Bone Lead Levels and Delinquent Behavior

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Objective.—To evaluate the association between body lead burden and social adjustment.

Design.—Retrospective cohort study.

Setting.—Public school community.

Participants.—From a population of 850 boys in the first grade at public schools, 503 were selected on the basis of a risk scale for antisocial behavior. All of the 850 boys who scored in the upper 30th percentile of the distribution on a self-reported antisocial behavior scale were matched with an equal number drawn by lot from the lower 70% of the distribution. From this sample, 301 students accepted the invitation to participate.

Exposure Measure.—K x-ray fluorescence spectroscopy of tibia at subjects' age of 12 years.

Main Outcome Measures.—Child Behavior Checklist (CBCL), teachers' and parents' reports, and subjects' self-report of antisocial behavior and delinquency at 7 and 11 years of age.

Results.—Subjects, teachers, and parents were blind to the bone lead measurements. At 7 years of age, borderline associations between teachers' aggression, delinquency, and externalizing scores and lead levels were observed after adjustment for covariates. At 11 years of age, parents reported a significant lead-related association with the following CBCL cluster scores: somatic complaints and delinquent, aggressive, internalizing, and externalizing behavior. Teachers reported significant associations of lead with somatic complaints, anxious/depressed behavior, social problems, attention problems, and delinquent, aggressive, internalizing, and externalizing behavior. High-lead subjects reported higher scores in subjects' self-reports of delinquency at 11 years. High-lead subjects were more likely to obtain worse scores on all items of the CBCL during the 4-year period of observation. High bone lead levels were associated with an increased risk of exceeding the clinical score (T>70) for attention, aggression, and delinquency.

Conclusion.—Lead exposure is associated with increased risk for antisocial and delinquent behavior, and the effect follows a developmental course.

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PARENTS of lead-poisoned children and pediatricians who have cared for those children have often observed that after the acute toxic episode subsides children are aggressive and difficult to manage. Fifty years ago, Byers noticed that some children who had been treated for acute plumbism were referred back to him "for violent, aggressive behavioral difficulties, such as attacking teachers with knives or scissors" (R. K. Byers, MD, unpublished data, 1986). It was this observation that resulted in the first follow-up study of the behavioral consequences of acute lead toxicity.[1] Considerable speculation has recently been offered on the nature of the relationship between childhood lead exposure, aggression, and delinquency, but empirical data on the question are sparse.

Since 1943, most studies of the behavioral effects of lead exposure in children have focused on psychometric intelligence to the exclusion of other behavioral outcomes. Those studies that have looked at other measures have found lead-related impaired reaction time, distractibility, disorganization, impulsivity, and restlessness.[2-5] These findings suggest that regulation of attention may be a sensitive target. Lead is also associated with higher scores on the Rutter B2 behavioral scale and on the conduct problem, inattentive-passive, and hyperactive scales of the Connor questionnaire.[3] In Scottish children, lead was related to hyperactivity and aggressive antisocial scores on the Rutter teacher scale.[6] New Zealand children had higher inattention and restlessness scores in relation to dentine lead levels.[7] In males, when attention-deficit hyperactivity disorder is accompanied by aggression, an individual is at strong risk for later delinquent behavior.[8]

For editorial comment see p 403. .

Only one investigation of lead in relation to disciplinary problems, juvenile delinquency, and adult criminality has been published.[9] Denno studied 987 African-American youths (487 males, 500 females) from birth through 22 years of age. After examining many factors, she found lead poisoning, in male subjects only, to be the most significant predictor of disciplinary problems and among the most significant predictors of delinquency and adult criminality.

These observations encourage the study of the role of lead exposure, at levels experienced by children in school, as a risk factor in the genesis of antisocial behavior. To pursue this question, we studied a sample of 301 boys in primary schools. We measured their bone lead concentrations by in vivo x-ray fluorescence (XRF), a measure of cumulative exposure, and examined the relationship of bone lead burden to reports of antisocial behavior from three separate sources: parents, teachers, and the subjects themselves. We also evaluated attentional function, neurobehavioral, and academic performance in relation to bone lead. To minimize confounding by other factors, we controlled for nine relevant social and economic variables and compared outcome before and after covariate adjustment. To identify any development of lead-related dysfunctions over time, we tested the subjects at two periods separated by approximately 24 months, and we evaluated behavioral

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Table 1.—Characteristics of Included and Excluded Subjects*

