Lead Exchange in Teeth and Bone—A Pilot Study Using Stable Lead Isotopes

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Stable lead isotopes and lead concentrations were measured in the enamel and dentine of permanent (n = 37) and deciduous teeth (n = 14) from 47 European immigrants to Australia to determine whether lead exchange occurs in teeth and how it relates to lead exchange in bone. Enamel exhibits no exchange of its European-origin lead with lead from the Australian environment. In contrast, dentine lead exchanges with Australian lead to the extent of ~1% per year. In one subject, trabecular bone from the tooth socket exchanged almost all its European lead with Australian lead over a 15-year period (turnover of ~6% per year), similar to the ~8% per year proposed for lead turnover in trabecular bone. The repository characteristics of intact circumpulpal dentine were investigated by analyses of four sets of contiguous slices from six teeth: 1) a set consisting of slices with intact circumpulpal dentine and cementum; 2) a set in which these areas were removed; 3) another set consisting of slices with intact circumpulpal dentine and cementum; and 4) a set without cementum. These analyses show relatively small differences in isotopic composition between contiguous slices except that circumpulpal dentine appears to be the dominant control on lead concentration. There is a significant correlation (R^2 = 0.19, p = 0.01, n = 34) of dentine lead concentration and rate of exchange with residence time from the country of origin and Australian lead, but there is no such correlation with enamel lead concentration. Analyses of permanent and deciduous teeth of subjects from other countries who have resided in Australia for varying lengths of time should resolve some of the questions arising from this pilot study. *Key words:* bone exchange, isotopes, lead, teeth. *Environ Health Perspect* 105:820–824 (1997)

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The skeleton is the main store of lead in the body, and most research on lead turnover or exchange has been directed towards bone analyses (*1*). Tooth analyses have been used as an alternative for skeletal lead to identify lead exposure in children (*2–4*).

Evidence for lead turnover or exchange in calcified tissue in humans is based on 1) relatively crude methods, such as X-ray fluorescence (XRF) measurements on tibia, calcaneus, or phalanges of occupationally exposed workers (*5–9*); 2) indirect methods based on comparisons of tooth and blood lead levels (*3,10,11*); and 3) short-term experiments on limited numbers of subjects using radioactive tracers (*12*) or longer experiments using stable isotopes (*13*). Rabinowitz (*1*) used some of the above techniques and calculated that the bulk turnover rates for lead in compact bone were ~2%/year and ~8%/year for the spine (trabecular bone).

We have shown that in blood of Australian subjects and in environmental samples (diet, air, house dust, gasoline), the $^{206}Pb/^{204}Pb$ ratio is <17.0 and the $^{207}Pb/^{206}Pb$ ratio is >0.91 (*14,15*). These ratios are totally different from those prevailing in other countries. Furthermore, we have established that lead in the blood of Australian migrants exchanged rapidly with lead in the Australian environment, especially in the first 3–6 months; even after >12 months residence, approximately 40–70% of lead in their blood was skeletally derived (*14*). As Australian lead was exchanging with the skeletal lead in the subjects, it was possible that exchange was also occurring in the dentine of teeth. If exchange in teeth was occurring, then there should be a greater contribution of Australian lead to dentine corresponding to residence time in Australia.

Thus, the aims of this pilot study were to determine if exchange of lead occurred in tooth dentine and, if so, at what rate and how this rate compared with that in bone.

Methods

Permanent teeth of Australian migrants were obtained from dental practitioners throughout Sydney. The subjects were mainly from Eastern and Southern Europe. Information regarding country and city of origin, age of subject, and residence time in Australia up until tooth extraction was requested, but not always obtained. Likewise, information regarding residence time in other countries prior to arrival in Australia was not generally available. In one subject [Table 1; Croatia 3 (I546, I547)] it was possible to analyze trabecular bone attached to the permanent tooth. Deciduous teeth were generally those from children whose mothers were enrolled in a related project; these deciduous teeth were analyzed to provide evidence for the skeletal lead isotopic signature of the mother.

