3 Bone Densitometry Techniques II: Single and Dual Energy X-ray Absorptiometry

section 3

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Introduction

If no fragility fractures are present, judging bone density from radiographs is insensitive and inaccurate. Clinical risk factors are poor in predicting the presence of osteopenia. Consequently there is a need for objective, non-invasive methods of bone densitometry which should be accurate, precise (reproducible), sensitive, inexpensive and involve minimal exposure to ionising radiation. Several of the photon absorptiometry techniques come close to these ideal requirements[1].

Historical Aspects

Single Photon Absorptiometry (SPA) was introduced in 1963 for bone densitometry in the appendicular skeleton. The technique used a single energy gamma ray source (^{125}I, photon energy, 27.3 keV) and a scintillation detector to measure the photons transmitted through a particular anatomical site (usually the forearm). The radionuclide source and detector were coupled and scanned in a rectilinear fashion across the area of interest. To correct for overlying soft tissue the anatomical site in which bone mineral density (BMD) was measured had to be surrounded either by water, water bags or water equivalent mouldable material, with an additional correction for adipose tissue. The technique was applied to peripheral skeletal sites, including the os calcis, but measurements were most often performed in the non-dominant forearm. For application to sites in the axial skeleton dual photon absorptiometry (DPA) was developed. The simultaneous measurement of the transmission of gamma radiation of two different energies compensates for the different thicknesses of soft tissue overlying clinically relevant sites for bone mineral density measurement such as the spine, hip and whole body. 153 Gd was most often the radionuclide source which provided the dual energy (44 and 100 keV) photons which were counted separately by scintillation detectors. Although SPA and DPA were widely used and provided many valuable clinical and research data, they had limitations. These resulted from the photon source being provided by a radionuclide. This decayed and needed to be replaced regularly, had a low photon flux which caused scanning times to be long (up to 40 minutes) and spatial resolution to be poor. These limitations have been overcome by the introduction of Single X-ray Absorptiometry (SXA) and Dual Energy X-ray Absorptiometry (DXA) in which the photons are produced from a low dose X-ray tube instead of from a radionuclide source. With the higher photon flux (50-1000 greater) scanning speeds are increased (to less than 5 minutes per site) and spatial resolution improved, with consequent enhancement of precision (coefficient of variation CV% better than 1% for the lumbar spine)[2,3]. SXA and DXA have therefore superseded SPA and DPA, and DXA is now the most widely applied method of bone densitometry[4].

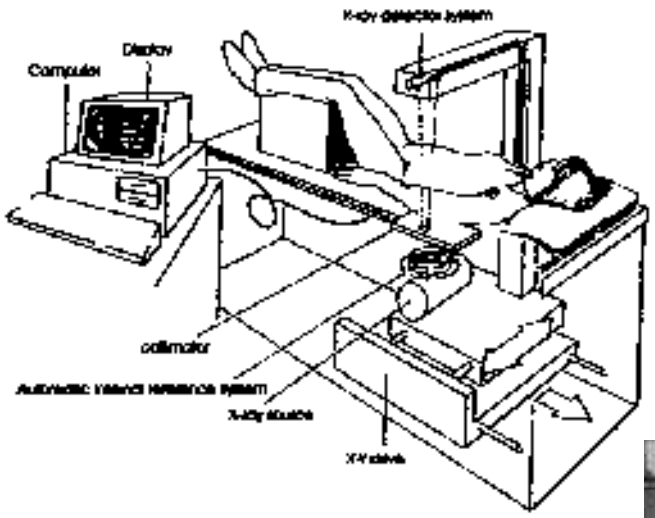
Single Energy X-ray Absorptiometry

In this equipment the photon source is an X-ray system (55 keV, 300 uA) with k-edge filtration and solid state detectors (Osteometer MediTech AS, Roedovre, Denmark). With a single energy X-ray beam the arm has to be placed in a water bath to allow correction for the soft tissue overlying bone. If a dual energy X-ray beam is used the water bath is not necessary. The equipment is relatively compact and mobile; scanning takes about five minutes with the forearm in a standardised position. Rectilinear scanning is performed in a distal (87% cortical bone) and ultradistal (mostly [65%] trabecular bone) site. Results are expressed as bone mineral content (BMC) in grams or BMD (g/cm^2). Accuracy is 3%, precision is better than 1% in the distal site and radiation dose (effective dose equivalent [EDE]) is less than 0.1 uSv. More recently an SXA scanner has been introduced to measure BMD in the os calcis (Osteoanalyser SXA 300, Dove Medical Systems, Norland Medical Systems, Newbury Park, California, USA). Scanning is performed in two minutes; precision is better than 1%.

