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Original Article

Axial and Total-Body Bone Densitometry Using a Narrow-Angle Fan-Beam

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Abstract. We assessed a new dual-energy bone densitometer, the PRODIGY, that uses a narrow-angle fan-beam (4.5°) oriented parallel to the longitudinal axis of the body (i.e., perpendicular to the usual orientation). High-resolution scans across the body can be stepped at 17 mm intervals. The energy-sensitive array detector uses cadmium zinc telluride, which allowed rapid photon counting. Spine and femur scans required 30 s, and total-body scans required 4–5 min; the dose was only 3.7 mrem and 0.04 mrem respectively, or about 5 to 10 times lower than conventional fan-beam densitometry. We found only a small influence of soft-tissue thickness on bone mineral density (BMD) results. There was also a small ($\pm$ 1%) influence of height above the tabletop on BMD results. A software correction for object height allowed a first-order correction for the large magnification effects of position on bone mineral content (BMC) and area. Consequently, the results for BMC and area, as well as BMD, with PRODIGY corresponded closely to those obtained using the predecessor DPX densitometer, both in vitro and in vivo; there was a generally high correlation (r = 0.98–0.99) for BMD values. Spine and femur values for BMC, area and BMD averaged within 0.5% in vivo (n = 122), as did total-body BMC and BMD (n = 46). PRODIGY values for total-body lean tissue and fat also corresponded within 1% to DPX values. Regional and total-body BMD were measured with 0.5% precision in vitro and 1% precision in vivo. The new PRODIGY densitometer appears to combine the low dose and high accuracy of pencil-beam densitometry with the speed of fan-beam densitometers.

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Introduction

Bone densitometry using dual-energy X-ray absorptiometry (DXA) has become the standard for management of metabolic bone disease, in terms of both assessment of fracture risk and monitoring of treatment efficacy [1–4]. The original DXA technology of a decade ago involved rectilinear scanning of a narrow ($\sim$3 mm) pencil-beam; standard spine or femur scans required 4–8 min. The X-ray source could either be rapidly switched between high and low energies (50 and 85 keV effective), or a stable beam could produce two energies (40 and 70 keV effective) using selective attenuation at the middle of the X-ray spectrum with a K-edge filter. In the latter case, an energy-sensitive detector is needed. Fan-beam DXA densitometers were commercially developed in 1991 [7–12]. The wide-angle fan-beam, oriented perpendicular to the longitudinal axis of the body, was scanned longitudinally along the femur or spine. The fan-beam covered an 11 cm wide path (30° angle) on the QDR densitometer and a 15 cm wide path (12° angle) on the EXPERT series [3,12]. These fan-beam densitometers reduced the scan times to 1 min or less; however, they used a relatively wide fan-angle and did not use energy-sensitive detectors with pulse-height counting. The radiation dose was about 10–30 times higher ($\sim$20 to 30 mrem for spine/femur scans) than for pencil-beam densitometers [1,13].

We report here the results with a new DXA instrument, the PRODIGY (Lunar, Madison, WI),

using a narrow angle fan-beam (4.5°); the densitometer uses a stable X-ray source with a K-edge filter, and an array detector made from energy-sensitive cadmium zinc telluride (CZT). Sorenson et al. [5] and Chakraborty et al. [6] have demonstrated that the photon-counting K-edge approach inherently produces a 3-fold better dose-utilization than the switched-energy approach. In addition, switched-energy densitometers require calibration on each pixel; one-third of the exposure time for each pixel is used for 'soft-tissue' calibration in plastic, one-third for 'bone' calibration in aluminum, and only one-third is dedicated to unobstructed patient measurement [1]. In contrast, the K-edge photon-counting approach, because of its inherent stability, does not require calibration for each pixel. Consequently, the photon-counting approach is roughly 10 times more efficient than an approach using switched-energies for each pixel (e.g., Hologic QDR-series), or approaches that use side-by-side detectors (Lunar *Expert*) or stacked detectors (Norland X-series). Count-rate limitations of energy-sensitive detectors, which until now have not been available as arrays, prevent this better dose utilization from being translated directly into faster scans; the CZT array allows dose-efficient scanning in a more rapid time.

