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Association between heavy metal exposure and pregnancy loss: evidence from NHANES 2011–2016

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Abstract

Objective Previous research suggests that heavy metal exposure may lead to pregnancy loss, but findings have varied. This study focuses on examining the relationship between heavy metal exposure (manganese, selenium, cadmium, lead, mercury) and pregnancy loss.

Methods Utilizing data from the 2011–2016 National Health and Nutrition Examination Survey (NHANES), this study included women between 20–80 years with complete pregnancy history, heavy metal exposure data, and covariate information. Pregnancy loss was self-reported by participants. Blood levels of manganese, selenium, cadmium, lead, and mercury were measured using mass spectrometry. Logistic regression, smooth curve fitting, and weighted quantile sum (WQS) regression were employed to investigate the association between heavy metal exposure and pregnancy loss. Subgroup analyses were conducted to verify the heterogeneity of the results.

Results A total of 3623 eligible women were included, with 1607 reporting pregnancy loss. Blood mercury levels were positively correlated with a higher risk of pregnancy loss (odds ratio 1.06, 95% confidence interval 1.03–1.09, $P < 0.001$), which remained significant in the two adjusted models. A nonlinear association between mercury levels and pregnancy loss was identified. The heterogeneity in this association was influenced by race, education level, body mass index, and age at menarche. No significant links were detected between pregnancy loss and cadmium, lead, manganese, and selenium. WQS regression highlighted the critical role of mercury in pregnancy loss.

Conclusion Mercury exposure may contribute to a higher risk of pregnancy loss. Reducing heavy metal pollution and minimizing mercury exposure could potentially help improve pregnancy outcomes.

Keywords Pregnancy loss, Miscarriage, Stillbirth, Heavy metal exposure, Toxic element, Mercury

Introduction

Pregnancy loss refers to fetal death at any stage during pregnancy and primarily includes miscarriage, stillbirth, ectopic pregnancy, and pregnancy termination [1]. It is estimated that approximately 15% of pregnancies globally end in miscarriage [2], and about 2.7 million stillbirths occur annually [3]. This not only has a profound impact on individual mental health and family harmony but also imposes significant economic burdens on society [2]. The causes of pregnancy loss are complex and diverse, including genetic, anatomical, endocrine, infectious, and environmental factors [4].

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Environmental factors, particularly heavy metal pollution, have gained increasing attention in the investigation of pregnancy loss causes. With rapid economic development and intensified industrialization, heavy metal pollution has become a major public health concern worldwide. Natural and human activities have significantly increased the release of heavy metals into the air, soil, and water, leading to their accumulation in living organisms through the food chain due to their resistance to biodegradation [5, 6]. In developing countries, people are more likely to be exposed to heavy metals, posing serious health threats [7].

Heavy metals can be categorized as either essential (manganese, selenium) or non-essential (cadmium, lead, mercury). Manganese acts as an enzymatic cofactor, participating in diverse metabolic processes [8]. Selenium is a key component of selenoproteins, crucial for maintaining redox homeostasis [9]. However, excessive intake of these metals can also lead to health effects. Studies have reported that overexposure to selenium or manganese may increase risks of pregnancy complications and infant morbidity [10–12]. In contrast, non-essential heavy metals have no physiological functions but exert toxic effects. First, they strongly bind to sulfur- or oxygen-containing functional groups [13], competing with essential metals for active sites in metalloenzymes, thereby impairing enzymatic activity and disrupting normal metabolic functions [14–17]. Second, these metals induce oxidative stress by depleting glutathione and generating reactive oxygen species, which synergistically impair mitochondrial function and cellular stress responses [18]. This oxidative damage not only disrupts the energy supply but also promotes inflammation and cell death [19]. Third, non-essential heavy metals act as endocrine disrupters by mimicking or antagonizing endogenous hormones through nuclear receptor binding, inhibiting steroidogenic enzymes, and altering hypothalamic-pituitary-gonadal axis signaling via inflammatory cytokine release [20]. This endocrine interference contributes to increased follicular atresia and decreased secondary follicles and corpora lutea [21], severely impairing female reproductive health [22, 23]. Fourth, emerging evidence also implicates that exposure to non-essential heavy metals can induce epigenetic modifications, leading to aberrant gene expression patterns that undermine cellular homeostasis [24]. Collectively, these toxic mechanisms contribute to a wide range of health issues, including neurotoxicity [25], nephrotoxicity [26], hepatotoxicity [27], cardiovascular diseases [28], and reproductive dysfunction [29].

