified and freeze-dried.

For the THg analyses, about 0.5 g of the freeze-dried samples were digested with a concentrated 1:1 sulfuric and nitric acid solution in a water bath at 60 °C until complete solubilization, after about 2 h. Then, a 5% potassium permanganate solution was added, followed by a further 15 min in the water bath in the same conditions. After removal from the water bath, the samples were left to stand overnight at room temperature. The following day, 1 mL of 12% hydroxylamine hydrochloride were added. THg concentrations were determined by cold vapor generator atomic absorption spectrometry, using a Flow Injection Mercury System (FIMS 400) coupled to an AS 93 Plus autosampler. All samples and analytical blanks were analyzed in triplicate. Analytical control was performed using a certified reference material (DORM-3, National Research Council, Canada), also analyzed in triplicate. The certified reference material Hg recovery value was of 93.07% (Observed value: 355.52 ± 5.46 mg kg^{-1}; certified value: 382.00 ± 0.06), and, thus, considered adequate (Eurachem, 1998).

2.2. Statistical analyses

The data were analyzed using the Statistica 7 software for

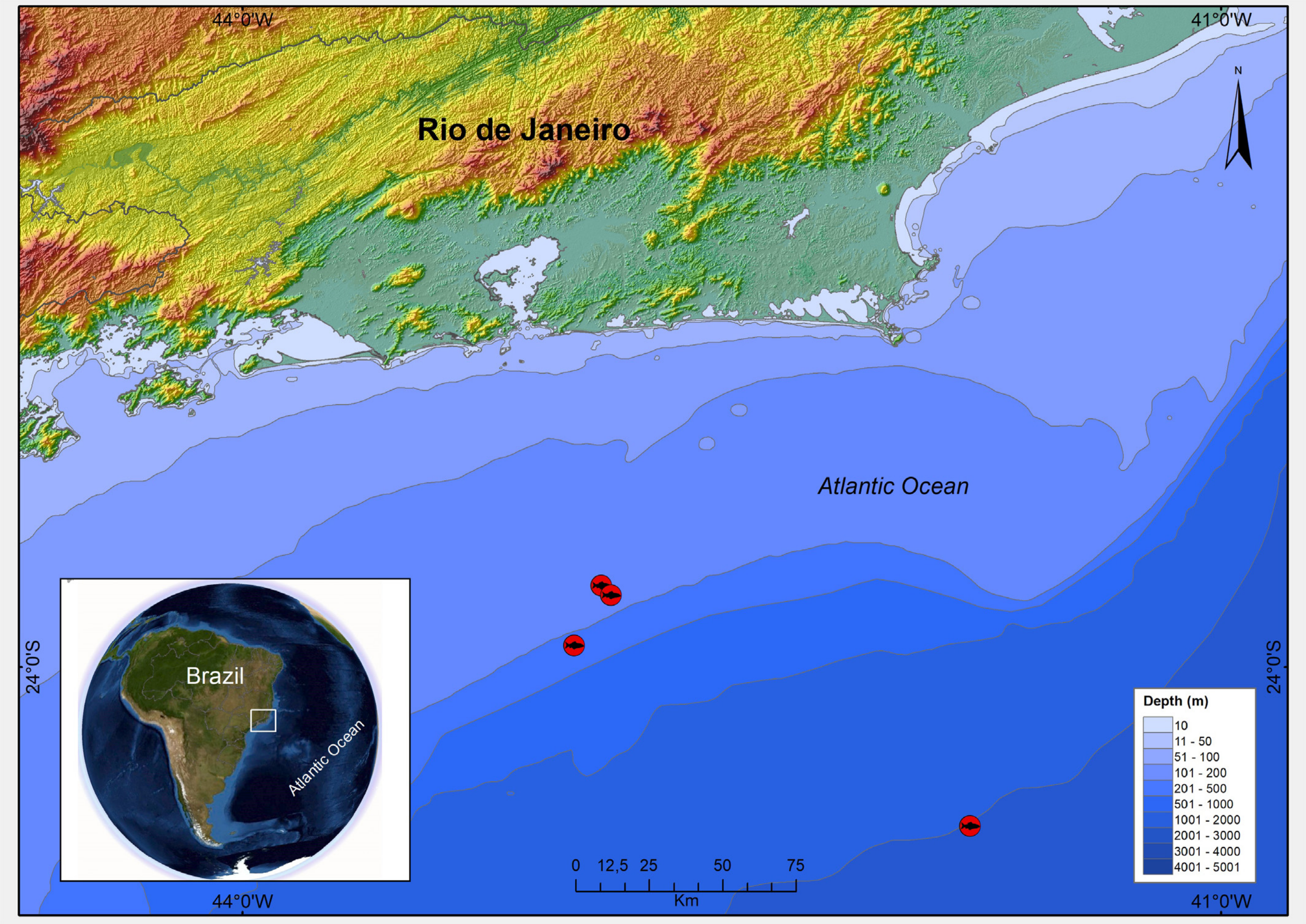

Fig. 1. *Squalus albicaudus* sampling points off the coast of Rio de Janeiro, Southeastern Brazil.

