A phantom for evaluating bone mineral density of the hand by dual-energy x-ray absorptiometry

S A Steel†§, P Swann‡, G Langley‡ and C M Langton†

† Centre for Metabolic Bone Disease, Hull Royal Infirmary, Hull, UK
‡ Medical Physics Department, Princess Royal Hospital, Hull, UK

Received 18 November 1996, in final form 3 March 1997

Abstract. Dual-energy x-ray absorptiometry (DXA) is a precise, widely used method for measuring bone mineral density (BMD), usually of the lumbar spine and femoral neck. Recent developments, such as a lower x-ray tube current and pixel by pixel analysis, enable smaller bones and thinner tissue volumes, as in the hand, to be measured. Measurements of hand bone mineral content (BMC) and BMD could be useful in assessing disease severity in early rheumatoid arthritis and in monitoring disease progression and response to therapeutic intervention. A phantom is required for evaluating the software, measuring long-term precision and comparing with other DXA methods.

This note describes the design and evaluation of a hand phantom for use on a Lunar DPX-L dual-energy x-ray absorptiometer. The phantom consists of three sections representing the metacarpals, and proximal and distal phalanges, using aluminium and Perspex as the bone and lean tissue equivalents respectively. The BMD of the three sections is approximately 1.0, 0.6 and 0.3 g cm^{-2}. The phantom demonstrates limitations in the potential accuracy of BMD determination at low densities using the Small Animal Software on the Lunar DPX-L. Improved recognition of low-density regions was obtained with the Lunar EXPERT with precision values of 0.9, 1.1 and 2.0% for the three sections of the phantom respectively.

Keywords: hand, phantom, bone densitometry, DXA

1. Introduction

Dual-energy x-ray absorptiometry (DXA) is a precise, widely used method for measuring bone mineral density (BMD, g cm^{-2}) to assess osteopenia and osteoporosis, usually of the lumbar spine and femoral neck. DXA is based on the attentuation of two x-ray energies by the body. The degree of attenuation depends on the beam characteristics in addition to the thickness and density of the material through which the rays pass. The theory of DXA assumes that there are only two substances in the region being measured, i.e. bone and soft tissue, requiring therefore two different energies to allow discrimination. The soft tissue is assumed to be of constant composition within the region being measured. The x-ray energies are chosen to optimize the differential attentuation between bone and soft tissue while minimizing the radiation dose to the patient. The optimal energies are 40–45 keV for the lower-energy photons and 75 keV for the higher (Rutt 1985). The DXA system in our centre, the Lunar DPX-L, uses a tube current of 750 or 3000 μA for performing scans of the lumbar spine and femoral neck. The analysis software identifies the regions of interest, for

§ Correspondence address: Centre for Metabolic Bone Disease, H S Brocklehurst Building, Hull Royal Infirmary, 220–236 Anlaby Road, Hull HU3 2RW, UK.

which BMD values will be calculated, and the soft-tissue baseline, to enable the attenuation due to soft tissue to be subtracted from the calculation. A minimum of 12 cm soft tissue throughout the scan region is required to calculate correct tissue baselines (Lunar). Recent developments in DXA such as a lower tube current of 150 μA and pixel by pixel analysis enable smaller bones and thinner tissue volumes to be measured.

The software available for the Lunar DPX-L machines utilizing these developments is called Small Animal Software and is intended for research use in assessing BMD, BMC (bone mineral content) and area of total body or appendicular bones in small animals. This software is designed for animals of 0.15–5 kg but with a minimum of 3.8 cm tissue depth within the region being measured for total-body composition (Lunar). This suggests that soft-tissue equivalent material may need to be added when using this technique for the human hand. Measurement of hand BMC and BMD could be useful in assessing disease severity in early rheumatoid arthritis, in monitoring disease progression and response to therapeutic intervention (Deodhar *et al* 1994, Peel *et al* 1994, Florescu *et al* 1993). A phantom is required for evaluation of this software for use in the measurement of BMC and BMD in the human hand, for measuring long-term precision and for comparison with other DXA methods.

