# Association of Prenatal and Childhood Blood Lead Concentrations with Criminal Arrests in Early Adulthood

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**Introduction**

Early onset of aggressive or violent behavior is a precursor to a life course marred by limited social and educational achievement, incarceration, underemployment, and premature mortality [1,2]. These maladaptive behavioral patterns, which often emerge early in life, remain highly stable [3]. These facts highlight the importance of identifying risk factors that may place youth on an early developmental trajectory toward a career of crime and violence.

A meta-analysis of 34 independent studies identified and prioritized risk factors for serious, violent criminal behavior [4]. The most consistent risk factors were male gender, prenatal exposure to tobacco smoke, having antisocial parents, and low family socioeconomic status. In contrast, few studies have evaluated the consequences of childhood lead exposure as a risk factor for criminal behavior.

Some epidemiological studies have found a relationship between childhood lead exposure and antisocial behavior. In a study of Philadelphia youth, a history of lead poisoning was among the most significant predictors of adolescent delinquency and adult criminality in males [5]. Bone lead levels were associated with delinquent behavior in a retrospective cohort study of 11-year-old Pittsburgh children [6]. In Cincinnati, prenatal and childhood blood lead concentrations were associated with an increased risk for antisocial behavior and delinquency in adolescence [7]. Finally, elevated bone lead levels were observed in juvenile court–adjudicated delinquents residing in Allegheny County, Pennsylvania compared to matched controls [8]. These studies suggest that exposure to environmental lead during childhood is associated with the development of conduct problems and delinquent behavior. In consideration of these findings, it is noteworthy that a number of recent ecological investigations correlating leaded gasoline sales or atmospheric lead levels with crime rates also support an association between lead exposure and criminal behavior [9–12]. Questions remain, however, because these studies were cross-sectional (hence causality cannot be firmly established), relied on indirect measures of lead exposure, or did not follow participants into adulthood.

Here, we report the results of a long-term prospective study on the effects of one potential childhood risk factor of adult arrests, elevated prenatal and childhood blood lead concentrations.

**Participants**

The Cincinnati Lead Study (CLS) is a birth cohort recruited from late 1979 to early 1984. The CLS enrolled women in their first or early second trimester of pregnancy who attended four prenatal clinics within impoverished Cincinnati neighborhoods with a high concentration of older, lead-contaminated housing [13]. Women were excluded or ineligible if they were known to be addicted to drugs, were known to have diabetes or a neurological or psychiatric condition, or refused prenatal participation. Newborns were excluded if their gestational age was less than 35 wk, birth weight less than 1,500 g, Apgar score at

5 min less than 6, or if genetic or other serious medical issues were present at birth. This process netted 376 newborns who were recruited at birth (i.e., informed oral and written consent was obtained from the mother in the hospital and a blood lead sample was obtained from the newborn). Of these newborns 305 were developmentally examined at the CLS follow-up clinic when they were 3 and 6 mo of age [14]. They were followed up quarterly through age 5 y and semiannually from age 5 to 6.5 y [15].

A total of 250 CLS participants who were between 19 and 24 y of age and had been followed at least through the first 6 y of life participated in the current study. Thus, individuals in the current analysis had serial blood lead concentrations spanning the entire preschool and early school-age period of development. Written informed consent was obtained by the investigator or a senior member of the research staff at each stage of this longitudinal study after it was determined that the participant or the participant's legal guardian understood the nature of the research. This protocol has been reviewed and approved by the institutional review boards of the University of Cincinnati College of Medicine and the Cincinnati Children's Hospital Medical Center.

The 250 participants in this analysis were not substantially different from those with missing data with regard to baseline perinatal characteristics such as birth weight (3,134 versus 3,138 g), sex (50% versus 54% male), 6-y average Hollingshead [16] socioeconomic status (SES) total score (18.0 versus 18.3), years of maternal education (11.2 versus 11.1 y), scores on the Home Observation for Measurement of the Environment (the preschool version of a quantitative observational measure of early nurturing and environmental stimulation [17]) (32.3 versus 33.4), and average childhood blood lead (13.4 versus 14.2 μg/dl).

