EPIDEMIC LEAD ABSORPTION NEAR AN ORE SMELTER

The Role of Particulate Lead

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Abstract Blood lead levels were determined on a random sample of persons in all age groups living near a lead-emitting smelter in El Paso, Texas. A blood lead level of ≥ 40 μg per 100 ml, which was considered indicative of undue lead absorption, was found in 53 per cent of the children one to nine years old living within 1.6 km of the smelter and in 18 per cent of those from 1.6 to 6.6 km; beyond that distance and in older persons levels were lower. Children in the first 1.6 km with blood levels of ≥ 40 μg per 100 ml were exposed to 3.1 times as much lead in dust as children there with lower blood values (6447 vs. 2067 ppm). There was also airborne lead exposure (8 to 10 μg per cubic meter, annual mean). Paint, water, food, and pottery were less important sources.

The data suggest that particulate lead in dust and air accounted for most of the lead absorption in El Paso children. The smelter was the principal source of this lead, especially within 1.6 km of itself. (N Engl J Med 292:123-129, 1975)

It is estimated that 166,000 metric tons of particulate lead are emitted into the atmosphere each year in the United States.[1] There is a growing realization that this lead, most of which is emitted by automobiles, may be a widespread and potentially important source of lead absorption among children.[2-6] Chronic ingestion and inhalation of particulate lead from contaminated dust, soil, and air may account in part for the higher mean blood lead levels of urban as compared to rural children,[2] and may account for the increased lead levels seen in children living near busy roadways.[7]

Stationary sources of lead particulates, such as smelters, account for only a small fraction of the total lead output. Environmental concentrations of lead, however, may reach especially high levels in the vicinity of stationary sources,[8-11] particularly where climatic conditions such as aridity, low wind velocity, and frequent thermal inversion minimize opportunities for pollutant dispersal. Study of human lead absorption in such localities might illustrate the potential health hazard posed by particulate lead and might better define the routes of its absorption from the environment.

The present studies were conducted in El Paso, Texas, near a large ore smelter that has been in operation since 1887 and has the capacity to extract lead, copper, and zinc from over 800,000 metric tons of ore concentrates annually. In December, 1971, the El Paso City—County Health Department found that this smelter had emitted 1012 metric tons of lead, as well as 508 metric tons of zinc, 11 metric tons of cadmium, and 1 metric ton of arsenic into the atmosphere through its stacks in the years 1969 through 1971.[12,13] In our studies we determined blood lead levels in a sample of persons living throughout El Paso, and we measured exposure of these persons to lead in dust, soil, air, paint, food, water, and pottery. Our purpose was to ascertain the prevalence and severity of lead absorption in this locale, and to evaluate the role here of particulate lead in lead uptake.

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BACKGROUND

El Paso, population 322,261 (1970 United States Census) is located in the Rio Grande Valley in west Texas. It is surrounded to the north, northwest, and west by high mountains. The climate is extremely arid (10 to 25 cm of rainfall per year),[14] and a fine, gritty dust is present in the air on many days. Winds are light, and calm is observed in 25 per cent of hourly readings.[15] Thermal inversions occur on 70 per cent of mornings.[15]

AIR SAMPLING*

Measurements were made of lead, zinc, cadmium, and arsenic concentrations in high-volume samples of airborne particulates, of the size distribution and content by size of suspended particles, of ratios of lead to bromine in high-volume samples, and of the heavy-metal content in dustfall.

High-volume air samples were collected upwind and downwind of the smelter at the property boundary, 60 to 120 m from the base of the main smelter stack, and at 39 other locations in El Paso. Collections were according to the method of the Texas State Department of Health[16]; lead, zinc, and cadmium determinations were by atomic absorption spectrophotometry and arsenic by an arsine method.[17] The annual mean lead concentration at the property boundary downwind of the smelter in 1971 was 92 μg per cubic meter (range, 15 to 269 μg per cubic meter). Levels fell rapidly with distance and reached background values at 4 to 5 km (Fig. 1). Cadmium, zinc, and arsenic levels were also highest immediately adjacent to the smelter and decreased with distance. Lead emissions were found intermittently adjacent to a battery-recovery plant, but no appreciable heavy-metal emissions were observed at any of 14 other industrial establishments tested. From June, 1972, through July, 1973, the lead concentra-

