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ORIGINAL ARTICLE

Mercury in Dried Market Fish of Hong Kong and San Francisco: Human Health Implications

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Background: Asian, Asian Pacific Islanders, and Asian American residents of San Francisco have higher exposure to mercury and the associated health risks associated with methylmercury toxicity from fish consumption than other demographics across the United States. Due to their higher annual fish consumption, Hong Kong Chinese residents have elevated risks to methylmercury exposure.

Objectives: We investigated samples of dried market fish from San Francisco and Hong Kong as potential sources of mercury contamination in fish commonly consumed by Asian and Asian American residents.

Methods: We analyzed 81 samples of dried market fish from San Francisco and Hong Kong for mercury concentration by inductively coupled plasma emission spectrograph and processing cold vapor atomic fluorescence spectrometry. We binned into market categories, trophic level, and habitat type for statistical analysis.

Results: No significant difference was observed in the mercury levels of samples from San Francisco and Hong Kong ($P = 0.47$). Dried samples showed higher rates of mercury than wet samples reported by the FDA. Data from dried market fish samples also showed evidence of bioaccumulation: the concentration of toxins in higher trophic levels of fish ($P < 0.01$). Eliminating apex predators, nearly all samples of fish from both locations and lower trophic levels had levels below the lowest health advisory thresholds of 0.5 ppm methylmercury by weight.

Discussion: Dried fish samples from markets in San Francisco and Hong Kong showed mercury levels with the potential to exceed guidelines set by the Environmental Protection Agency (EPA) and the European Food Safety Authority (EFSA); however, consumption rates are lacking to know if this threshold is actually being exceeded by consumers. We make recommendations regarding the health risks of dried market fish and of consuming or avoiding fish from certain trophic groups.

Key Words: Cumulative biological risk ▪ Asian American ▪ Environmental health ▪ Food safety ▪ Marine environment ▪ Environmental contamination ▪ Trophic levels

Mercury pollution is a cause for concern globally due to their toxic effects on both humans and wildlife.[1] Mercury enters the environment through natural and anthropogenic processes. Natural processes include volcanism and erosion, while anthropogenic processes contribute to the greater share of environmental mercury (although this is debated[2]) and include industrial and commercial disposal, mining, and the burning of fossil fuels.[3] Several species of environmental mercury are commonly found, including elemental mercury (Hg), inorganic mercurial salts (Hg^{+} and Hg^{2+}), and methylated mercury (MeHg). Several pathways that allow mercury compounds into the human body are known including respiration of elemental mercury[4] and absorption through the gastrointestinal (GI) tract.[5]

Mercury exists in several inorganic and organic states in water. Methylmercury, the most common organic form of mercury, quickly enters the aquatic food chain.[6] In most adult fish, 90–100% of the mercury is methylmercury. Methylated mercury is the species that is most readily absorbed by the GI tract and the principal species of mercury that bioaccumulates. Mercury is methylated through abiotic-reduction and bacterial detoxification pathways where it enters the food web.[2] One of the

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POPULAR SCIENTIFIC SUMMARY

- Asian residents of San Francisco have higher exposure to mercury from fish consumption than other demographics.
- We analyzed 81 samples of dried market fish from San Francisco and Hong Kong for mercury concentration and found they contained similar levels of mercury.
- Fish samples show bioaccumulation: the concentration of toxins in higher trophic levels of fish.
- Dried fish samples from markets in San Francisco and Hong Kong showed mercury levels with the potential to exceed public health guidelines.

common and well-studied pathways for mercury exposure in humans is the consumption of marine foods.[1,7,8] The first large-scale outbreak of mercury toxicity recorded in Minamata Japan in the 1950s and 1960s was associated with seafood consumption from Minamata Bay where the adjacent Chisso chemical plant released large amounts of mercury waste into the Hyakken Harbour of Minamata Bay. A marked increase in birth defects, developmental disorders, and neurodegeneration in the population was observed in the community, associated with methylmercury bioaccumulation in fish and shellfish in the Bay. A degenerative disease of the brain in both adults and infants caused by MeHg poisoning is referred to as Minamata disease. MeHg was first identified as the toxic agent responsible for the symptoms by Kurland et al.[9] However, recent analysis of preserved tissue of a cat experimentally fed the effluent from the Chisso chemical plant suggests that the plant discharged Đ-mercuri-acetaldehyde compounds or at least other organometallic mercury compounds and that these species, and not biotransformed methylmercury, were likely responsible for the outbreak of Minamata disease in the 1950s.[10] In 1968, regulations finally limited the Chisso chemical plant enough to reduce discharges of mercury in the Bay, and by the 1990s the bay was finally determined clean enough to allow fishing again.[4]

