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Levels, Spatial Distribution, and Impact Factors of Heavy Metals in the Hair of Metropolitan Residents in China and Human Health Implications

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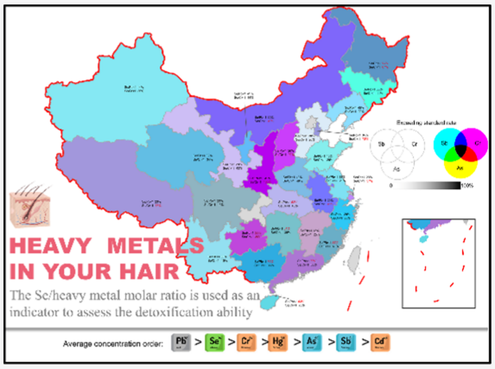
ABSTRACT: Chronic exposure to low levels of heavy metals threatens human health. However, few studies evaluated the health effects and spatial distributions of chronic exposure to heavy metals in metropolitan residents throughout mainland China using unified sampling methods and evaluation indicators at the national level. Here, the concentrations and spatial distributions of heavy metals (As, Cd, Cr, Sb, Pb, and Hg) in the hair of 1202 metropolitan residents from mainland China were analyzed, and differences in age and sex were evaluated. Most target metals exhibited higher concentrations in the hair of residents from South Central China. Generally, male hair had higher As and Se concentrations, whereas female hair had higher Cd and Pb levels ($p < 0.05$). A significant pairwise correlation existed between most metals in hair, especially Cd−Pb ($r = 0.638$, $p < 0.05$). The Se/heavy metal molar ratio is used as an indicator to assess the detoxification ability. The results demonstrated that protecting metropolitan residents in South Central China from heavy metals in their daily life is crucial, particularly for Hg, Pb, and Cr with Se/(Hg, Pb, or Cr) molar ratios < 1. This is the first study to comprehensively consider the antagonistic effects of Se and heavy metals using the molar ratio of Se/heavy metals to evaluate health implications and propose health management policies for metropolitan residents in China.



KEYWORDS: *human hair, heavy metals, regional variation, sex difference, antagonistic effects*

■ INTRODUCTION

Heavy metals refer to metals (e.g., Cr, Cd, Pb, Sb, and Hg) and metalloids (e.g., As) with an atomic density greater than 4.5 g cm^{-3}.[1] Some heavy metals, including Cd, Pb, As, Sb, and Hg, are nonessential xenobiotics known to be harmful to human health in terms of acute and chronic toxicity (i.e., reproduction impairment, endocrine disruption, immunosuppression, and neurotoxicity),[1−3] while others are essential for the human body but could be harmful to human health if they exceed their corresponding thresholds.[4] For instance, Cr deficiency promotes the development of diabetic complications, whereas chronic exposure to Cr(VI) amplifies centrosomes in the human lung cells, which is a phenotype generally found in lung tumors.[5,6] Although an acute high exposure to heavy metals can occur occasionally in the real world, exposure to heavy metals is usually chronic and at low levels in the general population.[7,8] Human exposure to heavy metals occurs mainly via pathways such as inhalation (breathing), dermal contact, and diet.[9] Among these pathways, diet is the primary source of exposure to heavy metals for the general population. For example, seafood consumption could result in chronic Hg exposure,[7] while emissions from electroplating and leather tanning, brake and tire wear, vehicle exhaust gas, the abuse of pesticides, and nonferrous metal smelting could lead to chronic exposure to Cr, Cd, Pb, As, and Sb.[7,10,11] Previous knowledge of the health effects of heavy metals is built on cases of occupationally exposed workers or people living around heavily polluted areas.[12−14] Recently, a few studies have attempted to address the potential health effects of chronic exposure to heavy metals on particularly susceptible individuals in industrialized cities, such as adolescents.[15,16] Because the body and especially the brain of adolescents are under development, heavy metals could influence maturation and have long-term effects throughout the adolescents' lives.[15] However, urban residents can be exposed to heavy metals at low levels for a long period of time without any discernible symptoms,[17] especially in highly populous metropolitan cities

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and developed economies and industries, of which there are many in China. Therefore, it is crucial to investigate the heavy metal exposure levels in metropolitan residents from different regions in China and to evaluate the associated health impacts using unified sampling methods and evaluation indicators.

The International Atomic Energy Agency (IAEA) has accepted and recommended human hair as an indicator of the chronic exposure of humans to trace elements.[18] Human hair has been widely used to estimate the nutritional status and environmental pollutant exposure and detect toxic drugs in forensic medicines, owing to the advantages of noninvasive and convenient collection, transport, and storage, enabling a trace over a specific time window or for long-term exposure, as compared to routine bioindicator materials such as blood and urine.[19] Metals in the hair have been used as exposure indicators under various scenarios. For example, heavy metal levels are higher in the hair of people living near mining, industrial activities, and waste incineration than those of general people in controlling areas.[12,20−22] Although a growing number of heavy metal biomonitoring studies have been published, most of these failed to assess the human health implications of the measured levels of exposure. For example, Zhou et al.[23] analyzed the As, Cd, and Pb levels in human hair samples from 11 cities in China and assessed the effects of food consumption, age, sex, and residence on these toxicant concentrations, without estimating the health impacts and spatial distribution of the heavy metals nationwide. To date, little is known about the spatial distribution, influencing factors, and potential health impacts of heavy metals accumulated in human hair, especially in the general population of China.

