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Equipment Design Issues for the *In Vivo* X-Ray Fluorescence Analysis of Bone Lead

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Several groups have reported the development of systems, based on the principle of X-ray fluorescence, for the *in vivo* measurement of bone lead concentrations. These systems have used the detection of either the characteristic L or K X-rays resulting from excitation by a suitable photon source. This paper examines design issues related to the development of these systems. These design issues are, in most instances, a result of consideration of the physical principles involved, and hence there are many features common to the systems developed by the individual groups. Design issues discussed in this paper include the selection of the site for measurement, source-sample-detector configuration, and collimation. Specific examples from published work are used to demonstrate the relevant features.

Introduction

In vivo X-ray fluorescence (XRF) analysis provides a method of measuring the concentration of lead in specific sites of the skeleton which, in the adult, contains approximately 90% of the whole body lead burden (*1*). Systems developed for this purpose have used excitation and detection of either the characteristic L or K X-rays of lead. The relatively low energy of the photons involved using either technique imposes a limitation on the bony sites that can be measured because of the strong attenuation of both the incident and emitted photons. This is particularly the case for the system using excitation and detection of L X-rays.

The intensity of characteristic lead X-rays excited is relatively low, particularly when bone lead concentrations in the normal range (10–20 ppm) are being measured. The limiting factor to the lower limit of detection is the contribution of this background radiation impinging upon the detector. The major contribution to the background is from source photons, which are Compton-scattered in the sample and/or in the detector assembly. In order to reduce this background contribution, consideration needs to be given to the source-detector configuration and to limiting the range of detection angles by the use of collimation. Design issues, resulting from consideration of these factors, are discussed in the following sections.

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Design Issues

General System Features

There have been three basic designs reported in the literature for the *in vivo* measurement of lead in bone by XRF analysis. Two of these use excitation and detection of the K X-rays of lead and the third uses excitation and detection of the L X-rays (*2*). The significant difference between the two K X-ray techniques is the excitation source employed: either ^{109}Cd (*3*) or ^{57}Co (*4,5*). The selection of a particular excitation source imposes restraints on the design, principally in terms of source-detector configuration. Schematic diagrams of systems using the three approaches are given in Figure 1. Details of sources and detectors used are given in Table 1.

Selection of the Source for Excitation

In consideration of the efficiency of excitation, the source should emit photons, ideally, of energy slightly above the K (or L) shell absorption edge (88 keV and 16 keV, respectively). However, in selecting a source, consideration needs also to be given to the half-life, availability, and cost of the excitation source as well as difficulties related to potential background from transmitted or scattered source photons. In addition, and particularly for the L X-ray technique, the penetration, or more particularly, the attenuation, of the incident photons is an important consideration.

Iodine-125 ($T_{½}$ = 59.7 d), which emits two X-rays (27.4 and 31.0 keV) following electron capture and a