Excessive levels of methylmercury are associated with various negative effects on human health, most notably neurological damage and reproductive and developmental abnormalities.[11] Outbreaks of mercury toxicity from several observational case studies reported by the World Health Organization (WHO) have helped us understand how mercury levels are deleterious to human health. These cases came from mercury exposure from contaminated grain in Iraq, and from fish-eating populations in New Zealand and Canada. The WHO considered measurements that were taken from human hair, a good proxy for blood level mercury (the conversion between blood to hair is 4 to 1). The investigators compared methyl mercury in hair to neurological symptoms in study subjects. The minimum level for 'Severe' effects were observed at 404 μg/g (hair), while evidence of 'psychomotor retardation' were seen at 10–20 μg/g (hair). Blood levels would be expected to be ~1600 and ~40–80 μg/L, respectively.[11] However, the lower threshold that mercury concentration would cause long term, potentially subtle, human health effects is unknown.[5]

Fish consumption trends

Fish and shellfish contain high-quality protein and other essential nutrients, are low in saturated fat, and contain omega-3 fatty acids. The benefits of omega-3 fatty acids and human health is an active area of research, and there are calls for additional research with definitive results about the health benefits of eating fish.[12] In a scientific advisory and literature review from the American Heart Association, fish consumption one to two times per week is attributed to some types of increased cardiovascular health, although greater amounts of fish do not show increased benefits.[13] The USDA dietary guidelines for Americans recommend that adults eat two to four-ounce servings of seafood each week.[14] The risk to mercury exposure can come from eating a high quantity of fish with lower to moderate levels of mercury (<0.5 ppm), or by eating fish with higher-than-average mercury levels. According to the Environmental Protection Agency[15], certain high-risk groups who eat more than 10 g of fish per day, which is equivalent to one fish sandwich per week, could be eating near or up to twice the recommended frequency dose (RfD) of mercury.

Top predatory fish (e.g. king mackerel, various bass species, pike, swordfish, and sharks) have higher-than-average mercury levels ranging from around 1.0 ppm to as high as 4 ppm and even higher, particularly in sharks. An observational study conducted on shark meat in South Korea[16] found that the mercury concentration in 77 of 105 shark meat samples exceeded 1 ppm. A study of four shark species in Baja, California found the average concentrations of mercury between 0.98 and 3.4 ppm.[17] The US FDA reports mercury levels between 0.398 and 0.975 ppm in tunas, marlin, groupers, sharks, and swordfish, all large predatory fish.[18] These results are consistent with the assumption that bioaccumulation leads to increased mercury levels in top predators. If the mercury concentration is greater than 0.5 ppm, even eating average amounts of fish can equal or exceed the recommended frequency dose, implying that consumption of top predatory fish should be reduced or completely avoided to limit mercury exposure.

Fish is a staple food in the Asian and Asian American diet, which puts these populations at a greater risk for mercury toxicity through the marine food pathway. Because of the higher amounts of fish in their diets, these ethnic groups need to be aware of the level of mercury in the fish they eat. An observational study analyzing data collected by the National Health and Nutritional Examination Survey from 1999 to 2002 found that Asians, Pacific Islanders, and Native Americans consumed 8.02 ± 1.95 (mean ± SE) fish/shellfish meals in the preceding 30 days.[19] This is approximately two times the average number of fish/shellfish meals consumed in the preceding 30 days of all other ethnic groups. Asians and Pacific Islanders were found to have the highest level of hair mercury levels in a study of women of childbearing age in Duval county, Florida, and the same study found that awareness of fish mercury advisories was low for all groups.[20]

Asian consumers are also at risk from a traditional dried seafood known as shark fin soup. An observational study demonstrated that most shark fins turned out to have five to 10 times more mercury than the legal maximum amount of 0.5 ppm,[21] as indicated by the Hong Kong government's Center for Food Safety. The highest amount was found in great hammerheads, which had mercury levels of 55.52 ppm. In 2017, Shea and To[22] reported an overall reduction in the trade of shark fins from 1998 to 2013; however, they warned of discrepancies in the reporting and suggested that the amount of shark fin traded is underreported. Eriksson and Clarke also found a decrease in shark fin production, but again caution that the data are incomplete.[23] Reasons for a possible decline in the trade of shark fins are either not stated by the authors or suggested to be either constrained resources, changing consumer attitudes, or regulatory action. Shark fin is easily transported under misleading labels (e.g. dried seafood), is easily smuggled, and recordkeeping and tracking shark fins through supply chains are particularly challenging. Regardless of the social, political, or environmental trends in the shark fin trade, avoiding or reducing consumption of all shark products is prudent in limiting mercury exposure.

Human blood plasma mercury levels in Hong Kong versus San Francisco

Measurement of blood mercury levels is considered the most accurate method for the detection of mercury in humans and was used to study mercury levels in Asian and Asian American adults living in the San Francisco Bay Area. Mercury blood levels were measured in 195 Chinese and Vietnamese adult participants who had lived in the San Francisco Bay Area for at least 1 year. Concentrations were reported in mercury with a geometric mean of 4.18 μg/L (3.01–5.51 95%CI).[24] Compared with two other populations, these numbers are unusually high. A blood-plasma mercury study of samples from 151 Hong Kong residents reported in total Hg (THg) with a mean value of 0.28 μg/L (range 0.13–2.08).[25] A larger study of 989 Asian and Asian Americans across the United States reported blood total mercury levels between 2013 and 2016. The geometric mean was calculated to be ~1.72 μg/L (1.41–2.02 95% CI).[26] The San Francisco population of Chinese and Vietnamese adult participants' blood mercury level was about three times higher than Asians in the United States and about four times higher than residents of Hong Kong (Table 1).