**Exposure and Outcome Assessments**

We examined three measures of blood lead. Prenatal maternal blood lead concentration [μg/dl]) was measured during the first or early second trimester of pregnancy. Approximately 50% of the prenatal samples were obtained during the first trimester of pregnancy. The difference between maternal blood lead concentration assessed in the first and second trimesters was not statistically significant ($p = 0.76$) [14]. Postnatal blood lead indices included average childhood blood lead (average of 23 blood lead concentrations obtained quarterly from age 3 to 60 mo and semiannually from 66 to 78 mo), and 6.5-y blood lead. If a 6.5-y blood lead value was not available for a child, we used the blood lead test from 6 y. We selected 6.5 y blood lead over other serial blood lead measures because preliminary analyses indicated that blood lead measured at 6 y was more highly associated with the number of arrests than blood lead measured at other ages. Complete blood lead data were available for 89%–92% of the cohort at any particular quarterly assessment from 3 mo to 5 y of age. Missing postnatal blood lead concentrations were imputed from a weighted average of a within-participant regression of blood lead on age. This imputation was done to avoid excluding those participants who may have one or only a few missing blood lead tests. Prenatal blood lead concentrations were available for 87% (217/250) of the participants.

The primary outcome variable in this study was the individual's number of criminal arrests since turning 18 y of age. We did not collect data on convictions. Arrest is a more proximate measure of criminal behavior than are conviction data. Arrest typically occurs at the scene of the criminal event or immediately thereafter. Arrest decisions, moreover, usually reflect the seriousness of the offense, the offender's prior record, and the desire of the victim to have the individual arrested. Conversely, conviction data are distal indicators of criminal behavior. Actual criminal convictions derived from a trial

represent less than 10% of all criminal arrests. Over 90% of all criminal cases are subject to plea bargaining, in which a plea of “guilty” is usually rewarded with a reduced charge and/or sentence. From the time of arrest it can take upward of 2 y or more before a defendant is tried in a court, or it can take over 1 y from the time of arrest to the time at which a plea deal is accepted by the court. Furthermore, a range of extra-legal variables can enter into the plea and trial process, including the defendant's economic status, support system, and access to quality defense counsel. We should also add that Hamilton County, Ohio (the study's catchment area) makes extensive use of “diversion” programs. These programs select individuals with specified problems or offenses, such as drunken driving or drug abuse and “divert” them from jail or prison into community-based rehabilitation programs. Upon successful completion of the program and a probationary term, many of these programs “erase” the individual's legal conviction, but not the arrest. Finally, at least for this study, arrest data are substantially more complete than are conviction data. Arrest data in Hamilton County, Ohio are compiled into a single county-wide database and are updated at regular intervals. Court data, however, are not updated regularly. This problem is endemic to court systems nationwide, because courts operate at different levels (city, county, state, Federal) and are under the guidance of individual judges.

**Data on Criminal Arrests**

Data on criminal arrests for participants and their mothers were obtained from a computer search of Hamilton County, Ohio criminal justice records. These records provided information on the nature, number, and disposition of arrests. Two reviewers who were blind to participants' blood lead concentrations independently coded each arrest into one of the following categories: violent offenses (e.g., murder, rape, domestic violence, assault, robbery, or possession of a weapon); offenses against property (e.g., burglary or arson); drug offenses (e.g., trafficking, abuse, or possession); fraud; obstruction of justice; serious motor vehicle offenses (e.g., driving without a license, driving under the influence of alcohol, or driving under suspension); disorderly conduct; and other offenses, which included offenses that did not fit in any previously mentioned category. Minor motor vehicle offenses, such as speeding, safety restraint violations, lights burned out, failing to stop, and pedestrian offenses were excluded from the analyses. We counted the number of arrests and coded the nature of the offense that led to each arrest. If an individual was charged with more than one offense during a single arrest, then the most serious offense was used for classification. Thus, arrest counts were lower than the total number of offenses. Legally determined guilt was not a factor in our coding. Only those offenses that were filed before 31 October 2005 were included in the analyses.

Inter-reviewer differences with respect to arrest and category of offense were resolved by a third reviewer who conducted the initial training for criminal record coding. Interobserver agreement as assessed by Cohen's kappa was 0.93 for maternal offenses and 0.97 for participant offenses.