An aluminium spine phantom is supplied with the Lunar DPX-L. This is a 16 cm $\times$ 4 cm block of aluminium of varying thickness representing the first four lumbar vertebrae. The lowest BMD of this phantom is approximately 0.9 g cm^{-2} and the phantom has raised edges to facilitate edge detection. This, therefore, cannot assess the precision of the system in the range of BMD encountered in the human hand and does not provide the same challenge to the edge detection algorithm as the small, almost rounded phalanges. The European Spine Phantom (ESP), although being anthropomorphic in shape with respect to the spine, is not designed to approximate the situation in the hand. Consequently, the lowest BMD (0.5 g cm^{-2}) is also too high and the soft-tissue equivalent block in which the vertebral components are imbedded provides soft-tissue attenuation which approximates that of 20 cm of human tissue, far more than is present in the human hand. The European Forearm Phantom (EFP) is similarly designed to approximate the forearm. Again, the BMD of 0.5–1.5 g cm^{-2} does not encompass the lower values found in the hand. This paper describes the specification and design of a hand phantom for use with the Lunar DPX-L Small Animal Software and includes results of measurement on the Lunar DPX-L and the newer Lunar EXPERT fan beam densitometer.

2. Methods and results

2.1. The Hull hand phantom

2.1.1. Phantom requirements. The aim was to design a phantom to assess precision and linearity of the system at low BMD values (0.3–0.9 g cm^{-2}). A simple geometric shape was desired rather than an anthropomorphic one as the phantom is also required to monitor long-term precision. A more complex shape would introduce more operator variability at the analysis stage. It was decided with this pilot design to use a mean of 3.8 cm of soft-tissue equivalence as recommended. This also enabled us to correlate the results with those of the forearm software on the same machine.

2.1.2. Choice of materials. The phantom was constructed from two materials simulating homogeneous soft tissue and bone mineral respectively. The choice of material was based upon the attenuation co-efficients, availability, construction considerations and cost.

Aluminium was chosen as the bone mineral substitute. The ratio of the mass attenuation co-efficient (μ/ρ) for aluminium to bone mineral is about 0.9 at x-ray energies of 10 keV–1 MeV. Perspex was chosen as the soft tissue and bone marrow substitute. The ratio of mass attenuation co-efficient for Perspex to lean tissue rises from 0.8 at 35 keV to 1.04 at 1 MeV (HPA 1977). Perfect tissue substitutes would have ratios of 1.0.

2.1.3. Design and construction. The design consists of aluminium tubes with a Perspex core simulating bone marrow within the medullary cavity. Hollow cylindrical tubes were chosen so as to mimic the cross sectional attenuation profile of the metacarpals and phalanges. The ability of the software to correctly detect the edges of a structure, closely resembling that encountered in the bones of the hand, can thus be tested. The relative diameters of aluminium tubes to Perspex rod were determined experimentally to give BMDs of about 0.8, 0.5 and 0.2 g cm^{-2}. The external dimensions of the 3 sets of tubes are 20 mm $\times$ 100 mm, 15 mm $\times$ 50 mm and 12 mm $\times$ 50 mm. These are embedded in a Perspex block to ensure mean equivalent soft tissue thickness of 3.8 cm as recommended when using the Small Animal total-body mode (Lunar). The phantom consists of three sections, representing the metacarpals, proximal phalanges, and middle and distal phalanges. Each section was also designed to be of different BMD representing the healthy normal and early and late stages of rheumatoid arthritis.

