ENVIRONMENTAL LEAD AND CHILDREN: THE OMAHA STUDY

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Blood lead (Pb B) was determined in 1232 samples from 831 children in Omaha and correlated with air lead (Pb A) concentrations of 0.02–1.69 μg/m³ from 1971 to 1977. A bivariate equation for ages 6–18 yr based on these data predicts an increase in Pb B of 1.4 μg/dl as Pb A increases from 1 to 2 μg/m³. Pb B increases 7 μg/dl as the mean values for soil and house dust Pb increase from 100 to 750 μg/g. Multiple regression analysis shows that the combined effects of air, soil, and house dust Pb account for 21% of the variance of Pb B, with a high intercorrelation of all 3 variables. Since the variance of repeat sampling in individuals accounted for 38% of the total variance of Pb B, approximately 40% is unexplained and requires measurement of Pb from dietary and other sources.

INTRODUCTION

The Environmental Protection Agency (1978) established the air quality standard for Pb at 1.5 μg/m³:

> This level was derived from the Agency's judgment that the maximum safe blood lead level (geometric mean) for a population of young children was 15 μg Pb/dl and, of this amount, 12 μg Pb/dl should be attributed to nonair sources. The difference of 3.0 μg Pb/dl was estimated to be the allowable safe contribution to mean population blood lead from lead in the air. With epidemiological data indicating a general relationship of 1:2

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between air lead (μg Pb/m^3) and blood lead (μg Pb/dl), EPA determined that the level for the proposed standard should be 1.5 $\mu g/m^3$.

This standard was based on the assumption of a crude average of background Pb, as data were insufficient "to predict the relationship between air lead levels, dustfall rates and resulting soil accumulation." Only four of the reported childhood studies—Roberts et al. (1974) in Toronto, Johnson et al. (1976) in California, Yankel et al. (1977) and Ashley (1976) in Idaho, and the El Paso study [*Morbidity and Mortality Monthly Report* (*MMMR*), 1978]—included data on soil and dust as well as air as related to blood Pb.

We have been monitoring air Pb in Omaha at three sites since 1970, simultaneously sampling house dust, soil, and dustfall Pb, for correlation with 1232 samples of blood lead (Pb B) from 831 preschool, school-age, and high school children (McIntire and Angle, 1972; Angle et al., 1974, 1975a–1975c; Angle and McIntire, 1975). This is a report of the correlation of childhood Pb B with air, soil, and house dust Pb as found in the 7-yr Omaha study.

METHODS

Subjects

Children participating in the study were all volunteers recruited with the cooperation of their schools and parents. Much of the support was related to public enthusiasm for the Clean Air Act of 1970. Throughout the study the children are categorized by school level and age: preschool, ages 1–5 yr, $n = 199$ (244 samples); grade school, junior and senior high school, ages 6–18; $n = 632$ (988 samples). Preschool children were sampled in 1974 only, whereas sampling of older children was distributed over 6 yr. The children live in three general areas in Omaha: urban-commercial (C), $n = 132$, in the vicinity of a small battery plant; urban-mixed (M), $n = 589$, a residential area contiguous with downtown Omaha; and suburban (S), $n = 110$, as shown in Fig. 1. There is potential bias in the selection of subjects since the children are all volunteers and subjects are not equally distributed among the three sites. Virtually all of the urban children (C and M) are black; all of the suburban children (S) are white. Our earlier research interests resulted in an initial selection of urban black children with a deficiency of red cell glucose-6-phosphate dehydrogenase. Data on these children are retained since this enzymatic defect has no effect on Pb B, although an increase in red cell Pb coexists with decreases in hemoglobin (Angle and McIntire, 1975). In the suburban high school population there is an excess of males; elsewhere there is an equal sex distribution of the subjects.

model 303 atomic absorption spectrophotometer. All assays from 1971 to 1977 were done in replicate, employing the method of addition for each individual sample.

