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Bone lead content assessed by L-line x-ray fluorescence in lead-exposed and non-lead-exposed suburban populations in the United States

(blood lead/soil lead/lead-processing factories/pollution)

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ABSTRACT **Measurements of lead (Pb) in bone reflect cumulative Pb exposure, whereas blood Pb levels are indices of absorption during the previous 21–30 days. This study was undertaken to estimate bone Pb concentrations by L-line x-ray fluorescence (LXRF) in a United States suburban population which was exposed to unusually high levels of Pb in emissions from an adjacent factory during 1963–1981, compared with concentrations similarly estimated in a matched suburban community without unusual Pb exposure. The mean bone Pb value in 269 residents of the highly exposed suburb (15 ppm) was 3-fold greater than that of the reference suburb (5 ppm). LXRF estimates of bone Pb identified those individuals at risk for adverse effects of Pb, whereas blood Pb levels were uninformative. Average LXRF-estimated bone Pb concentrations in residents of the unusually exposed suburb approximated estimated values in workers at Pb-processing factories.**

Measurement of Pb in blood is the most widely used laboratory indicator of excessive Pb exposure in humans (1). In instances where current Pb exposure can be reliably assumed to be at an excessive level, such as in occupationally exposed adults and in children living in deteriorating housing containing leaded paint, measurement of blood Pb is of considerable public health relevance as a screening method (1). However, for general populations, particularly with undocumented or suspected exposure histories, blood Pb values provide limited toxicological information, since the half-time of Pb in blood is 21–30 days (2) and blood Pb mainly reflects recent exposure only (2). Since blood Pb levels decline once excessive exposure is reduced (1, 3–5), blood Pb fails to reflect earlier time periods of increased exposure. Cumulative Pb exposure may be more closely related to health effect outcomes, compared with short-term exposure which is in the time frame captured by measurements of blood Pb. A large proportion of circulating Pb is not cleared but stored in various body compartments, with the skeletal compartment containing 75% and 95% of total body Pb in children and adults, respectively (1, 2, 6). Moreover, bone Pb stores are subject to release as an endogenous source of exposure (7–11), independent of current environmental sources. The assessment of bone Pb content with or without such release is, consequently, of clinical significance in populations with a history of excessive Pb exposure regardless of the length of the interval between exposure and assessment.

With the development of L-line (5, 12–16) and K-line x-ray fluorescence (LXRF and KXRF) techniques to estimate bone Pb stores noninvasively in lead-poisoned children (5, 12–16) and in adult workers (17–19), the technology now exists to assess bone Pb in a compartment with a residence time of months to years (2). LXRF and KXRF methodologies have the capability to open a wider time window in terms of establishing the occurrence of elevated Pb exposure and characterizing epidemiologically the potential expressions of lead's toxic effects.

The present study was undertaken to establish current baseline bone Pb values by LXRF§ in Moosic, Pennsylvania, a suburban residential community without unusual Pb exposure, to permit an interpretation of bone Pb values observed in Throop, Pennsylvania, a suburban residential community situated within a 1-mile radius of a source of high-level Pb contamination. A secondary purpose was to examine the usefulness of blood Pb concentrations as a prognostic of medical sequelae in populations previously exposed to inordinate levels of Pb, when such exposure pre-dated blood Pb testing by several months or years.

SUBJECTS AND METHODS

Throop is a valley community of about 4100 residents of low residential mobility whose wage-earners are mostly blue-collar workers. Residents of Throop live within 1 mile of a factory, where Pb was the primary toxicant from a battery-recycling plant and from its secondary Pb smelter, active from 1963 to 1981. This community was designated as a "superfund site" and slated for decontamination by the United States Environmental Protection Agency. The majority of residential soils identified for remediation contained Pb at concentrations averaging 2000 ppm, with some soil values as high as 19,000 ppm (20). Soil Pb values on the factory site were as high as 100,000 ppm (100 mg/g) (20). In contrast, the background soil Pb content in Lackawanna County, which includes Throop and Moosic, the control suburban community, was found to be 10 ppm (20). Although factory operations in Throop ended in 1981, remediation of residential yards and dwellings and the factory site started in 1988 (20), leaving the contaminated environment as a continuing source of exposure (20).

