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Blood and Urine Inorganic and Organic Mercury Levels in the United States from 1999 to 2016

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Abstract:	Introduction : Mercury is an environmental hazard. Organic mercury is biologically more toxic than inorganic mercury. Therefore, we studied recent trends in the blood level of organic and inorganic mercury in the United States. Methods : 56445 participants that had blood mercury and urine mercury measurements in NHANES 1999-2016 were included. The organic mercury level was obtained by subtracting the inorganic mercury level from the total mercury level. Results were analyzed using SPSS complex sample module version 25. Pregnant women, children aged <20 and different ethnicities were analyzed as subgroups. Results : Blood organic mercury level increased from (geometric mean [95% confidence interval]) 0.08 [0.07-0.10] to 0.17 [0.16-0.18] µg/L during 1999-2016. It increased significantly (p<0.001) from 0.03 [0.02-0.03] to 0.07 [0.06-0.07] µg/L in children aged <20 and from 0.14 [0.09-0.21] to 0.36 [0.16-0.83] µg/L in pregnant women in this period (p<0.001). In 2013-2016, non-Hispanic Asians had the highest blood organic mercury level among different ethnicities, 0.93 [0.82-1.05] µg/L (p<0.001). Blood inorganic mercury level decreased from 0.31 [0.31-0.31] in 1999-2000 to 0.21 [0.21-0.22] µg/L in 2015-2016 (p<0.001). Urine mercury level decreased from 0.75 [0.71-0.80] in 1999-2000 to 0.16 [0.16-0.17] µg/L in 2015-2016 (p<0.001). Conclusion : Blood organic mercury increased over the period 1999-2016 in the US population, including children and pregnant women, whereas there was a steady decline in both blood inorganic mercury level and urine mercury level.

Clinical significance

- Mercury is an environmental hazard that cannot be completely avoided.
- Organic mercury is found in seafood, particularly in larger fishes.
- The blood level of organic mercury has been increasing in the US population, including children and pregnant women.

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Running head: Blood and urine mercury level in the US

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MFT, AJC and BMYC designed the study. ASCS and MFT interpreted the data, wrote the first draft and performed the statistical analysis. BMYC reviewed and edited the first draft. TTC and BMYC contributed to the data interpretation of the data and the final version of the manuscript. All authors have read, approved the final version of the manuscript and had access to the data.

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Abstract

Introduction: Mercury is an environmental hazard. Organic mercury is biologically more toxic than inorganic mercury. Therefore, we studied recent trends in the blood level of organic and inorganic mercury in the United States.

Methods: 56445 participants that had blood mercury and urine mercury measurements in NHANES 1999-2016 were included. The organic mercury level was obtained by subtracting the inorganic mercury level from the total mercury level. Results were analyzed using SPSS complex sample module version 25. Pregnant women, children aged <20 and different ethnicities were analyzed as subgroups.

Results: Blood organic mercury level increased from (geometric mean [95% confidence interval]) 0.08 [0.07-0.10] to 0.17 [0.16-0.18] µg/L during 1999-2016. It increased significantly ($p<0.001$) from 0.03 [0.02-0.03] to 0.07 [0.06-0.07] µg/L in children aged <20 and from 0.14 [0.09-0.21] to 0.36 [0.16-0.83] µg/L in pregnant women in this period ($p<0.001$). In 2013-2016, non-Hispanic Asians had the highest blood organic mercury level among different ethnicities, 0.93 [0.82-1.05] µg/L ($p<0.001$). Blood inorganic mercury level decreased from 0.31 [0.31-0.31] in 1999-2000 to 0.21 [0.21-0.22] µg/L in 2015-2016 ($p<0.001$). Urine mercury level decreased from 0.75 [0.71-0.80] in 1999-2000 to 0.16 [0.16-0.17] µg/L in 2015-2016 ($p<0.001$).

Conclusion: Blood organic mercury increased over the period 1999-2016 in the US population, including children and pregnant women, whereas there was a steady decline in both blood inorganic mercury level and urine mercury level.

Keywords: Mercury; methylmercury; NHANES.

Introduction

Mercury exists in the environment in three different forms, namely elemental mercury, organic mercury and inorganic mercury.[1] Methylmercury, an example of organic mercury (CH3HgX), is often found in polluted water.[2] It is usually converted from elemental mercury by bacteria through biomethylation, which enables mercury to enter the food chain.[3] Methylmercury has occasionally been directly released into the water as in the Minamata disaster in Japan.[4] The mercury concentration is the highest in species at the top of the food chain, such as top predatory fish due to bioaccumulation and biomagnification.[5] The consumption of fish is by far the most significant source of ingestion-related organic mercury exposure in humans.[6] Humans can also be exposed to elemental mercury from improper use or disposal of mercury or mercury-containing objects such as sphygmomanometers and thermometers.[7] Furthermore, some cosmetic products in the commercial market contain inorganic mercury, particularly those with the effect of skin lightening.[8]

Exposure to mercury in the environment is inevitable. Mercury is harmful; its toxic effects can be observed in the brain, lungs and kidneys.[9] Mercury poisoning can result in several diseases such as Hunter-Russell syndrome and Minamata disease.[10] Mercury is particularly harmful to fetuses and pregnant women since it can cause severe neurological complex symptoms and birth defects.[11] Infants are also affected as methylmercury is excreted into breast milk and absorbed in the alimentary tract.[12] The effects of inorganic and organic mercury are different. Organic mercury is more toxic as it readily crosses the blood-brain barrier causing neurological toxicity, whereas inorganic mercury does not.[13]

We and others have reported decreasing blood mercury level in the United States (US).[13,14] However, it is uncertain if organic and inorganic mercury levels were both declining. It is important to differentiate them as the toxicity of organic mercury is greater than inorganic mercury. Therefore, we investigated the trends in both inorganic and organic mercury levels in the US population from 1999 to 2016 using data from the US National Health and Nutrition Examination Survey (NHANES). As mercury is harmful to the fetus and children, we studied pregnant women and children as subgroups.

Patients and Methods

Study subjects

NHANES 1999-2016 was a cross-sectional study designed to assess the health and nutritional status of adults and children in the United States. It was sponsored by the Centers for Disease Control and Prevention. The studies on mercury were sponsored by the US Food and Drug Administration, Environmental Protection Agency, National Oceanic and Atmospheric Administration, and the Department of Energy. NHANES data are released every two years. Detailed information about the methods and related protocols are available on its website.[15] Participants were randomly selected by a computer algorithm. Their participation was completely voluntary. They were interviewed at home and investigations were carried out in special mobile examination centers subsequently only if an informed consent was given. The US adults and children who had completed both household interviews and medical examinations were included. Individuals with missing total or inorganic blood mercury level were excluded.

The total and inorganic mercury levels in whole blood samples were determined with Triple Spike Isotope Dilution Gas Chromatography- Inductively Coupled Plasma Dynamic Reaction Cell Mass Spectrometry (TSID-GC-ICP-DRC-MS) by the Inorganic and Radiation Analytical Toxicology Branch of the Division of Laboratory Sciences at the National Center for Environmental Health of the Centers of Disease Control and Prevention.[16] Reducing agents, stannous chloride and sodium borohydride were used for inorganic and total mercury analysis, respectively. All blood collection materials were carefully conducted to avoid mercury contamination.

The urine mercury levels in urine samples were determined with Inductively Coupled Plasma Dynamic Reaction Cell Mass Spectrometry (ICP-DRC-MS) at the same center. Preservative (a solution of 200 g/L sulfamic acid, 0.01% Triton® X-100 solution) was added to prevent loss of mercury from urine before analysis.[17] A second urine specimen from the same subject was requested to replace the first one if it was not stored properly with preservative or was contaminated.