Several previous observational studies have demonstrated the link between elevated concentrations of lead, cadmium, mercury, manganese, and selenium in blood and placenta and the increased risk of pregnancy loss [30–35]. However, some studies have reported inconsistent findings using blood and urine samples [36–39]. The heterogeneity of these results may be due to differences in sample selection, small sample sizes (ranging from 64 to 501 participants), and failure to account for confounding factors. Given these limitations, we aimed to clarify the relationship between blood levels of these metals and pregnancy loss by leveraging the extensive dataset from the National Health and Nutrition Examination Survey (NHANES).

Methods

Data source and participants

All data were obtained from the NHANES public database (https://wwwn.cdc.gov/nchs/nhanes/Default.aspx). We analyzed data from three survey cycles: 2011–2012, 2013–2014, and 2015–2016. This study was approved by the National Center for Health Statistics Research Ethics Review Board, and informed consent was obtained from all participants (Protocol #2011–17). Initially, 29,902 participants aged 20 to 80 years were considered for this study. We excluded males ($n=14{,}751$), individuals younger than 20 years ($n=6348$), currently pregnant women ($n=136$), those with missing pregnancy data ($n=2865$), and those with missing heavy metal exposure data ($n=2179$). Ultimately, 3623 participants with complete data were involved. Figure S1 illustrates the study population selection procedure.

Exposure variables

Blood levels of cadmium, lead, manganese, mercury, and selenium were used as exposure variables. Blood samples were collected at mobile examination centers (MECs) and analyzed using mass spectrometry. A small portion of blood was extracted from a larger blood sample using anticoagulant tubes. Multiple aliquots were taken to obtain a homogeneous mixture. Samples containing clots or microclots were discarded to maintain consistency in testing. During analysis, the mixed sample was ionized using an electrospray ionization source and then transformed into argon gas. The first and second quadrupole mass filters were then used to detect the gas sequentially, and the mass-to-charge ratios of the heavy metals were measured and transformed into blood concentrations. Detailed testing procedures can be found at https://wwwn.cdc.gov/nchs/data/nhanes/public/2011/labmethods/pbcd_g_met_blood-metals.pdf.

Outcome variables

Pregnancy loss is defined as the cessation of pregnancy at any stage, encompassing miscarriage, stillbirth, and elective pregnancy termination. It was evaluated through self-reported reproductive health outcomes obtained

during computer-assisted personal interviews at MECs. Participants responded to two key questions: (1) How many times have you been pregnant? This includes current pregnancies, live births, miscarriages, stillbirths, ectopic pregnancies, and other pregnancies. (2) How many of these pregnancies resulted in live births? Pregnancy loss was confirmed if the reported number of pregnancies exceeded the number of live births by at least one in non-pregnant individuals. For further analysis, participants were categorized into two groups: pregnancy loss and non-pregnancy loss.

Covariates

According to the NHANES data available, this study included the following covariates: (1) demographic information, encompassing age, race, education level, marital status, and the ratio of family income to poverty (PIR); (2) pregnancy-related information, including age at first live birth, age at last live birth, number of pregnancies, number of live births, number of vaginal deliveries, number of cesarean sections, age at menarche, and history of female hormone use; (3) lifestyle behaviors, including drinking status and smoking status; and (4) clinical characteristics, including body mass index (BMI), hypertension history, and diabetes history.

Statistical analysis

Categorical baseline characteristics were compared using the Chi-square test. For continuous variables, the mean and standard deviation (SD) were reported if the data followed a normal distribution, while the median and interquartile range (IQR) were reported for skewed distributions. Differences between groups of continuous variables were compared using either the *t*-test or the Kruskal–Wallis H test, depending on the distribution.

