

## Tibia Lead Levels and Methodological Uncertainty in 12-Year-Old Children

A. C. Todd,\*<sup>1</sup> R. Buchanan,\* S. Carroll,\* E. L. Moshier,\* D. Popovac,† V. Slavkovich,‡ and J. H. Graziano‡

\*Department of Community and Preventive Medicine, The Mount Sinai School of Medicine, 1 Gustave L. Levy Place, Box 1057, New York, New York 10029; †University of Pristina, Pristina, Yugoslavia; and ‡Division of Environmental Health Science, School of Public Health, Columbia University, New York, New York 10027

Received September 29, 2000

***In vivo* bone lead measurements with <sup>109</sup>Cd-based K-shell X-ray fluorescence (XRF) have been used to assess long-term lead exposure in adults. Tibia lead levels were measured in 210 children (106 boys, 104 girls) of 11–12½ years of age in a lead smelter town and in a control (nonexposed) town. Tibia lead levels, methodological uncertainties, and models of some of the factors influencing them are presented. <sup>109</sup>Cd-based K-shell XRF tibia lead methodological uncertainty in children is comparable to that in adults.** © 2001 Academic Press

**Key Words:** X-ray fluorescence; bone; lead.

### INTRODUCTION

Environmental and occupational exposure to lead continues to be a widespread public health concern and the subject of much study. The body's largest repository for lead is the skeleton (Barry and Mossman, 1970; Barry, 1975), wherein the "half-life" is on the order of years (Chettle, 1995; Rabinowitz *et al.*, 1976), making bone lead a good surrogate for lifetime exposure (Somervaille *et al.*, 1988).

Lead in bone can be measured noninvasively and *in vivo* with the techniques of <sup>109</sup>Cd-based K-shell X-ray fluorescence (XRF) (Todd and Chettle, 1994). Although established for some time, efforts to improve the sensitivity of the technique have continued, as the populations studied have expanded from occupationally exposed workers (Somervaille *et al.*, 1988) to include environmentally exposed adults (Rothenberg *et al.*, 2000), adolescents (Moline *et al.*, 1998), and children. These groups present progressively greater challenges to the measure-

ment sensitivity because of their (on average) decreasing bone lead levels and, of particular concern for the <sup>109</sup>Cd-based technique, their decreasing bone mineral content (the <sup>109</sup>Cd-based technique uses coherent scattering from bone mineral to render measurement accuracy independent of several parameters such as overlying tissue thickness (Todd, 2000a,b; Todd and Chettle, 1994).

It has previously been suggested that the methodological uncertainty in children would be larger than that observed in adults but that the worsening was expected to be less than a factor of two (Todd and Chettle, 1994). This study shows that the worsening of methodological uncertainty is only a few percent in 12 year olds.

### MATERIALS AND METHODS

#### *X-Ray Fluorescence*

The <sup>109</sup>Cd source used (Model CUC.D4; Amersham Corp.) was of approximate activity 1.0 GBq (28 mCi), of active area 2 mm<sup>2</sup>, and of outer diameter 5.8 mm, and was housed within a W/Cu/Ni alloy source holder of 6 mm bore and 12 mm outer diameter. The source was mounted coaxially with, and in the center of, the polythene end cap of an intrinsic germanium detector (Model GL2020R; all equipment Canberra Industries, Meriden, CT) with a resistive feedback preamplifier (Model 2002CPSL). Detector output was then passed to a digital signal processor (Model 2060) that communicated with a personal computer *via* a multichannel analyzer board (Model S100) and software (Genie 2000, version 0.92b). The digital signal processor was operated with a rise time of 1.6 μs. Automatic ballistic deficit correction was used to set the "flat top" at 0.9 μs. Spectra were acquired for half-an-hour (true time). The

<sup>1</sup>To whom correspondence should be addressed. Fax: (212)423-9313. E-mail: [andrew.todd@mssm.edu](mailto:andrew.todd@mssm.edu).