No.	Status	Hollingshead Code, Mean±SD	Mother's Grade, Mean±SD	Mother's Age in y at Child's Birth, Mean±SD	Mother's IQ (Raven's), Mean±SD	No. of Children in Family, Mean±SD	Both Parents Present, %	High Risk Score, %	Subject's Full-Scale IQ, Mean±SD	Subject's Age in y, Mean±SD	Race, % White
503	Sample Pool	4.9±2.6	12.3±1.8	NA	NA	NA	NA	50.9	NA	12.5±.75	41.4
202	Excluded	5.0±2.7	12.3±1.8	NA	NA	NA	NA	44.1	NA	12.6±.76	45.5
301	Phase I	4.3±2.4	12.3±1.8	23.4±4.7	43.6±8.8	NA	NA	55.5	100.1±16.9	12.5±.74	38.5
69	Excluded	4.3±2.4	12.7±1.9	24.2±4.5	45.8±7.9	NA	NA	60.9	100.7±17.3	12.7±.76	55.1
232	Phase 2	3.7±2.0	12.7±1.7	23.2±4.8	42.9±8.9	3.1±1.4	33.6%	53.9	99.9±16.9	12.4±.73	32.3
20	Excluded	3.4±1.7	12.8±1.3	23.0±6.9	44.9±5.3	3.9±2.0	35.0%	30.0	95.2±19.9	12.5±.81	50.0
212	Analyzed	3.8±2.0	12.7±1.8	23.2±4.5	42.8±9.2	3.0±1.3	35.5%	56.1	100.3±16.5	12.4±.72	30.7

*IQ indicates intelligence quotient; NA, not available.

questionnaires obtained when the subjects were 7 and 11 years of age.

METHODS

Sample

Our sample was recruited from a cohort of students enrolled in the Pittsburgh Youth Study (PYS), a prospective, longitudinal study of the developmental course of delinquency.[10] The population was 850 first-grade boys in the Pittsburgh, Pa, public schools. From this group, subjects were selected to achieve a balanced sample at high and low risk of delinquency. Potential subjects were rated on an instrument composed of serious and potentially indictable behaviors extracted from the teachers' and parents' Child Behavior Checklist (CBCL) and the subjects' self-reports. All subjects who scored above the 30th percentile on the risk score (n=256) and an approximately equal number (n=247) randomly selected from the remainder of the distribution formed the sample. This method has been recommended in studies of delinquency to increase the number of potential offenders in the study.[11] Investigators and psychometricians for the study reported herein remained blind to the risk scores and to individual bone lead levels until data entry was completed.

Of the 503 eligible candidates, 202 families were not tested. Ninety-eight families refused to participate in our study; 17 families lived outside Allegheny County, Pennsylvania, and were not contacted; 33 families were not reachable after a minimum of three attempts by letter or telephone; 32 families repeatedly broke scheduled appointments. Recruitment efforts were dropped for 22 subjects without longitudinal data from the PYS.

Bone lead and psychological measures of subjects were obtained at two times: at mean subject age of 10.2 years (range, 9 to 13 years; n=301) and at mean subject age of 12.0 years (range, 11 to 14 years; n=232). Sixty-nine subjects either declined participation or were unable to be contacted at 12 years of age. Of the 232 subjects tested at 12 years of age, six were excluded from the data analysis because parents refused a repeat bone lead measurement. Fourteen subjects whose parental interview revealed a history of severe neurologic illness were excluded from data analysis. Table 1 describes the covariate structure, intelligence quotient (IQ), and risk scores in the included and excluded groups.

Measurement of Bone Lead

In vivo K XRF (KXRF) was used to determine subject bone (tibia) lead concentrations. Each subject sat in a low lead content ABS (acrylonitrile-butadiene-styrene terpolymer) chair with his target leg immobilized in a plastic restraint. In this technique, 88.035 keV photons from a ^{109}Cd source induce characteristic lead K x-rays, which are measured with a backscatter counting geometry. Bone lead concentrations were estimated from the lead $K\beta_{1+3}$ x-rays (84.94 and 84.45 keV).

The effective dose for a 10-year-old subject from a 30-minute exposure to our source was less than 200 nSv.[12] This procedure was approved by the University of Pittsburgh Institutional Review Board for Psychosocial Research and the Radiation Safety Committee. We modified the commercial bone lead analyzer by replacing the vendor-supplied data acquisition system with an Aptec model 3008 multichannel analyzer that improved signal processing threefold (Aptec Engineering Ltd, Concord, Ontario).

KXRF spectra from tibia phantoms (plaster of paris doped with lead acetate to concentrations ranging from 10 to 110 mg of lead per gram of plaster, with surrounding soft tissue simulated by water) were used to develop optimal peak-fitting routines, calibrate the instrument, and assess the precision of low lead concentration measurements. Plaster lead concentration was confirmed by inductively coupled plasma spectrometry.

Lead K x-ray and coherent scatter peak areas were obtained with a nonlinear minimization algorithm (SYSTAT Inc, Evanston, Ill). We fit gaussian peaks superimposed on monotonic background functions to model the functions. The signal was fit to two models: a monotonic background function as a "null hypothesis" (no lead signal) model and a peak-signal model. The net residual spectra (data-fitted model) of both models were examined for serial correlations that indicate the presence of detectable lead x-rays. The converged sum of squares (and reduced χ^2) values for the null model were then compared with those obtained from the peak-fit model values. In the presence of a significant lead peak, the net residuals for the fitted peak model were lower in magnitude and increased in randomness compared with the corresponding null hypothesis model. For virtually every subject, the lead $K\alpha$ signal was not detectable. In contrast, the $K\beta_{1+3}$ x-rays were routinely discerned and were thus used to estimate bone lead concentrations. For 57 subjects, the coherent scatter was great enough compared with the lead signal to yield negative bone lead values.