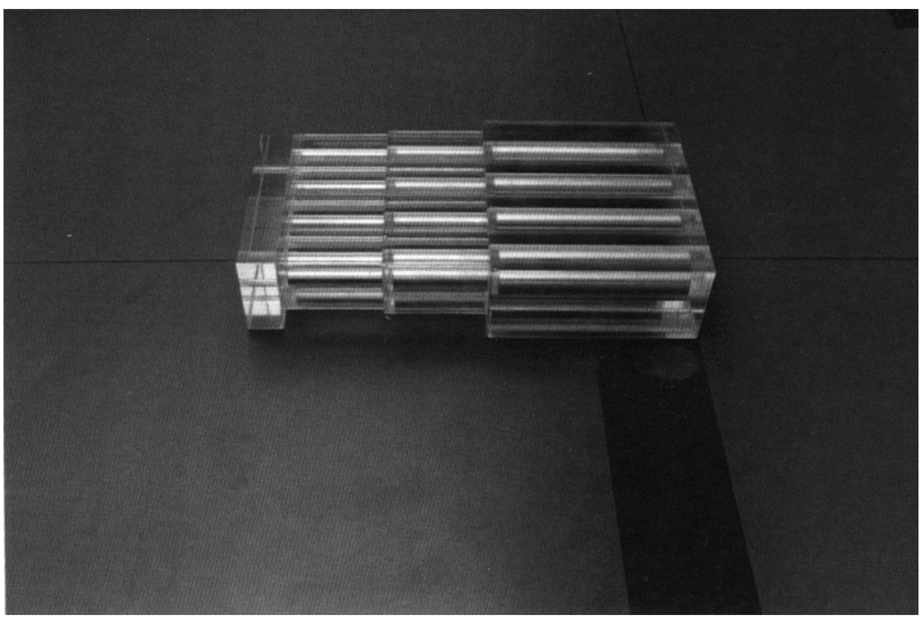

Figure 1. A photo of the hand phantom positioned on the DPX-L couch.

The phantom was constructed from a single block of Perspex drilled for insertion of the aluminium tubes (figure 1). Perspex spacers are positioned between the three sets of tubes, simulating the joint spaces. The dimensions of the aluminium tubes, and the inter-tube dimensions are, of course, known and this enables checking of the accuracy of, for example, measurements of joint spaces.

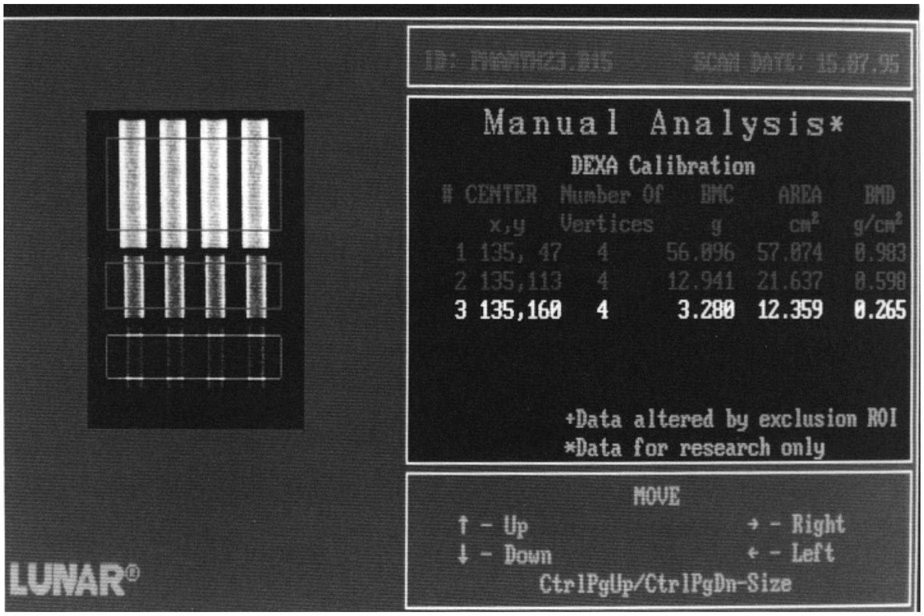

Figure 2. A DPX-L image achieved using Small Animal Software in high-resolution, slow mode with the three regions of interest identified.

