An Assessment of Mercury Concentration in Fish Tissues Caught from Three Compartments of the Bay of Bengal

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Abstract

To assess mercury (Hg) contamination in fishery resources of the Bengal Bay, a total of 78 specimens of 11 pelagic fish species were obtained during the joint survey of BIMSTEC member countries on Assessment and Management of Marine Resources, in November to December 2007. Individual specimen was coded, measured and weighed. The white flesh samples for Hg analyses were taken from the abdominal area of most fishes, and from the caudal area for sharks. Total Hg concentrations (expressed in ng/g wet weight) in the samples were as follow; 514±187 for bigeye thresher shark (*Alopias superciliosus*), 251±128 for copper shark (*Carcharhinus brachyurus*), 122±35 for silky shark (*Carcharhinus falciformis*), 48 for unidentified shark, 886±104 for tille travalley (*Caranx tille*), 64±62 for frigate tuna (*Auxis thazard*), 63±16 for kawakawa (*Euthynnus affinis*), 110±153 for skipjack tuna (*Katsuwonus pelamis*), 92±32 for yellowfin tuna (*Thunnus albacares*), 201 for bigeye tuna (*Thunnus obesus*), and 478 ± 416 for swordfish (*Xiphias gladius*). In general, the relationship between Hg levels in muscles and fish size was observed. Five of 8 bigeye thresher shark, only one tille travalley, 2 of 29 skipjack tuna and 5 of 16 swordfish had Hg concentrations in their fleshes exceeded the EU's upper limit of 0.5 μg/g. Moreover, the swordfish that weighed over 40 kg contained Hg in their tissues higher than 1 μg/g.

Key words: mercury, fish tissues, Bay of Bengal.

Introduction

Effect of mercury (Hg) and its compounds are currently well documented. Hg from either natural or anthropogenic sources enters the environment mainly as Hg vapor, is converted to organic form in aquatic environments by bacteria and phytoplankton (WHO, 1990 and 1991). It was found that total Hg found in fish tissue is chiefly present as methylmercury (MeHg) (Riisgard and Hansen 1990; Spry and Wiener, 1991; Bloom, 1992; Windom and Cranmer, 1998; Kehrig *et al.*, 2002; Branco *et al.*, 2007). MeHg is soluble, mobile, and quickly enters the aquatic food chain. It absorbed by fish when they eat smaller aquatic organisms and its binds to proteins in the fish tissue. MeHg then becomes biomagnified in the food chain through passage from bacteria, plankton, macroinvertebrates, herbivorous fish, piscivorous fish and finally, to humans (WHO, 1990 and 1991). The biomagnification of MeHg has been demonstrated by the elevated levels found in piscivorous fish compared with fish at lower levels of the food chain (Jackson 1991; Watras and Bloom

1992; Porcella 1994). Hg levels in animals may end up being 10,000–100,000 times higher than the initial concentration in the water (WHO 1990 and 1991; ATSDR, 1999).

Fish appear to accumulate MeHg from both food sources and the water column as it passes over the gills during respiration. MeHg can also be produced within the fish's gastrointestinal tract and on the external slime layer but the amount of MeHg contributed to tissue concentrations by these processes has not been quantified and is assumed to be insignificant. However, food was found to be the predominant source of Hg uptake in fish (Hall *et al.*, 1997).

The consumption of fish is recommended because it is a good source of omega-3 fatty acids, which have been associated with health benefits due to its cardio-protective effects. However, the content of heavy metals, especially Hg, discovered in some fish makes it difficult to establish clearly the role of fish consumption on a healthy diet. Currently, dietary intake of fish and fish products is recognized as the most important route of non-occupational exposure to Hg, with fish and other seafood products being the dominant source of Hg in the diet (WHO, 1990 and 1991). Tissues of long-lived, slow-growing and highly migratory oceanic fishes, such as tunas, billfishes and pelagic sharks accumulate high concentrations of Hg, often exceeding the limit recommended for human consumption (Barber and Whaling, 1983; Adams, 2004; Branco *et al.*, 2004).

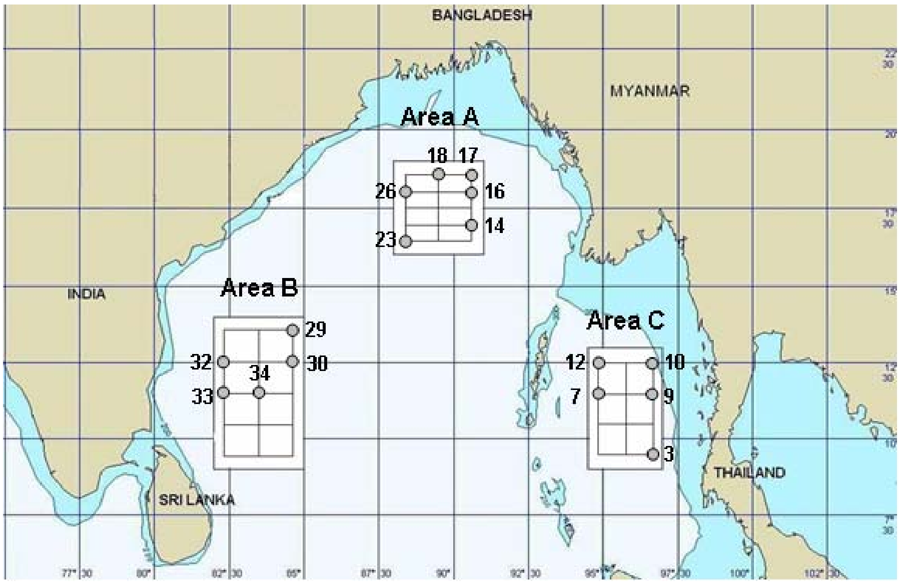
Therefore, contamination of Hg in top predators of pelagic food webs and large fish are of widespread interest and concern. The accumulation of Hg in swordfish (*Xiphias gladius*), a piscovorous fish, is widely recognized (Monteiro and Lopes, 1990; Mendez *et al.*, 2001; Storelli *et al.*, 2005; Kojadinovic *et al.*, 2006; Chien *et al.*, 2007). The presence of Hg in swordfish seems to be a fact independent of human pollution, since values in the range 0.45 and 0.9 μg/g were found in museum specimens caught between 1878 and 1909, that is before industrial activities began to pollute the ambient sea (Miller *et al.*, 1972).