Although hair analysis has been widely used to estimate the nutritional status and exposure to heavy metals, some vital limitations for setting health-based reference values remain, including the potential interference of external contamination and the lack of reliable analytical methodologies to evaluate exposure to heavy metals.[24] To compensate for these limitations, Se, which is known to have antagonistic effects on heavy metal toxicity, has been included in the analyses.[7,25] Generally, according to the Chinese adult hair Se classification standard,[26] Se levels in hair can be classified into five types: Se-deficient (<0.20 mg/kg), Se-marginal (0.20−0.25 mg/kg), Se-sufficient (0.25−0.50 mg/kg), Se-rich (0.50−3.00 mg/kg), and Se-excessive (>3.00 mg/kg). In addition, the molar ratio of Se to certain heavy metals is considered an important indicator for risk assessment and is often used to represent detoxification ability.[7] Because Se is a powerful antioxidant and an important component in glutathione peroxidases,[27] it can antagonize the toxicity of heavy metals by decreasing the uptake by humans.[7,27] For example, Hg/Se protein compounds are biologically nontoxic and derived from the interaction of Se−glutathione peroxidase and Hg.[27] Thus, Se/Hg molar ratios of 1 or greater are often interpreted as an indicator for detoxification or the binding of Hg, even though no Hg-associated toxic damage would occur at high Hg concentrations.[7,28] By contrast, a molar ratio <1 is considered a threshold for the emergence of adverse effects.[7] Evaluating the health effects of heavy metals on the human body without considering the protective effects of Se would thus be inadequate.[28]

This study aimed to analyze the heavy metal levels in the hair of metropolitan residents to map their spatial distribution patterns across mainland China, to determine the possible impacts of sex and age on the bioaccumulation of heavy metals, and to evaluate the antagonism of Se on heavy metal toxicity and possible health impacts on the human body. This is the first study that used the relative molar concentrations of Se and heavy metals to assess the potential health hazards of heavy metals to the metropolitan residents in China on a national scale.

MATERIALS AND METHODS

Sample Collection. Hair samples of 1202 participants from the general population of 29 provincial capitals across mainland China were collected from June to October 2020 (Figure S1). All the participants who had been living locally for more than 3 years without a long-term travel history were recruited from local barber shops through posters. Hair samples were collected by barbers during the routine haircut. Hair samples were cut as close as possible to the scalp from the occipital area using ceramic scissors, which were precleaned with 1% nitric acid and ultrapure water. Detailed information about the participants is presented in Table 1, including their residential region, sex, and age. All samples were wrapped in plastic bags and stored at −20 °C until analysis. This work was approved by the Medical Ethics Committee of the South

Table 1. Characteristics of the 1202 Participants Who Gave Hair Samples and Were Recruited in Barber Shops of 29 Provincial Capitals across Mainland China from June to October 2020

		sex		
regions	cities	female	male	ages (years old)
northeast (n = 76)	Harbin	20	16	17−49
	Shenyang	12	19	5−53
	Changchun	4	5	23−33
north (n = 210)	Hohhot	20	32	4−42
	Shijiazhuang	24	40	11−54
	Taiyuan	24	38	18−35
	Tianjin	17	15	18−54
east (n = 268)	Fuzhou	19	22	18−46
	Hangzhou	10	18	20−55
	Hefei	3	25	21−43
	Jinan	22	20	18−52
	Nanchang	17	42	15−47
	Nanjing	20	22	20−44
	Shanghai	8	20	8−55
south central (n = 295)	Guangzhou	29	23	11−42
	Haikou	20	20	20−40
	Nanning	23	20	18−53
	Wuhan	24	38	11−48
	Changsha	26	23	18−42
	Zhengzhou	31	18	20−45
northwest (n = 221)	Lanzhou	10	41	20−46
	Urumqi	13	31	10−50
	Xi'an	20	25	18−40
	Xining	21	26	5−50
	Yinchuan	18	16	13−43
southwest (n = 132)	Chengdu	20	21	6−35
	Guiyang	14	22	18−43
	Kunming	12	21	17−43
	Lhasa	7	15	19−46
sum up		508	694	4−55

Table 2. Hair Heavy Metal Concentrations from Different Regions across Mainland China (mg/kg)[a]