Statistical analysis

Data analysis was performed using SPSS complex sample module Version 25. Analytical results lower than the detection limit were replaced by the lower detection limit divided by the square root of 2. Detection limits of the laboratory data differed slightly in each data release cycle and are stated in the NHANES website. Since the mercury levels do not show normal distribution, they were log-transformed, and the geometric means are reported. The organic mercury level was obtained by subtracting the inorganic mercury from the total mercury level. Subtraction of the inorganic mercury level from the total mercury level may give rise to negative values due to measurement errors. Negative mercury concentrations are biologically implausible. To deal with this problem, organic mercury concentrations in µg/L were transformed using the formula ($M'=\{M+\sqrt{}(M2+0.0004)\}/2$) to eliminate negative values. The subtraction process may also give the value of 0 if the inorganic mercury equals the total mercury level. In this case, 0.00001 was imputed to allow log-transformation.

Given that pregnant women, children and adolescents are more vulnerable to mercury toxicity, these subgroups were also separately analyzed. The total, inorganic and organic blood mercury levels as well as urine mercury levels were reported separately according to their ages at screening and pregnancy test results. Those women who had positive pregnancy test results were regarded as pregnant. Those who were aged <20 years at the time of screening were subdivided into three age groups, namely <3 years, 3-12 years and 13-19 years.

Since fish and seafood consumption is known to be a major source of organic mercury, the correlation between seafood intake and the adjusted blood organic mercury level was analyzed. The frequency of consumption of 31 types of seafood (fish and shellfish) is available for NHANES 1999-2016. The Pearson correlation coefficients were adjusted for age and gender. A list of types of seafood in descending order of their correlation coefficients was generated.

NHANES participants were classified as one of six ethnicities (Mexican American, Other Hispanic, Non-Hispanic White, Non-Hispanic Black, Non-Hispanic Asian, Other Race – Including Multi-Racial) in NHANES 2013-6. Their total, inorganic, and organic blood mercury levels and urine mercury levels were compared using ANOVA after log transformation. The trends in blood organic mercury levels in the six ethnicities in 2011-6 were analyzed.

Results

The characteristics of participants with mercury measurement in NHANES 1999-2016 are shown in Table 1. The geometric means and the 95% confidence intervals (95% CI) of the blood total, inorganic, adjusted organic mercury levels, as well as the urine mercury levels of three groups of people, namely total participants, pregnant women and those younger than 20 years of age are listed in Table 2.

In NHANES 1999-2016, there was an increasing trend in the blood organic mercury level among all the participants ($p<0.001$). The adjusted blood organic mercury geometric mean was 0.08μg/L (95% CI: 0.07-0.10μg/L) in 1999-2000 and doubled by 2015-2016, reaching the level of 0.17μg/L (95% CI: 0.16-0.18μg/L) (Figure 1). In contrast, there was an overall decreasing trend in both blood inorganic mercury level and urine mercury level ($p<0.001$) in the total population. The geometric mean blood inorganic mercury level was 0.31μg/L (95% CI: 0.31-0.31μg/L) in 1999-2000 and dropped to 0.21μg/L (95% CI: 0.21-0.22μg/L) in 2015-2016 (Figure 1). The urinary mercury level also showed a similar trend; the geometric mean was 0.75μg/L (95% CI: 0.71-0.80μg/L) in 1999-2000 and declined gradually to 0.16μg/L (95% CI: 0.16-0.17μg/L) in 2015-2016 (Figure 2).

As for pregnant women and those younger than 20 years of age, there was also an increasing trend in their blood organic mercury levels ($p<0.001$). The adjusted blood organic mercury level in pregnant women was 0.14μg/L (95% CI: 0.09-0.21μg/L) in 1999-2000 and rose to 0.36 μg/L (95% CI: 0.16-0.83μg/L) in 2015-2016 (Figure 3). Meanwhile, the blood organic mercury level in children and adolescents, who were all under 20 years of age, was 0.03μg/L (95% CI: 0.02-0.03μg/L) in 1999-2000 and rose to 0.07μg/L (95% CI: 0.06-0.07μg/L) in 2015-2016 (Figure 4). Children <3 years, 3-12 years and 13-19 years, all showed similar increasing trends in the blood organic mercury level (Figure 5).

Figure 6 shows the blood (total, organic and inorganic) and urine mercury levels in different ethnic groups in 2013-2016. Blood total and organic mercury levels were significantly higher in non-Hispanic Asians compared to other ethnic groups ($p<0.001$). The geometric means of blood total and organic mercury levels in non-Hispanic Asians were 1.57 μg/L (95% CI: 1.46-1.70μg/L) and 0.93 μg/L (95% CI: 0.82-1.05μg/L) in 2013-2016, respectively (Figure 6). Figure 7 shows the blood organic mercury level in different ethnic groups from 2011 to 2016. The level in non-Hispanic Asians was significantly higher than other ethnic groups in every data release cycle ($p<0.001$). The geometric means of their blood organic mercury level were 1.05 μg/L (95% CI: 0.92-1.20μg/L), 0.98 μg/L (95% CI: 0.84-1.16μg/L) and 0.87 μg/L (95% CI: 0.72-1.05 μg/L) in 2011-2012, 2013-2014, 2015-2016 respectively (Figure 7).

Table 3 shows the correlation between frequency of consumption of different types of seafood with blood organic mercury level. In general, intake of large fishes showed a higher correlation with blood organic mercury level than smaller ones. The correlation coefficients of large fishes such as porgies, pikes and sharks were 0.229, 0.199, 0.165 respectively, whereas the correlation coefficients of small fishes such as sardine and trout were only 0.075 and 0.068 (Table 3). The intake frequency of different kinds of seafood of non-Hispanic Asians in 2011-2016 was the highest (Figure 8).

Discussion

This study used the most recent data from NHANES to examine the trends in blood and urine mercury levels between 1999 and 2016. The NHANES 1999-2016 sample population is representative of the population in the United States. It is one of the largest databases on blood and urine mercury levels of the general population at present.

In this study, we found a decreasing trend in both blood inorganic mercury and urine mercury level in the US population. Inorganic mercury is mainly produced by industry and emanates from factories. There are reports of excess mercury exposure in a fluorescent lamp factory and a silver refining plant.[18] In addition, dental amalgams and some skin lightening products contain inorganic mercury.[8,19] Stricter environmental management of worksites as well as testing for mercury in commercial products might account for the general reduction in blood inorganic level in the US population.

However, there was an increasing trend in organic blood mercury levels in the overall population from 1999 to 2016, especially in pregnancy women and participants younger than 20 years of age. This finding is in line with our previous study, which demonstrated that there had been an upsurge in blood organic mercury level in spite of the drop in blood inorganic mercury level from 2005 to 2010.[14] The present study therefore confirms the findings and trends in the previous study by extending the observation period for six more years.

This study also identified ethnic differences in blood organic mercury level. From 2011 to 2016, the blood organic mercury level was highest in non-Hispanic Asians and lowest in Mexican Americans. These results agreed with a previous study analyzing NHANES data in 1999-2000.[20]

The blood organic mercury level is strongly influenced by diet. Unlike inorganic mercury, which is mainly from the industrial sector and commercial products, the source of organic mercury is more associated with fish and seafood consumption. In recent years, there had been an increase in seafood consumption in the US.[21] Fish consumption is positively related to organic mercury absorption. A previous study using data from NHANES 1999-2000 showed that blood mercury concentration is related to the amount of fish eaten.[20] We have looked into the correlation between frequency of seafood intake and the blood mercury levels in the subjects of NHANES 1999-2016. Intake of some types of fish and seafood, which are mainly large in size, was moderately correlated with the calculated blood organic mercury level. Large fishes, which feed on smaller fishes, are prone to contain higher levels of organic mercury due to bioaccumulation through the food chain.[5]