To investigate potential co-exposure trends among blood heavy metals, Pearson correlation analysis was conducted, with results presented in the form of a heatmap. Logistic regression analysis was utilized to assess the independent associations between blood levels of cadmium, lead, manganese, mercury, and selenium, and the risk of pregnancy loss. Results were presented as odds ratios (OR) with 95% confidence intervals (CI). To adjust for confounding variables, two multivariable-adjusted models were constructed. Model I adjusted for age, while Model II adjusted for age, age at last live birth, race, education level, marital status, age at menarche, drinking status, and smoking status. Heavy metals significantly associated with pregnancy loss in the logistic regression models were further stratified into tertiles to explore their relationship with pregnancy loss. A smoothed fitted curve was then plotted to examine the potential linear or nonlinear associations between heavy metals and pregnancy. If a nonlinear relationship was observed, a likelihood ratio test was employed to determine any threshold effect. Additionally, a weighted quantile sum (WQS) regression analysis was utilized to evaluate the overall co-exposure effect of the five blood heavy metals on pregnancy loss risk and the contribution weights of each heavy metal component. Finally, subgroup analyses were performed based on age, race, education level, marital status, PIR, BMI, drinking status, smoking status, age at menarche, history of female hormone use, hypertension history, and diabetes history.

Multiple imputations were adopted to address missing covariate data. The sample size for this study was determined based on the data provided by NHANES, without prior statistical estimation. All statistical analyses were carried out using R software (v4.3.2) and EmpowerStats (v4.2), with a two-sided P value < 0.05 considered statistical significance.

Results

Baseline characteristics

Table 1 presents the characteristics of the participants. We finally included 3623 female participants aged between 20 to 80 years, of whom 1607 had experienced pregnancy loss, accounting for 44.36% of the total sample. Women with pregnancy loss had higher age at last live birth, number of pregnancies, number of vaginal deliveries, and number of cesarean sections than those without pregnancy loss. Statistically significant differences were found between the pregnancy loss group and the non-pregnancy loss group regarding age, race, education level, marital status, age at last live birth, number of pregnancies, age at menarche, drinking status, and smoking status ($P < 0.05$). Notably, blood levels of cadmium and mercury showed significant variation between the two groups ($P < 0.05$), suggesting differential exposure to heavy metals.

Correlation analysis of blood heavy metals

To investigate potential co-exposure patterns among the five heavy metals in the blood, Pearson correlation analysis was conducted. The Pearson correlation coefficient between cadmium and lead was 0.18 (Fig. 1).

Association between blood heavy metal levels and pregnancy loss

The results in Table 2 show that in the unadjusted model, blood mercury levels were positively associated with pregnancy loss (OR 1.06, 95%CI 1.03–1.09, $P < 0.001$). This association remained strong after adjusting for age in adjusted model I (OR 1.06, 95%CI 1.03–1.10, $P < 0.001$). In adjusted model II, each unit rise in blood mercury levels corresponded to a 5% increase in the risk