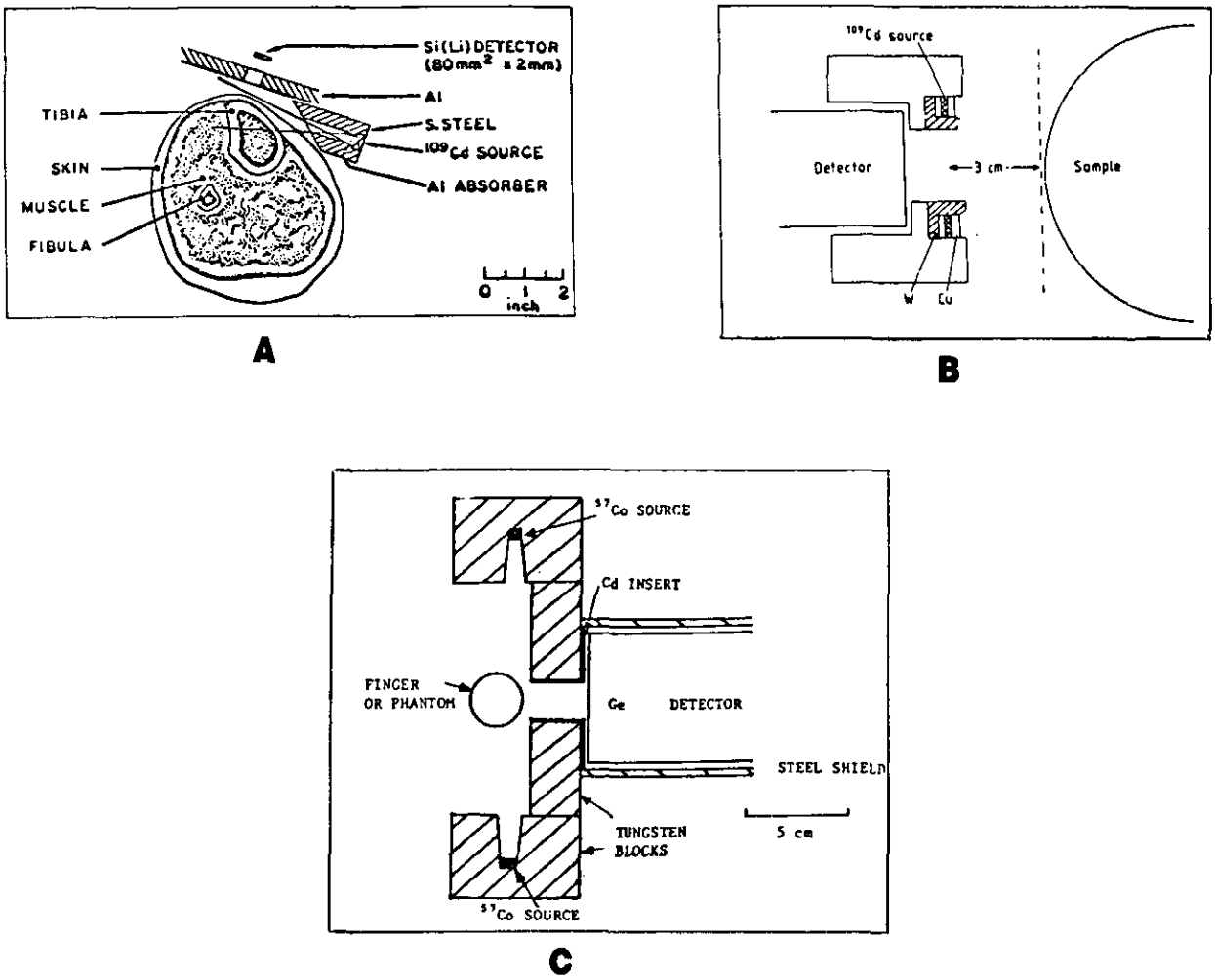


FIGURE 1. Schematic diagrams to illustrate the three basic designs of systems developed for the *in vivo* measurement of bone lead concentrations by XRF analysis. (*A*) A system using detection of L X-rays (*2*). (*B*) A system using detection of K X-rays and using ^{109}Cd as an excitation source (*3*). (*C*) A system using detection of K X-rays and using ^{57}Co as an excitation source (*5*); this system is very similar to that described Ahlgren and Mattsson (*4*).

Table 1. Typical source and detector details for *in vivo* X-ray fluorescence bone lead systems.

	System		
	1[a]	2[b]	3[c]
Source			
Isotope	^{125}I	^{109}Cd	^{57}Co
Unit activity	3.7	3.7 (annular)	2 times 1 unit activity
Energy of photons emitted, keV	27, 31, 36	88	122 (and others)
X-rays detected	L	K	K
Detector			
Type	Si (Li)	Ge	Ge
Dimensions	80 mm² × 2 mm	16 mmD × 7 mm	25 mmD × 7 mm
Resolution	200 eV at 5.9 keV	480 eV at 75 keV	450 eV at 75 keV
Source-detector configuration	~90°	~180°	~90°

[a] System 1 used by Weilopolski et al. (*2*).
[b] System 2 used by Somervaille et al. (*3*).
[c] System 3 used by Ahlgren and Mattsson (*4*) and Price et al. (*5*).