The higher blood organic mercury level found in non-Hispanic Asians might be explained by the higher amounts of seafood in the diet. Since seafood is a main source of organic mercury, the general public should be more aware of their intake of fish. Sushi, sashimi and fish oil are popular in recent years, but they may also increase the amount of organic mercury ingested.[22] Organic mercury is generally more harmful to bodily functions than inorganic mercury. Methylmercury, one type of organic mercury, releases oxygen radicals, which damage cell membranes by lipid peroxidation. It has a very long half-life in fish, approximately 2 years, which is two to five times the half-life of inorganic mercury.[23] Methylmercury is lipid soluble and is therefore toxic to the central nervous system.[24] Methylmercury crosses the placenta and the blood-brain barrier and thereby accumulates in the fetal brain. It crosses the placenta 10 times more than inorganic mercury.[25] Even worse, maternal organic mercury exposure may pose a further threat to newborn infants. Methylmercury has been found in breast milk and is absorbed in the gut of infants.[26]

In view of the recent increasing trend in blood organic mercury in pregnant women and those younger than 20 years of age, these vulnerable groups should be cautious about fish consumption. Pregnant women should be encouraged to refrain from fish consumption to a greater extent as organic mercury is harmful to their children both antenatally and postnatally. They may consider avoiding large fishes like tuna and limiting the intake of smaller fishes. As for those younger than 20 years of age, they may as well limit the intake of large fishes high up in the food chain that have higher mercury content.

There are several limitations to NHANES. First of all, it is cross-sectional and different participants are randomly recruited in successive cycles. It is not a cohort study and hence the trend in mercury levels in each individual could not be assessed. Secondly, although the trend in blood and urine mercury from 1999 to 2016 could be analyzed, its source could not be identified. While consumption of various foods is recorded in detail, their mercury level has not been measured. Food intake was determined by dietary recall, which can result in bias. For instance, the consumption, both the amount and the frequency, of different kinds of fish during the past 30 days was recorded in the survey. It would be difficult for subjects to recall their dietary intake accurately. It is not known if the participants had been exposed to other possible sources of mercury such as cosmetic products. Thirdly, while NHANES can provide a good national estimate of mercury levels and the prevalence of elevated mercury levels, it is not suitable for the study of the toxic effects of mercury because only a few percent of subjects had elevated mercury levels (≥5.8 μg/L) that could be regarded as potentially harmful.[25]

Conclusion

In conclusion, although the blood inorganic mercury level has been declining in the US between 1999 and 2016, blood organic blood mercury level had increased. This is of concern especially in vulnerable groups such as pregnant women and participants younger than 20 years of age. They should receive advice on appropriate fish consumption. The alarming trend in organic mercury means that monitoring of mercury level in the population must not be relaxed.

Competing interests

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

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Table 1. Characteristics of participants with mercury measurements in NHANES 1999-2016

Number (% of subjects in each data release cycle)	**NHANES 1999-2000**	**NHANES 2001-2002**	**NHANES 2003-2004**	**NHANES 2005-2006**	**NHANES 2007-2008**	**NHANES 2009-2010**	**NHANES 2011-2012**	**NHANES 2013-2014**	**NHANES 2015-2016**
N	2386 (100%)	2734 (100%)	8144 (100%)	8364 (100%)	8161 (100%)	8727 (100%)	7837 (100%)	5174 (100%)	4938 (100%)
Male:Female	374:2012 (15.7%:84.3%)	413:2321 (15.1%:84.9%)	4014:4130 (49.3%:50.3%)	4074:4290 (48.7%:51.3%)	4092:4069 (50.1%:49.9%)	4334:4393 (49.67%:50.3%)	3923:3914 (50.1%:49.9%)	2570:2604 (49.7%:50.3%)	2460:2478 (49.8%:50.2%)
Mean of Age at screening (years) ± SE	21.4±0.3	21.2±0.3	32.7±0.3	31.0±0.3	36.6±0.3	36.0±0.3	34.8±0.3	29.6±0.3	30.2±0.3
Number of pregnant participants	264 (11.06%)	318 (11.63%)	256 (3.14%)	351 (4.20%)	50 (0.61%)	64 (0.73%)	51 (0.65%)	28 (0.54%)	24 (0.49%)
Number of participants aged <20 years	1192 (49.96%)	1345 (49.20%)	3693 (45.35%)	3862 (46.17%)	2805 (34.37%)	2975 (34.09%)	2821 (36.00%)	2480 (47.93%)	2336 (47.31%)
Number of participants with total blood mercury >5.8 μg/L	92 (3.86%)	50 (1.83%)	182 (2.23%)	153 (1.83%)	198 (2.43%)	267 (3.06%)	280(3.57%)	137 (2.65%)	130 (2.63%)
Race/Ethnicity									
• Mexican American	841 (35.25%)	762 (27.87%)	2007 (24.64%)	2223 (26.58%)	1684 (20.63%)	1944 (22.28%)	1058 (13.50%)	958 (18.52%)	988 (20.01%)
• Other Hispanic	170 (7.12%)	149 (5.45%)	261 (3.20%)	277 (3.31%)	966 (11.84%)	944 (10.82%)	843 (10.76%)	508 (9.82%)	660 (13.37%)
• Non-Hispanic White	746 (31.27%)	1045 (38.22%)	3363 (41.29%)	3295 (39.40%)	3421 (41.92%)	3738 (42.83%)	2476 (31.59%)	1835 (35.47%)	1500 (30.38%)
• Non-Hispanic Black	529 (22.17%)	665 (24.32%)	2171 (26.66%)	2181 (26.08%)	1729 (21.19%)	1580 (18.10%)	2168 (27.66%)	1110 (21.45%)	1058 (21.43%)
• Others	100 (4.19%)	113 (4.13%)	342 (4.20%)	388 (4.64%)	361 (4.42%)	521 (5.97%)	1292 (16.49%)	763 (14.75%)	732 (14.82%)
○ Non-Hispanic Asian	○ N/A	○ N/A	○ N/A	○ N/A	○ N/A	○ N/A	○ 997 (12.72%)	○ 508 (9.82%)	○ 473 (9.58%)
○ Others – Include Multi-racial	○ N/A	○ N/A	○ N/A	○ N/A	○ N/A	○ N/A	○ 295 (3.76%)	○ 255 (4.93%)	○ 259 (5.25%)

Table 2. Geometric means and 95% confidence intervals of total, inorganic and organic blood mercury concentrations (μg/L) in NHANES 1999-2016

