Risk assessment of methylmercury based on internal exposure and fish and seafood consumption estimates in Taiwanese children

Shu Han You a, d, Shu Li Wang a , Wen Han Pan b , Wan Ching Chan a , Anna M. Fan c , Pinpin Lin a, d

a National Institute of Environmental Health Sciences, National Health Research Institutes, Miaoli, Taiwan
b Institute of Biomedical Sciences, Academia Sinica, Taipei, Taiwan
c California Environmental Protection Agency, Oakland/Sacramento, USA
Od Institute of Food Safety and Risk Management, National Taiwan Ocean University, Keelung, Taiwan

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ABSTRACT

Fish and seafood consumption is a major source of human exposure to methylmercury (MeHg). This study evaluated the potential health risk of MeHg in Taiwanese children from fish and seafood consumption using a toxicokinetic model, hazard quotients and hazard indices (HIs). Two biomonitoring programs provided an important resource for blood specimens for assessing MeHg exposure in human populations. For internal exposures, total mercury (THg) was measured as a biomarker of MeHg in whole blood (WB) and red blood cells using inductively coupled plasma mass spectrometry and cold-vapor atomic absorption spectroscopy, respectively. The THg concentrations were used to estimate MeHg concentrations. Consumption of fish and seafood was assessed using the National Food Consumption database in Taiwan, while mercury concentrations in edible fish and seafood were collected from published studies in Taiwan. Our results indicated that (1) the highest median THg (representing estimated MeHg) daily intakes were found to decrease with increasing age in children consuming saltwater fish for age groups 0–3, 4–6, 7–12, and 13–18 years: 0.03 > 0.02 > 0.017 > 0.007 (μg kg−1 BW−1 day−1); (2) HI greater than one, based on WB-THg, was found in 28% of 4–6-year-old children and (3) internal exposure estimates based on WB-THg, though slightly higher, were comparable to those based on fish and seafood consumption. The results support the use of dietary intake estimates as surrogates for internal blood MeHg levels in Taiwanese children to assess their exposure.

1. Introduction

Mercury (Hg) is a heavy metal widely used in industrial, medicinal, agricultural and other applications (Kidd and Batchelar, 2011). In addition to the human activities, Hg is released into the aquatic environment from natural sources (Ullrich et al., 2001). There are three forms of Hg in the aquatic ecosystems: elemental Hg (Hg0), inorganic Hg and organic Hg, such as methylmercury (MeHg). Inorganic Hg released into the air and deposited in the environment can be transformed into MeHg, which bioaccumulates and biomagnifies in the aquatic food web (Kidd and Batchelar, 2011). MeHg has been a worldwide concern for its potential impact on human health and ecosystems because of its persistence, bioaccumulation potential, widespread occurrence and toxicity (WHO, 1990). The developmental neurotoxicity of MeHg in humans and its potential adverse effects on cardiovascular and immune system have been documented (WHO, 2008; Roman et al., 2011; Nyland et al., 2012).

Humans are exposed to MeHg mainly through the consumption of freshwater and marine fish and other animals that eat fish (e.g., marine mammals) (WHO, 2008). However, the extent of human MeHg exposure depends on the species of fish and frequency of consumption (Cho et al., 2014; Sheehan et al., 2014). Fish and seafood are primary sources of proteins and lipids (i.e., omega-3 fatty acids) essential for preventing hypertension and coronary heart diseases (Eshak et al., 2014; Sioen et al., 2007).

Human exposure to environmental chemicals can be estimated indirectly by calculating dietary intake, from aggregating data on MeHg concentrations in edible fish and seafood tissues and consumption rates of fish and seafood, or directly by quantifying MeHg in individual’s biological materials. Biomarkers, such as total Hg (THg) levels in hair, whole blood (WB) or red blood cells (RBCs), have been used to reflect MeHg exposure (Groth, 2010; Karagas, 2012; WHO, 1990). Various studies have shown that 70–95% of THg in blood is in the form of MeHg (Mortensen et al., 2014) and bound to the sulphydryl groups of

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hemoglobin (Weed et al., 1962). There is a strong linear correlation between MeHg in WB and MeHg in RBCs (Berglund et al., 2005; Oken et al., 2008). The presence of Hg in blood indicates recent or current exposure to Hg, and there is a direct relationship between Hg concentrations in human blood and consumption of fish contaminated with MeHg (WHO, 2008). In this study, all THg concentrations in blood were used to estimate MeHg concentrations. But references to toxicity, hazard and risk were associated with MeHg.

