Tooth Analyses of Sources and Intensity of Lead Exposure in Children

Brian L. Gulson
Graduate School of the Environment, Macquarie University, Sydney, NSW 2109 and CSIRO/EM, North Ryde, NSW 2113 Australia

The sources and intensity of lead exposure in early childhood were determined using stable lead isotopic ratios and lead concentrations of deciduous teeth from 30 exposed and nonexposed children from the Broken Hill lead mining community in Australia. Incisal sections, consisting mostly of enamel, generally have low amounts of lead and isotopic compositions consistent with those expected in the mother during pregnancy. Cervical sections, consisting mostly of dentine with secondary dentine removed by resorption and remodelling, generally have higher amounts of lead than the enamel and isotopic compositions consistent with the source of postnatal exposure. There are statistically significant differences in lead concentrations between incisal and cervical sections, representing within-tooth variation, for children with low and high lead exposure (p = 0.0007, 2 × 10^−5, respectively) and for those who have ingested lead paint (p = 0.009). Statistically significant differences between incisal and cervical sections in these three exposure groups are also exhibited by the three sets of lead isotope ratios (e.g., p = 0.001 for 206Pb/207Pb ratio in the low exposure group). There are statistically significant differences between the low and high lead exposure groups for lead concentrations and isotope ratios in incisal (p = 0.005 for lead concentration and 6 × 10^−6 for 206Pb/207Pb ratio) and cervical sections (p = 5 × 10^−5 for lead concentration and 6 × 10^−6 for 206Pb/207Pb ratio). The dentine results reflect an increased exposure to lead from the lead-zinc-silver mineral deposit (orebody lead) during early childhood, probably associated with hand-to-mouth activity. Lead paint was identified as the source of elevated tooth lead in at least two cases. Increased exposure to lead from orebody and paint sources in utero is implicated in two cases, but there was no indication of previous exposure from the mothers’ current lead blood, suggesting an acute rather than a chronic exposure for the mothers. Permanent teeth from one subject had lower amounts of lead in the roots compared with the crowns, and the isotopic composition of the crowns was consistent with the data for the deciduous teeth from the same subject. Based on changes in the isotopic composition of enamel and dentine, it is provisionally estimated that lead is added to dentine at a rate of approximately 2–3% per year. Key words: children, teeth, lead exposure, pregnancy. Environ Health Perspect 104:306–312 (1996)

Exposure profiles are one of the fundamental aspects of studies of lead and its impact on neuropsychological and neurobehavioral outcomes in children. As the skeleton is the primary storage compartment for lead in the human body, it is a potential endogenous source of lead that may be released from the bones during pregnancy (1,2), during lactation (2), and after menopause (3). Chronic exposure to lead, such as from mouthing activity in early childhood, may be camouflaged by dilution of lead in bone during periods of rapid skeletal growth and so may not be detected by the normal methods of blood lead (PbB) analysis. Hence, knowledge of past lead exposure, especially in utero, is fundamental to any investigations of lead toxicity.

In many human epidemiological investigations, exposure profiles may be limited to a single PbB level (4), which may provide information only about recent exposure. The use of lead in whole deciduous teeth, enamel, or dentine as an indicator of past exposure of children to lead, and as a proxy for skeletal lead, has been well documented in a number of studies [see Gulson and Wilson (5) and Edwards-Bert et al. (6)]. The advantage of tooth lead is that it is an indicator of lead exposure over several years, from in utero to loss of the tooth, in contrast to blood lead, which has an approximate mean life of 30 days (7). However, because of differences in the type of tooth analyzed, the part of the tooth analyzed, and the analytical techniques used for lead measurement, tooth lead has not been widely accepted as an indicator of lead exposure. In a pilot study, Gulson and Wilson (5) showed that stable lead isotopic analyses and lead concentrations in cross-sectional slices of deciduous teeth provide evidence of in utero and earliest childhood exposure when using enamel, and the results for dentine provided evidence of exposure during early childhood, possibly up until the time the tooth was shed.

We evaluated the efficacy of the isotopic analyses of slices of teeth as an indicator of past exposure in 30 exposed and nonexposed children from a lead mining community. Resulting data would also allow an evaluation of the hypothesis that lead in dentine does not turn over (8,9), a hypothesis that has been misinterpreted to indicate that tooth lead, except from that in the circumpulpal dentine, is a passive reservoir for lead.