**Statistical Analyses**

We used negative binomial regression models to analyze these data because the counts of arrests were overdispersed when originally examined using Poisson regression models [18]. This model provided a very good fit to these data in terms of the estimated scale parameter. These models were used to estimate the association between blood lead concentrations and arrest rates adjusted for other important risk factors. We calculated separate models for each blood lead measure. Our dependent variable was the number of criminal arrests for each participant measured as discrete counts, which were positively skewed. To account for the number of years at risk of arrest, we used the log of current

age as an offset in all models. To control for potential confounding, we examined variables reflecting the effects of other neurotoxicants such as maternal cigarette and marijuana smoking and consumption of narcotics during pregnancy, as well as variables related to adult criminal involvement in prior studies. Our list of candidate covariates included: sex; a validated measure of the quality of early care-giving and environmental stimulation called the Home Observation for Measurement of the Environment (HOME) inventory score [17]; birth weight (g); maternal smoking during pregnancy (half-packs consumed per day); maternal alcohol, marijuana, or narcotic use (Y/N); maternal education level (highest grade); maternal IQ [19]; total prior maternal arrests; SES (average Hollingshead [16] score); number of children in the home; and whether the mother was on public assistance during the participant's childhood (Y/N). Data on fathers or male caregivers in the home were not available, since 84% of the households were headed by the mother or a male caregiver was not consistently present. Continuous covariates were examined using linear, polynomial, and log-transformed functions to assess whether simple linear terms were adequate for adjustment of covariate or confounder influences.

Candidate covariates or confounders remained in the final multivariable models if they were either statistically significant ($p \leq 0.05$) or if their inclusion in the model caused a change of ≥ 10% in the rate ratio estimates for lead, regardless of their level of statistical significance. We tested the interaction of lead by sex, since some studies have indicated that developing male central nervous systems may be more vulnerable than females' to environmental insults leading to later behavioral problems [20]. Before deciding upon a final multivariable model, regression diagnostics for collinearity and influence using the methods described in Belsley, et al. were employed [21]. As a measure of the absolute change in arrest rates between participants with higher levels of blood lead compared to those with lower blood lead levels, we defined attributable risk as the average difference in annual arrest rates between participants at the 95th percentile of blood lead and those at the 5th percentile. All significance tests were two-tailed. Results for blood lead variables are presented as adjusted rate ratios (RR) for total arrests and arrests for violent crimes. All statistical analyses were conducted with SAS (Statistical Analysis System), version 9.1 [22].

**Results**

The sample was largely African-American (90%), 50% of the participants were male, and 73% of families scored in the lowest two levels of the Hollingshead Four-Factor Index of Social Position [16]. A single female caregiver headed 84% of households.

Mean blood lead concentrations (μg/dl) were 8.3 (0.40 μmol/l) (range 1–26) for maternal prenatal, 13.4 (0.65 μmol/l) (range 4–37) for average childhood, and 8.3 (0.40 μmol/l) (range 2–33) for 6-y. The mean postnatal blood lead concentration of CLS participants increased to a peak of 17.7 (standard deviation [SD] 9.7) μg/dl (0.85 μmol/l) at 21 mo. After age 21 mo, average blood lead concentrations declined to a mean of 8.4 (SD 4.9) μg/dl (0.40 μmol/l) at 6.5 y. At 6.5 y of age, 67 children (26.9%) had a blood lead concentration above 10 μg/dl (0.48 μmol/l) (Table 1). Pearson correlations between blood lead indices examined in this study were 0.32 and 0.28 between prenatal and average childhood and 6-y respectively, and 0.80 between average childhood and 6 y.

**Table 1**

Characteristics of the Participants and of their Mothers in the Cincinnati Lead Study (*n* =250)

