Calcif Tissue Int (2000) 67:291–296
DOI: 10.1007/s002230001147

Calcified Tissue International

Evaluation of Differences Between Fan-Beam and Pencil-Beam Densitometers

R. B. Mazess, H. S. Barden

Lunar Corporation, 726 Heartland Trail, Madison, Wisconsin 53717, USA

Received: 23 February 2000 / Accepted: 14 April 2000 / Online publication: 27 July 2000

Abstract. We compared the bone and body composition results *in vivo* on two bone densitometers using fan-beam geometry (*EXPERT* and PRODIGY) with those using pencil-beam geometry (DPX). Measurements were made on large groups of adults ranging in weight from about 50 to 120 kg. Both spine and femur neck BMD on the fan-beam densitometers averaged within 1% of the pencil-beam results, and there was no magnitude dependence of the results by Bland-Altman analysis. Total body BMC and BMD on the PRODIGY and DPX were congruent, but on the *EXPERT*, BMC was about 2% lower and BMD 2% higher than corresponding values on the DPX. Soft-tissue composition was closely congruent for the PRODIGY and DPX; the comparable *EXPERT*-DPX differences showed greater scatter but no significant magnitude dependence. The smaller fan-angle of the PRODIGY (4°) probably contributed to its better congruence to pencil-beam results compared with the *EXPERT* (12°).

Key words: Densitometry — X-ray — Bones — Osteoporosis — Body composition

We have previously reported on the performance characteristics (speed, radiation dose, effects of thickness, and distance from table top) of a new fan-beam densitometer, PRODIGY (Lunar Corporation, Madison, WI), and examined the bone and body composition results compared with a pencil-beam device, the DPX-IQ, from the same manufacturer [1]. The PRODIGY is a narrow-angle (4°) fan-beam densitometer that uses dual-energy X-ray absorptiometry (DXA) for bone and body composition. The array detector uses dose-efficient, energy-sensitive cadmium zinc telluride; this enables rapid scanning (30 seconds for spine and femur and 4 minutes for total body). The dose is only slightly higher than that for a conventional pencil-beam (Table 1), rather than 10X higher as with other fan-beam densitometers. The narrow fan angle eliminates beam distortions at the ends of the beam path, and the software corrects for magnification based on either the actual object plane or an assumed object plane [1]. As a consequence, objects placed in the beam at different heights above the table-top produce invariant results for bone and body composition. We observed that the average values for BMC and BMD for spine, femur, and total body were almost identical with the PRODIGY and DPX-IQ, and soft-tissue components from total body scans were also highly correlated (r = >0.95), and had almost identical mean values [1]. Several earlier comparisons of fan-beam and pencil-beam DXA instruments have suggested that there were small (<3%), but occasionally significant, differences between them [2–7]. Moreover, Ellis and Shypailo [7] and Bouyoucef et al. [5] have previously shown that the large-angle (30°) fan-beam devices from another manufacturer (QDR from Hologic, Waltham, MA) had systematic differences from the pencil-beam densitometers that were dependent on the magnitude of the variable measured. Since we did not examine this "magnitude dependence" in our original publication, we performed Bland-Altman analyses [8] to ascertain if there were any systematic influences of the measured variables on PRODIGY results. We also compared BMD measurements with the *EXPERT-XL* densitometer (Lunar Corp.) to those using the DPX; the *EXPERT-XL* has a wider fan-beam angle (12°) than the PRODIGY. The *EXPERT-XL* uses scintillators coupled to photodiodes rather than cadmium zinc telluride, and the radiation dose is around 10x higher than that for the DPX or PRODIGY (Table 1). This higher dose is characteristic of photodiode-based fan-beam arrays, and is especially pronounced for total body scans (the usual 100x dose reduction compared with spine/femur scans cannot be achieved because a higher signal is needed to overcome the noise-floor of photodiodes).