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Vol. 292, January 1975

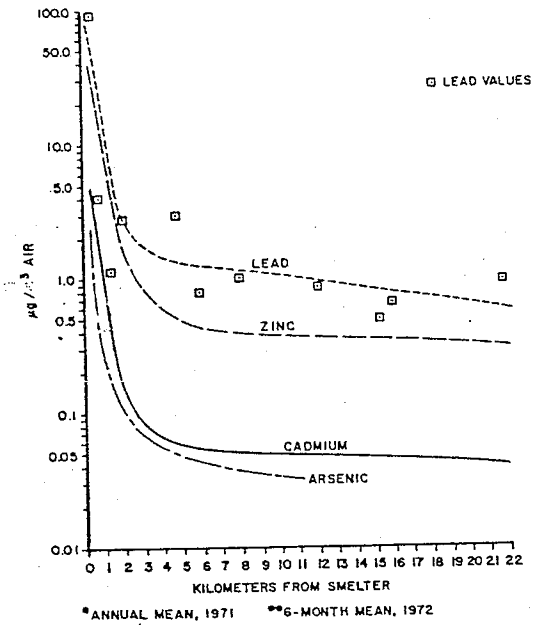

Figure 1. Air Lead,* Cadmium,* Zinc* and Arsenic** Concentrations (Suspended Particulates), According to Distance from Smelter, El Paso, Texas.

tion was again highest downwind of the smelter (12-month mean, 43 μg per cubic meter).

Data on the size distribution of particles were collected once a month[18] from August, 1972, through July, 1973, at a single site 250 m from the smelter with use of the Andersen particle-sizing head. The data indicated that 42 per cent of the particulate mass was contained in particles below 2.0 μm in diameter (12-month mean). Atomic absorption spectrophotometry of each size fraction was performed on the seven samples collected from January through July, 1973, and showed concentrations of lead to be highest in particles below 1 μm (Fig. 2).*

Additional high-volume air samples were analyzed† for lead and for bromine content[20] as a measure of the contribution of automotive sources to airborne lead; in commercial gasolines[21] and in automotive exhausts the ratio of lead to bromine is 2.6/1.0. Samples taken in February, 1972, at a site 200 m from the smelter showed a mean lead/bromine ratio of 62.8 (Fig. 3). Samples from the same location in May, 1973, had a ratio of 11.2. Additional 1973 samples showed that ratio to decrease rapidly with distance from the smelter and to approach a base-line value of approximately 2.6 at 5 to 6 km.

Dustfall (settleable particulate) samples were obtained from October, 1970, through July, 1971, at the smelter and at 10 other sites (Fig. 4).[12] Dustfall was greatest at the

*Respiratory lead absorption is inversely proportional to particle size. Reports indicate that at least 30 per cent of particles below 2 μm in diameter are retained and subsequently absorbed in the lungs. Between 10 and 30 per cent of particles of 2 to 5 μm and almost none larger than 5 μm are retained.[1,19] Larger particles, however, may be swallowed, contributing to gastrointestinal absorption.

†Determinations kindly performed by Dr. Jimmy Payne, of the Texas Air Control Board, Austin, TX, with use of an x-ray fluorescence technic.

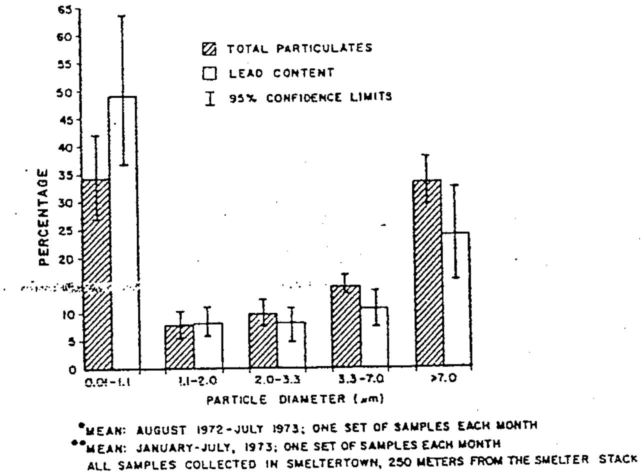

Figure 2. Size Distribution* and Lead Content** of Airborne Suspended Particulates, El Paso, Texas.

smelter and decreased with distance. Likewise, the content of each metal was highest at the smelter (10-month means, 204 mg per square meter per month for lead, 86 for cadmium, 999 for zinc, 553 for arsenic, and 1511 for copper). In areas shielded by mountains, background levels were observed closer to the smelter than in open areas of the valley.