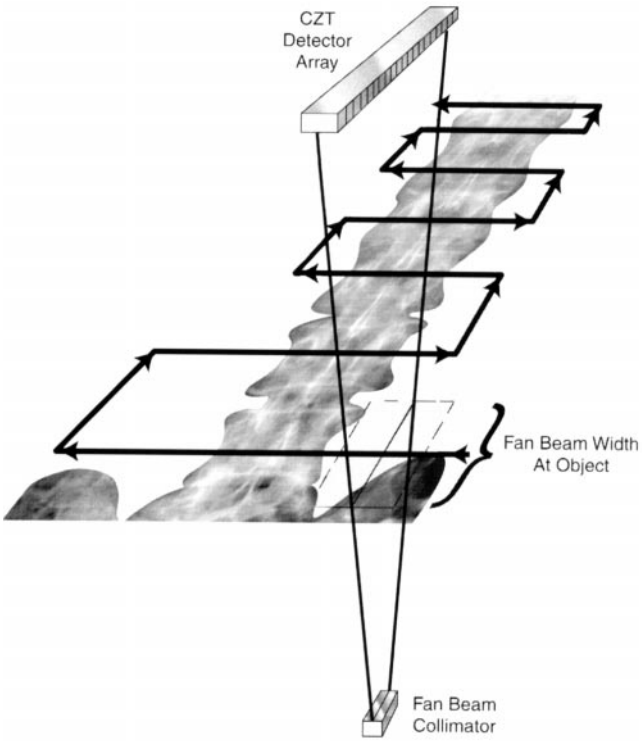

Fig. 1. Orientation of the fan-beam of radiation and CZT array detector for the PRODIGY densitometer. A series of overlapping transverse scans are made with a large step between them.

Methods

Measurements were made in vitro and in vivo with PRODIGY and DPX bone densitometers (Lunar, Madison, WI) at the Lunar headquarters and at the University of Wisconsin (Madison). The PRODIGY densitometer uses a dual-energy X-ray source similar to that of the DPX densitometer with a peak X-ray energy at 80 kVp and current at 3 mA [14,15]. A K-edge filter (cerium 300 mg/cm^2) gives effective energies of approximately 40 and 70 keV for low and high energy, respectively. Calibration is done using the basis material decomposition approach of Macovski and Alvarez as refined by subsequent workers [16,17]. The calibration is based on the standard DPX approach [18]. The fan-beam in the PRODIGY is oriented parallel to the long axis of the body rather than perpendicular to it (Fig. 1). The length of the array detector (16 elements each 3 mm wide) is approximately 5 cm. There is approximately 100% magnification at the image plane so that for a typical scan of the spine and femur, the effective imaging is done over 24 mm length. Consequently, the scanner is stepped longitudinally at approximately 17 mm intervals; this not only provides full coverage, but gives some overlap at scan edges (Figs 1, 2). Standard spine and femur scans were done in 30 s with a skin entrance exposure of 3.7 mrem. Total-body scans required under 5 min and had a total body exposure of 0.04 mrem. Exposure was determined using a ''pancake'' ion chamber and electrometer (Victoreen model 6000-532, Cleveland, OH).

Spine and femur scans are corrected to the actual effective object plane, typically about 10 cm above the tabletop. The object plane is determined in each scan. Adult total-body scans are corrected to an arbitrary 12 cm height above the tabletop; the arbitrary height is used because the skeletal structures have a complex distribution. Fan-beam densitometers typically have 30–100% magnification, which makes bone mineral content (BMC, in g) and area results highly dependent on position above the tabletop, even though bone mineral density (BMD, in g/cm^2) is relatively invariant [7,8,10].

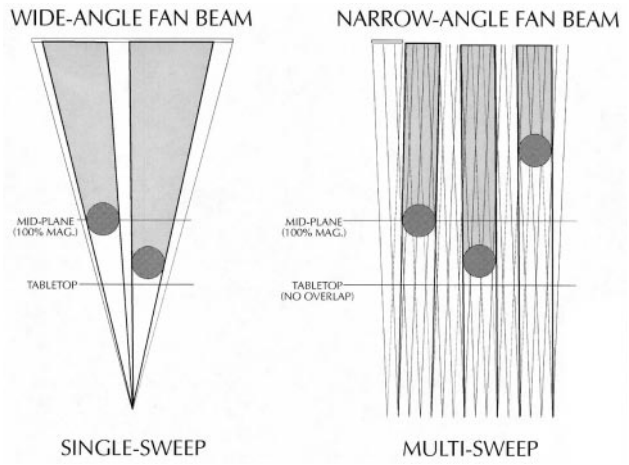

Fig. 2. Magnification effects with fan-beam geometry make bone mineral content (BMC) and area dependent on position in the beam with both wide-angle and narrow-angle beams; the latter have much fewer artifacts due to beam divergence at the edge of field.

By correcting for magnification, the PRODIGY is able to obtain accurate BMC and area measurements, as well as accurate BMD.

Measurements were done on standard aluminum phantoms [18], the European Spine Phantom (ESP) [19], and on human vertebrae encapsulated in a lucite block, to (a) evaluate precision, (b) assess inter-unit variation, and (c) check correspondence between PRODIGY and DPX results. Total-body scans were done on an isolated skeleton, partially affixed to lucite sheets; the orientation of some of the bones occasionally changed, making this a less useful phantom. The average values for the PRODIGY and DPX results were compared, and regression relationships were examined. Each of the DXA scans in vivo was reviewed by one experienced operator and regions of interest adjusted if necessary. The results of PRODIGY spine and femur scans on 122 subjects in vivo were compared with those using the DPX densitometer [14]. In addition, 46 subjects were measured using both PRODIGY and DPX densitometers to evaluate total-body scans [14,20]. The precision in vivo was assessed by short-term measurements in triplicate with relocation between measurements; there were triplicate measurements of the spine and femur in 51 of the 122 subjects, and in all, 46 of the subjects were used for total-body determinations. The standard error of estimate (SEE) in predicting DPX results from PRODIGY values was calculated.