Methods

Deciduous teeth, mostly upper and lower incisors, from 30 children from the Broken Hill lead mining community with differing exposure to lead were tested. In one subject, permanent teeth were also available, and these allowed a comparison of exposure through different stages of childhood. Estimates of exposure were based on information obtained from parents and included residence in areas identified as “high risk” by a blood lead survey of 800 children aged 1–4 years, early childhood, missing frequency, learning difficulties, and behavioral problems. With one exception, the mothers of the children were long-term residents of Broken Hill (>10 years).

Except for the permanent teeth and three deciduous canines with roots from the one subject, the samples consisted only of incisors, which had undergone varying amounts of resorption. For upper and lower incisors, the crowns were cut transversely into 1–2 mm thick slices from the incisal and cervical areas using a diamond-impregnated stainless-steel disc. The incisal section consisted of enamel and varying amounts of coronal dentine. In this paper, we use the nomenclature of Shapiro et al. (9): enamel, dentine, secondary dentine (the dentine zone around the pulp canal, also called circumpulpal dentine) and pulp. The locations from which the incisal, cervical and root sections were cut for the analyses in this paper are shown in Figure 1. As enamel and coronal dentine are formed before most...
children begin to crawl (11), they provide an indicator for in utero and earliest childhood exposure. For enamel samples, as much attached dentine as possible was removed. The pulpal canal in the cervical section was usually resorbed to varying degrees, but to ensure minimal contribution from secondary (circumpulpal) dentine, approximately 2 mm of the pulpal canal and dentine was reamed out. The dentine in the cervical section provides an integrated exposure to lead from the time of eruption of the tooth until the tooth is shed (12,13). Gulson and Wilson (5) suggested that the sectioning approach was superior to other methods of tooth preparation (or whole teeth), including that of circumpulpal wedges (9,12,13). They suggested that the major drawbacks of the circumpulpal wedge method were 1) the relatively limited quantity of the circumpulpal dentine in deciduous teeth, especially in naturally shed teeth, where there is variable resorption, 2) the high level of technical skill required to remove the wedge, 3) analytical difficulties on a routine basis, and 4) the strongest correlation of tooth lead and PbB was at about 4 years of age (12,13), after the maximum PbB levels in children. For permanent teeth, 1–2 mm sections of the outer crown and the root sample were taken from an area approximately 1–2 mm from the root tip (Fig. 1).

Tooth slices were decontaminated and analyzed as described by Gulson and Wilson (5), except that 1% HNO₃ was used, and tooth samples weighing 2–60 mg were completely dissolved in 6 M HCl.

The isotope dilution method was used to analyze the lead isotope abundances and lead concentrations in the same sample. This involves adding to the test sample, before digestion, a known amount of a 46% ²⁰³⁰Pb solution of known isotopic abundance (composition). The lead is separated from interfering elements by anion exchange chromatography. Processing "blank" levels were < 150 pg Pb; no corrections for this blank have been made to the data, as it is insignificant compared with the amount of lead in the analyzed sample.

High precision isotope ratios of ²⁰⁸Pb/²⁰⁶Pb, ²⁰⁷Pb/²⁰⁶Pb, and ²⁰⁶Pb/²⁰⁴Pb were measured on a VG Isomass 54E thermal ionization mass spectrometer (VG Isotopes, Winsford, UK) in fully automatic mode. The external precision of the ²⁰⁷Pb/²⁰⁶Pb isotope ratios is ± 0.06% (2σ), based on over 1800 analyses in the CSIRO laboratories of the internationally recognized Lead Standards SRM 981 and 982 of the National Bureau of Standards (NBS) and natural samples. An analysis of SRM 981 was performed with each batch of samples. Accuracy of the measured isotope ratios in the teeth samples is by way of normalization of the ratios to those given by NBS (now National Institute for Standards and Testing). Validation of the laboratory was a prerequisite for undertaking the project, "Biokinetics of Lead in Human Pregnancy."

Statistical procedures of t-tests for evaluating significant differences between means of data sets and regression analyses were provided in the Microsoft package Excel 5.0 (Microsoft Corp., Redmond, Washington). The use and interpretation of data with notched box plots are described in McGill et al. (14) and Cleveland (15).