Recently, increased attention has been focused on the vulnerability of children and adolescents to environmental chemicals (Ha et al., 2014; Ochoa-Martínez et al., 2016). MeHg may disturb the development of the nervous system in children, such as impairing their ability to learn and process information (Kim and Lee, 2010). In Taiwan, data on MeHg exposure assessment in children and adolescents are underrepresented (Hsi et al., 2016; Lee et al., 2012).

Seafood is an essential part of the Taiwanese diet among all ages of the general population, and its consumption was estimated at approximately 48% of total animal food consumption during 2014 (Taiwan CoA, 2017). Accordingly, the present study was undertaken to determine: 1) internal THg dose based on blood measurements; 2) intakes of THg from fish and seafood consumption and THg levels in the regional fish/seafood species of interest using data collected from previous surveys, and 3) the hazard indices (HIs) based on internal doses and intake estimates from fish/seafood consumption.

2. Materials and methods

2.1. Internal exposure assessment

2.1.1. Subject data collection

Two Taiwan human biomonitoring programs, mainly for children and adolescents, were used to assess the internal doses: 1) the “Taiwan Maternal and Infant Cohort Study, TMICS” during 2003. A total of 10 ml WB was collected into a heparinized tube and centrifuged immediately. One milliliter of RBCs and plasma, for quantifying nutrients and lipids while Hg was only measured in RBC.

To assess internal exposure from blood measurements, preschool children aged 4–6 years, school children aged 7–12 years and adolescents aged 13–18 years were chosen. A total of 815 subjects were randomly stratified by age and gender according to the population distribution in Taiwan. The participants’ inclusion criteria were described by Tsai et al. (2016). Institutional Review Board approvals from the Taiwan National Health Research Institutes were obtained for this study.

2.1.2. Determination of THg

For NAHSIT study, venous fasting blood specimens were obtained from children whose parents gave written informed consent in the TMICS study during 2003. A total of 10 ml WB was collected into a heparinized tube and centrifuged immediately. One milliliter of RBCs was transferred to a polypropylene tube and stored in liquid nitrogen. The samples were kept in at −20 °C during transportation to the Taiwan National Health Research Institutes laboratory (NHRI) and stored at −80 °C in Taiwan NHRI laboratory before analysis for THg. Detailed blood drawing and management flow were described by Tu et al. (2007).

THg levels were measured in 1 ml of WB from children aged 4–6 years using inductively coupled plasma mass spectrometry (ICP/MS, NexION 350X, Perkin-Elmer, UK) at the Linkou Chang Gung Memorial Hospital Department of Laboratory Medicine, Taoyuan, Taiwan. Duplicate samples were used to check the precision of the ICP/MS analysis. The relative standard deviation was less than 10%. All data used in the trend analysis met the certified laboratory’s QA/QC standards. The detection limit of WB-THg was 0.02 μg L⁻¹.

Approximately 1 ml of the archived RBCs from children aged 7–18 years was used to quantify THg levels using an atomic absorption spectrometry (AAS, AAnalyst 100, Perkin-Elmer, USA). The instrument was equipped with a cold-vapor flow injection analysis system (CV-FIAS 100, Perkin-Elmer, USA) and located at the Taiwan NHRI. Intra-assay precision was performed, in triplicate, by calculating the average of the area under the curve, standard deviation and relative standard deviation. The blank and spiked RBC samples were processed and analyzed concurrently with blood samples, to check the accuracy of the method, which was 101.5%. The recovery ranged from 94 to 108% and the mean relative error for duplicate analyses was less than 6%. The detection limit of RBC-THg was 0.13 μg L⁻¹.

2.1.3. Blood Hg-based toxicokinetic (TK) model

We used a simple blood THg-based TK model developed by the WHO (1990) to assess MeHg body burden in children based on WB-THg concentrations that can be estimated according to the following formula:

\[ D_b = C_b \times b \times V \times A \times f \times BW, \]  

where

- \( D_b \) is the estimated daily intake dose of THg (representing estimated MeHg) (μg kg⁻¹ BW⁻¹ day⁻¹),
- \( C_b \) is the THg concentration in the WB (WB-THg) (μg L⁻¹),
- \( b \) is the elimination constant for MeHg (0.014 day⁻¹),
- \( V \) is the blood volume (9% of BW),
- \( A \) is the fraction of MeHg in diet that is absorbed (0.95),
- \( f \) is the absorbed fraction of MeHg distributed to the blood volume (0.05), and
- \( BW \) is the body weight (kg) of children estimated from the NAHSIT 2005–2012. The input values of the parameter (such as \( b, A, \) and \( f \)) were adopted from Legrand et al. (2010).

