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The Association Between Blood Mercury Levels and Risk for Overweight in a General Adult Population: Results from the Korean National Health and Nutrition Examination Survey

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Abstract The primary objective of this study was to estimate the association between blood mercury levels and overweight in Korean adults. We analyzed cross-sectional data from 9228 participants (4283 men and 4945 women) who completed the Korean National Health and Nutrition Examination Survey (KNHANES), 2007–2013. The population was divided into two groups according to the body mass index (BMI) and waist circumference (WC). Blood mercury levels were analyzed using a gold amalgam method with a DMA-80 instrument, categorized into quartiles, and stratified by sex. After adjusting for all covariates, blood mercury was significantly associated with overweight in all subjects. According to the BMI criteria, the adjusted odds ratio of being in the highest blood mercury quartile was 1.75 (95 % confidence interval [CI], 1.53–2.01) overall, 2.09 (95 % CI, 1.71–2.55) in men, and 1.58 (95 % CI, 1.32–1.89) in women. According to the WC criteria, the adjusted odds ratio of being in the highest blood mercury quartile was 1.85 (95 % CI, 1.49–2.30) in men and 1.96 (95 % CI, 1.62–2.36) in women compared to the lowest quartile. Additionally, a trend in overweight across increasing blood mercury levels was observed by the *p* for trend test in the multiple diagnostic criteria.

Keywords Mercury · Overweight · Korean National Health and Nutrition Examination Survey · Weight gain · Heavy metals

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Introduction

Obesity has been increasingly recognized as a serious worldwide public health concern in the twenty-first century. The rising prevalence of overweight and obesity in several countries has been described as a global pandemic and has not stopped spreading. The number of individuals classified as overweight and obese has dramatically increased globally from 857 million to 2.1 billion over four decades [1]. Approximately 18.4 % of adults in the Organization for Economic Co-operation and Development countries were classified as obesity [2].

Many researchers have reported that overweight and obesity are major causes of comorbidities that can lead to further morbidity and mortality, including non-communicable diseases (i.e., type 2 diabetes, hypertension, certain types of cancer, heart disease, and musculoskeletal disorders) [3–5]. Furthermore, obesity can increase mortality from cardiovascular disease (CVD), which is the leading cause of death in most countries worldwide [6, 7]. Indeed, many deaths are attributable to obesity. In the USA, 14 % and 20 % of all deaths from cancer in men and women, respectively, are attributable to overweight or obesity [5, 8]. The related annual medical expenditure of governments and individuals for reducing the obesity rate and obesity-related illnesses increased by 209.7

billion dollars [9]. New regulations have been implemented to tackle obesity in the USA, Japan, and the UK. Considering the public health efforts for obesity, the trend of increasing obesity prevalence remains an important problem [2, 10].

Physical inactivity, lifestyles, and individual food consumption patterns are well-known risk factors for weight gain [5]. In many developing countries, increased adaptation of westernized lifestyle and diet transition has been associated with an increased prevalence of obesity [11]. Unexpectedly, it was indicated that socioeconomic status (SES) also has effects on the distribution of obesity. A study indicated that belonging to a lower SES class or working in a lower occupation position (i.e., manual workers) was associated with obesity [12].

Environmental risk factors, including heavy metals, air pollution, and traffic-related urban pollution, are other causes of weight gain; these risk factors are not well known but are important and should not be ignored [13–15]. Heavy metals are especially important because they have accumulated in the earth due to rapid industrialization and urbanization in the last three to four decades. As a result, many toxic heavy metals have gradually redistributed within the environment from the Earth's crust, thereby making it impossible for humans to escape the toxic heavy metals released through occupational and other environmental routes [16]. Most people are unaware of their exposure to toxic heavy metals via their environment and daily lifestyle, but interest has been generated in toxic trace elements and their role in the human body [17, 18].

Although there are countless risks for obesity, we focused here on environmental exposure of heavy metals, especially mercury. Mercury derived from natural and anthropogenic forms is widespread in the environment [19]. Mercury has volatile and unpredictable behavior at the Earth's surface, and therefore, it acts as a complex factor in one of the most scientifically challenging biogeochemical cycles. Due to relatively high vapor pressures, its gas phase is important geochemically [20]. Due to increased awareness of the impact of mercury as an environmental pollutant worldwide, health professionals have made considerable efforts to protect environmental and human health from the release of mercury and its compounds [21]. Despite international action, the mercury concentration in the environment has increased threefold compared to pre-condition [22].

A considerable amount of literature about overweight or obesity has been published. In these studies, it has been reported that socioeconomic disparities and eating disorders are associated with increased risk of weight gain. However, only one criterion was used in most studies to diagnose overweight or obesity, such as body mass index (BMI), waist circumference (WC), or waist-to-hip ratio [23, 24]. In this study, we used both BMI and WC criteria to diagnose overweight or obesity.

Some researchers have reported that mercury in human serum leads to overweight and general or central obesity [7, 13, 25–27], but the results of previously published studies have been inconsistent. The primary objective of this study was to estimate blood mercury concentrations in adults in relation to overweight, diagnosed by their BMI and WC.

