ORIGINAL ARTICLE

Heavy Metals Exposure and Hearing Loss in US Adolescents

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Introduction: Hearing loss is common and, in young persons, can compromise social development and educational achievement. Exposure to heavy metals has been proposed as an important risk factor for hearing loss.

Methods: We evaluated the cross-sectional associations between blood lead, blood mercury, and urinary cadmium and arsenic levels and audiometrically determined hearing loss in participants aged 12 to 19 years in the 2005-2008 National Health and Nutrition Examination Survey after accounting for the complex survey design. There were 2535 individuals available for analysis of blood lead and mercury levels, 878 for urinary cadmium levels, and 875 for urinary arsenic levels. Multivariate logistic regression was used to calculate adjusted odds ratios (ORs) and 95% CIs.

Results: A blood lead level greater than or equal to 2 µg/dL (to convert to micromoles per liter, multiply by 0.0483) compared with less than 1 µg/dL was associated with increased odds of high-frequency hearing loss (OR, 2.22; 95% CI, 1.39-3.56). Individuals in the highest quartile of urinary cadmium levels had significantly higher odds of low-frequency hearing loss than those in the lowest quartile (OR, 3.08; 95% CI, 1.02-9.25). There was no overall association between quartiles of blood mercury or urinary arsenic levels and hearing loss.

Conclusion: Blood lead levels well below the current recommended action level are associated with substantially increased odds of high-frequency hearing loss.

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HEARING LOSS IS A COMMON condition in the US population.[1] While it is highly prevalent in older adults,[2] it is also common in the pediatric age group, with 19.5% of US 6- to 19-year-olds demonstrating evidence of hearing loss.[3] Hearing loss is especially damaging in children, as it can impair the development of communication skills and affect educational experience, psychosocial function, and interpersonal relationships.[4] Even a slight loss (16-24 dB) may have clinical significance, as it can create a need for speech therapy, auditory training, and special accommodations in school-age children.[5]

Multiple ototoxic effects of heavy metals, specifically lead, cadmium, arsenic, and mercury, have been suggested.[6] Studies have also reported a possible association between lead exposure and an increased risk of hearing loss, especially in children.[7,8] In animal models, lead may impair axonal transport, inhibiting auditory processing proximal to the cochlea.[9] Animal studies have demonstrated cochlear toxic effects due to cadmium exposure,[10] and hearing changes have been observed in children who were exposed to environmental arsenic.[11] Also, methyl mercury,[12] dimethyl mercury, and mercuric sulfide[13] have all been shown to affect auditory brainstem responses.

While studies have reported possible associations between these heavy metals and hearing loss, the evidence is inconclusive. There is also a lack of current US nationally representative analyses of possible associations between these heavy metals and hearing loss in adolescents. Since the federally mandated removal of lead from paint, food containers, plumbing, and gasoline in the 1970s,[14] mean blood levels in the United States have decreased dramatically, and most children are now well below the limit of 10 ug/dL (to convert to micromoles per liter, multiply by 0.0483) recommended by the Centers for Disease Control and Prevention[15,16]; therefore, analyses based on current data are especially important for lead exposure. Therefore, we examined the most recent available data on the association between heavy metal exposure and prevalence of hearing loss in US adolescents and young adults aged 12 to 19 years

using the 2005-2006 National Health and Nutrition Examination Survey (NHANES).

METHODS

STUDY POPULATION

The 2005-2006 and 2007-2008 NHANES conducted audiometric examinations on participants aged 12 to 19 years (N = 3389). The NHANES provides nationally representative cross-sectional data on the health status of the civilian, noninstitutionalized US population. After selection using a complex survey design, the participants were interviewed and examined. The design of NHANES has been described previously.[17] Older individuals, Mexican Americans, and Black individuals were intentionally oversampled. Therefore, appropriate sample weights provided by NHANES were used to obtain weighted regression estimates, as per NHANES guidelines,[18] and the final results of our analyses are generalizable to the US population.[19] Protocols to recruit and study participants of NHANES 2005-2008 were reviewed and approved by the National Center for Health Statistics institutional review board.