Table 1. Summary of blood mercury concentrations from three different Asian populations.

	San Francisco	Hong Kong	United States
Mean Hg (μg/L)	4.18†	0.28	1.72†
95% CI	3.01–5.51	0.13–2.08*	1.41–2.02
Sample size	195	151	989

Notes: 1. San Francisco: Biomonitoring California, 2016; 2. Hong Kong: Liang et al., 2013; 3. United States: CDC, 2021. Units in μg/L. †represents geometric mean. *represents range, not confidence interval.

As mercury has several different pathways to enter the human body, there are many possible hypotheses to explain this difference. First, these results come from different studies not designed to compare these populations, so the different methods may have affected the outcomes. Also, there could be other food vectors (notably rice[5]:) or other environmental sources of elemental, inorganic, or methylated mercury controlling the difference we see between these populations. Nonetheless, because of the interest to human health and the importance of fish conservation we decided to do a preliminary investigation of dried fish as a potential vector for mercury in the Hong Kong and San Francisco populations. Dried fish was chosen as it was readily available for purchase, affordable to process and analyze, and is consumed by both populations.

METHODS

Collecting samples

Forty-one samples of dried fish were purchased from seafood shops located in San Francisco Chinatown and in the greater Bay Area (SF samples). Given the higher price and the known high concentrations of MeHg in large fish such as shark, swordfish, and tuna,[27] we purposely excluded these from this study, and instead focused on lesser studied and commonly consumed dried fish. Forty additional samples were purchased from fish markets located in Hong Kong's Shek Wu Hui, Sheung Wan, Tung Yick, and Des Voeux Road West markets (HK samples). The samples were selected at random from the fish available in the markets when visited in September 2020. Fish samples were purchased and stored in plastic bags for transport. Fish types were identified by the common name on labels, or on the bins in the case of dried fish sold in bulk cases. We accepted these labels as market categories of fish, and noted that these are not necessarily representative of fish species. The preparation involved trimming approximately 6 g of samples and storing them in a plastic container. This was done in an environment thoroughly wiped and sanitized by ethyl alcohol. San Francisco samples and Hong Kong fish samples were purchased at markets listed in Supplemental Table 2: Market Sample Locations.

Sample analysis

All 40 of the HK samples were sent to Eurofins Food Testing Hong Kong Limited laboratory and analyzed for mercury by inductively coupled plasma mass spectrometry (DIN EN 15763:2010 (2010-04), mod.). Results were presented in ppm mercury. Eighteen of the SF samples were sent to the Eurofins Microbiology Laboratory in Los Angeles for analysis of mercury concentration via inductively coupled plasma emission spectrograph (AOAC 2011.19, AOAC 993.14, JAOAC), and results were returned in ppm mercury. The remaining 23 SF samples were sent to the Wisconsin State Laboratory of Hygiene – Trace Element Clean Laboratory. The laboratory reported that their analysis was performed following the analytical portion of EPA 1630 (no distillation was performed) following Hammerschmidt and Fitzgerald. Portions of homogenized samples were weighed into Teflon vials and digested overnight in 4.5 M nitric acid. A 60°C water bath was not used (as in Hammerschmidt and Fitzgerald); instead used a convection oven set to 65°C. The samples were diluted with reagent water and the dilution volume was determined gravimetrically. An aliquot of the diluted sample was transferred to an autosampler vial, buffered to pH 4.5 with a 2 M acetate buffer, and ethylated with 1% sodium tetraethyl borate. The sealed vial was purged with argon and the gaseous sample introduced to a GC-CVAFS (Tekran 2700). The methylmercury concentration as analyzed was used to calculate the concentration in the solid sample based on the volume analyzed, dilution volume, and sample mass. Results were presented in ng/g MeHg.

Sample categorization

All 81 samples were binned into 18 market categories based on the market labels recorded at purchase (Table 2). We believe that these categories are broadly representative of the types of dried fish found in these markets based on labeling. Two of the San Francisco samples were unlabeled and discarded. The samples were additionally sub-categorized into three trophic and habitat levels following the scheme described by Bonito et al.[28] for grouping bioaccumulative and toxic pollutants in marine fish (Supplemental Table 1). The described scheme divides fish species from trophic and habitat descriptions found on Fishbase.[29] The trophic levels

Table 2. 18 Market categories and averages for Hong Kong, San Francisco and total across locations.