Mercury concentration (μg/L) All subjects	NHANES 1999-2000	NHANES 2001-2002	NHANES 2003-2004	NHANES 2005-2006	NHANES 2007-2008	NHANES 2009-2010	NHANES 2011-2012	NHANES 2013-2014	NHANES 2015-2016
N	2386	2734	8144	8364	8161	8727	7837	5174	4938
Total (blood)	0.74 (0.70-0.77)	0.58 (0.55-0.60)	0.67 (0.65-0.68)	0.69 (0.67-0.70)	0.69 (0.68-0.71)	0.75 (0.73-0.76)	0.68 (0.67-0.70)	0.59 (0.57-0.61)	0.58 (0.56-0.59)
Organic (blood)	0.08 (0.07-0.10)	0.10 (0.09-0.11)	0.05 (0.05-0.06)	0.14 (0.13-0.14)	0.14 (0.13-0.15)	0.20 (0.19-0.21)	0.22 (0.21-0.24)	0.19 (0.18-0.20)	0.17 (0.16-0.18)
Inorganic (blood)	0.31 (0.31-0.31)	0.29 (0.29-0.29)	0.34 (0.34-0.35)	0.30 (0.30-0.30)	0.29 (0.29-0.30)	0.27 (0.27-0.27)	0.23 (0.23-0.23)	0.22 (0.22-0.22)	0.21 (0.21-0.22)
N	1673	1855	2378	2399	2426	2615	2331	2493	2771
Urine mercury	0.75 (0.71-0.80)	0.61 (0.58-0.65)	0.41 (0.39-0.42)	0.44 (0.42-0.46)	0.43 (0.41-0.44)	0.37 (0.36-0.39)	0.34 (0.32-0.35)	0.25 (0.24-0.26)	0.16 (0.16-0.17)
Age <20 years									
N	1192	1345	3693	3862	2805	2975	2821	2480	2336
Total (blood)	0.51 (0.48-0.54)	0.40 (0.37-0.42)	0.45 (0.44-0.47)	0.47 (0.46-0.48)	0.42 (0.41-0.43)	0.44 (0.43-0.46)	0.39 (0.38-0.41)	0.39 (0.37-0.40)	0.37 (0.36-0.38)
Organic (blood)	0.03 (0.02-0.03)	0.04 (0.03-0.04)	0.02 (0.01-0.02)	0.05 (0.05-0.05)	0.04 (0.03-0.04)	0.05 (0.05-0.06)	0.07 (0.06-0.08)	0.08 (0.07-0.08)	0.07 (0.06-0.07)
Inorganic (blood)	0.30 (0.30-0.31)	0.29 (0.29-0.29)	0.33 (0.33-0.34)	0.29 (0.28-0.29)	0.27 (0.27-0.28)	0.26 (0.26-0.26)	0.21 (0.21-0.21)	0.20 (0.20-0.21)	0.20 (0.20-0.21)
N	505	497	908	939	662	769	701	739	1056
Urine mercury	0.66 (0.59-0.73)	0.55 (0.49-0.61)	0.36 (0.34-0.39)	0.38 (0.36-0.41)	0.37 (0.34-0.40)	0.32 (0.30-0.34)	0.29 (0.27-0.31)	0.19 (0.17-0.20)	0.12 (0.12-0.13)
Age <3 years									
N	315	392	388	451	291	371	270	327	324
Total (blood)	0.37 (0.33-0.42)	0.29 (0.26-0.32)	0.30 (0.27-0.32)	0.34 (0.32-0.36)	0.31 (0.29-0.34)	0.32 (0.30-0.34)	0.27 (0.25-0.30)	0.29 (0.27-0.31)	0.28 (0.26-0.30)
Organic (blood)	0.01 (0.01-0.01)	0.01 (0.01-0.02)	0.00 (0.00-0.00)	0.02 (0.01-0.02)	0.01 (0.01-0.02)	0.02 (0.01-0.02)	0.02 (0.02-0.03)	0.04 (0.03-0.05)	0.03 (0.03-0.04)
Inorganic (blood)	0.30 (0.30-0.30)	0.28 (0.28-0.29)	0.33 (0.32-0.33)	0.28 (0.27-0.29)	0.27 (0.26-0.28)	0.26 (0.25-0.26)	0.20 (0.20-0.21)	0.19 (0.19-0.19)	0.20 (0.19-0.20)
N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Urine mercury	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Age 3-≤12 years									
N	364	436	1491	1680	1571	1594	1568	1621	1511
Total (blood)	0.46 (0.41-0.51)	0.36 (0.32-0.39)	0.43 (0.41-0.45)	0.45 (0.44-0.47)	0.40 (0.38-0.41)	0.42 (0.41-0.44)	0.36 (0.34-0.37)	0.38 (0.37-0.40)	0.37 (0.36-0.39)
Organic (blood)	0.02 (0.01-0.03)	0.02 (0.02-0.03)	0.01 (0.01-0.02)	0.05 (0.04-0.05)	0.03 (0.03-0.04)	0.05 (0.04-0.05)	0.06 (0.05-0.06)	0.08 (0.07-0.08)	0.07 (0.06-0.08)
Inorganic (blood)	0.30 (0.30-0.31)	0.29 (0.28-0.30)	0.33 (0.33-0.33)	0.28 (0.28-0.29)	0.27 (0.27-0.27)	0.26 (0.26-0.27)	0.21 (0.20-0.21)	0.20 (0.20-0.21)	0.20 (0.20-0.21)

N	N/A	N/A	316	388	373	395	377	392	732
Urine mercury	N/A	N/A	0.31 (0.27-0.34)	0.36 (0.33-0.40)	0.34 (0.30-0.37)	0.30 (0.27-0.33)	0.27 (0.25-0.30)	0.17 (0.16-0.19)	0.12 (0.11-0.12)
Age 13-≤19 years									
N	513	517	1814	1731	943	1040	983	532	501
Total (blood)	0.68 (0.62-0.74)	0.55 (0.51-0.60)	0.52 (0.50-0.55)	0.52 (0.50-0.54)	0.51 (0.48-0.53)	0.54 (0.51-0.56)	0.50 (0.48-0.53)	0.48 (0.44-0.51)	0.43 (0.40-0.46)
Organic (blood)	0.07 (0.05-0.10)	0.10 (0.08-0.13)	0.03 (0.02-0.03)	0.07 (0.06-0.08)	0.07 (0.06-0.09)	0.09 (0.08-0.11)	0.13 (0.11-0.15)	0.13 (0.11-0.16)	0.10 (0.09-0.12)
Inorganic (blood)	0.31(0.30-0.31)	0.29 (0.29-0.30)	0.34 (0.33-0.34)	0.29 (0.28-0.29)	0.28 (0.27-0.28)	0.27 (0.26-0.27)	0.21 (0.21-0.22)	0.21 (0.20-0.22)	0.21 (0.20-0.21)
N	505	497	592	551	289	348	324	347	324
Urine mercury	0.66	0.55	0.39	0.40	0.42	0.34	0.32	0.20	0.13
Pregnant women									
N	264	318	256	351	50	64	51	28	24
Total (blood)	0.78 (0.68-0.89)	0.61 (0.54-0.68)	0.66 (0.60-0.74)	0.61 (0.57-0.67)	0.68 (0.54-0.85)	0.70 (0.57-0.85)	0.72 (0.54-0.94)	0.57 (0.43-0.78)	0.84 (0.53-1.31)
Organic (blood)	0.14 (0.09-0.21)	0.13 (0.10-0.18)	0.06 (0.04-0.10)	0.10 (0.08-0.14)	0.17 (0.08-0.33)	0.17 (0.09-0.33)	0.29 (0.17-0.51)	0.16 (0.08-0.35)	0.36 (0.16-0.83)
Inorganic (blood)	0.30 (0.30-0.31)	0.29 (0.28-0.30)	0.35 (0.34-0.37)	0.32 (0.30-0.33)	0.30 (0.27-0.33)	0.28 (0.25-0.30)	0.25 (0.22-0.28)	0.24 (0.20-0.30)	0.24 (0.20-0.28)
N	262	314	79	97	21	24	17	18	20
Urine mercury	0.68 (0.59-0.79)	0.62 (0.55-0.71)	0.43 (0.32-0.57)	0.46 (0.35-0.59)	0.70 (0.41-1.18)	0.39 (0.22-0.70)	0.33 (0.21-0.54)	0.28 (0.15-0.50)	0.25 (0.17-0.39)

Table 3. Pearson correlation coefficients between frequency of consumption of different types of seafood and the adjusted log blood organic mercury level

Seafood	**Correlation coefficient**	**P**
Porgy	0.229	0.002
Other unknown fish	0.202	<0.001
Pike	0.199	0.094
Shark	0.165	0.122
Salmon	0.163	<0.001
Tuna	0.154	<0.001
Shrimp	0.149	<0.001
Other fish	0.140	<0.001
Flatfish	0.135	<0.001
Pollock	0.122	<0.001
Haddock	0.121	<0.001
Catfish	0.117	<0.001
Other shellfish	0.114	<0.001
Bass	0.111	0.004
Mackerel	0.105	0.020
Perch	0.101	0.002
Clam	0.091	<0.001
Seabass	0.089	0.069
Swordfish	0.089	0.099
Crab	0.087	<0.001
Crayfish	0.086	0.032
Scallop	0.086	<0.001
Lobster	0.078	0.001
Cod	0.077	<0.001
Sardine	0.075	0.007
Trout	0.068	0.015
Oyster	0.062	0.010
Other unknown shellfish	0.047	0.656
Walleye	0.035	0.457
Mussel	0.034	0.274
Breaded fish	0.021	0.159

