Human exposure of methyl mercury through fish consumption: a Lake Ontario case study

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Abstract

The consumption of fish accounts for the most significant source of MeHg accumulation in human. The rate of mercury accumulation depends on many factors, including the amount, size, type and frequency of fish consumed, as well as the contamination levels of the aquatic habitat. The ability to accurately predict the human exposure of mercury through fish consumption is very critical for drawing public consumption guidelines. This paper describes the development of an innovative method for the estimation of human exposure of mercury through mathematical modelling. The paper provides a practicable mathematical tool for estimating the human mercury exposure through fish consumption, by a combination of fish mercury bioaccumulation models with surveyed information of fish-eating habit. The efficacy of the model is demonstrated through application to some common Lake Ontario fish species.
Keywords: methyl mercury, human exposure, fish, bioaccumulation, diet, concentration, fish consumption, mathematical models.

1 Introduction

Mercury and its compounds are widely distributed in the environment. Mercury occurs naturally in the environment as mercuric sulphide, from the degassing of the earth's crust through volcanic gases and the weathering of rock in mountains [17]. It has desirable properties such as the ability to alloy with most metals, liquidity at room temperature, electrical conductivity, and the ease of vaporizing and freezing, making mercury an important industrial metal. As a result, mercury has over 3,000 industrial applications, including gold-mining, electrical equipment, chloralkali, paint, fungicide, military, medicine, and dentistry [16].

When mercury is discharged into water bodies, it is first oxidized to the divalent mercuric ion (Hg^{2+}), and then transformed by bacteria action into a highly toxic, poisonous form called methyl mercury (MeHg) [2]. The MeHg in the water and sediments is almost 100% absorbed and stored by bottom fauna and plankton. This toxin gradually works its way up the food chain, causing an increased MeHg concentration in the upper trophic level fish, an effect known as bioaccumulation. It is commonly accepted that longer food chains result in greater bioaccumulation [14]. Once inside the body of a fish, MeHg is tightly bound to the protein of the fish tissues including muscles, and it is slowly metabolized or eliminated from the fish. Eventually, MeHg enters into human who consume the upper level top-predatory fish.

Fish is an important component of the human diet in the Canadian Food Guideline, since it provides dietary protein and many other nutrient benefits. The U.S. EPA estimates that approximately 85% of people consume fish or shellfish over the course of a month, while 60% consume fish four or more times a month, or, on average, at least once a week. As a result, the consumption of fish accounts for the most significant source of MeHg accumulation in human. Unfortunately, there is no known method of cooking or cleaning that is capable of removing MeHg in seafood. Therefore, human has a potentially high health risk when they consume contaminated fish. Mahaffey [10] estimated that the aquatic food web provides more than 95% of human MeHg intake, suggesting that fish is the predominant source of MeHg for most people.

Once MeHg enters into the body of human, it accumulates in the liver, kidneys, brain or blood, and causes a multitude of acute and chronic health effects. It also affects the central nervous system, and in severe cases irreversibly damages areas of the brain [15]. Adverse effects such as impairment of vision and speech, loss of motor coordination, neuropathy and death, and psychological symptoms such as memory loss, weakness and fatigue, anxiety and flight of ideas have been reported [7]. According to Health Canada [6], the maximum tolerable daily intake of mercury for the general population is 0.47 μg/kg of body weight, but the limit for women of childbearing age and children under 15 are more severe, at 0.20 μg/kg, since mercury can seriously damage the fast-growing brain and nervous system of a child or fetus. Since most of the MeHg is absorbed by humans through fish consumption, another guideline to protect the human health from mercury is through fish consumption advisories. As an example, the province of Ontario recommends that women of childbearing age and children eat no more than four meals of fish per month from what is called the “clear fish category”, and none at all from any other categories shown in its Guide to Eating Ontario Sport Fish [12].