Soil Sampling

Soil samples were collected from March, 1972, through June, 1973, at 99 sites in El Paso and at three remote sites. Samples were taken at the surface and at depths of 2.5, 5.0

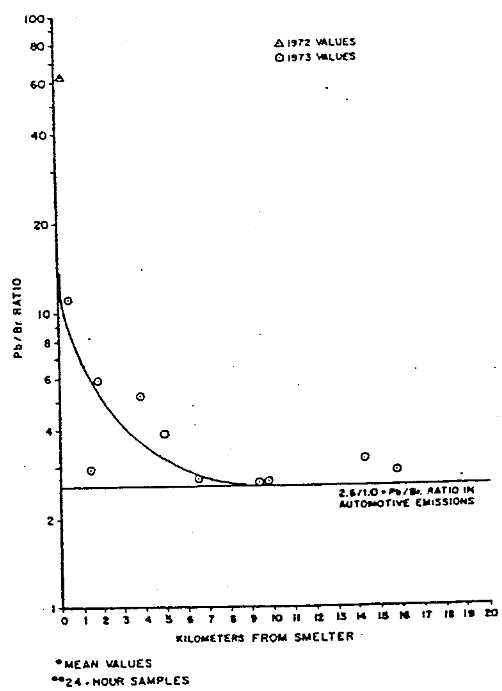

Figure 3. Lead/Bromine (Pb/Br.) Ratios* in Airborne Particulate Samples,** El Paso, Texas, in February, 1972, and April-July, 1973.

and 7.5 cm and analyzed for lead content by atomic absorption spectrophotometry. Only trace amounts of lead (<50 ppm) were found at the remote sites. Within the city, highest levels in 1972 were found within 200 m of the smelter (mean of 3457 ppm and range of 560 to 11,450 for 54 samples); lead content was consistently highest at the surface. Levels fell rapidly in the first 2 to 3 km from the smelter, but remained above background for as far as 10 km (Fig. 5). Similar though less extensive distributions were noted for zinc, cadmium, and arsenic. Distribution patterns for all these metals in 1973 were virtually unchanged from 1972.

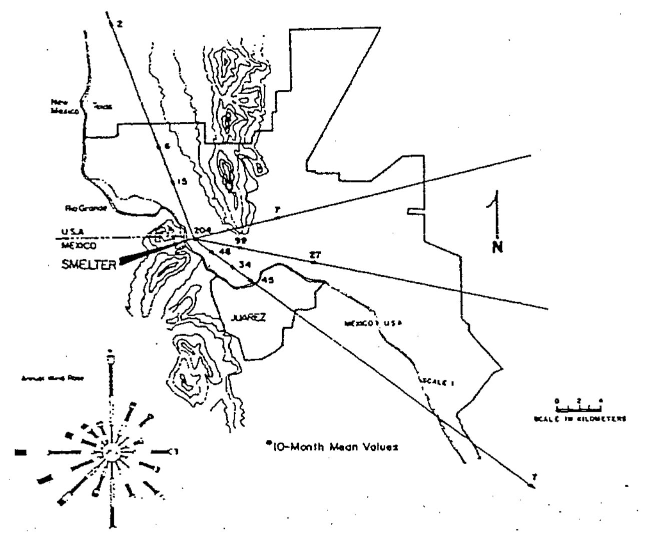

Figure 4. Lead in Dust Fall (Milligrams per Square Meter per Month), El Paso, Texas, October, 1970, to July, 1971.

Dust Sampling

Household dust samples were obtained once a month from July, 1972, through June, 1973, at 51 locations. Highest values were obtained in Smeltertown, a village adjacent to the smelter; geometric mean lead content in 53 samples there was 22,191 ppm (Table 1). Zinc, cadmium, and arsenic levels were also highest in Smeltertown, and all levels declined rapidly with distance.