At the beginning of our study, the activity of the ^{109}Cd excitation source was 4.5 GBq (120 mCi). This activity proved to be too intense, and the resulting background continuum obscured the lead x-rays from even high-lead phantoms. As a result, many spectra were difficult to analyze. Two years later, when the source strength was 1.5 GBq (40 mCi), the $K\beta_{1+3}$ lines were more readily detectable. Consequently, we report herein the bone lead measurements from the second testing period, when the subjects were 12 years of age. The neuropsychologic data are from the first testing period.

Measures of Antisocial Behavior

The PYS interviewed the parents and children at 6-month intervals in the home. They provided us with the following structured interview data: the Self-reported Antisocial Behavior scale[13] (SRA) (given at subjects' mean age of 7.4 years), the Self-reported Delinquency scale[14] (SRD) (subjects' mean age, 10.9 years), and the parents' and teachers' version of the CBCL (also administered at these ages).[15] The SRA is an inventory of violent and nonviolent antisocial behavior

(scored "never, once, twice, more often"). Eight questions were not understood by many of the subjects and were dropped. We computed a linear sum score from the remaining 22 items. We used 30 items to compute a sum score for the SRD (scored "never, N times"). The CBCL is a 112-item, three-point (scored "never, some, often") scale inventory of child behavior used widely in diagnosis and assessment of psychopathology.[16]

Neurobehavioral Measures

We also surveyed the neurobehavioral function of our subjects. Following the XRF measurement, subjects received a shortened form of the Wechsler Intelligence Scale for Children–Revised (WISC-R),[17] the noncomputerized subtests of the Mirsky attention battery (Stroop color-word test, trail-making test, letter cancellation test, Wisconsin card sort),[18] elements of the Neurobehavioral Evaluation System,[19] and Lanthony's desaturated hue test.[20] To reduce the length of the testing session, a split-half form of the WISC-R was used. The Neurobehavioral Evaluation System subtests given were finger tapping, simple reaction time, serial digit learning, pattern recognition, associate learning, and associate recall.

Covariates

To evaluate and minimize confounding from social and familial factors, we evaluated nine covariates spanning three areas: maternal intelligence, socioeconomic status, and quality of child rearing. The measures were chosen based on a priori knowledge of factors known to influence child development or that could be correlated with lead. The biological mother's IQ was measured with Raven's standard progressive matrices test.[21] Socioeconomic status was estimated by measuring the mother's occupation and education.[22] Family function was estimated by scoring the presence of both parents in the home, mothers' age at subjects' birth, and number of children in the family. In addition, subjects' race and history of noteworthy medical problems were obtained by structured questionnaire. Age was entered into the analyses except in the analysis of the WISC-R, which is age adjusted when scored.

Quality Assurance

Data entry accuracy for the neurobehavioral assessment and WISC-R was checked by entering all data twice into a separate file and counting discrepancies. The error rate for data entry for these instruments was 0.0035. All discrepancies were checked against the primary record and corrected.

To estimate data entry error rates for PYS files, a randomly selected 5% of the PYS sample were examined, and each entry in the computer file was compared to the original hard-copy records. The rate for the CBCL (parent and teacher) ranged between 0.0000 and 0.0046.

Two psychometricians independently scored the written subtests of the attention battery and the WISC-R. The two primary raters agreed on 92.5% of the WISC-R items and 87.6% of the attention battery items. For each item, any discrepancies were evaluated by a third psychometrician, who, after reviewing the original record, made a final decision and recorded it in the database.

Data Analysis

To deal with the large SD in the individual XRF $K\beta_{1+3}$ measures and 57 resultant net negative lead values, we first treated the bone lead estimates categorically in six groups. All negative XRF values were assigned to class 1, the lowest. The positive values were then grouped into quintiles. This grouping produced six ordered classes. A plot of the unadjusted scores on a number of our primary outcome variables vs the six classes of bone lead burden indicated a steep inflection in unadjusted scores beginning after the middle grouping of lead burdens (Figure 1). Responding to the shape of the relationships displayed, we then treated our data dichotomously, splitting the subjects at the upper bound of class 3, and used analysis of covariance (ANCOVA), adjusting for the covariates listed earlier. After analyzing the CBCL data adjusted for nine covariates, we added CBCL scores at 7 years to the model as a covariate and examined the association between lead and CBCL scores at 11 years.

All variables were checked for outliers. The CBCL cluster scores were calculated according to the 1991 scoring manual.[15] Linear sum scores of the selected SRA and SRD items were calculated for each subject. To reduce the effect of influential outliers, CBCL, SRA, and SRD outcome data were transformed by taking square roots of each scaled or summed score.