The United States 1980 census data and updates (21) provided the basis for selecting Moosic as a comparable community for Throop. Variables considered were size of population and per capita income, age distribution, education, occupations, residential mobility for 1975–1980, ethnicity, and school enrollment (Table 1) (21). Two communities, Olyphant and Jessup, were rejected because they are adja-

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Abbreviations: KXRF, K-line x-ray fluorescence; LXRF, L-line x-ray fluorescence; AAS, atomic absorption spectroscopy; GFAAS, graphite-furnace AAS; cnet, corrected net photon counts.

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Table 1. Selected variables for Throop and Moosic, Pennsylvania

	Throop	Moosic
Size of population	4166	6068
Per capita income	$7180	$7443
Age distribution, %		
5–12 years	8.6	9.6
13–17 years	15.7	15.2
≥18 years	39.5	41.0
Education (years completed), %		
<8	42.9	40.0
8–12	40.6	45.2
College	16.5	14.9
Occupation, %		
White collar	52.1	48.5
Blue collar	47.9	51.4
Residential mobility: standard metropolitan statistical area but not central city, %	92.8	90.3
Both parents "Catholic" (Italian, Irish, Polish, Hungarian), %	36.0	33.3
Enrollment in public schools, all levels, %	79.7	83.9

Data are from ref. 21.

cent in the valley and subject to the same prevailing wind pattern as Throop. Moosic is located beyond the valley.

Moosic and Throop have almost no multiple dwelling units: both have some trailer homes and share a common water supply. Each adjoins Scranton. Moosic has one major traffic artery; and since Throop does not, residents along this highway were not included in the Moosic test population to control for exposure to leaded gasoline.

Soil samples were obtained in Moosic on-site by laboratory personnel and subsequently analyzed for Pb by graphite-furnace atomic absorption spectroscopy (GFAAS). In Moosic, the majority (86%) of soil Pb values at 0–18 inches in depth were < 250 ppm. Samples with 250–499 and 500–1000 ppm represented 6% and 8%, respectively, of the total number. The significant difference between Moosic and Throop is the industrial Pb source in Throop. This conclusion was based upon extensive review of 56 United States Environmental Protection Agency reports, obtained from the Department of Environmental Resources, Commonwealth of Pennsylvania, which did not identify any comparable industrial Pb source in Moosic.

Any individual who resided in Throop from 1963 to 1989 could volunteer to undergo LXRF and blood Pb testing regardless of age and sex. However, former workers at the factory were excluded from the data presented in this analysis. Twelve volunteers from Throop and four from Moosic, all of whom were adults and teenagers with skin thickness ≥ 9 mm, were also excluded from these data because the amount of attenuation of incident photons from the LXRF instrument by epitibial soft tissue at thicknesses ≥ 9 mm is currently unresolved. Testing by the visiting medical survey team began in Throop during December 1989 and was continued in June 1990 and in September 1991. Volunteers from Moosic were recruited to meet the age and sex distribution of those assessed from Throop during 1989–1990 and were tested during March 1991. Volunteers from Throop and Moosic were divided for analysis into three age groups: 5–12, 13–17, and ≥ 18 years. This grouping was utilized to reflect age-related similarities in bone cell and calcium metabolism, as well as bone mineral accretion and remodeling rates (22, 23).