AUDIOMETRIC MEASURES

For the NHANES audiometric examination, audiometry was conducted in a dedicated sound-isolating room in the mobile examination center by trained examiners using a standardized protocol as provided by the National Center for Health Statistics.[17,20] Testing was conducted according to a modified Hughson-Westlake procedure, a standardized method of testing pure-tone hearing in which the listeners are presented with a signal and the intensity is either increased or decreased in set increments until they signal that they hear it or that they no longer hear it,[21] using the automated testing mode of the audiometer, except in cases in which the hearing thresholds were greater than 100 dB, in which case those frequencies were tested manually.[17] An audiometer was calibrated with the same specifications at the start and end of the testing at each field location. Air conduction thresholds were measured for each ear at 0.5, 1, 2, 3, 4, 6, and 8 kHz across an intensity range of –10 to 120 dB. The 1-kHz frequency was tested twice in each ear as a measure of the reliability of the participant's responses, and the first test response was used in the analyses. Pure-tone audiograms were not accepted if there was a 10-dB or greater difference between the 1-kHz test-retest thresholds. Participants using hearing aids who were not able to remove them for testing or those who had sufficient ear pain that they could not tolerate headphones at the time of the examination were excluded from the audiometry component.

In the 2005-2006 and 2007-2008 NHANES cycles, a crossover retesting protocol was performed whenever the observed threshold at any given frequency was poorer in one ear than the other by 25 dB at 0.5 and 1 kHz or at 40 dB at any higher frequency. Retesting was accomplished using insert earphones, which are smaller and have less direct contact with the head; therefore, a much louder stimulus was required before crossover occurred.

Consistent with previous investigations of hearing in this age group, the low-frequency pure-tone average (LPTA) was obtained by the average of air conduction pure-tone thresholds at 0.5, 1, and 2 kHz, and the high-frequency pure-tone average (HPTA) was obtained by the average of air conduction pure-tone thresholds at 3, 4, 6, and 8 kHz.[22] Low-frequency hearing loss was defined as an LPTA greater than 15 dB in either ear, and high-frequency hearing loss was defined as an HPTA greater than 15 dB in either ear. Any hearing loss was defined as an LPTA or an HPTA greater than 15 dB in either ear. Further, low- and high-frequency hearing losses were characterized as either unilateral or bilateral, mutually exclusive categories. These definitions have been used previously in studies of NHANES audiometric data.[2,22-24]

HEAVY METAL EXPOSURE

Blood Lead and Mercury

Whole-blood specimens were processed, stored, and shipped to the Division of Laboratory Sciences, National Center for Environmental Health, Centers for Disease Control and Prevention for analysis. Vials were stored under appropriate frozen (–20°C) conditions until they were shipped to the National Center for Environmental Health for testing. Whole-blood lead and mercury concentrations were determined using inductively coupled plasma mass spectrometry. In cases in which the result was below the limit of detection, the value for that variable was the detection limit divided by the square root of 2.[17]

Urinary Cadmium and Arsenic

Urinary heavy metals were measured in the 2005-2006 and 2007-2008 NHANES in one-third of participants aged 6 years and older. All urine specimens were processed, stored, and shipped to the Division of Laboratory Sciences, National Center for Environmental Health, Centers for Disease Control and Prevention for analysis. Vials were stored under appropriate frozen (–20°C) conditions until they were shipped to National Center for Environmental Health for testing. Urinary cadmium concentrations were determined using inductively coupled plasma mass spectrometry, and arsenic concentrations were determined using inductively coupled dynamic reaction cell mass spectrometry. In both techniques, liquid samples pass through a mass spectrometer that uses electrical properties of the metals to calculate the concentration of the metals in the urine.[18] In cases in which the urinary heavy metal measurements were below the limit of detection, the value for that variable was the detection value divided by the square root of 2.[17] All urinary heavy metal concentrations were corrected for urinary creatinine concentration (micrograms per gram of creatinine).