This pilot study was performed in two stages. The initial study of permanent teeth (n = 18) and deciduous teeth (n = 14) were from subjects from the Commonwealth of Independent States (CIS; the former Soviet Union), the former Yugoslavia, Poland, Bulgaria, and Lebanon. The second stage involved analyses of other permanent teeth (n = 19) for subjects from Turkey, Lebanon, Syria, Spain, Greece, Egypt, Italy, Uruguay, the United Kingdom, and Chile.

Deciduous and permanent teeth were analyzed. Deciduous teeth were crowns only, as the roots had been resorbed. 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 rationale and advantages of using cross-sectional slices were described in Gulson (*16*).

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 [see Fig. 1 in Gulson (*16*)]. In three teeth, the circumpulpal dentine and cementum were removed from slices of the root and compared with contiguous slices in which the circumpulpal dentine and cementum were retained to evaluate the effect of circumpulpal dentine on lead isotopic composition and concentration. In another three teeth, the cementum was removed from slices of root and compared with contiguous slices with retained circumpulpal canal and cementum.

Analytical methods follow those described in Gulson (*16*). Briefly, from 5 to 50 mg of specially cleaned tooth sections were dissolved in 6 M HCl to which a ^{202}Pb solution of known isotopic composition and concentration was added (the isotope dilution method). Lead was separated by ion exchange chromatography and the isotope

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ratios were measured by thermal ionization mass spectrometry. The precision of the isotopic ratios based on over 1,800 analyses of international standards and natural samples is ± 0.05% (2 Σ) for the $^{207}Pb/^{206}Pb$ ratio and ± 0.1% for the $^{206}Pb/^{204}Pb$ ratio. Data for replication of tooth analyses are given in Gulson and Wilson (*4*) and Gulson (*16*).

Gulson and Wilson (*4*) and Gulson (*16*) demonstrated the use of the lead isotope technique, combined with the well-established histology of teeth, in evaluating *in utero* and early childhood lead exposure from slices of deciduous teeth. In this approach, analysis of the enamel provides evidence of *in utero* exposure. Analysis of dentine provides evidence of exposure during the early childhood years, when hand-to-mouth activity is usually an important contributor to lead body burden, and potentially up to the time of tooth exfoliation (*2,3*).

In children exposed to lead sources from mining, paint, or gasoline in communities such as the Broken Hill lead mining community, Gulson and Wilson (*4*) and Gulson (*16*) showed that the source of lead from the incisal sections was different from the source of lead in the cervical sections of deciduous teeth, reflecting the change in lead from *in utero* exposure to early childhood.

These data also demonstrated that there was minimal exchange of lead in enamel in contrast to dentine. Using the lead in enamel as a fixed parameter, the changes in dentinal lead concentration and isotopic composition can be calculated simply by difference. In this paper, the differences are calculated by $(^{207}Pb/^{206}Pb)_{enamel}-(^{207}Pb/^{206}Pb)_{dentine} = \Delta(^{207}Pb/^{206}Pb)$.

Theoretical aspects of the lead isotope method are described in Gulson (*16*).

Results and Discussion

Lead isotopic and concentration data for the present investigation are presented in Tables 1 and 2 and Figure 1.

Variation in rate of exchange with residence time with tooth type. To estimate the reproducibility of any changes for a given subject, two teeth from four subjects were measured. Reproducibility was excellent for two sets of molars [Croatia 3 (I546/I547) and Yugoslavia 1 (I828) in Table 1]. In spite of quite different lead concentrations, the change in $^{207}Pb/^{206}Pb$ is identical in each pair of teeth. In a subject from Spain who had been in Australia for 21 years, the upper lateral incisor (M813/M814) exhibited no change compared with the molar (M815/M816) for which a change of 44 was observed. In a subject from Syria who had been in Australia for 19 years, the