Table 1. Comparison of scan speed and dose for the three types of densitometers used in this study

	DPX [9]	PRODIGY [1]	EXPERT
Fan-beam angles	0	4°	12°
Time (Seconds)			
Spine	60	30	6
Femur	100	30	6
Total body	550	240	240
Dose (μSv)			
Spine	2.4	3.7	26
Femur	2.4	3.7	26
Total body	0.01	0.04	10

Methods

As previously described [1], spine and femur scans were done on 122 subjects, on both the PRODIGY and DPX-IQ densitometers at

Correspondence to: R. B. Mazess

Table 2. PRODIGY-DPX differences

Variable	n	Mean values		Difference		Regression of the difference (y) versus average value (x)		
		PRODIGY	DPX	Mean	SD	Slope	Intercept	R^2
Spine BMD	122	1.149	1.147	0.002	0.03	−0.019	0.02	0.012
Femur neck BMD	122	0.903	0.910	−0.006	0.03	−0.039	0.03	0.046
Total body BMD	49	1.182	1.188	−0.006	0.020	−0.018	0.02	0.006
Total body BMC (g)	49	2580	2570	10	133	−0.029	84	0.011
Total body LTM (kg)	49	42.8	42.4	0.40	1.07	0.009	0.01	−0.005
Total body FTM (kg)	49	24.5	24.6	−0.08	1.04	−0.022	0.45	0.057
Total body %Fat	49	35.3	35.5	−0.21	1.6	−0.022	0.57	0.025

two facilities (Lunar and University of Wisconsin). There were 18 males and 104 females ranging in age from 20 to 81 years. In addition, total body measurements were done on the 46 subjects described in our earlier publication, plus an additional 3 smaller subjects (~50 kg) so that weight ranged from 48 to 118 kg (10–60% fat). Duplicate spine and femur scans were done on the PRODIGY, and the average results were used and compared with single DPX scans. Triplicate PRODIGY scans were done for total body determinations, and for 51 of the 122 subjects for spine and femur; the average values were used in these cases. Both bone mineral content (BMC in g) and bone mineral density (BMD in g/cm^2) were measured in total body scans (n = 49). Several soft-tissue variables from the total body scans were evaluated, including lean-tissue mass (LTM in kg), fat-tissue mass (FTM in kg), and percentage fat content (%FAT) [10].

In addition, measurements were made of spine BMD (n = 736) and femur neck BMD (n = 272) on the DPX and *EXPERT-XL* densitometers. Total body scans for bone and body composition were done on a total of 172 adults from 30 to 80 years of age (weight 33–90 kg; % fat 10–52%). Results were obtained at the Lunar facility itself, and at 10 other research sites (see Acknowledgments). There was no attempt to intercalibrate the *EXPERT* or DPX densitometers among centers, but all were producing results appropriate to the initial factory calibration using the phantom supplied with each densitometer. The studies were approved by the relevant Institutional Review Boards and subjects signed informed consents.

Bland-Altman analyses [8] were done by examining the difference between fan-beam (PRODIGY or *EXPERT*) and pencil-beam (DPX) results in relation to the average value of the variable measured. The pencil-beam results were considered the reference method. A detailed Bonferroni correction was not made to compensate for multiple comparisons, but a conservative level of significance ($P < 0.02$) was used.

Results

Table 2 outlines the statistical relationship of the PRODIGY-DPX difference to the measured variable. Table 3 shows the *EXPERT-DPX* differences in relation to the measured variable. The mean PRODIGY-DPX differences were generally small (<1% relative to the mean value) for both BMD and composition variables. The standard deviation of these differences was about 2–3% relative to the mean BMD, and the mean LTM or FTM. The *EXPERT*-DPX differences for spine and femur BMD were also small. Total body BMD with the *EXPERT* averaged almost 2% higher than the DPX value, and total body BMC was 2% lower ($P < 0.001$ by paired *t*-test). The SDs of the *EXPERT*-DPX differences were higher relative to the mean value (3–5%) than those for the PRODIGY-DPX differences. Also, the SDs for body composition variables (LTM, FTM, %FAT) were twice as large with *EXPERT* compared with PRODIGY. Less than 5% of the variance (R^2) of PRODIGY-DPX or *EXPERT*-DPX differences was associated with the measured variable, and the regression slopes were not significant.

Figures 1, 2, and 3 show the Bland-Altman plots of differences between fan-beam and pencil-beam results versus average BMD of the spine, femur, and total body. In each case, the slope of the regression line was close to zero. There was no systematic effect of the variable measured, and no significant offset (except for the offsets of total body BMC and BMD with the *EXPERT* noted above). Figures 4 and 5 show the LTM and FTM results. Again there was no significant effect of the measured LTM or FTM on the results and no offset from the expected, although LTM with *EXPERT* showed a nonsignificant trend toward underestimation at LTM values >50 kg. Figure 6 examines the same relationships for %FAT. Again there was no offset from the expected and no systematic effect on the measured variables. All *EXPERT*-DPX results showed increased scatter around the regression lines compared with PRODIGY-DPX results as shown by the SD of the differences (Tables 2 and 3).