In spite of the high official and public concern over the mercury pollution problem, a review of the scientific literature indicates that no commonly-accepted methodology is available for the estimation of human exposure of MeHg through the consumption of fish. This is because the rate of mercury accumulation depends on many factors, including the amount, size, type and frequency of fish consumed, as well as the contamination levels of the aquatic habitat and hence individual fish species. It has been observed that even for fish occupying similar trophic levels of the food chain, their choice of habitat and physiological profile can result in very different patterns of bioaccumulation [8]. The objective of this paper is to develop an innovative method for the estimation of human exposure of mercury through the predominant pathway of diet with the use of mathematical modelling. It is envisaged that the model will provide a highly practicable tool from which useful consumption guidelines for the public may be drawn, while remaining flexible enough to accommodate specific studies of localized populations.

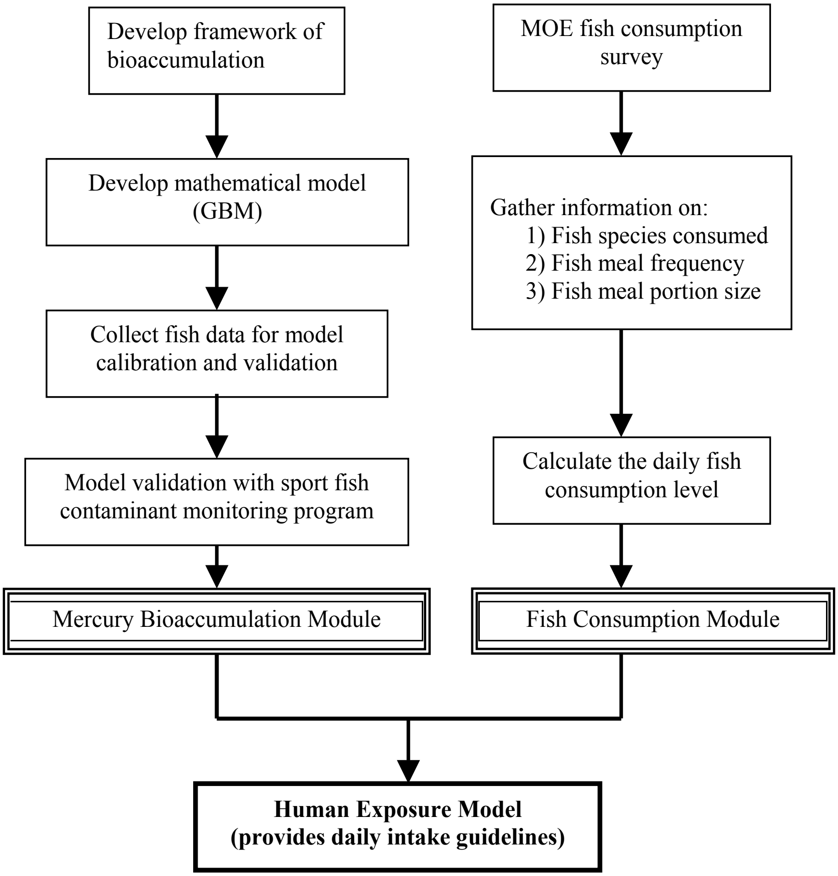


Figure 1: Organization chart for estimating MeHg dietary exposure.

2 Materials and methods

2.1 Study methodology

The wealth of information and research performed on past fish bioaccumulation models may serve as a framework for modeling the mercury exposure of human. The paper will demonstrate how localized surveyed information of fish consumption may be used to construct a scientifically-based estimation of the average daily exposure of mercury from the fish diet. Figure 1 is an organization chart describing the major components of the study methodology. The human exposure model is developed from two important components: the bioaccumulation module and the fish consumption module. The effectiveness of the developed model is demonstrated through application to two popular Lake Ontario fish species, Chinook Salmon (*Oncorhynchus tshawytscha*) and Lake Trout (*Salvelinus namaycush*).