Table 1. Lead isotopic and concentration data and isotopic shifts in $^{207}Pb/^{206}Pb$ between enamel (crown) and dentine (root) for immigrant teeth

Country	Tooth section	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{204}Pb$	Pb (ppm)	$^{207}Pb/^{206}Pb$ ($\Delta \times 1000$)	Tooth type	Age (year)	Years in Australia	N or R[a]
Lebanon 1	H909 CR	0.8794	17.64	2.8	138	PM	NA	NA	N
	H909 RT	0.8932	17.35	8.1					
Lebanon 2	CR	0.8748	17.77	1.0	15	LO M	NA	NA	N
	RT	0.8763	17.73	5.4					
Lebanon 3	CR	0.8798	17.66	1.4	39	LO M	NA	NA	N
	RT	0.8837	17.59	6.1					
Lebanon 4	CR	0.8774	17.70	1.8	108	PM	NA	NA	N
	RT	0.8882	17.45	12.6					
Lebanon 5	M819 CR	0.8666	18.00	4.9	549	LLO 2nd M	39	23	N
	M820 RT	0.9215	16.81	29.0					
Lebanon 6	M821 CR	0.9236	16.73	8.2	0	UL 2nd M	29	26	Total[b]
	M822 RT	0.9241	16.72	10.7					
Lebanon 7	M831 CR	0.8868	17.54	1.8	97	UR CI	NA	21	R
	M832 RT	0.8771	17.72	15.1					
Lebanon 8	M835 CR	0.8823	17.63	2.2	126	UR 1st M	41	1	N
	M836 RT	0.8949	17.33	7.7					
Lebanon 9	M837 CR	0.9130	16.98	1.0	233	LLO CA	46	32	R
	M838 RT	0.8897	17.47	11.2					
Spain 1[c]	M813 CR	0.8732	17.82	4.4	0	UR I	38	21	None
	M814 RT	0.8736	17.82	28.4					
Spain 1[c]	M815 CR	0.8749	17.78	5.1	44	UL M	38	21	R
	M816 RT	0.8705	17.91	18.8					
Syria 1[c]	M825 CR	0.8949	17.33	2.3	141	UL M	45	19	R
	M826 RT	0.8808	17.65	21.9					
Syria 1[c]	M827 CR	0.8900	17.45	2.4	60	UR CI	45	19	R
	M828 RT	0.8840	17.57	8.2					
Turkey 1	M823 CR	0.8796	17.68	3.1	123	UR 1st M	45	14	R
	M824 RT	0.8673	17.99	20.9					
Turkey 2	M833 CR	0.8647	17.99	1.0	145	LO 1st M	31	8	N
	M834 RT	0.8792	17.69	5.3					
Bulgaria 1	H914 CR	0.8544	18.27	16.2	50	LO I	NA	NA	N
	H914 RT	0.8594	18.13	25.4					
Bulgaria 2	H915 CR	0.8555	18.20	16.9	69	LO I	NA	NA	N
	H915 RT	0.8624	18.08	24.1					
Czech 1	H917 CR	0.8588	18.17	4.6	103	NA	NA	NA	N
	H917 RT	0.8691	17.92	20.0					
Czech 2	H918 CR	0.8670	17.94	4.1	20	NA	NA	NA	N
	H918 RT	0.8690	17.92	14.5					
Poland 1	I823 CR	0.8720	17.84	2.5	371	PM	69	43	N
	I823 RT R	0.9091	17.02	11.3					
	I823 RT NR	0.9159	16.88	18.8					
Poland 2	I824 CR	0.8733	17.79	3.4	519	CA	63	44	N
	I824 RT R	0.9236	16.72	34.5					
	I824 RT NR	0.9252	16.70	63.0					
Poland 5	0737 CR	0.8544	18.22	0.8	28	M	34	2	N
	0738 RT	0.8571	18.20	22.2					
Croatia 1	I544 CR	0.8494	18.39	6.5	123	LO M	55	12	N
	I544 RT	0.8544	18.25	17.2					
Croatia 2	I545 CR	0.8494	18.45	6.5	118	LO M	25	4	N
	I545 RT	0.8612	18.10	7.6					
Croatia 3[c]	I546 CR	0.8516	18.33	1.7	30	U M/1	45	15	N
	I546 RT	0.8546	18.26	4.1					
Croatia 3[c]	I547 CR	0.8508	18.34	2.2	31	U M/2	45	15	N
	I547 RT	0.8539	18.28	10.7					
	I547 BONE	0.9014	17.19	1.8	506				
Croatia 5	No crown					PM			
	I827 RT NR	0.8640	18.08	23.8					
	I827 RT R	0.8597	18.13	10.2					
Yugoslavia 1[c]	I828 CR	0.8524	18.36	0.4	167	M/1	30	?1	N
	I828 RT	0.8691	17.93	5.9					
Yugoslavia 1[c]	I828 CR	0.8530	18.34	0.4	170	M/2	30	?1	N
	I828 RT	0.8700	17.90	3.0					
CIS	0603 CR	0.8618	18.11	0.3	38	LLO M		2	N
	0771 RT	0.8656	18.01	3.2					
Egypt	M829 CR	0.8910	17.43	2.3	92	2nd M	50	15	R
	M830 RT	0.8818	17.63	6.3					