Materials and Methods

Design and Data Collection

The Korean National Health and Nutrition Examination Survey (KNHANES) is a series of nationally representative population-based cross-sectional surveys about health and nutritional status, involving a complex, stratified, multistage probability sample of Koreans, that have been conducted by the Korea Centers for Disease Control and Prevention [28]. The KNHANES IV–VI (2007–2013) survey data was used for analysis in this current study. From an initial sample of 58,423 men and women, we excluded those <20 years old, pregnant women, and those lacking data regarding age, sex, sociodemographic factors (i.e., education level, occupational status, household income, and residential area), or health behavioral factors (i.e., smoking status, exercise level, alcohol consumption, fish consumption, total calorie intake, and dietary calorie restriction). We further excluded those with missing anthropometric measurements, non-responses for self-reported questionnaires, and missing data or no measurement of blood mercury concentrations and hematocrit. All participants provided written informed consent. Ultimately, 9228 participants (4283 men and 4945 women) met the inclusion criteria for this study (Fig. 1).

Determination of Mercury Concentration in Whole Blood

Mercury exists in a variety of physical and chemical forms. The major forms of mercury are inorganic and organic species. Exposure to inorganic mercury occurs during cosmetic preparations, by consuming trace quantities in foods of plant origin, and occupationally. Methylmercury exposure results almost exclusively from fish, shellfish, and marine animal consumptions; these are a major source of mercury exposure for the general population [29, 30]. Mercury concentrations in whole blood reflect the exposure to both organic and inorganic mercury [30, 31]. Information about whole blood mercury concentrations was obtained from the KNHANES.

To assess the concentrations of heavy metals in whole blood, 3-mL blood samples were collected in standard commercial evacuated tubes containing sodium