Air Lead

Air lead (Pb A) samples were obtained as 24-h collections at 6-d intervals in Hi-Vol samplers (particle size 0.1–10 μm) at 15 ft elevation at schools in each of the 3 geographic areas. Previous studies showed no significant difference in the Pb A at 3 and 15 ft (Angle et al., 1974). The sampler at site C was approximately 500 yd from the emission source; all samplers were more than 15 yd from a roadway. In 1970 and 1971 the filters were assayed for Pb A by R. E. Enrione (Metals and Advanced Analysis Section, EPA, Cincinnati, Ohio). In 1972 and 1973 assays were done by E. R. Williams (South Carolina Department of Public Health under contract to the EPA). In 1974–1977, Pb A assays were done by the Omaha-Douglas County Health Department by atomic absorption spectrometry (AAS), using the method of Purdue et al. (1973). Concordance of Pb A values for 1973 was used to establish the reliability of the assays done by the Omaha laboratory. The values in 1971 were reported by Enrione as the composite of all filters for that month. Subsequent monthly means were derived from the individual values of filters every sixth day.

Dustfall Lead

Dustfall Pb was collected by the standard technique of total accumulation in a plastic container at a height of 4 ft at each of the 3 air collection sites and reported as milligrams of Pb deposited per square meter per 30-d collection. Dustfall, soil, and house dust were measured by AAS in the same laboratories as Pb A.

Soil Lead

All samples of soil Pb were collected as a 2-in core obtained halfway between the building and the lot line on all 4 sides and reported as the arithmetic mean. In 1972, soil and household Pb samples were collected from 37 individual houses for correlation with the Pb B of individual children. An additional 148 samples were taken at each child's school or preschool, with a total of 20 sites sampled 1 to 5 times.

Household Dust

Household dust was obtained at the same sites as soil. At most sites it was obtained by emptying the vacuum cleaner bag. Where there was no vacuum cleaner a composite was obtained by sweeping the floor and windowsills.

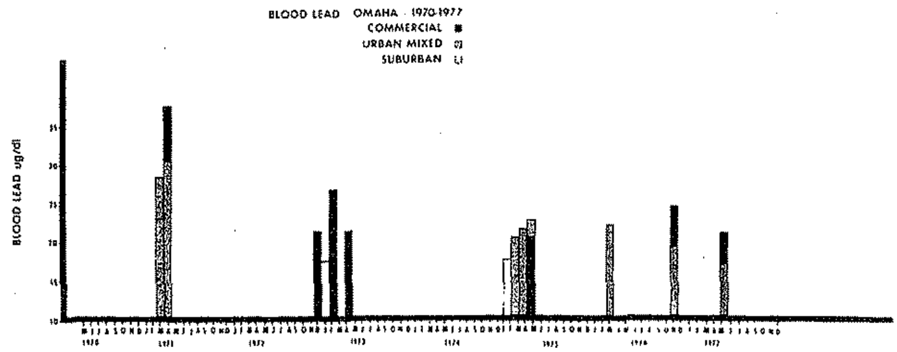

FIGURE 2. Pb B (arithmetic means) of 1232 samples from 831 children 1–18 yr old, 1971–1977.

Group distributions of Pb B showed the geometric mean and standard geometric deviation (GM ± SGD) of 24.8 ± 1.4 at site C to be significantly ($p < 0.001$) higher than the value of 22.0 ± 1.4 at site M, which was higher ($p < 0.001$) than the value of 18.0 ± 1.3 at site S. As shown in Fig. 2, Pb B decreased from 1971 to 1975 and there was no significant change from 1975 to 1977.

Analysis of the variance of Pb B (Table 1) showed that sampling variance, or the difference between repeat samples from one individual, accounted for 38% of total variance. Since all samples were done in replicate by the method of addition, no additional estimate is made of analytic variance.