Results

Effect of Thickness

Measurements were made at 10, 15, 20 and 25 cm thickness of acrylic on a single spine phantom on seven different PRODIGY densitometers (mean BMD 1.284 with SE = 0.004 g/cm^2) (Table 1). The effective water-equivalent thickness ranged from 12 to 30 cm. The variation (SD) among densitometers averaged under 0.01 g/cm^2. The variation with thickness ranged from 0.6% to 1% with a systematic increase of about 0.01 g/cm^2 between low and high thicknesses.

Spine scans were also done on a thick human subject (24 cm water-equivalent) before (n = 3) and after (n = 4) adding a 5 cm thickness of acrylic. The baseline spine BMD was 1.124 g/cm^2; the addition of 5 cm of acrylic decreased BMD by 1% to 1.109 g/cm^2.

Table 1. Effect of actual acrylic thickness (and water-equivalent thickness) on BMD (g/cm^2)

	Thickness (cm)			
Acrylic (water-equivalent)	10 (12)	15 (18)	20 (24)	25 (30)
BMD Mean	1.278	1.279	1.288	1.290
BMD SD	0.006	0.010	0.013	0.009

Inter-Unit Variation

The values obtained on phantoms on 65 PRODIGY densitometers were collated (Table 2). The inter-unit variation in BMD values for spine and femur phantoms was under 1%; the coefficient of variation (CV) for total-body BMD on a small skeleton was slightly over 1%, but the SD of 0.009 g/cm^2 was about 1% for typical skeletons which average 0.9–1.2 g/cm^2. The CV for this skeleton was larger than seen for a uniform phantom because slight changes of the bone orientation due to movement lead to alterations of apparent BMD.

Table 2. Inter-unit and intra-unit SD for BMD (g/cm^2) for a spine phantom containing human vertebrae, aluminum spine and femur phantoms, and a total skeleton measured on 65 PRODIGY densitometers

	Inter-unit		Intra-unit
	mean	SD	SD
Spine, human	1.026	0.005	0.002
Spine, aluminum	1.251	0.005	0.003
Femur aluminum	1.175	0.007	0.006
Total body	0.744	0.009	–

Effects of Height above Tabletop

Two sets of independent measurements were made on an encapsulated spine phantom at eight heights ranging from 1.2 to 19.1 cm above the tabletop. The actual average height of the phantom above the table was determined and compared with the values estimated from the scan (Fig. 3a). There was a close correspondence of the two values. Theoretically magnification should produce no change in BMD, while the effects on BMC and area depend on position in the beam (Fig. 3b). However, we observed a small residual effect of object plane on BMD of $\pm$1% compared with the 10 cm object plane (Fig. 3c). This was the result of a slightly greater effect of position on BMC ($\pm$3%) than on area ($\pm$1%). The net result, however, is that BMD can be determined with an uncertainty of under 1% for most patients, and even BMC has an associated uncertainty of only 2% for bones located at tabletop heights of from 5 to 15 cm.

Measurements on Phantoms

Measurements were made on spine phantoms containing encapsulated vertebrae (n = 9) in plastic spanning a range of adult densities from 0.75 to 1.25 g/cm^2. Three measurements were made on each phantom, each of which contained three vertebrae. BMC area, and BMD results with the DPX and PRODIGY were highly correlated (r = 0.99). The regression slope was close to