	United States		Hong Kong		Total	
Market category	**Mean PPM**	***N***	**Mean PPM**	***n***	**Mean PPM**	***n***
Anchovy	0.031	3	0.016	3	0.024	6
Bonito	0.081	1	0.19	1	0.135	2
Croaker	0.113	11	0.097	10	0.105	21
Cuttlefish	0.116	1	0.046	1	0.081	2
Eel	0.428	1	0.25	1	0.339	2
Fish Maw	0.027	1	0.014	1	0.021	2
Flounder	0.302	2	0.18	2	0.241	4
Herring	0.072	3	0.112	4	0.095	7
Mackerel	0.254	2	0.221	3	0.234	5
Noodlefish	0.03	2	0.053	2	0.041	4
Octopus	0.098	1	0.23	1	0.164	2
Pollock	0.031	2	0.082	2	0.057	4
Pomfret	0.041	1	0.013	1	0.027	2
Red Snapper Head	0.166	1	0.17	1	0.168	2
Scallop	0.008	1	0.052	1	0.03	2
Sea cucumber	0.014	2	0.008	2	0.011	4
Shrimp	0.017	1	0.075	1	0.046	2
Threadfin	0.111	2	0.108	2	0.11	4
Total	0.10784	38	0.1065	39	0.10718	77

Notes: n is the number of samples per category, per country.

described were as follows: H, herbivores; P, primary consumer; MP, middle consumer; TP, top consumer. and the habitat levels were: Benthic, Demersal, and Pelagic. Where our market categories returned multiple species from the Bonito et al. categories, the median trophic and habitat levels were adopted. For any species not categorized in the Bonito work we looked on Fishbase and Sealifebase[30] and used the same criteria to rate our market categories, using type species from the market categories and the FishBase Trophic estimator, when available, to determine the rankings.

Data analysis

All data were analyzed using R version 4.0.4, (R Development Core Team). All units were converted to parts per million (ppm), and methylmercury concentrations were pooled with mercury concentrations following the example set in Mercury Concentrations in Fish from the FDA Monitoring Program, 1990–2010.[31] A QQ plot of a linear model between the market categories revealed that the model residuals did not meet the criteria of normality, and therefore, the non-parametric Kruskal–Wallis test was performed to investigate the relationships between HK and SF sample mean ppm between the market categories, as well as the mean ppm between the trophic and benthic categories. Pooling the HK and SF samples into the same QQ plot revealed that the pooled samples by location did meet the criteria of normality, and thus, a Student's paired t-test was performed on the pooled sample means between the HK and SF samples. In addition, a paired t-test was performed between the dried food from this study and the wet food data reported by the FDA Monitoring Program. Four samples were excluded from the analysis 'Whole Fish' (only one HK sample) 'File Fish' (only one SF sample) and two 'Unknown' SF samples.

RESULTS

The Kruskal–Wallis test revealed no difference between the HK and SF samples (P = 0.471, Effect Size = −0.008). The paired t-test also revealed no difference between the market categories in HK and SF (P = 0.97). The means of the pooled HK samples (0.10 ppm mercury) and SF samples (0.11 ppm mercury) were within 1% of each other (Fig. 1).

After categorizing our samples by both habitat and trophic level (according to[28]), the Kruskal–Wallis test

