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Minimum detectable limits of measuring bone mineral density using an energy dispersive X-ray diffraction system

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Abstract

In the clinical environment, the most common method of assessing bone mineral density (BMD) loss is dual energy X-ray absorptiometry (DEXA), which relies on the transmission of X-ray photons through the volume of interest. Energy dispersive X-ray diffraction (EDXRD), which utilises coherent X-ray scattering, potentially is a more accurate method. As part of the development of a precision EDXRD system, an experiment was performed using a range of bone and fat mix phantoms, which were also used for DEXA evaluation. The results are presented here and suggest initial minimum detectable limits of the order of 5% BMD loss for the EDXRD experiment and 10–15% for the DEXA assessment.

Keywords: EDXRD; DEXA; Osteoporosis

1. Introduction

The increased porosity of bone resulting from a reduction of bone mineral density (BMD) is generally known as osteoporosis, which tends to manifest itself more significantly in regions with a greater surface area. Bone may be classified as one of two types, cortical or trabecular. Trabecular bone consists of a mass of bony struts that form a strengthening structure within the hard outer shell of cortical bone. Trabecular bone has a far greater surface area per unit mass than that of cortical bone and so is far more likely to sustain a significant manifestation of osteoporosis.

BMD is commonly measured using dual energy X-ray absorptiometry (DEXA). This method involves X-ray beam transmission through the region of interest, resulting in a measure of both cortical and trabecular bone density. It is thought that the detection of osteoporosis might be made more accurate if the BMD measurement was isolated to trabecular bone only. A technique to achieve this, utilising coherent scatter of X-ray photons, is under investigation. A scatter volume is positioned within a site of trabecular bone in order to eliminate the influence of cortical bone. The technique, known as energy dispersive X-ray diffraction (EDXRD), has been shown to provide a measure of trabecular BMD only (Farquharson and Speller, 1998).

The EDXRD experiment is shown (in two dimensions) in Fig. 1. A polyenergetic source of X-ray photons is generated using an X-ray tube. Primary lead slit collimators are used to closely collimate the pho-tons into a beam, which is aligned to be incident on the sample, within which coherent scattering occurs. Collimators are arranged at the experimental scatter angle ϕ so that only photons scattered at the chosen angle will be detected. The output beam resulting from this geometry is detected using a high purity germanium detector and processed using a multichannel analyser.

Since bone mineral (predominantly hydroxyapatite) has a crystal-like structure, Bragg's Law will describe the conditions under which the constructive interference of X-ray photons occurs (Eq. (1)).

$$n\lambda = 2d \sin\left(\frac{\phi}{2}\right), \tag{1}$$

where λ is the wavelength of the photons, d is the spacing between the scattering planes (of which there are many within the structure), $\phi/2$ is the Bragg scatter angle and n is the order of diffraction.

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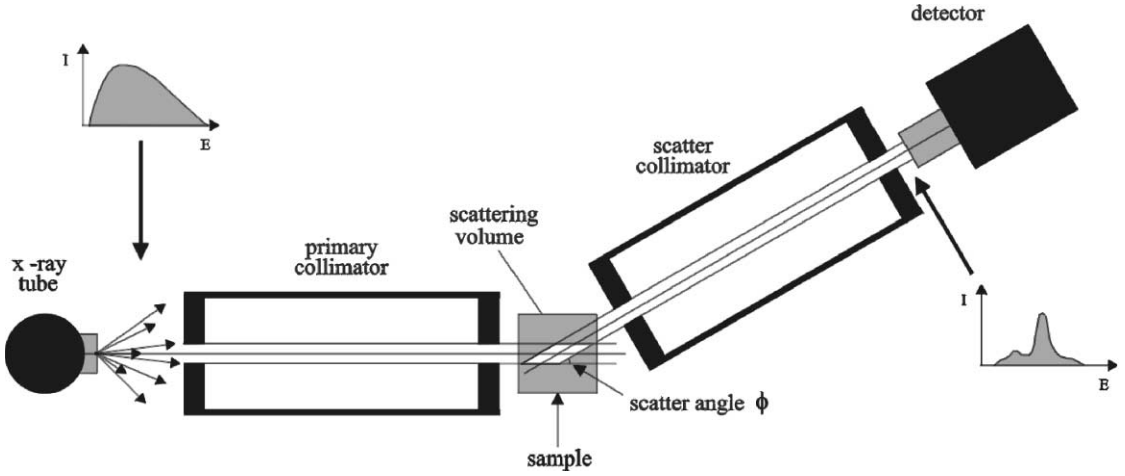

Fig. 1. EDXRD diffractometer.