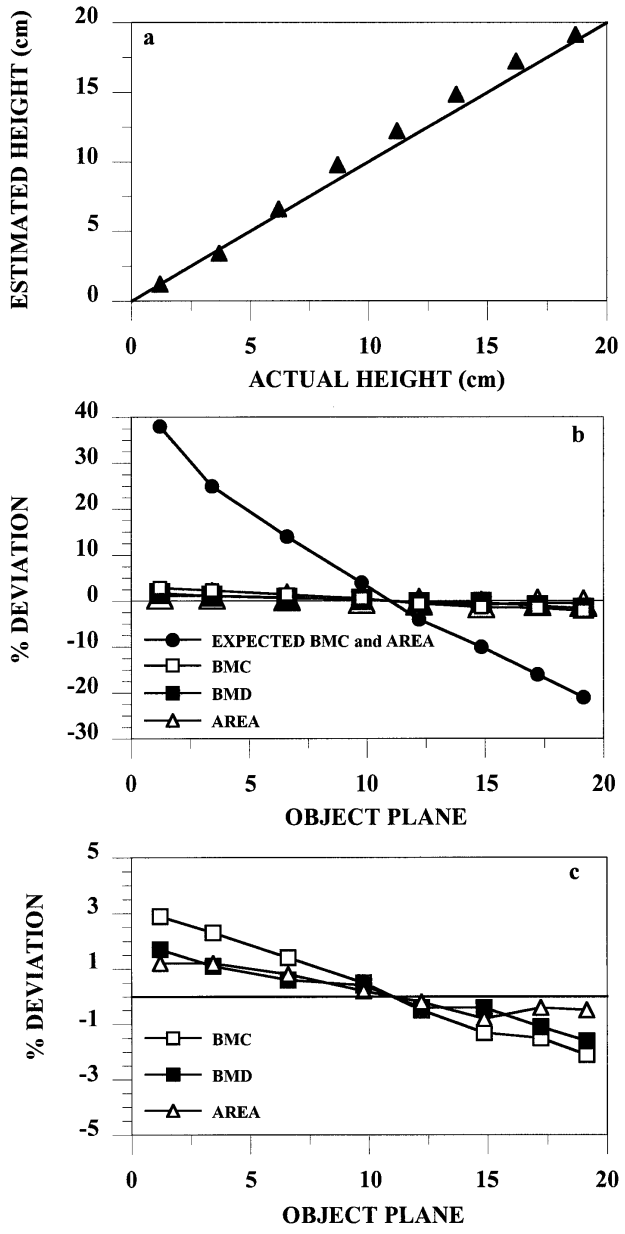

Fig. 3. a Comparison of the estimated height above the tabletop and measured height of a spine phantom. **b** The expected BMC and area change dramatically with height, but after correction for height the observed BMC, area and bone mineral density (BMD) varied slightly (relative to the values at 10 cm height). **c** magnified view of **b** showing the residual effect of object height.

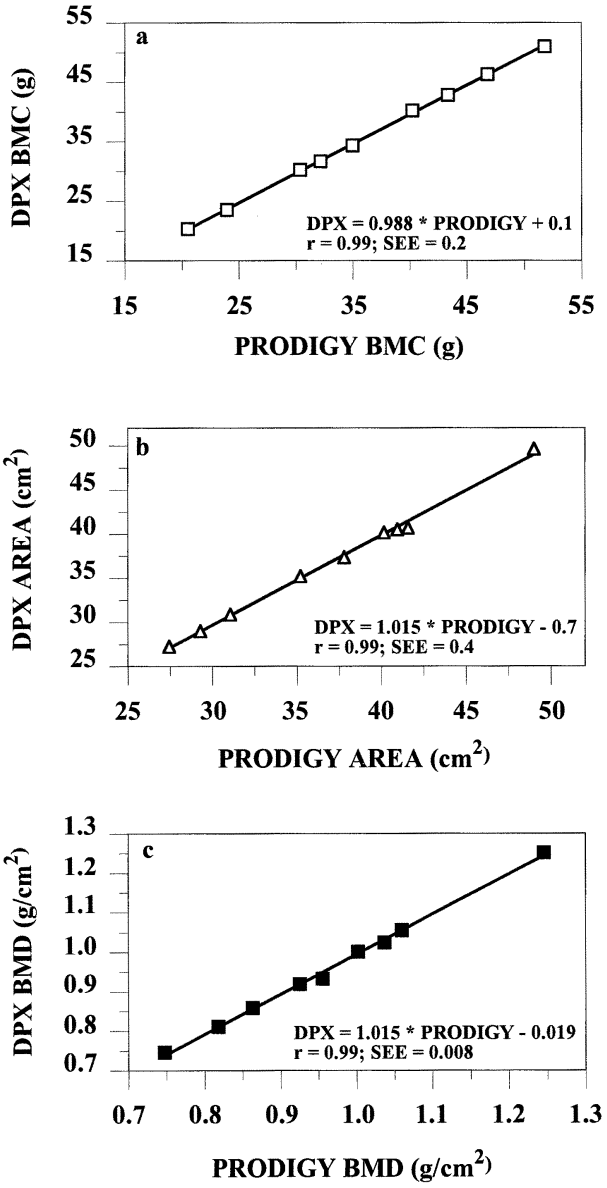

Fig. 4. Relationship between results using vertebral samples (n = 9) on PRODIGY and DPX machines for **a** BMC, **b** area and **c** BMD.

unity, and the SEE was under 1% (Fig. 4). A series of 10 measurements were made using DPX-IQ and PRODIGY densitometers on the ESP. The DPX and PRODIGY results for BMD were similar, and both were above the nominal BMD values (Table 3). The precision of measured BMD was about 0.4% with both densitometers; the precision errors of BMC and AREA were about 0.6%.

Precision In Vitro

Precision was evaluated on one PRODIGY machine that was used routinely for software testing. The short-term precision in vitro was measured on an aluminum phantom encased in a lucite block. A phantom was measured 82 times over a period of 2 weeks with a SD of 0.005 g/cm^2 (0.4%). The long-term precision measured on the same phantom over 8 months was 0.007 (0.5%).