Table 1 Baseline characteristics of participants

Variables	Total (*n* = 3623)	Non-pregnancy loss (*n* = 2016)	Pregnancy loss (*n* = 1607)	*P* value
Demographic information				
Age (years)	53.24 ± 16.19	53.95 ± 16.91	52.36 ± 15.21	0.003
Race				< 0.001
Mexican American	502 (13.86)	308 (15.28)	194 (12.07)	
Other Hispanic	429 (11.84)	223 (11.06)	206 (12.82)	
Non-Hispanic White	1396 (38.53)	829 (41.12)	567 (35.28)	
Non-Hispanic Black	845 (23.32)	419 (20.78)	426 (26.51)	
Other Race	451 (12.45)	237 (11.76)	214 (13.32)	
Education level				0.002
Less than 9th grade	384 (10.60)	232 (11.51)	152 (9.46)	
9-11th grade	504 (13.91)	291 (14.43)	213 (13.25)	
High school graduate/GED or equivalent	797 (22.00)	471 (23.36)	326 (20.29)	
Some college or AA degree	1159 (31.99)	597 (29.61)	562 (34.97)	
College graduate or above	779 (21.50)	425 (21.08)	354 (22.03)	
Marital status				0.021
Married/living with partner	2067 (57.05)	1175 (58.28)	892 (55.51)	
Widowed/divorced/separated	1208 (33.34)	671 (33.28)	537 (33.42)	
Never married	348 (9.61)	170 (8.43)	178 (11.08)	
PIR				0.150
Low-income (PIR ≤ 1)	908 (25.06)	484 (24.01)	424 (26.38)	
Middle-income (1 < PIR < 4)	1899 (52.42)	1084 (53.77)	815 (50.72)	
High-income (PIR ≥ 4)	816 (22.52)	448 (22.22)	368 (22.90)	
Pregnancy information				
Age at first live birth (years)	22.43 ± 5.03	22.44 ± 4.82	22.41 ± 5.29	0.881
Age at last live birth (years)	29.09 ± 5.89	28.70 ± 5.74	29.58 ± 6.05	< 0.001
Number of pregnancies	3.49 ± 1.97	2.72 ± 1.59	4.47 ± 1.98	< 0.001
Number of live births	2.72 ± 1.57	2.72 ± 1.59	2.72 ± 1.55	0.917
Number of vaginal deliveries	2.36 ± 1.83	2.32 ± 1.79	2.41 ± 1.87	0.172
Number of cesarean deliveries	0.45 ± 0.86	0.43 ± 0.83	0.48 ± 0.90	0.240
Age at menarche				< 0.001
< 10	140 (3.86)	56 (2.78)	84 (5.23)	
10 ≤ age < 15	2917 (80.51)	1640 (81.35)	1277 (79.46)	
≥ 15	566 (15.62)	320 (15.87)	246 (15.31)	
Ever use female hormones?				0.104
No	2896 (79.93)	1592 (78.97)	1304 (81.14)	
Yes	727 (20.07)	424 (21.03)	303 (18.86)	
Lifestyle behaviors				
Drinking status				< 0.001
No	1524 (42.06)	913 (45.29)	611 (38.02)	
Yes	2099 (57.94)	1103 (54.71)	996 (61.98)	
Smoking status				< 0.001
No	2326 (64.20)	1355 (67.21)	971 (60.42)	
Yes	1297 (35.80)	661 (32.79)	636 (39.58)	
Clinical characteristics				
BMI				0.084
Normal or low weight (< 25)	977 (26.97)	553 (27.43)	424 (26.38)	
Overweight (25 ≤ BMI < 30)	1025 (28.29)	593 (29.41)	432 (26.88)	
Obesity (≥ 30)	1621 (44.74)	870 (43.15)	751 (46.73)	
Hypertension history				0.930

Table 1 (continued)

Variables	Total ($n=3623$)	Non-pregnancy loss ($n=2016$)	Pregnancy loss ($n=1607$)	*P* value
No	2078 (57.36)	1155 (57.29)	923 (57.44)	
Yes	1545 (42.64)	861 (42.71)	684 (42.56)	
Diabetes history				0.833
No	3104 (85.67)	1725 (85.57)	1379 (85.81)	
Yes	519 (14.33)	291 (14.43)	228 (14.19)	
Heavy metals				
Lead (μg/dL)	1.23 ± 1.06	1.23 ± 1.06	1.23 ± 1.06	0.854
Cadmium (μg/L)	0.55 ± 0.58	0.53 ± 0.54	0.59 ± 0.62	0.001
Mercury (μg/L)	1.46 ± 2.37	1.33 ± 2.24	1.63 ± 2.51	< 0.001
Manganese (μg/L)	10.59 ± 4.37	10.52 ± 4.20	10.69 ± 4.57	0.240
Selenium (μg/L)	192.22 ± 26.90	191.96 ± 28.02	192.55 ± 25.43	0.513

Abbreviations: *GED* general educational development, *AA* associate of arts, *PIR* ratio of family income to poverty, *BMI* body mass index status