To date, there have been very few published studies on Hg in fish from the Bay of Bengal. The objectives of this study were hence to analyze and interpret the total Hg content in the pelagic fish species collected from the Bay of Bengal during November to December 2007. This study will provide baseline data of Hg levels in the fleshy tissues of swordfish, tille trevally, 5 species of tunas (skipjack tuna, kawakawa, yellowfin tuna, frigate tuna and bigeye tuna) and 4 species of shark originating from 3 geographically area of the Bay of Bengal. Because Hg levels almost consistently increase with the size of the fish (Bloom, 1992; Windom and Cranmer, 1998; Gilmour and Riedel, 2000; Stafford and Haines, 2001), relationship between Hg levels and fish sizes (length and weight) was investigated. Hg burden in the same species caught in different area was also compared.

Material and Methods

Sample Collection

Seventy eight specimens of 11 predatory fish species, caught by pelagic longline and drift gill net, were obtained from the joint survey of BIMSTEC member countries on Assessment and Management of Marine Resources during November to December 2007 in 3 compartments of the Bay of Bengal (Fig. 1). Species identification and measuring of fish sizes (length and weight) were carried out on board of M.V. SEAFDEC.



AREA

A: the deep sea area of the EEZ of Bangladesh, India and in the Bay of Bengal at sea depth from 2,000 to 2,600 m

B: western part of the Bay of Bengal included the international waters and the EEZ of India and Sri Lanka waters

C: within the Andaman Sea at sea depth from 1,128 to 2,841 m

Figure 1 Sampling stations in 3 geographically distant sites in the Bay of Bengal.

For practical reasons, white flesh in the abdominal area of the fish was sampled for Hg analysis, except caudal flesh and fin were sampled for all sharks. We considered that Hg is uniformly distributed in fish edible muscle as it has been shown for swordfish (Freeman and Home, 1973). The sampled muscle was conserved frozen and was shipped to the laboratory for Hg analysis.

Sample Digestion and Mercury Determination

All laboratory material was previously decontaminated overnight with 10% (v/v) HNO_3 and washed with deionized water nanopure level (resistivity >18 MΩ cm). Nanopure water was used throughout this work. Thawed samples were dissected under clean atmosphere in Laminar Flow Cabinet Class-100, only flesh were taken off and homogenized with stainless steel knife and laboratory spatula, then immediately kept frozen until analysis. Samples were digested based on wet weight with method modified from AOAC (1990) and US-EPA (2001). Briefly, homogenized subsample (approx. 300 mg) was accurately weighed in a 50-ml plastic lined screw-capped Pyrex tube, 1.5 ml of a 1 : 2 (v/v) mixture of concentrated H_2SO_4–HNO_3 was added and the tubes were placed in a heating box at 90–95°C for 30 minutes. After cooling, 38.5 ml of 0.02 N BrCl was added and was mixed thoroughly. The solution was then left to stand overnight. Immediately prior to the determination of Hg concentration, 1 ml of $NH_2OH.HCl$ solution (prepared by dissolving 12 g NaCl and 12 g $NH_2OH.HCl$ in 100 ml nanopure water) was added and vortex mixed until disappearance of the yellow-brown color. The determination was carried out by a Flow Injection Mercury Analyzer (Perkin-Elmer model FIMS^{TML}400). This instrument based on cold vapor atomic absorption spectrometric technique using 0.2% (w/v) $NaBH_4$ in 0.05% NaOH (prepared by dissolving 2 g $NaBH_4$ in 1 l of 0.05% NaOH) as reducing agent, 3% (v/v) HCl as carrier solution, and argon stream as an inert carrier to transport Hg vapor into the cell. Detection limit of the instrument is <0.01 µg/l. The relative accuracy for the measuring of Hg was evaluated comparing to the certified values for the National Research Council of Canada Certified Reference Materials (NRCC-CRM) DORM-2 (dogfish muscle) and DOLT-2 (dogfish liver). All blanks and the CRM were prepared in the same manure as the samples. Total Hg concentrations in fish flesh are reported as ng/g wet weight. Linear regression was used to describe relationship between fish size and total Hg concentration.

The method validation results are reported in table 1. Analytical precision of the analysis was determined by analyzing every tenth sample in duplicate. The coefficient of variation (SD/mean) for the duplicate samples was less than 10%.

