Osteoporos Int (1999) 10:95–101

Osteoporosis International

Original Article

Image Resolution of the Lunar Expert-XL

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Abstract. The Lunar Expert-XL is an example of the latest generation of fan beam densitometers, with the X-ray source and detector array mounted on a C-arm to enable supine lateral imaging. Image resolution for anteroposterior (AP) spine, femur, hand, forearm and lateral morphometry on the Expert-XL were assessed in vitro with the 07-541 Nuclear Associates line pair test pattern. Each scan type was investigated at all available tube currents and scan speeds, and at the maximum, minimum and default bed heights. The effect of soft tissue thickness on resolution was investigated by using varying amounts of Perspex attenuator. The in vitro median lateral (*x*-axis) resolutions at the default bed height for the default scan types were 0.9 line pairs (lps)/mm for the 5 mA fast AP spine and femur scans, and l.0 lps/mm for 1 mA fast hand, forearm and 5 mA fast morphometry scans. This equates to a resolution of about 1 mm. The best resolution achieved was 1.2 lps/mm (0.83 mm), obtainable on all scan modes with the bed at maximum elevation, but only consistently with the forearm mode. Lower tube current did not affect resolution but did change the range of soft tissue thickness over which an image could be resolved. Turbo scan modes greatly reduced longitudinal (*y*-axis) resolution but had little effect on lateral resolution. This study demonstrates the importance of including an assessment of resolution when validating new equipment, especially if morphometric investigations are to be conducted.

Keywords: Expert-XL; Densitometry; DXA; Quality assurance; Resolution

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Introduction

Effective assessment of bone fracture risk by dual-energy X-ray absorptiometry (DXA) requires accurate and precise information, derived from bone mineral density (BMD) or morphometric examination. The image resolution of DXA limits both image clarity and the ability of edge detection algorithms to distinguish between bone and soft tissue. Digital imaging produces a coarse representation of bone edges, with any edge pixel of an area containing both soft tissue and bone appearing in the image as a composite of both. This produces errors in edge detection, and so leads to inaccuracy in the measured bone area and potentially in calculated BMD [1].

Fan beam densitometers employ an array of detectors for rapid image acquisition. The use of an array eliminates the rectilinear motion required with traditional pencil beam densitometers, so the emitter/detector assembly has only to be moved longitudinally [2]. The increased speed of this system permits the improvement of resolution by the use of smaller detectors in the array and shorter incremental movements of the emitter/detector assembly. Maintaining the same number of counts per detector requires an increase in the overall photon flux and so increases the administered radiation dose, although the effective dose to patients remains well below that of equivalent radiographic procedures [3]. Improved resolution provides more anatomic detail, sufficient to allow morphometric assessment of the spine, although still not sufficient for differential diagnosis.

DXA images are derived by an emitter projecting the object onto the detector. Pencil beam densitometry produces an image of the same relative dimensions as the object. Fan beam densitometry distorts and magnifies the lateral (*x*-axis) dimension of the image by an amount dependent on the distance from the emitter to the object

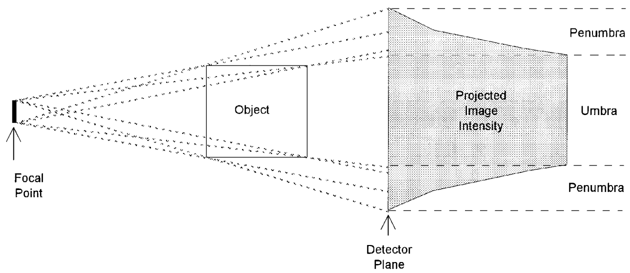


Fig. 1. Diagrammatic representation of the penumbra effect.

and the emitter to the detector. Fan beam distortion produces a lateral penumbra, whose width is determined by the focal point width, the object thickness and the object-to-focal point distance [4] (Fig. 1). However, the longitudinal (*y*-axis) dimensions remain unchanged. Conventional radiographic cone beams distort both the lateral and longitudinal dimensions.