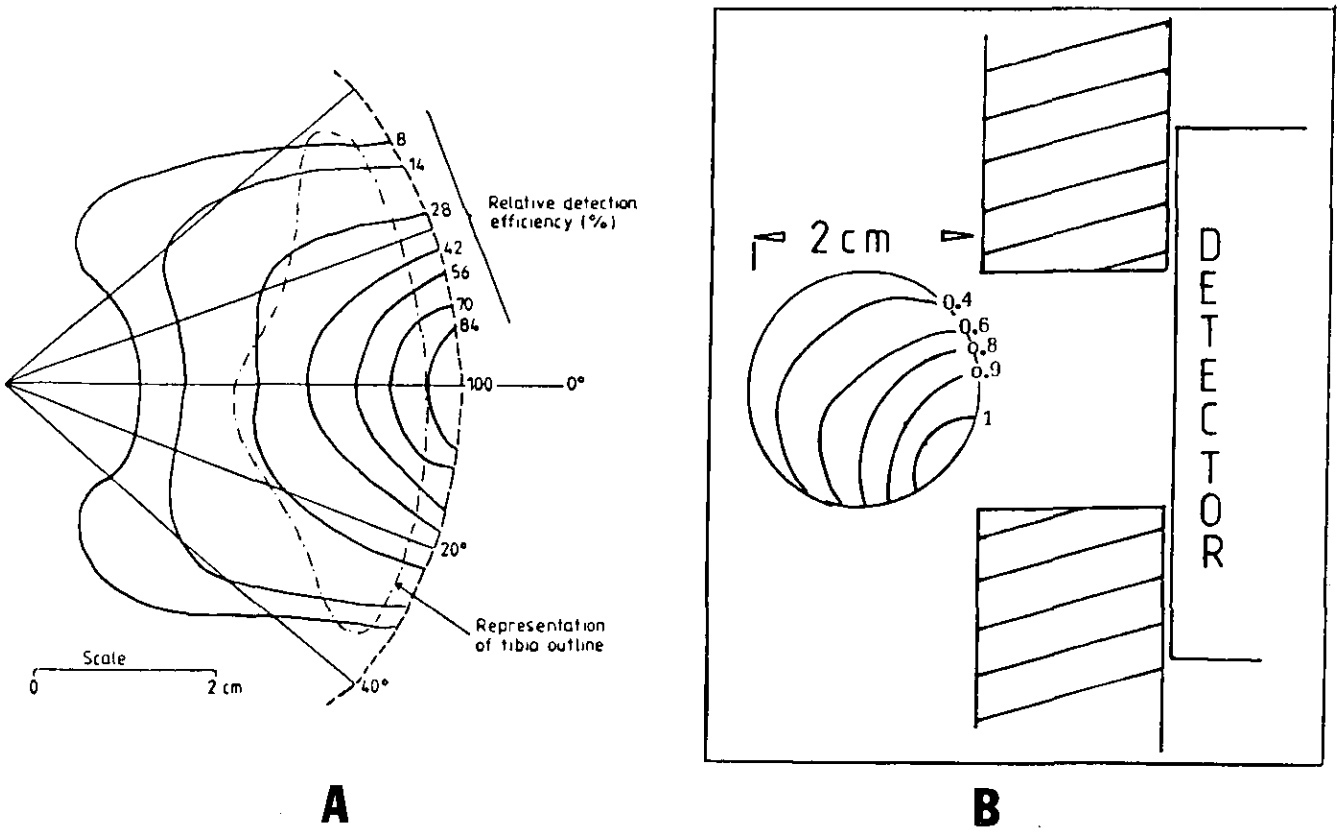


FIGURE 2. The relative detection efficiency for lead as a function of depth in appropriate phantoms. (*A*) Using a ^{109}Cd source in backscatter geometry (*3*); (*B*) using a ^{57}Co source and 90° geometry.