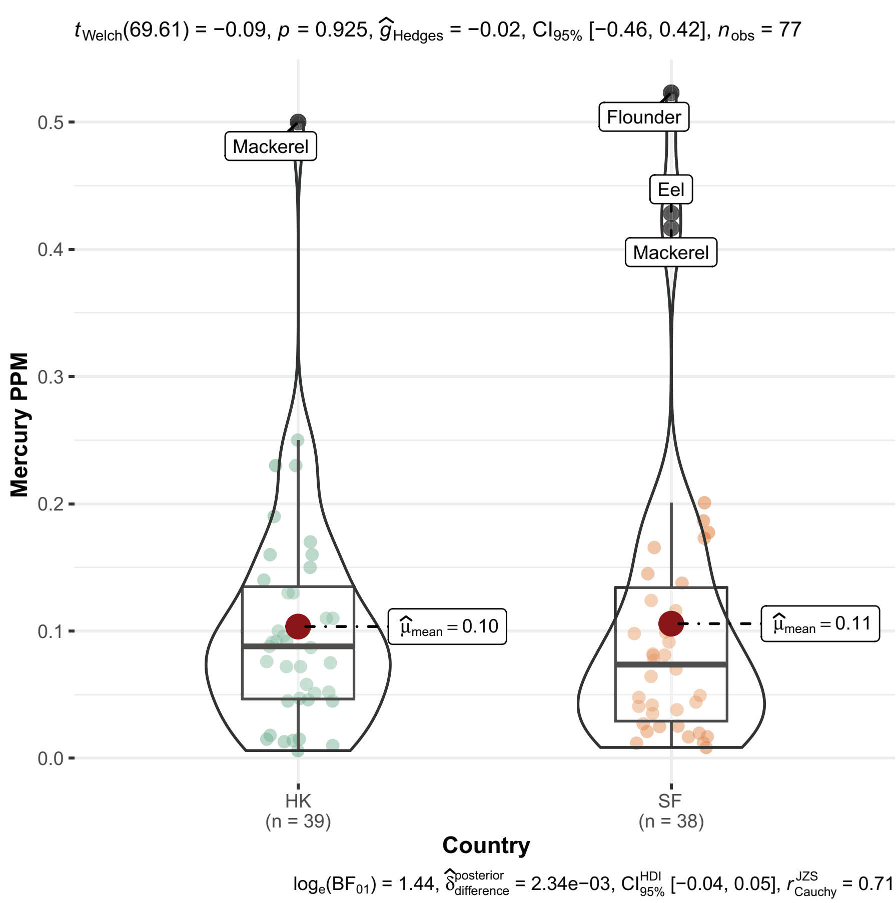

Figure 1. Mean ppm mercury boxplot showing IQR and mean of Hong Kong and San Francisco. Outliers labeled with the market category.

Table 3. Average mercury concentrations across trophic levels and habitat.

		Mean PPM	Median PPM	*N*
Trophic level	Primary consumer	0.048	0.044	29
	Middle consumer	0.143	0.105	42
	Top consumer	0.152	0.168	4
Habitat	Benthic	0.083	0.047	16
	Demersal	0.118	0.100	37
	Pelagic	0.105	0.076	22

Notes. Trophic and Habitat categorizations taken from Bonito et al.[28]

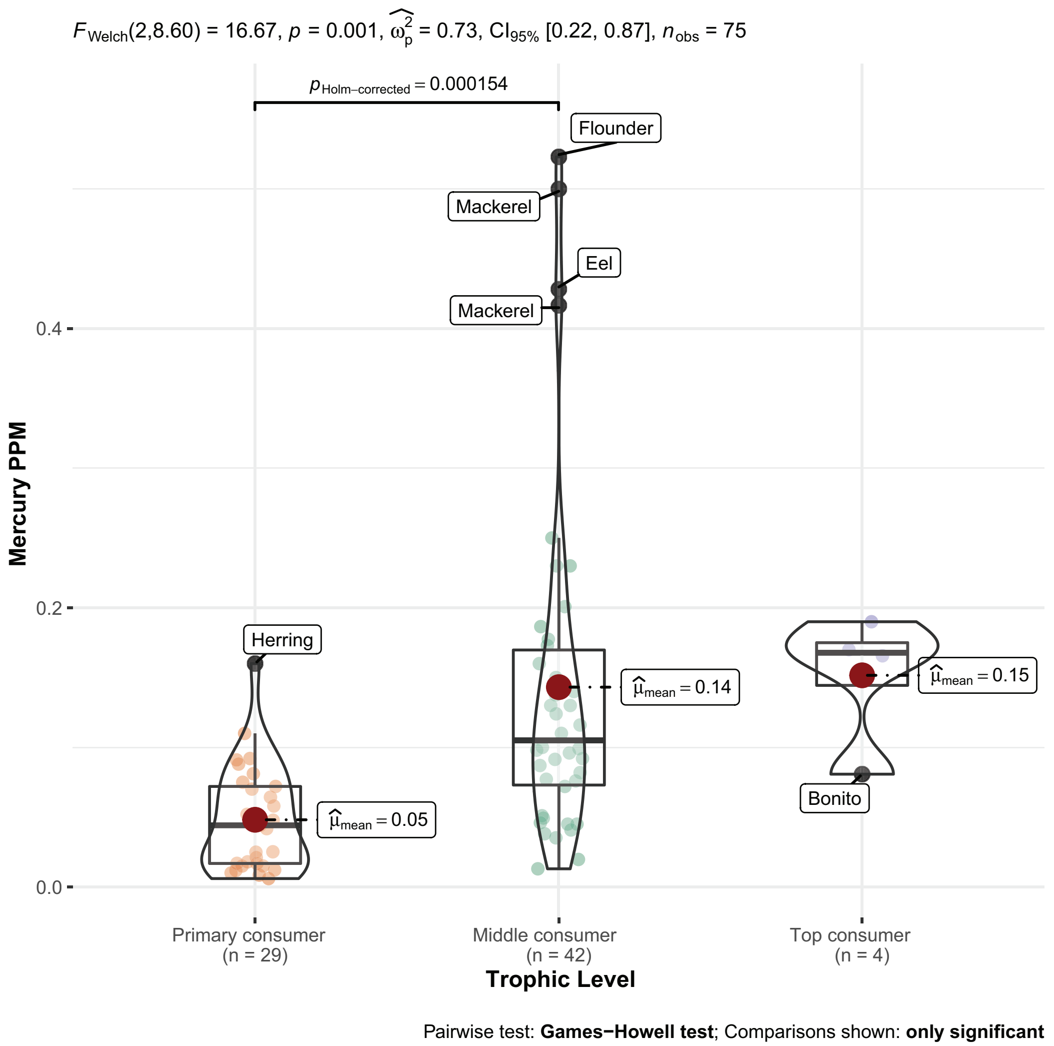

Fig. 2. Mercury concentration across trophic levels.

revealed a significant difference in the mean ppm mercury between trophic levels ($P < 0.01$, effect Size = 0.338). Furthermore, the means between the trophic groups increase with trophic level as predicted by biomagnification. Notable outliers include Herring, Mackerel, Eel, Flounder, and Bonito. The Kruskal–Wallis test for habitat showed significant variance between the habitat types ($P < 0.01$, effect size = 0.338), with Benthic showing the lowest rate of mercury (0.083 ppm) and Demersal showing the highest levels (0.118 ppm) (Table 3, Fig. 2).