Food and Water Sampling

Food and tap-water samples were obtained in March, 1972, from 13 homes, nine of them in Smeltertown. No lead was detected in any of these samples; the lower limit of detection for lead was 0.05 μg per milliliter.

Human Studies

In preliminary testing programs conducted throughout El Paso from January to April, 1972, whole-blood lead levels of $\geq$ 40 μg per 100 ml* were found in 94 (43 per cent) of 223 persons living within 1.6 km of the smelter, in 28 (8 per cent) of 363 from 1.6 to 3.2 km, and in 6 (1 per cent) of 425 beyond 3.2 km. Four children with blood lead levels of 80 to 90 μg per 100 ml were found; all were Smeltertown residents, and their ages were two, three, four, and four years respectively. No children were found to have symptoms of acute lead poisoning.

To define the distribution of blood lead values more precisely, a random-sample survey of all families in the 13 census tracts most closely adjacent to the smelter was undertaken in August, 1972. The survey area was divided along census-tract boundaries into three roughly concentric sections, each 1.6 to 2.6 km in diameter with the smelter at the center (Fig. 5). Area I included Smeltertown, population 500 (estimated from 1970 United States Census data), a cluster of adobe buildings 200 m from the smelter, as well as Old Fort Bliss, a group of wood and stucco tenement buildings. Mean annual family incomes in the three areas were $7,020, $6,143, and $5,487 respectively (1970 United States Census data).

To obtain data on the prevalence of blood lead levels $\geq$ 40 μg per 100 ml that would with 90 per cent confidence be accurate within $\pm$5 per cent, it was calculated (given an anticipated overall prevalence rate of 10 per cent), that 100 persons would need to be surveyed in each area for each age group. Accordingly, on the basis of family composition data, estimated from the 1970 United States Census, 220 households were selected in area I, 400 in area II, and 320 in area III. Because of a paucity of occupied units in area I, all families were included. In areas II and III, households were selected by blocks according to the randomization procedure described by Serfling,[23] and approximately 2 per cent of households were so selected. No substitutions were allowed for vacant houses or for families that refused to participate. Of the 940 housing units selected, 107 were unoccupied, and interviews were obtained in 670 (80.4 per cent) of the remaining 833. In

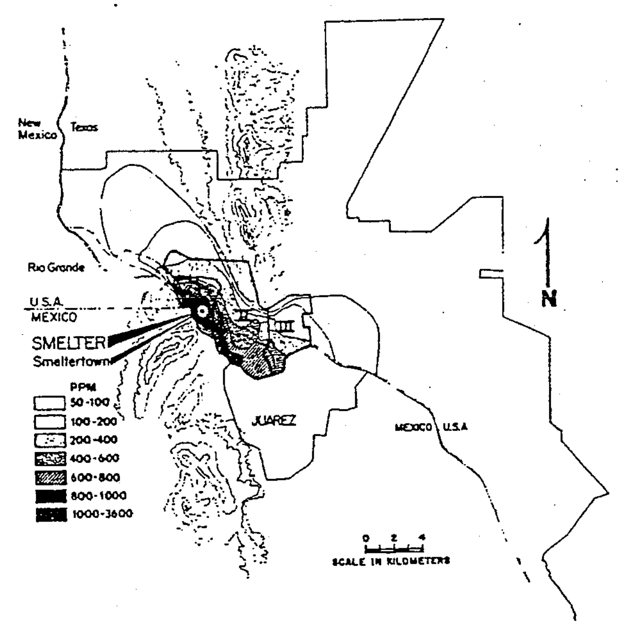

Figure 5. Surface-Soil Lead Levels and Survey Areas, El Paso, Texas, 1972.

*A whole-blood lead level of 40 μg or more per 100 ml is considered by the Surgeon General to be indicative of "undue lead absorption," and a confirmed level of 80 μg per 100 ml or more is considered to represent "unequivocal lead poisoning."[22]

Table 1. Lead Content in Household-Dust Samples El Paso, Texas, July, 1972, to June, 1973, as Compared with Philadelphia.[3]

Section Studied	No. of Samples	Lead Content (ppm)	
		Geometric Mean	Range
El Paso:			
Distance from smelter (km):			
0.0-1.6	53	22,191	2,800-103,750
1.7-3.2	219	2,124	100-84,000
3.3-6.4	209	1,552	100-29,386
>6.4	48	973	200-22,700
Philadelphia:			
Urban industrial area	16	3,855	929-15,680
Urban residential area	4	614	293-939
Suburban area	4	830	277-1,517

the group from one to 19 years of age this survey netted 758 of an anticipated 1200 individuals. This low count appears to have resulted from a somewhat lower than expected number of children per family and from the high frequency of unoccupied housing units.

