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Mercury content in commercial pelagic fish and its risk assessment in the Western Indian Ocean

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Abstract

As top predators of pelagic food webs, large fish naturally bioaccumulate mercury (Hg). Determining Hg burdens in commercialized fish is essential considering the concern about effects of contaminants on human health and the legal thresholds that are therefore set for local consumption and/or exportation. Total Hg levels were measured in the muscular tissue of 183 fish of five commercially important species from the tropical zone of the Western Indian Ocean. All individuals were measured and sexed in order to study the impregnation of Hg with size and sex within each species. Values of Hg found in this part of the Indian Ocean were comparable to Hg in muscular tissue of the same species studied in other areas. The highest Hg levels were noted in Swordfish (*Xiphias gladius*) caught in waters surrounding Reunion Island (3.97 ± 2.67 μg g^{-1} dry weight). Following the Swordfish, in decreasing order of Hg content, were the Yellowfin Tuna (*Thunnus albacares*) and the Skipjack (*Katsuwonus pelamis*), then the Common Dolphinfish (*Coryphaena hippurus*) and the Wahoo (*Acanthocybium solandri*). In the North of the Mozambique Channel, Swordfish had higher Hg levels than Yellowfin Tunas, and Dolphinfish exhibited intermediate Hg levels. The size of a fish was a determining factor of its Hg burden, as was the species. Differences in size–normalized Hg levels were observed between the two study zones for Swordfish and Common Dolphinfish. Sex, in contrast, did not influence Hg levels suggesting that females and males have similar feeding habits. The muscular Hg levels presented here suggest that consumers of fish originating from theWestern Indian Ocean should limit themselves to one Swordfish based meal per week, or one fish meal a day if they choose to eat tuna or Common Dolphinfish.

Keywords: Mercury; Impregnation levels; Pelagic fish; Reunion Island; Mozambique Channel; Health standards

1. Introduction

Historically, mercury (Hg) has been used by many cultures for a variety of symbolic and useful purposes, such as in good luck charms, to ward off evil, as material for ceremony objects (Egyptians), as colorant and as cosmetics (Boudou, 1982; Mercury Task Force, 2002).

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Mercury played a predominant role in alchemy, and was thought to have medicinal uses such as curing syphilis in the 19th century (Dracobly, 2004). The large scale accidents of Minamata in the 1950s, and in Iraq in the early 1970s have, however, caught the world's attention on the potential toxicity of this metal. Much research has been conducted since, and health and ecological hazards are relatively well assessed today. The major anthropogenic Hg sources stem from its use in industries such as the manufacture of plastic, chlorine, caustic soda (sodium hydroxide), caustic potash (potassium hydroxide) and antifouling paint. Fossil fuel burning, base metal smelting, waste incinerators and Hg based fungicides used in agriculture are also important input sources of Hg in the environment. Natural sources of Hg include volcanic emissions, degassing from soils, and volatilization from the ocean. As a natural element, Hg is present as Hg vapors in the atmosphere, as inorganic Hg in the geosphere (to a very large extent encountered as mercuric sulphide cinnabar) and as inorganic or organic Hg in the hydrosphere. Among organic Hg species, methylmercury (MeHg) is the most abundant, and is bioaccumulated by aquatic organisms and biomagnified through the food chain.

Because of MeHg's trophic transfer property, organisms occupying high trophic positions and characterized by long lifespans, such as tuna fish and billfish are susceptible to contain high Hg burdens. Indeed, Hg found in fish is chiefly present as MeHg (Cappon and Smith, 1981; Bloom, 1992; Wagemann et al., 1997; Kehrig et al., 2002). The study of Hg impregnation in top predators is crucial as it serves as evidence for environmental exposure levels. Furthermore Hg burdens in large predatory fish are of particular interest because fish represent the major source of human exposure (Svensson et al., 1992).

To the best of our knowledge, there have been very few published studies on Hg in fish from the Western Indian Ocean (Kureishy et al., 1979). Fisheries of the Western Indian Ocean represent 5% of worldwide catches. Tunas and associated species amount to approximately 30% of the catches in the Western Indian Ocean and 17% of worldwide tuna catches, which sets it in second place after the Pacific (Pianet, 1998). Among tunas and associated species, the major tunas, which include the Yellowfin (*Thunnus albacares*), the Skipjack (*Katsuwonus pelamis*), the Bigeye (*Thunnus obesus*), the Albacore (*Thunnus alalunga*) and the Southern Bluefin (*Thunnus maccoyii*), are of particular importance for fisheries since they correspond to 70% of all catches in the Indian Ocean. Swordfish (*Xiphias gladius*) also stand out in fishery reports. Longliners based in Reunion Island have been specializing in Swordfish since the early 1990s, with catches amounting to 1741 tons in 2000. Total catches in the Western Indian Ocean exceed 20 000 tons per year nowadays (Pianet, 1998). Furthermore, other species such as Wahoos (*Acanthocybium*

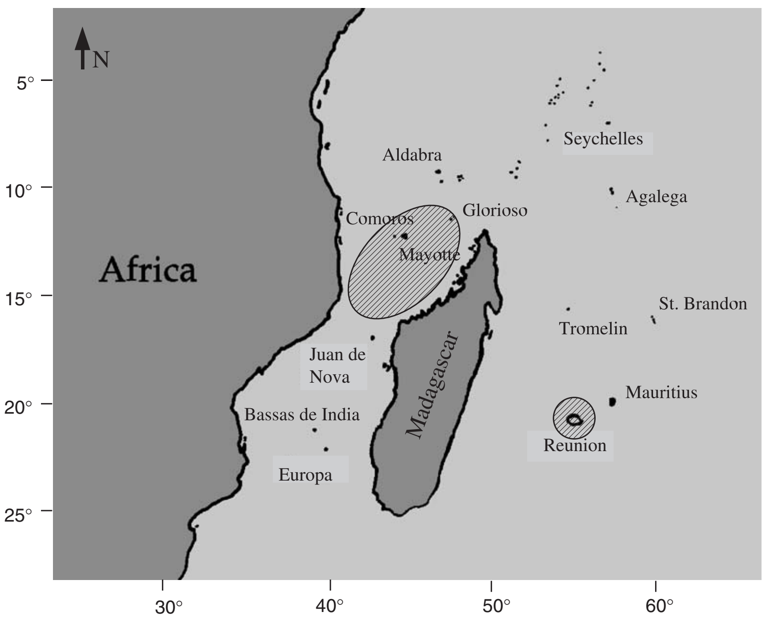

Fig. 1. Map of the study area with sampling zones materialized by shaded circles.

solandri) and Common Dolphinfish (*Coryphaena hippurus*) are targeted by sport fisherman.