An empirical equation (Eq. (2), Kershaw et al., 1980) was used to calibrate RBC-THg concentration (\( C_{b,RBC} \)) and estimate the WB-THg concentration (\( C_b \)), as indicated below:

\[ C_b = C_{b,RBC} \times h + C_p (1 - h), \]  

where

- \( C_{b,RBC} \) is the RBC-THg concentration that is derived from this study in children aged 7–12 and 13–18 years (μg L⁻¹),
- \( h \) is the hematocrit (39%) (Yen et al., 2008), and
- \( C_p \) is the plasma-THg concentration.

Here, because the ratio of RBC-THg concentration (\( C_{b,RBC} \)) to plasma-THg concentration (\( C_p \)) is 6.3–1 (Berglund et al., 2005), the value of \( 0.16 \times C_{b,RBC} \) can be used to substitute the \( C_p \).

2.2. External exposure assessment

2.2.1. Fish and seafood consumption

The data on fish and seafood consumption, obtained from the Taiwan National Food Consumption Database (TNFCD), during NAHSIT 2005–2012, targeting different populations and time periods. The NAHSIT 2005–2012 utilized a 24-h recall method that was based on the amount of daily intake per person. Targeted populations were preschoolers (2005–2008), elementary school students (2005–2008), and junior and senior high-school students (2010–2011). Detailed information on the study subjects and the sampling design were described by the Taiwan Ministry of Health and Welfare (TMHW, 2015).

We assessed external exposure by reanalyzing the daily intake rates of fish and seafood in children 0–3, 4–6, 7–12, and 13–18 years old, individually. Three categories of fish and seafood were included: (1) freshwater fish (F), (2) saltwater fish (S), and (3) shellfish, cephalopods...
and crustaceans (SCC).

2.2.2. Hg concentrations in fish and seafood

Hg and MeHg concentrations in fish and seafood were taken from previous studies conducted in Taiwan (Han, 2005; Han and Chien, 2006; Han, 2007; Chen et al., 2002; Chien and Chen, 2004; Chen et al., 2011, 2014; Chien et al., 2007), as shown in Table S1 and Fig. S1. We reorganized the Hg values of each fish species in the published articles and separated them into the three categories as shown in Fig. S1. In these studies, fish and seafood species were sampled from various locations, such as seaports, local markets, and aquaculture farms. Hg concentrations were determined in edible tissues reported between 2002 and 2014 using a cold-vapor atomic absorption spectrometry.

2.2.3. MeHg intake calculation

The estimated daily intake dose of THg (representing estimated MeHg) via consumption (including from F, SF, and SCC) was determined using the following Eq. (3) (Shao et al., 2012):

\[ D_i = \frac{C_i \times IR \times 10^{-8}}{BW} \]  

(3)

where

- \( D_i \) is the estimated daily intake doses of THg (representing estimated MeHg) (mg kg\(^{-1}\)BW\(^{-1}\) day\(^{-1}\))
- \( C_i \) is the estimated MeHg concentration (mg kg\(^{-1}\)) for the three categories of fish and seafood (F, SF, and SCC) (Table S1 and Fig. S1).

The 2012 European Food Safety Authority (EFSA) report assumed that 100% of the THg measured in fish meat was MeHg (EFSA, 2012). We compiled the Hg concentrations in each fish and seafood and converted them to estimated THg (representing estimated MeHg) concentrations by applying conversion factors of 1.0 for F and SF, and 0.8 for SCC (EFSA, 2012).

- \( IR \) and \( BW \) are the intake rate (g day\(^{-1}\)) and body weight (kg) of children, both estimated from the NAHSIT 2005–2012.

2.3. Health risk estimation

The potential health risk to children from MeHg exposure was estimated using the hazard quotient (HQ) approach (U.S. EPA, 2005), based on WB-THg or fish and seafood consumption divided by the reference dose (RfD),

\[ HQ = \frac{D_i}{RfD} \]  

(4)

where

- \( D_i \) is the \( D_o \) or \( D_s \) (μg kg\(^{-1}\)BW\(^{-1}\) day\(^{-1}\)) and
- \( RfD \) is the modified oral reference dose for MeHg (0.23, μg kg\(^{-1}\)BW\(^{-1}\) day\(^{-1}\)) that is derived from the WHO provisional tolerable weekly intake, established by the Joint FAO/WHO Expert Committee on Food Additives (Table S2) (JECFA/WHO, 2003, 2007), but adjusted for daily intake, and used instead of the USEPA oral reference dose.