We also calculated the proportion of subjects at 11 years of age who scored in the clinical ranges (the range within which psychiatrists will make a clinical diagnosis on that behavior) (T score ≥70) on the CBCL attention, aggression, and delinquency scales and cross-tabulated them against dichotomized bone lead category.

The Mirsky attention battery items were scored and factor analyzed. The optimal solution consisted of four factors. Factor 1 loaded primarily on Stroop, coding, trails, and letter cancellation. This factor corresponded to Mirsky's "focus/execute" factor. Factor 2 loaded on continuous performance test reaction time. This factor corresponds to Mirsky's "vigilance" factor. Factor 3 loaded on the continuous performance test errors. Factor 4 loaded on the perseveration item, arithmetic and digit span, and corresponded to Mirsky's "shift" factor. The relationship of the factors to bone lead were then analyzed by ANCOVA.

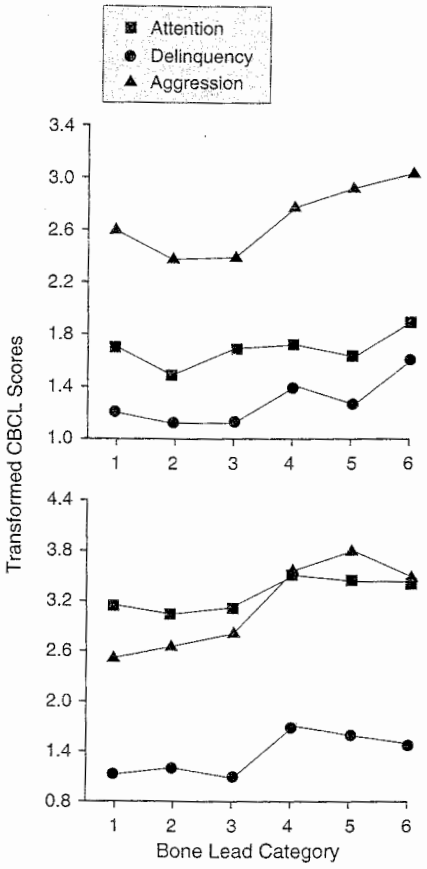

Figure 1.—The relationship between bone lead levels (in hextiles) and Child Behavior Checklist (CBCL) scores. Top, Parents' scores; bottom, teachers' scores. Three outcomes were examined: attention, delinquency, and aggression. Cluster scores were transformed by taking square roots. Group 1 contains all the negative bone lead measurements. The subjects with positive measurements were divided into quintiles.

RESULTS

Table 2 gives the ANCOVA analyses for both parents' and teachers' reports at 7 years of age. Tables 3 and 4 give the ANCOVA for CBCL at 11 years of age. Three models are presented in Tables 3 and 4: the unadjusted bivariate association of bone lead and CBCL cluster, adjustment for nine covariates, and adjustment for nine covariates and CBCL score at 7 years of age. *P* values are given for the third model. Table 5 presents the subjects' reports of their behavior at 7

and 11 years of age. Outcomes are reported with and without covariate adjustment.

The outcomes from all three informant groups were concordant and followed a developmental course. At subjects' age of 7 years (Table 2), parents reported no lead-related difficulties on the CBCL and subjects' SRA scores were not significant. Teachers reported borderline associations at 7 years between lead and somatic complaints, social problems, and delinquent, aggressive, and externalizing behaviors. At subjects' age of 11 years (Table 3), parents of high-lead subjects reported significantly more somatic complaints, more delinquent and aggressive behavior, and higher internalizing and externalizing scores. At 11 years of age, teachers reported significant increases in scores associated with bone lead on the following clusters: somatic complaints, anxious/depressed, social problems, attention problems, delinquent behavior, aggressive behavior, internalizing, and externalizing (Table 4). Adjustment for 7-year CBCL scores had practically no impact on the size of the lead effect.

Subjects' SRD at 11 years (Table 5) was significantly related to bone lead without covariate adjustment (P=.04). This finding was slightly altered by entering covariates (P=.07).

Table 6 gives the WISC-R, attention battery, and neurobehavioral outcome results. Lead level was positively related to verbal and full-scale IQ. This association was found in African-American subjects only. African Americans with high bone lead levels and IQ scores higher than 105 had mothers with higher Raven's scores, had more education and higher socioeconomic status, were more likely to come from two-parent families, and had fewer siblings, while African Americans with low bone lead levels and low IQs (<90) had mothers with lower Raven's scores, had less education and lower socioeconomic status, and had fewer fathers in the home and larger sibships. None of the Neurobehavioral Evaluation System items were related to lead.