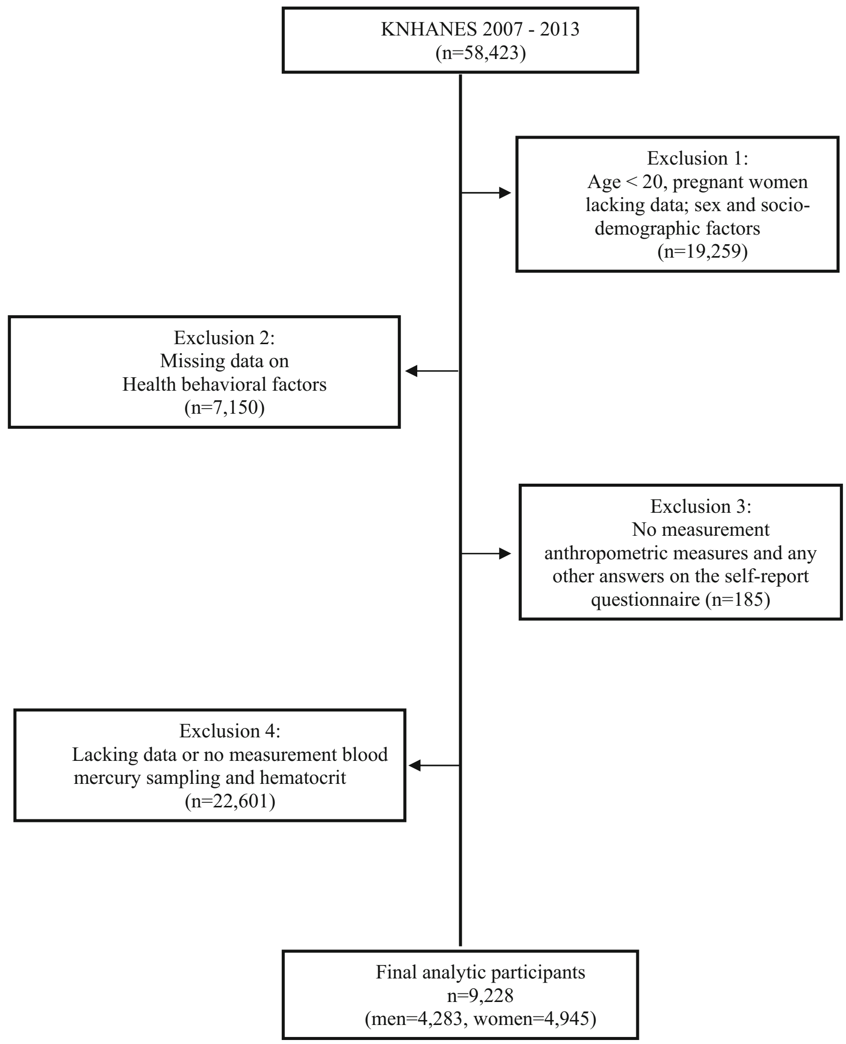

Fig. 1 Inclusion/exclusion criteria and study participants

heparin (Vacutainer). The blood mercury concentration was measured by a gold amalgam method with a DMA-80 instrument (Milestone, Bergamo, Italy). Blood mercury analyses were conducted at the Neodin Medical Institute (Seoul, South Korea), a central laboratory certified by the Korean Ministry of Health and Welfare. For internal quality assurance and control, commercial reference material was used (Lyphochek® Whole Blood Metals Control; Bio-Rad, Hercules, CA, USA) with coefficients of variation of 1.59–4.86 % in four reference samples. For external quality assurance and control, the Neodin Medical Institute approved both the German External Quality Assessment Scheme run by Friedrich-Alexander University and the Quality Assurance Program run by the Korea Occupational Safety and Health Agency. The institute is also certified by the Ministry of Employment and Labor as one of the designated laboratories for special chemicals, including heavy metals. The method detection limit for blood mercury was 0.158 μg/L in the present study [32].

Overweight Diagnostic Criteria

BMI is usually used to evaluate overweight and obesity, while WC is used to evaluate central obesity. However, there are clear genetic and ethnic differences in these criteria for overweight and obesity [33].

The World Health Organization (WHO) addressed the debate about interpretation of recommended BMI cutoff points for determining overweight and obesity in Asian populations. According to the BMI cutoff points, it was proposed that overweight and obesity were defined as a BMI of 23.0–27.5 and ≥27.5 kg/m^2, respectively [34, 35]. Ethnically specific WC cutoff points for abdominal obesity were also defined: ≥90 and ≥80 cm for South Asian and Chinese men and women, respectively [36]. Some researchers have reported the importance of evaluating overweight and overweight-related serious illnesses, including heart disease, cancer, and chronic lower respiratory disease [37, 38]. To evaluate the relationship between blood mercury levels and overweight in Korean adults, we used the WHO overweight (including obesity)

Table 1 Participant's characteristics of general adult population by body mass index (BMI) criteria

	Total (*n*=9228)					
	Men (*n*=4283)			Women (*n*=4945)		
	Normal	Overweight[a]	*p* value[b]	Normal	Overweight	*p* value
N (%)	1585 (37.0)	2698 (63.0)	<.0001	2567 (52.0)	2378 (48.0)	<.0001
Age (years)	44.5±15.6	45.5±14.0	0.0301	40.4±13.7	49.0±13.5	<.0001
Educational level, *n* (%)			0.0628			<.0001
Less than middle school	390 (24.6)	626 (23.2)		521 (20.3)	1083 (45.6)	
High school	652 (41.1)	1051 (39.0)		989 (38.5)	819 (34.4)	
College and more	543 (34.3)	1021 (37.8)		1057 (41.2)	476 (20.0)	
Household income, *n* (%)			<.0001			<.0001
1st quartile	257 (16.2)	313 (11.6)		300 (11.7)	470 (19.7)	
2nd quartile	421 (26.6)	674 (25.0)		622 (24.2)	710 (29.9)	
3rd quartile	482 (30.4)	781 (29.0)		768 (29.9)	640 (26.9)	
4th quartile	425 (26.8)	930 (34.4)		877 (34.2)	558 (23.5)	
Occupation, *n* (%)			<.0001			<.0001
Non-manual	376 (23.7)	819 (30.4)		663 (25.8)	316 (13.3)	
Manual	802 (50.6)	1326 (49.1)		676 (26.3)	889 (37.4)	
Unemployed	407 (25.7)	553 (20.5)		1228 (47.9)	1173 (49.3)	
Residence area, *n* (%)			0.6391			<.0001
Urban	1250 (78.9)	2144 (79.5)		2152 (83.8)	1848 (77.7)	
Rural	335 (21.1)	554 (20.5)		415 (16.2)	530 (22.3)	
Smoking status, *n* (%)			0.0001			0.2717
Non-smoker	369 (23.3)	517 (19.2)		2250 (87.7)	2118 (89.1)	
Former smoker	309 (19.5)	655 (24.3)		98 (3.8)	85 (3.6)	
Current smoker	907 (57.2)	1526 (56.5)		219 (8.5)	175 (7.3)	
Drinking status, *n* (%)			0.0001			<.0001
Never drink	215 (13.6)	341 (12.7)		735 (28.6)	853 (35.9)	
Moderate drink	1091 (68.8)	1736 (64.3)		1694 (66.0)	1425 (59.9)	
Heavy drink	279 (17.6)	621 (23.0)		138 (5.4)	100 (4.2)	
Exercise level, *n* (%)			0.0063			0.6920
None	890 (56.2)	1411 (52.3)		1837 (71.6)	1682 (70.7)	
Moderate	594 (37.5)	1053 (39.0)		585 (22.8)	566 (23.8)	
High	101 (6.4)	234 (8.7)		145 (5.6)	130 (5.5)	
Calorie intake (kcal/day)	2355.4±962.8	2411.3±950.5	0.0644	1742.4±710.2	1672.0±652.3	0.0003
Diet therapy, *n* (%)			<.0001			<.0001
Yes	202 (12.7)	668 (24.8)		542 (21.1)	807 (33.9)	
No	1383 (87.3)	2030 (75.2)		2025 (78.9)	1571 (66.1)	
With diet therapy (*n*=2219), *n* (%)			0.5133			0.5467
<2500 (kcal/day)	136 (67.3)	466 (69.8)		485 (89.5)	736 (91.2)	
<4000 (kcal/day)	53 (26.2)	172 (25.7)		53 (9.8)	65 (8.1)	
≥4000 (kcal/day)	13 (6.5)	30 (4.5)		4 (0.7)	6 (0.7)	
Without diet therapy (*n*=7009), *n* (%)			0.0773			0.0359
<2500 (kcal/day)	878 (63.5)	1211 (60.7)		1782 (88.0)	1417 (90.2)	
<4000 (kcal/day)	424 (30.7)	691 (34.0)		220 (10.9)	146 (9.3)	
≥4000 (kcal/day)	81 (5.8)	128 (6.3)		23 (1.1)	8 (0.5)	
Fish consumption frequency			0.0571			<.0001
Rare	285 (18.0)	408 (15.1)		413 (16.1)	551 (23.2)	