Information was obtained from each person surveyed on length of residence at current and previous addresses, on occupation or school attended, on the average number of hours spent out-of-doors each day, and on prior history of blood lead testing or treatment for undue lead absorption or lead poisoning. For children below the age of five years, parents were asked whether there was pica. A venous-blood sample for lead analysis was drawn in a lead-free vacuum tube from all persons one to 19 years old and from every second person above that age. Duplicate lead determinations were performed by a modified Delves-cup atomic absorption procedure.[24] If a person in the study population had had a blood lead assay by atomic absorption spectrophotometry within the preceding six months, no new sample was obtained, and instead the results of the prior test were used; that situation applied to 242 persons, all of them from area I.

In each home visited, paint, particularly on interior surfaces accessible to children, was checked for flaking or teethmarks, and two or more full-thickness paint samples were chipped off for lead analysis.[24] Any pottery vessel used for food preparation or storage was tested for lead release. One to two surface-soil and one to three household-dust samples were collected in each home for lead analysis.[24]

The highest blood lead levels were found in area I; the mean there was shown by analysis of variance with use of an F-test[25] to be significantly higher than the means in areas II and III ($p < 0.001$). Within area I the highest prevalence of blood lead levels of 40 to 59 μg per 100 ml and also of 60 μg per 100 ml and above was noted in Smeltertown. Prevalence rates elsewhere in area I were between those in Smeltertown and those in areas II and III (Fig. 6). The findings in areas II and III did not differ significantly from one another.

Highest lead levels were noted in the youngest age-groups. In area I, 55 per cent of children one to four years old had levels of 40 to 59 μg per 100 ml, and another 14 per cent had levels of 60 μg per 100 ml or higher (Table 2); the highest level noted was 83 μg per 100 ml, in a two-year-old girl in Smeltertown. Levels in the older groups were lower; levels ≥ 40 μg per 100 ml, however, were observed in 27 per cent of children five to nine years and in 14 per cent of those 10 to 14 years old from the three areas surveyed. Significant differences were noted in all age groups between mean levels in area I and those in areas II and III.

Analysis according to sex showed no consistent differences in the groups one to four and five to nine years of age. From the age of 10 onward, however, mean levels were found to be higher in males. The male-female difference was greatest in areas II and III, and in all areas, it became more highly significant with increasing age.

The frequency of pica was low in all areas. No children in area I with blood lead levels ≥ 60 μg per 100 ml gave a positive history for pica, whereas one three-year-old child in area II, with a blood level of 63 μg per 100 ml, had pica for dirt. No significant relation was found in any age group between hours per day spent out-of-doors and blood lead level. There were also no significant relations between blood level and school attended or occupation. Three households in the sample population were known to have included smelter employees; in none of those were any children with lead levels ≥ 40 μg per 100 ml found. In area I a relation was observed between length of residence and blood lead levels; only five (18 per cent) of 28 subjects one to 19 years old who had moved into area I in the two years before the survey had blood lead levels ≥ 40 μg per 100 ml, whereas 56 (43 per cent) of 130 children who had lived there for two or more years had such levels. In areas II and III emigration from Smeltertown did not contribute importantly to the distribution of blood lead levels; only four (8 per cent) of the 49 children in those areas with