Windows. Data normality was tested using the Shapiro-Wilk test, at a significance level of $p < 0.05$. Data distribution was assessed by the Shapiro-Wilke normality test. Significant differences between muscle, liver, gonads and brain Hg concentrations for each category were assessed by the Kruskal-Walls test (Zar, 1988). Significant correlations between THg values in each tissue were verified by Spearman's correlation test, applying. The correlation strength patterns proposed by Bryman and Cramer ((Bryman, 2012) were applied. In addition, maternal transfer was assessed by correlating muscle and liver Hg in the mothers to Hg concentrations in the embryos, also through Spearman's correlation test. Differences between THg concentrations in the different litters were assessed by the Kruskal-Walls ANOVA test (Zar, 1988).

3. Results and discussion

3.1. *Squalus albicaudus* biomorphometric

The biomorphometric data for the *Squalus albicaudus* individuals sampled off the coast of Rio de Janeiro are displayed in Table 1.

3.2. *Squalus albicaudus* THg concentrations

Total mercury concentrations in the muscle, liver, gonads and brain of *S. albicaudus* individuals sampled off the coast of Rio de Janeiro for each category are displayed in Fig. 2. Significantly lower ($p < 0.05$) liver, gonad and brain concentrations were observed compared to muscle in gravid females, whereas only significantly lower ($p < 0.05$) gonad concentrations in comparison to muscle where observed for non-gravid females. For juvenile females, significant differences ($p < 0.05$) were noted only between muscle and liver. For males (grouped, as only one juvenile individual was analyzed), significant differences ($p < 0.05$) were observed between muscle and gonads, and between muscle and brain. Although one of the sampling sites is located further offshore in comparison to the other three sites, many deep-water species present vertical migration in circadian cycles to epipelagic zones at night and

Table 1
Biomorphometric data for *Squalus albicaudus* individuals sampled from the Rio de Janeiro, Southeastern Brazil, categorized by age group for each sex. SD – standard deviation.

Sex	Category	N	Length (cm)				
			Mean	Median	Minimum	Maximum	SD
Female	Adult females	20	54.0	54.0	49.0	57.3	1.94
	Juvenile females	6	47.8	47.5	45.2	51.5	2.12
	Gravid females	13	54.45	54.25	51.5	57.3	1.59
Embryo	Embryos	34	12.14	12.95	3.200	18.50	4.32
Male	Adult male	5	46.6	46.1	41.8	53.6	4.31
	Juvenile male	1	46.7	46.7	46.7	46.7	–[a]

[a] No SD, only one sampled specimen.