Demographic and Hearing-Related Covariates

Age was categorized as 12-13, 14-15, 16-17, and 18-19 years old. Race-ethnicity was grouped as non-Hispanic black, non-Hispanic white, or Hispanic American (including responses of "Mexican American" or "other Hispanic"). The "other" race-ethnicity category was too small to be analyzed separately but was included in the overall estimates. The poverty-income ratio (PIR) was defined as the total family income divided by the poverty threshold, as determined by the US Bureau of the Census, for the year of the interview. The PIR values of less than 1 were below the official poverty threshold, whereas those of 1.00 or greater indicated income at or above the poverty level.[19] Participants were also asked whether they had ever had 3 or more ear infections and whether they had ever been exposed to steady loud noise or music for 5 or more hours in a week, either in a job or outside of a job. Smoking history was assessed as having ever tried smoking cigarettes or having anyone who smokes in the home, as both types of exposures to cigarette smoke have been shown to be associated with hearing loss.[25,26] If the response to either question was yes, then that individual was counted as having a positive smoking history. Responses were categorized into yes, no, and missing.

Table 1. Heavy Metal Exposure and Demographic Characteristics in US Adolescents and Young Adults Aged 12 to 19 Years, National Health and Nutrition Examination Survey, 2005-2008

Variable	Mean[a] (95% CI)							
	Blood Lead, µg/dL (n = 2535)[b]	*P* Value[c]	Blood Mercury, µg/L (n = 2535)[b]	*P* Value[c]	Urinary Cadmium,[d] µg/g of Creatinine (n = 878)[b]	*P* Value[c]	Urinary Arsenic,[d] µg/g of Creatinine (n = 875)[b]	*P* Value[c]
Age, y								
12-13[e]	1.00 (0.92-1.09)		0.59 (0.51-0.66)		0.08 (0.07-0.09)		8.36 (6.95-9.77)	
14-15	0.93 (0.87-0.99)	0.12	0.72 (0.59-0.84)	.04	0.09 (0.08-0.11)	.05	9.70 (6.88-12.52)	.42
16-17	0.85 (0.79-0.91)	<.01	0.76 (0.66-0.86)	<.01	0.09 (0.08-0.09)	.79	8.16 (6.13-10.19)	.85
18-19	0.93 (0.84-1.03)	0.21	0.85 (0.75-0.96)	<.01	0.09 (0.09-0.10)	.01	9.06 (7.53-10.58)	.46
Sex								
Male[e]	1.08 (1.00-1.17)		0.72 (0.63-0.80)		0.08 (0.07-0.09)		8.54 (7.13-9.95)	
Female	0.75 (0.71-0.80)	<.01	0.75 (0.66-0.84)	.46	0.10 (0.09-0.11)	<.01	9.18 (7.43-10.93)	.54
Race								
Non-Hispanic white[e]	0.84 (0.78-0.90)		0.68 (0.60-0.77)		0.08 (0.07-0.09)		8.22 (6.57-9.87)	
Non-Hispanic black	1.08 (0.92-1.24)	0.01	0.67 (0.59-0.74)	.74	0.10 (0.09-0.11)	.03	9.45 (7.13-11.77)	.40
Hispanic	1.02 (0.91-1.13)	0.01	0.62 (0.53-0.71)	.30	0.11 (0.09-0.13)	.01	8.22 (6.83-9.60)	.99
Poverty-income ratio								
≥1[e]	0.86 (0.82-0.91)		0.72 (0.64-0.79)		0.09 (0.08-0.09)		8.41 (7.09-9.74)	
<1	1.12 (1.00-1.24)	<.01	0.79 (0.69-0.88)	.19	0.10 (0.09-0.10)	.11	10.31 (7.96-12.65)	.17
Loud noise exposure								
No[e]	0.91 (0.85-0.97)		0.74 (0.66-0.82)		0.09 (0.08-0.10)		9.17 (7.66-10.68)	
Yes	0.96 (0.87-1.05)	0.28	0.72 (0.62-0.82)	.73	0.09 (0.08-0.09)	.74	8.19 (6.76-9.63)	.07
History of ≥3 ear infections								
No[e]	0.98 (0.92-1.04)		0.75 (0.67-0.83)		0.09 (0.09-0.10)		8.84 (7.29-10.40)	
Yes	0.84 (0.78-0.90)	<.01	0.71 (0.61-0.81)	.25	0.08 (0.07-0.09)	.23	8.87 (7.11-10.64)	.98
Smoking history								
No[e]	0.89 (0.84-0.94)		0.69 (0.63-0.67)		0.09 (0.08-0.10)		8.17 (6.76-9.59)	
Yes	0.96 (0.89-1.03)	.03	0.78 (0.68-0.87)	.06	0.09 (0.09-0.10)	.87	9.68 (7.58-11.78)	.26