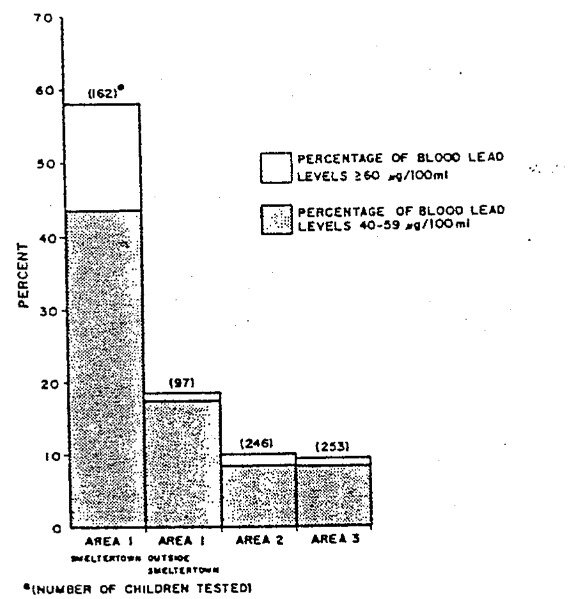

Figure 6. Distribution of Blood Lead Levels in Persons One to 19 Years of Age, According to Area, El Paso, Texas, August, 1972.

Table 2. Survey Results and Population Projections According to Area and Age-Group, El Paso, August, 1972.

Area	Age Group (Yr)	Survey Results			Population Projections		
		No. Tested	% with Blood Lead 40-59 μg /100 ml	% with Blood Lead ≥60 μg /100 ml	No. of Persons 1-19 Yr of Age*	Estimated No. with Blood Lead 40-59 μg /100 ml	Estimated No. with Blood Lead ≥60 μg /100 ml
I:	1-4	49	55	14	88	48	13
	5-9	101	34	11	131	44	14
	10-19	109	25	6	203	50	11
	20+	98	16	0			
II & III:							
	1-4	83	23	4	4,770	1,092	172
	5-9	124	12	0	6,179	747	0
	10-19	292	3	1	13,123	360	180
	20+	513	3	1			
Totals		1,369	9†	2†	24,494	2,341	390

*From 1970 US Census.

†Population-weighted average excluding ages ≥20 yr.

levels ≥ 40 μg per 100 ml had moved in within two years, and only one of the four immigrants had come from Smeltertown. No data were obtained on the frequency with which children living outside Smeltertown may have visited there.

Paint Exposure

A total of 1600 paint samples, 256, 667, and 677 by area, respectively, were collected for lead determination during the random sample survey. A lead content of 1.0 per cent or above by dry weight was found in at least one paint sample from 30 per cent of the homes studied in area I, from 75 per cent in area II, and from 25 per cent in area III. Within area I, paint with ≥ 1.0 per cent lead was noted in 23 per cent of Smeltertown homes (primarily adobe construction) and in 43 per cent of those outside Smeltertown (primarily wood-frame buildings). Flaking paint was observed in 87 of 95 (92 per cent) households examined in area I, and in 240 of 446 (54 per cent) of those in areas II and III. Paint with teethmarks was noted in three of 20 houses examined in area I, and in three of 349 in areas II and III. The lead content of toothmarked paint tended to be high (means of 2.6 per cent in area I, and 5.2 per cent in areas II and III). Blood lead levels of children one to six years old living in homes with toothmarked paint, however, did not tend to be higher than those of other young children living in the same areas: four of eight children exposed to toothmarked, leaded paint in area I had blood levels of 40 to 49 μg per 100 ml, whereas the levels in four were < 40 μg per 100 ml. One four-year-old child in area II, who lived in a home with 11.1 per cent paint lead content, had a blood level of 61 μg per 100 ml, whereas seven other children in areas II and III who were exposed to as much as 3.4 per cent lead in toothmarked paint all had levels < 40 μg per 100 ml. The exposure rates in the three survey areas of children one to four years old to paint with 1.0 per cent or more lead content were 42, 33, and 30 per cent respectively. The prevalence of a blood lead level of ≥ 40 μg per 100 ml was nearly the same for children exposed in their homes to paint with 1.0 per cent or more lead as for those without such an exposure (prevalence rates of 32 per cent and 39 per cent).

Pottery Exposure

Pottery vessels were found to have been used for food storage or preparation in 37 (6 per cent) of the 670 homes visited. The number with a lead release of ≥ 100 μg per 100 ml was two of six in area I, seven of 19 in area II, and three of 12 in area III. Another two vessels in area II and five in area III had lead release of 7 to 99 ppm.* A positive relation existed between blood lead levels in subjects one to 19 years old and lead release from pottery: six of 13 children exposed to pottery with lead release of ≥ 100 ppm had blood lead levels of ≥ 40 μg per 100 ml, and the group mean level was 37 μg per 100 ml; in contrast, only one of 14 children exposed to pottery with lead release below 100 ppm had a blood lead level of ≥40 μg per 100 ml, and the group mean level was 29 μg per 100 ml.