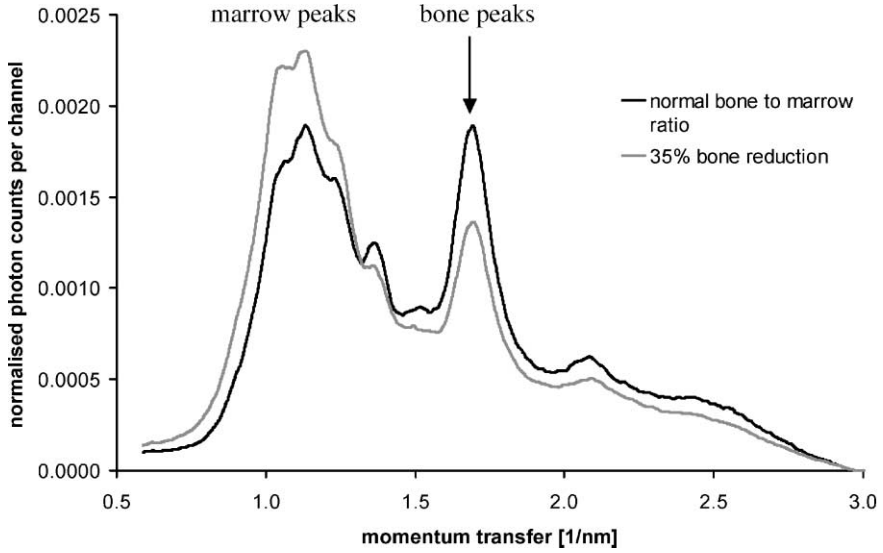

Fig. 2. EDXRD spectra illustrating reduction of bone to marrow ratio.

Constructive interference of the photons will occur when the wavelength is a whole multiple of $2d\sin(\phi/2)$. This leads to the detection of a spectrum of photon energies that provides a unique 'signature' related to the sample.

In order to investigate the efficiency of the EDXRD technique and to determine any improvement in accuracy over traditional methods, a study has been performed using phantoms. The phantoms were prepared as a set of 15 mm cubes containing a range of bone and fat mixture ratios. The mixture consists of ground clean bone and fat, which together simulate in vivo bone and marrow.

Two EDXRD spectra are shown in Fig. 2. One represents a healthy mix of bone and marrow (ratio of 20–80% by volume) and the other represents a 35% BMD reduction. The hydroxyapatite peaks are significantly reduced in intensity in the latter spectrum.

2. Experimental procedure

The experimental scatter angle (ϕ) was set to 6° and the collimator spacing was 1 mm. The phantom was translated along the scatter volume, the width of the total area traversed being 10 mm. The height of the

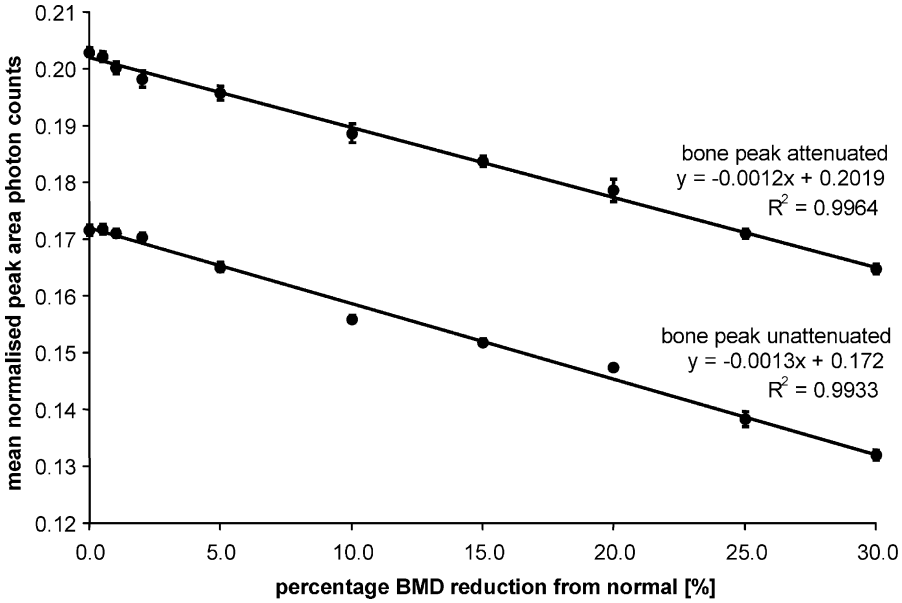

Fig. 3. EDXRD normalised bone peak photon counts.