DISCUSSION & CONCLUSION

Global fish trade

Dried fish in Hong Kong and San Francisco markets show no significant difference in the mean levels of mercury. The global fish trade ships product back and forth across the world for capture, processing, and sale. It is possible that the dried fish in both locations is coming from the same distributors, which could explain how fish in both locations have similar mercury concentrations. As we did not investigate species or sources in the market, we can only speculate if these fish are coming from the same fishery or distributors. A previous study found that dried fish in Hong Kong imported 2000 mt of dried fish from Mainland China, Bangladesh, Vietnam, India, Indonesia, Thailand, and Kenya, and in total, received dried fish imports from 73 different countries. Mainland China is both the largest supplier and receiver of exports and imports of dried fish in Hong Kong, likely of different categories of fish but available product codes did not distinguish the dried fish types being imported and exported.[32] A study on mite infestations on products imported to a port in Southern California found dried seafood products including fish, shrimp, squid, and shark fin imported from China, Hong Kong, Japan, Malaysia, the Philippine Islands, Singapore, and Thailand.[33] The complexity of the global fish market makes this explanation difficult to test. Although a common source is possible, the similarity of concentrations within similar trophic levels could also explain the results.

Mercury in fish populations

It is also possible that among these market categories, separate fish populations are homogenous in their levels for mercury. Mercury is transported globally through atmospheric processes from both natural and anthropogenic sources. It has been shown that mercury can be deposited through these systems into remote areas far from the point source of pollution. However, this process is not homogeneous as different sediments have been shown to have different levels of mercury contamination.[34] When deposited into marine systems, it must further be subject to transport by oceanic currents before being accumulated into biological systems. However, because of the complexity of the global fish trade, and the difficulty in determining the original fish populations that source each market category we cannot determine mercury levels per fish population.

Dried fish versus wet fish

As methylmercury is a stable compound, fat-soluble molecule, the loss of water from drying will result in higher concentrations than the equivalent weight of undried fish. We assumed that dried fish samples would have higher concentrations of mercury per unit weight than wet counterparts. Comparing our sample market categories with six matching and averaged equivalent species from the FDA published data on mercury in seafood[31], we did see higher concentrations in the dried samples (Fig. 3).

Human health dose & concentration

The EPA reference dose (RfD) for consumption of methyl mercury is 0.1 µg mercury/kg body weight/day. The RfD represents the exposure that a person can experience safely in his or her lifetime without noticeable harm. It is a conservative estimate, 'protective of neurodevelopmental effects' and includes a 10-fold uncertainty factor, which allows for differences among individuals and populations.[35] This means a 75 kg person could safely consume 7.5 µg of mercury per day, according to the EPA. Taking our croaker samples as an example, which have a mean concentration of 0.113 ppm mercury, a 100 g sample would contain an expected amount of 11.3 µg of mercury. This represents 0.15 µg mercury/kg for our 75-kg example person, or 150% of the EPA RfD. The level at which mercury affects human health is not universally agreed upon. A more permissive guideline for the consumption of mercury in human health is set by the European Food Safety Authority (EFSA), which updated their recommendation in 2012 to a total weekly intake (TWI) of 1.3 µg/kg body weight.[36] This is equivalent to 0.19 µg mercury/kg body weight/day, or close to twice the level set by the EPA.

While establishing threshold ppm limits for market fish, the EPA has calibrated its recommendations to reflect weekly consumption for the average American diet. Notably, our population of interest, Asian Americans and Asians in Hong Kong eat more fish than the average American. A study of 202 first- and second-generation Asian American and Pacific Islanders from King county, Washington found the average seafood rate to be 117.2 g/day with an average body weight of 62 kg per participant.[37] This was not dried seafood, but it does at least provide some reference frame for the potential consumption by Asian Americans. Still, when making recommendations for public health we must consider more vulnerable individuals. A hypothetical 45 kg person who ate an average of 120 g per day of the dried mackerel samples (0.234 ppm) from our study would be consuming 28.1 µg of mercury per day, which equals 0.62 µg mercury/kg body weight/day. This well exceeds the limits set by the EPA and the EFSA (by 620 and 326%, respectively).