2.2. Hand phantom measurement on a Lunar DPX-L

The phantom was placed directly on the scan table, aligned with the central axis and scanned using the Lunar Small Animal total-body software on a Lunar DPX-L. Ten scans of the phantom were performed over a period of 2 weeks using detail medium- and detail slow-scan modes. The scan and processing time involved using the other scan modes (high-resolution medium and high-resolution slow, of 45 min and 1 h respectively) was considered prohibitive in terms of the additional information this would provide. Only five scans were performed for the latter two modes, each over a period of 1 week. Analysis was performed using rectangular regions of interest placed over the three sections of the phantom. The regions of interest were of the same dimensions and locations on all scans (figure 2). The mean (standard deviation) BMD of the high-density region rises from 0.947 (0.021) g cm^{-2} using detail medium-scan mode to 0.990 (0.003) g cm^{-2} using the high-resolution slow-scan mode. There is a similar rise in the BMD of the medium-density area from 0.564 (0.019) to 0.609 (0.004) g cm^{-2}. The BMD for the low-density area falls from 0.310 (0.008) to 0.266 (0.003) g cm^{-2} using the detail medium and high-resolution slow mode respectively. The mean BMDs and precision, as percentage coefficients of variation, are shown in table 1. The mean values for the BMC of all three regions increased slightly from detail medium to high-resolution slow mode (table 2). The area within each region of interest defined by the software as containing a bone equivalent material is shown in table 3. The actual projected areas were 62.4 cm^2 for region one, 22.76 cm^2 for region two and 17.29 cm^2 for region three.

BMD measurement of the forearm using DXA is an accepted, widely used procedure. For comparison, the hand phantom was also scanned using the forearm software (fast speed) on the same machine. The forearm acquisition mode uses the same tube current of 150 μA and pixel size of 0.6 by 1.2 as the Small Animal high-resolution slow mode. The phantom

Table 1. Mean (standard deviation) and precision (% CV) of BMD for the three regions of interest assessed using the four scan modes of the Lunar Small Animal Software.

		Metacarpals		Proximal phalanges		Distal phalanges	
Scan mode	*n*	BMD (g cm^{-2}) mean (s.d.)	% CV	BMD (g cm^{-2}) mean (s.d.)	% CV	BMD (g cm^{-2}) mean (s.d.)	% CV
det. med	10	0.947 (0.021)	2.21	0.564 (0.019)	3.34	0.310 (0.008)	2.62
det. slow	10	0.949 (0.017)	1.88	0.575 (0.023)	4.07	0.306 (0.006)	1.83
hires. med	5	0.984 (0.002)	0.17	0.606 (0.002)	0.39	0.279 (0.002)	0.74
hires. slow	5	0.990 (0.003)	0.33	0.609 (0.004)	0.71	0.266 (0.003)	1.04

Table 2. Mean (standard deviation) and precision (% CV) of BMC for the three regions of interest assessed using the four scan modes of the Lunar Small Animal Software.

		Metacarpals		Proximal phalanges		Distal phalanges	
Scan mode	*n*	BMC (g) mean (s.d.)	% CV	BMC (g) mean (s.d.)	% CV	BMC (g) mean (s.d.)	% CV
det. med	10	57.88 (1.55)	2.68	12.74 (0.44)	3.46	2.02 (0.40)	19.81
det. slow	10	58.07 (1.60)	2.76	12.91 (0.49)	3.84	1.98 (0.48)	24.01
hires. med	5	60.80 (0.14)	0.24	13.77 (0.05)	0.39	3.58 (0.04)	1.10
hires. slow	5	61.23 (0.23)	0.38	13.81 (0.10)	0.72	3.68 (0.15)	4.20

Table 3. Mean (standard deviation) and precision (% CV) of measured area for the three regions of interest assessed using the four scan modes of the Lunar Small Animal Software. Actual projected areas containing 'bone' within each region are indicated.

		Metacarpals		Proximal phalanges		Distal phalanges	
Scan mode	*n*	Area (cm^2) mean (s.d.)	% CV	Area (cm^2) mean (s.d.)	% CV	Area (cm^2) mean (s.d.)	% CV
det. med	10	60.81 (0.85)	1.39	22.57 (0.37)	1.62	6.48 (1.15)	17.82
det. slow	10	61.21 (0.78)	1.28	22.45 (0.39)	1.75	6.47 (1.49)	23.01
hires. med	5	61.81 (0.06)	0.10	22.74 (0.01)	0.03	12.85 (0.11)	0.88
hires. slow	5	61.84 (0.06)	0.10	22.70 (0.03)	0.14	13.64 (0.42)	3.10
Actual projected area		62.40		22.76		17.29	

was scanned with and without the Delrin forearm positioning plate. By fixing the scan width to encompass only two of the aluminium rods, mimicking the radius and ulna, the phantom was suitable for use with the forearm analysis software. Rectangular regions of interest were positioned over the highest-BMD section (metacarpal), yielding BMD values of 0.767 and 0.755 g cm^{-2} with and without the positioning plate respectively. These are significantly lower than the BMD value of 0.992 g cm^{-2} obtained for the same region using the highest-resolution scan mode within the Small Animal Software.