Continued, next page.

Table 1 Continued.

Country	Tooth section	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{204}Pb$	Pb (ppm)	$^{207}Pb/^{206}Pb$ (Δ × 1000)	Tooth type	Age (year)	Years in Australia	N or R[a]
Greece	M809 CR	0.8602	18.17	5.0	35	UR 3rd M	53	28	R
	M810 RT	0.8567	18.23	24.3					
United Kingdom	0753 CR	0.9067	17.12	1.7	170	UL I	30	26	N
	0754 RT	0.9237	16.72	5.9					
Uruguay	0751 CR	0.8640	18.03	6.9	139	UR I	46	11	N
	0752 RT	0.8779	17.78	22.2					
Italy 1	0755 CR	0.8591	18.21	4.2		LLO I	54	32	N
	0756 RT NR	0.8797	17.78	28.5	206				
	0757 RT R	0.8801	17.73	29.0	210				
Italy 2	0758 CR	0.8670	18.00	1.6		UR M	72	36	N
	0759 RT NR	0.8771	17.76	19.8	101				
	0760 RT R	0.8739	17.85	19.1	69				
Chile	0761 CR	0.8779	17.74	5.5		RLO M	43	8	R
	0762 NR	0.8706	17.91	24.0	73				
	0763 R	0.8696	17.91	20.7	83				

Abbreviations: N, normal; R, reverse; CR, crown; RT, root; M, molar; PM, premolar; LO, lower; U, upper; CA, canine; I, incisor; CI, central incisor; LLO, left lower; UL, upper left; RLO,right lower; UR, upper right; RT R, circumpulpal material reamed out; RT NR, circumpulpal material not reamed out; NA, information not available.

[a]Normal means that the dentine lead relative to the enamel lead has shifted towards the Australian isotopic value (in this case ~16.7); reverse means that the dentine lead relative to the enamel lead has shifted away from the Australian value.

[b]These data show that there has possibly been total exchange with Australian lead as the subject came to Australia at 3 years of age.

[c]Different teeth from same subject.