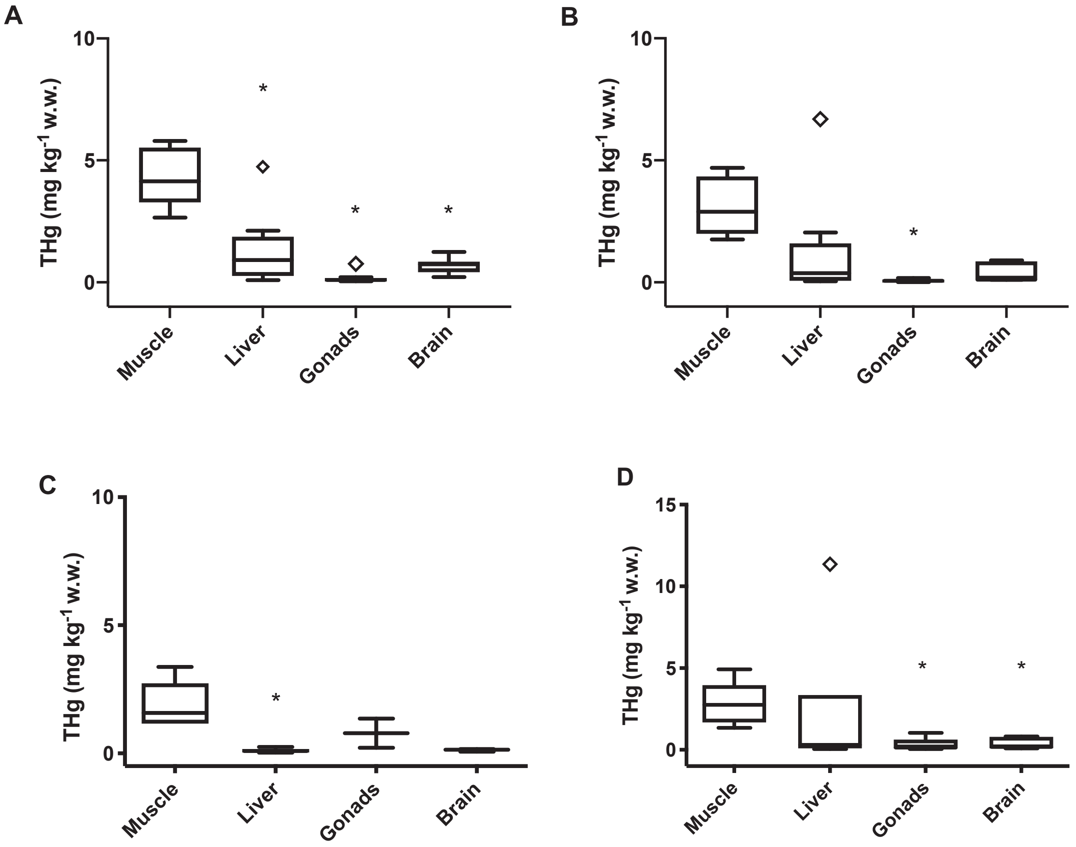

Fig. 2. Total mercury concentrations in the muscle, liver, gonads and brain of *Squalus albicaudus* individuals sampled off the Rio de Janeiro, Southeastern Brazil, categorized by group for each sex. Data are expressed as mg kg^{-1} wet weight. (A) Gravid females; (B) Non-gravid females; (C) Juvenile females; (D) Male adults and juveniles. ◇ indicate outliers by Tukey's test. Asterisks on different organ data indicate statistically significant differences between groups compared to muscle tissue at $p < 0.05$.

deeper waters during the day, as well as bathymetric reproductive migrations (Priede et al., 2006). Thus, sampling depth is relative in this case, and cannot be implicated in different Hg levels.

Correlation data between THg values in different tissues tested by Spearman's correlation test are displayed in Table 2. No significant correlations were observed for female juveniles.

The significant correlations observed between muscle and brain and liver, respectively, and indicate systemic Hg contamination and transport between organs, with Hg displaying the ability to cross the blood brain barrier, corroborating literature references (Zahir et al., 2005). A strong significant correlation between liver and gonad THg concentrations in males also indicates THg transport to reproductive organs, which may lead to reproductive concerns (Sandheinrich and Wiener, 2011), as Hg has been reported as disrupting reproductive functions in fish, i.e. by affecting sperm motility (Dietrich et al., 2010; Popek et al., 2006) and altering reproductive success (Crump and Trudeau, 2009; Van Look and Kime, 2003). However, ecotoxicological data for *S. albicaudus* is nonexistent. Therefore, comparisons with THg concentrations worldwide for other species belonging to the *Squalus* genus were performed and are displayed in Table 3.

The THg concentrations observed herein in *S. albicaudus* male muscle tissue are higher than those observed in other studies worldwide for most species belonging to the *Squalus* genus, similar only to male *S. mitsukurii* from Crete, Greece (Kousteni et al., 2006). Not many studies concerning liver THg concentrations are available, but the data presented herein are an order of magnitude higher than the THg concentrations reported in the only other study carried out on *Squalus* liver, by Endo et al. (2009) for both male and female *S. acanthias* liver samples from Japan. Concerning embryo concentrations, the data reported herein is also one order of magnitude higher than other studies reporting both male, female

Table 2
Spearman correlations between *Squalus albicaudus* tissues in individuals sampled from the Rio de Janeiro, Southeastern Brazil, categorized by group for each sex.

Association	Statistical parameters	Non-gravid females	Gravid females	Female juveniles	Males (grouped)
Muscle x liver	p	0.003	ns	ns	0.033
	R	0.879	ns	ns	0.890
Muscle x brain	p	ns	ns	ns	0.016
	R	ns	ns	ns	0.940
Brain x liver	p	ns	0.037	ns	0.016
	R	ns	0.762	ns	0.943
Liver x gonads	p	0.046	ns	ns	0.016
	R	0.738	ns	ns	1.000

Ns — non-significant association (p.0.05).

Table 3
Review of *Squalus* genus total Hg concentrations worldwide. Data are expressed as mg kg^{-1} wet weight.

Reference	Area	Species	Sex	n	Organ	THg concentrations (means ± SD)	THg range (minimum-maximum)
The present study	Rio de Janeiro, Brazil	*S. albicaudus*	Males	6	Muscle	2.86 ± 1.29	1.35–4.93
					Liver	2.13 ± 4.52	0.05–11.3
			Females	26	Muscle	1.02 ± 1.53	1.15–5.80
					Liver	3.37 ± 1.46	0.030–6.69
			Embryos	34	Whole embryos	0.21 ± 0.13	0.02–0.623
Forrester et al. (1972)	Strait of Georgia, British Columbia	*S. acanthias*	Males	82	Muscle	1.68	–
			Females	124	Muscle	1.96	–
			Embryos	12	Whole embryos	0.02 ± 0.01	0.01–0.05
Taguchi et al. (1979)	Japan	*S. mitsukurii*	Males	29	Muscle	1.12 ± 0.58	0.02–2.11
			Females	30	Muscle	1.29 ± 0.57	0.44–2.13
			Embryos (male)	27	Whole embryos	0.03	–
			Embryos (female)	20	Whole embryos	0.30	–
Pinho et al. (2002)	Between Espírito Santo and Bahia (Brazil)	***S. megalops***[a]	Males	3	Muscle	1.59 ± 1.0	–
			Females	18	Muscle	1.51 ± 0.5	–
		S. mitsukurii	Males	15	Muscle	2.08 ± 0.7	–
			Females	19	Muscle	2.34 ± 0.7	–
Kousteni et al. (2006)	Crete, Greece	*S. acanthias*	Males	36	Muscle	2.34 ± 1.94	0–3.78
			Females	11	Muscle	2.01 ± 0.94	0–5.78
Endo et al. (2009)	Japan	*S. acanthias*	Males	35	Liver	0.02 ± 0.01	0.01 ± 0.07
					Muscle	0.31 ± 0.20	0.11 ± 0.86
			Females	40	Liver	0.03 ± 0.22	0.01 ± 0.11
					Muscle	0.38 ± 0.38	0.112 ± 1.87
Pethybridge et al. (2010)	Southeastern Australia	*S. acanthias*	Adults	18	Muscle	1.40 ± 0.40	0.80–1.80
		S. megalops	Males	10	Muscle	1.40 ± 0.50	0.60–2.10
		S. mitsukurii	Adults (grouped)	13	Muscle	2.60 ± 0.70	1.80–3.70
			Males (juveniles)	8	Muscle	0.90 ± 0.10	0.80–1.00
(St. Gelais and Costa-Pierce, 2016)	Rhode Island, USA	*S. acanthias*	Male	57	Muscle	0.92 ± 0.30	–