This paper provides new data for Hg levels in the muscle of Swordfish, Yellowfin Tunas, Skipjacks, Wahoos and Common Dolphinfish originating from the Southwestern Indian Ocean. Potential differences in Hg bioaccumulation between sexes were tested. Because Hg levels almost invariably increase with the size of the fish (e.g. Mackay et al., 1975; Monteiro and Lopes, 1990; Bloom, 1992; Dietz et al., 1996; Gilmour and Riedel, 2000; Stafford and Haines, 2001), length-adjusted Hg levels were used to compare the Hg impregnation of each species found in Reunion Island waters and in the North of the Mozambique Channel. Species Hg impregnations were also compared within study zones. Considering the nutritional value of fish and the large quantities consumed in this part of the world, our results were discussed in the light of international guidelines for Hg intake, and of potential health risk for the populations which feed on these fish.

2. Materials and methods

2.1. Study sites and species

The samples of the five pelagic species studied during this investigation originated from two geographically distant sites in the Western Indian Ocean. The first site corresponds to waters surrounding Reunion Island, a 2512 km^2 French territory located 700 km East of Madagascar (21°7′S; 55°33′E). The second sampling zone was situated in the northern part of the Mozambique Channel, delimited by the following coordinates: 10°34′S and 17°07′S, and 41°11′E and 47°19′E (Fig. 1). These two sites correspond to two major fishing (seine and longline) areas of the Western Indian Ocean (Weenarain and Cayré, 1998).

The Swordfish is the largest of the sampled species averaging 165 cm LJLF (Lower Jaw Fork Length) in body length (FAO and SIDP, Oct. 2005). Females have a higher growth rate than males and therefore, reach greater lengths. In the Southwestern Indian Ocean, females may reach up to 250 cm LJLF, and males, up to 210 cm LJLF (Vanpouille et al., 2001). The Swordfish's lifespan is thought to be under 25 years (FAO and SIDP, Oct. 2005). Thirty-five thousand tons are fished in the Indian Ocean every year (Vanpouille et al., 2001).

Yellowfin Tunas measure around 155 cm FL (Fork Length), but they can grow up to 240 cm FL and weigh up to 175 kg (NOAA fisheries, Oct. 2005). The maximum reported age is 8 years (FAO and SIDP, Oct. 2005). This species is the second most coveted by industrial and artisanal fisheries. The Western Indian Ocean basin is characterized by some of the largest quantities of Yellowfin Tunas captures by seines and longliners in the world (around 300 000 tons per year in 1994) (Pianet, 1998).

The Skipjack is the smallest tuna in the Indian Ocean. It usually weighs less than 5 kg and measures around 60 cm FL, although it can reach up to 30 kg and 100 cm FL in length (Stéquert and Marsac, 1986; Quéro and Vayne, 1997). Estimates of longevity vary between 8 and 12 years (FAO and SIDP, Oct. 2005). This species is the most commercialized tuna with more than 1 000 000 tons fished per year in the world, of which 200 000 tons come from the Western Indian Ocean (Muus et al., 1998; Opic et al., 1994).

The maximum reported size for the Wahoo is 250 cm FL total length, with a maximum weight of 83 kg. Typically, individuals attain a size of 100–170 cm. It is believed that Wahoo lives up to 5–6 years of age (FAO and SIDP, Oct. 2005). Wahoo and other Seerfish annual catches approach 120 000 tons in the Indian Ocean (Pianet, 1998).

The Common Dolphinfish is known to reach a maximum of 200 cm FL in length and 30 kg in weight, but it more commonly measures 50–100 cm FL and weighs 14 kg. Longevity is estimated around 4 years (FAO and SIDP, Oct. 2005). Although they are not subject to specific fishing from longliners in the Western Indian Ocean, Common Dolphinfish commercialization is non-negligible (Gaertner et al., 2001). This fish is also highly prized as a gamefish.

Since 1988, fish aggregation devices (FADs) have multiplied around Reunion Island, representing 85% of coastal fishing by 1994 (Conand and Tessier, 1996). FADs characteristically concentrate young Yellowfin Tunas, Skipjacks, Wahoos and Dolphinfish.

2.2. Fish sampling and mercury analysis

A total of 65 fish (3 species) were caught with a traw line in the northern part of the Mozambique Channel and 118 fish (5 species) were collected by sport fishermen in Reunion waters. Each fish was measured, and weighed when possible. The Lower Jaw Fork Length (LJFL, from the tip of the lower jaw to the fork of the caudal fin) was measured on Swordfish whereas the Fork Length (FL, from the tip of the snout to the fork of the caudal fin) was noted for the others species. Individuals were sexed during dissection by the examination of the gonads. For practical reasons, white muscle was sampled for analysis in the abdominal area above the vent of the fish. We considered that Hg is uniformly

Table 1
Percentage of water in the white muscle of pelagic fish from Reunion Island and the Mozambique Channel (mean±standard deviation)

	White muscle moisture content			
	n	Mozambique	*n*	Reunion
Swordfish	37	76±6	7	69±8
Yellowfin Tuna	20	75±2	19	74±2
Skipjack Tuna		–	39	71±3
Wahoo		–	7	73±2
Common Dolphinfish	5	82±3	44	75±5

distributed in fish edible muscle as it has been shown for Swordfish (Freeman and Home, 1973). The sampled muscle was conserved frozen at −20 °C. It was then blended, dried in an oven at 50 °C to constant mass and grounded to a fine powder. Glass and plastic utensils were washed with detergent, plunged in a bath of mixed nitric acid (35 ml l^{-1}) and chlorhydric acid (50 ml l^{-1}) for a minimum of 24 h, rinsed 3 times in deionized (Milli-Q quality) water and dried in an oven at 50 °C before use.