When CBCL scores were compared over time, both parents and teachers reported that high-lead subjects were more likely to worsen between 7 and 11 years of age than low-lead subjects (Figures 2 and 3). More high-lead subjects had CBCL scores in the clinical range (T scores ≥70) than low-lead subjects. When we cross-tabulated bone lead split at the median against numbers of subjects with clinically defined scores of attention, aggression, and delinquency, the high bone lead subjects had a higher percentage of scores in the clinical range on every scale (Figure 4). The odds ratios for the outcomes ranged from 1.5 (parents' report of aggression) to 19.7 (parents' report of attention). The lower boundary of the 95% confidence interval was less than 1 on four of six scores (Table 7).

Table 2.—The Relationship of Bone Lead Concentration to Child Behavior Checklist (CBCL) Scores at Subject Age 7 Years*

	Unadjusted Scores		Adjusted Scores		
CBCL Cluster Ratings at Child's Age 7 y	Low-Lead Group	High-Lead Group	Low-Lead Group	High-Lead Group	P
Parents' scores					
Withdrawn	1.30	1.39	1.27	1.38	.32
Somatic complaint	0.79	0.75	0.80	0.74	.62
Anxious/depressed	1.64	1.70	1.62	1.69	.59
Social problems	1.53	1.49	1.52	1.48	.65
Thought problems	0.40	0.33	0.40	0.32	.41
Attention problems	2.04	2.06	2.03	2.05	.82
Delinquent behavior	1.55	1.58	1.54	1.58	.84
Aggressive behavior	3.04	3.10	3.01	3.10	.58
Internalizing	2.42	2.48	2.39	2.47	.57
Externalizing	3.46	3.52	3.43	3.52	.66
Teachers' scores					
Withdrawn	0.89	0.97	0.86	0.98	.51
Somatic complaint	0.14	0.26	0.14	0.26	.14
Anxious/depressed	1.04	1.13	1.03	1.15	.49
Social problems	0.93	1.16	0.95	1.17	.10
Thought problems	0.22	0.32	0.23	0.33	.22
Attention problems	2.79	2.87	2.77	2.88	.67
Delinquent behavior	0.82	1.06	0.83	1.08	.06
Aggressive behavior	2.02	2.49	2.07	2.52	.08
Internalizing	1.51	1.65	1.49	1.67	.40
Externalizing	2.28	2.77	2.32	2.81	.08

*Scores were transformed by square root. Covariates in the model were mother's intelligence quotient, mother's highest grade achieved, age at subject's birth, presence of father, child's age, Hollingshead code, family size, race, and health status. *P* values are given for covariate-adjusted analysis of covariance.

COMMENT

These findings are congruent with each other and in agreement with long-held clinical observations of disturbed social

Table 3.—The Relationship of Bone Lead Concentration to Parents' Child Behavior Checklist (CBCL) Scores at Subject Age 11 Years*

	Unadjusted Scores		Adjusted Scores		Adjusted Plus 7-y CBCL Scores		
Parents' CBCL Cluster Ratings at Child's Age 11 y	Low-Lead Group	High-Lead Group	Low-Lead Group	High-Lead Group	Low-Lead Group	High-Lead Group	P
Withdrawn	1.02	1.15	1.02	1.16	1.02	1.16	.26
Somatic complaint	0.52	0.83	0.52	0.85	0.52	0.85	.008
Anxious/depressed	1.10	1.34	1.08	1.35	1.08	1.35	.09
Social problems	1.16	1.32	1.16	1.32	1.16	1.32	.12
Thought problems	0.28	0.31	0.28	0.31	0.28	0.31	.54
Attention problems	1.66	1.76	1.65	1.76	1.65	1.76	.45
Delinquent behavior	1.19	1.44	1.18	1.45	1.18	1.45	.04
Aggressive behavior	2.48	2.90	2.43	2.9	2.43	2.98	.009
Internalizing	1.76	2.13	1.74	2.15	1.74	2.15	.03
Externalizing	2.82	3.31	2.78	3.31	2.78	3.31	.005

*Mean scores for each cluster are given. Test scores were transformed by square root before analysis of covariance. Covariates adjusted for in the model were mother's intelligence quotient (Raven's score), mother's highest grade achieved, mother's age at child's birth, both parents present in the home, child's age, caregiver's job code, number of siblings, race, and child's health status. Three models are given: unadjusted for covariates, adjusted for covariates, and adjusted for covariates plus 7-year CBCL score. *P* values are given for the final model.