Table 1 (continued)

	Total (n=9228)					
	Men (n=4283)			Women (n=4945)		
	Normal	Overweight[a]	p value[b]	Normal	Overweight	p value
<1 time/month	740 (46.7)	1286 (47.7)		1193 (46.5)	1082 (45.5)	
2–3 times/month	317 (20.0)	538 (19.9)		482 (18.8)	390 (16.4)	
≥4 times/month	243 (15.3)	466 (17.3)		479 (18.6)	355 (14.9)	
Hematocrit (%)	44.2±3.1	45.2±2.9	<.0001	38.9±2.8	39.5±2.9	<.0001
Anthropometric measures						
Height (cm)	170.6±6.6	170.4±6.4	0.4102	159.0±5.8	156.4±5.8	<.0001
Weight (kg)	61.3±6.3	75.5±9.5	<.0001	52.0±5.0	63.7±7.9	<.0001
Waist circumference (cm)	76.7±5.8	88.8±7.1	<.0001	71.0±5.9	84.5±7.7	<.0001
Body mass index (kg/m^2)	21.0±1.4	25.9±2.3	<.0001	20.5±1.6	26.0±2.6	<.0001
Blood mercury (μg/L)						
Mean mercury (μg/L)	4.6±3.0	6.1±4.6	<.0001	3.5±2.3	4.1±2.8	<.0001
Geometric mean mercury (μg/L)	3.9±0.6	5.0±0.6	<.0001	3.0±0.5	3.4±0.5	<.0001

[a] Overweight was estimated with BMI >23 kg/m^2

[b] p value by chi-square test and t test, p<0.05

criteria using BMI ≥23.0 kg/m^2 and the obesity criteria using WC for an Asian population. Blood mercury concentrations were categorized into quartiles (Q) and stratified by sex. The anthropometric measures (i.e., height, weight, WC, and BMI) were obtained by trained technicians. The participants' height was measured with an accuracy of 0.1 cm using a portable SECA stadiometer (Seca GmbH & Co. KG, Hamburg, Germany) with the participants standing up with bare feet. Body weight was measured to the nearest 0.1 kg using an electronic scale (GL-6000-20; CAS Co., Seoul, South Korea). WC was measured to the nearest 0.1 cm at the narrowest point between the lowest rib and the uppermost lateral border of the right iliac crest. BMI was defined as the participant's weight in kilograms divided by the height in meters squared (kg/m^2).

Measurement of Covariates

Data for sociodemographic and behavioral factors were obtained from the KNHANES. Due to social disparities, people with lower SES (i.e., poor education and working in lower occupation positions) are more likely to gain weight [2, 39]. Therefore, educational levels were categorized into three groups: middle school or less, high school, and college or more [32]. Household income was calculated using a standardized classification by 5-year age groups and sex, and then the value was compared with the standard income level of Korean citizens. Total household income was divided into four categories [40]. Type of residence was categorized into urban and rural areas according to the administrative divisions of cities in Korea [41]. Furthermore, occupational status also influences weight gain. For example, belonging to a manual worker group in adulthood was significantly associated with increased general obesity in older women [42, 43]. Additionally, exposure to inorganic mercury can occur occupationally [40]. High inorganic mercury exposures can result in increased whole blood mercury [30]. Therefore, occupational status was categorized as manual, non-manual, or unemployed based on the KNHANES data. Individuals in sales and services, agriculture, forestry, fishery, engineering, assembling, technical work, and manual labor were classified as manual workers. Managers, experts and related workers, and office workers were classified as non-manual workers. Individuals with no job, students, and housewives were classified as unemployed.