Measurements In Vivo

Measurements were made of the spine and femur on 122 subjects aged 22–81 years. The correlation between DPX

Table 3. Results on the European Spine Phantom with the PRODIGY (n = 10) and DPX-IQ (n = 10) densitometries

Nominal BMD	BMD (g/cm^2)				BMC (g)				Area (cm^2)			
	Prodigy		DPX-IQ		Prodigy		DPX-IQ		Prodigy		DPX-IQ	
	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
Low – 0.5	0.621	0.005	0.610	0.006	5.2	0.04	5.1	0.08	8.4	0.08	8.3	0.11
Medium – 1.0	1.072	0.008	1.095	0.010	10.6	0.10	10.6	0.06	9.9	0.05	9.6	0.06
High – 1.5	1.616	0.013	1.609	0.009	16.8	0.18	16.2	0.10	10.4	0.12	10.1	0.06
Combined	1.136	0.004	1.136	0.005	32.6	0.20	31.8	0.12	28.7	0.17	28.0	0.16

and PRODIGY spine BMD was 0.98 with a SEE of 0.034 g/cm^2. The regression was close to unity with an intercept of only −0.006 g/cm^2 (Fig. 5). There was a similarly high correlation for BMC and area (Table 4). The correlation for femoral neck BMD was 0.98 with a SEE of 0.03 g/cm^2. The regression was close to unity (Fig. 6) with a −0.015 intercept. The results for BMC and area also were similar with both PRODIGY and DPX densitometers (Table 4). The correlation for total femur BMD was 0.99 and the SEE was 0.020 g/cm^2.

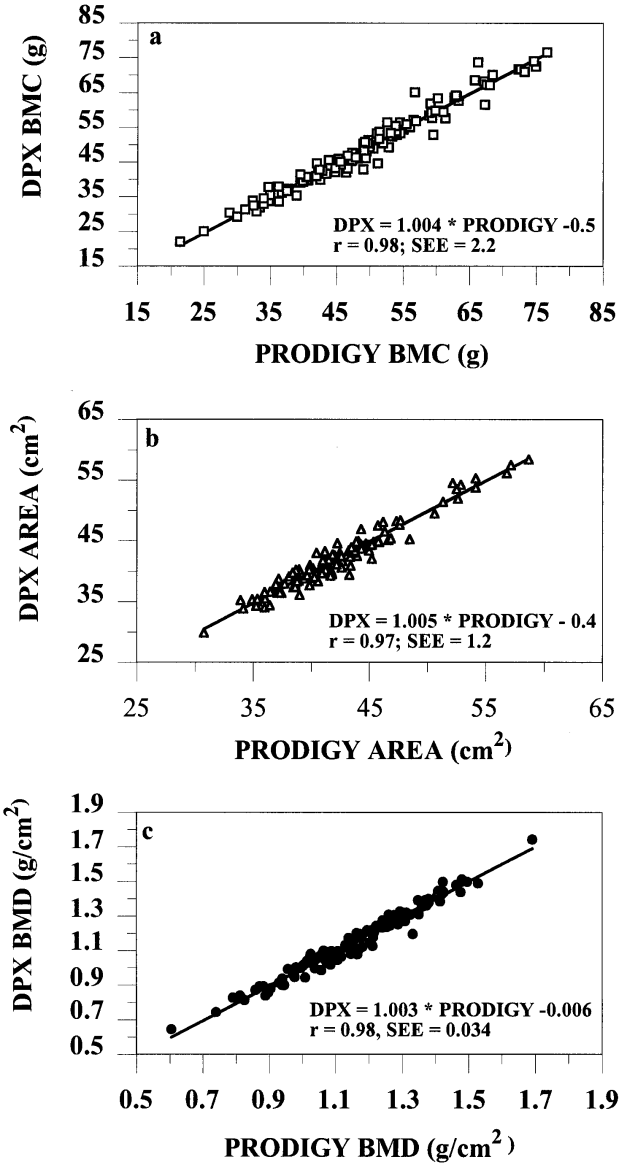

Fig. 5. Relationship between spine results in vivo (n = 122) for **a** BMC, **b** area and **c** BMD.

The short-term precision error for spine BMD from triplicate determinations on 51 subjects was 0.013 g/cm^2 (1.2%) (Table 5). The precision error for total femur BMD in triplicate measurements was 0.008 g/cm^2 (or 0.8%). We examined precision in vivo further by analyzing the influence of BMD on precision error.

Measurements were done 10 times on an isolated skeleton placed on plastic sheets to evaluate the precision of total-body determinations in vitro; the precision error for total-body BMD was 0.004 g/cm^2. The precision of lean tissue mass and of fat tissue mass was approximately 100 g. The precision error assessed by triplicate determinations on 46 subjects in vivo was somewhat larger (0.01 g/cm^2 for total body BMD, and 300 g for lean tissue mass and fat tissue mass) (Table 6). The percentage error for tissue components depends on the amount of lean tissue and fat tissue present, but at typical adult levels the error is under 1% for fat/lean tissue and ∼2% for fat mass.

Measurements were made using the PRODIGY on a variable-composition total-body phantom to assess the percentage fat. There was close correspondence between the observed and nominal values over a full range of fat (Table 7).