The LXRF instrument directs partially polarized photons at the subcutaneous, medial mid-tibia (5, 12–16). An LXRF spectrum analyzer collects and counts photons in the 10.5-keV Pb Lα region (5, 12–16). The effective dose is calculated to be <3 μSv (24, 25), about 1/20th of that for one dental x-ray (24). For a tibia with 5 mm of overlying anteromedial epitibial soft tissue, the minimum detection limit (MDL) for an ≈18-min test was estimated as 5 ppm. This MDL, normalized to an epitibial thickness of 5 mm, was calculated from the square root of mean background counts from nine amputated limbs used for instrument calibration (5, 12, 13). This value was multiplied by 2.0 to express the estimated MDL at the 95% confidence limit. Attenuation of the fluorescence signal by epitibial soft tissue was corrected by using a formula based on tissue thickness measured ultrasonically with a 5-MHz transducer. To convert photon counts to ppm, an average effective exponential attenuation coefficient (0.45 ± 0.06, mean ± SE) was derived from nine photon count ratios, which were recorded from nine surgically amputated limbs measured by LXRF before and after removal of epitibial soft tissue (5, 12, 13). The same tibial bones were used for quantification of bone Pb (in the cross section of the tibia taken at the LXRF assay level) by GFAAS analysis of dissolved bone (5, 12, 13). The mean value of the ratio of tibial bone Pb content (in ppm of wet weight) to the net LXRF photon count, normalized to a median epitibial soft tissue thickness of 5 mm, was 0.10 ± 0.01 (mean ± SE) (5, 12, 13). The day-to-day reproducibility of the instrument (4.1%; 95% confidence limit), during the entire period of this study, was used to correct net photon counts (expressed as cnet). A standard deviation of ±1 ppm for each LXRF test was calculated (16) from replicate measurements of 37 Pb-paint-poisoned children at different tibial sites. The r value for these replicate measurements was 0.984 with bone Pb values of 8–47 ppm (16). Data in Fig. 1 are expressed as ppm and cnet, normalized to a median skin thickness of 5.0 mm. Nominal bone Pb concentrations in excessively exposed or baseline populations may change somewhat in tandem, either upward or downward, as more amputated limbs are studied. However, the ratios of the estimates of absolute bone Pb concentrations across populations with comparable skin thicknesses are extremely unlikely to change substantially.

Blood Pb levels were also measured by GFAAS, with methods detailed previously (5, 12, 13). By an analysis of variance of duplicate measurements, the 95% confidence limit of blood Pb measurements was ±1 μg/dl (5, 12, 13).

Statistical comparisons between all group means were determined by Student's t test.

RESULTS

For this analysis, subjects from Moosic and Throop were divided into three age groups (Fig. 1). Upper cutoff values in ppm and cnet for each age group, rounded to the nearest whole number, were established for Moosic by summing the mean and twice the SE, which yielded age-related cutoffs (Fig. 1). For Moosic subjects in the age groups 5–12, 13–17, and ≥ 18 years, these cutoffs in ppm (cnet) were 6 (71), 8 (90), and 7 (88), respectively (Fig. 1). No statistically significant differences ($P > 0.10$) in tibial Pb were discerned among the three age groups in Moosic ($P > 0.10$). In Throop, for the 5–12, 13–17, and ≥18 age groups, respectively, tibial Pb concentrations in ppm (cnet) were 12 ± 1 (124 ± 7), 15 ± 2 (122 ± 8), and 12 ± 1 (128 ± 9) (mean ± SE; Fig. 1). In Throop, bone Pb values were similar ($P > 0.10$) in each of the three age groups. The ppm and cnet values from Throop were significantly higher than those from Moosic in each age group at $P < 0.0002$ and $P < 0.00001$, respectively.

The blood Pb levels in Throop, expressed as the mean ± SE in the three age groups, 5–12, 13–17, and ≥18 years, were 0.32 ± 0.01, 0.27 ± 0.01, and 0.35 ± 0.01 μM, respectively. These blood Pb concentrations are below the Centers for Disease Control's current definition of childhood lead poisoning (≥0.48 μM) (4) and are within national averages (1).