For health behavioral factors, smoking status was classified as non-smoker (fewer than 100 cigarettes ever), former smoker (past smoker but not smoking at the time of the survey), and current smoker (currently smoking) [32]. Alcohol drinking was differentiated by sex as heavy drinking, which was defined as at least seven glasses of alcohol on two or more occasions per week for men and at least five glasses of alcohol on two or more occasions per week for women. Exercise activity levels were classified as none, moderate (between none and high), and high (≥20 min at least three times per week of activity that results in increased respiration). Information regarding fish consumption frequency, total calorie intake, and current diet therapy was obtained using a 24-h dietary recall questionnaire administered by a trained nutritionist. Fish consumption is highly influenced by cultural and socioeconomic factors [41]. Furthermore, fish is a staple food in

Table 2 Participant's characteristics of general adult population by waist circumference (WC) criteria

	Total (n=9228)					
	Men (n=4283)			Women (n=4945)		
	Normal	Abdominal obesity[a]	p value[b]	Normal	Abdominal obesity	p value
N (%)	3175 (74.1)	1108 (25.9)	<.0001	3063 (61.9)	1882 (38.1)	<.0001
Age (years)	44.1±14.7	47.9±14.1	<.0001	40.6±13.3	51.0±13.4	<.0001
Educational level, n (%)			0.0269			<.0001
Less than middle school	724 (22.8)	292 (26.4)		646 (21.1)	958 (50.9)	
High school	1293 (40.7)	410 (37.0)		1200 (39.2)	608 (32.3)	
College and more	1158 (36.5)	406 (36.6		1217 (39.7)	316 (16.8)	
Household income, n (%)			0.0741			<.0001
1st quartile	426 (13.4)	144 (13.0)		336 (11.0)	434 (23.0)	
2nd quartile	818 (25.8)	277 (25.0)		768 (25.1)	564 (30.0)	
3rd quartile	960 (30.2)	303 (27.4)		917 (29.9)	491 (26.1)	
4th quartile	971 (30.6)	384 (34.6)		1042 (34.0)	393 (20.9)	
Occupation, n (%)			0.7709			<.0001
Non-manual	877 (27.6)	318 (28.7)		773 (25.2)	206 (11.0)	
Manual	1586 (50.0)	542 (48.9)		842 (27.5)	723 (38.4)	
Unemployed	712 (22.4)	248 (22.4)		1448 (47.3)	953 (50.6)	
Residence area, n (%)			0.0706			<.0001
Urban	2537 (79.9)	857 (77.4)		2596 (84.7)	1404 (74.6)	
Rural	638 (20.1)	251 (22.6)		467 (15.3)	478 (25.4)	
Smoking status, n (%)			0.0003			0.1656
Non-smoker	703 (22.1)	183 (16.5)		2686 (87.7)	1682 (89.4)	
Former smoker	697 (22.0)	267 (24.1)		123 (4.0)	60 (3.2)	
Current smoker	1775 (55.9)	658 (59.4)		254 (8.3)	140 (7.4)	
Drinking status, n (%)			<.0001			<.0001
Never drink	407 (12.8)	149 (13.4)		880 (28.7)	708 (37.6)	
Moderate drink	2149 (67.7)	678 (61.2)		2023 (66.1)	1096 (58.3)	
Heavy drink	619 (19.5)	281 (25.4)		160 (5.2)	78 (4.1)	
Exercise level, n (%)			0.1846			0.0007
None	1680 (52.9)	621 (56.0)		2121 (69.3)	1398 (74.3)	
Moderate	1245 (39.2)	402 (36.3)		757 (24.7)	394 (20.9)	
High	250 (7.9)	85 (7.7)		185 (6.0)	90 (4.8)	
Calorie intake (kcal/day)	2386.7±954.9	2401.9±956.8	0.6485	1729.6±696.2	1674.3±661.9	0.0051
Diet therapy, n (%)			<.0001			<.0001
Yes	588 (18.5)	282 (25.5)		727 (23.7)	622 (33.1)	
No	2587 (81.2)	826 (74.5)		2336 (76.3)	1260 (66.9)	
With diet therapy (n=2219), n (%)			0.4207			0.7839
<2500 (kcal/day)	404 (68.7)	198 (70.2)		655 (90.1)	566 (91.0)	
<4000 (kcal/day)	151 (25.7)	74 (26.2)		67 (9.2)	51 (8.2)	
≥4000 (kcal/day)	33 (5.6)	10 (3.6)		5 (0.7)	5 (0.8)	
Without diet therapy (n=7009), n (%)			0.6753			0.2286
<2500 (kcal/day)	1592 (61.5)	497 (60.2)		2064 (88.4)	1135 (90.1)	
<4000 (kcal/day)	841 (32.5)	274 (33.2)		249 (10.7)	117 (9.3)	
≥4000 (kcal/day)	154 (6.0)	55 (6.6)		23 (0.9)	8 (0.6)	
Fish consumption frequency			0.4181			<.0001
Rare	516 (16.2)	177 (16.0)		476 (15.5)	488 (25.9)	

Table 2 (continued)