Results and Discussion

The lead isotope technique uses the four isotopes of lead. Three are the stable end products of radioactive decay of uranium and thorium: ²³⁵U to ²⁰⁶Pb, ²³⁵U to ²⁰⁷Pb, and ²³²Th to ²⁰⁸Pb. The abundance of the fourth, ²⁰⁴Pb, is essentially constant, and this isotope is commonly used as a reference isotope. Because three isotopes of lead are produced by radioactive decay, the amounts (abundances) have changed over geological time, and this is reflected in the geological source of the lead. The abundances are usually expressed as ratios so that lead from the geologically old (about 1700 million years old) lead–zinc–silver deposits of Broken Hill in New South Wales has an abundance ratio of the ²⁰⁶Pb isotope to the ²⁰⁴Pb isotope (²⁰⁶Pb/²⁰⁴Pb) of 16.0, whereas the ratio is 18.1–18.3 for geologically young deposits (500–400 million years old) on the same continent. The isotopic differences are used to evaluate the source of lead in the environment, humans, and animals. Interpretations of lead isotopic data may not be straightforward because lead in the environment or animals may be a mixture of lead from different sources (mines). Hence, lead that is introduced to the body from soil, dust, air, food, or water is largely dependent on the source of lead in the environment, which in turn is dependent on the age and isotopic composition of the rocks and ores from which the lead in the environment is derived.

The ability to obtain on each sample three sets of lead isotope values, representing variations in the abundances of the isotopes, as well as lead concentrations, allows for more rigorous evaluation of the data than, for example, a single value of lead concentration or isotope ratio. Hence, the statistical results listed in Table 1 incorporate the three sets of measured ratios as well as lead concentrations. For simplicity, usually only one isotope ratio is discussed, most commonly, the abundance of ²⁰⁶Pb to ²⁰⁴Pb, as the ²⁰⁶Pb/²⁰⁴Pb ratio.

Table 1. Statistics for within-tooth variation and between groups of subjects from Broken Hill with low and high exposures to lead and with lead exposure from ingested paint

| Comparison      | Pb concentration | ²⁰⁶Pb/²⁰⁴Pb | ²⁰⁷Pb/²⁰⁶Pb | ²⁰⁴Pb/²⁰⁶Pb | df | p-value |
|-----------------|------------------|------------|------------|------------|----|---------|
| Within tooth    |                  |            |            |            |    |         |
| Low-I-low C     | 0.0007           | 0.0005     | 0.0004     | 0.001      | 12 |         |
| High-I-high C   | 2 x10⁻⁶         | 2 x10⁻⁶    | 5 x10⁻⁶    | 0.003      | 22 |         |
| Paint-I-paint C | 0.009            | 0.27       | 0.31       | 0.28       | 7  |         |
| Between group   |                  |            |            |            |    |         |
| Low-high, I     | 0.005            | 6 x10⁻⁶    | 3 x10⁻⁶    | 6 x10⁻⁶    | 34 |         |
| Low-high, C     | 5 x10⁻⁵          | 0.0002     | 1 x10⁻⁵    | 6 x10⁻⁶    | 34 |         |
| Low-paint, I    | 0.002            | 0.05       | 0.016      | 0.013      | 19 |         |
| Low-paint, C    | 0.001            | 0.0004     | 0.006      | 0.009      | 19 |         |
| High-paint, I   | 0.08             | 4 x10⁻⁸    | 1 x10⁻⁴    | 3 x10⁻⁴    | 29 |         |
| High-paint, C   | 0.35             | 1 x10⁻⁷    | 5 x10⁻⁸    | 7 x10⁻⁸    | 29 |         |

Abbreviations: I, incisal section; C, cervical section.
Broken Hill is a city of approximately 25,000 inhabitants, about 930 km west of Sydney, New South Wales, Australia, and centered about the world's largest currently mined lead–zinc–silver deposit. Mining activities, including underground and open-pit operations and smelters in the latter part of the past century, have been conducted for more than 100 years. This area is desert and subject to severe windstorms, and the dust from the mining activities and potentially from weathering of the lead–zinc–silver mineral deposit over millions of years is considered to be the main point source of lead in children from inhalation and ingestion of contaminated soil and household dust. The isotopic composition of the potential sources of lead in the Broken Hill community are summarized in Figure 2. The 206Pb/204Pb ratio generally ranges from 16.0 to 16.2 for the orebody lead and dust from ceilings, vacuum cleaners, and kitchen wipes (16). The other potential sources of lead are food, water, and air. Food and water contain < 10 ppb and < 3 ppb lead, respectively, and are the main contributors to background PbB concentrations of 6 ± 2 μg/dl, which have been estimated from 38 minimally exposed female adults (16). Apart from orebody lead, another major source of lead in air is from gasoline; at the time of the investigation, approximately 60% of automobiles in Broken Hill used leaded gasoline, with approximately 0.8 g/l lead and with a 206Pb/204Pb ratio of 16.56. Gasoline was considered to be a significant source of lead in adult females from Broken Hill (16). Until the lead isotopic investigations of Gulson et al. (16), paint had been largely ignored as a potential contributor to blood lead in children from Broken Hill. Houses built before the 1970s commonly contain lead paint and far outnumber newer dwellings. Renovation of houses is extremely common in Broken Hill. Isotopic ratios measured in paint (Fig. 2) illustrate the complexity of lead sources but do not negate the use of isotopic analyses for elucidating sources in Broken Hill.