Figure 1

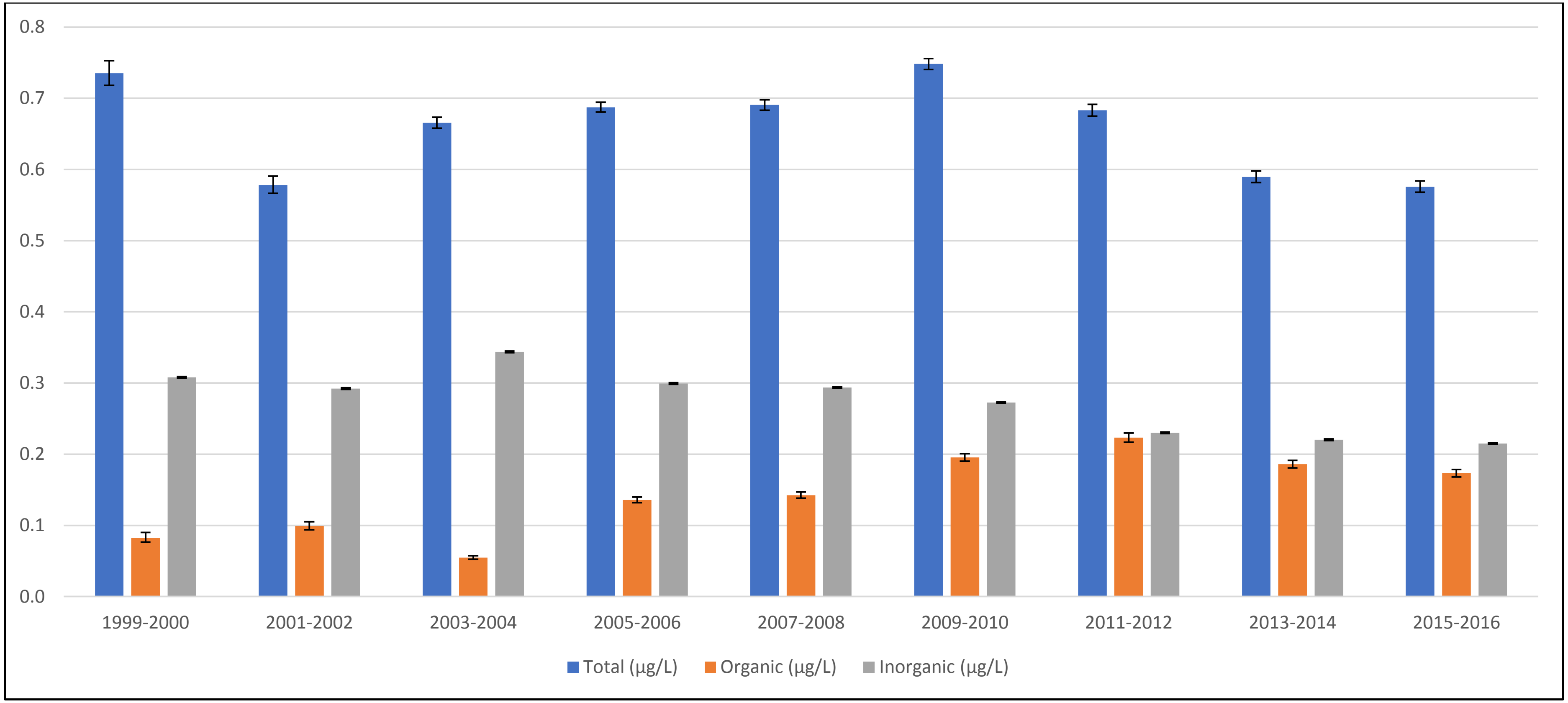

Figure 1. Total, inorganic and organic blood mercury concentration (μg/L) of all participants in NHANES 1999-2016 (Geometric means and standard errors are shown)

Figure 2

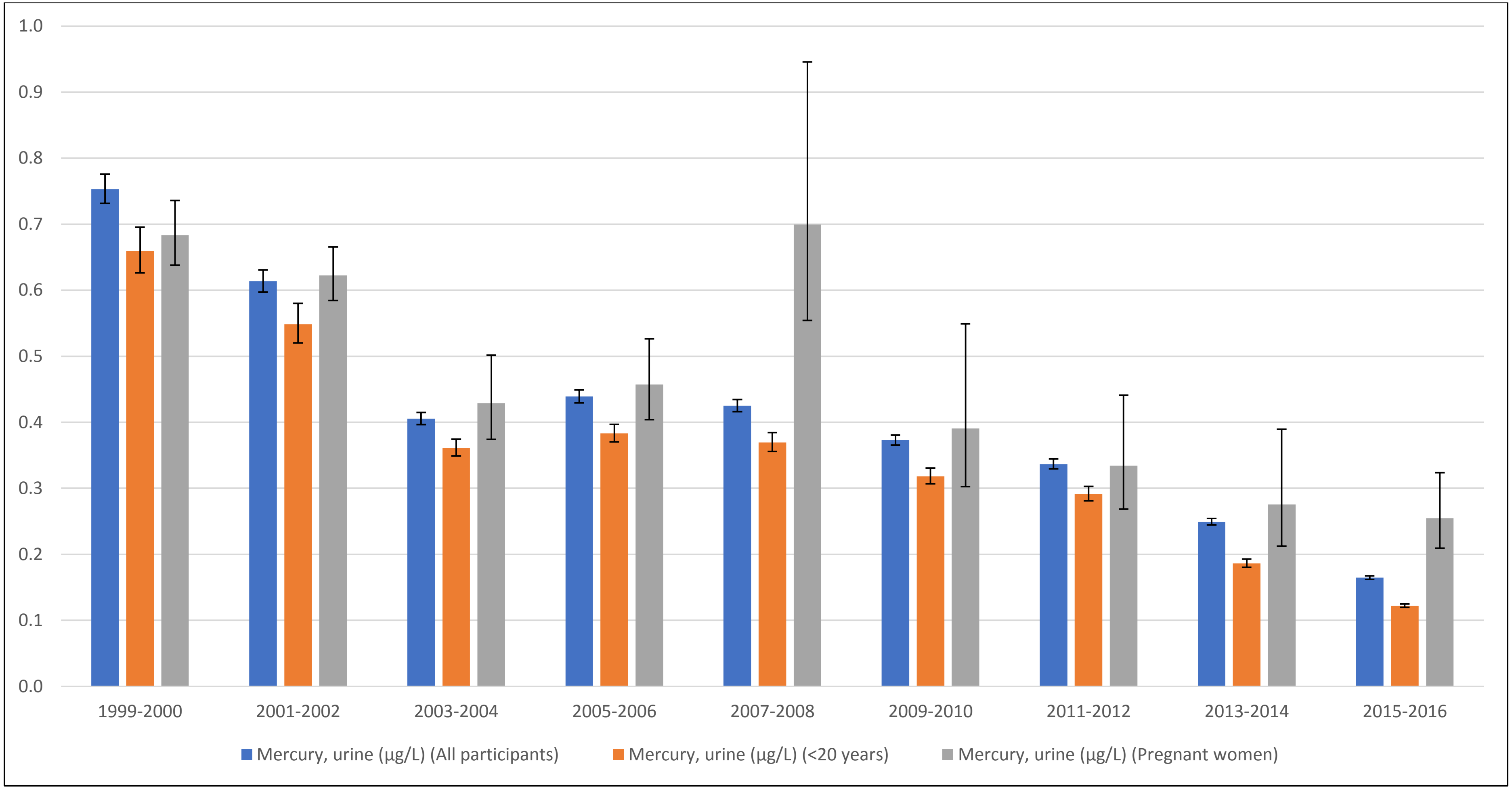

Figure 2. Urine mercury concentration (µg/L) in all participants, participants <20 years of age and pregnant women in NHANES 1999-2016 (Geometric means and standard errors are shown)