Discussion

We found little overall difference between the two fan-beam densitometers and the pencil-beam densitometer for spine, femur, and total body BMD. The only notable disparity was a higher (0.018 g/cm^2 or 2%) total body BMD on the *EXPERT* than the DPX. The close correspondence suggests that users of older DPX densitometers could upgrade to the fan-beam counterparts with little difficulty, at least for routine clinical bone densitometry. The reported average differences in BMD are small for other fan-beam densitometers as well [2–7]. Three reports [3–5] showed that the mean spine and femur neck BMD with the QDR-2000 in fan-beam mode, or the QDR-4500, which has only a fan-beam mode, were within 1% of pencil-beam results; surprisingly, however, the total femur BMD was systematically overestimated by 1–3% on the QDR-4500 [3, 5]. The congruence of BMD in fan-beam and pencil-beam densitometers is due to the fact that magnification effect of fan-beams influences area and BMC equally and hence does not influence BMD. Typical magnification with fan-beam densitometers is ~3%/cm for BMC and area, but under 0.5%/cm for BMD [1, 4, 11].

Table 3. *EXPERT*-DPX differences

		Mean values		Difference		Regression of the difference (y) versus average value (x)		
Variable	n	*EXPERT*	DPX	Mean	SD	Slope	Intercept	R^2
Spine BMD	736	1.063	1.065	−0.002	0.05	0.032	−0.04	0.017
Femur neck BMD	272	0.846	0.851	−0.006	0.03	0.033	−0.03	0.017
Total body BMD	172	1.099	1.082	0.018[a]	0.032	0.026	−0.01	0.006
Total body BMC (g)	172	2094	2133	−38[a]	114	−0.061	91	0.041
Total body LTM (kg)	172	37.8	37.7	0.07	2.82	−0.071	2.74	0.031
Total body FTM (kg)	172	22.3	22.5	−0.21	2.64	0.026	−0.79	0.005
Total body %Fat	172	36.4	36.8	−0.41	4.35	−0.029	0.66	0.003

[a] Significant at $P < 0.001$

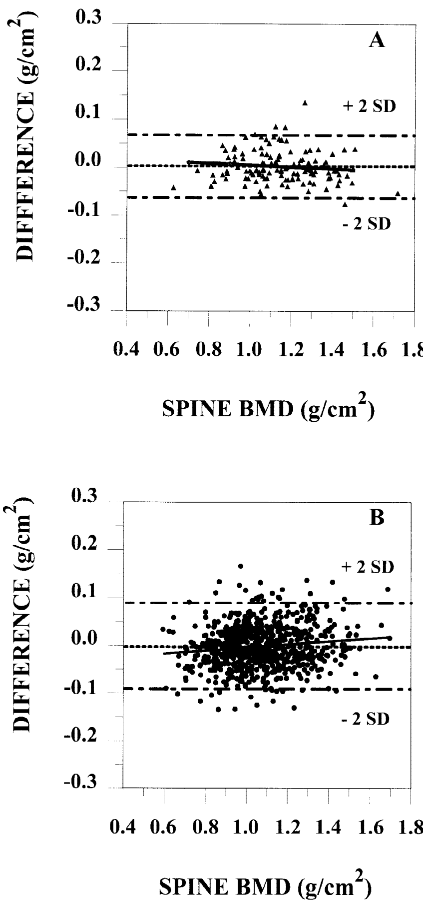

Fig. 1. PRODIGY-DPX differences **(A)** and *EXPERT*-DPX differences **(B)** versus average spine BMD.

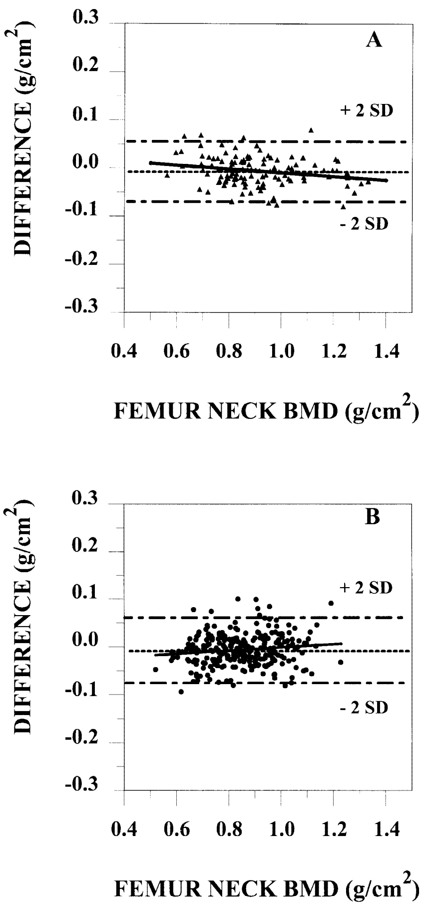

Fig. 2. PRODIGY-DPX differences **(A)** and *EXPERT*-DPX differences **(B)** versus average femur neck BMD.