It is possible to estimate relative proportions of lead from some sources using the isotopic ratios, such as the orebody and gasoline. For example, given that the orebody has a 206Pb/204Pb value of approximately 16.0 and gasoline 16.56, a tooth slice with a ratio of 16.28 would have a 50% contribution from each source. Estimating proportions for paint is more complex, but in some cases it is still possible to obtain approximate contributions.

Subjects with low exposure. Descriptive statistics for subjects with low and high lead exposure are illustrated with notched box plots in Figures 3 and 4, and tests of significance are listed in Table 1; detailed isotopic results for subjects with low and high exposure can be obtained from the author. In general, the lead concentrations in the incisal sections for subjects with low exposure range from 0.4 to 3.5 ppm Pb, with a mean value and standard deviation of 1.2 ± 0.8 ppm. These low lead concentrations demonstrate that the children were exposed to low levels of lead in utero and
during early childhood. The low lead concentrations are consistent with those found in unexposed populations (17,18) but are up to 100 times greater than natural levels (19). The \(^{206}\text{Pb}/^{204}\text{Pb}\) ratios range from 16.31 to 16.64 (mean 16.48 ± 0.10), consistent with those found in the blood of female adults (16).

Variable lead concentrations and \(^{206}\text{Pb}/^{204}\text{Pb}\) ratios are observed in the cervical sections, but there does not appear to be any simple relationship such as increasing lead concentration with decreasing \(^{206}\text{Pb}/^{204}\text{Pb}\), which would reflect an increasing amount of lead from an orebody source as a result of hand-to-mouth activity. The correlation coefficients for \(^{206}\text{Pb}/^{204}\text{Pb}\) versus Pb (ppm) in the incisal and cervical sections are -0.10 (\(p = 0.75\)) and -0.12 (\(p = 0.69\)), respectively. The lack of simple relationships is also indicated by the observation that the lead concentrations in both cervical and incisal sections of one subject are low, and yet the isotopic composition indicates that the child has a substantial component (approximately 40\%) of orebody lead in the teeth.

In general, within-tooth variations show that the cervical section has higher amounts of lead (\(p = 0.0007\); Table 1) and lower \(^{206}\text{Pb}/^{204}\text{Pb}\) ratio (\(p = 0.001\) in Table 1) than the incisal section, indicating that during early childhood, the individuals’ intake of orebody lead exceeded that from other sources.

**Subjects with high exposure.** Lead concentrations and \(^{206}\text{Pb}/^{204}\text{Pb}\) ratios are variable in incisal and cervical sections for these subjects (Table 1; Figs. 3 and 4). Low lead concentrations of < 2 ppm and higher \(^{206}\text{Pb}/^{204}\text{Pb}\) ratios of > 16.4 in the incisal tooth slices of some subjects reflect a low-lead exposure in utero and during early childhood. There are higher concentrations of lead in the cervical sections compared with incisal sections (\(p = 2 \times 10^{-6}; \text{22 df}\)), and there is a stronger correlation of increasing lead concentration with decreasing \(^{206}\text{Pb}/^{204}\text{Pb}\) in the cervical (correlation of -0.64; \(p = 0.0004\)) compared with the incisal section (correlation of 0.15; \(p = 0.46\)). The within-tooth variation, represented by the difference between the incisal and cervical sections, is slightly larger (\(p = 0.003\) in \(^{206}\text{Pb}/^{204}\text{Pb}\) than in the low-exposure subjects. The differences are also greater in the order: \(^{206}\text{Pb}/^{204}\text{Pb} = 207\text{Pb}/^{206}\text{Pb} > 206\text{Pb}/^{204}\text{Pb}\). In the statistical analyses, the data are included in the high exposure group for deciduous teeth from the one family (Table 3) who suffered high lead exposure from orebody lead during renovations.