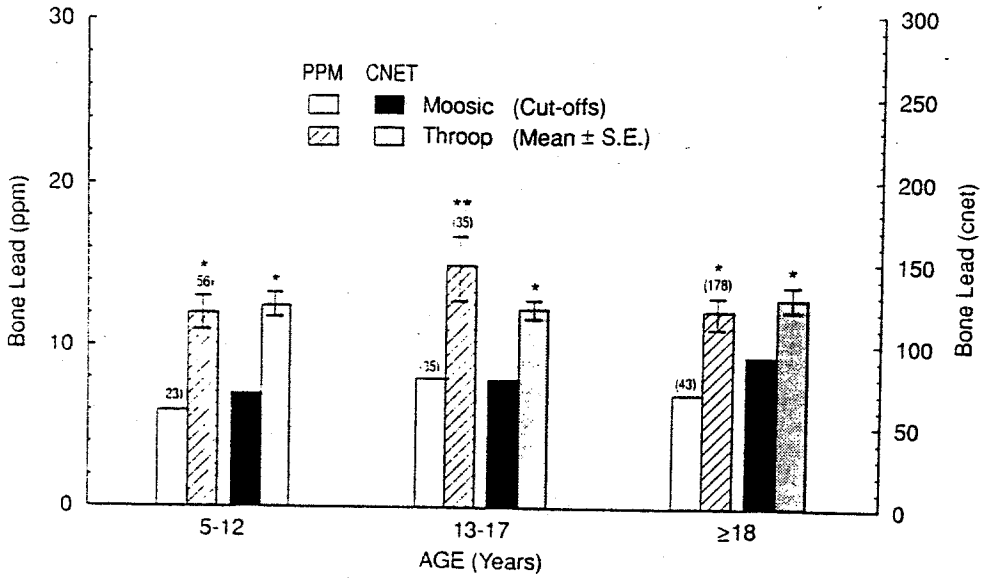

FIG. 1. Estimates of Pb in bone by LXRF in Throop and Moosic. Values for Throop are the mean ± SE (indicated by error bars for data from Throop). The heights of the bars of Moosic data represent upper limit cutoffs of estimated bone Pb values in a normally exposed United States population. The total number of tested individuals in each age group is shown in parentheses. *, $P < 0.00001$; **, $P < 0.0002$, Throop vs. Moosic; ppm = μg of Pb per g of wet bone; cnet = photon counts corrected for the day-to-day instrument reproducibility.

The blood Pb concentrations in Throop were higher ($P < 0.0001$) than the corresponding levels in Moosic: 0.23 ± 0.01, 0.17 ± 0.01, and 0.24 ± 0.01 μM. Although blood Pb concentrations in Throop and Moosic were both within the current United States average (1, 4), there was a small but statistically significant difference of about 2 μg/dl (≈0.1 μM) between the volunteers in Throop and Moosic in each age group.

DISCUSSION

This study demonstrates that the baseline values for bone Pb in the normally exposed population of Moosic, estimated by LXRF, can serve as a reference baseline for contemporary bone Pb levels in similar communities within the United States. Mean tibial Pb levels in each of the three age groups of Throop, where all residents lived within 1 mile of the factory, were significantly higher than baseline. The bone Pb levels reported here for both suburban communities were comparable to those in other studies of normally and excessively exposed children (6, 26–28), in teenagers (16, 29), and in adults (18, 19, 30, 31) measured by KXRF and by atomic absorption spectroscopy (AAS). For instance, Pb concentrations of 2–5 ppm (wet weight), measured by AAS, have been reported in the whole teeth of normally exposed children (6), compared with values of 12–18 ppm in smelter-exposed children (27, 28). Somervaille *et al.* (18), using the KXRF technique, reported a bone Pb content of 9 ± 2 ppm (mean ± SD) in 20 normally exposed adults, in contrast to a value of 18 ± 2 ppm in adult workers in each of two Pb-processing factories in England.[*] Average LXRF-estimated bone Pb values in Throop residents approximated those of the KXRF estimates for occupationally exposed English workers (18).