Results and Discussion

A total of 78 specimens of 11 pelagic predatory fish species including 8 bigeye thresher shark (*Alopias superciliosus*), 1 copper shark (*Carcharhinus brachyurus*), 3 silky shark (*Carcharhinus falciformis*), 1 unidentified shark, 12 frigate tuna (*Auxis thazard*), 1 tille travalley (*Caranx tille*), 4 kawakawa (tuna) (*Euthynnus affinis*), 29 skipjack tuna (*Katsuwonus pelamis*), 2 yellowfin tuna (*Thunnus albacares*), 1 bigeye tuna (*Thunnus obesus*) and 16 swordfish (*Xiphias gladius*) were analyzed. The concentrations of Hg range from 48-862 ng/g wet weight for 4 species of shark flesh, 5-625 ng/g wet weight for 5 species of tuna and 23-1245 for swordfish. The mean concentrations of Hg in ng/g wet weight of the fresh tissue were 514±187 for bigeye thresher shark, 251±128 for copper shark, 125±35 for silky shark, 48 for unidentified shark, 886±104 for tille travalley, 64±42 for frigate tuna, 63±16 for kawakawa, 110±153 for skipjack tuna, 92±32 for yellowfin tuna, 201 for bigeye tuna and 478±416 for swordfish. Summary statistics for Hg levels in the fish flesh of each species are presented in table 2.

In skipjack tuna and swordfish, Hg levels were found to be positively correlated with the length and weight of the fish (Fig. 2). This indicates that these fishes can accumulate relatively high levels of Hg with increasing size. This relationship can not be seen in bigeye tresher shark and frigate tuna. Because of too small number of individuals for each species, the rest species are not interpreted.

Box-and-Whisker diagram (Fig. 3) is used to compare Hg concentration in different species and to compare with the CODEX and EU guideline level for total Hg concentration of 0.5 μg/g (or 500 ng/g) for all fish except some predatory fish which a higher level of 1 μg/g is permitted (EU, 2001). According to the median of Hg level in fish tissue, most fish species had Hg contents less than 500 ng/g wet weight, except bigeye thresher shark and tille travalley. Some swordfishes, weighed over 40 kg, contained Hg higher than the EU and CODEX upper limit of 1 μg/g.

To answer the question "would there still be differences in Hg burden among species if there all had the same average size?," mean Hg content against mean sizes (weight and length) has been plotted as shown in fig. 4. Tille trevally (CT) had high Hg levels with respect to their sizes when compared to the other species. In contrast, yellowfin tuna (TA) had low Hg levels with respect to their sizes. The 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 diet. According to fig. 4, the fillets from fish smaller than approx. 15 kg (or 150 cm in length) are not expected to have Hg exceed the EU and CODEX limit of 0.5 μg/g. However, both tille trevally and yellowfin tuna contain excessively small sample size, as well as some other species. A more extensive sampling would be necessary to better estimate Hg levels in these species.

In comparison among 3 different geographically sites of the Bay of Bengal, samples from area C (the Andaman Sea) showed the highest Hg level in all 3 species (bigeye thresher shark, skipjack tuna and swordfish) (Fig. 5). As compare with weight and length, the probably reason for the high Hg level might due to the fish caught in this area was generally larger than those of other areas.

Table 1 Validation of digestion methods for determination of Hg (mean±standard deviation) in μg/g dry weight against NRCC-CRM DORM-2 and DOLT-2.

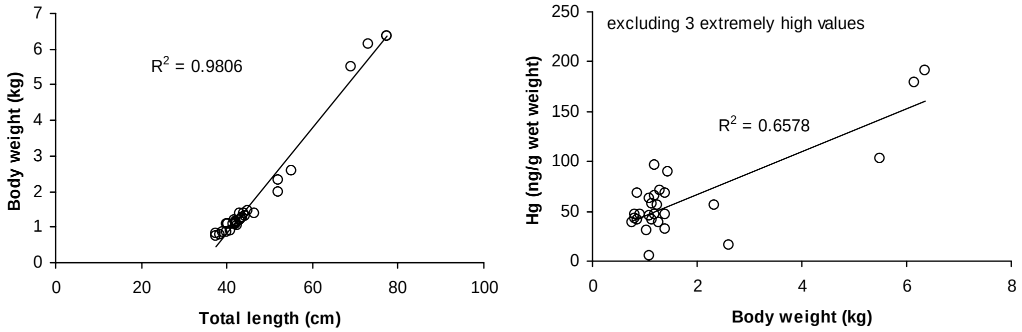
NRCC-CRM	n	Certified values (μg/g dry weight)	Obtained values (μg/g dry weight)	% Recovery
DORM-2	20	4.64±0.26	4.314±0.324	92.9
DOLT-2	20	2.14±0.28	2.136±0.123	99.8

Table 2 Mean±standard deviation and range of total length (cm), body weight (kg) and Hg levels (ng/g wet weight) in predatory fish flesh collected from the Bay of Bengal during November to December 2006.