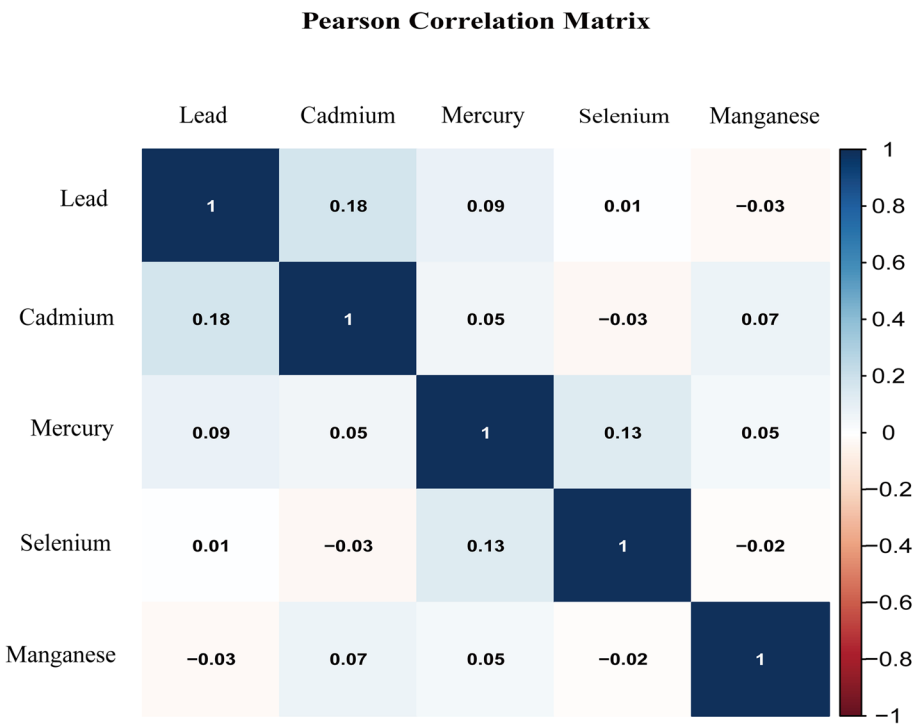

Fig. 1 Heatmap of Pearson correlation model

of pregnancy loss (OR 1.05, 95%CI 1.02–1.09, $P=0.001$). Sensitivity analysis using tertiles of blood mercury levels as a categorical variable also showed significant results (OR 1.38, 95%CI: 1.16–1.65, $P<0.001$). In adjusted model II, women in the highest tertile (T3) of blood mercury levels had a 38% greater risk of pregnancy loss compared to those in the lowest tertile (T1) ($P<0.05$) (Table 3).

Smoothed fit curve and threshold effect analysis

The results of the smoothed fit curve indicated that the risk of pregnancy loss increased with rising blood mercury levels, with the increase slowing after saturation (Fig. 2). This suggests a substantive association between higher blood mercury levels and increased pregnancy loss risk.

After adjusting for covariates, the threshold effect analysis revealed a turning point at 3.40 μg/L (Table 4). On

Table 2 The association between heavy metal exposure and pregnancy loss

Exposure	Unadjusted model OR (95%CI)	*P* value	Adjusted model I OR (95%CI)	*P* value	Adjusted model II OR (95%CI)	*P* value
Lead (μg/dL)	0.99 (0.93, 1.06)	0.854	1.03 (0.96, 1.10)	0.426	1.00 (0.93, 1.07)	0.992
Cadmium (μg/L)	1.21 (1.08, 1.35)	0.001	1.21 (1.08, 1.36)	0.001	1.10 (0.97, 1.26)	0.135
Mercury (μg/L)	1.06 (1.03, 1.09)	< 0.001	1.06 (1.03, 1.10)	< 0.001	1.05 (1.02, 1.09)	0.001
Selenium (μg/L)	1.00 (1.00, 1.00)	0.513	1.00 (1.00, 1.00)	0.522	1.00 (1.00, 1.00)	0.390
Manganese (μg/L)	1.01 (0.99, 1.02)	0.241	1.01 (0.99, 1.02)	0.495	1.01 (1.00, 1.03)	0.160

Adjusted model I was adjusted for age

Adjusted model II was adjusted for age, age at last live birth, race, education level, marital status, age at menarche, drinking status, and smoking status

Abbreviations: *OR* odds ratio, *CI* confidence interval

Table 3 The association between mercury exposure and pregnancy loss

Exposure	Unadjusted Model OR (95%CI)	*P* value	Adjusted Model I OR (95%CI)	*P* value	Adjusted Model II OR (95%CI)	*P* value
Mercury (μg/L)	1.06 (1.03, 1.09)	< 0.001	1.06 (1.03, 1.10)	< 0.001	1.05 (1.02, 1.09)	0.001
T1 (0.11,0.52)	Ref		Ref		Ref	
T2 (0.53,1.22)	1.17 (1.00, 1.38)	0.056	1.20 (1.02, 1.41)	0.029	1.11 (0.94, 1.32)	0.207
T3 (1.23,40.60)	1.48 (1.26, 1.74)	< 0.001	1.54 (1.31, 1.81)	< 0.001	1.38 (1.16, 1.65)	< 0.001
P for trend		< 0.001		< 0.001		< 0.001

Adjusted model I was adjusted for age

Adjusted model II was adjusted for age, age at last live birth, race, education level, marital status, age at menarche, drinking status, and smoking status

Abbreviations: *OR* odds ratio, *CI* confidence interval

the left side of this threshold, blood mercury levels were significantly positively associated with pregnancy loss, while this association was not significant on the right side.