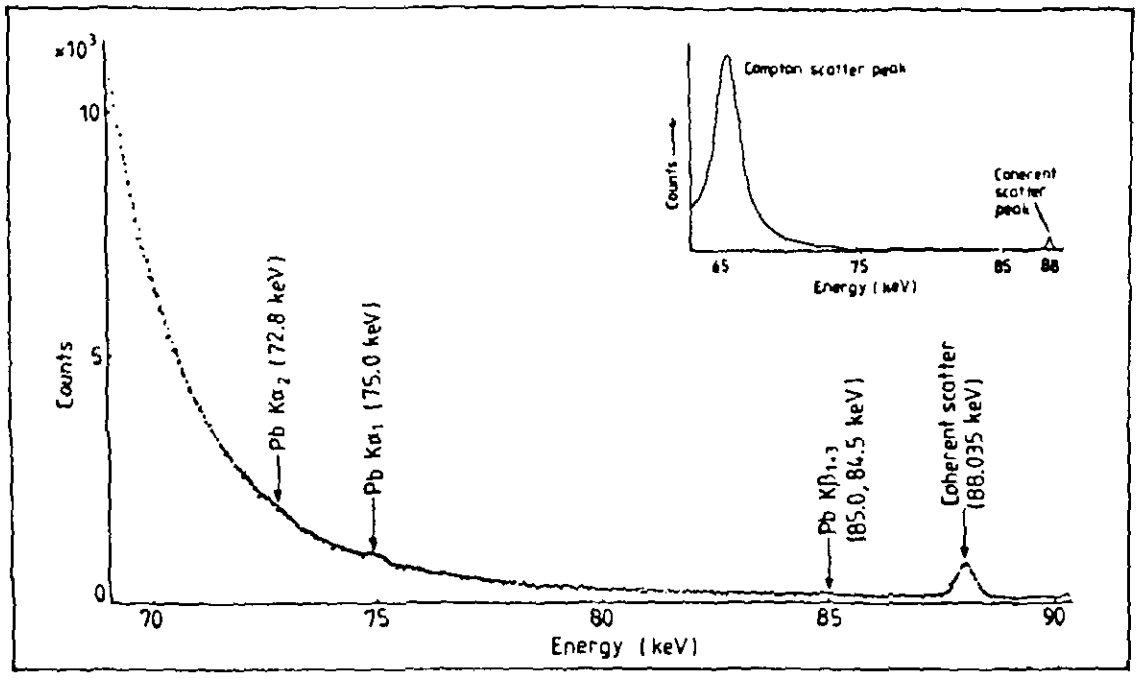
gamma ray (35.5 keV), was the source used by Wielopolski et al. for the excitation of L X-rays (*2*). The relative intensities of the three photons is 1.0, 0.2, and 0.6, respectively. The photons emitted by this source are somewhat higher in energy than those required for maximum excitation of the L X-rays of lead. However, the use of lower energy photons for excitation would accentuate problems related to attenuation of the primary beam, e.g., the 99% sampled depth using ^{125}I is 2.8 mm in bone, which would be reduced to approximately 2.5 mm if, for example, Ag X-rays (22 and 25 keV) from a ^{109}Cd source were used for excitation. Corrections need to be made for attenuation due to overlying soft tissue as each millimeter of soft tissue results in reduction of the intensity of the L X-rays by approximately 25%. Application of these corrections requires an estimate of soft tissue thickness. Wielopolski et al. (*2*) used ultrasound techniques for this estimation. The uncertainty in this ultrasound technique was ± 0.3 mm. This contributes an uncertainty of about ± 10% to the estimation of the lead concentration in the bone.

^{109}Cd and ^{57}Co have been used to excite the characteristic K X-rays of lead. As discussed later, different source-detector configurations must be employed: 180° (i.e., "backscatter") when using ^{109}Cd, and 90° when using ^{57}Co. ^{109}Cd ($E\gamma$ = 88 keV) provides more efficient excitation compared with ^{57}Co ($E\gamma$ = 122, 136 keV and others). When using a ^{109}Cd source, a thin (0.5 mm) copper foil must be placed in front of the source to reduce the total count rate resulting from Ag X-rays emitted by the source (Fig. 1*B*).