Little work on the resolution of fan beam densitometers has been conducted. Lunar Corporation (Madison, WI) have produced the Expert series of fan beam densitometers, with the initial Expert system released in 1992 being superseded upon the release of the Expert-XL in 1994. Felsenberg et al. [5] have reported a resolution of between 0.95 and 0.7 line pairs (lps)/mm (1.05 and 1.43 mm) for the Expert and 0.7 and 0.5 lps/mm (1.43 and 2.00 mm) for the Hologic QDR 2000+ (Hologic Inc., Waltham, MA). No resolution for the Expert-XL has yet been reported outside the proprietary literature, which states a range of maximal resolutions varying from 2 to 1.6 lps/mm (0.5 mm to 0.625 mm). The aim of this investigation was therefore to measure the image resolution of an Expert-XL in routine clinical use at a district general hospital.

Equipment and Method

Lunar Expert-XL

The Lunar Expert-XL is an example of the latest generation of fan beam densitometers, with both X-ray emitter and detector array mounted on a rotatable C-arm to enable both anteroposterior (AP) and lateral imaging [6]. The emitter assembly consists of a Varian A-I 46 rotating anode X-ray tube, operating at a voltage of 134 keV, with 1 mm of aluminum filtration and a focal spot size of 0.3 mm. The distance from the focal point to the detector array is 112 cm. The detector array contains 288 solid state detectors, each 0.8 mm $\times$ 1.6 mm, arranged in two rows. A layer of copper over one row of detectors prevents low energy X-rays from reaching it, thus providing the required discrimination between high and low energies. The Expert-XL can perform eight different investigative procedures at five different sites. It is also possible to vary the X-ray tube current, scan speed and scan width for most procedures. The available investigations are summarized in Table 1. In addition, the scanning table is motorized and the height can be varied between 15.9 cm and 39.2 cm above the detector for optimal image registration and resolution for the type of investigation being performed. The accompanying workstation at this center is equipped with a 21-inch Dell Ultrascan 21TE monitor.

Resolution Test Pattern

Resolution was assessed subjectively using the 07-541 Nuclear Associates (Carle Place, NY) line pair resolution test pattern (Fig. 2a). The 07-541 test pattern contains 15 sets of lead line pairs, arranged horizontally and vertically, covering a range of 0.6 to 3.4 line pairs per milimeter. The test pattern is 0.1 mm thick and is encapsulated in a 3 mm thickness of material mimicking soft tissue.

Method

The five scan types most commonly used in clinical practice were investigated (AP spine, AP femur, forearm, hand, lateral morphometry). The test pattern was imaged at the minimum, maximum and default bed heights for each appropriate scan type. For AP spine and

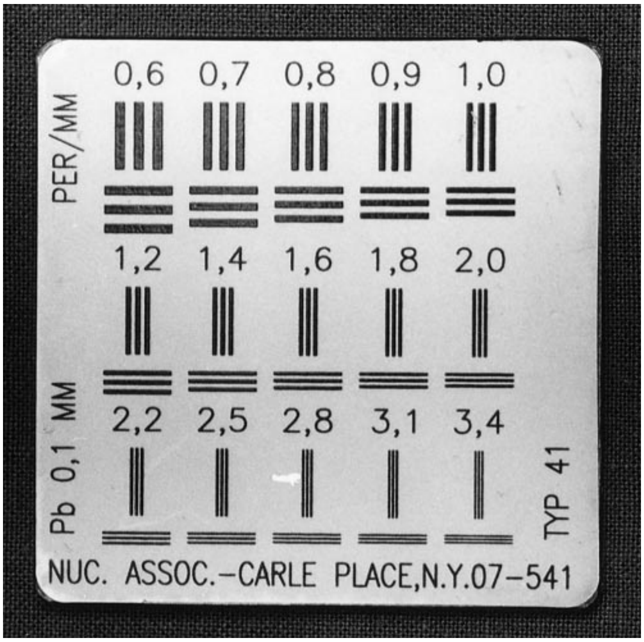
Table 1. Range of settings available for each scan type