The above results address only the mean offset of values, and not magnitude-dependent trends. We found no magnitude dependence of BMD results for either the *EXPERT* or PRODIGY fan-beam densitometers. The correspondence of the *EXPERT* and PRODIGY with the pencil-beam DPX over a wide range of values may reflect both software adjustments and their narrow fan angles (12° and 4°, respectively). Bouyoucef et al. [5] reported that the QDR-4500 overestimated spine and femur neck BMD at low values (by about 3%) and underestimated it at high values (by almost 5% at 1 g/cm^2). This magnitude dependence could become important in relation to patient evaluations because it decreases the range between normal and abnormal by about 5–8% on the average, or the equivalent of about 0.5 SD in T-score.

The total body results with PRODIGY are reassuring for those clinicians and researchers who are interested in measuring BMC or BMD over a wide range of physiognomy. Total body BMD with the *EXPERT*, however, was systematically overestimated by ~2%, and BMC was underesti-

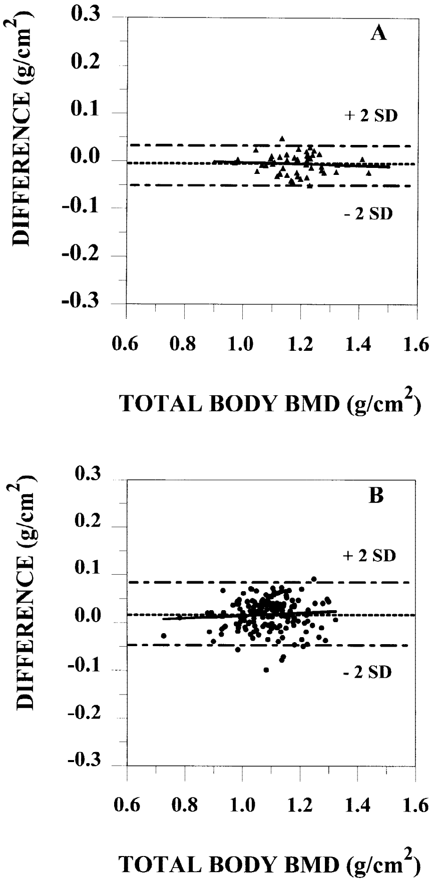

Fig. 3. PRODIGY-DPX differences **(A)** and *EXPERT*-DPX differences **(B)** versus total body BMD.

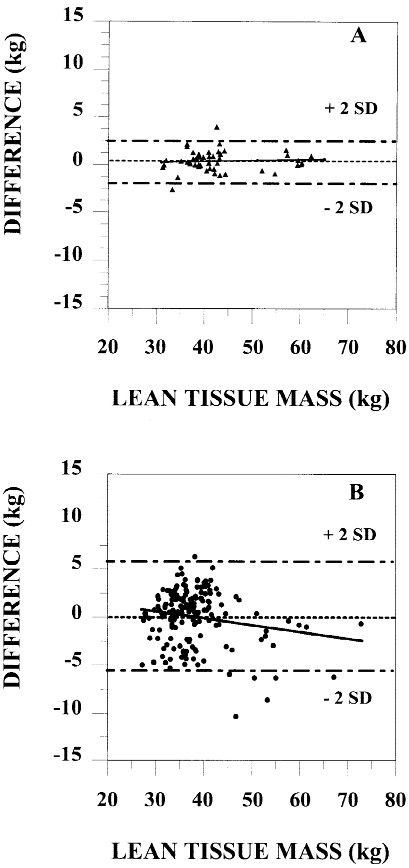

Fig. 4. PRODIGY-DPX differences **(A)** and *EXPERT*-DPX differences **(B)** versus average lean tissue mass.