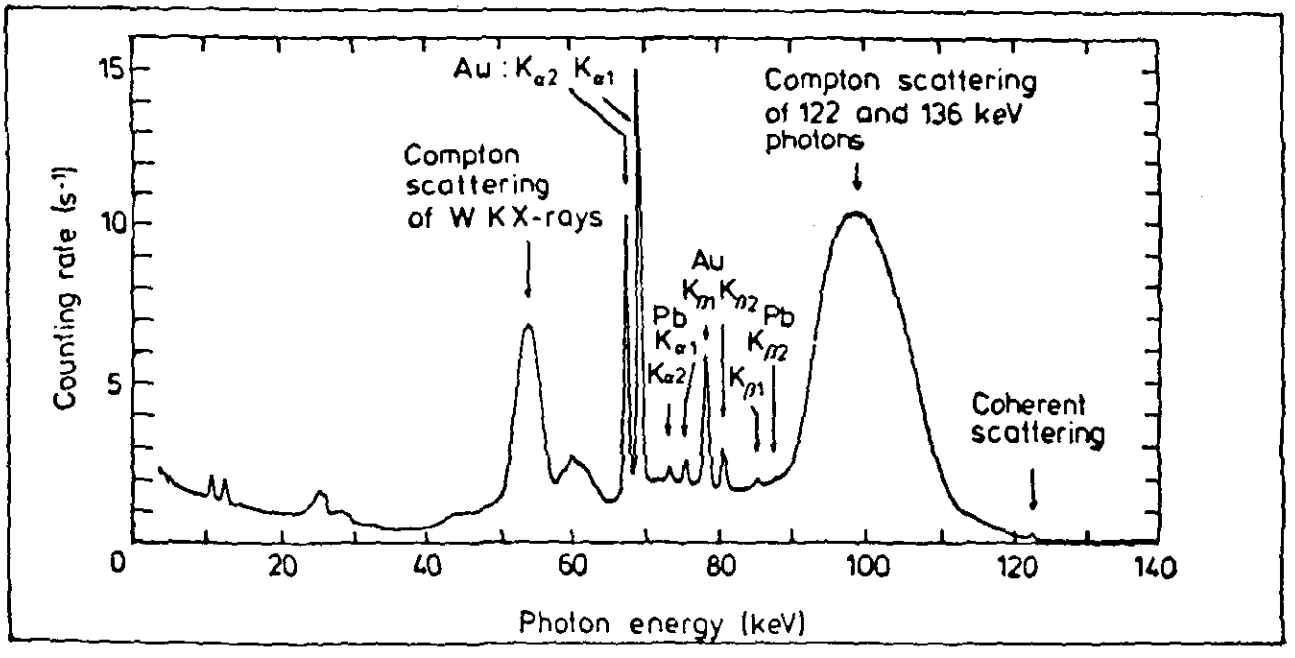
^{57}Co has the slight disadvantage that higher energy gamma rays (up to 707 keV) are also emitted, although at low intensities. Thus, thicker collimators are required. Both sources are similar in cost per unit activity and typically need to be replaced at approximately 2- to 3-year intervals, although this period can be extended if longer measurement times can be tolerated.

Selection of Measurement Site

Both types of systems, i.e., using detection of either K or L X-rays, involve relatively low energy incident and emitted photons and hence are limited to measurement of lead in superficial bony sites. In this respect the system using excitation and detection of the L X-rays has been applied only to measurement of the cortical region of the tibia where the overlying tissue is sufficiently thin (2–3 mm) so that the low energy photons have adequate penetration. Even so, the strong attenuation of the photons limits the measurement to a sampled depth of approximately 2.8 mm. To



A



B

FIGURE 3. Typical spectra obtained in the K X-ray technique. (*A*) Using ^{109}Cd as an excitation source and a backscatter geometry (*3*); (*B*) Using ^{57}Co as an excitation source and a 90° geometry (*4*).

assist comparison with the K X-ray technique, it is worth noting that the depth at which the sensitivity decreases to 30% is approximately 1.3 mm in the L X-ray technique. This limitation may be an advantage in some ways as it is less than the cortical bone thickness and therefore results in a measurement involving a reasonably constant mass of bone (*2*). However, the strong attenuation of the photons remains a major

concern in the application of the L X-ray technique.