regions	values	Cr	Se	As	Cd	Sb	Pb	Hg
northeast (*n* = 76)	min	0.050	0.077	0.004	ND	0.003	0.055	0.030
	max	5.61	0.615	0.369	0.550	0.372	19.8	0.951
	median	0.188	0.352	0.048	0.027	0.033	0.908	0.174
	average	0.344	0.357	0.070	0.042	0.041	2.48	0.204
	St. Dev	0.672	0.119	0.070	0.071	0.047	3.82	0.139
north (*n* = 210)	min	0.047	0.043	0.002	0.001	ND	0.037	0.012
	max	3.53	0.934	0.284	0.408	0.355	8.90	3.12
	median	0.263	0.309	0.046	0.019	0.018	0.565	0.135
	average	0.347	0.321	0.055	0.036	0.029	0.842	0.191
	St. Dev	0.353	0.090	0.039	0.057	0.038	1.01	0.274
east (*n* = 268)	min	ND	0.09571	ND	ND	0.001	0.063	ND
	max	3.50	59.0	0.464	0.734	0.533	107	12.5
	median	0.182	0.416	0.056	0.017	0.027	0.694	0.259
	average	0.286	0.907	0.074	0.039	0.038	1.70	0.364
	St. Dev	0.390	4.26	0.062	0.079	0.046	6.89	0.788
south central (*n* = 295)	min	0.025	ND	0.001	ND	ND	0.047	0.048
	max	15.3	2.24	1.18	0.645	0.327	36.1	4.56
	median	0.198	0.383	0.072	0.030	0.029	1.17	0.327
	average	0.348	0.388	0.088	0.055	0.040	1.95	0.439
	St. Dev	1.02	0.163	0.092	0.075	0.037	3.29	0.436
northwest (*n* = 221)	min	0.043	0.057	ND	ND	ND	0.023	0.002
	max	124	200	1.50	1.26	1.90	54.3	1.02
	median	0.232	0.342	0.053	0.014	0.027	0.498	0.138
	average	2.23	1.48	0.070	0.036	0.050	1.28	0.159
	St. Dev	13.8	13.5	0.107	0.106	0.145	4.62	0.114
southwest (*n* = 132)	min	ND	ND	ND	0.0008	ND	0.086	0.012
	max	124	2.77	0.852	2.17	0.463	11.7	3.13
	median	0.246	0.339	0.057	0.019	0.021	0.674	0.219
	average	1.48	0.375	0.078	0.043	0.033	1.16	0.288
	St. Dev	10.4	0.263	0.081	0.123	0.050	1.530	0.271

[a] St. Dev—standard deviation, ND—not detectable

China Institute of Environmental Science, Ministry of Ecology and Environment.

Sample Preparation and Analysis. The hair samples were washed using the procedure recommended by the IAEA, which entailed washing the samples first with acetone, then three times with ultrapure water, and then acetone again, after which they were freeze-dried to a constant weight without dust.[29]

Preparations of the hair samples for the analysis of metals, except for Hg, were based on the methodologies reported in our previous study,[30] with minor modifications. In brief, exactly 0.1 g of a hair sample was added into a dry, clean microwave digestion tube. Four milliliters of nitric acid (69%, ppt grade; ANPEL Laboratory Technologies (Shanghai) Inc.) and 1 mL of 30% hydrogen peroxide (granted reagent; ANPEL Laboratory Technologies (Shanghai) Inc.) were then added to the sample. The digestion program was conducted as follows: start at 25 °C, ramp to 120 °C in 15 min, hold for 20 min, ramp to 190 °C in 10 min, and hold for 40 min. After cooling to around 25 °C, the digest was diluted to 40 mL with ultrapure water. The levels of Cd, Pb, Sb, As, and Se were analyzed via inductively coupled plasma mass spectrometry (ICP−MS, NexION2000, PerkinElmer).

Analysis of Hg in the hair samples was conducted following the EPA Method 7473 (U.S. Environmental Protection Agency (USEPA), 2007);[31,32] 0.05−0.1 g of precleaned and dry hair was weighed into a ceramic boat and analyzed via thermal decomposition, amalgamation, and atomic absorption spectrophotometry (Hydra-C, Leeman).

Quality Assurance and Quality Control. For the ICP−MS analyses, procedural blanks were prepared along with each batch of hair samples. For the total Hg analyses, the blank level (empty ceramic boat) was always below the limit of detection (LOD). The certified reference material (CRM) of Hg in hair, IAEA-086 (Vienna, Austria), was run for every 20 samples. The recoveries of the CRMs (GBW07601a and IAEA-086) ranged from 81 to 118%, indicating a precision of up to 20%. The LODs of the heavy metals (Cr, Se, As, Cd, Sb, Pb, and Hg) ranged from 0.9 to 85 μg/kg.

Statistical Analysis. Statistical analyses were carried out using IBM SPSS Statistics (version 21.0). More than 90% of the elements analyzed in the hair were above the LOD. Concentrations below the LODs were assigned as half of the LOD (LOD/2) during the statistical analysis. Shapiro−Wilk tests were used to evaluate the normality of the data. The differences in the metals in the hair between any two groups (sex, age, and region) were examined by the Mann−Whitney-*U* test considering the non-normality of the data. Spearman correlation analysis was performed to examine the relationship between the levels of metals and influencing factors such as age, gross domestic product (GDP), population density, the per capita consumption of aquatic products, and car ownerships. The statistical significance was set at $p < 0.05$. Data for the GDP, population density, the per capita consumption of aquatic products, and car ownership of the cities investigated in