2.2 Mercury bioaccumulation module

Numerous examples are available on the mathematical models of mercury bioaccumulation in fish [3, 5, 8, 9, 13]. These existing models may be classified into two main categories: the first type is based on regression analysis of collected fish data [3], and the second type is based on the concept of fish bioenergetics [8, 9, 13]. The bioenergetics-based modeling framework is gaining popularity because it incorporates a direct correlation between the energy requirement, the diet, and the pollutant bioaccumulation of the fish. In addition, it allows for a detailed mechanistic representation of all the major pathways of accumulation, whereby model parameters can be related to the physiochemical properties of the fish. For the demonstration of this study, a generic bioaccumulation model (GBM) [9] is chosen to describe the bioaccumulation of MeHg in Lake Ontario's fish. The model has a clear representation for the pathways of mercury intake and excretion, and has been validated to effectively predict the mercury concentrations in many species of fish [1]. It is based on the concept of bioenergetics, derived from an energy balance of fish from food source to support normal activities and growth. Fish needs energy for various life functions such as swimming and foraging activities. To satisfy these requirements, they feed on zooplankton, crustacean and small fish from their diet. In addition, they take in water through the gills for oxygen exchange. When the water and diet items are contaminated with MeHg, mercury will enter the fish's body along with these intake pathways. Therefore, a direct correlation can usually be observed between the metabolic activity level of the fish, the diet requirements, and the pollutant accumulation. The model is based on a mass-balance of the MeHg that enters into the fish body through the pathways of water and food, and leaves through excretion, as follows:

$$\left[\frac{dP}{dt}\right]_{body} = \left[\frac{dP}{dt}\right]_{food} + \left[\frac{dP}{dt}\right]_{water} - \left[\frac{dP}{dt}\right]_{clearance} \qquad (1)$$

where P is the total body burden of mercury in the fish per unit wet weight (ppm); and t is the time (weeks). When the bioenergetics expressions are incorporated into the equation, the final mass-balance equation is given by:

$$\left[\frac{dP}{dt}\right] = \left[\frac{E_{pf} \; C_{pf}}{q_{fd} \; E_{fd}}\right] \left[\alpha_{lr} \; W^{\tau} + \; q_f(\beta+1) \; \left(\frac{dW}{dt}\right)\right] + \left[\frac{E_{pw} \; C_{pw}}{E_{ox} \; C_{ox} \; q_{ox}}\right] \left[\alpha_{lr} \; W^{\tau} \; + \; q_f \; \beta \; \left(\frac{dW}{dt}\right)\right] - \; k_{cl} \; P \qquad (2)$$

In the equation, E is the efficiency of assimilation; C is the concentration of mercury (ppm); q is the energy equivalence (kcal/(g-wk)); α_{lr} is the low routine metabolism (kcal/(wk-g$^{\tau}$)); W is the wet weight of the fish (g); τ is the body weight exponent for metabolism; β is the proportion of growth rate that represents the energy for food conversion; and k_{cl} is the clearance rate combining waste egestion and growth dilution (wk^{-1}). The subscripts '*pf*' and '*pw'* represent pollutant from food and water respectively, '*fd'* is the value of the food or prey, '*f*' is the value of the fish, and '*ox'* represents values of oxygen.

A computer program was developed in Visual Basic 5.0 [9] to provide weekly simulation with graphical display of the mercury bioaccumulation patterns in different fish species. One of the most important input for the model is the composition and the level of contamination of the diet of individual fish, which is age and species-specific. An attempt is made to re-construct the diet pattern, based on food web information and data collected from past studies on fish stomach's contents, as demonstrated in Table 1 [1, 3].

2.3 Fish consumption module

Since 1978, the Ontario Ministry of Environment (MOE) has periodically surveyed the fishing habit and fish consumption by the Lake Ontario population. The survey is carried out once every few years, in which questionnaires on fishing habit and consumption are randomly sent to residents of Ontario. Based on the results, the MOE publishes consumption advice to people in the province in the form of a bi-annual edition of "Guide to Eating Ontario Sportfish" [12]. The survey is made up of 19 questions, ranging from the respondent's personal information, knowledge of the Fish Guide, to fishing frequency, fishing locations, and fish consumption habits (on both sport and commercial fish). For this paper, the latest-published survey data set collected in 1995 [11] is selected to represent the fish consumption habit by Ontarians of different age groups. From the results of the survey, information on the distribution of the fish species consumed, fish meal frequency, and the meal portion size may be obtained.

Table 1: Re-constructed diet composition.