Total Hg analyses were carried out with an Advanced Mercury Analyzer (combustion analyzer ALTEC 254) on aliquots ranging from 7 to 24 mg of dried sample weighed to the nearest 0.01 mg. Accuracy of the preparation was tested by preparing replicate TORT-2 reference standards and blanks along with each set of samples. The detection limits and recovery rates of Hg were respectively equal to 0.0007 μg g^{-1} and 101± 3.5%. Reproducibility was estimated as the closeness of 2 replicate measurements. The coefficient of variation given by relative standard deviations was always lower than 10%. Element levels are expressed in microgram per gram of dry weight (d.w.), and the mean moisture content of each tissue is provided in Table 1. These values were used for the conversion of our results to wet weight (w.w.) basis for comparison with other studies.

2.3. Data analysis

Prior to statistical analysis, bivariate plots of Hg levels against fish's lengths were visually examined for outliers. Statistical analysis were performed using the GNU R statistical system (R Development Core Team, 2005). All statistical samples submitted to tests were first checked for normality by means of Shapiro–Wilk tests. In the case of non-departure from normality, parametric tests were used in the subsequent analyzes, otherwise, non-parametric analogues were used.

The validity of the replicates of the level measures was tested by means of *t*-tests for paired samples. The influence of species on elemental levels was tested by means Kruskal–Wallis tests followed by Wilcoxon tests for independent samples using Bonferroni's *p*-value correction. The influence of sex and sampling location on Hg levels were tested by means of *t*-tests or Wilcoxon tests, after having checked samples for normality by means of Shapiro–Wilk tests.

Simple linear regression models (RMs) were estimated to explain the relationship between Hg and size. The

Table 2
Mean Hg levels (μg g^{-1} d.w.), inter-specific and inter-locational comparisons results in pelagic fish from two areas of the tropical Western Indian Ocean

Species	Mozambique Channel				Reunion Island				Comparing locations
	n	Length (cm)	Hg levels		*n*	Length (cm)	Hg levels		
		Mean	Mean±SD			Mean	Mean±SD		
		(Min–max)	CV(%)			(Min–max)	CV(%)		
Swordfish	37	123	1.61±1.11	a|Y	7	126	3.97±2.67	b|X	W: 0.002
Xiphias gladius		(75–191)	69			(90–187)	67		
Yellowfin Tuna	20	109	0.51±0.32	a|Z	19	104	0.70±0.49	a|Y	W: NS
Thunnus albacares		(82–156)	62			(49–170)	70		
Skipjack Tuna	0				39	68	0.67±0.26	Y	
Katsuwonus pelamis						(41–85)	39		
Wahoo	0				7	95	0.13±0.08	Z	
Acanthocybium solandri						(68–114)	62		
Common Dolphinfish	5	109	0.98±0.92	a|YZ	44	87	0.21±0.19	b|Z	W: <0.001
Coryphanea hippurus		(100–115)	94			(61–112)	91		
Comparing species			KW: <0.001				KW: <0.001		

SD stands for standard deviation and CV for coefficient of variation. For each species, the significance of the Hg level differences among locations is given in the last column. In case of significant difference, the letters a and b are used to indicate which subgroups differ. Subgroups sharing the same letter do not differ significantly. The significance of the Hg level differences between species is given in the bottom line. In case of significant difference, the letters X, Y and Z, are used to indicate which subgroups differ.

Table 3
p-values of pairwise t-tests or Wilcoxon tests for the comparison of Hg level in males and females of each species, in the Mozambique Channel and Reunion Island

	Comparing sexual Hg levels	
	Mozambique	Reunion
Swordfish	W: 0.286	–
Yellowfin Tuna	W: 0.115	W: 0.142
Skipjack Tuna		t: 0.135
Wahoo		–
Common Dolphinfish	–	W: 0.925

(–) Indicates subgroups for which samples had too few values to be tested.

best determination coefficients of Hg content against fish length regressions were obtained using logarithmic transformations of both variables. The RMs were thus realized on log Hg values (μg g^{-1} d.w.) and log lengths (cm). RMs were also used to estimate the average size above which Hg content may exceed tissue levels that were used to set consumption advisories.

In most fish, muscle Hg content increases with the size of the individual (Mackay et al., 1975; Monteiro and Lopes, 1990; Bloom, 1992; Dietz et al., 1996; Gilmour and Riedel, 2000; Stafford and Haines, 2001). The difference in the average length of fish is thus a bias when comparing subsamples using comparison tests such as those described above. In order to truly measure the effect of other potential influencing factors such as the sampling location or the species, tested subgroups should contain fish of the same mean size. To test the influence of the location, an analysis of covariance (ANCOVA) was performed for each species, in order to adjust the Hg levels in both sampling sites (Mozambique Channel and Reunion Island) using fish length as a covariate. The ANCOVA was also used to adjust the Hg levels in each species, using fish length as a covariate, to test whether size was the only explanatory factor of the differences observed between species. In the Mozambique Channel, Dolphinfish were excluded from the ANCOVA because of their very small sample size once the outliers were removed. The ANCOVAs were realized on log Hg values and log lengths. Residuals were checked for normality by means of Shapiro tests, and for homocedaticity by plotting fitted values vs. residuals (Venables and Ripley, 2002; Faraway, 2005).