Soil Exposure

A total of 466 surface soil samples were collected — 82, 184, and 200 by area respectively. The geometric mean lead level in the samples from area I (1791 ppm) was found to be significantly higher than those in the samples from areas II (684 ppm) and III (370 ppm); mean levels in the latter two areas did not differ significantly from one another. In area I a significant relation ($p < 0.05$) was found between soil lead content and blood lead levels in subjects one to 19 years old (Fig. 7). The geometric mean soil content at the homes of children with blood lead levels of ≥ 40 μg per 100 ml was 2587 ppm; for children with blood levels below 40 μg per 100 ml the mean was 1419 ppm. This relation was not found in areas II and III, presumably because of the much lower mean soil lead level.

Dust Exposure

Five hundred and ninety-four household-dust samples were obtained—106, 234, and 254 by area. Again, the geometric mean lead content was significantly higher in area I (mean of 4022 ppm for area I versus 922 ppm for area II and 816 ppm for area III). In area I a highly signifi-

*Lead release of ≥ 100 ppm was considered capable of causing acute severe poisoning, and release of 7 to 99 ppm might cause chronic poisoning with continuous use.[26]

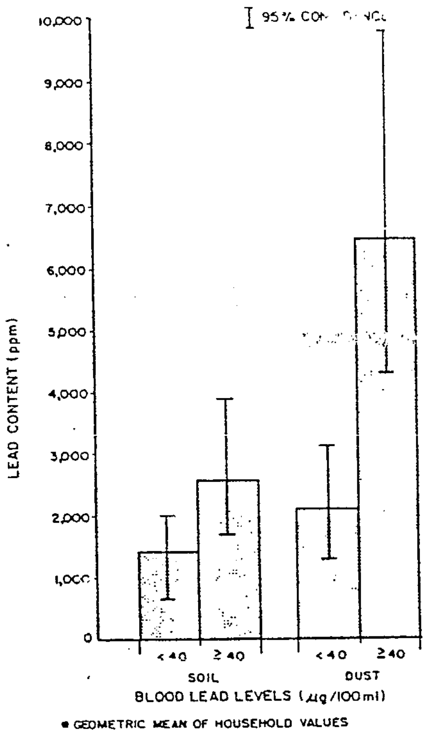

Figure 7. Blood Lead Levels in Persons One to 19 Years of Age and Household Exposure to Lead in Soil* and Dust* in Survey Area I, El Paso, Texas, August, 1972.

cant relation ($p < 0.0001$) was noted between the lead content of household dust and lead levels in the blood of children one to 19 years old (Fig. 7). Children with blood levels of ≥ 40 µg per 100 ml lived in homes where the geometric mean lead content in dust was 6447 ppm, whereas in the homes of those with levels less than 40 µg per 100 ml, lead in blood contained 2067 ppm in dust. No positive relation was found between household dust and blood lead levels in areas II and III, presumably because of the much lower mean lead level in dust.

Discussion

A whole-blood lead level of 40 µg per 100 ml was chosen in this study as the criterion of abnormal lead absorption.[22] This value has been shown to be 2 standard deviations above the mean in populations of children without abnormal lead exposure[27,28] and is the level at which the first biochemical manifestation of lead toxicity becomes evident.[1]

Abnormal lead absorption, so defined, was found in 43.2 per cent of children one to 19 years old and 52.7 per cent of those one to nine years old living within 1.6 km of the smelter, as well as in 9.8 per cent of children one to 19 and in 17.9 per cent of those one to nine years old living from 1.6 to 6.6 km (Table 2). From these data, which were obtained in a randomized survey intended to be representative of the entire population in the areas surveyed, it is possible to estimate the total number of children in the survey areas who may have had blood lead levels of ≥ 40 µg per 100 ml at the time of the survey (Table 2). A potential pitfall in this projection is that it is based on only a single series of blood samples; thus, both biologic and laboratory variations are unchecked by a second series of bloods.[22] The large number of samples (758 from children one to 19 years old) and the fact that duplicate analyses were performed on all might be expected, however, to minimize such potential sources of error. It was projected, on the basis of 1970 United States Census data, that over 2700 children one to 19 years old in the areas of El Paso surveyed may have had blood lead levels of 40 µg per 100 ml or higher at the time of the survey (Table 2).