Dual Energy X-ray Absorptiometry (DXA)

DXA was introduced in 1987 and has become the "gold standard" for clinical bone densitometry techniques. X-ray beams of two peak energies are produced by a variety of techniques by different manufacturers. The energies used are selected to optimise separation of the mineralised and soft tissue components of the sites scanned. Scanners manufactured by Hologic (Waltham, Massachusetts, USA) use an energy switching system in which the X-ray tube potential is switched rapidly from 70 to 140 kVp alternating at 60 per second with an internal rotating disc of calibration materials (Fig 1). Scanners made by the Lunar Corporation (Madison, Wisconsin, USA), Norland Medical Systems (Fort Atkinson, Wisconsin, USA) and Sopha (Buc Cedex, France) use a constant potential X-ray source combined with a rare earth filter with energy specific absorption characteristics due to K edge of the atomic structure of the element (K edge filtration). Using K edge filtration the X-ray beam is separated into two components of "high" (70-80 keV) and "low" (40-50 keV) energy photons.

(a)



(b)

Figure 1

DXA. (a) schematic diagram showing principles of DXA with X-rays passing through the rotating calibration disc and patient and transmitted radiation being measured in the detectors in the scanning arm (from Hologic; with permission). (b) patient positioned on scanner (Lunar DPX-L) for scanning of lumbar spine.

Sites scanned

DXA is most commonly applied to scanning the lumbar spine (L1-L4) (Fig 2), the proximal femur (regions of analysis include the femoral neck, trochanter, Ward's area and total hip) and whole body (Fig 3). The latter can be used to give total and regional measurements of bone mineral density and body composition (fat mass and lean muscle mass). Analysis programmes, principally used for research, are also available for measuring BMD around hip prostheses, in bone specimens, neonates and small animals.

(a) (b) (c)

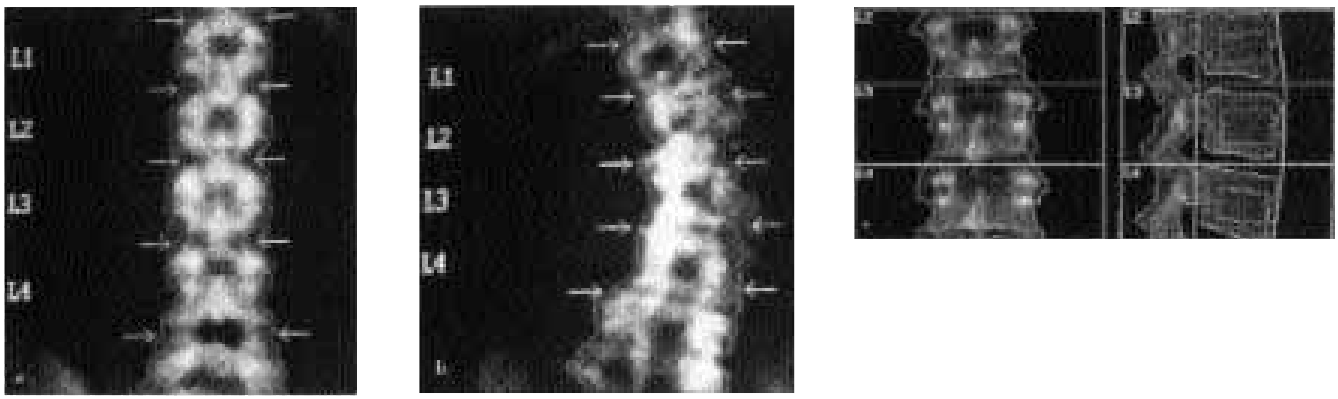


Figure 2

DXA lumbar spine. (a) PA scan of normal lumbar spine. (b) Lumbar spine with scoliosis and hyperostosis (osteophytes) at L2/3 and L3/4 which cause overestimation of BMD. (c) PA (left) and lateral (right) scans from which "volumetric" bone density can be estimated. Lateral scans allow analysis to exclude hyperostotic changes and have a higher proportion of trabecular bone than PA scans which include the neural arches

(a) (b)