Scan type	Tube current (mA)				Scan speed (s)			Scan width (cm)						
	5	2	1.5	1	Turbo	Fast	Medium	57.6	17.3	14.7	14.4	12.2	11.2	9.4
AP spine	Yes	Yes			7.7	**14.9**			**Yes**	Yes			Yes	
AP femur	Yes	Yes			7.7	**14.9**			Yes	**Yes**			Yes	
Orthopedic hip	Yes	Yes				**16.5**			Yes	**Yes**			Yes	
Lateral spine MM	Yes					**46.5**					**Yes**	Yes		Yes
Lateral spine BMD	Yes					**24.5**					**Yes**	Yes		Yes
Total body			Yes			**119.9**	238.9	**Yes**						
Forearm				Yes		**9.6**					Yes	**Yes**		Yes
Hand				Yes		**18.9**					**Yes**	Yes		Yes

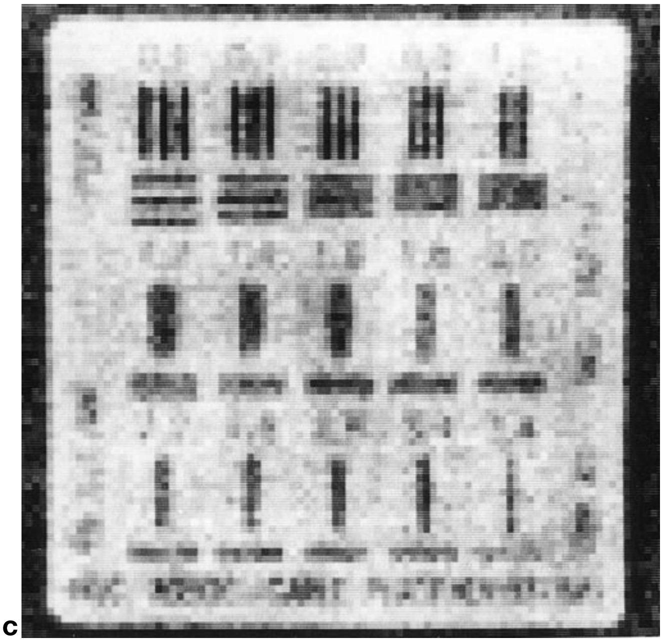
Tube voltage, 134 keV; focal spot size, 0.3 mm; software version, 1.63.
Default scan speeds and widths are shown in **bold** type. Default current settings are dependent on subject mass.
MM: morphometry mode.

AP femur, both 5 mA and 2 mA tube current options were assessed at the default bed heights, but only the 5 mA option was used at the maximum and minimum bed heights. Similarly, when both fast and turbo scan speeds were available, both were used at the default bed height but only the fast speed was used at the maximum and minimum bed heights. For AP spine and AP femur, images were acquired both with and without the mattress on the bed.

The required energy attenuation was achieved by positioning the test pattern between sheets of Perspex (polymethylmethacrylate, also known as Lucite or Plexiglas) which, at the relevant energy levels concerned, have a mass attenuation coefficient of 0.92 relative to lean tissue. Perspex was chosen as it was readily available and simple both to handle and to machine accurately. The initial thickness was determined from that which might be expected clinically for the particular type of scan. The thickness was varied for each scan type in an attempt to determine both the effect on resolution and the range of tissue thickness that could be successfully imaged. For spine and femur scans, the total range of Perspex used was 4–28 cm and 4–20 cm respectively, with 4–8 cm placed beneath the test pattern. For forearm and hand scans, the total range used was 0–12 cm and 0–9 cm respectively, with the Perspex beneath the test pattern varied from 0 to 6 cm for the forearm and 0 to 1 cm for the hand. For hand and forearm acquisitions, the mattress was removed and the forearm positioner placed on the bed, in accordance with normal operating procedure. For the morphometry scan mode, both Perspex and test pattern were stood vertically