Figure 3

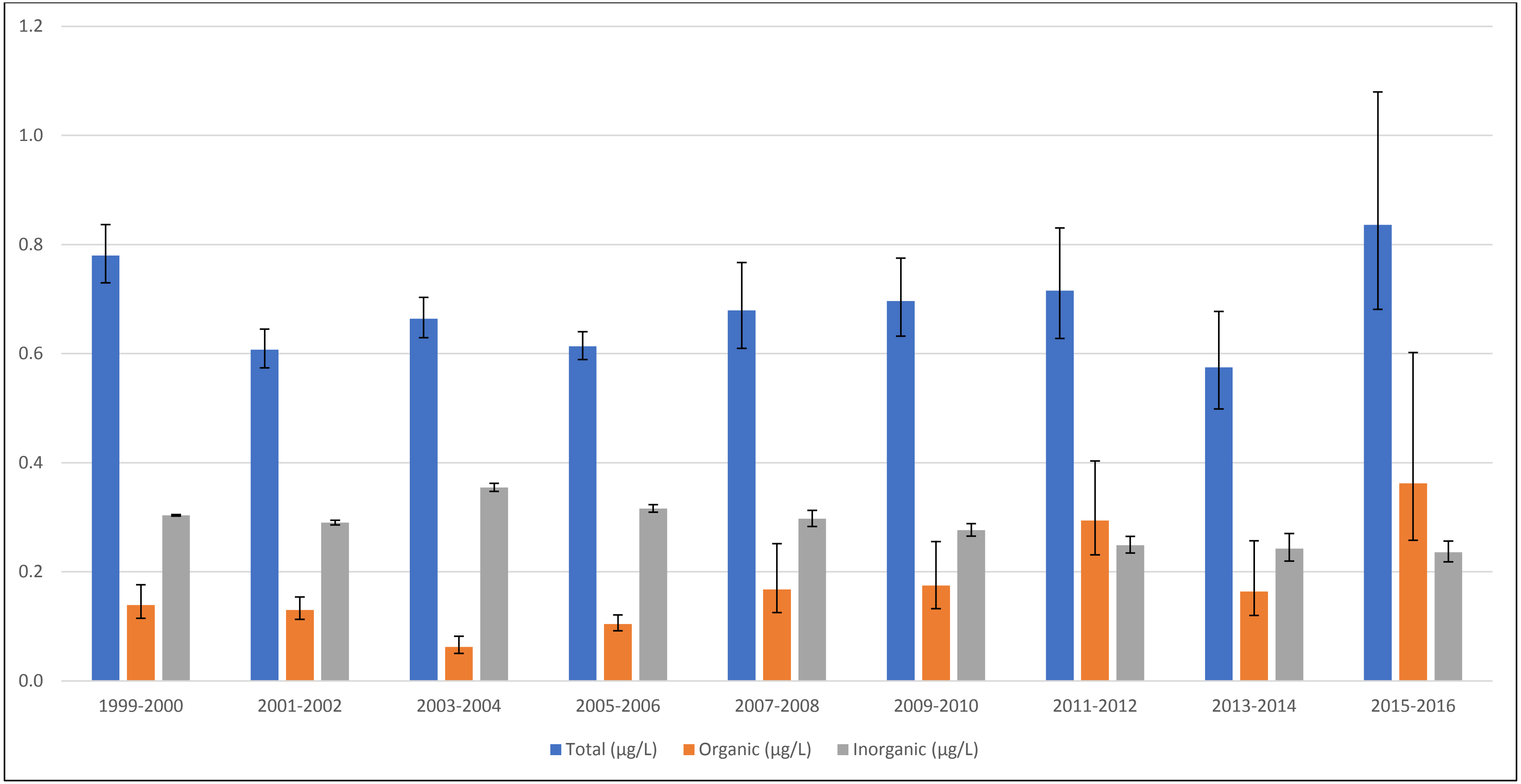

Figure 3. Total, inorganic and organic blood mercury concentration (µg/L) of pregnant women in NHANES 1999-2016 (Geometric means and standard errors are shown)

Figure 4

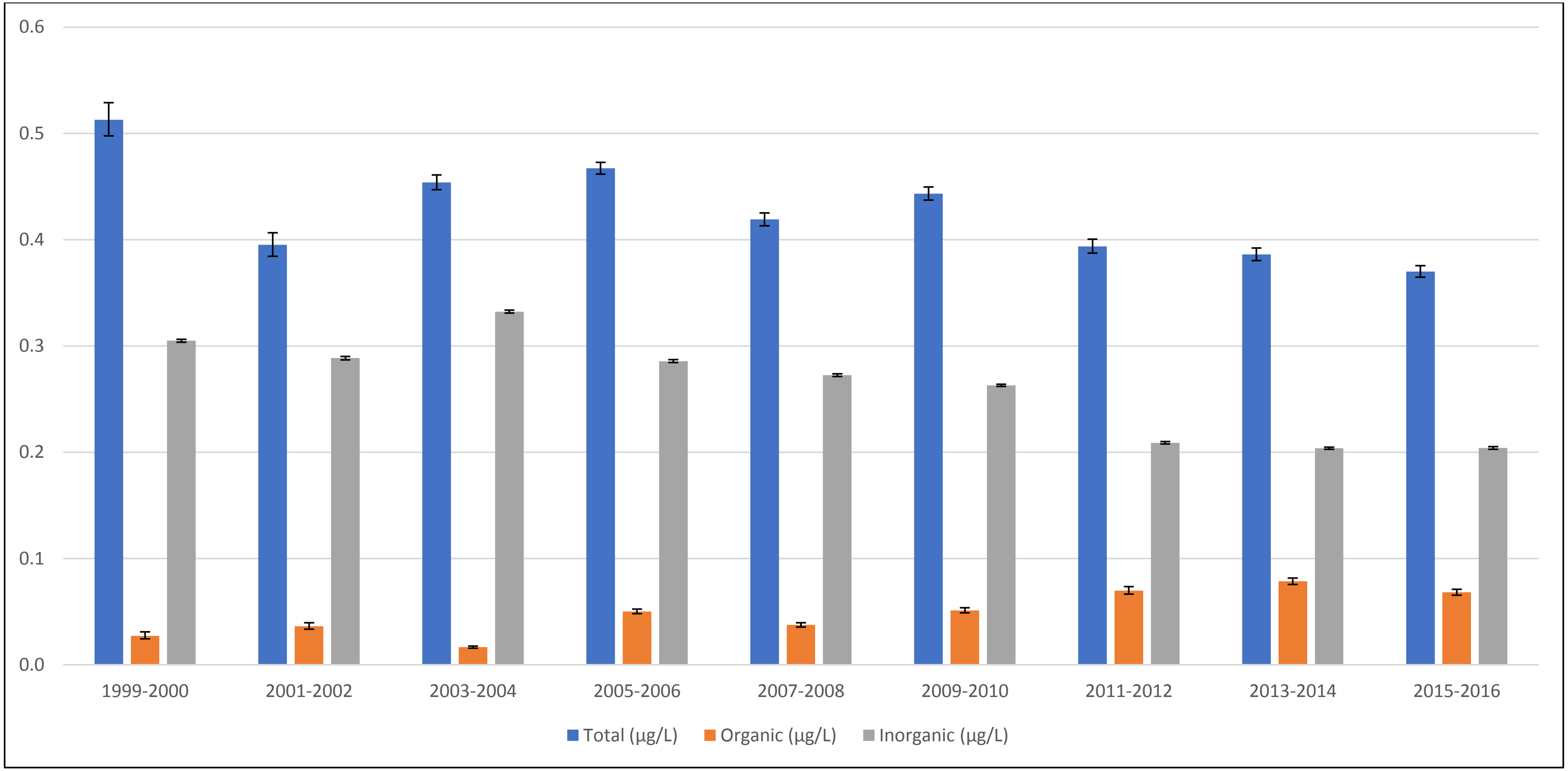

Figure 4. Total, inorganic and organic blood mercury concentration (µg/L) of participants <20 years of age in NHANES 1999-2016 (Geometric means and standard errors are shown)