However, these are hypothetical scenarios, and the dose received is dependent on the actual frequency of consumption and fish consumed. Furthermore, a study of the childbearing age women of the Seychelles islands who daily consume large amounts of fish averaging 0.3 µg/g MeHg found no significant developmental impairments in a cohort of 779 mother–infant pairs.[38] The mean value of fish consumed in the Seychelles was about

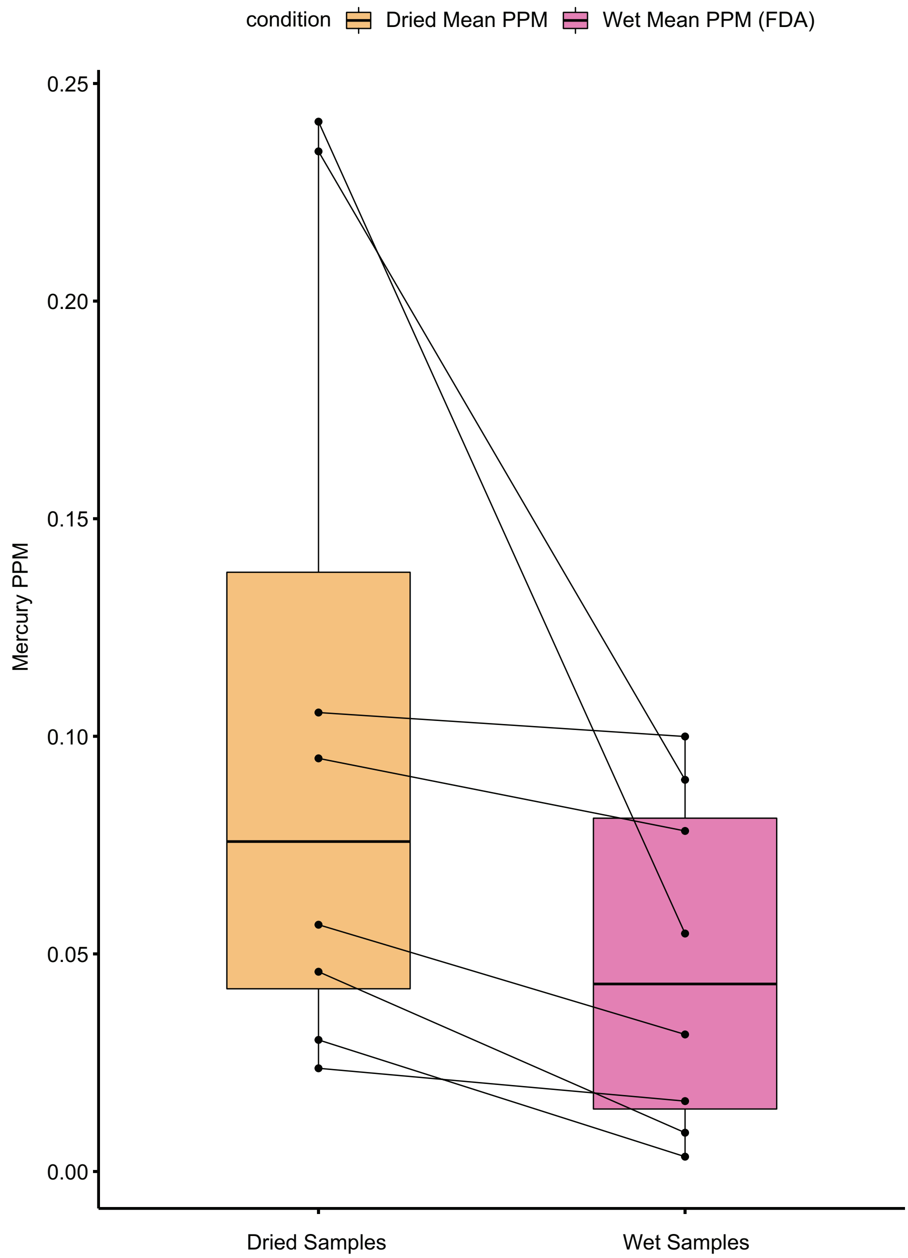

Fig. 3. Paired averages for dried samples versus the FDA wet sample data. Only six market categories matched the species in the FDA data (Anchovy, Croaker, Flounder, Herring, Mackerel, Pollock, Scallop and Shrimp)

three times larger than that of our samples with seemingly no health impacts. We know the consumption levels set by the EPA have a 10-fold safety factor built into the threshold, which could explain why the Seychelles population did not exhibit mercury poisoning.

Another limitation of this study is that we combine the metrics of mercury and methyl mercury and assume methylmercury as a proxy for total mercury. This is not without precedence as the FDA combined the concentration of mercury and methylmercury when reporting means of mercury concentrations in fish[18], but methyl mercury is widely reported as more bioavailable and thus more likely to be absorbed into the human body.[4,39–41] The portion of our samples, which were analyzed by inductively coupled plasma mass spectrometry, would not distinguish between inorganic, elemental, and organic sources of mercury. A brief comparison by Student's t-test of the means of methyl mercury in our samples from Wisconsin State University with the total mercury reported by the two Eurofins Laboratories suggests that there is no significant difference between the methylated and unmethylated means in our samples (P = 0.45); however, this study does not make a conclusive statement about this ratio.