Table 4.—The Relationship of Bone Lead Concentration to Teachers' Child Behavior Checklist (CBCL) Scores at Subject Age 11 Years*

Teachers' CBCL Cluster Ratings at Child's Age 11 y*	Unadjusted Scores		Adjusted Scores		Adjusted Scores		
	Low-Lead Group	High-Lead Group	Low-Lead Group	High-Lead Group	Low-Lead Group	High-Lead Group	P
Withdrawn	1.28	1.53	1.25	1.53	1.25	1.53	.08
Somatic complaint	0.27	0.64	0.24	0.65	0.24	0.65	<.001
Anxious/depressed	1.37	1.94	1.35	1.95	1.35	1.95	<.001
Social problems	1.19	1.71	1.18	1.71	1.18	1.71	.001
Thought problems	0.35	0.55	0.35	0.56	0.35	0.56	.06
Attention problems	3.08	3.50	3.07	3.51	3.07	3.51	.05
Delinquent behavior	1.09	1.64	1.04	1.63	1.04	1.63	<.001
Aggressive behavior	2.60	3.69	2.56	3.71	2.56	3.71	<.001
Internalizing	2.04	2.68	1.99	2.69	1.99	2.69	.004
Externalizing	2.88	4.09	2.82	4.10	2.82	4.1	<.001

*Mean scores for each cluster are given. Test scores were transformed by square root before analysis of covariance. Covariates adjusted for in the model were mother's intelligence quotient (Raven's score), mother's highest grade achieved, mother's age at child's birth, both parents present in the home, child's age, caregiver's job code, number of siblings, race, and child's health status. Three models are given: unadjusted for covariates, adjusted for covariates, and adjusted for covariates plus 7-year CBCL score. *P* values are given for the final model.

Table 5.—Analysis of Covariance (ANCOVA) of Self-report of Delinquency at Ages 7 and 11 Years*

Self-report	Unadjusted Scores			Adjusted Scores		
	Low-Lead Group	High-Lead Group	P	Low-Lead Group	High-Lead Group	P
Antisocial behavior at age 7 y	2.08	2.35	.56	2.12	2.40	.51
Delinquency at age 11 y	1.51	2.39	.04	1.50	2.44	.07

*Test scores were transformed by square root before ANCOVA. Covariates adjusted for in the model were Mother's intelligence quotient (Raven's score), mother's highest grade achieved, mother's age at child's birth, both parents present in the home, child's age, caregiver's job code, number of siblings, race, and child's health status.

Table 6.—Bone Lead Concentrations and Intelligence Quotient (IQ), Attention, and Neurobehavioral Evaluation System Scores*

Test	Mean Low-Lead Level	Mean High-Lead Level	P
Wechsler Intelligence Scale for Children–Revised			
Verbal IQ	96.54	101.08	.006
Performance IQ	102.18	103.14	.68
Full-scale IQ	99.14	102.15	.07
Attention Battery			
Factor 1 Focus/execute	−.043	−.017	.71
Factor 2 Reaction time/vigilance	.112	−.143	.09
Factor 3 Continuous Performance Test errors	−.018	.068	.62
Factor 4 Shift	.002	.079	.55
Neurobehavioral Evaluation System			
Finger tapping, No. of taps	122.96	122.79	.96
Reaction time, mean ms†	351.73	356.54	.68
Reaction time SD, ms†	138.87	139.56	.94
Serial digit learning†	3.11	2.68	.26
Pattern recognition, mean latency, on correct trials	5.27	5.08	.30
Associate learning across three trials, No. correct per trial	3.41	3.29	.46
Associate recall, No. correct	3.44	3.30	.55

*Covariate-adjusted mean scores are given. Covariates in the model are the same as in Tables 2, 3, and 4. IQ score analyses are not adjusted for age.
†Lower scores indicate better performance.

behavior in children who recovered from clinical lead poisoning. They extend the relationship downward in dose to asymptomatic youths with elevated body burdens. In this study, male children considered asymptomatic for lead toxicity with elevated bone lead levels at 11 years of age were judged by both parents and teachers to be more aggressive, have higher delinquent scores, and have more somatic complaints than their low-lead counterparts. The subjects themselves reported lead-related increases in antisocial acts at the same age. High-lead subjects were more likely than low-lead subjects to worsen on all scores of parents' and teachers' CBCL during the 4-year observation period. These results were not altered by control for nine social and familial covariates, indicating that confounding was not influential in our sample.

Other investigators have reported lead-related increases in CBCL scores. Sciarillo[5] found similar effects in African-American children aged 2 to 5 years using parents' ratings alone. Subjects with blood lead levels greater than 0.73 μmol/L (15 μg/dL) had higher scores on the internalizing and externalizing scales and higher total behavior problem scores. Males had higher rates of scores in the clinical range on aggression, delinquency, sex problems, and immaturity. Bellinger et al[23] evaluated teachers' CBCL ratings in a large sample of 8-year-olds. Dentine lead levels were related to total behavioral problem scores, internalizing scores, and externalizing scores. Our study extends these earlier reports by measuring both teachers' and parents' scores and adding the subjects' own ratings of their behavior.

