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FEASIBILITY STUDY FOR THE IN VIVO MEASUREMENT OF LEAD IN BONE USING L-X-RAY FLUORESCENCE

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Summary

Lead deposits in bone were detected by x-ray fluorescence using x-rays from either a ^{125}I or a ^{109}Cd source. Measurements were taken from tibia in intact human legs, post-mortem. On the basis of preliminary measurements, it was concluded that an exposure of one rad is adequate for determination of lead in bone.

Both the advantages and the disadvantages of L-x-rays, used in the technique developed for this study, are compared with those of K-x-rays.

Introduction

Lead is widely distributed in the environment and presents a potential health hazard. Its concentration in human tissue has been found to be highly variable. A large, detailed scientific literature provides evidence of increased lead burdens in occupationally exposed workers. A recent report by NIOSH[1] identifies 150 occupations with lead exposures that have potential health hazard. Neuropathy, nephropathy and blood changes have been documented. The level at which lead contamination becomes seriously detrimental to health is controversial.

Children comprise a second group highly susceptible to lead. Lead burdens in children are considered to be particularly serious with regard to effects on the central nervous system.[2,3]

The skeleton is the chief repository of lead in the body. From 90 to 95% of the total body lead burden of adults is found in bone.[4] The biological half-life of lead is estimated to be about 10 years. Blood and urine lead levels decline promptly after exposure to lead ceases, and may not be indicative of total body lead burden. Thus, it is desirable to sample bone for a sound estimation of lead burden.

X-ray fluorescence systems used in various studies for *in vivo* determination of bone lead concentrations have been described.[5,6] The characteristic K_α- and K_β-x-rays, 75 and 85 keV, respectively, are utilized. The system employed in the present study utilizes the L_α- and L_β-x-rays. The energies of the L_α- and L_β-x-rays are 10.5 and 12.6 keV, respectively. A description of the system and the preliminary results of the feasibility studies are presented in the following sections.

X-ray Fluorescence System

Both K- and L-x-rays are suitable for the analysis of lead in bone. To induce K-x-ray fluorescence, the incident radiation has to be above the 88 keV K-absorption edge. ^{109}Cd, ^{153}Gd, ^{57}Co, or ^{139}Ce sources provide satisfactory incident radiation. As the L-absorption edge is 15.87 keV, the incident radiation can be provided by low energy sources such as ^{109}Cd and ^{125}I.

Since the samples are large, the matrix effects differ significantly for the energy ranges of the K- and L-x-rays. With the assumption of a semi-infinite bone medium with a homogeneous distribution of lead at a trace level and beams that enter and leave the medium at right angles to the surface, the lead signal, I_s, is proportional to:

$$I_s \propto \tau_E (1-J)\,\omega/(\mu_{iE} + \mu) \qquad (1)$$

where

- τ_E - photoelectric cross section for lead at incident energy, E
- J - jump ratio for K or L shell in lead
- ω - x-ray fluorescence yield in lead for K or L shell
- μ_{iE} - total attenuation coefficient in the bone matrix at the incident energy, E
- μ - total attenuation coefficient in the bone matrix for the outgoing characteristic K- or L-x-rays.

If the solid angle and detector efficiency remains the same for the K- and L-x-rays, the intensity of the signal for 122 keV (^{57}Co) incident radiation is approximately one order of magnitude greater than that of the signal calculated for 22 keV (^{109}Cd) incident radiation.

In similar fashion, the Compton intensity, I_c, is proportional to:

$$I_c \propto \sigma_E/(\mu_{iE} + \mu_{oE}) \qquad (2)$$

where

- σ_E Compton cross section in the bone matrix at incident energy, E
- μ_{oE} total attenuation coefficient in the matrix for outgoing photons after Compton scattering.

For the energies under consideration here, Compton scattered radiation is about an order of magnitude greater for 122 keV than for 22 keV incident radiation. Since the background under the lead peaks is proportional to the scattered radiation, this finding suggests that the overall detectability is about three times better for K-x-rays than for L-x-rays. However, while the background in the lead region is proportional to the Compton peak, the different shapes of the background in the two methods introduce different proportionality constants. Thus considering this difference and the different flux to dose rate conversion factors, the detection limits of both methods are comparable.

The use of L-x-rays for lead analysis *in vivo* is limited by the thickness of the overlying tissue. In practice, the use of L-x-rays is restricted to superficial bones such as the tibia for which the overlying tissue is 2-3 mm thick, (see Fig. 1). The advantage of reducing the energy of the incident radiation is that the dose to the bone marrow is lowered significantly. In addition, a constant volume of the bone cortex is sampled, as the mean free path for the L_β radiation in the bone is about 0.5 mm, as compared to approximately 25 mm for K-x-rays.

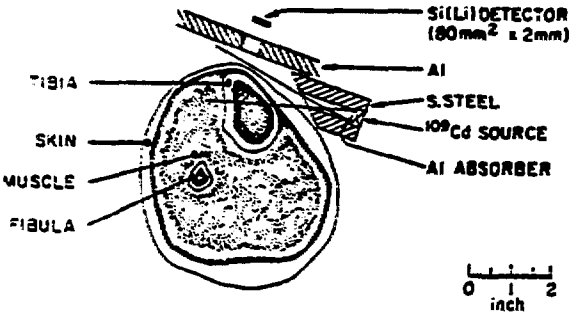

Fig 1.-Cross section of the left leg below the knee and the arrangement of the detection system.

While the detection limits are comparable in both methods, there is nevertheless some advantage to the use of the more easily polarized L-x-rays, inasmuch as the detector total count-rate, and subsequently the dose and the background can be further reduced with polarized radiation.[7-9] A unique feature employing low energy excitation radiation is that K-x-rays from elements such as strontium in the bone, bromine and rubidium in the soft tissue, appear in the measured spectrum simultaneously with lead peaks. For these reasons, L-x-rays were selected for use in the present study.