Trophic levels & habitat

The analysis of our samples categorized by trophic level suggests that biomagnification of mercury can be observed in dried market fish. Methylmercury biomagnifies up the food chain as it is passed from a lower trophic level to a subsequently higher food chain level through consumption of prey or predators. Fish at the top of the aquatic food chain, such as pike, bass, shark and swordfish, bioaccumulate methylmercury approximately 1 to 10 million times greater than dissolved methylmercury concentrations found in surrounding waters.[15] Biomagnification of mercury in marine ecosystems is a well-documented phenomenon[28,42–45] and we observe the effect within our samples.

We consider our trophic levels to be rough estimates as we did not identify our samples with species, or taxonomic groupings and instead relied upon the labeling found on packages and bins. Our categories are market derived which should be considered a loose proxy for species information. Mislabeling of market fish is a studied problem and appears prevalent in all markets. A 2019 study found the global average rate of mislabeling to be 8%[46] but regional market studies have reported much higher rates of mislabeling. A report published in 2019 by Oceana[47] looked at over 400 samples in over 25 locations in the United States and found that one in five, or 20%, of the fish were mislabeled. The same technique revealed a 16% mislabeling rate in restaurants in the United States.[48] In South Korea DNA Barcoding revealed a 8% mislabeling rate.[49] The commonly reported reason for mislabeling appears to be identifying fish as more profitable species. We expect that in instances where the fish is less recognizable because it is sold as meal, fillet, or dried that mislabeling rates could be worse.

Owing to the well-understood effects of biomagnification on mercury in marine ecosystems, it is important to consider what trophic levels we are consuming. A study on the inhabitants of the Faroe Islands who regularly consume whale meat and fish concluded that consumption pilot whale meat (in the Bonito et al. scheme a Top consumer) was responsible for the 'high and harmful levels of methylmercury' in the diet of Faroe Islanders, while cod fish, *Gadus morhua* (a Middle consumer) was not a significant contributor.[50] It is reasonable to conclude that generally speaking there is a positive relationship between trophic levels and mercury levels, therefore we can generally reduce mercury exposure by eating closer to the base of the food web.

We also detected a difference in mercury concentrations when grouped by habitat using the categorization scheme of Bonito et al. They reported no significant link to habitat across five pollutants with the exception of mercury, which showed ppm concentrations of: Benthic 0.4161, Demersal 0.4190, and Pelagic 0.4285. Our findings showed samples categorized as demersal to have the highest concentrations of mercury but given the uncertainty around the fish labeling and the generally weak signal found in pollutants by the habitat categorization scheme we do not consider the habitat results to have real-world significance.

Conclusion

Our data showed no statistical significance in the difference of mercury in samples from Hong Kong and San Francisco, and therefore, we accept the null hypothesis that these two populations of market fish are similar in terms of mercury contamination. Further research exploring the source of the fish is required to better understand why these two populations have indistinguishable mercury levels. If dried fish are a contributing factor explaining the higher observed blood mercury levels in the San Francisco population, it would have to rest upon a different rate of consumption. This seems unlikely, considering that residents of Hong Kong consume fish at a high rate (175 g fish per week – Liang et al.[25]). Another possibility is the additive effects of exposure from other pathways by Chinese American consumers, for example, water, soils, and other food sources. An investigation into the actual consumption rates of dried fish for residents of Hong Kong and San Francisco is needed to determine whether dried fish are a significant contributor to a difference in blood mercury levels between these two populations.

Our data suggest that it is possible that some individuals could be at risk from excessive consumption of mercury in dried fish, and other fish even at levels below the health advisory level if large amounts are consumed. Knowing the amount and types of fish consumed by Asian residents of Hong Kong and San Francisco, as well as the proportion of organic mercury in these samples, would provide a better estimate of any risk to human health. Understanding the total exposure including fish consumption rates and patterns, we cannot make an estimate of this risk. Until further evidence is presented, we recommend Asian and Asian American consumers to follow the consumption guidelines under the respective health agencies.

Regarding the risk of mercury exposure through fish consumption, our data contribute to the body of evidence that consuming fish from lower trophic levels in the food web is healthier than consuming large predatory fish like shark, tuna, tilefish, and swordfish. A lack of health advisory signage in the fish markets indicates a general need for increased awareness regarding mercury risks in the Asian community, and we suggest increasing public health education targeting this high-risk demographic.

Although we do not make recommendations on specific species or market categories to eat; if we desire sustainable relationships with the marine ecosystem that also support human health we should avoid consuming heavily exploited species and species high in mercury. In most cases this means eating lower trophic levels is generally advisable.

ARTICLE INFORMATION

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Data sharing

Data and R script available at the following link: https://github.com/kidconcept/methylmercury

Conflict of interest and funding

The authors declare that they have no actual or potential competing financial interests.

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