a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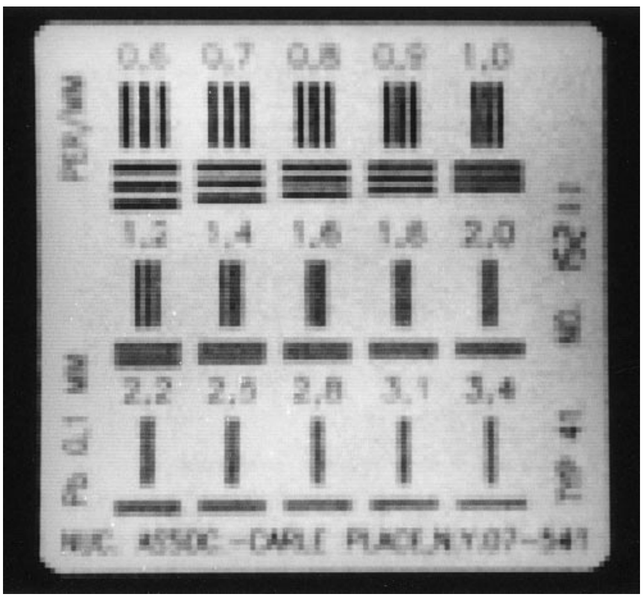
b

Fig. 2a–c. The Nuclear Associates 07-541 line pair resolution test pattern. **a** Photograph. **b** Resolution on forearm scan mode at maximum bed height, with 3 cm Perspex. **c** Resolution on AP spine mode at default bed height, with 20 cm Perspex.

on a single horizontal Perspex sheet. The total amount of attenuator was varied from 20 to 27 cm, with 10–14 cm on the side closest to the X-ray tube.

Images were analyzed immediately, to allow sufficient time for the X-ray tube to cool before the next acquisition. A single operator manually adjusted the image levels (displayed range), contrast and brightness controls until an optimal resolution was reached. The achieved resolution was measured from the screen, with the image at 300% magnification, and was defined as the last bar section in which a clear distinction could be seen between lines and spaces. The image magnification was sufficient to allow individual image pixels to be easily seen. The expected geometric lateral magnification was also calculated for each scan, taking into account the set bed height and the thickness of underlying Perspex. When the mattress was used for spine and hip acquisitions, an additional 1 cm was added to allow for the thickness of the mattress under compression. For hand and forearm scans, the height of the forearm positioner was added.

Results

The median and range of the resolutions achieved for each scan mode at the default bed height using different depths of Perspex are shown in Table 2. Sample images are shown in Fig. 2b and c. Both 5 mA and 2 mA image acquisitions were found to require a minimum thickness of soft tissue, below which an image could not be formed. As the thickness of soft tissue was then increased, the image became degraded by an increasing scatter component. Although the 2 mA images were visibly poorer than the 5 mA tube current images at large tissue thickness, the measured resolution was found to be approximately equal up to 24 cm of Perspex. Beyond this point the 2 mA images suddenly deteriorated in quality and the resolution was reduced to a level poorer than that which could be measured on the test pattern (i.e., <0.6 lps/mm), whilst the 5mA tube current produced images of 0.7 lps/mm resolution at the maximum soft tissue thickness of 28 cm. The 1 mA hand and forearm modes produced images of 1.0 lps/mm resolution at the maximum tested soft tissue thickness of 12 cm. Resolution was not affected by either the mattress or the forearm positioner.

Tube current had little effect on the achievable resolution, provided the current chosen was appropriate for the amount of soft tissue present in the region of interest. Accordingly, the tube current did change the range of tissue thickness over which an image could be resolved: from 9 to at least 28 cm Perspex for 5 mA, from 5 to 24 cm for 2 mA, and from 0 to at least 12 cm for 1 mA. The use of the turbo scan speed dramatically degraded the longitudinal resolution but did not cause any significant decrease in lateral resolution.

Scan speed did not appear to have much effect on lateral resolution. The median and range of lateral resolution for the AP femur scan were the same for both fast and turbo scan speeds at both 5 mA and 2 mA (median 0.9 lps/mm, range 1.0–0.8 lps/mm). For the AP