WQS regression analysis of the association between blood heavy metal levels and pregnancy loss

After fully adjusting for covariates, a significant positive correlation was found between the WQS index and pregnancy loss risk (Fig. 3). Each unit increase in the WQS index resulted in a 22% heightened risk of pregnancy loss (OR 1.22, 95%CI 1.06–1.41, $P=0.006$). Mercury was identified as the most important component, contributing 45.67% to the WQS index, highlighting its critical role in pregnancy loss risk.

Subgroup analysis

Subgroup analyses were conducted to determine the relationship between blood mercury levels and pregnancy loss risk across different population characteristics. The results indicated significant interactions of race, education level, BMI, and age at menarche on the association between blood mercury levels and pregnancy loss risk (P for interaction < 0.05) (Figure S2). No notable interactions were found in the remaining subgroups (P for interaction > 0.05).

Discussion

This study demonstrated a significant positive relationship between blood mercury levels and pregnancy loss, which was further validated in adjusted models. A nonlinear relationship was observed in this association. Subgroup analyses indicated significant interactions were observed between race, education level, BMI, and age at menarche regarding the relationship between blood mercury levels and pregnancy loss. No significant associations were found between cadmium, manganese, lead, selenium, and pregnancy loss.

Mercury is a naturally occurring metal found in the environment in three distinct forms: elemental, inorganic, and organic mercury. Each form is highly toxic [40]. Elemental mercury is the most prevalent form of mercury pollution, persisting as vapor in the atmosphere for long periods and spreading globally. Inorganic and organic mercury accumulate in soil and water, producing substantial bioaccumulation in the food chain [41]. The primary toxic mechanism of mercury is its high affinity for sulfhydryl groups in amino acids, proteins, and enzymes, which allows it to bind irreversibly to sulfur-containing molecules [42]. This binding disrupts the normal function of protein and enzymes, impairing cellular function and tissue health [43]. Sulfhydryl groups are also present in antioxidant enzymes, such as glutathione

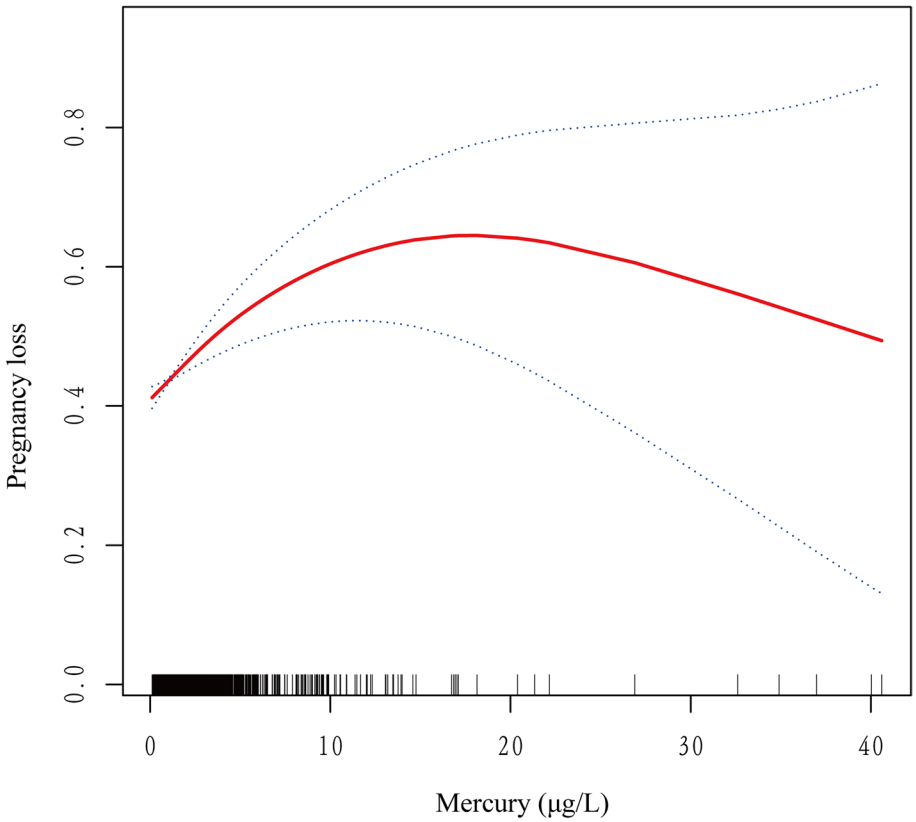

Fig. 2 Association between mercury and the risk of pregnancy loss. The red curve indicates a smooth curve fit between the variables. The blue curve indicates the 95% confidence intervals of the fitted results