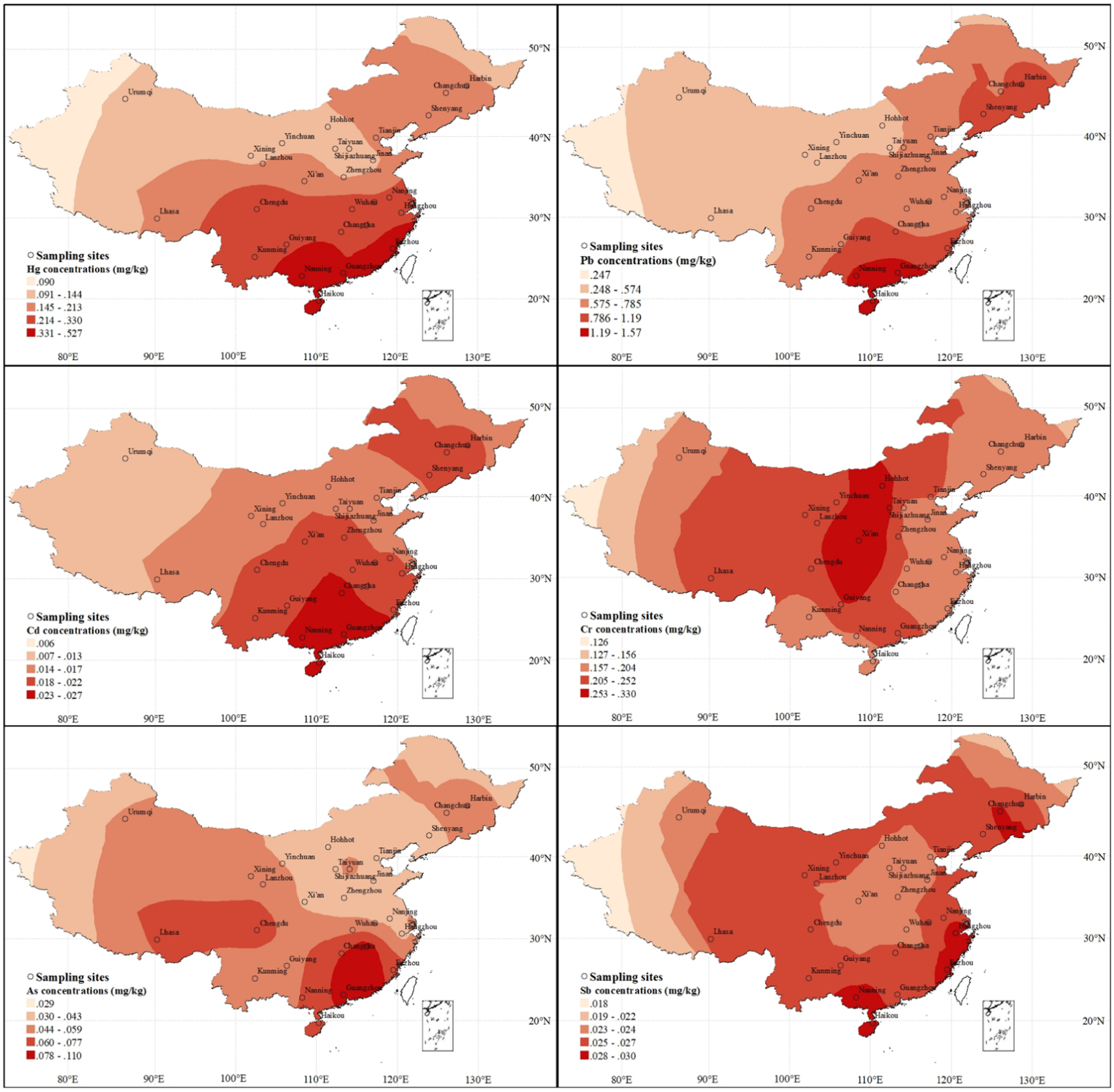

Figure 1. Spatial distribution for estimated levels of heavy metals in human hair in China using the Experience Bayes Kriging method.

this study during 2018−2019 were obtained from the City Statistical Yearbook and the China Statistical Yearbook published by the State Statistics Bureau. The Experience Bayes Kriging method in the Geostatistical Analyst in ArcGIS v.10.3 (ESRI Co., Redlands, USA) was used to evaluate the spatial distribution of the heavy metals measured in the hair of participants from throughout China. The molar ratios of Se to the heavy metals were estimated using the following equation

$$\text{Se/heavy metal molar ratio} = \frac{C_{\text{Se}} \times {\text{Ar}_{\text{Se}}}^{-1}}{C_{\text{h}} \times {\text{Ar}_{\text{h}}}^{-1}}$$

where C_{Se} is the Se concentrations in hair samples (mg/kg); Ar_{Se} is the relative atomic mass of Se; C_{h} is the respective heavy metal concentration in hair samples (mg/kg), and Ar_{h} is the relative atomic mass of the respective heavy metal.

RESULTS AND DISCUSSION

Levels and Spatial Distribution Patterns. The heavy metal concentrations obtained from the analyzed hair samples are presented in Table 2. The average concentrations of the heavy metals in hair decreased in the following order: Pb > Se > Cr > Hg > As > Sb > Cd.

The heavy metal levels obtained in this study were of the same order of magnitude as those in the hair of the general population worldwide (Table S1). However, the average levels of Cr and Pb in the present study were significantly lower than those (average values of 36.9 and 56.2 mg/kg, respectively) obtained from college freshmen in a previous study in China.[33] This is likely because of the difference in age of the sampling group, as Bai et al.[33] sampled hair from college freshmen aged 17−19 years; thus, their results represent solely the exposure to heavy metals of the population in this age group. Moreover, the levels of Cr, Cd, Sb, and Pb in the hair of metropolitan residents in China were considerably lower than those of workers from the metal market and individuals residing near mine waste dumps and smelting districts (Table S1).

Geographically, mainland China is divided into six administrative divisions: Northeast China (NE), North China (NC), Northwest China (NW), East China (EC), South Central China (SC), and Southwest China (SW) (Figure S2). As shown in Figure 1, the concentrations of Hg, Pb, and Cd decreased gradually from SC to NW, with hotspots in Nanning, Guangzhou, Haikou, and Harbin, which is consistent with the spatial distribution of these heavy metals in soil or urban dust.[34,35] Notably, the Cd levels, which differed from Hg and Pb levels, in the hair of residents from Changsha were as high as those form Guangzhou, Nanning, and Haikou. Hunan Province is considered to be historically metal-contaminated, and rice in this region is heavily polluted by Cd due to mining activities.[36] According to a study conducted across 19 provinces in China, the Cd levels in rice exceeded the national limit (0.2 mg/kg) in four provinces, that is, in Hunan, eastern Sichuan, Guangxi, and Anhui.[37] Conformably, participants from these four provinces also had high Cd levels in their hair, as analyzed in this study. Moreover, the Hg levels in SC were significantly higher than those in NC, with the Qinling−Huai River line acting as the boundary ($p < 0.05$). Moreover, a strong significant negative correlation between hair Hg contents with the latitudes of these metropolises was observed ($r = -0.724$, $p < 0.01$).