Scientific name (Common name)	Code	n	Tissue	Total length (cm) (min-max)	Weight (kg) (min-max)	Hg (ng/g) (min-max)
Alopias superciliosus (Bigeye thresher shark)	AS	8	Caudal and fin	265.8±31.8 205-319	56.3±20.1 31- 90	514±187 198-862
*Carcharhinus brachyurus** (Copper shark)	CB	1	Caudal and fins	131.1	12.2	251±128 108-419
Carcharhinus falciformis (Silky shark)	CF	3	Caudal and fin	101.9±7.1 93.6-111.0	5.8±1.5 3.7-7.2	122±35 74-158
Shrk (Unidentified shark)	Shk	1	Caudal and fin	87.6	3.2	48
*Caranx tille*** (Tille trevally)	CT	1	Caudal/Abdominal	66.8	3.3	886±104 (782-990)
Auxis thazard (Frigate tuna)	AT	12	Abdominal	37.5±2.3 (31.5-40.0)	0.8±0.1 (0.4-1.0)	64±42 (39-202)
Euthynnus affinis (Kawakawa)	EA	4	Abdominal	39.1±2.2 (37-42)	0.9±0.1 (0.75-1.05)	63±16 (46-88)
Katsuwonus pelamis (Skipjack tuna)	KP	29	Abdominal	46.2±10.1 (37.4-77.5)	1.7±1.5 (0.75-6.35)	110±153 (5-625)
Thunnus albacares (Yellowfin tuna)	TA	2	Abdominal	138.5±1.5 (137-140)	36.5±1.5 (35-38)	92±32 (61-124)
Thunnus obesus (Bigeye tuna)	TO	1	Abdominal	52.0	2.0	201
Xiphias gladius (Swordfish)	XG	16	Abdominal	198.3±43.3 (129-262)	25.7±17.9 (5-60)	478±416 (23-1245)

* analysis of 3 parts in one fish
** analysis of 2 part in one fish

Katsuwonus pelamis (skipjack tuna)



Xiphias gladius (swordfish)

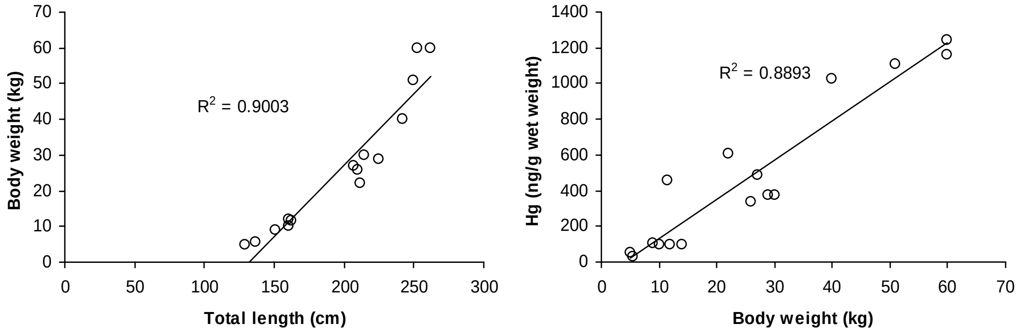


Figure 2 Relationships of body weight against total length (left), and Hg levels against body weight (right) of *Katsuwonus pelamis* (skipjack tuna) and *Xiphias gladius* (sword fish).

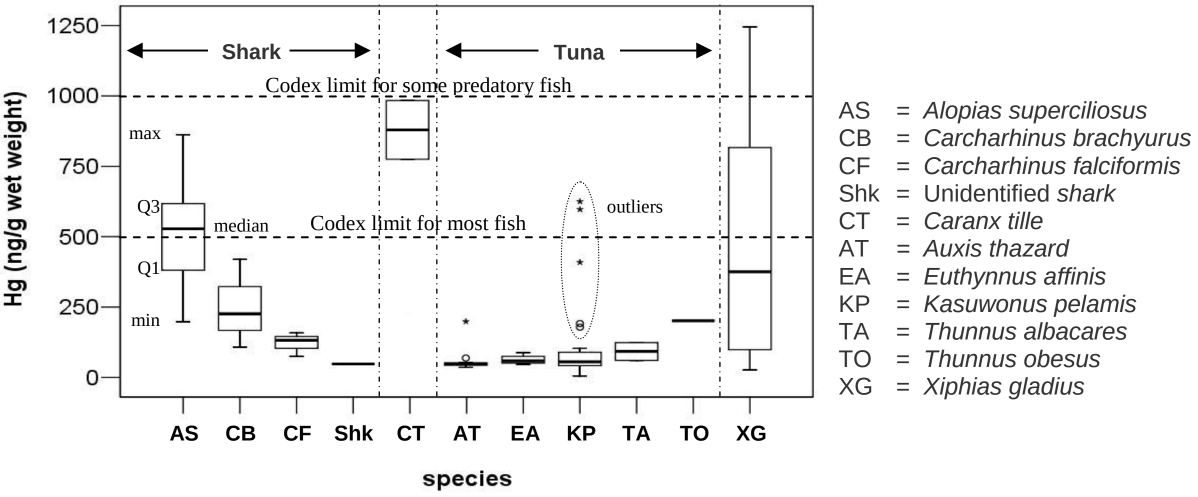


Figure 3 Box-and-Whisker diagram showing a comparison of total Hg concentration in fish flesh of different 11 pelagic fish species in the Bay of Bengal.

(The spacing between the different parts of the box indicates the degree of dispersion and skewness in the data, and identifies outliers.)