[a] Possibly *S. albicaudus*, due to aforementioned recent taxonomic revision.

and grouped embryo *S. acanthias* and *S. mitsukurii* concentrations from British Columbia (Forrester et al., 1972) and Japan (Taguchi et al., 1979), respectively.

Comparisons to Brazilian elasmobranch fisheries in Southeastern Brazil are scarce in general, and even more so for members of the *Squalus* genus. The only study carried out in this regard in this area was performed by Pinho et al. who noted means and standard deviations of 1.59 ± 1.00 mg kg^{-1} w.w. and 1.09 ± 0.50 mg kg^{-1} w.w. for male and female *S. megalops* muscle tissue and 2.08 ± 0.70 mg kg^{-1} w.w. and 2.34 ± 0.70 mg kg^{-1} w.w. for male and female *S. mitsukirri* muscle tissue, respectively (Pinho et al., 2002). Compared to our findings, higher Hg levels in muscle tissue was observed for male *S. albicaudus* specimens compared to *both S. megalops* and *S. mitsukirri*, and lower levels for females, which may be due to maternal offloading. The same authors also assessed other elasmobranchs, such as *Mustelus canis* (dusky smooth-hound, or smooth dogfish) and *Mustelus norrisi* (narrowfin smooth-hound), reporting values of 0.45 ± 0.40 mg kg^{-1} w.w. and 0.35 ± 0.30 mg kg^{-1} w.w. for male and female of the former species, and 0.50 ± 0.30 mg kg^{-1} w.w. and 0.29 ± 0.30 mg kg^{-1} w.w. for male and females of the later species. It is important, to note, however, that the sampling area assessed by Pinho et al. was quite large, ranging from south to northeastern Brazil within 200 miles from the coast. In addition, both *Squalus* species are categorized as a higher trophic level, as they prey on fish, when compared to both *Mustelus* species, who feed on invertebrates (Pinho et al., 2002) accounting for the observed differences in Hg concentrations.

In another study carried out in Southeastern Brazil, Lacerda et al. sampled three elasmobranchs off the coast of northeastern Rio de Janeiro, *Rhizoprionodon lalandii* (Valenciennes, 1841), *Rhizoprionodon porosus* (Poey, 1861) and *Mustelus higmani* (Springer & Lowe, 1963) (Lacerda et al., 2000). Mean values for each species were as follows: *R. lalandii*, 17.9 ng g^{-1} wet weight; *R. porosus*, 9.4 ng g^{-1} wet weight and *M. higmani*, 13.4 ng g^{-1} wet weight. No further standard deviation or sex information is given in this assessment. Differences among Hg concentrations were also indicated by the authors as due to feeding habits, as *R. lalandii* is piscivorous, while *R. porosus* and *M. higmani* are omnivorous, feeding on mollusks and crustaceans (Lacerda et al., 2000).

In a study carried out in southern Brazil, Mársico et al. analyzed three elasmobranchs, *Prionace glauca* (blue shark) *Isurus oxyrinchus* (shortfin mako) and *Sphyrna zygaena* (smooth hammerhead shark), samples at depths of about 50 m and at approximately 190 miles off the coast of Santa Catarina. Mean muscle Hg concentrations were of 0.34 ± 0.29 mg kg^{-1} w.w. for *P. glauca*, 0.384 ± 0.24 mg kg^{-1} w.w. for *I. oxyrinchus* and 0.44 ± 0.30 mg kg^{-1} w.w. for *S. zygaena*, although data were grouped for both male and females (Mársico et al., 2007).

Finally, in a study concerning *P. glauca* specimens sampled from an area ranging from south to northeastern Brazil, Dias et al. reported total mean muscle Hg levels as 0.76 mg kg^{-1} w.w. No further standard deviation or sex information is given in this assessment (Dias et al., 2008).

Compared to Hg concentrations from members of the *Squalus* genus, as well as other elasmobranchs species caught in the same fishery and in other Brazilian regions, *S. albicaudus* Hg values are higher in all cases, except for females compared to Pinho et al. (2002).