SI conversion factors: To convert lead values to micromoles per liter, multiply by 0.0483; mercury to nanomoles per liter, multiply by 4.985.
[a] All mean values are weighted to be nationally representative of the US population.
[b] Unweighted number of participants.
[c] All *P* values represent comparisons with the reference groups.
[d] All urinary values are creatinine corrected.
[e] Reference group.

Analytic Sample

Of the 3389 twelve- to nineteen-year-old individuals who were eligible for audiometric testing from 2005 through 2008, a total of 854 were excluded because of an incomplete examination, missing frequency values, or a 10-dB or greater difference between the 1-kHz test-retest thresholds; therefore, 2535 participants were available for analysis. Those participants who underwent testing for the specified heavy metal were included in the analyses for that specific metal. Therefore, 2535 individuals were available for analysis of blood lead and mercury concentrations, 878 for urinary cadmium concentrations, and 875 for urinary arsenic concentrations. Participants with incomplete data did not differ in age, sex, race-ethnicity, or PIR from participants with complete data.

STATISTICAL ANALYSES

We calculated the mean heavy metal exposure measurements with 95% CIs for the individual demographic categories for US 12- to 19-year-olds participating in the NHANES 2005-2006 and 2007-2008 survey cycles. The prevalence of hearing loss (any, low frequency, high frequency) was calculated for each quartile of the individual metal exposure. Multivariate logistic regression was performed for each of the metals independently, with age, sex, race-ethnicity, PIR, history of 3 or more ear infections, loud noise exposure, and smoking as covariates and any low- or high-frequency hearing loss as the outcome. Because of the recent proposal to lower the blood lead action level in the United States from 10 to 2 µg/dL[27] (to convert to micromoles per liter, multiply by 0.0483), multivariate analyses were performed with categorical variables of blood lead values (<1, 1-1.99, and ≥2 µg/dL). All *P* values were 2-sided. Data analysis was performed using SAS version 9.2 (SAS Institute).

RESULTS

The demographic and heavy metal exposure characteristics of US adolescents and young adults aged 12 to 19 years are shown in the **Table 1**. Blood lead levels were significantly higher in males, individuals of non-Hispanic black and Hispanic ethnicity, and individuals from families living below the national poverty level. Blood mercury levels increased with age (*P* for trend, <.01). Urinary cadmium levels were highest in females and Hispanic individuals. No significant differences were observed for urinary arsenic exposure among the different demographic categories.

The percent prevalence of hearing loss for each quartile of exposure for the individual heavy metals is presented in **Table 2**, which also shows the multivariate

Table 2. Multivariate Analysis of the Association Between Heavy Metal Exposure and Hearing Loss in US Adolescents and Young Adults Aged 12 to 19 Years in the National Health and Nutrition Examination Survey, 2005-2008[a]