The validity of stuctured behavioral inventories in the measurement of conduct disorder and prediction of future outcome has been shown in many studies, and the CBCL has found wide acceptance since its publication. Children with CBCL T scores above 70, the clinical cutoff, have much higher referral rates to psychiatric clinics than those who score below the cutoff.[15] A follow-up study of 1613 subjects who had received the CBCL scales demonstrated that scores on the delinquency cluster were the best predictor of later adjustment difficulty, as measured by academic failure, behavior problems, police contacts, need for mental health services, or substance abuse. The best predictor of suicidal threats or attempts was high aggression scores on the CBCL.[24]

Early reports of conduct disorder or aggression, demonstrated in these subjects, are strong predictors of later criminality. These behaviors, when displayed early in early childhood, are stable. Farrington studied 411 males in London and

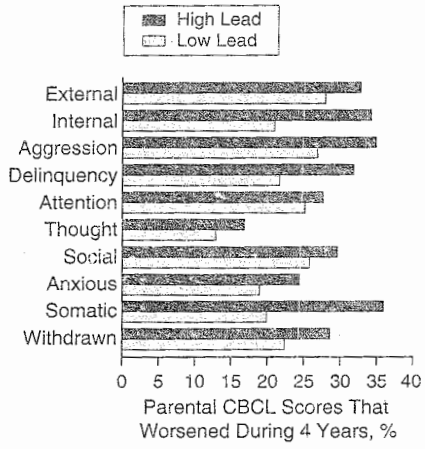

Figure 2.—The change in parental Child Behavior Checklist (CBCL) scores during 4 years in relation to bone lead concentrations. Subjects are classified as "high lead" (above the median) and "low lead" (below the median).

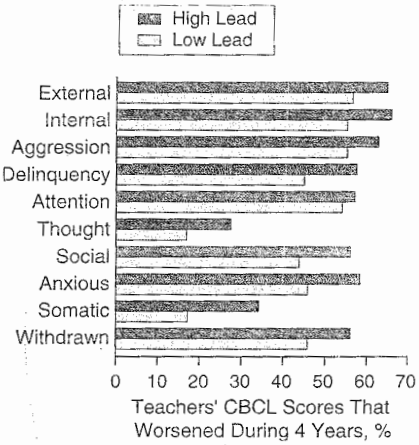

Figure 3.—The change in teachers' Child Behavior Checklist (CBCL) scores during 4 years in relation to bone lead concentrations. Subjects are classified as "high lead" (above the median) and "low lead" (below the median).

found that children reported to be "troublesome" on a rating scale by their teachers at 8 years of age were significantly more likely to be adjudicated as delinquent at 18 years of age, to rate themselves as aggressive at 32 years of age, and to have been convicted of a violent crime by 32 years of age.[25]

Any study of lead must confront the fact that lead exposure is higher in samples who have more nonlead risk factors. Lead levels are higher in minorities and in subjects with low income. Delinquency is associated with minority status, poverty, and disorganized families. In this study, adjusting for nine covariates did not substantially alter the strength of the association. While we did not control for all nonlead covariates, the

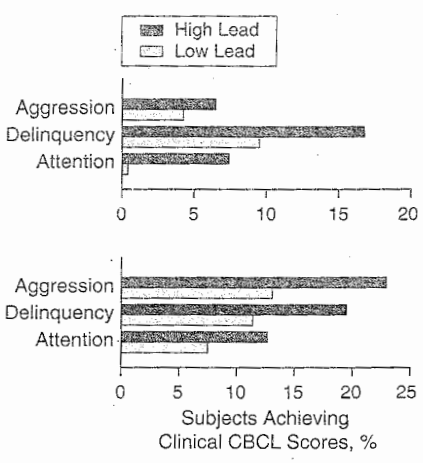

Figure 4.—The association between bone lead concentation and clinical Child Behavior Checklist (CBCL) (T>70) scores for aggression, delinquency, and attention. Subjects are classified as "high lead" (above the median) and "low lead" (below the median). Both parents' CBCL scores (top) and teachers' scores (bottom) are displayed.

Table 7.—The Relationship Between Bone Lead and Clinical Child Behavior Checklist (CBCL) Scores

CBCL Cluster/Rater	OR	95% CI
Attention		
Parent	19.35	8.9-41.6
Teacher	1.71	0.57-5.1
Delinquency		
Parent	1.89	0.83-4.3
Teacher	2.16	0.96-4.6
Aggression		
Parent	1.49	0.45-4.9
Teacher	2.18	1.03-4.6

*OR indicates odds ratio; CI; confidence interval.

factors we entered into the model did capture parental education and occupation (an index of socioeconomic status), race, mother's age at subject's birth, and presence of father in the home (indexes of family intactness and support). The small alteration in effect size when the covariates were entered into the model suggest that confounding is not great in this sample. It is possible, of course, that some unmeasured socioeconomic factor is influencing outcome and is associated with lead. It is unlikely that such a factor would not be correlated with any of the nine socioeconomic variates for which we controlled.

The positive association between bone lead and IQ that we encountered was limited to African-American subjects. High-IQ, high-lead subjects were favored on all nonlead factors when compared with low-IQ, low-lead subjects, who were disfavored on the same factors. This finding suggests that at these low levels of internal dose, social rearing factors were more influential than lead on IQ and that imperfect control of covariates or error in measuring them may explain the positive association. When we stratified subjects by IQ (<90, 91 to 104, >104) and examined the effect of lead on CBCL scores, we found that within each IQ stratum, high-lead subjects had higher CBCL scores. This finding was true for both races.