| Category | Characteristic | Total ($n$ =250) No. (%) or Mean (SD) | Participant Never Arrested ($n$ =114) No. (%) or Mean (SD) | Participant Ever Arrested ($n$ =136) No. (%) or Mean (SD) |
|---|---|---|---|---|
| Participant characteristics | Male | 125 (50.0%) | 34 (29.8%) | 91 (66.9%) |
| | African-American | 225 (90.0%) | 99 (86.8%) | 126 (92.7%) |
| | Age at study date, y | 22.5 (1.5) | 21.9 (4.8) | 22.5 (4.5) |
| | Marijuana use | 29 (11.6%) | 13 (11.4%) | 16 (11.8%) |
| Blood lead, μg/dl[a] | Prenatal blood lead[b] | 8.3 (3.8) | 7.9 (3.2) | 8.7 (4.1) |
| | Average childhood blood lead | 13.4 (6.1) | 13.3 (6.7) | 13.5 (5.5) |
| | 6-year blood lead | 8.3 (4.8) | 7.6 (4.3) | 8.8 (5.0) |
| Maternal characteristics | Age at delivery, y | 22.5 (4.2) | 22.0 (4.0) | 22.9 (4.4) |
| | Maternal IQ (points) | 75.3 (9.3) | 76.9 (10.4) | 73.9 (8.1) |
| | High school graduate | 132 (52.8%) | 68 (59.6%) | 64 (47.1%) |
| | HOME inventory at age 3 y (points) | 32.3 (6.6) | 33.6 (6.3) | 31.6 (6.7) |
| | Socioeconomic status (Hollingshead score) | 18.0 (4.8) | 18.5 (5.1) | 17.8 (4.5) |
| Marital status | Married | 39 (15.6%) | 21 (18.4%) | 18 (13.2%) |
| | Single | 155 (62.0%) | 70 (61.4%) | 85 (62.5%) |
| | Other | 56 (22.4%) | 23 (20.2%) | 33 (24.3%) |
| Smoked during pregnancy | | 129 (51.6%) | 62 (54.4%) | 67 (49.3%) |
| Number of children in home | | 3.0 (1.4) | 2.9 (1.4) | 3.1 (1.3) |
| Public assistance | | 190 (76%) | 82 (71.9%) | 108 (79.4%) |

Data presented as $n$ (%) or mean (SD). Average childhood blood lead concentration was defined as the mean of blood lead tests taken from 3 months through the 6-year blood lead test.
[a]To convert blood lead to μmol/l multiply by 0.04826.
[b]$n$ = 217 for prenatal blood lead.
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We identified a total of 800 arrests within the sample. Of these arrests, 108 (14%) were for violent offenses, 90 (11%) involved theft or fraud, 216 (28%) involved drugs, 35 (5%) were for obstruction of justice, 211 (27%) were related to serious motor vehicle offenses, 35 (5%) were for disorderly conduct, and 82 (11%) other. Approximately 55% of participants (62.8% of males, 36.3% of females) had at least one arrest. The mean number of arrests among males was 5.2, which was significantly higher than the mean number of 1.1 for females ($p < 0.001$). The overall mean arrest rate was 0.68 per year after age 18, but the mean arrest rate for males was 4.5 times higher than the female arrest rate (1.1 versus 0.25 per year).

Preliminary analysis of the association between blood lead measures and covariates revealed generally weak correlation coefficients ranging from 0.24 to 0.35, indicating a relatively small potential for confounding. In multivariable regression analyses of the total number of arrests, we found that the associations between prenatal and 6-y blood lead concentrations were statistically significant. In each model, the blood lead association was adjusted for the cofactors of maternal IQ, sex, SES score, and maternal education. The RRs for total arrests increased for each 5 μg/dl (0.24 μmol/l) increment in blood lead concentration; the RRs were 1.40 (95% confidence interval [CI] 1.07–1.85) for prenatal blood lead, 1.07 (95% CI 0.88–1.29) for average childhood blood lead, and 1.27 (95% CI 1.03–1.57) for 6-y blood lead. The attributable risk was 0.48 arrests/year (95% CI 0.29–0.79) for prenatal blood lead, 0.13 (95% CI 0.03–0.33) for average childhood blood lead, and 0.39 (95% CI 0.21–0.68) for 6-y blood lead (Table 2). The rate of total arrests was modeled as a log-linear function of increasing blood lead concentrations for each of the three blood lead assessments: maternal prenatal (Figure 1A), early childhood (Figure 1B), and 6 y (Figure 1C).