Table 4
Mean mercury concentrations in *Squalus albicaudus* mother-embryo pairs sampled off the Rio de Janeiro, Southeastern Brazil. Concentrations expressed as mg g^{-1} wet weight.

Mother ID	Embryo ID	Individual embryo THg	THg litter means	THg mother muscle	THg mother liver
SM03	1	0.22	0.23 ± 0.04	4.11	0.79
	2	0.28			
	3	0.19			
SM04	1	0.21	0.18 ± 0.04	2.7	0.10
	2	0.14			
SM10	1	0.30	0.30 ± 0.01	5.09	1.26
	2	0.29			
	3	0.30			
SM11	1	0.62	0.38 ± 0.21	5.53	2.12
	2	0.21			
	3	0.31			
SM12	1	0.21	0.21	5.80	1.24
SM13	1	0.35	0.30 ± 0.09	5.31	1.87
	2	0.37			
	3	0.20			
SM14	1	0.45	0.38 ± 0.09	3.98	4.74
	2	0.27			
	3	0.42			
SM15	1	0.02	0.02 ± 0.00	1.94	0.06
	2	0.02			
SM18	1	0.04	0.03 ± 0.01	2.91	0.09
	2	0.02			
	3	0.03			
SM19	1	0.14	0.11 ± 0.03	5.79	0.91
	2	0.11			
	3	0.08			
SM20	1	0.09	0.13 ± 0.05	3.89	0.26
	2	0.09			
	3	0.11			
	4	0.21			
SM33	1	0.16	0.19 ± 0.05	2.53	1.16
	2	0.23			
SM35	1	0.27	0.23 ± 0.05	4.58	2.04
	2	0.20			

Guanabara Bay Hg contamination derives from several sources, including the discharge of contaminated rivers, atmospheric deposition, landfill runoff, a chlor-alkali Plant located on the northwestern side of the Bay and several diffuse sources (Covelli et al., 2012). The bay acts as an exporter for this and many other contaminants, due to oceanic currents and a local upwelling phenomenon (Carreira et al., 2012; Martins et al., 2016). In addition, Hg biomagnification and bioaccumulation assessed in local trophic webs have been reported for this area, where Hg in its most toxic form, methylmercury, has been shown to biomagnify from prey (microplankton, mesoplankton and fish with different feeding habits) to top predators (pelagic-demersal fish) (Kehrig et al., 2011). Thus, Hg contamination off the coast of Rio de Janeiro is of concern and should be further assessed.

Mercury is considered a potent neurotoxin, due to its high protein affinity and ability to accumulate in several organs including the brain, as it is able cross the blood-brain barrier (Zahir et al., 2005). Several altered biochemical responses such as increased reactive oxygen species, cellular and DNA damage and altered nervous system enzymatic activity have been reported at Hg concentrations as low as 0.008 mg kg^{-1} wet weight in muscle, while the threshold for vital behavioral changes in fish, such as swimming, foraging and reproduction activities have been reported at approximately 0.135 mg kg^{-1} wet weight in muscle (Sandheinrich and Wiener, 2011). This may indicate concerns regarding *S. albicaudus*, as Hg concentrations in adults were significantly higher than these toxic thresholds, while embryo concentrations also exceeded both aforementioned thresholds for fish, albeit to a lesser extent. It is important to note, however, that the aforementioned thresholds are for freshwater species, and that no that no thresholds for marine fish have yet been determined. Thus, these thresholds may not be appropriate for comparisons, as many predatory marine fish species present higher Hg levels in muscle tissue than the stipulated 0.135 mg kg^{-1} wet weight threshold and, apparently, do not seem to display deleterious behavior and/or biochemical responses, although further studies are required in this regard.

3.3. Maternal transfer data

Maternal offloading was assessed by comparing contaminant concentrations between mother and embryo liver and muscle tissue (Dutton and Venuti, 2019), and are displayed in Table 4.

No significant correlations were observed when assessing each mother's mean muscle or liver THg concentrations and their respective embryos. However, when Hg data for all mothers and all embryos were grouped (i.e. averaged data for all mothers concerning (i) muscle Hg and (ii) liver (Hg) correlated to averaged Hg data for all litters (whole embryos), a significant very strong correlation was noted between mother liver THg concentrations and litter THg concentrations ($p = 0.0000$; $r = 0.912$). The significant very strong correlation observed herein contrasts with previous literature assessments in this regard, compared to the only two studies concerning maternal Hg transfer for *Squalus* species are available, from the 70s (Forrester et al., 1972; Taguchi et al., 1979).

Maternal contaminant transfer, an important *in utero* contaminant exposure pathway, is a passive process consisting in the transfer of bioaccumulated contaminants from mother to offspring during lactation or gestation (van Hees and Ebert, 2017). *S. albicaudus* is presumably aplacental like the rest of its genus. Embryos of aplacental sharks display lecithotrophy, i.e. they feed on external and internal yolk sac reserves, and no supplementary maternal contribution occurs (Braccini et al., 2012; Guallart and Vicent, 2001; Kousteni and Megalofonou, 2016).