		Hearing Loss					
		Any >15 dB		High-Frequency		Low-Frequency	
Quartile	Median	Prevalence, %	Multivariate OR (95% CI)	Prevalence, %	Multivariate OR (95% CI)	Prevalence, %	Multivariate OR (95% CI)
Blood lead level, µg/dL							
1	0.47	20	1 [Reference]	17	1 [Reference]	9	1 [Reference]
2	0.67	19	0.87 (0.58-1.30)	17	0.69 (0.37-1.30)	7	0.78 (0.52-1.18)
3	0.94	20	1.18 (0.81-1.74)	16	0.68 (0.38-1.20)	9	0.98 (0.57-1.69)
4	1.59	23	1.26 (0.83-1.91)	20	1.29 (0.72-2.10)	12	1.32 (0.74-2.34)
Blood mercury level, µg/L							
1	0.20	25	1 [Reference]	21	1 [Reference]	13	1 [Reference]
2	0.39	23	0.90 (0.57-1.43)	19	0.92 (0.62-1.38)	9	0.70 (0.35-1.43)
3	0.63	17	0.64 (0.38-1.08)	15	0.71 (0.48-1.05)	8	0.58 (0.24-1.38)
4	1.28	17	0.65 (0.34-1.24)	14	0.67 (0.34-1.23)	7	0.54 (0.24-1.20)
Urinary cadmium level,[b] µg/g of creatinine							
1	0.04	14	1 [Reference]	13	1 [Reference]	6	1 [Reference]
2	0.07	22	1.63 (0.80-3.34)	19	1.46 (0.70-3.03)	14	2.47 (0.93-6.56)
3	0.10	20	1.59 (0.74-3.42)	15	1.23 (0.50-3.02)	8	1.42 (0.62-3.27)
4	0.15	22	1.88 (0.83-4.27)	17	1.53 (0.71-3.27)	15	3.08 (1.02-9.25)
Urinary arsenic level,[b] µg/g of creatinine							
1	2.8	24	1 [Reference]	21	1 [Reference]	12	1 [Reference]
2	4.29	18	0.71 (0.36-1.44)	13	0.56 (0.32-1.0)	13	1.18 (0.50-2.77)
3	6.33	14	0.57 (0.35-0.93)	13	0.58 (0.34-0.96)	8	0.68 (0.31-1.49)
4	14.75	21	0.95 (0.53-1.73)	18	0.94 (0.51-1.72)	10	0.87 (0.41-1.85)

Abbreviation: OR, odds ratio.
SI conversion factors: To convert lead values to micromoles per liter, multiply by 0.0483; mercury to nanomoles per liter, multiply by 4.985.
[a] Multivariate analyses are adjusted for age, sex, race, poverty-income ratio, history of 3 or more ear infections, loud noise exposure, and smoking.
[b] All urinary values are creatinine corrected.

Table 3. Multivariate Adjusted Odds Ratios (ORs) for Blood Lead Levels and Hearing Loss in US Adolescents and Young Adults Aged 12 to 19 Years in the National Health and Nutrition Examination Survey, 2005-2008[a]

	Hearing Loss								
	Any >15 dB			High-Frequency			Low-Frequency		
Blood Lead Level, µg/dL (% of Population)	Prevalence, %	Univariate OR (95% CI)	Multivariate OR (95% CI)	Prevalence, %	Univariate OR (95% CI)	Multivariate OR (95% CI)	Prevalence, %	Univariate OR (95% CI)	Multivariate OR (95% CI)
<1 (73.5)	17	1 [Reference]	1 [Reference]	13	1 [Reference]	1 [Reference]	9	1 [Reference]	1 [Reference]
1-1.99 (21.1)	20	1.18 (0.82-1.69)	0.99 (0.67-1.46)	19	1.58 (1.13-2.21)	1.20 (0.80-1.80)	9	1.27 (0.85-1.88)	1.24 (0.82-1.86)
≥2 (5.4)	31	2.07 (1.41-3.04)	1.95 (1.24-3.07)	28	2.31 (1.49-3.56)	2.22 (1.39-3.56)	8	1.08 (0.57-2.02)	1.13 (0.61-2.07)

Abbreviation: OR, odds ratio.
SI conversion factor: To convert lead values to micromoles per liter, multiply by 0.0483.
[a] Multivariate analyses are adjusted for age, sex, race, poverty-income ratio, history of 3 or more ear infections, loud noise exposure, and smoking.

odds ratios (ORs) of the association between exposure and hearing loss risk for blood lead and mercury and creatinine-corrected urinary cadmium and arsenic levels. There were no significant associations between the individual quartiles of lead, mercury, or arsenic exposure and any high- or low-frequency hearing loss risk. Although there were no significant associations between urinary cadmium levels and any or high-frequency hearing loss, there was a significantly increased OR for the fourth quartile (OR, 3.08; 95% CI, 1.02-9.25) and low-frequency hearing loss. However, a dose response was not observed (*P* for trend, .13).