Systems using excitation and detection of K X-rays are less subject to this limitation; however, the penetration is such that the sensitivity is reduced to approximately 30% at sites approximately 25 mm from the surface (Fig. 2). Systems using the K X-rays have been used for measurement of lead in sections of the phalanx or tibia and potentially could be used for other bony sites.

When the phalanx is the site chosen for measurement, bilateral irradiation will significantly improve the variation in sensitivity with depth in tissue. In theory, rotating the finger (by 180°) for half the measurement time in a bilateral irradiation facility will produce a measurement that is relatively position insensitive—at least within the 1 cm length of the phalanx studied.

Source-Detector Configuration

In systems using the detection of K X-rays, the principal limitation on sensitivity is the magnitude and width of the broad peak in the spectrum resulting from source photons Compton-scattered in the sample (Fig. 3).

Considerations of the energy and intensity of the Compton-scattered photons indicate that source and detector should be arranged at 180° for a system using a ^{109}Cd source and 90° for a system using a ^{57}Co source. A single scatter of a-122 keV (^{57}Co) photon cannot overlap the $K\alpha_1$ X-ray energy of 75 keV no matter how large the scattering angle. However, scattering of photons within the detector assembly itself produces a broad, low-energy tail to the spectrum which overlaps the K X-ray energies of lead (*6*) (Fig. 3*B*). This is the most important factor determining the lower limit of detection. The magnitude of this effect can be reduced using collimation of both the source photons and on the detector face to limit the possible angle of source photons scattered into the detector and so that the detector views only the irradiated volume. Reducing the diameter of the collimator reduces the effect due to scattered radiation but also reduces the efficiency of detection of the excited characteristic X-rays. Collimation of 0.7 to 1.0 cm provides a compromise between the two effects.

The backscatter geometry used in a ^{109}Cd system is best achieved with an annular source as shown in Figure 1*B*. The collimator is designed to limit the possible angle of source photons scattered into the detector to the range 140 to 180° (approximate). Use of this arrangement provides a better signal-to-noise ratio than obtained with the ^{57}Co system and hence a somewhat lower limit of detection.

In both K X-ray designs, tungsten (or other heavy metal) is used as the collimating material. Shielding is less of a problem with an ^{125}I source in an L X-ray system because of the (very) low energy of the photons used. Light and relatively thin materials can be used. Wielopolski et al. (*2*) used a 90° source-detector geometry. However, the backscatter geometry should also be applicable if the ^{125}I source is available in annular form. As with the K X-ray systems, collimation is designed to reduce the intensity of the detected Compton-scattered photons.

Conclusion

Some of the design issues related to development of systems for the *in vivo* measurement of bone lead by X-ray fluorescense analysis have been discussed. As mentioned earlier, these design issues are a result of consideration of the physical principles involved, mainly in respect to Compton scatter of source photons, attenuation of source, and emitted photons and detector response. The successful application of the methods discussed permits the *in vivo* measurement of bone lead concentrations at and above normal levels.

Development of a suitable system is first determined by a decision as to the bony site to be measured. If only the cortical layer of a (superficial) bone is to be examined, then the L X-ray method must be employed. If it is considered important to involve larger volumes of bone in the measurement, then a K X-ray method must be used. As Wielopolski et al. have noted (*2*), "the two measurements complement each other," and at this stage provide the only methods of measurement of the lead concentration in a selected bony site. Whether the results of these measurements can be used as an index of total body lead burden requires further investigation. In this respect, development of systems capable of sampling, in a reasonable time, larger volumes of bone and possibly at less superficial sites needs to be considered.

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