Table 2. Image resolution of the Expert-XL at default bed height settings

Scan mode		n	Resolution (lps/mm)[a]				Perspex attenuator (cm)[b]	
Tube current (mA)	Speed		Lateral		Longitudinal		Range tested	Minimum required for image
			Median[c]	Range	Median[c]	Range		
AP spine								
5	Fast	24	0.9	0.7–1.0	0.8	<0.6–0.9	5–28	9
	Turbo	11	0.9	<0.6–0.9	<0.6	<0.6	5–28	9
2	Fast	13	0.8	0.6–0.9	0.8	<0.6–0.9	4–28	5
	Turbo	10	0.9	<0.6–1.0	<0.6	<0.6	4–28	5
AP femur								
5	Fast	10	0.9	0.8–1.0	0.9	0.7–0.9	5–20	9
	Turbo	10	0.9	0.8–1.0	<0.6	<0.6	5–20	9
2	Fast	10	0.9	0.8–1.0	0.8	0.7–0.9	4–20	5
	Turbo	10	0.9	0.8–1.0	<0.6	<0.6	4–20	5
Hand								
1	Fast	10	1.0	1.0–1.2	1.0	1.0–1.0	0–9	0
Forearm								
1	Fast	10	1.0	1.0–1.2	1.0	0.9–1.0	0–12	0
Morphometry								
5	Fast	12	1.0	1.0–1.2	0.7	<0.6–0.7	20–27	<20

[a]There are 15 discrete line pairs on the 07-541 test pattern, ranging from 0.6 to 3.4 line pairs per millimetre (lps/mm). Resolution in lps/mm = 1/(resolution in mm). In the table, 0.6, 0.7, 0.8, 0.9, 1 and 1.2 lps/mm correspond to 1.67, 1.43, 1.25, 1.11, 1.00 and 0.83 mm.
[b]Ratio of attenuation coefficients between Perspex and lean tissue = 0.92.
[c]Acquisitions that did not produce viable images were excluded from median calculations.

Table 3. Image resolution of default scan types at minimum, default and maximum bed elevation

Scan mode	*n*	Bed height (cm)[a]	Object distance from detector array (cm)[b]	Expected lateral magnification[c]	Resolution (lps/mm) Lateral		Longitudinal	
					Median	Range	Median	Range
AP spine	10	0.2 (minimum)	20.7–24.7	1.23–1.28	0.9	0.7–0.9	0.8	$<$0.6–0.9
(5 mA fast)	24	–2.0 (default)	22.9–26.9	1.26–1.32	0.9	0.7–1.0	0.8	$<$0.6–0.9
	10	–23.5 (maximum)	44.4–48.4	1.66–1.76	1.1	0.8–1.2	0.9	0.8–1.0
AP Femur	10	0.2 (minimum)	20.7–24.7	1.23–1.28	0.8	0.7–0.9	0.9	0.7–0.9
(5 mA fast)	10	–2.0 (default)	22.9–26.9	1.26–1.32	0.9	0.8–1.0	0.9	0.7–0.9
	10	–23.5 (maximum)	44.4–48.4	1.66–1.76	1.0	1.0–1.2	0.9	0.8–1.0
Hand	10	0.2 (minimum)	19.5–20.5	1.21–1.22	0.9	0.8–0.9	0.9	0.9–1.0
(1 mA fast)	10	–17.5 (default)	37.2–38.2	1.50–1.52	1.0	1.0–1.2	1.0	1.0–1.0
	12	–23.5 (maximum)	43.2–44.2	1.63–1.65	1.0	1.0–1.2	1.0	0.9–1.2
Forearm	10	0.2 (minimum)	19.5–25.5	1.21–1.29	0.9	0.8–0.9	1.0	0.9–1.0
(1 mA fast)	10	–17.5 (default)	37.2–43.2	1.50–1.63	1.0	1.0–1.2	1.0	0.9–1.0
	10	–23.5 (maximum)	43.2–49.2	1.63–1.78	1.2	1.0–1.2	1.0	0.9–1.0
Morphometry (5 mA fast)	12	–15.5 (default)	40	1.56	1.0	1.0–1.2	0.7	$<$0.6–0.7

[a]As defined by Lunar Software, where height = 0 is the minimum height permitted by the hardware. Software limits the height to 0.2 cm above this.
[b]Includes thickness of underlying Perspex. Hand and forearm scan modes include elevation caused by the forearm positioner. AP spine and femur calculations assume a compressed mattress thickness of 1 cm.
[c]Calculated from: focal point-to-detector distance/focal point-to-object distance. Distance from the tube focal point to the detector array = 112 cm.

spine scan, the median lateral resolution of the 2 mA fast scan was slightly inferior to the turbo mode (0.8 lps/mm for 2 mA fast, 0.9 lps/mm for 2 mA turbo). However, scan speed produced a clear effect on longitudinal resolution, with no turbo scan achieving a resolution that could be measured on the test object (resolution $<$0.6 lps/mm).