The relationship between categories of blood lead level and risk of hearing loss is shown in **Table 3**. Compared with individuals with blood lead levels of less than 1 µg/dL, individuals with blood lead levels of 2 µg/dL or higher had significantly increased odds of any hearing loss (OR, 1.95; 95% CI, 1.24-3.07); however, this increase was attributable to the association with high-frequency hearing loss (OR, 2.22; 95% CI, 1.39-3.56). No significant associations were observed between blood lead levels and low-frequency hearing loss.

To examine whether the relationship between blood lead categories and hearing loss varied by sex, PIR, history of loud noise exposure, or smoking, further analyses that were stratified by these factors were performed (data not shown). Although significant associations of greater magnitude were observed between the odds of

hearing loss and blood lead levels greater than or equal to 2 µg/dL in individuals with a PIR less than 1 (OR, 2.23; 95% CI, 1.21-4.12) compared with those with a PIR greater than 1 (OR, 1.32; 95% CI, 0.56-3.15) and in individuals with no history of loud noise exposure (OR, 2.16; 95% CI, 1.30-3.59) compared with those with a history of loud noise exposure (OR, 0.72; 95% CI, 0.23-2.21), there were no significant interactions between the odds of any hearing loss and categories of blood lead levels and sex (*P* for interaction, .33), PIR (*P* for interaction, .22), noise exposure history (*P* for interaction, .21), or smoking history (*P* for interaction, .38).

COMMENT

The odds of any hearing loss and high-frequency hearing loss were nearly double in individuals with a blood lead level greater than or equal to 2 µg/dL compared with those with a blood lead level less than 1 µg/dL. No association between quartiles of blood lead, blood mercury, or urinary creatinine-corrected cadmium or arsenic measurements and hearing loss was observed in the 2005-2008 NHANES. While urinary cadmium levels were associated with increased odds of low-frequency hearing loss in the highest quartile, there was no overall trend.

Hearing loss is a prevalent and potentially disruptive condition. In adolescents, even a slight change in the hearing threshold can impair learning and speech understanding.[28] In school-age individuals, hearing loss can affect learning, speech perception, social skill development, and self-image.[4] Although definitions of hearing loss have not been standardized among all investigations,[29] the 15-dB threshold has been used to define hearing loss consistently in studies of children and young adults.[3,22,23,30]

Lead, mercury, cadmium, and arsenic are the most commonly encountered toxic heavy metals.[6] Even trace amounts of these metals have been associated with various adverse health effects.[17,31] Numerous past studies have evaluated possible associations between heavy metal exposure and hearing loss. Cadmium has been shown to be toxic to rat cochlear cells, even at very low doses of exposure.[10] Likewise, mercury and arsenic exposure have demonstrated cochlear toxic reactions in animal models[32,33] as well as in certain exposed human populations.[11,12] Methyl mercury, dimethyl mercury, and mercuric sulfide may delay auditory brainstem evoked potentials in children. Our study used blood levels of total mercury, a measure of recent exposure to both organic and inorganic mercury. People are exposed to methyl mercury through fish consumption and to inorganic and elemental mercury from occupational exposures, latex-based paints, dental amalgams, mercury spills, ethnic folk medicine, or religious objects. The mercury assay used in NHANES assesses only the current body burden of the heavy metal as influenced by recent exposure. Longer-term mercury exposure would be better measured by mercury levels in hair. Likewise, spot urinary cadmium only measures recent exposure, and a 24-hour urine collection would better assess long-term exposure. However, neither of these values was measured in NHANES.