2.3. Hand phantom measurement on a Lunar EXPERT

The Lunar EXPERT calculates BMD values using dual-energy x-rays as for the Lunar DPX-L machine but, using a higher tube current and smaller sampling size, producing high-resolution images of almost radiographic quality. This system has acquisition and analysis capabilities specifically for the hand. The hand phantom was placed on the forearm positioner and scanned using the 1 μA fast mode with the table set at the manufacturer's recommended height. Analysis was performed using three rectangular regions of interest as for the DPX-L (figure 3). The analysis software on the EXPERT machine incorporates a facility to display the characterization of individual pixels, i.e. whether the software has coded them as bone, soft tissue, air, neutral or artefacts. Any pixel incorrectly characterized can be manually redefined.

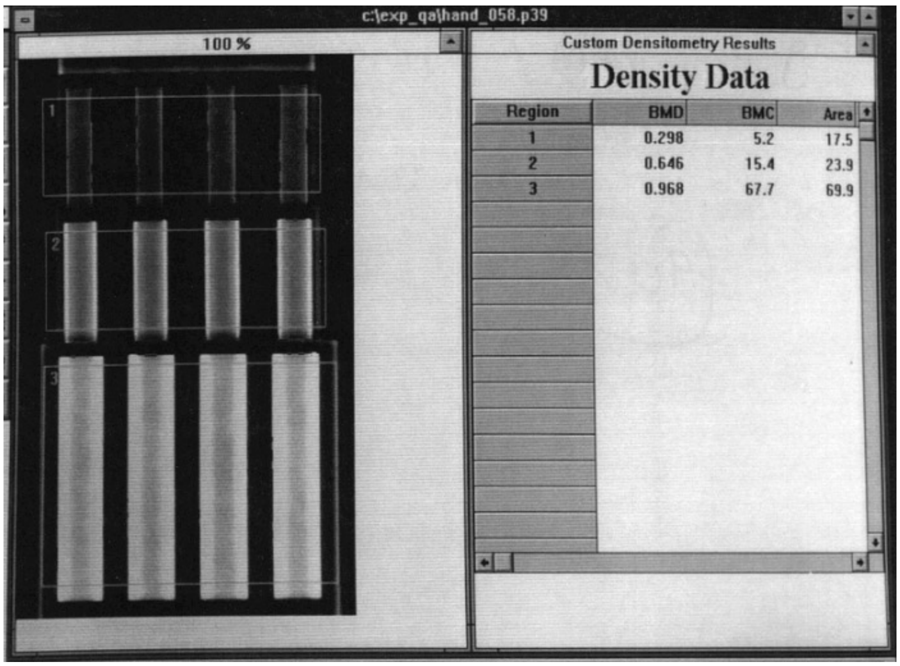

Figure 3. An EXPERT image achieved using hand acquisition mode with the three regions of interest identified.

The Lunar EXPERT correctly categorized all pixels as being bone or soft tissue and no adjustments were required. The hand phantom was scanned daily over 23 weeks on the EXPERT machine: the mean BMD (precision, CV %) values are 0.972 g cm^{-2} (0.9%) for the metacarpal region, 0.646 g cm^{-2} (1.1%) for the proximal phalanges region and 0.292 g cm^{-2} (2.0%) for the distal phalanges region.

3. Discussion

Using Lunar Small Animal Software on the DPX-L, the BMD for the metacarpal and proximal phalanges regions increases slightly with increasing resolution of the measurement but that for the distal phalanges region decreases. The mean precision (% CV) for each scan mode was 2.7% for detail medium, 2.6% for detail slow, 0.43% for high-resolution medium and 0.69% for high-resolution slow. The difference in BMD between the different scan modes may be due to a difference in measured BMC and/or area. The bone mineral content of the three regions follows a similar pattern with a slight increase with increasing resolution. This may be due to the partial-volume effect of the larger pixels of lower-resolution scans containing part bone and part soft tissue at the boundaries.