In an effort to facilitate the interpretation of the results we have adopted classical conventions throughout this paper. Kruskal–Wallis, ANCOVA, Wilcoxon and t-tests will be represented, respectively, by the following acronyms : KW, AOCV, W and t.

3. Results

Summary statistics for Hg levels in the white muscle of each species caught in the Mozambique Channel and Reunion waters are presented in Table 2.

Males and females were pooled since no influence of sex was revealed within the species–location subgroups which were tested (Table 3).

3.1. Size-specific Hg levels

The large individual variations in Hg levels within species–location subgroups (high CVs in Table 2) can be explained by the large range of sizes of the fish in each subgroup. Indeed, Hg levels were found to be positively correlated with the length of the fish (Fig. 2). The relationships between the Hg levels ([Hg]) and the length (L) were best fitted by the regression of the form: $[\mathrm{Hg}]=a \cdot L^b$, where a and b are equation parameters estimated from the data and given for each species–location subgroup in Table 4. These regression models were significantly better than constant models in all but one cases, Reunion Swordfish, probably because of a too small number of individuals. Besides, the model linking Hg and length in Mozambique Channel Dolphinfish is not given because of the excessively small sample size when ignoring the outliers.

3.2. Site differences

From the results given in Table 2 it appears as though the levels of muscular Hg differed between Swordfish and Common Dolphinfish caught in Reunion waters and those caught in the Mozambique Channel. However, the average size of the individuals collected in both zones were not identical (Table 2), and as it has been discussed in Section 3.1, Hg levels vary with the fish's length. ANCOVAs were realized, for Swordfish, in order to assess whether fish length differences alone explained the Hg levels variation noted between both sampling areas. The ANCOVA results indicated that the regression slopes of muscular Hg levels against fish length were not significantly different between areas ($p=0.548$), but that the intercepts were significantly different ($p<0.001$). We may thus conclude that, for Swordfish, muscular Hg accumulates at the same rate with respect to length in both locations, but that Hg levels were different, with higher levels in Reunion Swordfish.

Despite the different ranges of sizes of Yellowfin Tunas sampled in the Reunion and Mozambique areas, Hg levels did not significantly differ between these two groups (Table 2). Non-significantly different regression slopes of Hg on fish length (AOCV: $p = 0.152$) and non-significantly different intercepts (AOCV: $p = 0.051$) between areas confirmed that there were no Hg level differences between Mozambique Channel and Reunion Island fish, and that Hg was bioaccumulated at the same rate with respect to size in Yellowfin Tunas of both zones.

3.3. Mercury level variations among species

In both study areas, the Swordfish showed the highest Hg levels of all species. In Reunion, it was followed by the Yellowfin Tuna, the Skipjack, the Common Dolphinfish and the Wahoo in order of decreasing Hg burdens (Table 2). In the Mozambique Channel, the large sizes of the sampled Dolphinfish