Bed elevation produced a direct effect on the lateral resolution, as shown in Table 3. Included in the table is a calculation of the geometric fan beam lateral magnification for each bed height. The estimate takes into account the thickness of Perspex underlying the test pattern, and the height of the forearm positioner is included for the hand and forearm modes. A maximum lateral resolution of 1.2 lps/mm was achieved on the forearm, hand and morphometry scan modes with the bed at the default height, and on all modes with the bed at the maximum elevation. The median lateral resolutions varied at the maximum bed elevation, with 1.1 lps/mm for AP spine, 1.0 lp/mm for AP femur and hand, and 1.2 lps/mm for the forearm. As expected, the poorest lateral resolutions, of 0.9–0.7 lps/mm, occurred at minimum bed elevation.

Surprisingly, longitudinal resolution was also improved slightly by bed elevation. The median resolutions for the AP spine scan improved from 0.8 lps/mm (range: 0.9 to $<$0.6 lps/mm) at the minimum bed height to 0.9 (1.0 to 0.8) lps/mm at the maximum. The median resolutions for the AP femur scan were the same (0.9 lps/mm) at both minimum and maximum bed heights, but the range varied from 0.9–0.7 lps/mm at the minimum bed height to 1.0–0.8 lps/mm at the maximum. The hand mode also showed improvement, from a median and range of 0.9 (1.0–0.9) lps/mm at the minimum bed height to 1.0 (1.2–0.9) lps/mm at the maximum. The forearm mode was an exception to the trend, with no change in median or range of resolution over the full variation in bed height.

Discussion

This investigation has demonstrated the image resolution achievable on the Expert-XL over the range of investigations that may typically be performed as part of a clinical investigation. Lateral resolution was found to be strongly influenced by bed height, whilst longitudinal resolution was slightly influenced. For comparison, we attempted to determine the resolution of the Lunar DPXL pencil beam using the same phantom, but failed. Even on the highest resolution mode the DPXL was not able to image the coarsest line pair pattern of 0.6 lps/mm, thus indicating a resolution of poorer than 1.67 mm. The 07-541 test pattern provides only a discrete and subjective measure of resolution within a limited range. Assessment of pencil beam resolution would require a coarser line pair test pattern.

It was expected that as soft tissue thickness increased, the resolution of lower tube current scans would deteriorate faster than those performed with a higher tube current. Although increasing thickness of soft tissue visibly produced more random scatter in the image, the 07-541 line pair test pattern did not reveal the effect of scatter on the resolution. As a result, it was not possible to identify the optimum ranges of soft tissue thickness for each tube current, only the absolute range. A hole phantom might better demonstrate the effect of scatter but would be less susceptible to the penumbra effect, making it inappropriate for measuring the effect of bed height upon resolution.

At a tube current of 5 mA, the Expert-XL produced a viable image in vitro at a Perspex thickness ranging from 9 cm to at least 28 cm. However, under normal use BMD values are calibrated to be accurate within an expected thickness of soft tissue, based on the subject's weight and the anatomic region of interest. If the actual thickness of soft tissue differs greatly from the expected, the calculated BMD value will be inaccurate. Although Perspex provides a close attenuation match to lean tissue at the X-ray energies used, the difference is sufficient to require caution when extrapolating between in vitro and in vivo applications.