full-width-at-half-maximum was approximately 790 eV for the 88.034-keV coherent scatter peak from calibration phantoms and approximately 810 eV for *in vivo* measurements. The XRF system was calibrated *via* lead-doped plaster-of-Paris phantoms that ranged in lead concentration from a nominal blank to 265  $\mu\text{g}$  lead *per g* plaster (equivalent to 387  $\mu\text{g}$  lead *per g* bone mineral (Todd, 2000a)). The methodological uncertainty on an individual measurement was calculated by use of published algorithms (Gordon *et al.*, 1994; Todd, 2000b) for each of the two lead K-shell X-ray peaks used (IUPAC notation K-L<sub>3</sub> and K-M<sub>3</sub>; Siegbahn notation K $\alpha_1$  and K $\beta_1$ ; energies 74.969 and 84.936 keV, respectively). The two independent measures were then combined into a single estimate of the bone lead content (Gordon *et al.*, 1994; Todd, 2000a). Methodological uncertainty dictates that, for low bone lead levels, a single estimate of the bone lead level can be zero or even negative. According to Farias *et al.* (1998), "retention of all point estimates [of bone lead concentration] makes better use of the data in epidemiological studies (Kim *et al.*, 1995a)," although Farias *et al.* (1998) acknowledge that a minimum detectable limit of twice the methodological uncertainty in an individual measurement "has been proposed for interpreting an individual's bone lead estimate" (Gordon *et al.*, 1993).

It has been shown that the methodological uncertainty, evaluated with these algorithms, is not identical to the standard deviation of repeated measurements (Todd *et al.*, 2000). Nevertheless, the methodological uncertainty is still of interest because it is a measure of the statistical uncertainty in the estimate of an individual's tibia lead concentration.

The bone lead measurement system was calibrated continuously; i.e., calibration phantoms were measured whenever *in vivo* measurements were not being performed. During the day, all phantoms were measured, and during the night repeated measurements of the same phantom (the blank or the 48- $\mu\text{g}/\text{g}$  bone mineral phantom) were acquired. Three-hundred-five calibration measurements were performed in 10 days in Mitrovica, and 402 calibration measurements were performed in 12 days in Pristina. Calibration line intercepts from each day revealed no contamination, and the sensitivity (the calibration line slope) from day to day did not vary significantly.

### Materials and Measurements

The study participants were children enrolled in a long-term prospective study of environmental lead

exposure, half of whom were relatively heavily exposed to lead from the prenatal period onward and half of whom were relatively unexposed. The children resided in two towns in Kosovo, Yugoslavia; one, Kosovska Mitrovica, is the site of a lead smelter refinery and battery plant, whereas the other, Pristina, is relatively unexposed. This group of children is unique in that they are well characterized as to exposure history since blood lead was measured prenatally and every 6 months from birth onward. Exposure histories and health outcomes in this cohort have been summarized in a review by Factor-Litvak *et al.* (1999). Bone lead measurements were conducted in the summer of 1998, i.e., prior to the outbreak of war in Kosovo in 1999. The study was approved by the Institutional Review Boards (ethics committees) of The Mount Sinai School of Medicine, The Columbia Presbyterian Medical Center, and The University of Pristina. Written informed consent was obtained from the parents of each child, and assent was obtained from all participants.

The measurements were performed in a clinic in Mitrovica and in a hospital in Pristina. Although Mitrovica is the "exposed" town, calibration standards of nominal zero lead concentration showed no evidence of contamination of the calibration standards or of the room where bone lead measurements were performed (for a full discussion of the sources of contamination and how to correct for them, see Todd (2000b)). Contamination of the *in vivo* bone lead measurements was guarded against by washing of the left lower leg with a weak EDTA solution and then by wiping with 5% glacial acetic acid, a protocol that has been successful in removing lead in past surveys. One child showed a high tibia lead concentration that was met with disbelief but yielded the same concentration upon remeasurement after recleaning the leg on a subsequent day, suggesting that the lead signal was indeed coming from the child's bone.

Height and weight were measured with a stadiometer. Shoulder width (measured from left to right acromion) was measured with a shoulder-width caliper; tibia length and calf circumference at the mid-tibial diaphysis were measured with a flexible tape measure. Tibia width and overlying tissue thickness were both measured at the mid-tibial diaphysis with a skin-fold-thickness caliper. Body mass index and skeletal volume (approximated here by the product of height and the square of shoulder width) were calculated from the anthropometric measurements.

Venous blood samples were obtained for blood lead measurement. Samples were appropriately stored

and transported to Columbia University for biochemical assays. The Columbia laboratory participates in the Centers for Disease Control and Prevention quality control program for blood lead analyses; during the course of this study, the intraclass correlation coefficient for agreement was 0.97.