Earlier studies (32–34) reported increases in bone Pb values with age, but the Moosic data did not show such gradation. The most likely explanation seems to be that in earlier eras, normally exposed individuals experienced higher and longer-term levels of environmental exposure and that the present adults encountered lower levels of exposure (35). Prior to the early to mid 1980s, exposure to Pb primarily from gasoline but also from solder and food (1) probably accounted for these age-related differences. In fact, from earlier studies (32–34), estimates of bone Pb values by AAS in normally exposed adults yielded values of about 30–50 ppm (wet weight). In this regard, comparison of bone Pb values obtained 10 years ago and recently yielded a decline in bone Pb values by a factor of 2–3 (36). The data were obtained from the same laboratory by identical methods (36). Furthermore, a normal average bone Pb value of 9 ppm, obtained by the KXRF technique and reported in 1988 (18), further confirms the results reported herein. The concentration of 7 ppm for normally exposed adults in Moosic is identical to the value (7 ppm) recalculated (37) for adults in 1991 from data of Wittmers *et al.* (34) reported in 1988; this recalculation was based on measurements of ancient human skeletons and performed in an ultraclean laboratory by isotope-dilution mass spectroscopy (37).

From knowledge of skeletal mass (22, 23) and the metabolism of Pb in children and teenagers (1, 38, 39), we surmise that the 7-year interval between closure of the factory and the start of remediation at the factory and at nearby residential sites accounts for elevated bone Pb values in Throop children and teenagers, who were primarily exposed to Pb present in the surrounding contaminated soil and dust (40). Pb adsorbed from soil surfaces and household dust onto hands and clothes of children and teenagers is recognized as a major exposure pathway via the gastrointestinal tract (39), and this accumulation adds to the body burden of Pb as an integral, rather than as an age-specific, relationship in unusually contaminated areas (39). In Throop, soil Pb values in residential yards, gardens, and playgrounds were 200–1900 times higher than the background concentration in Lackawanna County. Furthermore, in teenagers who experienced exposure to earlier factory emissions as young children, complete and rapid uptake via the pulmonary route is to be expected (39). Autopsy data of lung tissue have shown that Pb accumulation by this route is not age-dependent (6). Moreover, because children and teenagers have higher metabolic rates, more rapid gas exchange, higher Pb retention rates, and accelerated accretion of bone mass compared with adults (2, 22, 23,

[*] The KXRF instrument uses a ^{109}Cd source at 88.035 keV; data are expressed as μg of Pb normalized to back-scattering γ rays, which reflect, in large part, bone mineral content (18). In contrast, LXRF utilizes a low-energy x-ray generator at 20 keV; data are expressed as μg of Pb per g of wet weight (5, 12–14).

38), it was not surprising to document elevated bone Pb content in the two younger age groups from Throop.

Blood Pb levels are recognized to be inadequate indices of Pb exposure and accumulation in populations such as the one in Throop, because these measurements capture only a short time frame of previous exposure limited to 21–30 days (2). The slightly higher (≈2 μg/dl) blood Pb concentrations observed in Throop, compared with those in Moosic, are best explained by the continuing exposure to Pb from ongoing activities during remediation of contaminated soil and dust and from release of Pb from bone stores into blood.

Current evidence linking release of bone Pb to blood is conclusive. Studies of Pb workers, under conditions when there is a change in exposure, have demonstrated release of Pb from bone to blood (19, 41). Blood Pb concentrations in retired workers are strongly influenced by bone Pb content; and two distinct kinetic compartments of Pb in bone have been described (19). These compartments have half-times of about 1 and 13 years, respectively (19). Significant contributions to blood Pb concentrations from bone stores have been documented during pregnancy (7–9), in postmenopausal women (10), and in immobilized children (casted for long bone fractures) who were previously Pb-poisoned (11). Elevations in bone Pb content have also been correlated diagnostically with renal disease in adults (42) and with neurobehavioral deficits in children (43). The above studies have been complemented by observations in normal adult volunteers, treated with stable Pb isotopes, indicating that bone Pb is in equilibrium with blood Pb and that alterations in exposure produce changes in the bone–blood equilibrium (2, 44). Hence, in populations excessively exposed to Pb months to years before LXRF assessment, such as residents of Throop, calculated estimates of bone Pb content could serve to identify those at risk for future adverse effects of Pb released from bone.

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