Lateral resolution showed improvement with increasing bed elevation, although not to the extent that might be expected for the degree of geometric magnification. It seems likely that the degradation of the image was due to the thickness of soft tissue used, but this could not be demonstrated convincingly with the 07-541 test pattern. In general, although lateral resolution can be improved by the elevation of the object, there is a limit. As an object is moved toward the source of a fan beam, the beam is concentrated on a smaller target area, increasing the localized dose. Additionally, if the object is of finite depth, layers of the object at different depths are magnified by different amounts, so producing a penumbra (area of partial shadow) around the object. The width of the penumbra depends on the thickness of the object and the width of the focal spot, as well as the distance from the object to both the source and the detector. Penumbra, projection and radiation dose increase as an object approaches the source. Optimal lateral resolution is therefore a balance between the positive influence of the projection effect against the negative factors of the penumbra effect and radiation dose. The manufacturer's default bed heights for each scan mode place the region of interest at an imaging plane determined, presumably, from consideration of these factors.

Unexpectedly, the longitudinal resolution also showed some improvement with bed elevation, most noticeably with the range of resolutions achieved with the AP spine and femur investigations. This was most probably due to scatter, as the AP spine and femur investigations included the greatest thickness of soft tissue. Resolution is degraded when a photon interacting with an object is deflected rather than absorbed, and still reaches the detector. If the angle of deflection is too great, the photon misses the detector altogether, so is not present in the final image. As the distance from the detector to the object decreases, the range of angles of scattered photons reaching the detector is increased, reducing resolution. The longitudinal resolution is therefore dependent on detector element length and scan speed, as well as the object's distance from the detector and relative attenuation characteristics.

Clinically, resolution is important for both BMD and morphometric studies. BMD studies employ an edge detection algorithm to differentiate between bone and soft tissue, but the efficacy of the algorithm is limited by the resolution. Poor resolution produces a coarse representation of bone edges, leading to a potential misidentification by the automated point-typing algorithm. Higher-resolution densitometry systems should therefore provide better estimates of bone area. This has been demonstrated by Bärenholdt et al. [7], who found a better bone area estimate for the Expert than for the QDR 4500, although other factors may still be involved. Vertebral morphometry studies depend on good resolution to adequately identify the edges of the vertebral bodies. A large-scale MXA reference data study by Rea et al. [8] compared MXA with radiography and found some difference with corresponding wedge and biconcave ratios, but not with crush ratios. In addition, they also reported small but statistically significant differences between the DXA systems used (three Hologic QDR 2000+ and one QDR 4500). Two phantom-based studies at this center have demonstrated that the Expert-XL underestimates the severity of biconcavities by an average of 8% [9], and furthermore that small angles of spinal malalignment (2.5°) can produce an increase in the measured vertebral height [10]. The system resolution was identified as a potential cause of both errors. Resolution varies between modalities (MXA and radiography) and between DXA systems; therefore machine-specific MXA reference data may be required.

The resolutions across the width of the fan beam that might be expected using the Expert-XL at the respective default bed heights are 0.9 lps/mm for the AP spine and femur, and 1.0 lp/mm for the hand, forearm and vertebral morphometry investigations. For the fast scan speed, the longitudinal resolutions at the respective default bed heights are 0.8 lps/mm for the AP spine, 0.9 lps/mm (at 5 mA) or 0.8 lps/mm (at 2 mA) for the AP femur, 1.0 lp/mm for the hand and forearm, and 0.7 lps/mm for vertebral morphometry. Using the turbo scan speed, the longitudinal resolution is always poorer than 0.6 lps/mm, irrespective of the site of interest. The maximum lateral and longitudinal resolution achieved by this investigation is 1.2 lps/mm, equivalent to 0.83 mm, but only the lateral resolution of forearm scans with the bed at maximum elevation consistently achieves this level. The resolution attained with the machine at this district general hospital does not concur with the 2–1.6 lps/mm (0.5–0.625 mm) reported by the manufacturer, but the resolution achieved is superior to that of the DPXL pencil beam densitometer. However, even at the highest bed elevation, the measured resolution of the Expert-XL does not approach the approximately 3.5 lps/mm (0.29 mm) resolution reported for lateral spine radiography by Felsenberg et al. [5]. When considering use of improved DXA technology for morphometric purposes, determination of the resolution should be considered as part of the validation procedure.

Acknowledgements. The authors gratefully acknowledge the financial support provided for this study by the local osteoporosis charity OSPREY.

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Received for publication 26 November 1998
Accepted in revised form 15 February 1999