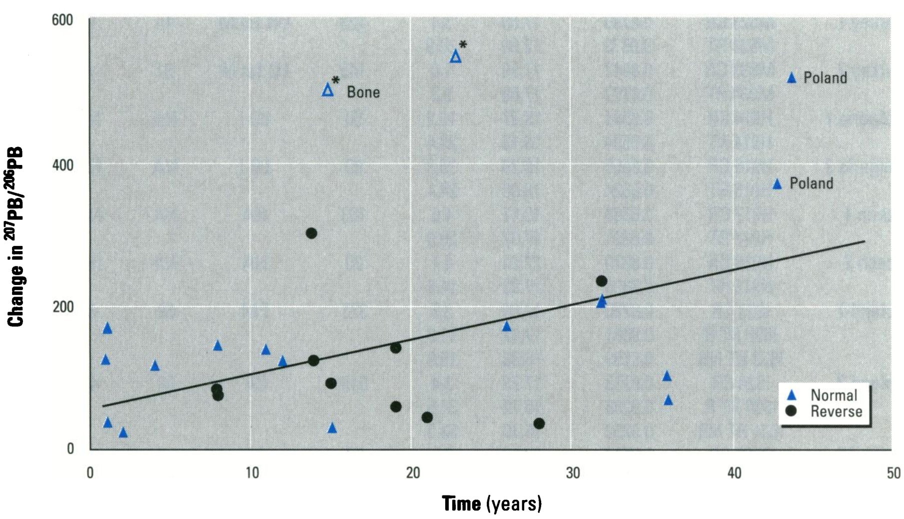

Figure 1. Change in $^{207}Pb/^{206}Pb$ ratio in dentine relative to enamel versus the length of time the subject has resided in Australia. Note the increase in the change with time as the dentine approaches the Australian lead value. Normal means that the dentine lead relative to the enamel lead has shifted towards the Australian isotopic value (in this case ~16.7); reverse means that the dentine lead relative to the enamel lead has shifted away from the Australian value.
*The data for the bone sample and that for a tooth with a value of change of 549 (Δ) are excluded from the regression analysis.

molar exhibited more than twice the change observed in the upper central incisor. The difference in change between the Spanish and Syrian teeth may be a function of lead concentration as the root dentine of the central incisor of the Spanish subject contained more than three times that in the Syrian incisor, as discussed below.

Tooth type. In adults, tooth type was not usually considered to be important when evaluating lead accumulation (*17,18–20*), although it was attributed significance in some investigations (*21–23*). Tooth type does not appear to be of concern in the evaluation of isotopic compositions in deciduous teeth (*4,16*); however, in this study, tooth type does appear important in some cases. For example, in two cases, the subjects arrived in Australia when they were about 3–4 years old and have resided there for 26 years [Lebanon 6 (M821/M822) and the United Kingdom (O753/O754)]. The Lebanese tooth was a second molar and there was no isotopic difference between the enamel and dentine. In contrast, the U.K. tooth was an incisor and the dentine showed significant exchange with Australian lead (Table 1). Other than the higher lead concentration in the Lebanese tooth, the explanation for the difference in exchange rate may be the time of formation of the teeth. In the U.K. case, the crown (enamel) in the permanent incisor was already formed and the subject had been exposed to U.K. lead, by 4 years of age, whereas the crown of the molar in the Lebanese subject was only just forming (or not even so) at the age of 3 years.

Enamel and dentine. For permanent teeth in this study, enamel always contained lower lead concentrations compared with dentine in the roots. The ratio of dentine Pb/enamel Pb varies from 1.2 to 18.5, but most are in the range 1–8. For deciduous teeth the ratio varies from 1.5 to 4.1. There is a significant correlation of enamel and dentine lead (R^2 0.40, $p<0.0001$; Table 2).

Removal of circumpulpal dentine. Rabinowitz et al. (*2,10,11*) identified a correlation between tooth and blood lead concentrations in deciduous teeth using a wedge sampling approach whereby a wedge of coronal dentine and the circumpulpal canal was analyzed. Part of the correlation may have arisen from the inclusion of the pulpal canal, whose lead probably reflects that of more recent origin, such as in blood leads. To evaluate the contribution from the circumpulpal canal to the root analysis, slices of root were analyzed with the canal and cementum intact and compared with contiguous slices from which the circumpulpal canal and cementum had been removed. Samples in which the circumpulpal dentine has been removed exhibited a poorer correlation with the rate of exchange with residence time of dentine lead and Australian lead than those with intact circumpulpal dentine.