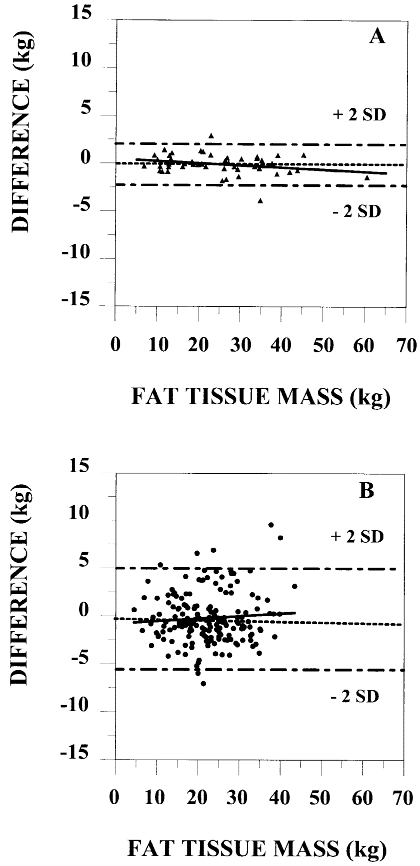

Fig. 5. PRODIGY-DPX differences **(A)** and *EXPERT*-DPX differences **(B)** versus average fat tissue mass.

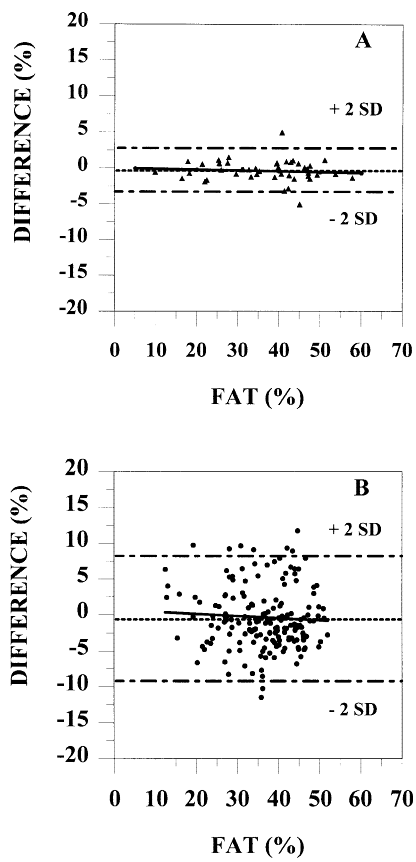

Fig. 6. PRODIGY-DPX differences **(A)** and *EXPERT*-DPX differences **(B)** versus percent fat content.

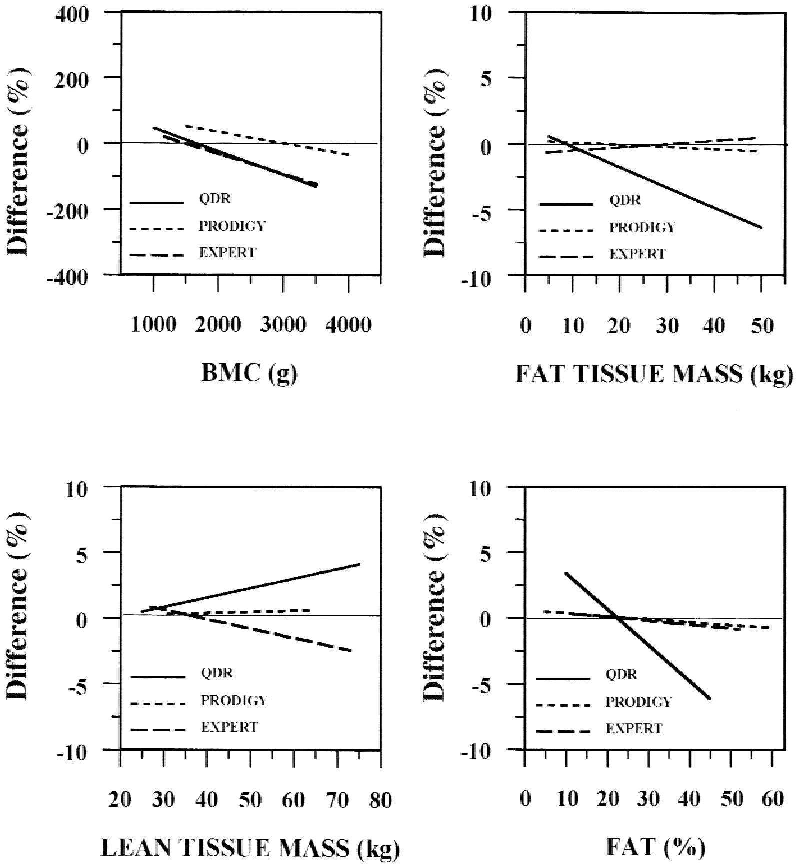

Fig. 7. Differences between fan-beam and pencil-beam densitometers versus average results for PRODIGY-DPX (-), *EXPERT*-DPX (--), and for the QDR2000 (----); the latter results from Ellis et al. [7].