Through what mechanisms could a toxic metal influence a child's social adjustment? A number of neurochemical alterations offer potential explanatory mechanisms. For example, lead has been shown to interfere with norepinephrine-mediated inhibition in the rodent.[26] By disrupting inhibitory processes, lead could result in unmediated rapid responses to stimuli, which could be expressed as impulsivity. Lead exposure peaks between 2 and 3 years of life in children, the time of pruning back neuronal fibers. Goldstein suggests that by increasing the response to a given stimulus, lead could disturb the orderly pruning and result in later overresponsiveness.[27] Studies of teachers' reports of classroom behavior[2,3,28] have shown a lead-related increase in impulsivity, hyperactivity, and frustratibility.

Experimental studies in subhuman primates report similar effects of lead on behavior. Infant rhesus monkeys given low doses of lead that raised their blood lead levels to 3.30 μmol/L (70 μg/dL) showed disruptions in social behavior that lasted well past the time of administration, when blood lead levels had declined to 1.45 μmol/L (30 μg/dL).[29]

In children, attentional impairment[30] is a strong risk factor for delinquent behavior. Lead has been shown in a number of studies to affect attention: signaled reaction time,[2] teachers' ratings of classroom behavior,[2,3] and scores on structured behavioral inventories.[3] Monkeys dosed with lead from birth onward to reach a mean blood lead level of 0.73 μmol/L (15 μg/dL) showed perseveration, increased distractibility, inability to inhibit inappropriate responding, and difficulty in changing response strategy.[31] In our subjects, scores on the vigilance factor of the attention battery and clinical scores on the attention cluster of the CBCL were related to bone lead level.

Lead exposure is associated with reduced verbal competence, increased rates of reading disabilities, frustration, and increased academic failure. Reduced verbal skills could interfere with the use of internal language to mediate behavior and to delay immediate responding. Another factor that may be an intervening variable in the causal chain between lead and delinquency is academic failure, a demonstrated consequence of lead exposure. Subjects with elevated tooth lead levels in childhood, when followed into adulthood, had a sevenfold increase in the rate of high school failure and a sixfold increase in reading disability.[32] Stu-

dents who fail to graduate from high school and have poor reading skills have dim employment prospects, which could readily increase the risk of antisocial behavior. The sample reported herein is too young for this mechanism to express itself. Bone lead burden was not associated with inferior school performance in this study.

We cannot readily relate our XRF data to current or past blood lead standards. Our subjects were considered asymptomatic for lead and were attending ordinary public school. This circumstance suggests that the distribution of lead levels in our sample was in the range of community exposures in 1982, when the estimated prevalence of blood lead levels of greater than 0.73 μmol/L (15 μg/dL) of all US children was 16%.[33] The appearance of lead-related effects at the median bone lead level suggests that in some samples lead may contribute to dysfunction in an appreciable proportion of the community. Further work is needed to define the relationship between XRF measures and past blood lead concentrations.

If the findings reported herein are found to extend to the population of US children, the contribution of lead to delinquent behavior would be substantial. Large numbers of US children continue to have lead burdens in the neurotoxic range. Between 1976 and 1991, mean blood lead levels in children have decreased 77%, from 0.66 μmol/L (13.7 μg/dL) to 0.15 μmol/L (3.2 μg/dL). But many thousands of children continue to have toxic lead burdens, especially in minority urban communities. The prevalence of blood lead levels greater than 0.48 μmol/L (10 μg/dL), the current Centers for Disease Control and Prevention effect level, in non-Hispanic blacks is 21%.[34]

Delinquent behavior is a complex and multifaceted problem in which the search for causes has centered on two groups of determinants: social or experiential factors and those that are subsumed under the class of biological causes. In *Crime and Human Nature*,[35] Wilson and Herrnstein, arguing that criminality is primarily constitutional in origin, observed the following correlates with criminal behavior: criminality is more common in males, the rate of criminality is higher in African Americans, criminals have lower verbal IQ scores, and criminals frequently have histories of hyperactivity. It is intriguing that these factors are also associated with lead, either as risks for lead exposure or as effects of lead.

The interrelations between biological and experiential roots are tightly interwoven and difficult to disentangle. Among the biological factors, brain injury is recognized to impair social adjustment and occasionally to lead to violence or criminality.[9,10,36] The role of brain damage due to neurotoxins in eliciting antisocial behavior has, with the exception of alcohol, been largely ignored. The convergent findings in this report from three separate sources, parents, teachers, and the subjects themselves, in the absence of consistent psychometric or neurobehavioral effects, suggest that altered social behavior may be among the earliest expressions of lead toxicity. These data argue that environmental lead exposure, a preventable occurrence, should be included when considering the many factors contributing to delinquent behavior.

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