The hazard index (HI) approach was used to assess the cumulative Hg exposure for all three categories of fish and seafood. The estimated HI was calculated as the sum of the HQs (U.S. EPA, 2005) as follows:

\[ HI = \Sigma_i HQ_i \]  

(5)

Where \( k \) is the estimated HQ values based on each fish and seafood consumption exposure (including F, SF, and SCC). An HI exceeding one represents a potential concern for neurodevelopmental risk, due to MeHg exposure via fish and seafood consumption in children.

3. Results

The study framework for assessing MeHg exposure from fish and seafood consumption is illustrated in Fig. 1. Because most Hg in fish, seafood, human RBC and human WB was MeHg, which is the most toxic form of Hg, estimated MeHg concentrations from THg was used to evaluate effects on child neurodevelopment using the HI approach.

3.1. Internal doses and potential health risk

Fig. 2 illustrates the estimated daily intake doses of MeHg from fish consumption and HIs, based on WB- and RBC-THg in children. The median ± SD of WB-THg concentrations were 6.81 ± 6.22, 5.33 ± 3.29, and 4.03 ± 2.34 μg L\(^{-1}\) for preschoolers (4–6 years old), elementary students (7–12 years old), and adolescents (13–18 years old), respectively (Fig. 2A). Fig. 2B shows that the estimated median daily intake doses were 0.15 (95% CI: 0.04–0.54), 0.12 (0.04–0.31), and 0.09 (0.03–0.23) μg kg-body weight (BW)\(^{-1}\) day\(^{-1}\) for preschoolers, elementary students, and adolescents, respectively. The median HIs were 0.65 (95% CI: 0.18–2.35), 0.51 (0.19–1.37), and 0.38 (0.15–0.99) for preschoolers, elementary students, and adolescents, respectively (Fig. 2C). For approximately 28% preschoolers and 9% elementary students, the HI was greater than one.

3.2. Exposure from fish and seafood consumption

The estimated fish and seafood median intake rates, estimated MeHg concentrations in different fish and seafood categories, and children’s body weight (BW) are summarized in Table 1. Based on the TNFCD, the estimated median intake rates were found to decrease with intake rates in the following: SF (2.72) > F (0.71) > SCC (0.42) g day\(^{-1}\). The highest estimated median intake rates (g day\(^{-1}\)) of SF, according to age groups, were 2.95 (0–3 years old), 2.94 (4–6 years old), 3.57 (7–12 years old), and 2.50 (13–18 years old). The estimated median MeHg concentrations in fish (μg kg\(^{-1}\)) were in the following: SF (0.12) > F (0.04) > SCC (0.01). The means of the BWs (kg), according to age groups, were 12.92 (0–3 years old), 20.51 (4–6 years old), 34.00 (7–12 years old), and 56.89 (13–18 years old).
seafood consumption in children. The estimated median (95% CI) MeHg intakes (μg kg-BW⁻¹ day⁻¹) from SF were found to decrease with intake rates in the following: 0.03 (0.001, 1.10) (0–3 years old) > 0.02 (0.001, 0.65) (4–6 years old) > 0.02 (0.001, 0.67) (7–12 years old), and 0.007 (0.0002, 0.27) (13–18 years old).

3.3. Potential health risk for fish and seafood consumption

The HQs for only SF was greater than 1 (Fig. S2). The median HQ (95% CI) values expressed in μg kg-BW⁻¹ day⁻¹ from SF intake were found to decrease with age in the following for age groups 0–3, 4–6, 7–12, and 13–18 years: 0.13 (0.004, 4.80) > 0.10 (0.003, 2.80) > 0.09 (0.002, 1.10) > 0.07 (0.001, 0.67) (13–18 years old).

Table 1
Estimated daily intake rates among age groups and estimated THg (representing estimated MeHg) concentrations.