The areas determined by the software to contain bone or bone equivalent material within the metacarpal region of interest and the proximal phalanges region of interest were approximately equal to the actual areas of aluminium within each of those regions using all four scan modes. The software thus appears to correctly identify the boundaries of the aluminium tubes in these two regions of the phantom having BMD of approximately 0.95 and 0.6 g cm^{-2}. However, the areas determined for the distal phalanges region, of actual area 17.3 and BMD of 0.3 g cm^{-2}, were at best an underestimate of 21% (13.6 cm^2) and at worst 62% (6.5 cm^2). The system, therefore, is not defining the whole of the aluminium tubes within this area as 'bone' and, as BMD is BMC/area, the measured BMD may also be inaccurate. As the software does not enable display or adjustment of pixel categorization, it is difficult to determine whether the error is occurring at the outer edges or in the Perspex filled centre of the tubes and there is no mechanism to correct for it. The density of these smaller tubes appears to be below a software defined bone threshold on the DPX-L machine.

The Small Animal high-resolution slow mode and forearm software (fast) use the same tube current of 150 μA and pixel size of 0.6 mm $\times$ 1.2 mm and the software determined areas in each case are similar to the actual area. However, there is a significant difference in the estimate of BMD between the forearm and Small Animal Software.

Using the point typing facility on the Lunar EXPERT it was possible to confirm that all the aluminium components of the hand phantom were correctly identified as being bone pixels even at densities as low as 0.3 g cm^{-2}. The long-term precision as percentage coefficient of variation for the high-, medium- and low-BMD regions over a period of 23 weeks was 0.9, 1.1 and 2.0% respectively. The BMD estimated by the Lunar EXPERT is similar to that of the DPX-L for both the metacarpals and distal phalanges. However, the BMD of the proximal phalanges region appears significantly higher on the EXPERT. Due to inaccuracies noted in area determination on the DPX-L, this discrepancy is more likely to be due to an underestimate of BMD on that machine.

4. Conclusion

The hand phantom described covers the range of BMD likely to be experienced in clinical practice and enables monitoring of precision and linearity at these low densities. It was designed for use on the Lunar DPX-L but should be suitable for dual-energy x-ray machines using similar x-ray energies. Studies are now under way involving the measurement of this phantom on a range of machines. It is not designed as a truly anthropomorphic phantom and cannot be used to assess accuracy of BMD measurement as it has not been calibrated against standards of known bone density.

The phantom demonstrates some limitations in the potential accuracy of BMD determination at low densities using the Lunar DPX-L. A facility to display profiles, as is available with DPX-L AP spine software, or point typing as on the EXPERT, could enable these errors to be detected and corrected. The phantom also demonstrates differences in BMD when estimated using different software packages on the Lunar DPX-L.

The Lunar EXPERT correctly identifies all aluminium components as being bone pixels even at densities as low as 0.3 g cm^{-2} with a precision of 0.9–2% at the range of BMD values used in the phantom.

References

Deodhar A A, Brabyn J, Jones P W, Davis M J and Woolf A D 1994 Measurement of hand bone-mineral content by dual-energy x-ray absorptiometry—development of the method, and its application in normal volunteers and in patients with rheumatoid-arthritis *Ann. Rheumatic Dis.* **53** 685–90

Florescu A, Podenphant J, Thamsborg G, Hansen M, Leffers A M and Andersen V 1993 Distal metacarpal bone-mineral density by dual-energy x-ray absorptiometry (dexa) scan—methodological investigation and application in rheumatoid-arthritis *Clin. Exp. Rheumatology* **11** 635–38

Hospital Physicists Association (HPA) 1977 *Phantom Materials for Photons and Electrons* (Windsor: Reedprint)

Lunar *Lunar DPX-L Operator's Manual* version 1.3 (Madison, WI: Lunar)

Peel N F A, Spittlehouse A J, Bax D E and Eastell R 1994 Bone-mineral density of the hand in rheumatoid-arthritis *Arth. Rheumatism* **37** 983–91

Rutt B 1985 Optimised kVp, filtration and detection parameters for dual-energy imaging *Med. Phys.* **12** 536