The higher Pb B from May through October suggested seasonal changes as one component of sampling variance, but in the absence of a 12-mo sampling of a comparable age group at one site, seasonal variance could not be validated.

TABLE 1. Variance of Pb B

Age (yr)	Individuals	Samples	$\bar{X}$ ± SD (μg/dl)	Total variance[a]	Intra-individual variance[b]	Between-individual variance[c]
1–5	199	244	23.9 ± 9.2	84.6	37.4 (44%)	56%
6–18	632	988	22.3 ± 7.7	60.1	27.7 (46%)	54%
Total	831	1232	21.3 ± 8.1	65.6	25.2 (38%)	62%

[a]Total variance is the square of the standard deviation.

[b]Intra-individual variance $= \Sigma (X_i - \bar{X}_i)^2/[(r-1)/n]$, where X_i is a single sample (replicate average) from an individual, $\bar{X}_i$ is the average of all samples from the individual, r is the number of repeat samples for the individual, and n is the number of individuals.

[c]Between-individual variance is total variance (100%) minus individual variance. Calculations are derived from Lucas (1977).

Soil Lead

Geometric means and ranges of soil Pb (μg/g), with the number of samples in parentheses, were as follows:

	GM	Range
Site C (69)	262	53–1615
Site M (56)	339	20–4792
Site S (51)	81	16–341

The geometric mean soil Pb assigned to 1074 blood samples was 227 μg/g with a ninety-fifth percentile of 843 μg/g.

House Dust Lead

House dust Pb (μg/g) at the three sites showed no significant urban-suburban difference in the geometric mean (number of samples in parentheses):

	GM	Range
Site C (26)	479	76–5571
Site M (14)	300	76–860
Site S (26)	211	18–845

The geometric mean of house dust Pb assigned to the 1074 samples was 337 μg/g with a ninety-fifth percentile of 894 μg/g.

Environmental Correlation

Simple Pearson correlations showed a distinct difference in the log-log correlation of Pb B with the Pb A and dustfall lead (Pb DF) between preschool and school-age children, although correlations with soil (Pb S) and house dust (Pb HD) were similar:

	Pb A	Pb DF	Pb S	Pb HD
Pb B, 1–5 yr	−0.44	−0.30	0.27	0.29
Pb B, 6–18 yr	0.31	0.04	0.40	0.29

There was no significant difference in correlation according to year of collection, race, or sex. Differences between urban and suburban children are discussed in connection with the bivariate correlations.

TABLE 2. Correlation of Pb B with Environmental Pb

Age (yr)	Samples	Equation	SEE[a]	SE coeff[b]	r[c]
		Pb A			
1–18	1074	log Pb B = 1.3475 + 0.0269 log Pb A	0.1449	0.0081	0.10**
1–5	242	log Pb B = 1.2461 − 0.1331 log Pb A	0.1422	0.0172	−0.44
Urban	204	1.2901 − 0.1150	0.1293	0.0167	−0.43
Suburban	38	1.1316 − 0.0451	0.0837	0.0321	−0.23
6–18	832	log Pb B = 1.3660 + 0.0834 log Pb A	0.1346	0.0089	0.31**
Urban—all	620	1.3823 + 0.0899	0.1363	0.0102	0.33**
Battery plant	153	1.4522 + 0.3196	0.1239	0.0372	0.57**
Suburban	212	1.2591 − 0.0171	0.1132	0.0189	−0.06
		Pb S			
1–18	1074	log Pb B = 0.9766 + 0.1515 log Pb S	0.1348	0.0113	0.38**
1–5	242	log Pb B = 0.8936 + 0.2033 log Pb S	0.1532	0.0474	0.27*
Urban	204	1.2895 + 0.0417	0.1430	0.0491	0.06
Suburban	38	0.5288 + 0.3074	0.0843	0.2559	0.20
6–18	832	log Pb B = 0.9563 + 0.1560 log Pb S	0.1273	0.0112	0.44**
Urban	620	0.9203 + 0.1695	0.1313	0.0147	0.42**
Suburban	212	1.3160 + 0.0231	0.1134	0.0802	0.02
		Pb HD			
1–18	1074	log Pb B = 0.9145 + 0.1655 log Pb HD	0.1393	0.0165	0.29**
1–5	242	log Pb B = 0.7494 + 0.2170 log Pb HD	0.1520	0.0460	0.29**
Urban	204	0.8320 + 0.1979	0.1395	0.0614	0.22*
Suburban	38	1.0555 + 0.0384	0.0848	0.0382	0.17
6–18	832	log Pb B = 0.8557 + 0.1921 log Pb HD	0.1347	0.0207	0.31**
Urban	620	B = 0.7950 + 0.2258	0.1334	0.0216	0.39**
Suburban	212	1.2327 + 0.0151	0.1134	0.0563	0.02