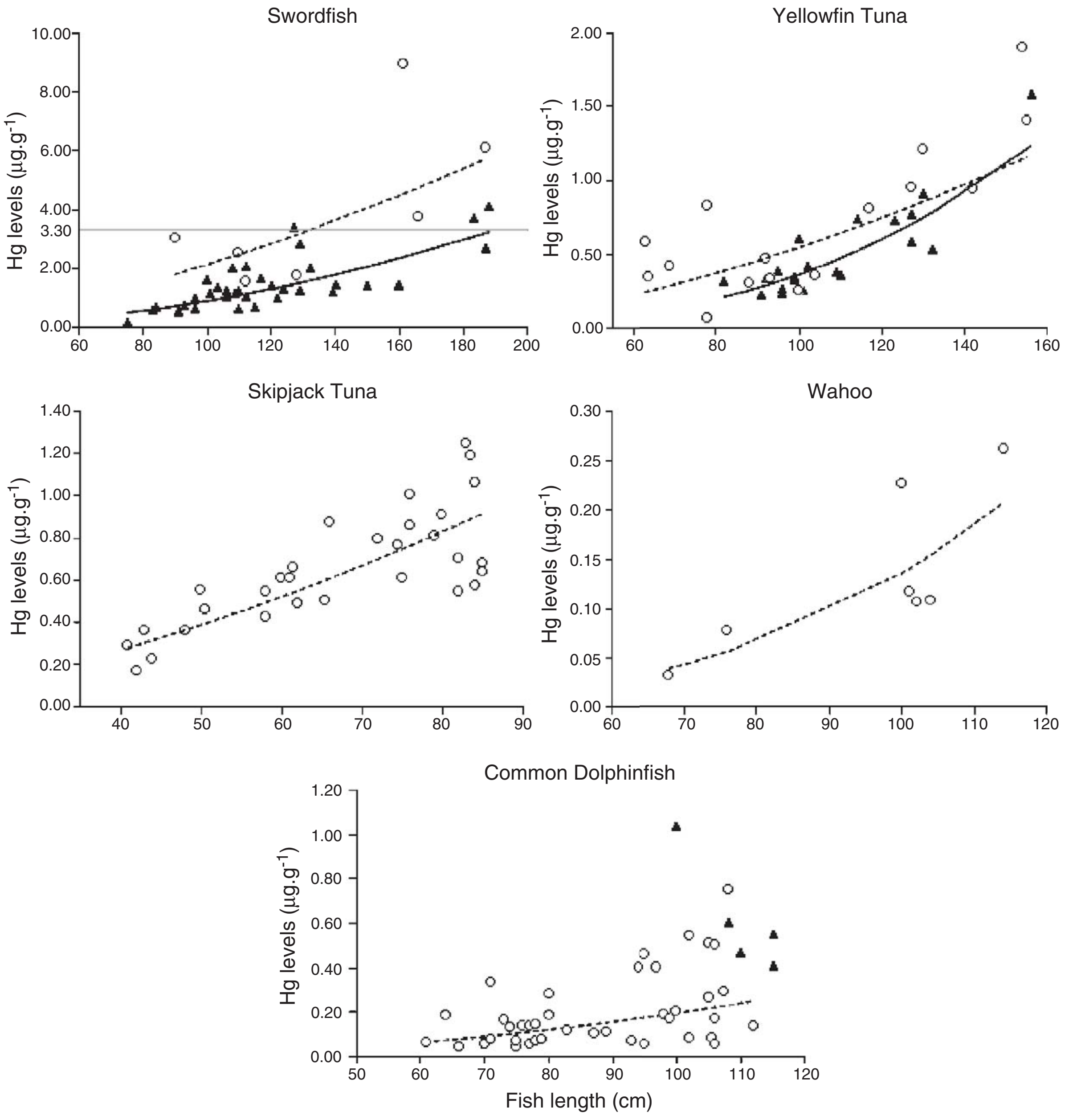

Fig. 2. Mercury levels (μg g^{-1} d.w.) against fish length (cm). Mozambique and Reunion data are represented by ▲ and ○, respectively, and the corresponding regression curves by full and dotted lines, respectively. The gray horizontal line materializes the threshold level for human consumption (1 μg g^{-1}) set by WHO.

Table 4
Regression models linking Hg levels ([Hg]) to length (L): $[Hg]=a \cdot L^b$

Species	n	a	b	r^2	p-value
Mozambique Channel					
Swordfish	37	$9.142 \cdot 10^{-5}$	2.002	0.57	<0.001
Yellowfin Tuna	20	$1.224 \cdot 10^{-6}$	2.738	0.73	<0.001
Reunion					
Swordfish	7	$1.555 \cdot 10^{-3}$	1.570	0.44	0.105
Yellowfin Tuna	19	$2.057 \cdot 10^{-4}$	1.713	0.40	0.008
Skipjack Tuna	39	$6.961 \cdot 10^{-4}$	1.616	0.70	<0.001
Wahoo	7	$4.767 \cdot 10^{-8}$	3.227	0.75	0.011
Common Dolphinfish	44	$8.850 \cdot 10^{-6}$	2.174	0.23	0.001

resulted in higher muscular Hg levels than in Yellowfin Tunas. A more extensive sampling of Dolphinfish in the Mozambique Channel would be necessary to better estimate Hg levels in this species.

ANCOVAs were realized, for both sites, to set aside the effect of length in order to assess whether other factors aside from length were responsible for the variations in Hg levels among species. In other words, would there still be differences in Hg burden among species if they all had the same average size? In both sites, the answer was positive, since the intercepts of the regression of Hg burdens against length were significantly different between species ($p<0.001$). We may conclude that factors inherent to the species had an influence on Hg levels in these fish. Furthermore, the regression slopes of Hg burdens against length were the same for Swordfish and Yellowfin Tunas from the Mozambique Channel ($p=0.212$) and for the five species from Reunion waters ($p=0.619$). Hence, Hg levels in muscle seemed to be bioaccumulated at the same rate with respect to fish length in all species.

4. Discussion

4.1. Mercury, size, sex, species and location

The size of a fish is known as a determining factor of its Hg burden (Mackay et al., 1975; Jaffar and Ashraf, 1988; Bloom, 1992; Dietz et al., 1996; Gilmour and Riedel, 2000; Stafford and Haines, 2001; Kraepiel et al., 2003), and has been confirmed here.

For Swordfish larger than 125 cm LJFL, females' growth rate is higher than that of male (Kume and Joseph, 1969; Quéro and Vayne, 1997; NOAA fisheries, Oct. 2005), and more generally, females are proportionally heavier than males of equal length (Ward and Elscot, 2000). It can be suspected that these physiological differences may affect length–Hg relations. In this study, no difference in Hg levels was observed in any of the five species. The influence of sex-differentiated growth rates between male and female Swordfish for individuals larger than 125 cm was probably diluted since very few fish were above this length: two females and two males among Reunion samples, and in the Mozambique Channel lot, only one female measured more than 125 cm in length.

According to the average sizes of the five teleost species investigated here (Section 2.1), the Swordfish is the largest followed by the Yellowfin Tuna, the Wahoo, the Common Dolphinfish and the Skipjack in decreasing order. In the Mozambique sample, the Common Dolphinfish had the same mean length as the Yellowfin Tunas, in consequence, their muscular Hg levels were not significantly different (Table 2 and Fig. 3). Among Reunion fish, Skipjacks had high Hg levels with respect to their size when compared to the other species (Fig. 3). The opposite was observed for Wahoos. For example, Skipjacks caught around Reunion Island were smaller than Common Dolphinfish but exhibited higher Hg values, and Wahoos, which were in average larger than both of the latter, had the lowest Hg levels (Table 2). These inter-specific differences in Hg levels were probably linked to differences in each species physiology, feeding rate, growth rate, lifespan, migratory patterns, foraging habits and/or diet. For instance, the low Hg levels in Wahoos could be explained by the surface foraging habits of this species (0–12 m) which contrasts with the others which feed from the surface to great depths (up to 800 m for Swordfish) where Hg methylation, in these poorly oxygenated waters, enhances its bioaccumulation (Monteiro et al., 1996; Kraepiel et al., 2003). A clear example of differential vertical distribution of Hg levels in fish is given by Monteiro et al. (1996), who found a 4-fold increase in Hg levels from epipelagic (100–150 m) to mesopelagic (300–1 200 m) lanternfish species in the sub-tropical mid-North Atlantic.