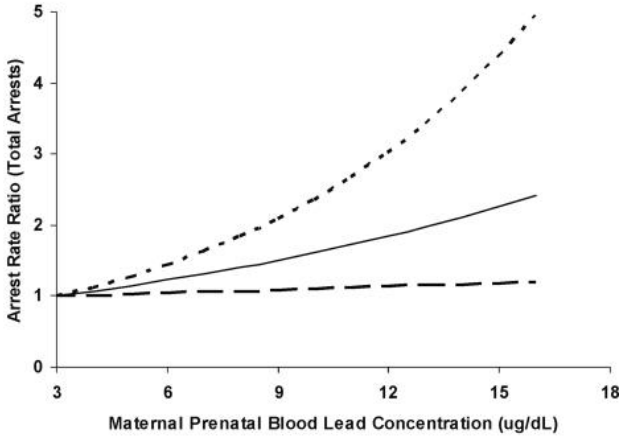
**Table 2**

Relationship of Prenatal, Early Childhood Average, and Six-Year Blood Lead Concentrations with Total Arrest Rates in Young Adults

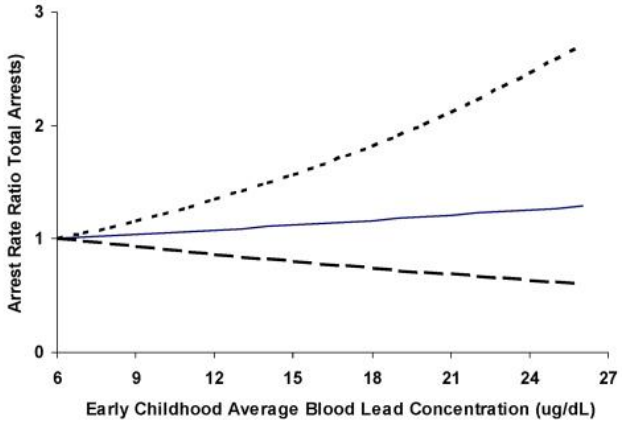
| Blood Lead Variable | Median (5th–95th Percentile), μg/dl [a] | Attributable Risk (95% CI), per Year | Rate Ratio for 5 μg/dl Increase in Blood Lead (95% CI) |
|---|---|---|---|
| Prenatal | 7.8 (2.9–16.0) | 0.48 (0.29–0.79) | 1.40 (1.07–1.85) |
| Early Childhood Average | 12.3 (6.0–26.3) | 0.13 (0.03–0.33) | 1.07 (0.88–1.29) |
| Six-Year | 6.8 (3.4–18.3) | 0.39 (0.21–0.68) | 1.27 (1.03–1.57) |

Estimates adjusted for maternal IQ, sex, SES using the Hollingshead Score, and maternal education level.
[a]To convert blood lead to μmol/l multiply by 0.04826.
doi:10.1371/journal.pmed.0050101.t002

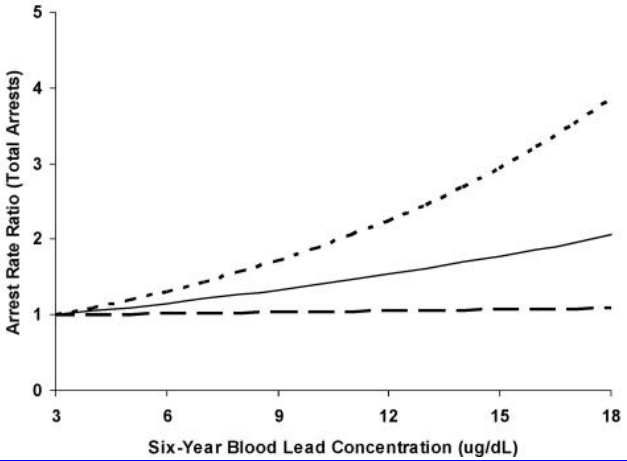
**A**


Arrest Rate Ratio (Total Arrests)
0
1
2
3
4
5
3
6
9
12
15
18
Maternal Prenatal Blood Lead Concentration (ug/dL)

**B**


Arrest Rate Ratio Total Arrests)
0
1
2
3
6
9
12
15
18
21
24
27
Early Childhood Average Blood Lead Concentration (ug/dL)

**C**


Arrest Rate Ratio (Total Arrests)
0
1
2
3
4
5
3
6
9
12
15
18
Six-Year Blood Lead Concentration (ug/dL)

**Adjusted Relationship between Blood Lead Concentration and Arrest Rate Ratio For Total Arrests**

Shown are data for maternal prenatal blood lead concentration (A), early childhood average blood lead concentration (B), and 6-year blood lead concentration (C). Rate ratios are plotted as a function of increasing blood lead from the 5th to the 95th percentiles of blood lead relative to participants at the 5th percentile. Dashed lines are 95% confidence intervals. To convert to μmol/l: (μg/dl) × 0.04826.