Our study, however, did not identify a significant overall association between increased levels of blood mercury or urinary arsenic and hearing loss, and it identified a significant association only between the highest quartile of urinary cadmium levels and low-frequency hearing loss. A possible reason for the difference between our findings and those of previous studies is that, while plausible biologic mechanisms explain the possible toxic reactions of these substances to the human cochlea, the levels of exposure of US adolescents may not have a significant effect on hearing function. The mean urinary cadmium level measured in the general US population, for example, is more than twice as high as in the adolescent age group.[31] Likewise, data encompassing pediatric and adult age groups have demonstrated that measurements of cadmium, mercury, and arsenic all increase with age.[31] A cumulative effect of heavy metal exposure on hearing ability may also exist, which may not have been detected in this study. Another possibility is that the biologic effects of these heavy metals may not be significant in the adolescent age group. The effects may be more clinically significant in younger children, or there may be a lag time between exposure and clinically apparent outcomes, whereas the effects of exposure may not be apparent until later in adulthood. Exposure to heavy metals may also have a greater effect on hearing when it occurs at certain critical periods of development, such as early childhood. Human studies that have shown significant associations between mercury or arsenic levels and hearing loss have focused on children younger than those in our study.[11,12] To our knowledge, this study is the first to analyze the associations between cadmium, mercury, and arsenic exposure and hearing loss in a US nationally representative sample of adolescents and young adults.

Lead exposure, especially in childhood, has been shown to affect multiple organ systems. While the current Centers for Disease Control and Prevention–defined blood lead action level for children is 10 µg/dL, there is evidence that much lower levels may be associated with adverse cognitive and neurologic effects.[27,34] As 2 µg/dL has been proposed as the new blood lead action limit,[27] we evaluated whether blood lead levels equal to or greater than 2 µg/dL were associated with hearing loss in US adolescents. Although our study demonstrated no association between quartiles of blood lead levels and hearing loss, our findings may be attributable to low blood lead levels in even the highest quartile. A blood lead level of 2 µg/dL or greater, however, was significantly associated with high-frequency hearing loss. Notably, high-frequency hearing loss is likely to indicate acquired sensorineural hearing loss in this age group.[35] Therefore, the results of the blood lead analyses in our study are consistent with previous studies that have demonstrated neurotoxic effects from lead at low levels.

The strengths and limitations of this study should be considered. Data from NHANES are comprehensive and nationally representative, drawing from a large and diverse sample of participants. The NHANES audiomet-

ric assessment of hearing loss is the criterion standard objective measure and has been shown to be reliable in numerous studies.[2,22,36] However, because of the cross-sectional methodology of this study, causality with respect to risk factors for hearing loss cannot be determined. Also, because only one-third of the participants underwent urine testing for cadmium and arsenic, the number of individuals available limited the range of heavy metal exposure values available for analysis. Although blood lead levels have a relatively short half-life of approximately 30 days, they are the accepted measure of assessing current lead exposure.[37] The single spot measurement of urinary cadmium adequately reflects the chronic total body burden, but such analyses of arsenic levels more accurately reflect recent exposure; longer-term exposures are better measured by 24-hour urinary arsenic levels, but these were not available.[38] Likewise, longer-term mercury levels may be better measured by mercury levels in hair.[39] It is also possible that higher levels of exposure to cadmium and arsenic than those available for our analyses may have ototoxic effects. Although we included the known potential risk factors for hearing loss in the analyses, the data on risk factors for adolescent hearing loss are currently limited, and other confounders may exist that were not included in our multivariate models.

In conclusion, measurements of blood mercury and urinary arsenic exposure were not associated with hearing loss in US adolescents and young adults. The highest quartile of urinary cadmium was associated with increased odds of low-frequency hearing loss. Blood lead levels greater than or equal to 2 µg/dL were significantly associated with increased odds of high-frequency hearing loss. Blood lead levels that are currently under the action level for children's exposure may increase the risk of hearing loss; therefore, the acceptable level of blood lead in adolescents may need to be reevaluated.

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