Optimization of measurement distance of ^{109}Cd *K* XRF system for obese subjects

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Abstract The precision of results obtained from the ^{109}Cd *K* XRF *in vivo* measurement system of bone lead for obese subjects with high BMI (body mass index) was poor. The main factor affecting the precision was the distance between tibia and detector. Compared with the standard phantom, a large phantom was used to simulate the obese subject in the measurements at different distances to the detector. The counts of Compton scattering increased highly because of the tissue overlying and surrounding tibia of the obese subject. When the distance between leg and detector was too small, the instrument would produce the distorted X-ray spectra, so that the obtained data were inaccurate. In order to ensure good measurement precision and accuracy, the distance between leg and detector should be maintained at 25 mm during the counting period. Meanwhile, the dead time displayed instantly on the instrument should be controlled to around 30%.

Keywords Measurement distance, X-ray fluorescence, Bone lead, Obese subjects

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1 Introduction

During recent decades, the lead concentration in blood has been the most commonly used as the indicator of lead exposure and risk. In fact, the main organ of accumulation for lead is bone, which contains over 90% of the body burden. Measurement of bone lead has benefited greatly from the recent development of X-ray fluorescence (XRF) instruments, which can make rapid, safe, accurate, and relatively precise measurements of lead in bone. Now the ^{109}Cd *K* XRF bone lead measurement systems have been the most widely validated and used.[1] The ^{109}Cd *K* XRF system consists of a ^{109}Cd source and an X-ray spectrometer based on a low energy HPGe detector and modular electronics.

In a neurotoxicity study,[2] 530 subjects had their tibia lead content measured by two similar ^{109}Cd *K* XRF systems. In its subsequent study,[3] an investigation was made of the effect of body mass index (BMI) of these subjects on the measurement precision. It showed that measurement uncertainty increased with BMI, which was an estimate of obesity. The factors affecting the precision were complex. In this study we adjusted the measurement distance and controlled some measurement parameters to minimize the measurement uncertainty for the obese subjects.

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2 Methods

The content of bone lead were obtained by the linear correlation between the lead concentration in bone and the ratio of *K* X-ray intensity to coherent intensity, i.e. the ratio of *K* X-ray peak area to coherent peak area. In the measured X-ray spectrum, the coherent peak was relatively easy to calculate as the peak was clearly visible. The background of regions of lead *K* X-ray peaks was very high, because the Compton scattering was the dominant contributor to the observed spectrum. The normalization of lead X-rays to the coherent peak results in a measure of lead in μg Pb/(g bone mineral) and makes the measurement very robust. The normalization has been reported to render the measurement accuracy independent of tissue overlay sickness, bone shape, size, mass and subject motion.[4, 5] Therefore, when constructing the calibration line, we can just use a set of standard addition lead-doped plaster of Paris phantoms (standard phantom) in the nominal concentration range from 0 to 200 μg Pb/(g plaster), which were cylinders with 50 mm diameter and 70 mm height to be simulated as tibias. But still, the measurement precision of lead results strongly depended on error of the peak areas, especially error of the coherent peak area.

Those subjects with high BMI (obese subjects) have more tissue overlying the tibia. This will attenuate the lead X-rays and coherent scattering signals. On the contrary, the Compton scattering counts increase dramatically. So, the total count rate will be very high, and the dead time will increase with the total count rate. If the total count rate is too high, the spectra shape will change significantly due to the pulse pile-up effect. To simulate leg of the subjects with high BMI, we used a large phantom, a combination of a leg phantom and a tibia phantom (Fig.1). The leg phantom was a cylinder with 150 mm diameter and 100 mm height, made of tissue equivalent material. In the hole of the leg phantom was a tibia phantom, a cylinder with 25 mm diameter and 100 mm height, made of lead-doped plaster of Paris.

A measurement arrangement of the phantom and the detector in the ^{109}Cd *K* XRF system is illustrated in Fig.1. Measurement parameters, such as total count rate, dead time of the measurement, location and area of the coherent peak, vary with the change of the distance between detector and phantom. For both standard phantom and large phantom, a series of measurements were made with different distances between phantom and detector. In order to minimize the measurement uncertainty for the obese subjects, we compared these measurement parameters for the two phantoms to find out the optimized distance from leg to detector.

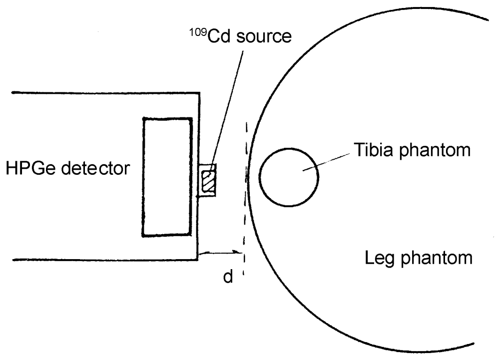

Fig.1 Measurement geometry of the phantom and the detector.

3 Results and discussion

The counting time of the measurements was 1800 s. The distance from detector to phantom varies every 5 mm in the range from 35 mm to 15 mm. The total count rate, dead time, coherent peak location, and coherent peak area and its statistic error, of these measurements, were summarized in Table 1.

Table 1 Measurement parameters for different distances between detector and phantom

		Distance between detector and phantom (mm)				
		35	30	25	20	15
Total count rate (cps)	Large phantom	50988	69408	75379	89907	76709
	Standard phantom	28498	36873	48357	66001	89749
Dead time (%)	Large phantom	23.7	27.6	32.5	37.0	33.6
	Standard phantom	14.3	18.0	22.7	29.3	36.9
Coherent peak location (channel)	Large phantom	1748	1747	1747	1746	1726
	Standard phantom	1748	1747	1747	1746	1743
Coherent peak area ±error(%)	Large phantom	25827±1.12%	30914±1.05%	38554±0.96%	46350±0.89%	31178±1.59%
	Standard phantom	82434±0.40%	104508±0.36%	131048±0.32%	164520±0.29%	198520±0.27%

As can be seen from Table 1, with a change of distance from 35 mm to 20 mm, the total count rate and dead time increased gradually; at the same time, the coherent peak location shifted forwards 1 to 2 channels, and the coherent peak area increased and its error decreased. But, for the measurement of large phantom, at the distance of 15 mm, the total count rate was so high that the coherent peak location shifted forwards up to 22 channels. This indicated that the instrument was not in a proper working condition, so the spectral shape was distorted significantly.

In general, with decrease of the distance from phantom to detector, more signals were received from the bone, hence measurement error decreased. However, when the distance was too small, the Compton scattering from the tissue overlying tibia increased highly, and the instrument would produce the distorted X-ray spectra because of the pulse pile-up effect. Therefore, we should control the distance between detector and leg to ensure precision of the measurement. The dead time was displayed instantly on the instrument. It could be used as an indicator of the working condition of the measurement system. Considering the inevitability of a small movement of the subject's leg in approximately 40 min counting time, it is suggested that, for subjects with high BMI (obese subjects), the measurement distance between detector and leg should be maintained at 25 mm. Thus, if the leg moved within 5 mm, the instrument still worked properly. It is also suggested that, during the measurement, the dead time should be controlled to around 30%. If a big change of the dead time was observed, which might be attributed to the leg's movement, an adjustment should be necessary to make the leg back in the original position.

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