In multivariable analyses of violent criminal arrests, we found statistically significant associations with both average childhood and 6-y blood lead variables. The RRs for arrests involving violent crimes increased for each 5 μg/dl (0.24 μmol/l) increment in blood lead; the RRs were1.34 (95% CI 0.88–2.03) for prenatal blood lead, 1.30 (95% CI 1.03–1.64) for average childhood blood lead, and 1.48 (95% CI 1.15–1.89) for 6-y blood lead. The attributable risk was 0.055 arrests/year (95% CI 0.026–0.118) for prenatal blood lead, 0.077 (95% CI 0.039–0.156) for average childhood blood lead, and 0.087 (95% CI 0.049–0.152) for 6-y blood lead (Table 3). As with the analyses for total arrests, the rate of arrests for violent offenses was modeled as a log-linear function of each of the blood lead indices: maternal prenatal (Figure 2A), early childhood (Figure 2B), and 6 y (Figure 2C).

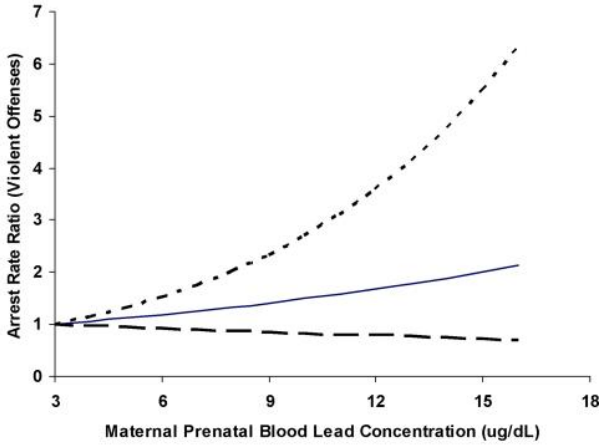
**Table 3**

Relationship of Prenatal, Early Childhood Average, and Six-Year Blood Lead Concentrations with Violent Crime Arrest Rates in Young Adults

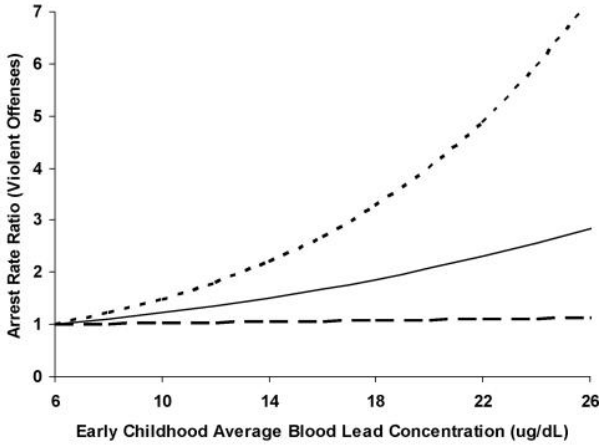
| Blood Lead Variable | Median (5th–95th Percentile), μg/dl[a] | Attributable Risk (95% CI), per Year | Rate Ratio for 5 μg/dl Increase in Blood Lead (95% CI) |
|---|---|---|---|
| Prenatal | 7.8 (2.9–16.0) | 0.055 (0.026–0.118) | 1.34 (0.88–2.03) |
| Early Childhood Average | 12.3 (6.0–26.3) | 0.077 (0.039–0.156) | 1.30 (1.03–1.64) |
| Six-Year | 6.8 (3.4–18.3) | 0.087 (0.049–0.152) | 1.48 (1.15–1.89) |

Estimates adjusted for maternal IQ, sex, SES using the Hollingshead Score, and maternal education level.
[a]To convert blood lead to μmol/l multiply by 0.04826.
doi:10.1371/journal.pmed.0050101.t003