Results

The results of the studies performed on the tibia, post-mortem, are shown in Table 1. The intensities noted represent the net number of counts in the peaks, without correction for the attenuation in the tissue overlying the bone or for the matrix effect. A spectrum from a tibia, seen in the upper part of Fig. 2, shows lead and strontium peaks from the bone, and bromine peaks from the overlying soft tissue. A measurement of soft tissue from mid-calf was used as a control (see lower portion of Fig. 2). Neither the lead nor the strontium peaks appeared, but the peak of rubidium, an element known to be located in soft tissue, was revealed. Post-mortem bone samples were taken from the measured sites for subsequent lead analysis by x-ray fluorescence and atomic absorption spectrophotometry. These results are not yet available.

To demonstrate the applicability of polarized radiation for x-ray fluorescence analysis, a simple arrangement of polarized radiation from a ^{125}I source was tested on lead nitrate, 10,000 ppm by weight, dissolved in water. The results are shown in Fig. 3. Reduction of the detector total count rate by a factor of two occurred. Subsequent reduction in background by the same factor is clearly visible. The lead peaks and the pulser peak have the same height. With improved design, it may be possible to lower the detection limit by a factor of five.[10]

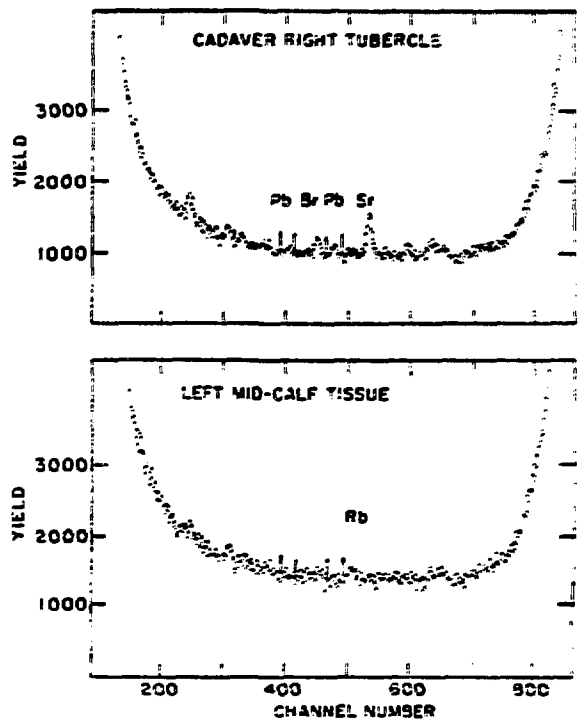

Fig 2.-Spectra measured from a leg, post-mortem. The markers indicate the region of the lead peaks.

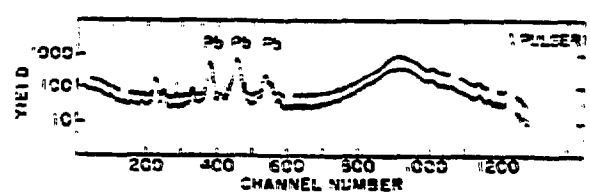

Fig 3.-Comparison between an excitation of 10^4 ppm of lead in water by unpolarized (upper) and polarized (lower) incident radiation.

Table 1

Lead Measurements (Tibia)

Age (Yrs)	Occupation	Source	Dose (rads)	Pb - L_γ * Intensity**	Pb - L_β Intensity	Sr - K_α Intensity
58	Maintenance	^{125}I	0.95	364 ± 124	365 ± 106	1407 ± 125
65	Baker	^{125}I	1.68	419 ± 191	456 ± 190	3183 ± 173
63	Cook	^{125}I	0.815	#	#	916 ± 122
57	Carpenter	^{125}I	0.7	250 ± 107	70 ± 102	840 ± 101
65	Doorman	^{125}I	0.7	#	#	1048 ± 116
64	Clerk	^{109}Cd	0.5	92 ± 101	229 ± 110	1493 ± 107

* No correction of intensity has been made for matrix effects or for attenuation in overlying tissue.

** Net number of counts in the peak

\# Not observed

Discussion

Bone is a heterogeneous tissue in which the arrangements of the cellular and mineral components are both complex and varied. Great discontinuities of density and composition occur over spatial dimensions that are frequently of the same order of magnitude as the ranges of the ionizing radiation. Since the actual condition of the bone at the time of measurement for lead is unknown, accurate analysis for lead poses a formidable problem. The study demonstrates that L-x-ray fluorescence can be used for the in vivo measurement of lead concentration in the tibia. When results obtained with L-x-rays are compared to those made with K-x-rays, it appears that the methods complement each other in terms of the effective volume sampled from the bone. The higher polarizability of the incident radiation at lower energies may improve the overall performance of the system. A study is underway to correlate the strontium peak with the calcium content of the sampled mass of the bone. This may be advantageous in normalizing the measured lead intensities. Presently, the detection limit for lead can be, at best, estimated between 10-20 ppm by weight on the basis of values in the literature for ambient levels of lead in adults. A more reliable value for the detection limit will be determined later. The reproducibility of the system, as estimated from measurements of the strontium peak, is about ± 10%.Correction of the intensities of the lead peaks for the attenuation in the overlying tissue may be made in three ways: (1) with the use of the intensity ratio of the L_α and L_β peaks; (2) with the Compton/Rayleigh ratio since there is a difference in the effective Z of the bone and soft tissue; or (3) with a beta backscattering gauge. The most suitable method will be determined in future work.

Acknowledgements

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