Locational differences between the North of the Mozambique Channel and Reunion waters were confirmed for Swordfish. More data on Dolphinfish from the Mozambique Channel are needed to verify whether these fish have higher Hg burdens than those collected in Reunion waters, irrespective of their size. If the latter is confirmed, it would go against the results obtained for Swordfish. Consequently, it could be hypothesized that the differences in fish Hg impregnation were due to differences in their dietary prey composition and/or in the trophic position they occupy in both areas,

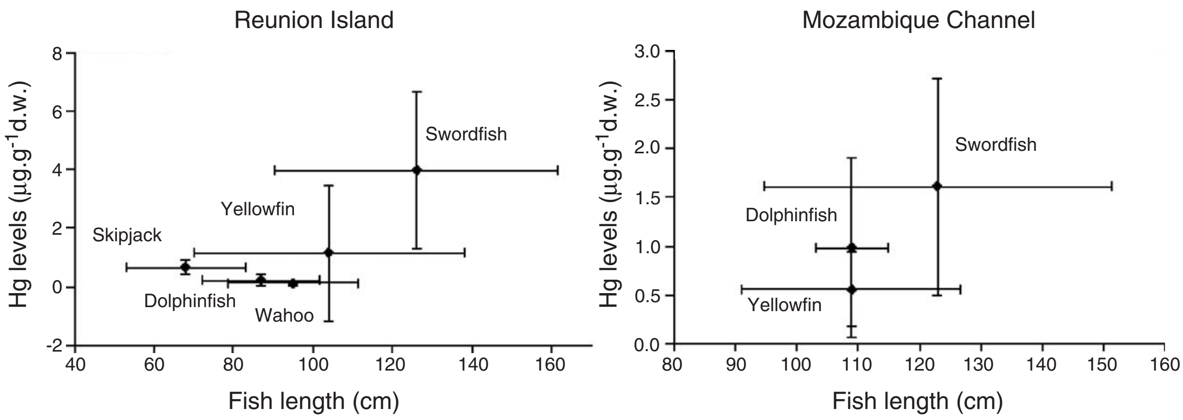

Fig. 3. Position of species in relation to their mean length and mean Hg levels in both study zones. Error bars represent the standard deviation.

rather than differences in environmental Hg levels. Conversely, the intense volcanic activity on Reunion Island could account for higher Hg levels in Swordfish caught in the waters surrounding this island. This second hypothesis would be more likely if Dolphinfish did not show higher levels in the Mozambique Channel.

4.2. Comparison with published data

The Hg levels detected in pelagic fishes during this study were quite similar to phylogenetically related species from oceans around the world as shown in Table 5, especially given that the fish compared here vary in sizes. On the Southwestern Indian Ocean scale, Seychelles

Table 5
Mercury levels (mean ± standard deviation, μg g^{-1} wet weight) in muscle of marine fish from various geographical areas

Species	Origin	*n*	Sex	Weight/length	Hg	References
Swordfish (*Xiphias gladius*)	Mozambique Channel*	37	F/M	21 kg	0.38 ± 0.26	This study
	Reunion Is.*	7	F/M	22 kg	1.24 ± 0.83	This study
	Atlantic Ocean	192	F/M	–	0.62 ± 0.35	Mendez et al. (2001)
	Atlantic Ocean	88	F	–	0.93 ± 0.07	Monteiro and Lopes (1990)
	Atlantic Ocean	48	M	–	1.30 ± 0.17	Monteiro and Lopes (1990)
	Unidentified	305	F/M	–	0.97	
Yellowfin Tuna (*Thunnus albacares*)	Mozambique Channel*	20	F/M	22 kg	0.13 ± 0.09	This study
	Reunion Is.*	19	F/M	24 kg	0.21 ± 0.15	This study
	Seychelles	5	–	17 kg	0.23 ± 0.10	Matthews (1983)
	Pacific Ocean	105	–	–	0.21 ± 0.11	Kraepiel et al. (2003)
	Atlantic Ocean	56	F/M	84 cm FL	0.25 ± 0.12	Adams (2004)
	Unidentified	50	–	–	0.65 ± 0.10	
Bluefin Tuna (*Thunnus thunnus*)	Arabian Sea	17	–	–	0.08 ± 0.01	Jaffar and Ashraf (1988)
Longtail Tuna (*Thunnus tonggel*)	Arabian Sea	18	–	–	0.03 ± 0.01	Jaffar and Ashraf (1988)
Skipjack Tuna (*Katsuwonus pelamis*)	Reunion Is.*	39	F/M	9 kg	0.19 ± 0.66	This study
	Indian Ocean	1	M	–	0.53	Kureishy et al. (1979)
	Seychelles	5	–	5 kg	0.34 ± 0.11	Matthews (1983)
Wahoo (*Acanthocybium solandri*)	Reunion Is.*	7	F/M	–	0.10 ± 0.08	This sudy
	Seychelles	5	–	16 kg	0.57 ± 0.41	Matthews (1983)
	Indian Ocean	4	F/M	5 kg	0.11 ± 0.03	Kureishy et al. (1979)
Blue fin Tuna (*Kishinoella tonggol*)	Indian Ocean	1	F	–	0.12 ± 0.01	Kureishy et al. (1979)
Common Dolphinfish (*Coryphanea hippurus*)	Mozambique Channel*	5	F/M	9 kg	0.17 ± 0.16	This study
	Reunion Is.*	44	F/M	5 kg	0.01 ± 0.05	This study
	Indian Ocean	4	F	–	0.07 ± 0.004	Kureishy et al. (1979)
	Indian Ocean	1	F	–	0.14 ± 0.01	Kureishy et al. (1979)
	Indian Ocean	1	F	–	0.12 ± 0.01	Kureishy et al. (1979)
	Unidentified	18	F/M	–	0.18	

*Indicates the locations for which data were transformed from dry weight to wet weight basis.