China is divided by the "Hu Line" into two parts with similar areas of land but a striking contrast in population: the ratio of the population in the northwest to that in the southeast is approximately 6/94.[38] In previous studies, Se deficiency was proven to be one of the essential factors for the etiology of the Kashin−Beck disease (KBD) and the Keshan disease (KD).[39,40] China has the highest incidences of KBD and KD, with cases occurring in more than 300 counties around the "Hu Line," including counties in Heilongjiang, Jilin, Liaoning, Inner Mongolia, Hebei, Shandong, Shanxi, Shaanxi, Gansu, and Sichuan.[41,42] Interestingly, we found that the Se concentration was low around the "Hu Line" (Figure S5), that is, low along the NE−SW area and high on both sides away from the "Hu Line," which was similar to the Se distribution found in soil in China.[40] Furthermore, the Se contents in hair in SC and EC were significantly higher than those in NE and NC ($p < 0.05$), probably because the per capita consumption of aquatic products by the population in SC and EC was higher than that of the population in NE and NC (Table S2), that is, the Se levels were significantly correlated with the per capita consumption of aquatic products (Figure S6). The hair Se concentrations of residents from Sichuan, Yunnan, and Gansu were slightly higher than those of the other provinces around the "Hu Line," which may be due to the Se supplementation in salt, food, and other dietary intakes.

Overall, high concentrations of As were observed in SC, while low concentrations were noted in NC, NW, and NE (Figure 1), which was highly similar to the spatial distribution of As in urban soils across China.[35] Additionally, the distribution of hair As was concentrated in the Jiangxi, Guangdong, eastern Hunan, and western Fujian provinces, similar to the distribution of As in rice.[37]

The distribution of Cr was found to be significantly different from those of the other metals. Specifically, high hair Cr contents were concentrated in the surrounding cities of Shaanxi Province, including Hohhot and Taiyuan, which was similar to the spatial distribution of Cr in urban soils across China.[35] In particular, hair Cr concentrations in Xi'an were markedly higher than those in the other cities ($p < 0.01$). Xi'an has a long history of Cr pollution in groundwater and farmlands, caused by the high levels of Cr in the wastewater from electroplating, iron and steel, dyes, leather making, machinery, and chemical industries.[43]

The spatial distribution of Sb was found to be opposite to that of Cr, with higher levels in EC, NE, SW, and the southern part of SC and lower levels in NC and the northern part of SC, including Xi'an and its surrounding cities. The most abundant Sb resource deposits worldwide are located in China,[44] especially in the Hunan, Guangxi, Yunnan, and Guizhou Provinces, the residents of which also have high levels of Sb in their hair. Moreover, Sb and its compounds have been applied in various industries, such as for the manufacturing of flame retardants (e.g., Sb_2O_3) for plastics and textiles, most of which eventually end up in municipal waste and are released into the atmosphere during combustion.[44] Tian et al.[44] estimated that 61.8% of the total Sb atmospheric emissions originated from coal combustion, followed by nonferrous metal smelting and MSW incineration (26.7 and 7.4%, respectively). Furthermore, according to the China Statistical Yearbook 2020, the number of municipal waste incinerators in EC and SC accounts for more than half of those throughout the country, which may explain the high levels of Sb in the hair of residents from EC and SC.

Both the Pb and Hg levels in hair were significantly correlated with the GDP, population density, and the per capita consumption of aquatic products for individual cities (Figure S3). In particular, the diversity in fish and rice consumption may play a vital role in the spatial distribution of Hg levels in China, along with soil pollution.[9,45] High fish consumption may be the primary source of Hg exposure in Southeast China,[27] whereas rice may be the predominant intake pathway in inland China.[45] Furthermore, Hg mining may also contribute to the high Hg concentrations in SW, such as the Tongren Mercury Mine in Guizhou Province.[34] Our results also revealed a significantly strong pairwise correlation ($r \geq 0.6$, $p < 0.001$) between Cd and Pb (Figure S4), with a similar spatial distribution across China. The same relationship was found in human hair and blood from e-waste recycling, mining, and metal recycling areas.[12−14] Thus, Cd and Pb in human hair likely originate from similar sources, including municipal solid waste and coal combustion,[46] tire wear, lubricating oil, and metal smelting exhaust emissions.[47] Additionally, chronic exposure experiments in mice indicated a synergistic effect of immunosuppression between Cd and Pb.[48] Significant negative relationships were observed between Pb and Fe and between Cd and Fe, which may be related to their similar valence states, such as divalent cations, of Pb and Cd in the human body.[14,49−51]

Overall, the hotspot for heavy metals in human hair was concentrated in SC, an area with a long history of urbanization and industrialization, and aquatic food as an important dietary component.[35,52] A higher content of heavy metals was also found in the soil of SC, as compared with that of NC.[35] Thus, protecting the residents of SC from heavy metal exposure in their daily life, especially for Hg, Pb, As, and Cd, should be a priority.