For most subjects, the isotopic ratios in the cervical (and often incisal) sections indicate that during early childhood, the individuals’ intake of orebody lead exceeded that from other sources.

**Differences in tooth components.** In addition to within-tooth differences in lead concentration and isotopic ratios, there were significant differences between the high and low lead-exposed children for the incisal and cervical sections (Table 1; Figs. 3 and 4).

**Lead from a paint source.** The problem of source identification is highlighted by the siblings 517, whose teeth have some of the highest lead concentrations analyzed so far in this cohort. Until paint was identified as a potential lead source in Broken Hill (16), paint was largely ignored because of the obvious point source of the lead orebody and associated mining activities. Results are presented in Table 2. The \(^{206}\text{Pb}/^{204}\text{Pb}\) ratios in both incisal and cervical sections for the siblings from house 517 are in the range 16.45–16.67. Even though the family lived within 300 m of mining activities and > 90\% of the lead in the surface dust and soil from the house was derived from an orebody source, the isotopic data indicated that there was a significant contribution of lead from another source, such as paint.

Paint was not, however, considered to be a source of lead by the parents because extensive renovations were supposed to have been carried out several years before the children were born. However, an initial vacuum cleaner dust sample had a \(^{206}\text{Pb}/^{204}\text{Pb}\) ratio of 16.98, totally different from the orebody and indicative of a source from paint. Inspection of the vacuum dust by optical and scanning electron microscopy identified numerous lead paint flakes with evidence of burning. It is estimated from the isotopic ratios in the paint flakes (18.37, 18.31) that the lead in the children’s enamel and dentine consists of approximately 30\% paint lead and 70\% orebody lead.
Table 2. Lead isotopic ratios and lead concentrations in teeth from Broken Hill subjects who ingested paint

| Subject | Tooth section | Tooth type | $^{206}$Pb/$^{204}$Pb | $^{207}$Pb/$^{204}$Pb | $^{208}$Pb/$^{204}$Pb | Pb (ppm) | Age (years) |
|---------|---------------|------------|----------------------|----------------------|----------------------|---------|-------------|
| 517F    | I             | 71         | 2.1856               | 0.9290               | 16.62                | 5.43    | 6           |
| 517F    | C             | 53         | 2.1827               | 0.9287               | 16.57                | 3.33    |             |
| 517F    | C-1           | 63         | 2.1879               | 0.9300               | 16.61                | 4.53    |             |
| 517F    | C             | 63         | 2.1868               | 0.9287               | 16.64                | 15.5    |             |
| 517M    | I-2           | 53         | 2.1839               | 0.9273               | 16.67                | 4.70    | 8           |
| 517M    | C-2           | 53         | 2.1867               | 0.9306               | 16.61                | 9.16    |             |
| 517M    | C             | 61         | 2.1858               | 0.9376               | 16.45                | 10.0    |             |
| 533M1   | I             | 61         | 2.1977               | 0.9402               | 16.37                | 1.91    | 6           |
| 533M1   | C             | 61         | 2.1989               | 0.9406               | 16.37                | 4.57    |             |
| 533M2   | I             | 53         | 2.1827               | 0.9285               | 16.61                | 0.99    | 8           |
| 533M2   | C             | 61         | 2.1963               | 0.9389               | 16.41                | 4.38    |             |
| 549M    | I             | 54         | 2.1876               | 0.9324               | 16.54                | 0.94    | 10          |
| 549M    | C             | 61         | 2.1637               | 0.9121               | 16.92                | 6.79    |             |

Abbreviations: I, incisal section; C, cervical section; numbers following tooth section designations indicate repeat analyses of the same tooth; numbers following some male subjects indicate same-sex siblings in one household.

Table 3. Lead isotopic ratios and lead concentrations in teeth from one Broken Hill family