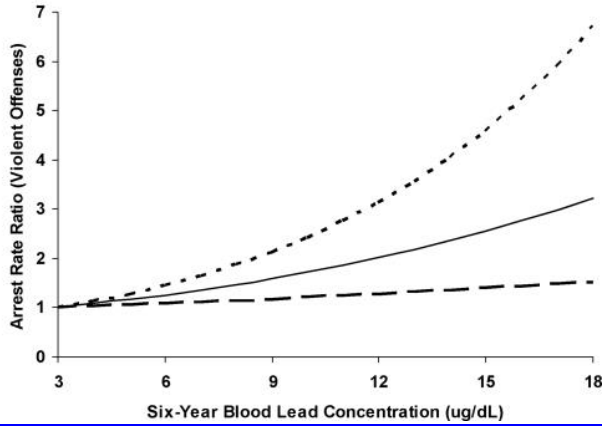
**A**


Arrest Rate Ratio (Violent Offenses)
0
1
2
3
4
5
6
7
3
6
9
12
15
18
Maternal Prenatal Blood Lead Concentration (ug/dL)

**B**


Arrest Rate Ratio (Violent Offenses)
0
1
2
3
4
5
6
7
6
10
14
18
22
26
Early Childhood Average Blood Lead Concentration (ug/dL)

**C**


Arrest Rate Ratio (Violent Offenses)
0
1
2
3
4
5
6
7
3
6
9
12
15
18
Six-Year Blood Lead Concentration (ug/dL)

**Adjusted Relationship between Blood Lead Concentration and Arrest Rate Ratio For Violent Offenses**

Shown are data for maternal prenatal blood lead concentration (A), early childhood average blood lead concentration (B), and 6-year blood lead concentration (C). Rate ratios are plotted as a function of increasing blood lead from the 5th to the 95th percentiles of blood lead relative to participants at the 5th percentile. Dashed lines are 95% confidence intervals. To convert to μmol/l: (μg/dl) × 0.04826.

The results for analyses restricted to arrests for nonviolent crimes were similar to those found for all arrests. Specifically, the RRs for nonviolent arrests for each 5 μg/dl (0.24 μmol/l) in blood lead were 1.40 (95% CI 1.06–1.84) for prenatal blood lead, 1.05 (95% CI 0.86–1.28) for average childhood blood lead, and 1.22 (95% CI 0.97–1.53) for 6-y blood lead.

There was no statistical evidence that the shape of the exposure-response relationship differed by sex with any of the blood lead indices for total arrests or arrests for violent offenses. The interaction term for sex was statistically nonsignificant (*p*-values for interaction term ranged from 0.42 to 0.79). However, the attributable risk for males was considerably higher than for females. For example, the attributable risk for 6-y blood lead rate was 0.85 arrests/year (95% CI 0.48–1.47) for males and 0.18 (95% CI 0.09–0.33) for females.

**Discussion**

In a prospective birth cohort, we found that prenatal and childhood blood lead concentrations were predictors of adult arrests. Prenatal and 6-y blood lead concentrations were significantly associated with higher RRs for total arrests. Average childhood as well as later (6-y) blood lead concentrations were significantly associated with higher RRs for arrests involving a violent offense. Data from several recent prospective studies suggest that blood lead concentrations in the later preschool years may be more predictive of cognitive and behavioral problems [23]. However, the potential importance of prenatal blood lead concentrations should not be underestimated, as they were predictive of total arrests in our data. The number of arrests in the CLS cohort was significantly higher in males. However, no significant interactions between sex and blood lead with arrest rates were found.

Environmental lead levels as well as crime have dropped over the last 30 y in the US [9]. However, the overall reduction was not uniform; inner-city children, who are predominately African-American, remain particularly vulnerable [24]. Crime and violent crime are concentrated in urban centers in the US where many poor African-Americans reside. One factor in the disproportional representation of African-Americans in crime statistics could well be the historically higher exposures to lead in these communities. Furthermore, recent data from epidemiological studies implicate blood lead concentrations well below the current level of concern adopted by the United States Centers for Disease Control in the development of neurobehavioral deficits [25]. We were unable to explore racial differences in our data since almost all participants were African-American. However, Needleman found that the lead-associated risk for juvenile court-adjudicated delinquency was present in both African-American and white youth, indicating that these findings are not restricted to any one racial or ethnic group [8].