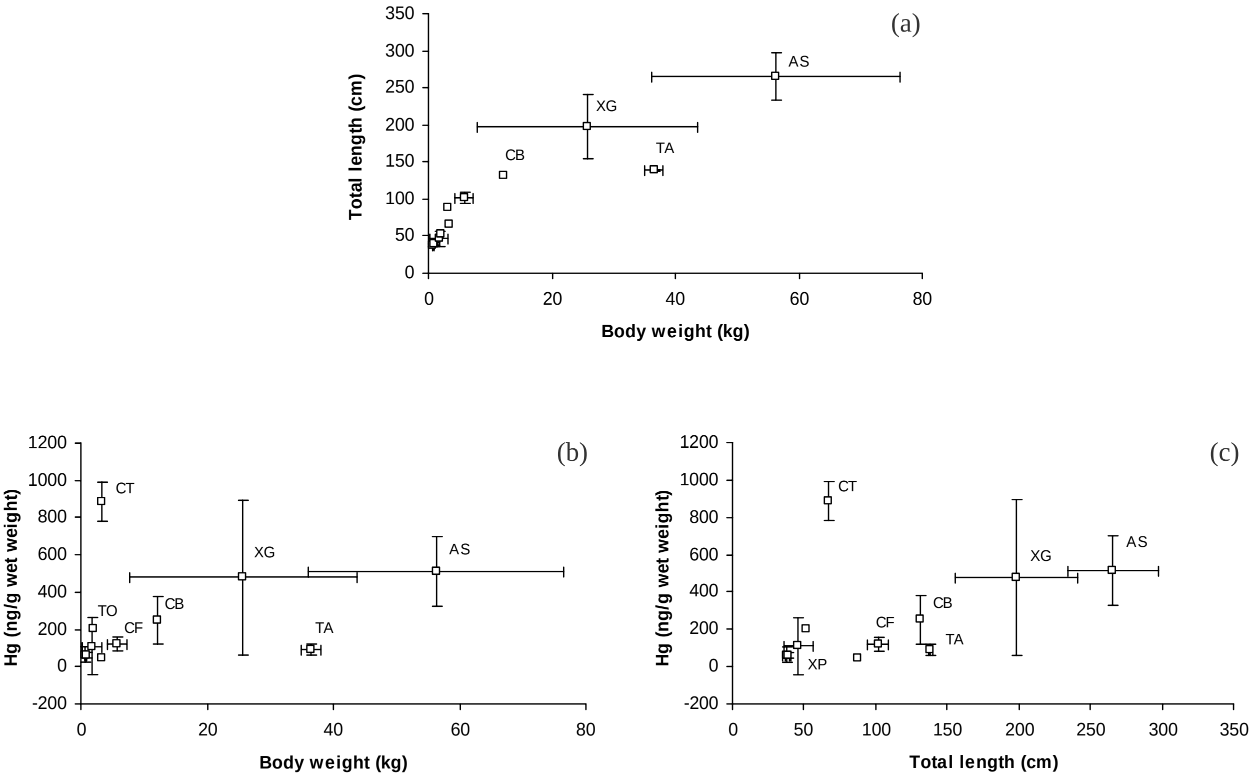


Figure 4 Position of species in relation to their mean value: (a) mean length against mean body weight; (b) mean Hg levels against mean body weight; and (c) mean Hg levels against mean length.
(Error bars represent the standard deviation.)

The highest Hg concentration was found in swordfish caught in area C, particularly in the fish that larger than 40 kg, which contained Hg in their tissues over 1000 ng/g wet weight. Swordfish are quite different to tuna and to other billfish, such as blue marlin. They have a wider geographical distribution than those other species and regularly move between surface waters down to great depths where they tolerate extreme cold. They move with prevailing currents and use their superior eyesight to locate prey. They can grow to enormous sizes. Male and female swordfish grow at different rates and have different distributions. In some areas they regularly descend from the sea surface down to depths of 1000 m or more (Carey and Robinson 1981). Juvenile swordfish are most abundant in tropical and subtropical waters. They migrate to lower latitudes as they mature (Yabe *et al.*, 1959). Adult swordfish are opportunistic feeders, taking a wide variety of prey. Their diet varies with location and the species available. A major portion of swordfish diets is comprised of squid, fish and occasionally crustaceans and octopus (Palko *et al.*, 1981). The daily ration of food required by adult swordfish has been estimated at 0.9% to 1.6% of body weight, with their yearly consumption ranging from 3-6 times their average body weight per year (Stillwell and Kohler, 1985). Because swordfish is long-lived fish and being top predator with a relatively high metabolic rate, high concentrations of heavy metals, especially Hg, may accumulate in the flesh (Monteiro and Lopes, 1990).