### Statistical Analyses

Statistical analyses were performed with SAS (SAS Institute Inc., Cary, NC). Standardized values were compared to the critical  $t$  value to identify the "extreme" results within a group at the 5% level of significance (two-sided). Spread *versus* level and box plots were examined to determine whether a Tukey power transformation was necessary to render the data sufficiently homogeneous and/or normally distributed.

Multiple linear regression was used to model tibia lead and tibia lead methodological uncertainty, controlling for such variables as age and anthropometric measures. No preselection of variables was performed (Altman, 1991), and both stepwise and backward elimination methods were compared. All linear regression models were evaluated for the influence of outliers, multicollinearity, departures from normality, and heteroscedasticity. Partial residual plots were used to examine final regression models for linearity, influential points, and homoscedasticity.

## RESULTS

### XRF System Performance

The instrumental "limits of detection" (Currie, 1968) were: 3.1, 1.4, 1.5, and 1.5  $\mu\text{g Pb/g}$  bone mineral for the  $K\alpha$  in Mitrovica, the  $K\beta_1$  in Mitrovica, the  $K\alpha_1$  in Pristina, and the  $K\beta_1$  in Pristina, respectively. The IUPAC (International Union of Pure and Applied Chemistry) lower limits of detection (three times the standard deviation of the predicted concentrations obtained from repeated measurements of a low-level sample) for a plaster-of-Paris calibration phantom of nominal zero lead concentration were 5.5, 5.9, 5.4, and 5.5  $\mu\text{g/g}$  bone mineral for the same X-ray peak/town combinations. Further comparison between the level of tibia lead concentrations and the "noise" of the XRF can be gleaned from the fact that none of the 111 children in the exposed town, but 58 of the 99 children in the control town, had estimates of their tibia lead concentration that were less than the methodological uncertainty (i.e., were zero within uncertainties).

One of the authors (Todd, 2000c) has previously addressed the detection of and adjustment for environmental contamination of the XRF measurement system. There was no evidence of any deposition of environmental lead either on the calibration standards or on the XRF measurement equipment itself in this study.

### Tibia Lead

The data obtained are summarized in Table 1. The children ranged (mean  $\pm$  SD) in age from just under 11 to 12 $\frac{1}{2}$  ( $11.9 \pm 0.4$ ) years. Their tibia lead levels ranged from 5 to 190 ( $39 \pm 24$ )  $\mu\text{g/g}$  of lead per gram of bone mineral (hereafter  $\mu\text{g/g}$ ) in the exposed town and from  $-14$  (i.e., not detectable) to 16 ( $1 \pm 7$ )  $\mu\text{g/g}$  in the control town. Tibia lead methodological uncertainty ranged from 2.1 to 6.0 ( $3.2 \pm 0.6$ )  $\mu\text{g/g}$  in girls and from 1.9 to 7.3 ( $2.9 \pm 0.7$ )  $\mu\text{g/g}$  in boys. Blood lead levels at the time of tibia measurement ranged from 6 to 55 ( $31 \pm 10$ )  $\mu\text{g/dl}$  in the exposed town and 3 to 13 ( $6 \pm 2$ )  $\mu\text{g/dl}$  in the control town.

The highest tibia lead level recorded was  $190 \pm 3$   $\mu\text{g/g}$  from a boy in the exposed town. This value was recorded early in the survey and received with skepticism. The measurement was therefore repeated another day after the skin was washed

**TABLE 1**  
Characteristics of 210 Yugoslavian Children Who Underwent Tibia Lead Measurements

Parameter (units)	Mean	Standard deviation		
		Minimum	Maximum	
Age (years)	11.9	0.4	11.0	12.6
Tibia lead, exposed ( $\mu\text{g/g}$ )	39	24	5	190
Tibia lead, control ( $\mu\text{g/g}$ )	1	7	-14	16
Tibia lead methodological uncertainty (boys) ( $\mu\text{g/g}$ ) <sup>a</sup>	2.9	0.7	1.9	7.3
Tibia lead methodological uncertainty (girls) ( $\mu\text{g/g}$ ) <sup>a</sup>	3.2	0.6	2.1	6.0
Blood lead, exposed ( $\mu\text{g/dl}$ )	31	10	6	55
Blood lead, control ( $\mu\text{g/dl}$ )	6	2	3	13
Height (m)	1.46	0.08	1.25	1.70
Weight (kg)	38.8	8.6	24	77
Body mass index ( $\text{kg/m}^2$ )	17.8	2.7	12.1	29.7
Skeletal volume ( $\text{m}^3$ )	0.1591	0.0258	0.1043	0.2327
Tibia length (cm)	32.7	2.5	24.5	32.5
Calf circumference (cm)	28.5	3.2	22	39.5
Tibia width (mm)	33	5	23	45
Overlying tissue thickness (mm)	3.6	1.5	1.5	10

Note.  $\mu\text{g/g}$ ,  $\mu\text{g}$  of lead per gram of bone mineral.  
<sup>a</sup>Exposed and control towns combined.