Recent studies in this regard are scarce, with only one report for a *Squalus* member, *S. megalops*, available, where embryos presented lower Hg concentrations than their mothers in muscle and liver tissues (Le Bourg et al., 2014), similarly to the present findings. Concerning other aplacental elasmobranchs, Dutton and Venuti also observed lower embryo Hg concentrations compared to mother tissues (Dutton and Venuti, 2019).

Embryo Hg concentrations as a percentage of mother muscle and liver concentrations were calculated for *S. albicaudus* (4.9%) and were similar, albeit slightly lower than that reported for another aplacental species, *Alopias vulpinus* by both Dutton and Venuti (6.6%) (Dutton and Venuti, 2019) and Lyons and Lowe et al. of 8.1% (Lyons and Lowe, 2013). This low value is expected for an aplacental species, due to the aforementioned lecithotrophy characteristic. Embryo Hg percentage compared to mother liver values, however, were much higher, at 41.5%, not reported by the aforementioned authors, as they analyzed only muscle tissue.

3.4. Human consumption implications

All Hg values in the muscle tissue of the assessed *S. albicaudus* specimens were above the stipulated limit of 0.5 mg kg^{-1} THg in seafood for the European Union (European Commission, 2006) and the World Health Organization (FAO/WHO, 2010), as well as above Brazilian's ANVISA recommendations of 0.5 mg kg^{-1} for non-predatory fish and 1.0 mg kg^{-1} for predatory species. However, as shark meat is sold in Brazil under the generic designation of *cação*, consumers may be buying shark meat without knowing (Bornatowski et al., 2018) and, thus, ingesting high Hg amounts. Thus, consumer health risks are a possibility, as there seems to be no safe amount for *S. albicaudus* consumption.

4. Conclusions

This is, to the best of our knowledge, the first report on Hg data for *Squalus albicaudus* from southeastern Brazil. Mercury was detected in all assessed organs, indicating systemic Hg contamination and inter-organ transport, and concentrations were above the only toxic thresholds set for fish. These values, however, are set for freshwater species only, indicating a lack of adequate thresholds for marine species.

Maternal THg transfer was observed, and lower embryo THg concentrations were observed compared to mother concentrations, corroborating previous assessments on aplacental sharks. Embryo THg concentrations were also above the aforementioned toxic thresholds set for fish.

In general, higher THg concentrations were noted compared to other studies conducted both worldwide and in Brazil, some in the same Rio de Janeiro fisheries, for *Squalus* members and also other elasmobranchs, probably due to the neighboring Guanabara Bay oceanographic dynamics, leading to high Hg contamination off the coast of Rio de Janeiro. In addition, THg levels were above the maximum permissible limits stipulated by several regulation agencies, indicating potential consumer health risks regarding *S. albicaudus* ingestion.

As a mesopredator, this species is an essential trophic regulator, and potential ecological risks due to the high Hg contamination described in this study in this recently described and totally biologically unknown species are a concern.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Rachel Ann Hauser-Davis: Data curation, Visualization, Writing - original draft, Writing - review & editing. **Camila Ferreira Pereira:** Visualization, Investigation, Validation, Data curation. **Fernando Pinto:** Conceptualization, Resources, Funding acquisition, Writing - original draft. **João Paulo M. Torres:** Conceptualization, Resources, Funding acquisition, Writing - original draft. **Olaf Malm:** Conceptualization, Resources, Funding acquisition, Writing - original draft. **Marcelo Vianna:** Conceptualization, Funding acquisition, Project administration, Writing - original draft, Writing - review & editing, Supervision.

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References

Ali, H., Khan, E., Ilahi, I., 2019. Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity, and bioaccumulation. J. Chem. 2019, 1–14.

Andrade, A.C., Silva-Junior, L.C., Vianna, M., 2008. Reproductive biology and population variables of the Brazilian sharpnose shark Rhizoprionodon lalandii (Müller & Henle, 1839) captured in coastal waters of south-eastern Brazil. J. Fish. Biol. 72, 473–484.

Bornatowski, H., Braga, R.R., Barreto, R.P., 2018. Elasmobranchs consumption in Brazil: impacts and consequences. In: Rossi-Santos, M.R., Finkl, C.W. (Eds.), Advances in Marine Vertebrate Research in Latin America. Coastal Research Library, pp. 251–262.

Braccini, M., van Rijn, J., Frick, L., 2012. High post-capture survival for sharks, rays and chimaeras discarded in the main shark fishery of Australia? PloS One 7, e32547.

Bryman, A., 2012. Quantitative data analysis with IBM SPSS 17, 18 & 19, Quantitative Data Analysis with IBM SPSS, 17, pp. 18–19.

Carreira, R. da S., Canuel, E.A., Macko, S.A., Lopes, M.B., Luz, L.G., Jasmim, L.N., 2012. On the accumulation of organic matter on the southeastern Brazilian continental shelf: a case study based on a sediment core from the shelf off Rio de Janeiro. Braz. J. Oceanogr. 60, 75–87.

Cortés, E., 2004. Life history patterns, demography, and population dynamics. In: Biology of Sharks and Their Relatives, pp. 449–470.