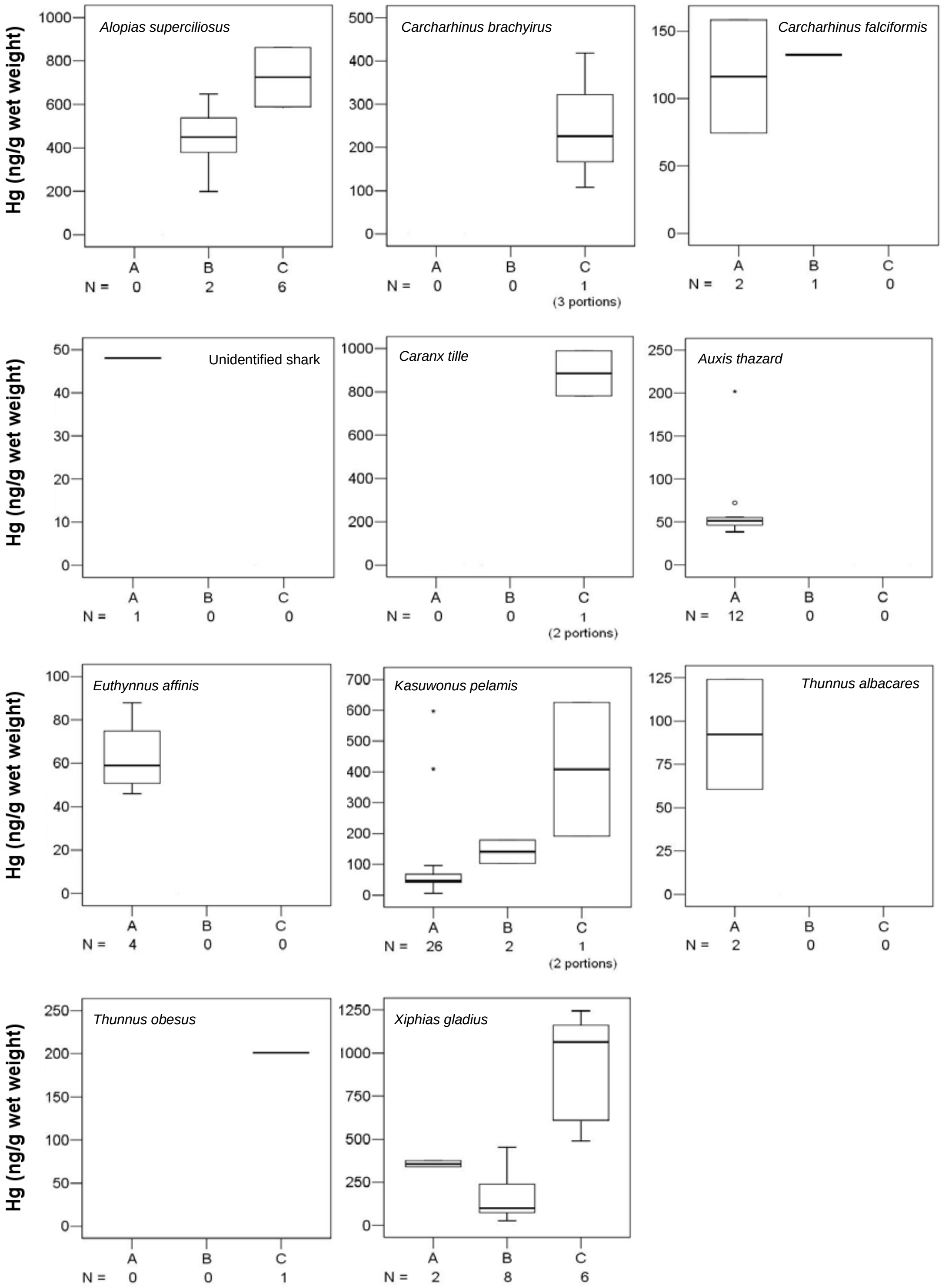


Figure 5 Box-and-Whisker diagrams showing a comparison of total Hg concentration in 11 predatory fish species in 3 different geographically sites of the Bay of Bengal.

The spacing between the different parts of the box indicates the degree of dispersion and skewness in the data, and identifies outliers.

In 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 3.

Table 3 Mercury levels (mean±standard deviation or minimum-maximum in µg/g wet weight) in muscle of marine fish from various geographical areas.

Species	**Origin**	**n**	**Hg (µg/g wet weight)**	**References**
Alopias superciliosus (Bigeye tresher shark)	Bay of Bengal (area B)	6	0.444±0.144	This study
	Andaman Sea (area C)	2	0.726±0.137	This study
Carcharhinus brachyurus (Copper shark)	Andaman Sea (area C)	1	0.251±0.128	This study
Carcharhinus falciformis (Silky shark)	Bay of Bengal (area A)	2	0.116±0.040	This study
	Bay of Bengal (area B)	1	0.133	This study
Prionace glauca (Blue shark)	Atlantic Ocean, near Azores	37	0.22-1.3	Branco *et al.* (2007)
	Atlantic Ocean, equator	27	0.68-2.5	Branco *et al.* (2007)
Unidentified shark	Bay of Bengal (area A)	1	0.048	This study
4 species of shark	Andaman Sea		0.057-0.478	Menasveta and Siriyong (1977)
Shark	Sea around Taiwan	41	0.73±0.54	Chien *et al.* (2007)
Auxis thazard (Frigate tuna)	Bay of Bengal (area A)	12	0.064±0.042	This study
Caranx tille (Tille trevally)	Andaman Sea (area C)	1	0.886±0.104	This study
Euthynnus affinis (Kawakawa)	Bay of Bengal (area A)	4	0.063±0.016	This study
	Sea around Malaysia	5	0.01±0.01	Hajeb *et al.* (2009)
Katsuwonus pelamis (Skipjack tuna)	Bay of Bengal (area A)	26	0.085±0.125	This study
	Bay of Bengal (area B)	2	0.141±0.038	This study
	Andaman Sea (area C)	1	0.408±0.217	This study
	Reunion Island*	39	0.19±0.66	Kojadinovic *et al.* (2006)
	Indian Ocean	1	0.53	Kureishy *et al.* (1979)
	Seuchells	5	0.34±0.11	Matthews (1983)
Thunnus albacares (Yellowfin tuna)	Bay of Bengal (area A)	2	0.092±0.032	This study
	Andaman Sea		0.026-0.234	Menasveta and Siriyong (1977)
	Seychells	5	0.23±0.10	Matthews (1983)
	Pacific Ocean	105	0.21±0.11	Kraepiel *et al.* (2003)
	Atlantic Ocean	56	0.25±0.12	Adams (2004)
	Mozambique Channel*	20	0.13±0.09	Kojadinovic *et al.* (2006)
	Reunion Island*	19	0.21±0.15	Kojadinovic *et al.* (2006)
Thunnus obesus (Bigeye tuna)	Andaman Sea (area C)	1	0.201	This study
Parathunnus sibi (Bigeye tuna)	Andaman Sea		0.027-0.233	Menasveta and Siriyong (1977)
Thunnus thynnus (Bluefin tuna)	Mediterranean Sea	73	0.20±0.07	Storelli *et al.* (2005)
Xiphias gladius (Swordfish)	Bay of Bengal (area A)	2	0.357±0.018	This study
	Bay of Bengal (area B)	8	0.163±0.149	This study
	Andaman Sea (area C)	6	0.939±0.286	This study
	Atlantic Ocean, near Azores	88	0.93±0.07	Monteiro and Lopes (1990)
	Atlantic Ocean, near Azores	48	1.30±0.17	Monteiro and Lopes (1990)
	Southwest Atlantic Ocean	192	0.62±0.35	Mendez *et al.* (2001)
	Mediterranean Sea	58	0.07±0.04	Storelli *et al.* (2005)
	Mozambique Channel*	37	0.38±0.26	Kojadinovic *et al.* (2006)
	Reunion Island*	7	1.24±0.83	Kojadinovic *et al.* (2006)
	Atlantic Ocean, near Azores	29	0.031-2.4	Branco *ei al.* (2007)
	Atlantic Ocean, equator	23	0.90-2.3	Branco *ei al.* (2007)
	Sea around Taiwan	58	0.77±0.83	Chien *et al.* (2007)