Figure 5

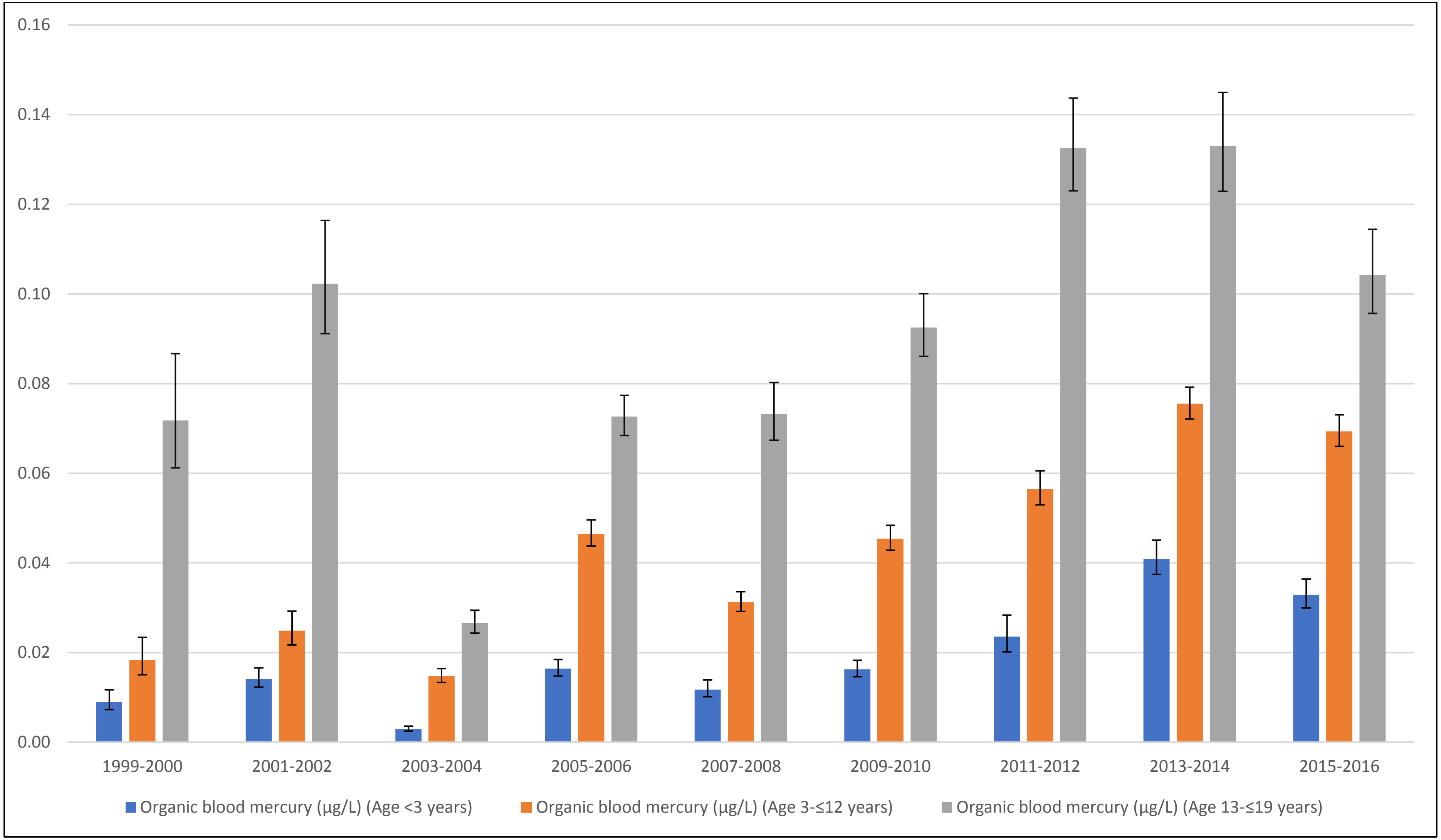

Figure 5. Organic blood mercury concentration (µg/L) in children of the age of <3 years, 3-12 years and 13-19 years (Geometric means and standard errors are shown)

Figure 6

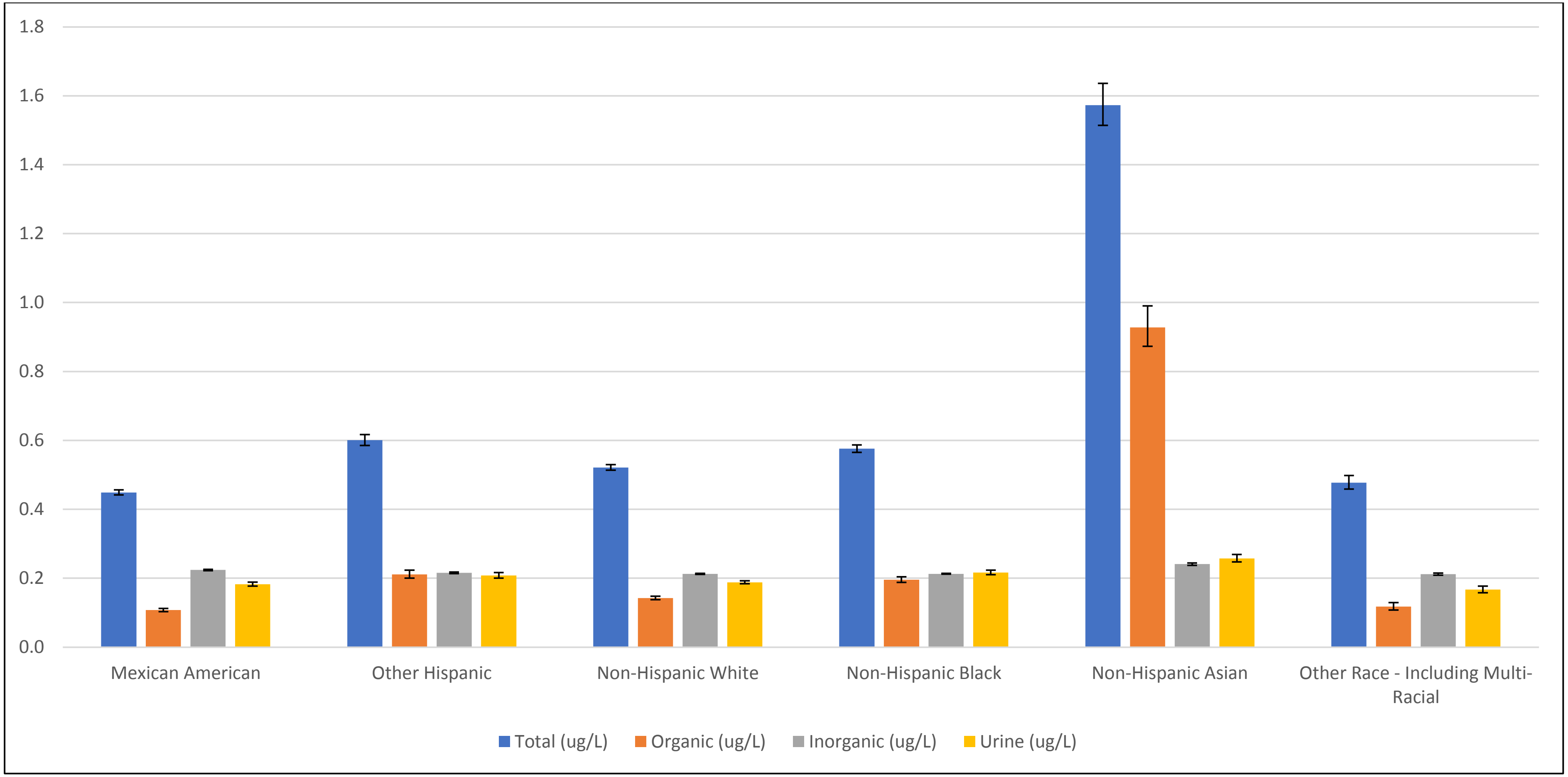

Figure 6. Blood (total, organic, inorganic) and urine mercury levels (μg/L) among different ethnicities in NHANES 2013-2016 (Geometric means and standard errors are shown)