PRODIGY total-body scans were compared with DPX scans on 46 subjects. The correlation for total-body BMD was high (r = 0.98) with a regression at unity (Fig. 7). Lean tissue mass and fat mass were also highly correlated (r = 0.99) with the two densitometers, and in each case the slope did not differ significantly (p>0.05) from unity (Fig. 8). The mean value for the total-body bone and soft-tissue variables all were highly congruent with the PRODIGY and DPX densitometers (Table 4).

Discussion

The results presented here confirm that densitometry of the spine, femur and total body with the PRODIGY

Table 4. Mean BMC (g), area (cm^2) and BMD (g/cm^2) for scans in vivo: spine and femur (n = 122) and total body (n = 46)

Site	Variable	PRODIGY		DPX-IQ		r
		mean	SD	mean	SD	
Spine (L2–4)	BMD	1.149	0.189	1.147	0.192	0.98
	BMC	48.93	11.39	48.60	11.63	0.98
	Area	42.28	4.99	42.11	5.17	0.97
Femur (neck)	BMD	0.903	0.163	0.910	0.169	0.98
	BMC	4.45	0.94	4.41	1.00	0.98
	Area	4.92	0.46	4.83	0.44	0.91
Femur (total)	BMD	0.939	0.160	0.942	0.169	0.99
	BMC	30.31	6.21	30.51	6.72	0.99
	Area	32.23	2.82	32.29	2.96	0.97
Total body	BMD	1.184	0.098	1.187	0.100	0.98
	BMC	2603	503	2588	520	0.96
	LTM	43.3	8.4	42.8	8.4	0.99
	% fat	36.3	11.0	36.7	11.1	0.99
	Total	71.5	13.2	71.2	13.2	0.99

LTM, lean tissue mass.

Table 5. Short-term precision error (SD and CV%) for BMD (g/cm^2) in vivo (with repositioning): results for all 51 subjects, and for those below and above the median BMD

	All (n = 51)			Below median (n = 26)			Above median (n = 25)		
	Mean	SD	CV(%)	Mean	SD	CV(%)	Mean	SD	CV(%)
Age	51	17	–	55	16	–	43	16	–
Spine	1.190	0.013	1.0	1.055	0.013	1.2	1.329	0.013	1.0
Femur (total)	1.004	0.008	0.8	0.879	0.007	0.8	1.135	0.009	0.8
Femur (neck)	0.966	0.013	1.4	0.832	0.013	1.5	1.105	0.013	1.2

Table 6. Precision for triplicate total-body scans in vivo on 46 subjects

	mean	SD	% CV
BMC (g)	2594	25	1.0
BMD (g/cm^2)	1.182	0.010	0.8
% fat	41.6	0.5	1.3
Fat mass (kg)	29.3	0.4	1.3
Lean mass (kg)	39.4	0.4	1.0
Tissue mass (kg)	68.7	0.2	0.3
Total mass (kg)	71.3	0.2	0.3

Table 7. Percent fat in the variable-composition phantom

% fat	
Nominal	Observed
43.0	44.2
36.7	37.3
27.1	26.6
20.4	20.3
14.1	13.8

densitometer not only gave BMD results that averaged within about 0.003 g/cm^2 (under 0.5%) to those for the DPX, but gave results for BMC and area that averaged within 1% as well. The SEE was 1% for BMD, BMC and area in vitro (Fig. 4) but was larger for determinations in vivo: 2–3% for BMD, and 3–5% for BMC and area. These SEE values are typical when comparing different DXA densitometers, and it should be noted that the deviation in individual cases can be several times larger than the SEE.

The scan speed of the PRODIGY is 2 to 10 times faster than first-generation DXA densitometers, and comparable to that of second-generation fan-beam instruments [1–3]. Precision is close to 1% in vivo and 0.5% in vitro, and the radiation dose is comparable to that of pencil-beam densitometers. The PRODIGY differs technically in several ways from the DPX. First, the cerium filter is thinner and therefore there is more potential for beam hardening. However, the more sophisticated calibration procedure allows effective dual-energy results to be obtained over a wide thickness range. In addition, because much less of the beam is subtended by each of the CZT elements, the count rate on each is lower than that for the large-area NaI detector,