**TABLE 2**  
**Linear Regression Modeling Results Identifying Predictors of (*ln* Transformed) Tibia Lead Levels and Tibia Lead Measurement Uncertainty in Yugoslavian Children**

Independent variables	Units of $\beta$ coefficient	$\beta$ coefficient	SE $\beta$	<i>P</i> value	Adjusted <i>R</i> <sup>2</sup>
Tibia lead levels ( <i>n</i> = 206)					
Intercept		3.751	0.171	< 0.0001	70.6%
Town	μg/g	- 1.16984	0.05387	< 0.0001	
Female	μg/g	0.15577	0.05472	0.0049	
Skeletal volume	(μg/g)/m <sup>3</sup>	- 2.73780	1.06428	0.0108	
Town × female	μg/g	0.24777	0.10834	0.0232	
Tibia lead uncertainty ( <i>n</i> = 201)					
Intercept		1.19647	0.27506	< 0.0001	46.2%
Overlying tissue thickness	(μg/g)/mm	0.08868	0.01215	< 0.0001	
Calf circumference	(μg/g)/cm	0.03885	0.01132	0.0007	
Female	(μg/g)	0.13127	0.05128	0.0112	

*Note.* μg/g, μg of lead *per* gram of bone mineral; SE, standard error.

with a weak EDTA solution, but the result was little changed:  $197 \pm 3$ . Statistical considerations resulted in the exclusion of this child.

Analysis of variance (ANOVA) revealed a significant effect of both town and gender on tibia lead level in two-way ANOVA of the overall dataset, but showed a significant effect of gender only in the control town in one-way ANOVA of the data obtained in each town.

Tibia lead levels were normally distributed in the control town but right-skewed in the exposed town; all tibia lead levels were therefore *ln* transformed. After four outliers were excluded (three negative values from the control town and the 190 μg/g value from the exposed town), town, gender, skeletal volume, and an interaction term between town and gender were all found to be significant predictors of *ln* transformed tibia lead level (Table 2). After skeletal volume was adjusted, the boys and girls in the exposed town had, on average, 32.5 and 35.3 μg/g more tibia lead than the boys and girls, respectively, in the control town. After skeletal volume was adjusted, the boys in the exposed town had, on average, 1.6 μg/g more tibia lead than girls in the exposed town, but this difference was not significant (*P* = 0.67). After skeletal volume was adjusted, the boys in the control town had, on average, 4.3 μg/g more tibia lead than girls in the control town (*P* < 0.03), despite the fact that the tibia lead levels were low in the control town. The weak interaction term probably achieves statistical significance because the difference in tibia lead levels between boys and girls is significant only in the control town.

Skeletal volume was found to be an independent negative predictor of tibia lead level; children with skeletons of greater volume had lower tibia lead concentrations. The final model, with four variables, accounted for 71% of the variability observed in the tibia lead levels of the children. The model was unchanged when body mass index, overlying tissue thickness, tibia length, and tibia width were forced into the model.

#### *Tibia Lead Methodological Uncertainty*

Gender, but not town, was found to have a significant effect on tibia lead methodological uncertainty, both within the overall dataset (two-way ANOVA) and within each town (one-way ANOVA).

After nine outliers were excluded (none of which were the same as the four children who were excluded for the tibia lead modeling), overlying tissue thickness, calf circumference, and being female were found to be independent positive predictors of tibia lead methodological uncertainty (Table 2). After overlying tissue thickness and calf circumference were adjusted, girls had, on average, a 0.13-μg/g greater methodological uncertainty in their tibia lead measurement than boys, a minor but statistically significant difference (*P* = 0.0112).

The final model, with three parameters, accounted for 46% of the variability observed in the tibia lead methodological uncertainties. When tibia lead methodological uncertainty was modeled for girls alone (from both towns), overlying tissue thickness, calf circumference, and source to skin distance were

all independent, positive predictors (model not shown). When tibia lead methodological uncertainty was modeled for boys alone (from both towns), overlying tissue thickness and body mass index were independent positive predictors.