Table 4 Results of the threshold effect analysis

Model	Pregnancy loss OR (95%CI)	*P* value
Model I		
One line effect	1.05 (1.02,1.09)	0.001
Model II		
Inflection point (K)	3.40	
< K	1.18 (1.10,1.28)	< 0.001
> K	1.01 (0.97,1.05)	0.710
Log-likelihood ratio	0.001	

Adjusted model I was adjusted for age

Adjusted model II was adjusted for age, age at last live birth, race, education level, marital status, age at menarche, drinking status, and smoking status

peroxidase (GSH-Px), superoxide dismutase (SOD), and catalase, which explains why mercury toxicity often leads to oxidative stress [44, 45], mitochondrial dysfunction [46], and apoptosis [47].

Once bound to biological molecules, mercury ions are rapidly transported to multiple organs, including the intestines, kidneys, liver, brain, and placenta [42]. Previous research has shown that mercury levels detected in the placenta and umbilical cord blood are higher than those in maternal blood [48, 49], contributing to fetal congenital defects or abnormalities. Additionally, pregnant women exposed to mercury exhibit significantly lower GSH-Px and SOD activity in their blood compared to unexposed women [50], suggesting that mercury exposure impairs the antioxidant defense system. During pregnancy, physiological and metabolic changes in the mother increase oxidative stress; however, the body's antioxidant system typically adjusts to maintain a balance between oxidative and antioxidant activity [51]. Mercury-induced reductions in antioxidant activity disrupt this balance, potentially increasing the risk of miscarriage, stillbirth, preterm birth, and low birth weight [52, 53].

El-Badry et al. tracked the obstetric outcomes of dental professionals with long-term mercury exposure ($n=64$) and recruited unexposed pregnant women as controls ($n=60$). The exposed group had significantly higher urinary mercury levels throughout pregnancy and experienced miscarriage more frequently [50]. Similarly, Lindbohm et al. reported increased miscarriage