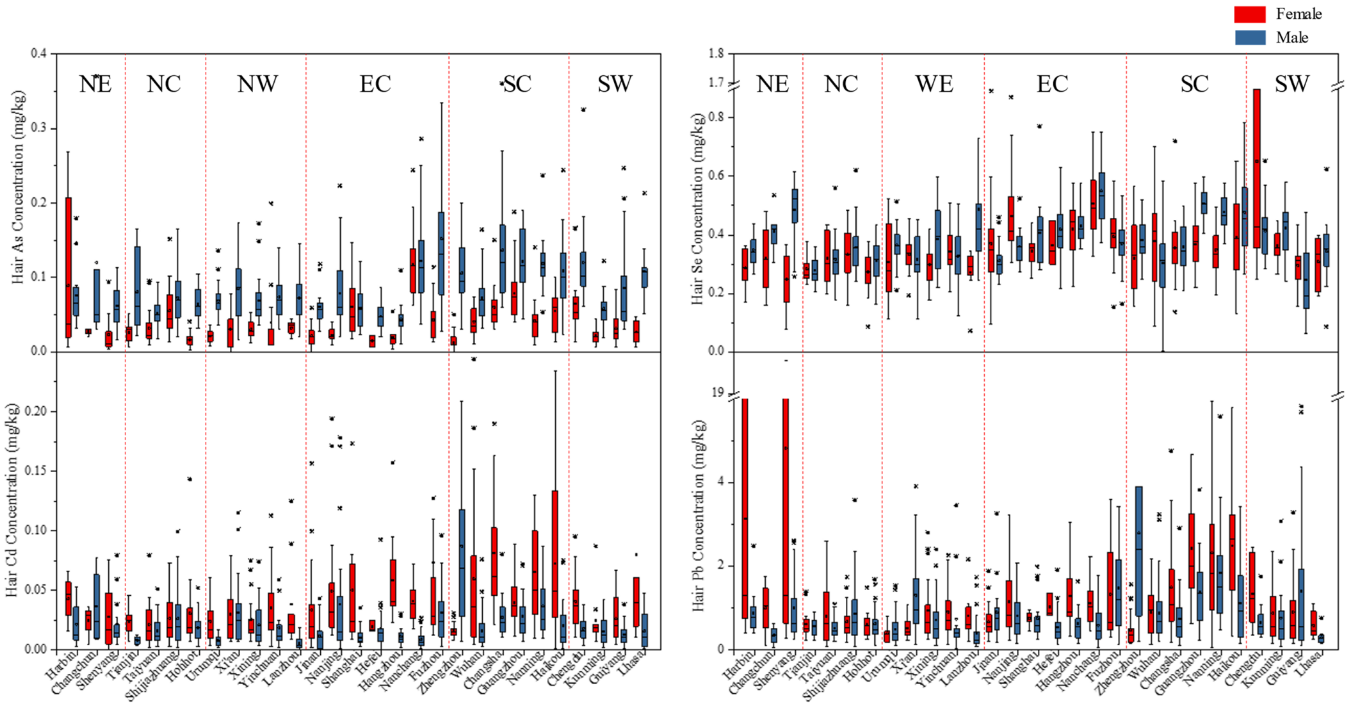

Figure 2. As, Se, Cd, and Pb concentrations in female and male hair in six regions across China.

Potential Impact of Sex and Age. The median concentrations of the analyzed heavy metals in the hair of residents of different sex are given in Table S3. No significant differences related to sex were observed for Hg, Cr, and Sb in the hair of participants from China, which is consistent with the results of previous studies.[53,54]

For all regions, the As levels in the hair of males were significantly higher than those in female hair ($p < 0.001$) (Figure 2), which is in agreement with previous investigations.[10,23] A study from an endemic arsenism area in China found a significantly higher risk of arsenicosis among male than female, which is probably associated with sex-based differences in DNA methylation, arsenic methylation metabolism, basal metabolism, and behavior linked with the metabolism mechanism of As.[55] However, an opposite result was reported for an analysis of the hair of 50 residents from the Pearl River Delta; this was likely because participants with dyed hair were not excluded.[56]

The Se concentrations in male hair for four regions, including NE, NC, NW, and SC, were significantly higher than those in female hair ($p < 0.05$) (Figure 2). At the national level, the Se content in male hair was markedly higher than that in female hair ($p < 0.001$). Likewise, a study conducted from 2018 to 2019 by Li et al.,[57] which aimed to evaluate Se levels in the hair of middle-aged and elderly populations from 15 provinces in China, also found that males had significantly higher levels than females ($p < 0.001$). Additionally, higher levels of Se in the urine of males, as compared to that of females, were also found by Berglund et al.[58]

By contrast, female hair tended to have higher levels of Cd and Pb than male hair in all regions, except for Pb in NC ($p < 0.05$) (Figure 2). This result is in agreement with those of previous studies.[23,59] Similarly, Olsson et al.[51] and Berglund et al.[58] found that female had higher levels of Cd in blood and urine. Biologically, females have proportionately more body fat but lower renal clearance rates than males; hence, they may store relatively more lipophilic metal ions, thus increasing contaminant concentrations,[49] such as that of methylmercury. Moreover, a low Fe^{2+} status enhances the absorption of other ingested divalent cations in female blood, as compared to male blood, including that of Cd.[49−51] Therefore, to protect against heavy metal pollution, it is recommended that female residents take appropriate blood iron supplements. However, other related reports on occupational exposure are contradictory, possibly due to the higher frequency and intensity of outdoor work for males as compared to females.[12,60]