Lead concentrations in sections with the canal and cementum removed were approximately half those with the canal intact, and the isotopic composition exhibited a slightly higher proportion of Australian lead (Poland 2, Croatia 5, and Yugoslavia 1 in Table 1). These data are consistent with earlier data obtained on deciduous teeth (*4*).

Removal of cementum. Slices of root with intact circumpulpal canal and cementum had relatively similar isotopic compositions and lead concentrations to contiguous slices from which the cementum was removed (Italian and Chilean subjects in Table 1). From these and the above analy-

Table 2. Results of regression analyses of the change in $^{207}Pb/^{206}Pb$

Variables	Number	R^2	*p*-value
Time in Australia	27	0.3	0.003
Enamel Pb (excluding two Bulgarian teeth with 16 ppm Pb)	32	0.004	0.73
Dentine Pb (excluding sample with 63 ppm Pb)	34	0.19	0.01
Age of subject (all data)	25	0.07	0.19
Age of subject (one deletion)[a]	24	0.17	0.05
Dentine Pb versus enamel Pb (includes deciduous teeth)	42	0.40	<0.0001

[a]Subject was deleted for age regression because it was deleted for the regression versus time in Australia (Δ in Fig. 1).

ses, it would appear that the circumpulpal canal exerts the most significant control on lead concentration.

Rate of exchange with residence time and lead concentration. As expected, given the impervious nature of enamel, there is no significant correlation of rate of exchange with residence time of Australian lead and the concentration of lead in enamel (Table 2). Rate of exchange is significantly correlated with residence time and dentine lead concentration [R^2 = 0.19 (p = 0.01; Table 2)], as suggested above for individual subjects. A correlation between dentine lead and rate of exchange with residence time may be expected, as the dentine contains lead of more recent exposure (*2,10,11*). Such a hypothesis is supported by the observation that, in analyses of contiguous slices where the circumpulpal dentine was intact and removed, the data for the slice with removed circumpulpal dentine is invariably of poorer correlation compared with the slice where the circumpulpal dentine is retained.

Rate of exchange with residence time in Australia. Figure 1 shows the difference in the $^{207}Pb/^{206}Pb$ ratio for enamel and dentine plotted against the time the subject has lived in Australia. For adult subjects who have lived <3 years in Australia, the exchange of European lead with Australian lead in dentine was usually not detectable, i.e., there was an insignificant difference in the isotopic composition of the crown (enamel) and root (dentine). Regression analysis of the data in Figure 1, excluding the bone sample and that for one Lebanese subject, gives an R^2 of 0.30 (p = 0.003; n = 27). Exclusion of the other two Polish points with the largest exchange in $^{207}Pb/^{206}Pb$ (Poland 1 and Poland 2) reduces the correlation to nonsignificance with an R^2 of 0.05 and p of 0.3.

The rate of exchange with residence time in dentine of European and Australian lead is estimated from the slope of the regression line in Figure 1, relative to a value in European lead of 0.862 and that in Australian lead of 0.922. The estimated rate of exchange with residence time or turnover of lead in dentine is ~1 ± 0.3%/year. Perhaps, fortuitously, this is similar to the rate estimated for lead turnover in cortical bone by Rabinowitz (*3*), or it may reflect the similarity in processes that occur in lead in bone and dentine, notwithstanding the absence of osteoclasts and osteoblasts in dentine. In the lead isotope study of deciduous teeth from Broken Hill children, Gulson (*16*) estimated that lead was added to dentine at a rate of approximately 2–3%/year.

Rate of exchange with residence time in trabecular socket bone. Croatia 3 (I547) lived in Australia for 15 years prior to tooth extraction. There was little change in isotopic composition between enamel and dentine over this time, but there has been almost total exchange with Australian lead in the bone (Table 1). Although based on only one analysis, the estimated rate of exchange with residence time of lead in trabecular bone relative to enamel is ~6%, approximately six times that of dentine/enamel. This value is similar to the lead turnover of ~8% in trabecular bone estimated by Rabinowitz (*3*) using a quite different approach. The almost complete isotopic exchange in socket bone (trabecular bone) lead with Australian lead for subject I547 over a 15-year period is consistent with half-lives of 7–13 years estimated from measurements on tibia/calcaneus/phalange by the XRF method and blood lead analyses on occupationally exposed subjects (*5–9*).