Covelli, S., Protopsalti, I., Acquavita, A., Sperle, M., Bonardi, M., Emili, A., 2012. Spatial variation, speciation and sedimentary records of mercury in the Guanabara Bay (Rio de Janeiro, Brazil). Continent. Shelf Res. 35, 29–42.

Crump, K.L., Trudeau, V.L., 2009. Mercury-induced reproductive impairment in fish. Environ. Toxicol. Chem. 28 (5), 895–907.

de Lacerda, L.D., Malm, O., 2008. Contaminação por mercúrio em ecossistemas aquáticos: Uma análise das áreas críticas. Estud. Avançados 22, 173–190.

Dias, A.C.L., Guimarães, J.R.D., Malm, O., Costa, P.A.S., 2008. Mercúrio total em músculo de cação Prionace glauca (Linnaeus, 1758) e de espadarte Xiphias gladius Linnaeus, 1758, na costa sul-sudeste do Brasil e suas implicações para a saúde pública. Cad. Saúde Pública 24, 2063–2070.

Dietrich, G.J., Dietrich, M., Kowalski, R.K., Dobosz, S., Karol, H., Demianowicz, W., Glogowski, J., 2010. Exposure of rainbow trout milt to mercury and cadmium alters sperm motility parameters and reproductive success. Aquat. Toxicol. 97, 277–284.

Dulvy, N.K., Fowler, S.L., Musick, J.A., Cavanagh, R.D., Kyne, P.M., Harrison, L.R., Carlson, J.K., Davidson, L.N.K., Fordham, S.V., Francis, M.P., Pollock, C.M., Simpfendorfer, C.A., Burgess, G.H., Carpenter, K.E., Compagno, L.J.V., Ebert, D.A., Gibson, C., Heupel, M.R., Livingstone, S.R., Sanciangco, J.C., Stevens, J.D., Valenti, S., White, W.T., 2014. Extinction risk and conservation of the world's sharks and rays. Elife, 2014, e00590.

Dutton, J., Venuti, V.M., 2019. Comparison of maternal and embryonic trace element concentrations in common thresher shark (Alopias vulpinus) muscle tissue. Bull. Environ. Contam. Toxicol. 103, 380–384.

Edwards, A., 1986. Sharks of the World, Marine Pollution Bulletin. Harper Collins

Publishers, London.

Endo, T., Hisamichi, Y., Kimura, O., Kotaki, Y., Kato, Y., Ohta, C., Koga, N., Haraguchi, K., 2009. Contamination levels of mercury in the muscle of female and male spiny dogfishes (Squalus acanthias) caught off the coast of Japan. Chemosphere 77, 1333–1337.

Eurachem, 1998. The Fitness for Purpose of Analytical Methods. Eurachem Guide, 0-94948926-12-0.

European Commission, 2006. COMMISSION REGULATION (EC) No 1881/2006 of 19 December 2006. Official Journal of the European Union.

FAO/WHO, 2010. Seventy-second Meeting Rome, 16–25 February 2010. Group.

Forrester, C.R., Ketchen, K.S., Wong, C.C., 1972. Mercury content of spiny dogfish (Squalus acanthias) in the strait of Georgia, British Columbia. J. Fish. Res. Board Can. 29, 1487–1490.

Guallart, J., Vicent, J.J., 2001. Changes in composition during embryo development of the gulper shark, Centrophorus granulosus (Elasmobranchii, Centrophoridae): an assessment of maternal-embryonic nutritional relationships. Environ. Biol. Fish. 61, 135–150.

Harding, G., Dalziel, J., Vass, P., 2018. Bioaccumulation of methylmercury within the marine food web of the outer Bay of Fundy, Gulf of Maine. PloS One 13, e0197220.

Hauser-Davis, R.A., Silva-Junior, D.R., Linde-Arias, A.R., Vianna, M., 2019. Hepatic metal and metallothionein levels in a potential sentinel teleost, dules auriga, from a southeastern Brazilian estuary. Bull. Environ. Contam. Toxicol. 103, 538–543.

Kehrig, H.A., Malm, O., Palermo, E.F.A., Seixas, T.G., Baêta, A.P., Moreira, I., 2011. Bioconcentração e biomagnificação de metilmercúrio na baía de guanabara, Rio de Janeiro. Quim. Nova 34, 377–384.

Kjerfve, B., Ribeiro, C.H.A., Dias, G.T.M., Filippo, A.M., Quaresma, V. da S., 1997. Oceanographic characteristics of an impacted coastal bay: baia de Guanahara, Rio de Janeiro, Brazil. Continent. Shelf Res. 17, 1609–1643.

Kousteni, V., Megalofonou, P., 2016. Observations on the biological traits of the rare shark Oxynotus centrina (chondrichthyes: oxynotidae) in the hellenic seas. J. Fish. Biol. 89, 1880–1888.

Kousteni, V., Megalofonou, P., Dassenakis, M., Stathopoulou, E., 2006. Total mercury concentrations in edible tissues of two elasmobranch species from Crete (eastern Mediterranean sea). In: Cybium, pp. 119–123.