[a] Standard error of the estimate.
[b] *Standard error of the coefficient.*
[c] Significant and positive at (*) $p < 0.01$ and (**) $p < 0.001$.

employed to investigate the total variance attributed to all three sources:

$$\log \text{Pb B} = a + b \log \text{Pb A} + c \log \text{Pb S} + d \log \text{Pb HD}$$

In the preschool children, sampled only in 1974, the multiple regression showed significant positive correlations only with house dust and soil, which accounted ($r^2 \times 100$) for a total of 11% of the variance of Pb B. For ages 6–18 yr there was a significant positive correlation of Pb B with air, soil, and house dust Pb as entered in this order: Pb B = 8.1 Pb $A^{0.03}$ Pb $S^{0.10}$ Pb $HD^{0.07}$ (standard error of estimate, 1.3; $r = 0.46$; $p < 0.001$). The cumulative increases in $r^2 \times 100$ showed air, soil, and house dust to account for 21% of the variance of Pb B. Because of the high

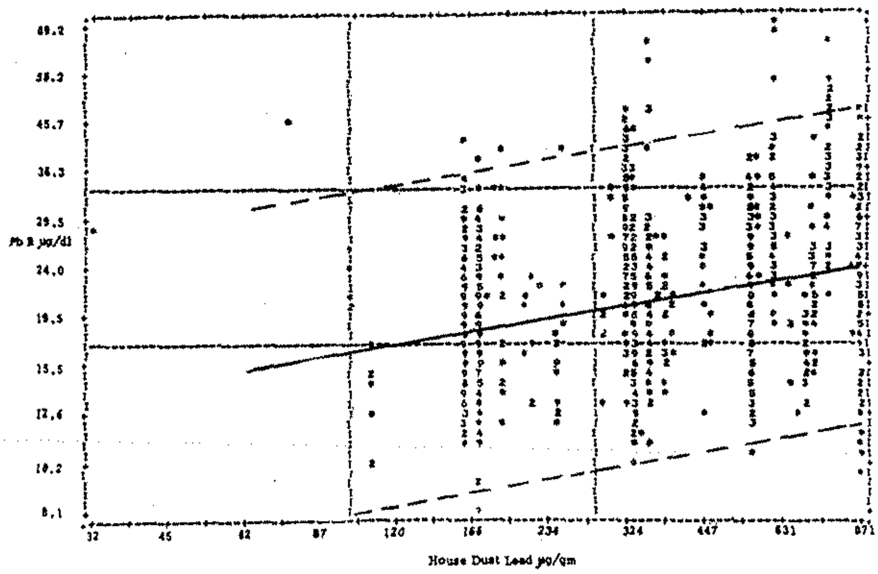

FIGURE 6. Scattergram showing the correlation of 1074 samples of Pb B with Pb HD in 831 children 1–18 *yr old*: $Pb\ B \approx 8.2\ Pb\ HD^{0.16}$. Dashed lines are drawn at twice the standard error of the estimate.

multicollinearity of the independent variables, it was not statistically valid to attribute a discrete percentage to each source.