<table>
<thead>
<tr>
<th>Age groups</th>
<th>Fish and seafood categories</th>
<th>Estimated MeHg concentrations (mg/kg)³, median (minimum-maximum)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Freshwater fish</td>
<td>0.42 (3 × 10⁻³–1.64)</td>
</tr>
<tr>
<td></td>
<td>Saltwater fish</td>
<td>2.35 (3 × 10⁻³–2.26)</td>
</tr>
<tr>
<td></td>
<td>Shellfish, cephalopods, and crustaceans</td>
<td>0.09 (1 × 10⁻³–49.53)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.48 (1 × 10⁻³–188.95)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.49 (1 × 10⁻³–158.75)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.36 (2 × 10⁻⁴–262.10)</td>
</tr>
</tbody>
</table>

³ Estimated based on published papers (Han, 2005; Han and Chien, 2006; Han, 2007; Chen et al., 2002; Chen and Chen, 2004; Chen et al., 2011, 2014; Chien et al., 2007) (Table S1 and Fig. S1).
2.84) > 0.08 (0.02, 2.90) > 0.03 (0.001, 1.17), respectively. Table 2 shows that the percentage of HQs was in the range 87–91% in the HIs. The percentages of children consuming SF with HIs higher than 1 were in the range 6–22%, for children between the age of 4–18 years old.

### Table 2

<table>
<thead>
<tr>
<th>Age (years old)</th>
<th>Freshwater fish (%)</th>
<th>Saltwater fish (%)</th>
<th>Shellfish, cephalopods, and crustaceans (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–3</td>
<td>8</td>
<td>91</td>
<td>1</td>
</tr>
<tr>
<td>3–6</td>
<td>10</td>
<td>88</td>
<td>2</td>
</tr>
<tr>
<td>7–12</td>
<td>7</td>
<td>92</td>
<td>1</td>
</tr>
<tr>
<td>13–18</td>
<td>11</td>
<td>87</td>
<td>1</td>
</tr>
</tbody>
</table>

4. Discussion

This study was carried out to assess the potential health risk of MeHg exposure to Taiwanese children from fish and seafood consumption. It is well-documented that most of the Hg measured in fish, seafood, human RBCs and human WB is mainly MeHg which is the most toxic form of Hg. In this study, THg concentrations in these specimens were used to estimate MeHg intakes for risk assessment. The results showed that the estimated MeHg daily intakes were comparable when using WB versus fish and seafood consumption data in children aged 4–18 years. The highest median estimated MeHg daily intakes among the three age groups, based on the TNFCD, were found from the consumption of SF. 6–22% of the studied children had HIs greater than 1, indicating that SF is a major source of MeHg exposure.

The geometric mean of blood THg levels in the studied Taiwanese children (aged 4–18 years) was 5.38 μL−1. This value is 10 times higher than those reported in Canadian children (aged 6–19 years, 0.3 μL−1) (Lye et al., 2013) and US children (aged 1–5 years, 0.33 μL−1) (Nielsen et al., 2014). Conversely, it is similar to those found in Korean (aged 0–18 years, 2.09 μL−1) (Park et al., 2014) and Japanese children (aged 9 years, 4.55 μL−1) (Ilimiawati et al., 2015). Typically, residents of the island countries, such as Japan and Taiwan, consume more fish than those living inland and therefore elevated blood THg levels are expected (Kim and Lee, 2010).

The present study showed that the estimated MeHg daily intakes calculated based on internal exposure were slightly higher than intakes derived from fish and seafood consumption in Taiwanese children, though statistically not significant (Table 3). Furthermore, we noted a decreasing trend in the daily intakes among different children’s age groups. A similar pattern was seen in a Korean study (Park et al., 2014), but the exact reasons for this observation are unknown and beyond the scope of the present study. However, it might be related to other factors such as Hg-contaminated rice (Xu et al., 2017) low individual socio-economic status (Lim et al., 2015).

We found that children consuming SF have the highest mean estimated MeHg daily intakes. Similar findings were reported in other countries (Burger and Gochfeld, 2011; Hsi et al., 2014). However, children eat different types of fish and seafood. For example, Rothenberg et al. (2016) found that shrimp and finfish were mostly consumed in children aged 2–19 years according to the National Health and Nutrition Examination Survey (NHANES) 2007–2011. Lee et al. (2012) observed significantly higher blood THg in residents of Taiwan’s coastal sites (median: 11.2 μL−1) than those living in Taiwan inland sites (8.1 μL−1) because they ate small deep-sea fish, shrimp, oyster, and octopus. Therefore, we recommend considering different sub-categories of SF in the total diet surveys that assess MeHg exposure.