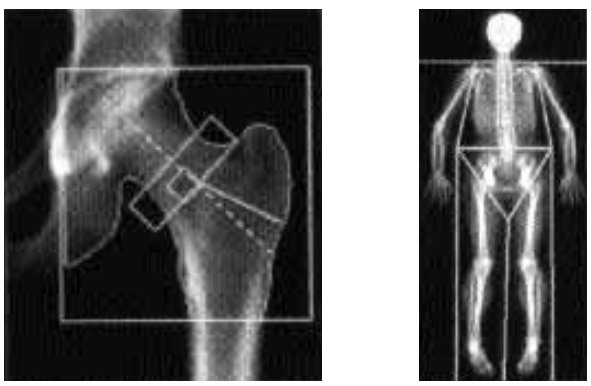


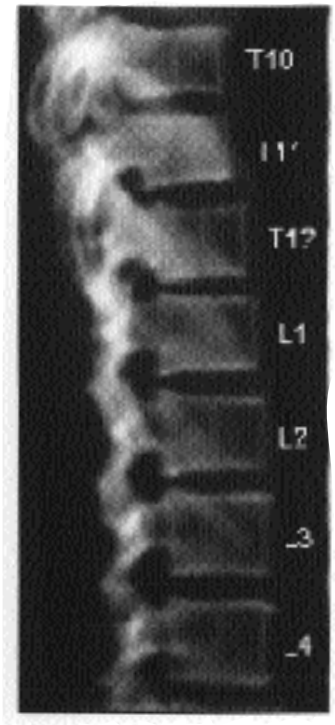
Figure 3

DXA – (a) proximal femur showing regions of interests analysed; femoral neck (oblong box), Ward's area (small box) and trochanter. Total hip BMD can also be obtained. (b) whole body scan with regional analysis for bone mass measurement. With appropriate software programmes information on whole and regional body composition (muscle and fat mass) can be obtained. (from Hologic, with permission)

Measurements

DXA measures integral (trabecular and cortical) bone mass with cortical/trabecular ratios of 50/50 in the lumbar spine (PA), 10/90 in the lateral spine projection, 60/40 in the proximal femur and 80/20 in the whole body (Fig 5). The bone mineral content (BMC) is expressed in grams. This value is divided by the area of bone scanned to provide BMD in g/cm^2.

Figure 4



Morphometric results
Lateral spine

	Central Hit		A/P Ratio		Fracture Index
	% Normal	z-Score	% Normal	z-Score	
T5	98	-0.2	98	-0.3	Normal
T6	99	-0.1	102	+0.3	Normal
T7	101	+0.1	94	-0.3	Normal
T8	98	-0.2	102	+0.4	Normal
T9	94	-0.7	94	-0.9	Normal
T10	98	-0.3	99	-0.2	Normal
T11	95	-0.6	96	-0.6	Normal
T12	94	-0.8	98	-0.3	Normal
L1	95	-0.6	97	-0.5	Normal
L2	93	-1.0	84	-2.7	Normal
L3	93	-1.0	93	-1.2	Normal
L4	93	-0.7	98	-0.3	Normal

Figure 4

Lateral DXA scan of thoraco-lumbar spine showing morphometric (MXA) measurements and results (from Lunar – with permission).

The accuracy of DXA is 3-8%. Precision (CV%) spine (PA) better than 1%, proximal femur between 1-5% depending upon site analysed, being better in the neck and trochanter (1-2%) than in Ward's area (2.5-5%)[6-8]. Positioning of the femoral neck is critical to maintaining good precision since differences in position can cause significant errors in BMD measured by DXA in the proximal femur (errors 0.9-4.5% in the neck; 1-6.7% at Ward's area and 0.4-3.1% in the trochanter)[9,10]. Scanning times are approximately 10-15 minutes per site scanned.

DXA body scanners can be used to measure BMD in the forearm. Measurements are made in the ultradistal (predominantly trabecular bone), distal (designated mid-radius) and shaft (designated 1/3 radius – predominantly cortical bone) regions of the forearm[11]. However there is now a desktop DXA scanner specific to scanning the forearm (pDEXA Norland Medical Systems, Fort Atkinson, Wisconsin, USA). Measurements are made in the distal radius and ulnar (predominantly trabecular bone) and in the shaft of the radius and ulnar (cortical bone). Scanning takes about five minutes.

Technical Developments

Lateral spinal DXA

In DXA of the spine (PA) the BMD is an "areal" density of integral bone which includes both the vertebral body and neural arch (cortical trabecular bone ratio 50/50). All the mineral within the path of the photon beam contributes to the BMD. Extraneous calcification such as in the walls of the aorta, and more particularly associated with degenerative disc and apophyseal joint disease with consequent hyperostosis, causes inaccuracies and over-estimation of BMD[12,13]. This limits the usefulness and sensitivity of PA spinal DXA in the elderly population in whom degenerative changes are commonly (greater than 60%) present at age 70 years or more. This has resulted in the development of lateral DXA scanning of the lumbar spine[14,15]. On the early generation scanners this required the patient to be repositioned for scanning in the decubitus position. This limited precision and was impractical in some patients. On scanners with mobile "C" arms, lateral scanning can be performed with the patient remaining in the supine position which is more practical and has better precision than scanning in the decubitus position. Ideally one would wish to analyse all four lumbar vertebrae (L1-L4) on lateral DXA, but L1 and L2 may have rib superimposed and more significantly L4 is frequently overlapped by the ileum. In some patients only analysis of L3 is feasible[16]. Precision for lateral DXA in the decubitus position is 2.8-5.9%; with a patient in a supine position 1.6-2%.