	Total (n=9228)					
	Men (n=4283)			Women (n=4945)		
	Normal	Abdominal obesity[a]	p value[b]	Normal	Abdominal obesity	p value
<1 time/month	1522 (47.9)	504 (45.5)		1470 (48.0)	805 (42.8)	
2–3 times/month	624 (19.7)	231 (20.8)		579 (18.9)	293 (15.6)	
≥4 times/month	513 (16.2)	196 (17.7)		538 (17.6)	296 (15.7)	
Hematocrit (%)	44.7±3.0	45.4±2.9	<.0001	38.9±2.8	39.5±2.9	<.0001
Anthropometric measures						
Height (cm)	170.1±6.5	171.7±6.3	<.0001	158.4±5.9	156.8±5.9	<.0001
Weight (kg)	66.4±8.2	81.3±10.3	<.0001	53.4±5.8	64.6±8.4	<.0001
Waist circumference (cm)	80.4±6.2	95.5±5.2	<.0001	71.4±5.3	87.4±6.3	<.0001
Body mass index (kg/m^2)	22.9±2.3	27.5±2.6	<.0001	21.3±2.1	26.2±2.9	<.0001
Blood mercury (μg/L)						
Mean mercury (μg/L)	5.2±3.7	6.7±5.1	<.0001	3.5±2.2	4.2±3.0	<.0001
Geometric mean mercury (μg/L)	4.3±0.6	5.4±0.7	<.0001	3.0±0.5	3.6±0.5	<.0001

[a] Abdominal obesity was estimated with WC ≥90 cm for men and ≥80 cm for women

[b] p value by chi-square test and t test, $p<0.05$

Korea and can be the primary exposure pathway for methylmercury. Information about fish consumption frequency was obtained from the KNHANES. Participants completed a simple food frequency questionnaire containing only questions about consumption frequency, but not the consumption amount. The number of respondents who indicated that they consumed fish "6–11 times/year" or "over 1 time/day" was limited; therefore, the categories in the questionnaire were combined into the following categories for the present study: rare, ≤1 time/month, 2–3 times/month, and ≥4 times/month [44]. Furthermore, hematocrit is an appropriate confounding variable because at least 80 % of the methylmercury in blood binds to red blood cells [45]. To evaluate more definite blood mercury effect on human body, hematocrit was estimated by sampling.

Statistical Analysis

Statistical analyses were performed using SAS statistical software (version 9.4; SAS Institute Inc., Cary, NC, USA). The baseline characteristics of the study population were evaluated by Student's t tests and χ^2 tests. The association between blood mercury levels and overweight according to BMI and abdominal obesity according to WC was evaluated by three different logistic regressions. Subjects in Q1 of blood mercury levels were considered as the reference group for data analyses. Model 1 was adjusted only for age. Sociodemographic variables were added to the second set of models. Finally, for a fully adjusted model, health behavior variables and hematocrit were added as additional confounders in the third set of models. A two-tailed p value <0.05 was considered statistically significant. We also performed p for trend tests to evaluate whether there was a trend in the overweight in adults across increasing blood mercury concentrations.

Results

Participant characteristics based on the BMI and WC criteria are presented in Tables 1 and 2, respectively; 2698 men (63.0 %) and 2378 women (48.0 %) were in the overweight group, and 1108 men (25.9 %) and 1882 women (38.1 %) were in the abdominal obesity group. Mean blood mercury concentrations were 6.1 and 6.7 μg/L in men and 4.1 and 4.2 μg/L in women.

When grouped according to the BMI criteria, age, household income, occupational status, drinking status, diet therapy, hematocrit, weight, WC, BMI, and mean blood mercury levels significantly differed in both men and women. Education level, residence area, total calorie intake, fish consumption, and height were significant in only women, whereas smoking status and exercise level were significant in only men.

When grouped according to the WC cutoff point, there were significant differences in age, education, drinking status, diet therapy, hematocrit, anthropometric measures, and mean blood mercury levels in both men and women. Household income, occupational status, residence area, exercise level, total calorie intake, and fish consumption were significant in only women, whereas only smoking status was significant in men.

The mean concentration of blood mercury was 6.7 μg/L in men and 4.2 μg/L in women. The blood mercury quartile categories for the overall general population were as follows:

Q1, ≤2.52 μg/L; Q2, 2.52–3.70 μg/L; Q3, 3.70–5.58 μg/L; and Q4, ≥5.58 μg/L. The quartiles for men were as follows: Q1, ≤3.04 μg/L; Q2, 3.04–4.52 μg/L; Q3, 4.52–6.84 μg/L; and Q4, ≥6.84 μg/L. Moreover, the quartiles for women were as follows: Q1, ≤2.24 μg/L; Q2, 2.24–3.17 μg/L; Q3, 3.17–4.55 μg/L; and Q4, ≥4.55 μg/L.

The relationship between blood mercury levels and overweight based on BMI using logistic regression with different models is shown in Table 3. The odds ratio (OR) (95 % confidence interval [CI]) for the highest versus reference blood mercury level, fully adjusted for age, sociodemographic factors, health behavioral factors, and hematocrit, was 1.75 (1.53–2.01) in the overall general population, 2.09 (1.71–2.55) in men, and 1.58 (1.32–1.89) in women. In all models, a trend in overweight among adults across increasing blood mercury levels was revealed by a p for trend test (p trend <0.0001).