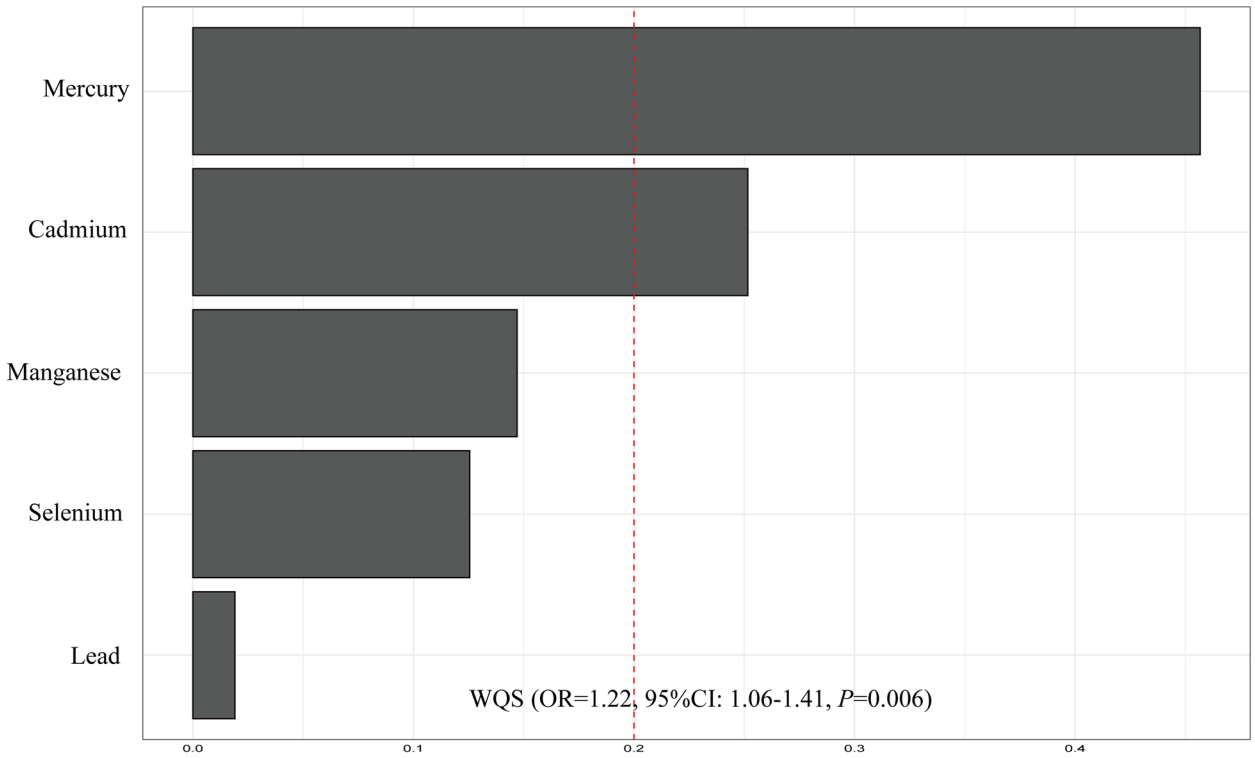

Fig. 3 The WQS regression model estimated the weights of each blood heavy metal associated with pregnancy loss. This model was adjusted for age, age at last live birth, race, education level, marital status, age at menarche, drinking status, and smoking status

risk among dental workers with moderate to high levels of mercury exposure, although mercury exposure was estimated based on the frequency of handling mercury-amalgam dental materials at work [54]. In a study of pregnancy outcomes among women involved in artisanal and small-scale gold mining ($n=788$) and non-mining women ($n=173$), Nyanza et al. observed a positive relationship between elevated blood and urinary mercury levels and the occurrence of stillbirths and visible congenital abnormalities [55]. However, several other studies did not find a significant link between mercury exposure and miscarriage or stillbirth [36, 56]. In our study, a positive relationship between blood mercury levels and pregnancy loss risk was observed, supporting previous findings that mercury exposure may increase pregnancy loss occurrence.

The strength of this study is its comprehensive and representative sample, drawn from NHANES data, which allowed for the examination of the associations between exposure to heavy metals and pregnancy loss. Adjusting for potential confounding factors strengthened the reliability of our findings. Moreover, the combined effects of mercury on pregnancy loss were further elucidated using WQS regression. Subgroup analyses were also conducted to explore the robustness of the link between mercury exposure and pregnancy loss across different populations. However, several limitations should be noted. First, as a cross-sectional study, causality cannot be established. Second, the diagnosis of pregnancy loss was determined through self-reported questionnaires, which introduces the possibility of selection bias. Third, despite adjusting for lifestyle and clinical confounding factors, not all potential confounders could be addressed, and we cannot rule out the possibility of other causes of pregnancy loss. Therefore, further studies of different types are needed to confirm the association between heavy metal exposure and pregnancy loss.

Conclusion

Our findings suggest that higher blood mercury levels may result in a higher risk of pregnancy loss. This emphasizes the importance of managing heavy metal pollution and protecting the environment, which may help reduce the risk of pregnancy loss and improve pregnancy outcomes.

Abbreviations

NHANES	National Health and Nutrition Examination Survey
MEC	Mobile examination center
PIR	Ratio of family income to poverty
BMI	Body mass index
SD	Standard deviation

IQR	Interquartile range
OR	Odds ratios
CI	Confidence intervals
WQS	Weighted quantile sum
GSH-Px	Glutathione peroxidase
SOD	Superoxide dismutase

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12958-025-01373-4.

Supplementary Material 1.

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Not applicable.

Authors' contributions
Chiyang Yu: Conceptualization, Validation, and Writing – original draft. Qingxia You: Data curation, Formal analysis. Xue Bai: Visualization. Fangxiang Mu: Conceptualization, Writing – review and editing. All authors have read and approved this final version.

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Data availability
The data analyzed in this study are involved in the main text.

Declarations

Ethics approval and consent to participate
This research received approval from the National Center for Health Statistics Research Ethics Review Board, and participants signed informed consent forms (Protocol #2011–17). The procedures used in this study in accordance with the Declaration of Helsinki.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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