waters seem to be richer in Hg than the Mozambique Channel and Reunion waters, since Yellowfin Tunas, Skipjacks and Wahoos caught there had higher Hg levels than those analyzed in this study. These values are however relatively low in comparison with Hg levels that can be found in the muscular tissue of fish analyzed in polluted coastal areas, or in deep-water benthopelagic fish. For example, the small piscivorous *Acestrorhynchus guianensis* from the Amazon basin, which is polluted by goldmining, exhibits Hg levels as high as 4.3 μg g^{-1} d.w. (Durrieu et al., 2005). Furthermore, median Hg levels of 13 μg g^{-1} d.w. were reported for the small deep-sea Smooth Grenadier, *Nezumia aequalis*, found in the 500–1750 m bathymetric zones of the Rockall Trough, North West of the British Isles (Mormede and Davies, 2001). The record of highest Hg levels in teleost species is also noteworthy since it was found in Black Marlins from the apparently unpolluted waters off North-Eastern Australia, with 24 μg g^{-1} d.w. reported in its muscle tissue (Mackay et al., 1975).

4.3. Risk to the fish and their predators

Mercury in fish can pose health risks to the fish themselves and to their predators, including humans. Mercury levels of 5 μg g^{-1} w.w. in fish muscle can be associated with loss of appetite, emaciation, decrease coordination and mortality in fish itself (Eisler, 1987), while levels of 15 μg g^{-1} w.w. are required for provoking adverse effects in their predators (Spry and Wiener, 1991). In this study, the highest Hg level recorded was 2.68 μg g^{-1} w.w. in a Swordfish, suggesting that Hg is not a threat to the fish themselves, nor to their predators.

Since the large scale MeHg poisoning accident of Minamata in Japan in 1957, Hg levels in fish have been thoroughly examined in view of human consumption. In 1979, the Food and Drug Administration in the United States (US FDA) established an action level of 1 μg g^{-1} w.w. to regulate MeHg content in commercial fish. Although guidance or standards for Hg in fish tissues are not always uniform (Burger and Gochfeld, 2005), most international standards have, since then, adopted an action limit of 0.5 μg g^{-1} w.w., except for predatory fish (such as billfish, tunas and other high-Hg level fish) for which the allowed level is 1 μg g^{-1} w.w. (IPCS, 1987; EPA, 1994). It is recommended that the population restrains from consuming, on a regular basis, species exceeding these values. Based on this, Hg is considered as a potential safety hazard for Skipjacks, Halibuts, the Spanish Mackerel (*Scomberomorous maculatus*), the King Mackerel (*S. cavalla*), Marlins, Sharks, the Swordfish and the Bluefin Tuna (Mendez et al., 2001; Dua and Gupta, 2005).

Because a large percentage of Hg is present as MeHg in the edible portions of fish (Cappon and Smith, 1981; Bloom, 1992; Wagemann et al., 1997), we assumed that concentration of total Hg (*T*-Hg) was equal to that of MeHg in the muscle. None of the Common Dolphinfish or Skipjacks considered in this study were above the 1 μg g^{-1} guideline. Yellowfin Tunas caught in the Mozambique Channel were also under this limit whereas, one of the 20 Yellowfin Tunas fished around Reunion Island exceeded the provisional maximum permissible level. In the Mozambique Channel and Reunion Island, 2.6% and 42.9% of the swordfish, respectively, were above the authorized limits. This last result on Reunion Swordfish should however be taken very cautiously and not generalized owing to the very small sample size (7 fish). Further analyses should be conducted to provide a truly valid percentage. Furthermore, the body length of these fish, which is a major variation factor of Hg levels (Section 3.1), is to be considered when addressing the problem of potential health risks as the consumption of smaller fish reduces the amount of Hg ingested. Moreover, the thresholds established for Hg in fish muscle destinated to human consumption do not take into account the amount of fish ingested by consumers. To evaluate the potential health risk to people through consumption of these fish, Hg intake rates were estimated on the basis of the Hg levels in fish muscle (our results transformed into wet weight basis) and daily fish consumption found in the literature (Antoine, 1995; FAO, 2001; Mauritius Central Statistics Office, 2002). The daily human exposure to Hg from fish consumption can be calculated with the following formula:

$$\mu g\ Hg \cdot day^{-1} = \mu g\ Hg \cdot g\ fish^{-1} \times g\ fish \cdot day^{-1}$$

Different Acceptable Daily Intake (ADI) limits have been established by national and international instances. The ADI set by the World Health Organization (WHO) for *T*-Hg is 0.71 μg day^{-1} kg^{-1} body weight, and restricted to 0.35 μg day^{-1} kg^{-1} body weight for pregnant women because foetus are more sensitive to Hg toxicity, for nursing mothers, and for children less than 10 years (Chan, 1998; DHHS and EPA, 2004). The French (AFSSA) and the Canadian health agencies follow the same guidelines as the WHO, whereas the US FDA and US Environmental Protection Agency (EPA) have set more restrictive ADI limits for MeHg (0.4 and

Table 6
Estimated daily consumption of *T*-Hg (μg), in various countries in which people are likely to eat fish captured in the Mozambique Channel and Reunion waters

	Mozambique	Madagascar	France		Comoros	Mauritius
			Mainland central regions	Coastal regions & Reunion		
Yearly fish consumption per capita	6 kg	10 kg	7 kg	15 kg	19 kg	20 kg
Mozambique						
Swordfish	**6.23**	**10.38**	**7.27**	**15.58**	**19.73**	20.77
Yellow Tuna	**2.20**	**3.67**	**2.57**	**5.51**	**6.98**	7.35
Common Dolphinfish	**2.85**	**4.76**	**3.33**	**7.14**	**9.04**	9.51
Reunion						
Swordfish	20.35	33.91	**23.74**	**50.86**	64.43	**67.82**
Yellow Tuna	4.98	8.30	**5.81**	**12.44**	15.76	**16.59**
Skipjack	3.18	5.30	**3.71**	**7.95**	10.07	**10.60**
Wahoo	2.74	1.64	**5.21**	**4.11**	4.11	**1.92**
Commom Dolphinfish	0.22	0.37	**0.26**	**0.55**	0.70	**0.74**

The bold values indicate the most probable consumer countries. The shadowed values are above the ADI set by the WHO. The values in dotted boxes are above the ADI set by the EPA. The countries' average yearly fish consumption per capita (kilogram fresh weight) is given under each country considered (Antoine, 1995; Mauritius Central Statistics Office, 2002; FAO and SIDP, Oct. 2005).