Table 3 Results of unadjusted and adjusted odds ratio (95 % CI) for assessment of the relationship between blood mercury level and overweight using logistic regressions

	Blood mercury level category				p for trend
	1st quartile	2nd quartile	3rd quartile	4th quartile	
Overall					
Range of blood mercury	<2.52 μg/L	2.52–3.70 μg/L	3.70–5.58 μg/L	5.58 μg/L≤	
Subjects (n=9228)	2303	2293	2321	2311	
Overweight[a] [n (%)]	1020 (20.09)	1147 (22.60)	1355 (26.69)	1554 (30.61)	
Odds ratio (95 % CI)					
Unadjusted	1.00	1.25* (1.12–1.41)	1.76** (1.57–1.98)	2.58** (2.29–2.91)	<.0001
Model 1	1.00	1.17* (1.03–1.31)	1.51** (1.34–1.71)	1.94** (1.71–2.20)	<.0001
Model 2	1.00	1.17* (1.04–1.32)	1.52** (1.35–1.72)	1.97** (1.73–2.24)	<.0001
Model 3	1.00	1.11* (0.98–1.25)	1.41** (1.24–1.60)	1.75** (1.53–2.01)	<.0001
Men					
Range of blood mercury	<3.04 μg/L	3.04–4.52 μg/L	4.52–6.84 μg/L	6.84 μg/L≤	
Subjects (n=4283)	1065	1071	1076	1071	
Overweight[a] [n (%)]	553 (20.50)	632 (23.42)	708 (26.24)	805 (29.84)	
Odds ratio (95 % CI)					
Unadjusted	1.00	1.33* (1.12–1.58)	1.78** (1.49–2.12)	2.80** (2.33–3.36)	<.0001
Model 1	1.00	1.33* (1.12–1.57)	1.77** (1.49–2.11)	2.78** (2.31–3.35)	<.0001
Model 2	1.00	1.28* (1.08–1.53)	1.65** (1.38–1.97)	2.51** (2.08–3.04)	<.0001
Model 3	1.00	1.17* (0.97–1.39)	1.45** (1.21–1.75)	2.09** (1.71–2.55)	<.0001
Women					
Range of blood mercury	<2.24 μg/L	2.24–3.17 μg/L	3.17–4.55 μg/L	4.55 μg/L≤	
Subjects (n=4945)	1226	1238	1241	1240	
Overweight[a] [n (%)]	491 (20.65)	563 (23.68)	624 (26.24)	700 (29.44)	
Odds ratio (95 % CI)					
Unadjusted	1.00	1.24* (1.06–1.46)	1.51** (1.29–1.77)	1.94** (1.65–2.27)	<.0001
Model 1	1.00	1.20* (1.01–1.42)	1.43** (1.21–1.69)	1.61** (1.36–1.90)	<.0001
Model 2	1.00	1.23* (1.04–1.46)	1.47** (1.24–1.75)	1.66** (1.40–1.98)	<.0001
Model 3	1.00	1.20* (1.01–1.43)	1.43** (1.20–1.70)	1.58** (1.32–1.89)	<.0001

Model 1 adjusted for age

Model 2: Model 1 plus adjustment for sociodemographic factors (education, occupation, household income, and residence)

Model 3: Model 2 plus adjustment for health behavioral factors (smoking, alcohol drinking, and exercise level and calorie intake, diet therapy, fish consumption) and hematocrit

Model 3 is a fully adjusted model including all relevant covariates

CI confidence interval

*p<0.05; **p<.0001

[a] Overweight was estimated with BMI >23 kg/m^2

Table 4 Results of unadjusted and adjusted odds ratio (95 % CI) for assessment of the relationship between blood mercury level and abdominal obesity using logistic regressions.

	Blood mercury level category				*P* for trend
	1st quartile	2nd quartile	3rd quartile	4th quartile	
Men					
Range of blood mercury	<3.04 μg/L	3.04–4.52 μg/L	4.52–6.84 μg/L	6.84 μg/L≤	
Subjects (*n*=4283)	1065	1071	1076	1071	
Abdominal obesity[a] [*n* (%)]	188 (17.65)	266 (24.01)	281 (25.36)	373 (33.66)	
Odds ratio (95 % CI)					
Unadjusted	1.00	1.54** (1.25–1.90)	1.64** (1.33–2.03)	2.49** (2.03–3.04)	<.0001
Model 1	1.00	1.51** (1.22–1.86)	1.58** (1.28–1.95)	2.30** (1.88–2.82)	<.0001
Model 2	1.00	1.49** (1.20–1.84)	1.55** (1.25–1.92)	2.36** (1.81–2.75)	<.0001
Model 3	1.00	1.39** (1.12–1.72)	1.37** (1.10–1.70)	1.85** (1.49–2.30)	<.0001
Women					
Range of blood mercury	<2.24 μg/L	2.24–3.17 μg/L	3.17–4.55 μg/L	4.55 μg/L≤	
Subjects (*n*=4945)	1226	1238	1241	1240	
Abdominal obesity [a] [*n* (%)]	345 (18.38)	441 (23.43)	504 (26.78)	591 (31.40)	
Odds ratio (95 % CI)					
Unadjusted	1.00	1.40** (1.18–1.66)	1.73** (1.47–2.05)	2.31** (1.96–2.73)	<.0001
Model 1	1.00	1.38** (1.15–1.66)	1.69** (1.41–2.02)	1.94** (1.62–2.32)	<.0001
Model 2	1.00	1.44** (1.20–1.73)	1.78** (1.48–2.14)	2.04** (1.70–2.45)	<.0001
Model 3	1.00	1.40** (1.16–1.69)	1.74** (1.44–2.09)	1.96** (1.62–2.36)	<.0001