The neurodevelopmental consequences associated with lead exposure in previous studies, such as lower IQ, less tolerance for frustration, deficits in attention, hyperactivity, and weak executive control functions, are potent predictors of delinquent and criminal behaviors [26–29]. Attention deficit

hyperactivity disorder (ADHD) is a common finding among juvenile delinquents, and those with ADHD are more likely to have severe cognitive impairments [30]. ADHD is also a known risk factor for criminal behavior in adulthood [31]. A recent analysis of data from the third National Health and Nutrition Examination Survey (NHANES-III) found that higher blood lead concentrations were significantly associated with ADHD. Children with blood lead concentrations greater than 2 μg/dl were at a 4.1-fold increased risk of ADHD [32]. Similarly, in experiments with rodents, felines, and nonhuman primates, early lead exposure was associated with increased impulsivity, aggression, antagonistic interactions, reduced social play and abnormal mother–infant interaction [33–36]. Childhood lead exposure therefore seems to place individuals at risk for multiple underlying neurobehavioral deficits associated with a higher probability of later criminal behavior.

A number of mechanisms may be at work. Lead interferes with synapse formation, disrupts dopamine systems, and lowers serotonin levels. Lead exposure has been shown to reduce MAO A (monoamine oxidase A) activity, and low MAO A activity has been associated with violent and criminal behaviors [37]. One consequence of these alterations could be neural dysfunction in areas of the brain involved in arousal, emotion, judgment, and behavioral inhibition such as the prefrontal cortex [38].

This study has several limitations. First, most criminal behavior never comes to the attention of authorities; thus, our measure of arrest underestimates actual criminal activity. Had we been able to account for all criminal acts, it is possible that the results of our study may have been different. For example, it could be argued that lead-associated lower intelligence makes it more likely that an offender will be caught (i.e., arrested). However, a recent large-scale prospective study of school-aged children with early blood lead levels similar to those in the CLS suggests that lead impacts social behaviors somewhat independently of IQ [39]. Furthermore, we did not adjust arrest rates for child IQ in our analyses because controlling for a variable that might potentially be on the causal pathway is clearly inappropriate in studies of this kind. Variables along the causal pathway between exposure and outcome cannot be bona fide confounders [40]. Second, we examined only Hamilton County, Ohio records. Although most participants in our cohort continued to reside in Hamilton County, we may have missed some arrests that occurred in other counties. Third, official records of arrest were available only when the participants reached 18 y of age. Thus, the average follow-up was under 5 y. The possibility of bias introduced by nonrandom attrition in the CLS cohort cannot be ruled out, although we found no important differences on key exposure and demographic variables. Fourth, it is always possible in observational studies to have uncontrolled confounding. This can be problematic when it comes to measuring SES, since global assessments of social standing such as the one used in this [16] and many other studies fail to capture all potentially relevant factors [41]. As pointed out by Weiss and Bellinger [42] in their discussion of the social ecology of exposure to environmental pollutants, neurotoxicant exposures are not randomly distributed, but are “chained” to many other risks to normal development that are sometimes quite difficult to partition. Finally, as with all studies of this kind, our measure of dose to the critical organ (brain) was indirect. Blood, as well as other tissues in which lead is often measured such as teeth or bone, are surrogates for dose to the central nervous system.

On the other hand, this study has a number of qualities that contribute to the validity of our findings. To our knowledge this is the first prospective study to directly examine the relationship between early exposure to lead and official documentation of arrests in adulthood. Lead dose as assessed by frequent serial blood lead determinations, assessment of a large number of potentially important covariate factors, and careful documentation of criminal arrests were unique aspects of this investigation.

Furthermore, the sample was relatively homogenous with respect to sociodemographic variables such as SES and ethnicity; thus decreasing the extent to which strong confounding factors might generate spurious associations. Therefore, we conclude that these data implicate early exposure to lead as a risk factor for behaviors leading to criminal arrest.

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**Abbreviations**

| | |
|---|---|
| ADHD | attention deficit hyperactivity disorder |
| CI | confidence interval |
| RR | rate ratio |
| SES | socioeconomic status |

**Footnotes**

**Author contributions.** JPW, KND, MDR, and BPL designed the experiments/the study. SDW and KND collected data or did experiments for the study. RWH, MH and JPW analyzed the data. KND and SDW enrolled patients. JPW and KND wrote the first draft of the paper. JPW, KND, MDR, RWH, SDW, BPL, and MNR contributed to writing the paper.

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