A two-way exchange of lead in dentine. In the initial study, all analyses showed a normal change in the isotopic composition of the dentine. That is, there was a positive shift in the $^{207}Pb/^{206}Pb$ ratio from the country of origin, manifested by the isotopic composition in the enamel, towards the Australia values. Negative changes (reverse data in Table 1) signify interactions with other sources of lead. When the study was expanded, 9 of 19 enamel/dentine pairs exhibited a reversal of this trend. At this stage, no explanation for the reversal is obvious apart from lack of information about previous residence history, occupational/hobby exposure, or their diets in Australia. Diet is not considered a major contributor to the reverse isotopic changes in dentine because analyses of teeth and bones from Australian residents indicate that the $^{206}Pb/^{204}Pb$ ratio has been <17.0 (or $^{207}Pb/^{206}Pb$ >0.91) for decades. This long-term low value is also indicated by the data for Lebanon 6 (M821/M822) who arrived in Australia at 3 years of age and thus experienced 26 years of exposure to Australian lead. Any trace of his maternal skeletal lead has been replaced with Australian lead. Furthermore, it is only over the last few years that the Australian diet has $^{206}Pb/^{204}Pb$ values of >17 (*15*).

Alternative explanations for the reverse isotopic trends in dentine may be that the lead is mobilized from an endogenous source, such as cortical bone, and introduced to the dentine via the dentinal tubules, or that they reflect a two-way migration of lead in dentine.

Based on epidemiological data, Steenhout (*23*) argued for a one-way exchange of lead in tooth dentine but, given the structure of teeth and that collagen could theoretically act as an ion exchange medium, there is no reason to preclude a two-way exchange of lead. In evaluating models of tooth lead kinetics, Rabinowitz et al. (*11*) found that tooth lead/blood lead data were compatible with a model that allows lead to be slowly removed from dentine, a conclusion also reached by Gulson and Wilson (*4*) and Gulson (*16*).

Bercovitz and Laufer (*20*) were able to procure paired trabecular bone and tooth samples from 97 Israeli subjects 9–81 years of age. They found higher concentrations of lead in bone than in teeth until the age of 50; after 50 years of age the reverse was noted. These changes were attributed to the release of lead from trabecular bone, which is detectable after age 35.

Rate of exchange with residence time and age. There are variable correlations of rate of exchange with residence time in the $^{207}Pb/^{206}Pb$ ratio and the age of the subject. For all data, the R^2 is 0.07 and p = 0.19 (n = 25), but with the exclusion of the extreme data point for Lebanon 5 (M819), the correlation assumes significance (R^2 = 0.17, p = 0.05, n = 24; Table 2).

Conclusions

Results of this study of permanent teeth support the earlier investigation of deciduous teeth in demonstrating that, relative to enamel, lead can be added to dentine. In contrast to deciduous teeth and the initial part of this study, reversals were observed in the predicted trends of lead added to dentine. These reversals may arise from changes in environmental sources, from endogenous mobilization of lead from the skeleton, or from a two-way exchange of lead in dentine. A systematic study of (anterior) teeth from several subjects, for example, from two countries, who have lived in Australia for >5 years (preferably >10 years), would provide evidence of lead turnover in teeth. A small sample of socket bone would provide even more convincing data on lead turnover in teeth and bone.

Given the limited amount of data for bone lead turnover in children, an investigation of teeth from children who have lived >1 year in Australia may provide evidence of lead turnover in a period of rapid skeletal development.