Various potential sources and vectors of absorbed lead were considered. Paint ingestion could not adequately account for the geographic pattern or age distribution of lead absorption in El Paso. Although some children undoubtedly ingested lead-based paint, the content of lead in paint was no higher in area I than in areas II and III, and no higher in the homes of children with blood lead levels ≥ 40 µg per 100 ml than in the homes of those with lower levels. Also, the prevalence in El Paso of paint with a lead content of ≥ 1.0 per cent (30 per cent prevalence rate) was much lower than that in the homes of Philadelphia (57 per cent) and New York City (76 per cent) children with lead poisoning.[2] Food and water were found to have made no more than a negligible contribution to lead uptake. Pottery probably caused lead absorption in some persons, as indicated by the elevated mean blood levels in children exposed to leaded pottery, but pottery was not widely used for culinary purposes, and pottery with a potentially dangerous lead content was found in only 2.8 per cent of the homes visited.

Environmental particulate lead, on the other hand, had a geographic distribution very similar to that of the blood lead levels of ≥ 40 µg per 100 ml. The highest environmental levels of particulate lead were found in dust, and a close relation ($p < 0.0001$) was observed in area I between blood lead levels and concentrations of lead in dust (Fig. 7). These data were taken to indicate that chronic oral ingestion and gastrointestinal absorption of particulate lead from dust were a major source of lead uptake, at least within 1.6 km of the smelter. Airborne particulate lead also appears to have been readily available for human uptake, and air lead levels in Smeltertown were sufficient to have produced substantial pulmonary absorption (Fig. 1).[6,29,30] Transpulmonary uptake may have been further enhanced by the preferential concentration of lead that was noted in the smaller-size particles (Fig. 2); such preferential concentration has been noted in several previous studies.[31,32] Particulate lead from soil appears to have contributed relatively less to lead uptake in El Paso (Fig. 7).

It appears that the more mobile fractions of environmental particulate lead — that is, the lead in dust and air — were those most closely associated with human uptake. Future studies of lead absorption from the environment should perhaps focus on these fractions. Soil lead, although valuable as an index of environmental contamination, appears to be relatively immobile and thus less accessible for absorption. This construct might explain the finding in previous studies of elevated dentine,[3] hair,[4] and blood[5] lead levels in children exposed to high levels of lead in dust or air (or both) and at the same time would explain the failure to demonstrate blood lead levels of ≥ 40 μg per 100 ml in British children exposed to high concentrations of lead in soil, but in an area of relatively heavy rainfall and negligible air lead content.[33] Although our data on the possible importance of environmental particulate lead need to be corroborated by future studies, they tend to confirm the concept that such lead is biologically accessible and that it may be an important cause of chronic, low-level lead absorption in childhood.[2-6]

Our findings indicate that within a 1.6-km radius of itself, the El Paso smelter was the principal source of particulate lead in the environment. It may therefore be concluded that in that area, the smelter was the major source of the lead absorbed by children. In addition, there is evidence from our soil, air, and dust data, that lead emitted by the smelter had been deposited in the environment at a distance well beyond 1.6 km. Whether such lead may also have contributed to human absorption is less clear; there appears, however, to be no source of lead in El Paso other than the smelter that can account, in areas II and III, for the 27 per cent prevalence among children one to four years old and for the 12 per cent prevalence among those five to nine years old of blood levels of ≥ 40 μg per 100 ml. Further studies of possible neurologic and psychologic dysfunction resulting in El Paso children from chronic low-level lead absorption have been conducted.

Note added in proof: An article describing lead absorption in children living near a smelter in Toronto, Ontario, Canada, has recently been published in *Science*.[34]

We are indebted to Mr. John C. Ross, city attorney for El Paso, for support and encouragement and to J. Julian Chisolm, Jr., M.D., of the Department of Pediatrics, Johns Hopkins University School of Medicine, for a critical review of the manuscript.

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