| Subject* | Tooth section | Tooth type | $^{206}$Pb/$^{204}$Pb | $^{207}$Pb/$^{204}$Pb | $^{208}$Pb/$^{204}$Pb | Pb (ppm) |
|----------|---------------|------------|----------------------|----------------------|----------------------|---------|
| 534M     | I             | 51         | 2.2095               | 0.9494               | 16.18                | 3.05    |
| 534M     | C             | 53         | 2.2142               | 0.9524               | 16.14                | 10.5    |
| 534M     | I             | 54         | 2.2077               | 0.9477               | 16.22                | 1.56    |
| 534M     | C-1           | 53         | 2.2128               | 0.9517               | 16.16                | 10.5    |
| 534M     | C-2           | 53         | 2.2122               | 0.9503               | 16.21                | 9.06    |
| 534M     | EN            | 24-3       | 2.2160               | 0.9537               | 16.15                | 9.36    |
| 534M     | RT-1          | 53         | 2.2120               | 0.9569               | 16.15                | 8.57    |
| 534M     | RT-2          | 53         | 2.2112               | 0.9507               | 16.18                | 6.96    |
| 534M     | EN            | 34-3       | 2.2162               | 0.9535               | 16.12                | 7.88    |
| 534M     | RT            | 53         | 2.2086               | 0.9491               | 16.22                | 5.09    |
| 534M     | EN            | 56         | 2.2150               | 0.9533               | 16.10                | 8.62    |
| 534M     | RT            | 56         | 2.2114               | 0.9512               | 16.14                | 7.17    |
| 534M     | I             | 56         | 2.2128               | 0.9513               | 16.17                | 3.94    |
| 534M     | C             | 56         | 2.2147               | 0.9522               | 16.15                | 8.12    |
| 534M     | EN            | 56         | 2.2148               | 0.9532               | 16.11                | 10.4    |
| 534M     | RT            | 56         | 2.2135               | 0.9508               | 16.20                | 5.14    |
| 534F     | I             | 56         | 2.2048               | 0.9455               | 16.29                | 1.67    |
| 534F     | C             | 56         | 2.2127               | 0.9512               | 16.17                | 9.98    |
| 534F     | I             | 54         | 2.2042               | 0.9451               | 16.29                | 1.73    |
| 534F     | C             | 54         | 2.2110               | 0.9503               | 16.20                | 9.07    |

Abbreviations: I, incisal section; C, cervical section; EN, enamel from crown; RT, root (numbers after section designations indicate repeat analysis of same tooth); M, molar.

*Subject 534M was 11 years old; subject 534F was 9 years old.

(assuming gasoline to be a minor contributor). After obtaining these results, and upon further discussions with the parents, it was revealed that they had burned off many layers of paint from skirting boards and doorways when the children were very young.

The data for the incisal tooth sections indicate that the children received a lead insult in utero and during early childhood. However, the mother exhibited no evidence of an earlier increased lead burden, as her PbB was 4.7 µg/dl and her $^{206}$Pb/$^{204}$Pb ratio was 16.57, consistent with other female adults from Broken Hill. Similarly, there was no evidence of this past exposure in the father, whose urine lead was normal at 4.1 µg/l and whose $^{206}$Pb/$^{204}$Pb was 16.42. These normal results for the parents suggest that their exposure was acute and lead from paint was not transferred in significant amounts to long-term bone compartments. In contrast, PbB levels in the children were relatively elevated for their age: approximately 14 µg/dl and with similar $^{206}$Pb/$^{204}$Pb ratios of 16.40, perhaps reflecting leakage (mobilization) of lead from earlier accumulated skeletal stores and/or from ongoing exposure. (The deficiencies observed by the mother in reading, bilateral coordination, and balance and visual motor control of the older male sibling may be related to a chronic insult in utero and early childhood.)

There are statistically significant differences in lead concentration for the incisal and cervical sections of the paint-exposed children ($p = 0.009$) but not in isotopic composition (Table 1; Figs. 3 and 4).

Variations during pregnancy and between deciduous and permanent teeth. The contribution to enamel lead from different sources and the impact of renovations during pregnancy were mentioned above for siblings from house 517. In another family, it was possible to obtain several teeth, including deciduous and permanent teeth, from two siblings. Extensive contamination from renovations of this house, located within 500 m of the mining activities, occurred during the pregnancy with the older sibling. Additional contamination may have resulted from transport of lead dust to the residence on the clothes of the male adult, who was employed as an underground worker in the mine for over 20 years. The mine work clothes were laundered at home in Broken Hill.

Incisal and cervical tooth sections from the male sibling (subject 534 M) exhibit the highest contribution of orobe lead of any subject so far analyzed in Broken Hill (Table 3). The data are consistent with a larger insult of orobe lead than for the younger female sibling, although the lead concentrations for the same tooth type (primary molar) are similar.