Model 1 adjusted for age

Model 2: Model 1 plus adjustment for sociodemographic factors (education, occupation, household income, and residence)

Model 3: Model 2 plus adjustment for health behavioral factors (smoking, alcohol drinking, and exercise level and calorie intake, diet therapy, fish consumption) and hematocrit

Model 3 is a fully adjusted model including all relevant covariates

CI confidence interval

**p*<0.05; ***p*<.0001

[a] Abdominal obesity was estimated with WC ≥90 cm for men and ≥80 cm for women

The results of logistic regression analyses based on WC are shown in Table 4. The fully adjusted OR (95 % CI) for the highest versus reference blood mercury level was 1.85 (1.49–2.30) in men and 1.96 (1.62–2.36) in women. Similarly, based on BMI, a trend in obesity among adults across increasing blood mercury levels was revealed by a *p* for trend test in all models (*p* trend <0.0001).

Discussion

In the present study, after adjusting for possible potential confounders, we found a positive association between blood mercury concentration and overweight in a large population-based Korean dataset representative of the Korean population.

Previous researchers have examined the association between blood mercury concentration and obesity, but with inconsistent results [7, 13, 25–27]. In some investigations, a significant association between blood mercury level and obesity was demonstrated in Korean adults [25–27]. Similarly, a significant association between hair mercury levels and BMI was observed in a previous study [13]. Conversely, there was no notable relationship between blood mercury concentrations and obesity in another study [7]. These previous studies adjusted for only SES or food consumption, but not for other potential confounding factors (i.e., occupational status). Furthermore, there were fewer study participants, which decreased their statistical power, compared to our study population.

Some researchers have postulated possible mechanisms for the association between blood mercury levels and weight gain. According to current knowledge, mercury may play an important role in the development of weight gain by causing not only adipose tissue endocrine dysfunction but also dysregulation of lipid metabolism and glucose metabolism [27, 46, 47]. According to a recent in vivo research about mechanism of blood mercury's effect on weight gain, mercuric chloride injected mice showed a decrease in adipose tissue content such as adiponectin and leptin. Furthermore, a significant inhibition of both peroxisome proliferator activated receptor (PPAR) α and γ translation of mRNA in adipocytes has been indicated, while PPARs regulated the cellular differentiation and metabolism of carbohydrate and lipid. Those results suppose that the observed changes may play an important role in the development of weight gain associated–pathology [48]. Furthermore, weight gain induced by environmental exposure to mercury supports potential risk factors of CVDs [13, 48, 49]. Therefore, it is important to tighten the environmental restrictions regarding mercury exposure.

In the current study, we estimated the relationship between overweight and blood mercury levels in a Korean general adult population using different diagnostic criteria.

There are several limitations in the current study. First, we used a cross-sectional study design, which does not allow an estimation of a cause–effect relationship between parameters. Second, the mercury in hair, toenails, and urine reflects long-term exposure; however, we used total blood mercury as an exposure biomarker for mercury in this study. Although the blood mercury level reflects relatively short term exposure during several months, it has been widely used in epidemiological studies as a marker for monitoring the mercury exposure of populations at risk and for comparisons with other populations [19]. Third, the nutrition data of study participants were obtained using a 24-h dietary recall questionnaire, leading to potential recall bias.

Despite these limitations, the major strengths of this study are that it involved a large sample size, and therefore, the results are representative of Korean adults. Second, obesity is influenced by ethnicity [23], but an ethnically homogenous Korean population participated in this study [50]. Thirdly, we evaluated overweight based on two different criteria (i.e., BMI and WC), whereas only a single criterion was used in numerous previously published studies. Finally, even after adjusting for fish consumption, hematocrit, occupational position, and many other confounder variables, we still found a significant association between blood mercury levels and overweight.

In conclusion, we found meaningful associations between blood mercury level and overweight in a dose-dependent manner, thereby enhancing our understanding of the effect of blood mercury levels on the increasing trend of weight gain. The specific mechanism that blood mercury leads to weight gain has not yet been reported. Further experimental, cohort, clinical, and epidemiological studies are necessary to overcome the limitations of this study. Additionally, international awareness and continuous management for protecting populations against environmental exposure are required.

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