Figure 7

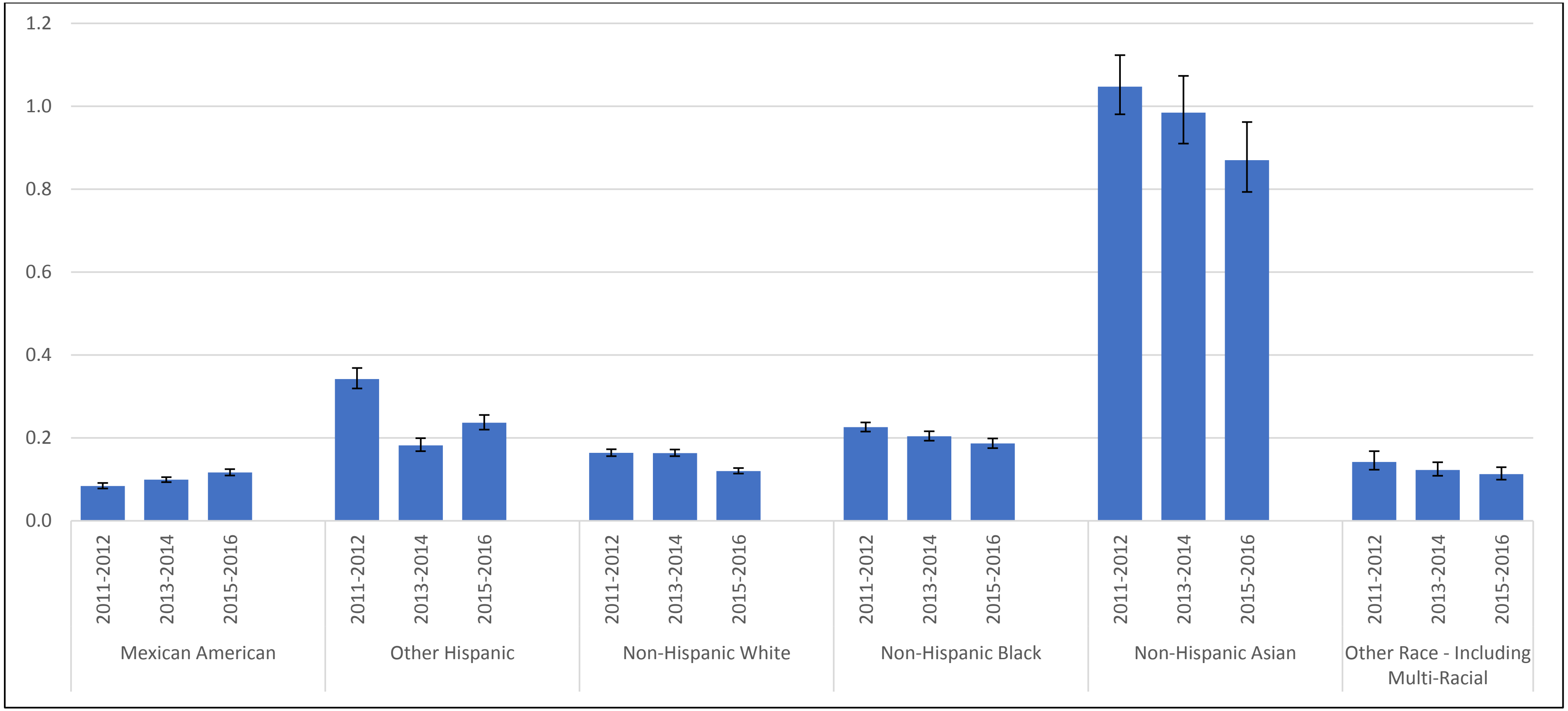

Figure 7. Blood organic mercury levels (μg/L) among different ethnicities in NHANES 2011-2016 (Geometric means and standard errors are shown)

Figure 8

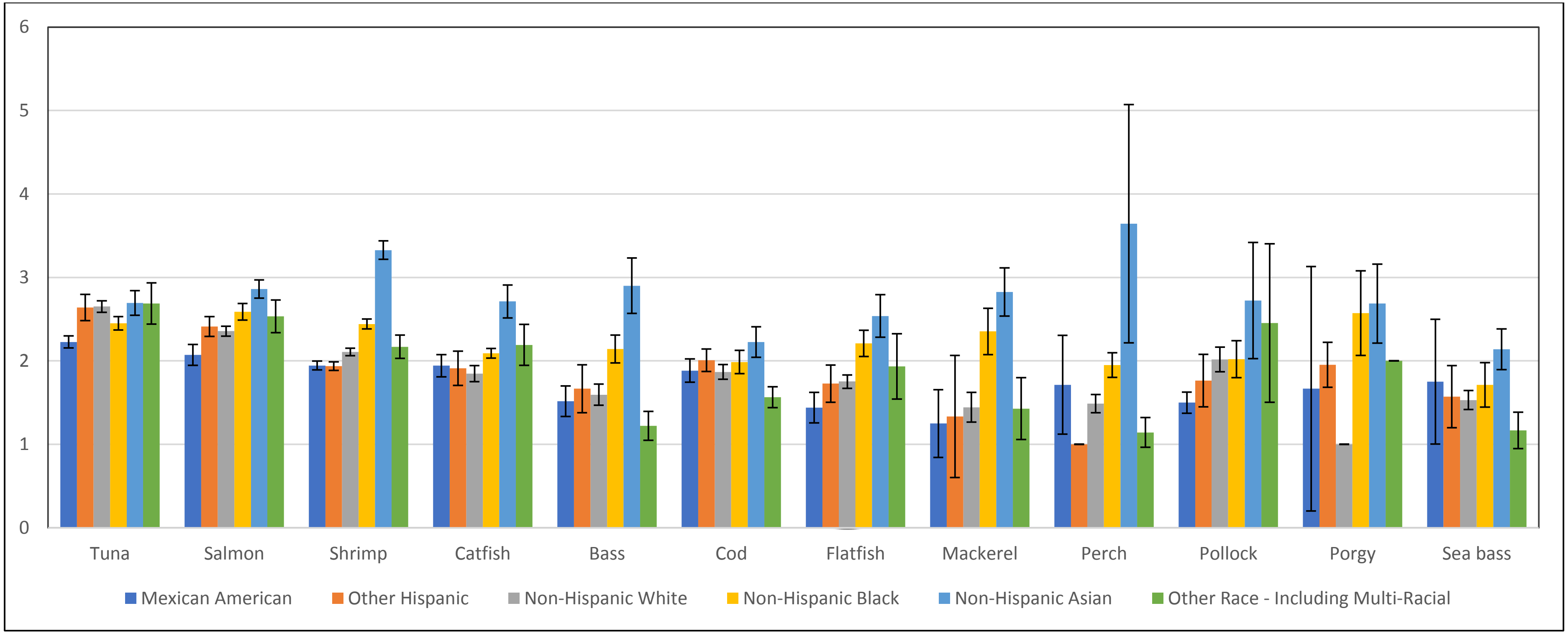

Figure 8. Mean frequencies (times) of seafood intake in 30 days prior to the survey among seafood eaters of different ethnicities in 2011-2016 (Arithmetic means and standard errors are shown)