"Volumetric" bone density can be estimated from the PA and lateral DXA measurements (Fig 2). Spinal scoliosis, severe kyphosis and anomalous vertebral segmentation make DXA scanning technically difficult and limit its clinical usefulness and precision.

Vertebral morphometry

In recent years the introduction of a fan beam source of X-rays, a strip of detectors and mobile C-arm units (Lunar Expert; Hologic 4500 Acclaim) has resulted in faster scanning times (5 minutes or less per site per scan compared with 15 minutes for rectilinear scanners) and improved spatial resolution. The high photon flux enables lateral imaging of the entire spine (single or dual energy) from which morphometric X-ray absorptiometric (MXA) analysis of vertebral shape and fractures can be made[17] (Fig 4). Scans of the proximal femur have also been used for anatomical morphometric measurements. In 1994 Faulkner et al reported the automation of measurement of hip axis length (HAL) from DXA scans and its predictive value for hip fractures[18].

Radiation Dose

The radiation doses in DXA are extremely low in comparison to conventional radiographic examinations (i.e. chest X-ray 60 µSv; lateral lumbar spine 700-2000 µv) and is not much greater than natural background radiation[19]. For pencil beam DXA the dose is 1 uSv per site scanned (up to 6 µSv in scans of the proximal femur in women). The radiation dose from fan beam exposures is higher by a factor of about 10, but may be up to 62 µSv[20].

Interpretation

The BMD results from DXA in individual patients are expressed in g/cm^2 and compared with appropriate race/sex matched reference ranges, generally supplied by the scanner manufacturers. Comparison can be made with either age match reference data or peak bone mass (BMD of young normals). The results can be expressed as standard deviation scores (Z score-age-matched; T score-peak bone mass) or percentage of expected or percentile of mean for age-matched or peak bone mass mean values. Most of the reference data are for Caucasian races; there is a paucity of appropriate reference data for other ethnic groups. There is not, as yet, any consensus on how these diagnostic definitions of bone mineral density might most appropriately be related to therapeutic interventions. There are limited reference data available for children of all ethnic origins. Because DXA is not a true volumetric, but an areal, density it is very dependent on size which limits its usefulness currently in children. It is suggested that bone mineral content and BMD of the lumbar spine and the femoral neck should be normalised as described to avoid over diagnosis of osteoporosis in persons of petite body stature and under diagnosis in tall ones[21].

Anatomical Site to be Measured, Correlations and Follow-up

There is much discussion on which site BMD should optimally be measured. For clinical diagnosis measurements in the lumbar spine, proximal femur and forearm are most commonly performed. Whole body DXA currently remains a research tool. BMD measured by different techniques in the same individual are variously correlated (r = 0.2-0.9). Such variable correlations are to be expected since the techniques measure different types of bone (cortical, trabecular, integral) in various skeletal sites. However, because of the dispersion around the regression line of correlations between techniques, BMD results obtained by one method cannot be used to predict the result which would be obtained by using another method in the same, or a different, anatomical site.

Because of the slow turnover of bone longitudinal measures of BMD by DXA in individual patients should be performed at a minimum period of one year, but preferably two years should elapse between measurements to ensure that the change in BMD is significant (change must be approximately x 3 the precision to be statistically significant). The ideal interval of time between BMD measurements in an individual patient would be related to the technique used, its precision, the site of measurement (axial or appendicular skeleton) the type of bone measured (cortical, trabecular or integral) and the expected rate of change in bone density.

Conclusions

DXA (and SXA) have become important non-invasive techniques of bone densitometry that provide precise and acceptably accurate measures of BMD in clinically relevant sites of osteoporotic fractures (spine, hip, wrist) with extremely low radiation doses. Cost of equipment ranges from £20,000 (SXA) to £40,000-£50,000 for first generation pencil beam DXA scanners to between £80,000-£100,000 for the latest generation of fan beam scanners with spinal morphometry capabilities. The main limitations for DXA are the inaccuracies caused by degenerative changes in the lumbar spine in an elderly population and the size dependency of results in children.

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