0.1 μg day^{-1} kg^{-1} body weight, respectively, for all the population) (Hirsch, 2002).

Considering an average adult body weight of 70 kg (EPA, 1994), the *T*-Hg WHO ADI can be approximated as 50 μg day^{-1} adult^{-1}. This health risk limit was compared to the estimated daily consumption of Hg in various countries where fish originating from the two study zones are susceptible to be eaten (Table 6). The *T*-Hg values exceeding the most restrictive guidelines set by the EPA (equivalent to 10.5 μg *T*-Hg day^{-1} adult^{-1}) are also indicated in Table 6, but will not be discussed. Only 4 of the 7 locations seemed confronted with potential health risks due to Hg, i.e. Reunion and coastal Mainland France. Furthermore, these conclusions are valid only if the population's fish intake is restricted to Swordfish caught in Reunion waters. This obviously rarely represents the reality. For example, inhabitants of the Comoros and Creoles from Reunion Island, chiefly eat demersal fish (Ministère de la production et de l'environnement, 2000). French living on Mainland France do favor pelagic fish such as Tuna, Marlin and Swordfish, but also eat local demersal fish (Antoine, 1995). Moreover, the risk for human health can be minimized if the consumption of Swordfish is limited to a certain size. For example, given the limited data in this study, Hg levels seem to exceed the permissible level only in individuals measuring more than 132 cm in length (Fig. 2). For smaller Swordfish the health risk is considered as null, with average daily Hg intakes per capita of 28.78 μg in Reunion and coastal France, 36.45 μg in Comoros and 38.37 μg in Mauritius. In the same way, Western Indian Ocean Yellowfin Tunas measuring less than 224 cm should be under the 1 μg g^{-1} advisory level, as would be Skipjacks, Wahoos and Common Dolphinfish of any size. There is, however, a non-negligible drawback in encouraging the consumption of small Swordfish since most of these individuals are immature: the smallest mature female recorded in the Western Indian Ocean measured 127 cm LJFL (Taquet, 2003). Targeting immatures can pose a great threat to the entire Swordfish stock.

In order to better appreciate the amounts of fish safe for consumption, exposure limits can be expressed as the number of meals that an adult can eat per day, or per week, and be under the 50 μg Hg day^{-1} ADI (hence 350 μg Hg week^{-1}). In risk assessment, the standard portion size of uncooked fish eaten by an average adult

Table 7
Safety limits (WHO), expressed as the frequency of meals for which fish is the main element, based on an adult standard portion size of 230 g

	Hg safety limits	
	Mozambique	Reunion
Swordfish	4 meals per week	1 meal per week
Yellowfin Tuna	1 meal per day	1 meal per day
Skipjack Tuna		1 meal per day
Wahoo		1 meal per day
Common Dolphinfish	1 meal per day	>3 meals per day

These estimations do not apply for pregnant woman and children.

is estimated to be 230 g (EPA, 1994; Brodberg and Klasing, 2003). Safety limits, expressed as the frequency of meals for which fish is the main element, based on the Hg levels reported in this study are given in Table 7. For individuals weighing more, or less, than 70 kg, it is assumed that their consumption rates will be proportionally higher or lower, respectively, yielding an overall similar exposure level following the consumption of equally contaminated fish (Brodberg and Klasing, 2003).

Nevertheless, consumers should bear in mind that standards have a safety margin. A concrete example of the limitations of the guidelines for Hg is given by two decades of investigation on the neighboring Seychellois population. During the Seychelles Child Development study, 779 children from the Seychelles whose mothers ate great amounts of Hg-contaminated fish (0.3 μg g^{-1} w.w. mean content) during their pregnancies (on average 12 meals per week) were followed from birth to adulthood and showed no significant evidence of verbal, motor, memory or reasoning skills deficits (Matthews, 1983; Myers et al., 2003; Shamlaye et al., 2004). Furthermore, a dietary survey carried out with 26 adult women from a fish-eating community in the Brazilian Amazon indicated that eating tropical fruit reduced Hg exposure from fish consumption (Passos et al., 2003).

5. Conclusion

This study confirms that Swordfish has high Hg levels in comparison with most other pelagic fish. The large size of this species is one of the main explanatory factor of the high Hg burdens as they increases with fish length. Besides, the Swordfish was the only species for which clear differences in Hg levels were noted between fish from both study areas.

As far as human safety is concerned, the results of this study suggest that consumers of fish originating from the Southwestern Indian Ocean should limit themselves to one meal a day if they consume tunas, Wahoo or Common Dolphinfish, or one meal a week if they eat Swordfish. Pregnant women, nursing mothers and children should limit their consumption of the largest pelagic species. Mercury level determination would be of interest in other edible tissues such as liver and gonads where Hg is known to accumulate (Cizdziel et al., 2003; Bustamante et al., 2003). Further investigations should also include other large commercialized teleost species such as Marlins. In any case, consumers should bear in mind that standards have a margin of safety and that fish provides essential nutrients such as Omega-3 fatty acids, phosphorus, calcium, and various vitamins and minerals. Moreover, fish constitutes an important source of protein, and is often the main livelihood for many people throughout the world. For these reasons, it is important to adapt Hg thresholds to local population's true exposure levels.

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