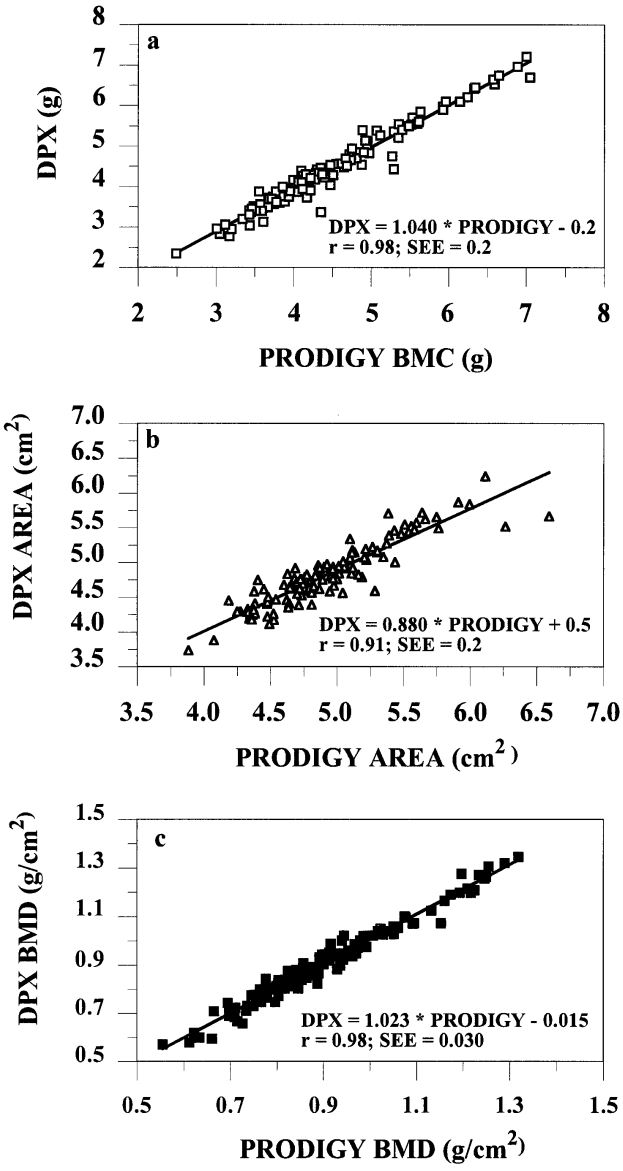

Fig. 6. Relationship between femoral neck results in vivo (n = 122) for **a** BMC, **b** area and **c** BMD.

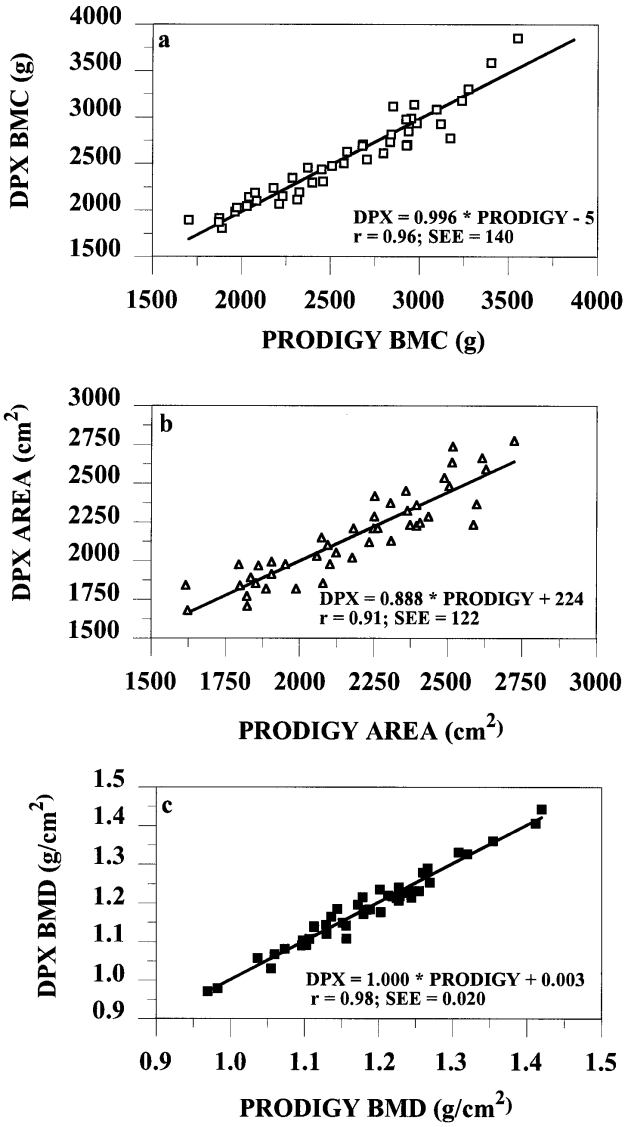

Fig. 7. Relationship between total-body skeletal results in vivo (n = 46) for **a** BMC, **b** area and **c** BMD.

even though the overall count by the detector is high. Nonlinearity of response is compensated for by the calibration scheme of the densitometer as shown in the Results. Second, the PRODIGY uses a fan-beam with resultant magnification of BMC and area depending on the position of the object in the beam. However, the magnification correction produced BMC and area results that varied only slightly with position above the tabletop.

Mean values for BMD obtained on the PRODIGY were within 1% of DPX values both in vitro and in vivo. This is noteworthy because previous studies have shown systematic differences of from 1% to 4% between the pencil-beam QDR-1000 and fan-beam QDR-2000, or QDR-4500 [7–11,21,22]. The PRODIGY results for BMD on the ESP phantom, like the DPX results, were linear, but overestimated the nominal BMD (Table 3). This was expected for the PRODIGY since it utilizes the DPX calibration.