DISCUSSION

The multiple variables in childhood Pb B and the difficulty of arriving at environmental criteria from community studies are well illustrated by the Omaha study of urban and suburban children in 1971 to 1977. The variables include the nonnormal distribution of Pb B, sampling error, seasonal change, the intrinsic error in any attempt to correlate individual Pb B with environmental samples from communal and stationary sites, and the unmeasured contribution of dietary Pb.

Sampling Variance

As noted in the analysis of variance (Table 1), 38% of the variability in Pb B could be attributed to differences between repeat samples from an individual. The between-individual variance of 62% compares favorably with the 12–61% residual variance that Lucas (1977) found on analysis of the studies of Azar et al. (1975), Tepper and Levin (1975), McLaughlin et al. (1976), and Johnson et al. (1976). The contribution of intrinsic seasonal variation is suggested by the higher Pb B levels of summer, which do not coincide with our seasonal peaks of Pb A, January through March. Air studies in Denver by Edwards and Wheat (1978) showed a similar pattern.

TABLE 3. *Omaha Equation and Four Community Studies*[a]

Study	Pb A ($\mu g/m^3$)	Pb S ($\mu g/g$)	Pb HD ($\mu g/g$)	Pb B ($\mu g/dl$)	Estimated Bk ($\mu g/dl$)	Predicted Pb B ($\mu g/dl$)
Idaho	1.0	500	3000	26.7	8.1	26.4
	2.0	1000	3000	28.1		28.9
Los Angeles						
Lancaster	0.64	66	(66)	9.6	4.8	9.7
Los Angeles	6.3	1000	(1000)	14.6		16.4
Toronto						
Control	0.82	99	713	17	6.9	17.2
Smelter	3.01	1715	1550	27		25.1
El Paso						
1977	1.3	427	1479	20.1	6.6	20.3
1972	4.4	1791	22191	31.2		29.4

[a]The regression equation Pb B = Bk Pb $A^{0.03}$ Pb $S^{0.10}$ Pb $HD^{0.07}$ was applied to the means of Pb A, Pb S, Pb HD, and Pb B of four epidemiologic studies of children. Idaho data are taken from the predicted equation of Yankel et al. (1977) with the substitution of the average household dust as cited by Ashley (1976, p. 107). Toronto data are from Roberts et al. (1974). The Pb HD cited for El Paso (*MMMR*, 1978) is actually for exterior dust. Los Angeles data (Johnson, 1974) equate soil with house dust. Background Pb B (Bk) was estimated by substituting community data at the lower level of Pb A in the Omaha equation. This Bk was then used to predict Pb B at the higher Pb A. Estimated Bk in Idaho was identical to that in Omaha. The Omaha regression predicts Pb B within 2 $\mu g/dl$ in all 4 studies.

sources in arriving at environmental standards. Intestinal absorption of Pb may be as high as 42% in children (Ziegler et al., 1978) and, in the absence of pica or unusual sources, dietary Pb is the principal component of the body burden. As reviewed by Mahaffey (1977), dietary intake of Pb by infants averages 75–120 $\mu g/d$ but may be as high as 716 $\mu g/d$.

The determination of the blood-environmental Pb response in community studies is therefore not a matter of a simple correlation, particularly over long periods of surveillance. Community-wide changes in Pb B are multifactorial; air, soil, water, housing, and socioeconomic shifts have an additive or even a synergistic effect. The Lead Paint Poison Prevention Act has a great potential for reducing and ultimately eradicating Pb contamination in housing. The Paint Act and the introduction of unleaded gasoline in 1973 have attacked major components of environmental Pb contamination and may account for the rapid changes in childhood Pb B in large cities (Billick and Gray, 1978). If control of Pb A continues, the existing Pb in the environment will most likely continue to be more important than Pb A in contributing to Pb B levels.

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