Data for the permanent teeth show an interesting contrast to those for deciduous teeth (Table 3). Crowns (enamel) of the permanent teeth contain higher amounts of lead than the roots, in contrast to that observed in most deciduous teeth from children at Broken Hill and also from this same subject. This is not unexpected as the development of enamel in permanent first molars is completed at 2.5–3 years (11), the time of maximum moulting activity (20). The roots of the permanent teeth of subject 534 M contain relatively high amounts of lead, and the $^{206}$Pb/$^{204}$Pb ratios are slightly higher than the enamel, indicating a contribution of lead from food, water, and air; the $^{206}$Pb/$^{204}$Pb ratios in these media are generally >16.3 in
wholetooth

of lead to dentine from endogenous and exogenous sources but, at this stage, provide no evidence for the reverse process.

Nevertheless, it should be possible to obtain an estimate of the rate of change, or addition, of lead to dentine in the isotopic composition and lead concentration, assuming that the isotopic composition and lead concentration were the same in enamel and dentine at the time of tooth eruption. The estimation for the rate of change can be calculated from the difference between the incisal and cervical sections from the 206Pb/204Pb, 205Pb/204Pb and lead concentrations in each deciduous tooth. The change from enamel to dentine (incisal to cervical section) in 206Pb/204Pb for high lead-exposed children ranges from 0 to 24 units and 1 to 20 in the low-exposed children. Even though there is a large overall variation, there is fairly good agreement with the change in values for teeth from the same subject. The Student's t-test for 207Pb/204Pb and 206Pb/204Pb J high- and low-exposed children gives p-values of 0.14 and 0.19, respectively (18 df), which are not statistically different. The mean change of about 10 units in 206Pb/204Pb relative to the overall change of 56 units (the difference between petrol at 16.56 and orebody at 16.00) gives an estimate of between 2–3% per year lead addition over a period of 7–8 years. This rate of change of lead in dentine in deciduous teeth is the same as what we measured in permanent teeth for immigrants to Australia who resided in Australia for varying lengths of time (Gulson et al., in preparation). At this stage, the rate of loss of lead from dentine is unknown.

Conclusions

The approach of slicing teeth into incisal and cervical sections, combined with lead isotope measurements, provides an excellent history of lead exposure for children. If there are no changes to lead exposure over the lifetime of the deciduous tooth (e.g., approximately 7 years), then it is feasible to use a whole tooth for analysis. Teeth from children with low lead exposure generally contained < 2 ppm in the incisal section (predominantly enamel and primary dentine), and the isotopic compositions were consistent with the lead exposure in utero. The cervical sections (predominantly dentine) contained up to 9 ppm Pb, and the isotopic compositions varied depending on the source of the lead. The low lead concentrations in coronal dentine were consistent with those observed in other studies of unexposed children. In high to moderately lead-exposed children, the amounts of lead and isotopic compositions in incisal and cervical sections varied widely; the cervical sections generally contained more lead, and the isotopic compositions reflect the dominant source(s). Two siblings from Broken Hill with the highest amounts of tooth lead appear to have derived this lead in utero and during early childhood from lead paint released during renovations, even though the dwelling was within 300 m of mining activities. In another subject from Broken Hill, increased exposure in utero and early childhood showed the lead in teeth was derived from an orebody source, probably also during renovations. In both these cases, there was no indication from the mothers’ current blood lead of any previous high exposure to lead. Crowns and roots of permanent teeth from one subject yielded data that were consistent with those from his deciduous teeth. Introduction of lead into dentine of deciduous teeth is provisionally estimated to occur at a rate of 2-3% per year, but the rate of loss from dentine is unknown at present.

REFERENCES

1. Thompson GN, Robertson EF, and Fitzgerald S. Lead mobilization during pregnancy. Med J Aust 143:131 (1985).

2. Manton WI. Total contribution of airborne lead to blood lead. Br J Ind Med 42:168–172 (1985).

3. Silbergeld EK, Schwarz J, Mahaffey K. Lead and osteoporosis: mobilization of lead from bone in postmenopausal women. Environ Res 47:79–94 (1988).

4. Bellinger D. Interpreting the literature on lead and child development: the neglected role of the "experimental system". Neurotoxicol Teratol 17:201–212 (1995).

5. Gulson BL, Wilson D. History of lead exposure in children revealed from isotopic analyses of teeth. Arch Environ Health 49:279–283 (1994).

6. Edwards-Bert P, Callan P, Bentley K, Baghurst P, eds. Proceedings of the international meeting on non-occupational exposure to lead, 5–9 October 1992, Adelaide, South Australia. Adelaide: South Australian Health Commission, Commonwealth Department of Health, Housing, Local Government and Community Services, 1993.