Various factors might affect the concentrations of THg in fish. Predatory fish accumulate THg that tends to increase with fish size/age (Bosch et al., 2016; Luczyńska et al., 2016). Xu and Wang (2017) measured THg concentrations in numerous kinds of fish and found that carnivorous fish had higher THg concentrations than omnivore and herbivore fish. Furthermore, environmental factors, such as water temperature, water pH value, and oxygen concentration can affect THg levels in fish (Dijkstra et al., 2013; Jardine et al., 2013).

An empirical TK model has been used by scientists in several countries to estimate MeHg daily intakes, based on blood or hair Hg levels (Jo et al., 2015; U.S. EPA, 1995; WHO, 1990). However, it has shortcomings in providing information on uptake and disposition of different Hg species in the individual’s organs and tissues (Clewell et al., 1999; Carrier et al., 2001; Smith and Farries, 1996). Consequently, it is crucial to develop a physiologically-based pharmacokinetic model for simulating the appropriate dose levels of MeHg in children (Krishnan and Chebekoue, 2017).

Certain factors associated with exposure assessments involve uncertainties that should be considered when interpreting risk estimates. Studies reported that cooking processes might affect the Hg concentration in fish (Cano-Sancho et al., 2015; Costa et al., 2015; Matos et al., 2015; Ouédraogo and Amyot, 2011). Therefore, it is necessary to evaluate the influence of cooking methods on MeHg levels in fish and seafood.

While it is important to discuss the potential health risks of MeHg from the fish intake, it is also essential to mention the health benefits from fish consumption. The FAO/WHO Joint Expert Consultation on the Risks and Benefits of Fish Consumption (FAO/WHO, 2010) noted five important observations regarding fish consumption: (1) it provides nutritional benefits; (2) it is an important aspect of culture in many places worldwide; (3) it lowers the risk of mortality from coronary heart disease, though, no evidence of risk of coronary heart disease associated with MeHg was reported; (4) it is a source of long chain omega-3 polyunsaturated fatty acids, which is essential for women of childbearing age in lowering the risk of suboptimal neurodevelopment in their offspring; and (5) there are insufficient data available among infants, children, and adolescents that help to derive a quantitative framework of the health risks and health benefits of eating fish. However, early life healthy dietary patterns that include fish consumption would influence health during adult life.

Among the various studies reviewed by WHO (2010), two prospective cohort studies provided quantitative data that showed neurodevelopment benefits of the omega-3 fatty acid, docosahexaenoic acid (DHA), in children following maternal fish consumption during gestation. The Avon Longitudinal Study of Parents and Children (ALSPAC) (Hibbeln et al., 2007) which included 7223 mother-child pairs in England, and Project Viva (Oken et al., 2008) which included 341 mother-child pairs in the US, showed dose-response relationships between maternal fish consumption and child verbal IQ gains.
5. Study limitations

The present study had some limitations. First, the fish and seafood consumption data were based on a 24-h recall method that may not represent the precise consumed foods in specific populations. Second, the Hg concentrations were obtained from fish and seafood species collected during different seasons and from various locations in Taiwan. Third, a conversion factor of 1.0 for Hg ingested from F and SF was assumed, which could result in an overestimation of exposures (the actual exposures could be less). Finally, this study could not distinguish MeHg concentrations in all types of fish and seafood, based on the data available. We have excluded processed products of fish and seafood, which can be considered in future studies.

6. Conclusions

The present study showed that the estimated MeHg daily intakes, based on blood measurements of studied subjects, correlated with estimates obtained from fish and seafood consumption rates in Taiwanese children. We, therefore, recommend using dietary intake estimates as surrogates for internal blood MeHg levels in Taiwanese children to assess their exposure. This study revealed that approximately 28% of the children aged 4–6 years had a median Hg greater than one, based on WB-Thg, suggesting a potential health concern and that some risk-management measures should be taken to reduce the risk. Though fetuses are most susceptible to the neurodevelopmental effects of MeHg, the brain remains vulnerable throughout childhood and into the teenage years. Future efforts should consider more accurate data for estimating exposure and explore possible measures or interventions for reducing MeHg exposure in children, especially preschool children, recognizing the benefits of eating fish in this age group. Overall, there is a need to update and refine food consumption databases, monitor Thg/MeHg in fish and seafood, and provision of health advisories or safe fish-eating guidelines to the public. In particular, information and guidance need to be provided to women of childbearing age and the developing young for them to make informed decisions to choose to eat fish and seafood with low Thg/MeHg levels.

Conflict of interest

The authors declare no conflict of interest.

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