There was little influence of total tissue thickness from 10 to 30 cm on observed results (Table 1). The standard scan mode, therefore, can be used for children, adults and even large adults, given the much wider range of thickness measurable with the PRODIGY compared with the DPX. A slower scan mode (60 s) for spine and femur determinations is recommended for subjects weighing over 90 kg. Short-term precision of the PRODIGY for spine, femur and total-body BMD appears quite comparable to published results for the DPX and DPX-IQ [14,15,20] despite the shorter scan time.

There also was little influence of height of the bone ‘object’ above the tabletop. Fan-beam systems have substantial magnification which has direct effects on estimated BMC and area (about 3% per cm) and may

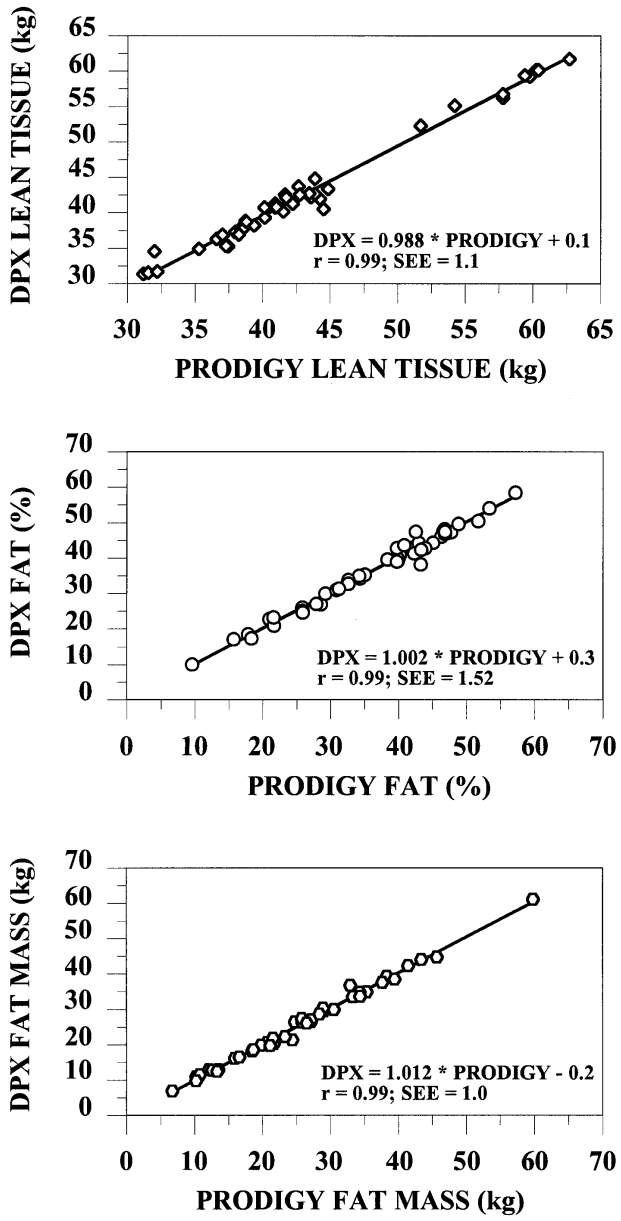

Fig. 8. Relationship between total-body soft-tissue results in vivo (n = 46) for **a** lean tissue mass, **b** % fat and **c** fat mass.

even have some residual effect on BMD [9,22–24]. This also would be the case for the PRODIGY without software corrections for the proper object plane. Fortunately most clinical applications of DXA involve BMD, rather than BMC or area, but in some applications a direct measure of BMC is primary. Pediatric applications often require a measure of regional or total-body BMC, which is then normalized for stature and body weight, rather than projected bone area. Pediatric patients differ widely in body size, and even the same individual changes rapidly over time, so magnification can be a problem. Body composition applications require direct determination of BMC. A similar problem occurs in measuring BMC changes during weight loss or weight gain. Fan-beam systems can provide an estimate of total-body BMC, but results vary with position in the beam. In the case of osteoporosis, a direct measurement of area may prove useful since patients with small bone area at any BMD level preferentially fracture. In addition accurate measurement of hip axis length requires correction for magnification [23,24].

The unique geometry of the PRODIGY with the fan-beam along the long axis eliminates problems of positioning that are associated with conventional fan-beam densitometers oriented perpendicular to the body axis. The latter require careful positioning of the spine and femur in the beam, and scout scans are needed for localization. In the case of the PRODIGY, the software automatically located the bone and centered the scan field around the bone so that no scout scans were needed.

Our study shows that rapid densitometry can be achieved with a narrow-angle fan-beam, and that the energy-sensitive detector allows this to be attained with a radiation dose comparable to pencil-beam densitometry. The BMD results for regional and total-body scans on the PRODIGY were comparable to DPX values. Moreover, the magnification correction of BMC and area results to a fixed object plane allowed these variables to be directly comparable to DPX values.

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