* the western Indian Ocean

Conclusion

The study provided baseline data for Hg accumulated in fishery resources of the Bay of Bengal. Most fish analyzed in this study still had Hg concentration in the tissue within the EU and CODEX limit of 0.5 μg/g, particularly when fish size not exceeding approx. 15 kg in weight or 150 cm in length. As a predator fish of such longivity, bigeye thresher shark and swordfish are expected to bioaccumulate Hg. The Hg burden in the tissue of both fishes reported in this study was the highest. In addition, swordfish which weighed more than 40 kg accumulated very high Hg contents in their flesh exceeding 1 μg/g wet weight which over the upper limit of the CODEX and EU guideline levels. From the data of 3 species (bigeye thresher shark, skipjack tuna and swordfish) that distributed in all 3 different geographically areas of the Bay of Bengal, fishes caught in the Andaman Sea seems to have higher Hg concentration than those of other areas. The most likely reason might due to the age of fish caught in the Andaman Sea which may be older than those of other areas as compared with length and weight.

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References

Adams, D. 2004. Total mercury levels in tunas from offshore waters of the Florida Atlantic coast. *Mar. Poll. Bull.* 49:659-667.

ATSDR. 1999. Toxicological Profile for Mercury. Agency for Toxic Substances and Disease Registry (ATSDR), U. S. Department of health and Human Services, Atlanta, Georgia. 676 pp. Available Source: http://www.atsdr.cdc.gov/toxprofiles/tp46.pdf; accessed. September 4, 2008.

AOAC. 1990. Association of official agricultural chemists. Mercury in fish. Method 977.15 (modified). **In:** Official Methods of Analysis of the Association of Official Analytical Chemists (AOAC), 15th editon. Arlington, VA, USA.

Barber, R. T. and P. J. Whaling. 1983. Mercury in marlin and sailfish. *Mar. Poll. Bull.* 14:395-396.

Bloom, N. S. 1992. On the chemical form of mercury in edible fish and marine invertebrate tissue. *Can. J. Fish. Aquat. Sci.* 49:1010-1017.

Branco, V., J. Canário, C. Vale, J. Raimundo and C. Reis. 2004. Total and organic mercury concentrations in muscle tissue of the blue shark (*Prionace glauca* L. 1758) from the Northeast Atlantic. *Mar. Poll. Bull.* 49:854-874.

Carey, F. G. and B. H. Robinson. 1981. Daily patterns in the activities of swordfish, *Xiphias gladius*, observed by acoustic telemetry. *Fish. Bull.* 79(2):277-292.

Chien, L. C., C. Y. Yeh, C. B. Jiang, C. S. Hsu and B. C. Han. 2007. Estimation of accepatable mercury intake from fish in Taiwan. *Chemosphere* 67:29-35.

EU. 2001. European Union (EU) Commission Regulation 466/2001 setting maximum levels for certain contaminants in foodstuffs (Consolidated version 2004). 26 pp.

Freeman, H. C. and D. A. Home. 1973. Sampling the edible muscle of the swordfish (*Xiphias gladius*) for the total mercury content. *J. Fish. Res. Board Can.* 30:1251-1252.

Gilmour, C. C. and G. S. Riedel. 2000. A survey of size-specific mercury concentrations in game fish from Maryland fresh and estuarine waters. *Arch. Environ. Contam. Toxicol.* 39(1):53-9.

Hall, B. D., R. A. Bodaly, R. J. .P. Fudge, J. W. M. Rudd and D. M. Rosenberg. 1997. Food as the dominant pathway of methylmercury uptake by fish. *Water Air Soil Pollut.* 100(1-2):13-24.