7. Rabinowitz MB, Wertherli GW, Kopple JD. Kinetic analysis of lead metabolism in healthy humans. J Clin Invest 58:260–270 (1976).

8. Strehlow CD. The use of deciduous teeth as indicators of lead exposure (PhD thesis). New York: New York University, 1972.

9. Shapiro IM, Mitchell G, Davidson I, Solomon HK. The lead content of teeth. Arch Environ Health 30:483–486 (1975).

10. Jacobs M. Lead in the environment—can we live with it? Presented at the Australian Institute Environmental Health Western Regional Conference, 6–9 May 1992, Broken Hill, New South Wales, Australia.

11. Lunt RC, Law DB. A review of the chronology of calcification of deciduous teeth. J Am Dental...
Articles

12. Rabinowitz MB, Leviton A, Bellinger DC. Blood lead-tooth lead relationship among Boston children. Bull Environ Contam Toxicol 43:485–492 (1989).
13. Rabinowitz MB, Bellinger D, Leviton A, Wand J-D. Lead levels among various deciduous tooth types. Bull Environ contam Toxicol 47:485–492 (1991).
14. McGill R, Tukey JW, Larsen WA. Variations of box plots. Am Stat 32:12–16 (1978).
15. Cleveland WS. Univariate data. In: Visualizing data. Summit, NJ: Hobart Press, 1993:16–85.
16. Gulson BL, Mizon KJ, Law AJ, Davis JJ, Howarth D. Sources and pathways of lead in humans from the Broken Hill mining community: an alternative use of exploration methods. Econ Geol 89:889–908 (1994).
17. Delves HT, Clayton BE, Carmichael A, Bubear M, Smith M. An appraisal of the analytical significance of tooth-lead measurements as possible indices of environmental exposure of children to lead. Ann Clin Biochem 19:329–337 (1982).
18. Grandjean P, Lyngbye T, Hansen ON. Lead concentration in deciduous teeth: variation related to tooth type and analytical technique. J Toxicol Environ Health 20:437–445 (1986).
19. Patterson C, Ericson J, Manea-Krichten M, Shirahata H. Natural skeletal levels of lead in Homo sapiens uncontaminated by technological lead. Sci Total Environ 107:205–236 (1991).
20. Davies DJA, Thornton I, Watt JM, Culbard EB, Harvey PG, Delves HT, Sherlock JC, Smart GA, Thomas JFA, Quinn MJ. Lead intake and blood lead in two-year-old urban children. Sci Total Environ 90:13–29 (1990).
21. Gulson BL, Mahaffey KR, Mizon KJ, Korsch MJ, Cameron M, Vimpani G. Contribution of tissue lead to blood lead in adult female subjects based on stable lead isotope methods. J Lab Clin Med 125:703–712 (1995).
22. Malik SR, Fremlin JH. A study of lead distribution in human teeth, using charged particle activation analysis. Caries Res 8:283–292 (1974).
23. Orban B. Oral histology and embryology. St Louis: The C.V. Mosby Company, 1953.
24. Manea-Krichten M, Patterson C, Miller G, Sensie D, Erel Y. Comparative increases of lead and barium with age in human tooth enamel, rib and ulna. Sci Total Environ 107:179–203 (1991).
25. Steenhout A. Kinetics of lead storage in teeth and bones: an epidemiologic approach. Arch Environ Health 37:224–239 (1982).
26. Bercovitz K, Laufer D. Lead release from trabecular bone. In: Impact of heavy metals on the environment (Vernet J-P, ed). Amsterdam: Elsevier, 1992:1–13.
27. Rabinowitz MB, Leviton A, Bellinger D. Relationship between serial blood lead levels and exfoliated tooth dentin lead levels: models of tooth lead kinetics. Calcif Tissue Int 53:338–341 (1993).

---

**Occupational Health and Safety in Progress**

*Northern-Baltic-Karelian Regional Symposium*

Organized by the Finnish Institute of Occupational Health

Main themes will include:
- Occupational Health Services
- Occupational and Environmental Health
- Hygiene and Toxicology
- Physiology, Ergonomics
- Safety and Risk Management
- Occupational Medicine
- Occupational Psychology

August 12–14, 1996
Lappeenranta, Finland

Deadline for Abstracts: April 30, 1996

Deadline for early registration: June 15, 1996

For more information:
Occupational Health and Safety in Progress
c/o Finnish Institute of Occupational Health
Syposium Secretariat, Anneli Vartio
Topeliuksenkatu 41 a A
FIN-00250 Helsinki
FINLAND