## DISCUSSION

There are few previous reports of  $^{109}\text{Cd}$ -based K-shell XRF measurements in children. Kosnett *et al.* (1994) measured tibia lead concentration in three children between the ages of 10 and 12 years. Visual inspection of the figure given in Kosnett *et al.* (1994) suggests that the tibia lead concentrations of these children were  $-1$ ,  $1$ , and  $4 \mu\text{g Pb/g}$  bone mineral (no methodological uncertainties are given for these individuals). Needleman *et al.* (1996) measured tibia lead concentrations in 232 children of 11–14 years of age. Needleman *et al.* (1996) categorized their tibia lead concentrations, and so we cannot compare our data to theirs. Needleman *et al.* (1996) do state, however, that 57 of the children gave “net negative lead values”. Farias *et al.* (1998) measured tibia lead concentration in 11 children of 11–14 years of age and found a mean (SD) tibia lead concentration of  $0.8$  ( $11$ )  $\mu\text{g/g}$ .

Before the study, we did not know whether the current XRF methodology was adequate for the measurement of tibia lead levels in children. The measurements of the children in the exposed town firmly assuage that concern. The measurements of the children in the control town equally firmly indicate that more work is required if  $^{109}\text{Cd}$ -based K-shell XRF measurements are to be able to discriminate between different degrees of low-level environmental lead exposure in children. Nevertheless, the methodology that we used is sufficient to detect a statistically significant difference in the tibia lead levels of boys and girls with low-level exposure.

That boys and girls had different, although low, tibia lead levels in the control town but not in the exposed town suggests that the gender difference is overwhelmed by the lead exposure suffered by the children in the exposed town. Age is usually predictive of tibia lead level but was not found to be so in this cohort, probably because of the narrow age range of the children.

The inverse association between tibia lead and skeletal volume is not entirely new. A study of occupationally exposed adults (Schwartz *et al.*, 1999) found an inverse association between tibia lead level and height. Skeletal volume and height are (obviously) related, and both findings point to a form of

dilution effect on bone lead concentration for children with larger skeletal volumes exposed to a fixed amount of lead. However, an alternate explanation is also possible: lead exposure is responsible for inhibition of growth (Kim *et al.*, 1995b) and consequent lower skeletal volume.

Ascertainment of the sequelae of release of the bone lead stores in these children that might occur during puberty, pregnancy, lactation, and menopause would require further study. The methodological uncertainties obtained with these children ( $\pm 2.9 \mu\text{g/g}$ , average, in boys and  $\pm 3.2 \mu\text{g/g}$ , average, in girls) compare well to the average methodological uncertainty of  $2.8 \mu\text{g/g}$  obtained from measurements performed with the same electronics and a source of similar strength in a group of 60 American adult males with limited occupational lead exposure.

In the modeling of tibia lead methodological uncertainty, it is interesting that height, weight, shoulder width, skeletal volume, tibia width, tibia length, and tibia lead level itself were not found to be significant predictors. (Body mass index was a significant predictor when only the boys' methodological uncertainties were modeled.) The parameters that were found to be predictive were those expected *a priori*: the thickness of overlying tissue (which attenuates the X-ray and coherent signals) and the calf circumference (which relates to the magnitude of the Compton-scattered background of the bone lead measurement). Females have been noted before to give higher methodological uncertainties (Gordon *et al.*, 1994), but our report suggests a gender difference in children that is independent of the anthropometric measures. However, less than half of the variability in the methodological uncertainties was accounted for by the final regression model, indicating that there are factors not measured that differentiate the tibia lead methodological uncertainties of these children.

## CONCLUSIONS

We conclude that the XRF methodology that we employed is sufficiently sensitive to determine different tibia lead levels in boys and girls with low-level environmental exposure and that the methodological uncertainty for 12-year-old children is comparable to that obtained in adults.

## ACKNOWLEDGMENTS

The authors are grateful to J. H. Godbold, Ph.D, for statistical guidance. This project was supported by Grants ES03460,

ES05697, and ES06616 from the National Institute of Environmental Health Sciences.