Fish species	Age group (age group)	% Diet items	MeHg conc. (ppm)
Chinook Salmon	Juvenile (0 – 1)	Terrestrial insects 100%	0.0040
	Mature (1 – 7)	8% Small invertebrates 11% Medium rainbow smelt 82% Medium alewife	0.0500 0.0355 0.0300
Lake Trout	Juvenile (0 – 2)	45% Small slimy sculpin 35% Small rainbow smelt 20% Small alewife	0.0240 0.0215 0.0165
	Young (2 – 4)	18% Medium slimy sculpin 45% Medium rainbow smelt 38% Medium alewife	0.0315 0.0285 0.0300
	Mature (4 – 8)	30% Medium rainbow smelt 70% Large alewife	0.0355 0.0430

3 Model results

3.1 Tolerable daily intake

Health Canada recommends a maximum tolerable daily intake (TDI) of mercury for the general population as 0.47 μg/kg, and for children and women of childbearing age as 0.20 μg/kg. Since the acceptable mercury intake is highly dependent on body weight, some estimation of the human weight distribution would be required to calculate the tolerable intake for different spectrum of the population, and the data by Halls and Hanson [4] is adopted. For the demonstration in this study, five major groups of the population are identified: Children, women of childbearing age, young adults, mature adults, and seniors. The maximum daily tolerable mercury uptakes for these groups are calculated in Table 2.

3.2 Factor of safety

Fish is not the only source of mercury for human, since appreciable amounts of mercury may be absorbed by human from breathing contaminated air, from consuming other contaminated food sources, and from other unknown sources. As such, a safety factor of 2 is considered appropriate to apply to the acceptable intake of mercury from fish for the general population. Applying this safety factor, the tolerable levels of mercury intake for the four identified groups are re-established and included with the original levels in Table 2. In general, males can accept 10% higher daily mercury consumption than can females.

Table 2: Maximum daily tolerable mercury uptakes for 5 study groups.

Study groups	Age range	TDI (μg)
Children	10 – 15	4.5
Women of Childbearing age	20 – 35	6.1
Young adults	20 – 25	15.1
Mature adults	40 – 55	16.5
Seniors	≥ 65	10.3

3.3 Actual mercury uptake from fish consumption

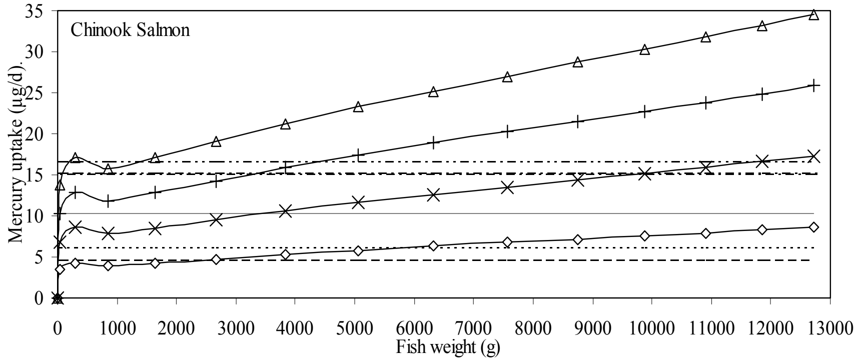
The amount of fish consumed on a daily basis may be estimated from the survey data, based on the information collected on fish consumption habits. With this, the actual mercury uptake from fish consumption may then be estimated for the two study species as summarized in Figure 2. Calculations are performed for people eating anywhere between one to four meals of fish per week. The symbol curves represent the total amount of mercury consumption of different diet habits, and the horizontal lines are the suggested TDI levels for various groups of population. Whenever the curves are higher than the TDI, there is a health concern. Therefore, the intersection point of the curves and TDI may be used to estimate the size restriction of fish consumption.