References

1. International workshop on lead in bone: implications for dosimetry and toxicology. Environ Health Perspect 91:3–86 (1991).
2. Rabinowitz MB, Leviton A, Bellinger DC. Blood lead–tooth lead relationship among Boston children. Bull Environ Contam Toxicol 43:485–492 (1989).
3. Rabinowitz MB. Toxicokinetics of bone lead. Eviron Health Perspect 91:33–37 (1991).
4. Gulson BL, Wilson D. History of lead exposure in children revealed from isotopic analyses of teeth. Arch Environ Health 49:279–283 (1994).
5. O'Flaherty EJ, Hammond PB, Lerner SI. Dependence of apparent blood lead half-life on the length of previous lead exposure in humans. Fundam Appl Toxicol 2:49–54 (1982).
6. Hryhorczuk D, Rabinowitz M, Hessl S, Hoffman D, Hogan M. Elimination kinetics of blood lead in workers with chronic lead intoxication. Am J Ind Med 8:33–42 (1985).
7. Christoffersson JO, Ahlgren L, Schutz A, Skerfving S, Mattsson S. Decrease of skeletal lead levels in man after end of occupational exposure. Arch Environ Health 41:312–318 (1986).
8. Nilsson U, Attewell R, Christoffersson JO, Schutz A, Ahlgren L, Skerfving S, Mattsson S. Kinetics of lead in bone and blood after end of occupational exposure. Pharmacol Toxicol 69:477–484 (1991).
9. Erkkila J, Armstrong R, Riihimaki V, Chettle DR, Paakkari A, Scott M, Somervaille L, Starck J, Kock B, Aitio A. *In vivo* measurements of lead in bone at four anatomical sites: long term occupational and consequent endogenous exposure. Br J Ind Med 49:631–644 (1992).
10. Rabinowitz MB, Bellinger D, Leviton A, Wand J-D. Lead levels among various deciduous tooth types. Bull Environ Contam Toxicol 47: 602–608 (1991).
11. Rabinowitz MB, Leviton A, Bellinger D. Relationships between serial blood lead levels and exfoliated tooth dentin lead levels: models of tooth lead kinetics. Calcif Tissue Int 53:338–341 (1993).
12. Chamberlain AC, Heard MJ, Little P, Newton D, Wells AC, Wiffen RD. Investigations into Lead from Motor Vehicles. Report AERE R9198. Harwell, UK:Atomic Energy Authority, 1978.
13. Rabinowitz MB, Wetherill GW, Kopple JD. Kinetic analysis of lead metabolism in healthy humans. J Clin Invest 58:260–270 (1976).
14. Gulson BL, Mahaffey KR, Mizon KJ, Korsch MJ, Cameron MA, 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).
15. Gulson BL, Pisaniello D, McMichael AJ, Mahaffey KR, Luke C, Mizon KJ, Korsch MJ, Ashbolt R, Vimpani G, Pederson DC. Stable lead isotope profiles in smelter and general urban communities. Comparison of biological and environmental measures. Environ Geochem Health 18:147–163 (1996).
16. Gulson BL. Tooth analyses of sources and intensity of lead exposure in children. Environ Health Perspect 104:306–312 (1996).
17. Steenhout A, Pourtois M. Lead accumulation in teeth as a function of age with different exposures. Br J Ind Med 38:297–303 (1981).
18. Bercovitz K, Laufer D. Tooth type as indicator of exposure to lead of adults and children. Arch Oral Biol 35:895–897 (1990).
19. Bercovitz K, Laufer D. Age and gender influence on lead accumulation in root dentine of human permanent teeth. Arch Oral Biol 36:671–673 (1991).
20. Bercovitz K, Laufer D. Lead release from trabecular bone. In: Impact of Heavy Metals on the Environment (Vernet JP, ed). Amsterdam: Elsevier, 1992;1–13.
21. 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).
22. 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).
23. Steenhout A. Kinetics of lead storage in teeth and bones: an epidemiological approach. Arch Environ Health 37:224–239 (1982).