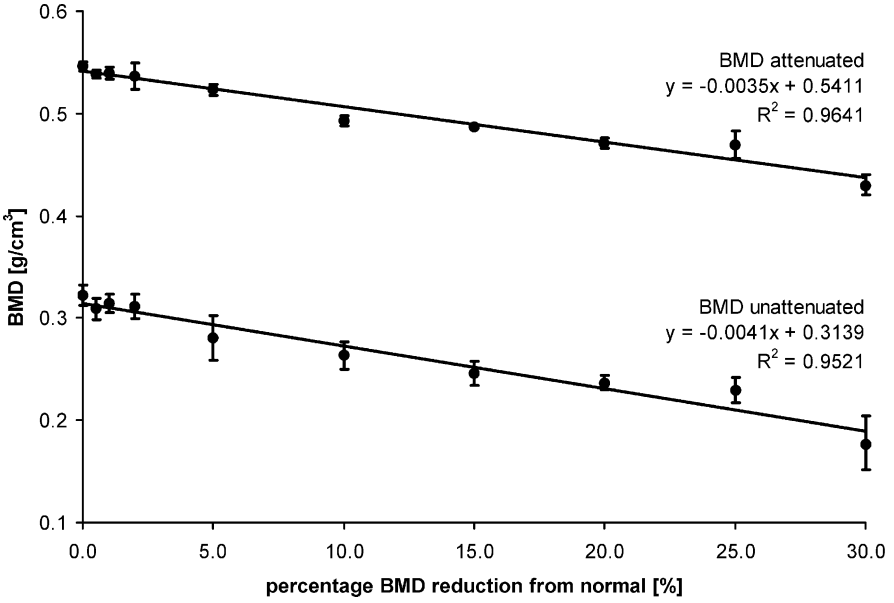

Fig. 4. DEXA bone mineral density measurements.

volume was fixed at 10 mm by the height of the collimation slit. The X-ray source was set to 70 kVp, 8 mA and measurements were recorded with a collection time of 1000 s per spectrum.

DEXA measurements were collected using the same phantom set on a Hologic QDR 4500 machine at University College Hospital, London.

EDXRD and DEXA measurements were collected with the X-ray source applied directly to the phantoms and then repeated with attenuation in the primary beam to simulate cortical bone (1.5 mm of aluminium) and soft tissue (5 mm Perspex).

3. Results

EDXRD results are presented in Fig. 3. Over the whole range of the trend, the minimum detectable

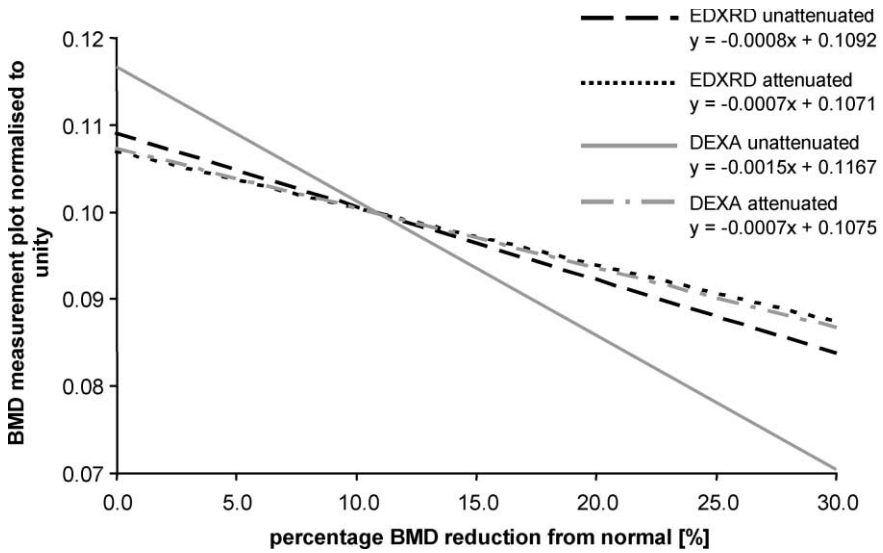

Fig. 5. Comparison of EDXRD and DEXA plot gradients.

resolution (considering error spread) was a BMD loss of 5%. Attenuation did not change this minimum resolution. DEXA results are presented in Fig. 4. The minimum detectable resolution was a BMD loss of 15%, unattenuated. The additional attenuation improved the minimum resolution to 10%. Errors are presented as $\pm$ two standard deviations.

An indication of the sensitivity of each data set may be realised by comparing the gradient of each trendline (i.e. the steeper the gradient, the more likely that different bone densities may be distinguished). To allow direct comparison, each trend plot was normalised to unity. Fig. 5 presents normalised gradients for EDXRD and DEXA, unattenuated and attenuated. With attenuation, the EDXRD gradient was reduced to 88% of its unattenuated gradient whereas the DEXA gradient was reduced to 47% of its unattenuated gradient.

4. Discussion

Results that are presented provide an indication of the minimum detectable limit achievable using this EDXRD system compared with that of a DEXA system. They have shown that EDXRD may resolve a minimum BMD change of 5% (unattenuated or attenuated) and that DEXA may resolve 15% unattenuated or 10% attenuated. It can be stated that DEXA is more than four times as sensitive to the applied attenuation than an EDXRD equivalent. The in vivo condition is simulated more accurately with the attenuation in place.

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