Hajeb, P., S. Jinap, A. Ismail, A. B. Fatimah, B. Jamilah and M. A. Rahim. 2009. Assessment of mercury level in commonly consumed marine fishes in Malaysia. *Food Control* 20:79-84. Available Source: www.elsevier.com/locate/foodcont. September 1, 2008.

Jackson, T. A. 1991. Biological and environmental control of mercury accumulation by fish in lakes and reservoirs of northern Manitoba, Canada. *Can. J. Fish. Aquat. Sci.* 48(12): 2449-2470.

Kehrig, H. A., M. Costa, I. Moreira and O. Malm. 2002. Total and methylmercury in a Brazilian estuary, Rio de Janeiro. *Mar. Poll. Bull.* 44(10):1018-1023.

Kojadinovic, J., M. Potier, M. Le Corre, R. P. Cosson and P. Bustamante. 2006. Mercury content in commercial pelagic fish and its risk assessment in the Western Indian Ocean. *Sci. Total Envi.* 366:688-700.

Kraepiel, A. M. L, K. Keller, H. B. Chin, E. G. Malcolm and F. M. M. Morel. 2003. Sources and variations of mercury in tuna. *Environ. Sci. Technol.* 37:5551-5558.

Kureishy, T. W., M. D. George and R. S. Gupta. 1979. Total mercury content in some marine fish from the Indian Ocean. *Mar. Poll. Bull.* 10:357-360.

Matthews, A. D. 1983. Mercury content of commercial important fish of the Seychelles and their mercury levels of a selected part of the population. *Environ. Res.* 30:305-312.

Menasveta, P. and R. Siriyong. 1977. Mercury content of several predacious fish in the Andaman Sea. *Mar. Poll. Bull.* 8:200-204.

Mendez, E., H. Giudice, A. Pereira, G. Inocente and D. Medina. 2001. Total mercury content – fish weight relationship in swordfish (*Xiphias gladius*) caught in the Southwest Atlantic Ocean. *J. Food Comp. Anal.* 14:453-460.

Miller, E. E., P. M. Grant, R. Kishore, F. J. Steinkruger, F. S. Rowland and V. P. Guinn. 1972. Mercury concentrations in museum specimens of tuna and sword fish. New York. *Science* 175:1121-1122.

Monteiro, L. R. and H. D. Lopes. 1990. Mercury content of sword fish (*Xiphias gladius*) in relation to length, weight, age and sex. *Mar. Pollut. Bull.* 21:293-296.

Palko, B. J., G. L. Beardslay and W. J. Richards. 1981. Synopsis of the biology of the swordfish (*Xiphias gladius)* Linnaeus. United States Department of Commerce, NOAA Technical Report NMFS Circular 441 (FAO Fisheries Synopsis No. 127).

Porcella, D. B. 1994. Mercury in the environment: Biogeochemistry. **In:** Watras C. J. and J. W. Huckabee. (eds.). Mercury Pollution Integration and Synthesis. Boca Raton, Florida: Lewis Publishers. p. 3-19.

Riisgard, H. U. and S. Hansen. 1990. Biomagnification of mercury in a marine grazing food-chain: Algal cells *Phaeodactylum tricornutum*, mussels *Mytilus edulis* and flounders *Platichthys flesus* studied by means of a stepwise-reduction-CVAA method. *Mar. Ecol. Prog. Ser.* 62(3):259-270.

Spry, D. J. and J.G. Wiener. 1991. Metal bioavailability and toxicity to fish in low-alkalinity lakes: A critical review. *Environ. Pollut.* 71:243-304.

Stafford, C. P. and T. A. Haines. 2001. Mercury contamination and growth rate in two piscivore populations. *Environ. Toxicol. Chem.* 20:2099-2101.

Stillwell, C. E. and N. E. Kohler. 1985. Food and feeding ecology of the swordfish *Xiphias gladius* in the western North Atlantic Ocean with estimates of daily ration. *Mar. Ecol. Prog. Series* 22:239-247.

Storelli, M. M., R. G. Stuffler, A. Storelli and G. O. Marcotrigiano. 2005. Accumulation of mercury, cadmium, lead and arsenic in swordfish and bluefin tuna from the Mediterranean Sea: A comparative study. *Mar. Poll. Bull.* 50:993-1018.

US-EPA. 2001. Appendix to Method 1631 Total Mercury in Tissue, Sludge, Sediment, and Soil by Acid Digestion and BrCl Oxidation. Based on a standard operating procedure provided by Frontier Geosciences, Inc.

Watras, C. J. and N. S. Bloom. 1992. Mercury and methylmercury in individual zooplankton: Implications for bioaccumulation. *Limnol. Oceanogr.* 37:1313-1318.

WHO. 1990. Methyl mercury. World Health Organization, International Programme on Chemical Safety. Geneva, Switzerland Vol.101.

WHO . 1991. Inorganic mercury. World Health Organization, International Programme on Chemical Safety. Geneva, Switzerland. Vol.118. 168 p.

Windom, H. L and G. Cranmer. 1998. Lack of observed impacts of gas production of Bongkot field, Thailand on Marine Biota. *Mar. Poll. Bull.* 36(10):799-807.

Yabe, H., S. Ueyanagi, S. Kikawa and H. Watanabe. 1959. Study on the life history of the sword-fish (*Xiphias gladius)* Linnaeus. Report of the Nankai Regional Fisheries Research Laboratories. 10:107-150.