With respect to age, no significant relationship was observed with the heavy metal levels in hair (Table S4); thus, the correlation between the heavy metal content in human hair and age remains controversial.[13] A previous study indicated that heavy metal concentrations in the body increase with age due to a gradual lifelong accumulation[61] because such metals cannot be easily excreted from human bodies. However, other studies found different results, that is, the age of volunteers had no relationship or a negative correlation with the metal concentrations in their hair.[17,51]

Human Health Implications Combined with Heavy Metal Levels and Their Antagonism with Selenium. China has been identified as one of 40 Se-deficient countries.[62] While Se deficiency can cause KBD and KD,[39,40] excessive Se intake can also lead to adverse health effects, such as hair and nail loss, skin lesions, nervous system disorders, paralysis, and even death.[63] In general, most participants (72%) of this study were classified as Se-sufficient, followed by Se-rich, Se-marginal, and Se-deficient (Table S5), consistent with the results of a survey of the middle-aged and elderly Chinese population.[57] In particular, the Se concentrations in the hair of eight participants (0.67%) from EC and NW exceeded 3.00 μg/g, that is, they were classified as Se-excessive. By contrast, approximately 5.6% of volunteers were affected by Se deficiency, higher than the 2.88% reported by Li.[54] Notably, the proportions of Se-deficient residents in NE and SW were

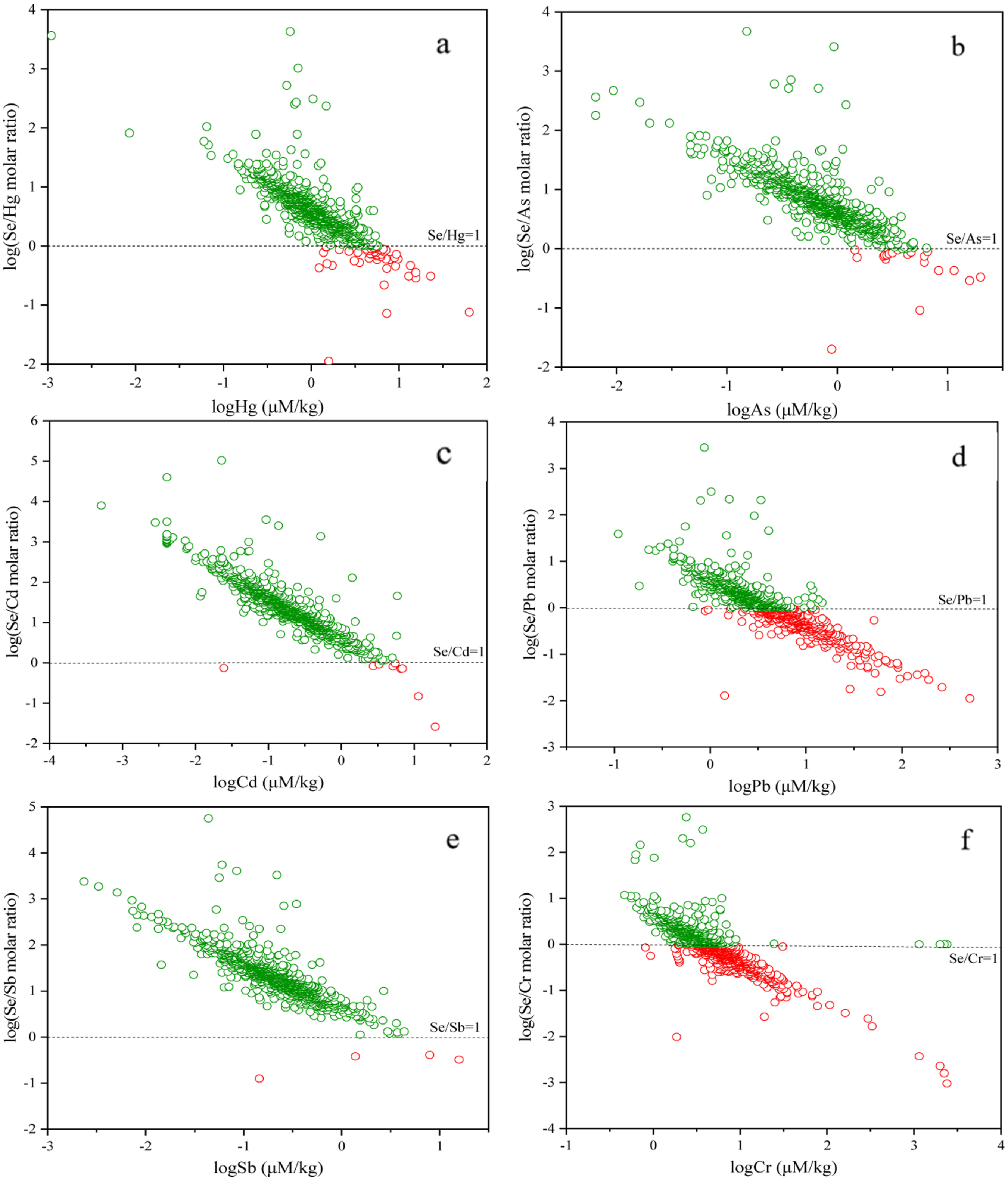

Figure 3. Scatter plot of logarithm of levels of certain heavy metal (*μ*M/kg) and log (Se/certain heavy metal molar ratio) in hair (a,b,c,d,e,f is for Hg, As, Cd, Pb, Sb, and Cr, respectively).