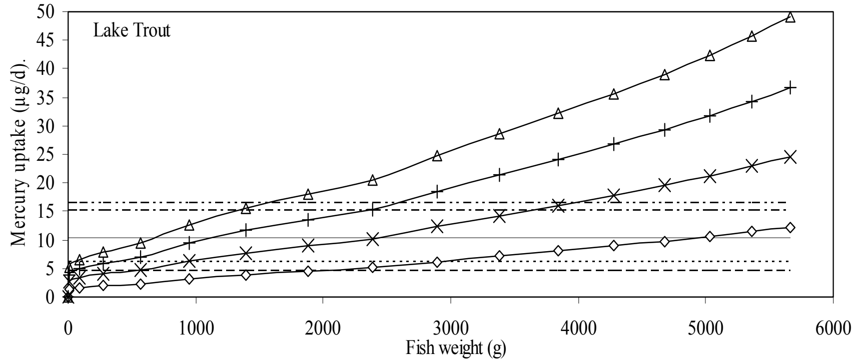
4 Discussion

A lot of useful recommendations may be drawn from Figure 2. For example, the results show that there is practically no risk for the general population who regularly eat 1 meal or less of Chinook Salmon per week. This, however, does not apply to children under 15 and women of childbearing age, because a part of the 1-week curve is above the TDI for these groups.

The results can also give some recommendations on the selection of fish size to be consumed. As an example, for a senior who eats 2 meals of normal serving portion (of around 220 g) of Chinook Salmon per week, the results show that he should limit the consumption to a maximum fish size of 10 kg total weight. Obviously, the more frequent is the fish consumption, the more stringent is this size restriction. Therefore, the same group eating Chinook Salmon three times a week should consume a fish less than 3.5 kg to be on the safe side. If this size happens to be much less than the typical size available for that fish, then three meals a week is simply too much for the study group, and consumption frequency should be reduced.

Another important result from the analysis is the level of contamination of the different species. Of the two fish species, Lake Trout has a higher risk than Chinook Salmon. Therefore, a person who is concerned about MeHg exposure should make a point of selecting a less contaminated fish species habitually. As demonstrated from this research, a lot of highly useful recommendations on the choice of fish may be provided if a multiple-species analysis of commonly available fish is carried out.





Legend

Frequency of fish per Week	Once ◊	Twice x	3 Times +	4 Times Δ	
Study Group	Children - - - - - - - -	Women of c/b age …………	Young adults —·—·—·—	Mature adults —··—··—	Seniors ————

Figure 2: Results of the MeHg human exposure model.

Results from this research also reveal two very important guidelines for the consumers. Firstly, moderate fish consumption of less than twice a week should pose no major risk to the general population in terms of MeHg exposure. On the other hand, a person eating four fish meals a week should be very vigilant over the type and size of the fish consumed. Secondly, even though most consumers prefer a bigger fish because of the ease of preparation and absence of fine bones, results from this analysis clearly indicates that the choice may not be a healthy one. This is especially significant considering that no amount of cooking or cleaning will remove the accumulated mercury of the fish. In addition, unlike other types of fat-soluble contaminants such as PCBs which can be avoided if the skin, intestines, and head of the fish are removed, mercury is protein-bound and tends to accumulate in the tissues or meat of the fish quite uniformly.

Another factor to consider is the highly cumulative effect of mercury in human. While the tolerable daily intake of mercury provides some guidelines on daily fish consumption, the bioaccumulation effect of mercury over the life span should not be neglected. Results from this and other studies have clearly confirmed that mercury is bioaccumulated in human and animals over time and it is only eliminated from the body at a very slow rate. Therefore, while it may be acceptable to exceed the tolerable daily limit occasionally, a fish-lover who consumes fish consistently as a regular part of the diet should be more cautious about the possible cumulative effect.

5 Conclusions

Fish is an important dietary component of human, containing a good source of proteins, omega-3 fatty acids, and many other nutrient benefits. However, consumption of fish on a regular basis may also lead to an increased risk of MeHg exposure. This paper describes the development of an innovative method for the estimation of human exposure of mercury through mathematical modelling. By a judicious combination of fish mercury bioaccumulation models with surveyed information of fish-eating habit, it was found that the method provided a scientifically-based estimation of the average daily exposure of mercury from fish consumption. It provides a highly practicable tool from which useful consumption guidelines for the public may be drawn, while remaining flexible enough to accommodate specific studies of some localized individual populations. To reduce the potential mercury exposure in the human body, people should choose smaller fish within a species, because they are typically younger and haven't been exposed to mercury for as long as the older, bigger fish. It is also better to eat a variety of fish, especially the less contaminated species, to avoid high exposure to mercury.

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