Lacerda, L.D., Paraquetti, H.H., Marins, R.V., Rezende, C.E., Zalmon, I.R., Gomes, M.P., Farias, V., 2000. Mercury content in shark species from the South-Eastern Brazilian coast. Braz. J. Biol. 60, 571–576.

Le Bourg, B., Kiszka, J., Bustamante, P., 2014. Mother-embryo isotope (δ15N, δ13C) fractionation and mercury (Hg) transfer in aplacental deep-sea sharks. J. Fish. Biol. 84, 1574–1581.

Lyons, K., Lowe, C.G., 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.

Mace, G.M., Collar, N.J., Gaston, K.J., Hilton-Taylor, C., Akçakaya, H.R., Leader-Williams, N., Milner-Gulland, E.J., Stuart, S.N., 2008. Quantification of extinction risk: IUCN's system for classifying threatened species. Conserv. Biol. 22 (6), 1424–1442.

Mársico, E.T., Machado, M.E.S., Knoff, M., São Clemente, S.C., 2007. Total mercury in sharks along the southern Brazilian coast. Arq. Bras. Med. Vet. Zootec. 59, 1593–1596.

Martins, J.M.A., Silva, T.S.M., Fernandes, A.M., Massone, C.G., Carreira, R.S., 2016. Characterization of particulate organic matter in a Guanabara Baycoastal ocean transect using elemental, isotopic and molecular markers. Pan Am. J. Aquat. Sci. 11, 276–291.

Pethybridge, H., Cossa, D., Butler, E.C.V., 2010. Mercury in 16 demersal sharks from southeast Australia: biotic and abiotic sources of variation and consumer health implications. Mar. Environ. Res. 69, 18–26.

Pinho, A.P., Guimarães, J.R.D., Martins, A.S., Costa, P.A.S., Olavo, G., Valentin, J., 2002. Total mercury in muscle tissue of five shark species from Brazilian offshore waters: effects of feeding habit, sex, and length. Environ. Res. 89, 250–258.

Popek, W., Dietrich, G., Glogowski, J., Demska-Zakeś, K., Drag-Kozak, E., Sionkowski, J., Łuszczek-Trojan, E., Epler, P., Demianowicz, W., Sarosiek, B., Kowalski, R., Jankun, M., Zakeś, Z., Król, J., Czerniak, S., Szczepkowski, M., 2006. Influence of heavy metals and 4-nonylphenol on reproductive function in fish. Reprod. Biol. 6, 175–188.

Priede, I.G., Froese, R., Bailey, D.M., Bergstad, O.A., Collins, M.A., Dyb, J.E., Henriques, C., Jones, E.G., King, N., 2006. The absence of sharks from abyssal regions of the world's oceans. Proc. R. Soc. B Biol. Sci. 273, 1435–1441.

Rosenfelder, N., Lehnert, K., Kaffarnik, S., Torres, J.P.M., Vianna, M., Vetter, W., 2012. Thorough analysis of polyhalogenated compounds in ray liver samples off the coast of Rio de Janeiro, Brazil. Environ. Sci. Pollut. Res. 19, 379–389.

Sandheinrich, M.B., Wiener, J.G., 2011. Methylmercury freshwater Fish : recent advances in assessing toxicity and environmentally relevant exposures. Environ. Contam. Biota 169–191.

Departamento de Zoologia, Instituto de Biociências, U.D.S.P., Straube, F.C. (Mülleriana: S.F.M.D.C.N. Silveira, Luis Fábio, 2009. Livro, Revista Brasileira de Cirurgia Cardiovascular.

St. Gelais, A.T., Costa-Pierce, B.A., 2016. Mercury concentrations in Northwest Atlantic winter-caught, male spiny dogfish (Squalus acanthias): a geographic mercury comparison and risk-reward framework for human consumption. Mar. Pollut. Bull. 102, 199–205.

Taguchi, M., Yasuda, K., Toda, S., Shimizu, M., 1979. Study of metal contents of elasmobranch fishes: part 1-metal concentration in the muscle tissues of a dogfish, squalus mitsukurii. Mar. Environ. Res. 2, 239–249.

van Hees, K.E., Ebert, D.A., 2017. An evaluation of mercury offloading in two Central California elasmobranchs. Sci. Total Environ. 590–591, 154–162.

Van Look, K.J.W., Kime, D.E., 2003. Automated sperm morphology analysis in fishes: the effect of mercury on goldfish sperm. J. Fish. Biol. 63, 1020–1033.

Viana, S.T.F., Carvalho, M.R., Gomes, U.L., 2016. Taxonomy and morphology of species of the genus Squalus linnaeus, 1758 from the southwestern atlantic ocean (chondrichthyes: squaliformes: squalidae). Zootaxa 4133, 1–89.

Zahir, F., Rizwi, S.J., Haq, S.K., Khan, R.H., 2005. Low dose mercury toxicity and human health. Environ. Toxicol. Pharmacol. 20, 351–360.

Zar, J.H., 1988. Notice concerning making good preparations for the beginning of the new school year, 1988. Annu. Rev. Popul. Law 15, 218.