2−10 folds higher than those in other areas. Our results demonstrate the imperativeness for residents in NE and SW around the “Hu Line” to consume sufficient Se supplements daily, while this is not required for residents in EC and NW.

Hg concentrations in the hair of all residents participating in this study were lower than the threshold level for neurotoxic effects (50 mg/kg) established by the World Health Organization (1990)[64] and only 0.5% exceeded the recommended limit (2.0 mg/kg).[27] Only one subject from Fuzhou had a hair Hg level that was more than twice as high (12.5 mg/kg) as the recommendation of Health Canada for Hg levels in the hair (6 mg/kg).[65] When compared to the recommendation of USEPA (1 mg/kg),[66,67] 3.0% of participants had higher Hg levels in hair (Table S6). The fact that hair Hg levels in 81% of participants exceed 1 mg/kg came from SC and EC, revealing that though Hg pollution in the participants was slight, participants from southeastern coastal areas should endeavor to protect themselves against Hg exposure. Furthermore, the Se/Hg molar ratios were >1 for most participants (95.4%) (Figure 3), indicating that most of the metropolitan residents may be less susceptible to the potential neurotoxicity of Hg in the human body. Particularly, 10.5% of those participants with Se/Hg molar ratios < 1 were from SC (Table S7). In the general population, Hg exposure occurs primarily through the consumption of fish and marine mammals.[68] Furthermore, a significant positive correlation was observed between the per capita consumption of aquatic products and Hg concentrations in hair. Thus, residents in southeast coastal areas need to create a scientific and reasonable dietary structure, reducing the intake of aquatic products owing to their high Hg levels and low Se/Hg molar ratios.

In a study by Miekeley et al. in 1998, hair reference intervals for heavy metals were proposed (Table S6).[69] For Cd and Pb, the hair concentrations in most participants were less than the reference intervals for human hair.[69] However, 37.6% of the participants had a Se/Pb ratio < 1, indicating the possibility of Pb toxicity, especially among residents in SC (52.7%). Concentrations of As in hairs of approximately 9.5% of participants exceeded the reference intervals for human hair.[69] However, the Se/As molar ratios were >1 for most participants (98.3%), indicating that As in the human body could be combined with or detoxicated by Se.

Approximately half of the study's participants (42.8 and 34.5%, respectively) had Sb and Cr concentrations in hair exceeding the normal concentration ranges for human hair. Particularly, Sb levels in 81% of the participants from Nanning exceeded the normal concentration range. Thus, metropolitan residents need to be concerned about Sb exposure protection in China, especially the residents of Nanning. Regarding Cr, 98, 76, 72, 60, 54, and 54% of the participants in Xi'an, Taiyuan, Guiyang, Hohhot, Guangzhou, and Hefei, respectively, had Cr levels in hair exceeding the normal concentration range by 2−10 times. Furthermore, 48.3% of the Se/Cr ratios were <1, and the ratio in Xi'an was 100%, suggesting that metropolitan residents in China could possibly face potential health risks due to Cr. Thus, residents across the country need to be aware of the Cr pollution from industrial sources, especially the population of Xi'an.

In summary, metropolitan residents in China are moderately affected by the pollution of heavy metals, especially Sb, Cr, and As, based on the heavy metal concentrations obtained from human hair. Furthermore, the populations in NE and SW are still affected by a Se deficiency. Selenium could combine with and even eliminate a large proportion of the toxicity of Hg, As, Sb, and Cd in most metropolitan residents in China; however, this is not the case for Cr and Pb. Thus, metropolitan residents in China need to stay away from the pollution sources of Sb, Cr, As, and Pb and supplement their diet with foods rich in vitamin C and proteins, such as fruits, milk, and animal liver, which can help detoxify Cr and Pb. With industrial and economic developments and the further urbanization of metropolises across China, it is essential to establish guidelines and reference values for heavy metals in human hair to guide people in distinguishing and evaluating the health risks associated with heavy metals.

Nevertheless, it should be noted that there are several limitations to this study. Human health problems related to heavy metals were not included in the questionnaire; blood or urine samples that paired with hair samples were not collected to analyze the related health indicators either. Further studies are urgent to investigate the correlation between heavy metals in human hair and environmental media, food, and clinical health indicators.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c02001.

> Sampling sites and quantity regional distribution; six geographical subdivisions of China; five sites in a uniformly distributed area were selected randomly for experience Bayes Kriging model validation. interpolation precision of the experience Bayes Kriging model; correlation between human hair metals and index of 29 metropolises; scatter plot and relationship of Cd and Pb concentrations in the hair of residents; spatial distribution of estimated Se concentrations in human hair in China; scatter plot and relationship of the per capita consumption of the aquatic products of each metropolitan and geometric mean concentrations of Hg and Se in hair; comparisons of heavy metals in hair (median/mean and range) in the present study with those reported in other studies (mg/kg); statistics for each sampling points from the City Statistical Yearbook published by The Bureau of Statistics for every city; median concentrations of heavy metals in the hair of participants with different sexes (mg/kg); Spearman correlation between elements and ages; classification of Se levels in participants from different regions across mainland China; proportions of participants with hair heavy metal concentrations exceeding recommended values (%); and proportions of molar ratios of Se/heavy metal exceeding 1 by region, age, and sex (%) (PDF)

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Notes

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