## REFERENCES

- Altman, D. (1991). "Practical Statistics for Medical Research." Chapman & Hall, London.
- Barry, P. (1975). A comparison of concentrations of lead in human tissues. *Br. J. Ind. Med.* **32**, 119-139.
- Barry, P., and Mossman, D. (1970). Lead concentrations in human tissues. *Br. J. Ind. Med.* **27**, 339-351.
- Chettle, D. (1995). *In vivo* X-ray fluorescence of lead and other toxic trace elements. In "Advances in X-Ray Analysis," (P. Predecki, Ed.), Vol. 38, pp. 563-572. Plenum, New York.
- Currie, L. (1968). Limits for qualitative detection and quantitative determination. *Anal. Chem.* **40**, 586-593.
- Factor-Litvak, P., Wasserman, G., and Graziano, J. (1999). The Yugoslavia prospective study of environmental lead exposure. *Environ. Health Perspect.* **107**, 9-15.
- Farias, P., Hu, H., Rubenstein, E., Meneses-Gonzalez, F., Fishbein, E., Palazuelos, E., Aro, A., and Hernandez-Avila, M. (1998). Determinants of bone and blood lead levels among teenagers living in urban areas with high lead exposure. *Environ. Health Perspect.* **106**, 733-737.
- Gordon, C., Chettle, D., and Webber, C. (1993). An improved instrument for the *in vivo* detection of lead in bone. *Br. J. Ind. Med.* **50**, 637-641.
- Gordon, C., Webber, C., and Chettle, D. (1994). The reproducibility of <sup>109</sup>Cd-based X-ray fluorescence measurements of bone lead. *Environ. Health Perspect.* **102**, 690-694.
- Kim, R., Aro, A., Rotnitzky, A., Amarasiriwardena, C., and Hu, H. (1995a). K X-ray fluorescence measurements of bone lead concentration: The analysis of low-level data. *Phys. Med. Biol.* **40**, 1475-1485.
- Kim, R., Hu, H., Rotnitzky, A., Bellinger, D., and Needleman, H. (1995b). A longitudinal study of chronic lead exposure and physical growth in Boston children. *Environ. Health Perspect.* **103**, 952-957.
- Kosnett, M., Becker, C., Osterloh, J., Kelly, T., and Pasta, D. (1994). Factors influencing bone lead concentration in a suburban community assessed by noninvasive K X-ray fluorescence. *J. Am. Med. Assoc.* **271**, 197-203.
- Moline, J., Golden, A., Todd, A., Godbold, J., and Berkowitz, G. (1998). Lead exposure among young urban women. *Salud Pùbl. Mèxico* **41**, S82-S87.
- Needleman, H., Riess, J., Tobin, M., Biesecker, G., and Greenhouse, J. (1996). Bone lead levels and delinquent behavior. *J. Am. Med. Assoc.* **275**, 363-369.
- Rabinowitz, M., Wetherill, G., and Kopple, J. (1976). Kinetic analysis of lead metabolism in healthy humans. *J. Clin. Invest.* **58**, 260-270.
- Rothenberg, S., Khan, F., Manalo, M., Jiang, J., Cuellar, R., Reyes, S., Acosta, S., Jauregui, M., Diaz, M., Sanchez, M., Todd, A., and Johnson, C. (2000). Maternal bone lead contribution to blood lead during and after pregnancy. *Environ. Res.* **82**, 81-90.
- Schwartz, B., Stewart, W., Todd, A., and Links, J. (1999). Predictors of dimercaptosuccinic acid chelatable lead levels and tibial lead levels in organolead manufacturing workers. *Occup. Environ. Med.* **56**, 22-29.
- Somervaille, L., Chettle, D., Scott, M., Tennant, D., McKiernan, M., Skilbeck, A., and Trethowan, W. (1988). *In vivo* tibia lead measurements as an index of cumulative exposure in occupationally exposed subjects. *Br. J. Ind. Med.* **45**, 174-181.
- Todd, A. (2000a). Calculating bone-lead measurement variance. *Environ. Health Perspect.* **108**, 383-386.
- Todd, A. (2000b). Coherent scattering and matrix correction in bone-lead measurements. *Phys. Med. Biol.* **45**, 1953-1963.
- Todd, A. (2000c). Contamination of *in vivo* bone-lead measurements. *Phys. Med. Biol.* **45**, 229-240.
- Todd, A., Carroll, S., Godbold, J., Moshier, E., and Khan, F. (2000). Variability in XRF-measured tibia lead levels. *Phys. Med. Biol.* **45**, 3737-3748.
- Todd, A., and Chettle, D. (1994). *In vivo* X-ray fluorescence of lead in bone: Review and current issues. *Environ. Health Perspect.* **102**, 172-177.