mated compared with the DPX value. These differences reflected the difficulty of measuring low-density bone with the *EXPERT* because of its low contrast at the higher energy used in this device. The PRODIGY-DPX difference for soft-tissue variables also had low scatter. In contrast, the *EXPERT*-DPX differences for soft-tissue variables averaged 2.6X greater than PRODIGY-DPX differences. This probably reflects differential magnification and distortions inherent with the wider-angle beam of the *EXPERT* compared with the PRODIGY. Clinical concerns about body composition often relate to thin, cachexic patients or to overweight patients.

Our results suggest that the PRODIGY provides accuracy comparable to that of a standard pencil-beam device for subjects in this study (48 to 118 kg) measured in the standard adult mode. We did not test the special "thin" modes of the PRODIGY and *EXPERT* that are used for smaller subjects, or slower modes used for thick subjects. There did appear to be some magnitude dependence for the *EXPERT* in measuring BMC and LTM, even though the trends were not significant. Ellis and Shypailo [7] reported a magnitude dependence for LTM using the QDR-2000 densitometer in fan-beam mode, as well as underestimation of FTM (Fig. 7). The underestimation of FTM and overestimation of LTM, reported using wide-angle fan-beam densitometers [12–14], could be due to magnification effects, and/or to beam divergence. Diessel et al. [15] showed that body composition results with the QDR-4500 were highly dependent on position of fat and lean tissue in the divergent fan-beam; these discrepancies were eliminated when only the central beam was measured. We could not examine the effect of beam divergence with the PRODIGY or *EXPERT* because the fan-angles were so narrow.

In conclusion, there did not appear to be either clinically important offsets or magnitude dependence for spine, femur, or total body results with the PRODIGY and *EXPERT* densitometers. There did appear to be an offset of the *EXPERT* for bone measurements, as well as scatter for soft-tissue variables; the latter confirms theoretical expectations that as the fan-angle increases, total body composition results become more uncertain.

The authors are employees of Lunar Corporation, the manufacturer of the bone densitometers used in this study.

Acknowledgments. We gratefully acknowledge the help of Russ Nord, Wynn Wacker, and Don Settergren in the collection and analysis of data. In addition, many investigators provided comparative data for the project, including:

1. Carmelo A. Formica and Robert Lindsay, Helen Hayes Hospital, West Haverstraw, NY
2. Michael A. Wilson, University of Wisconsin, Madison, WI
3. Edward Gotti, St. John's Hospital, Springfield, MO
4. Luis del Rio, CENTIR, Barcelona, Spain
5. Sergio Ragi-Eis, SEDOES, Vitoria, Brazil
6. Nick Pocock, St. Vincent's Hospital, Sydney, Australia

7. Patrick Butler and Richard Smart, St. George's Hospital, Sydney, Australia
8. Barry Chatterton, Royal Adelaide Hospital, Adelaide, Australia
9. Ian Reid, University of Auckland, Auckland, New Zealand
10. Carlos Mautalen and Alicia Bagur, Centro de Osteopatias Medicas, Buenos Aires, Argentina
11. Michael Hooper, Concord Hospital, Sydney, Australia
12. Kazuhiro Kushida and Kaoru Yamazaki, Hamamatsu University, Japan

References

1. Mazess RB, Hanson JA, Payne R, Nord R, Wilson M (2000) Axial and total body bone densitometry using a narrow-angle fan-beam. Osteoporos Int 11:158–166
2. Abrahamsen B, Gram J, Hansen TB, Beck-Nielsen H (1995) Cross-calibration of QDR-2000 and QDR-1000 dual-energy x-ray densitometers for bone mineral and soft-tissue measurements. Bone 16:385–390 DOI: 10.1016/8756-3282(94)00054-9
3. Barthe N, Braillon P, Ducassou D, Basse-Cathalinat B (1997) Comparison of two Hologic DXA systems (QDR 1000 and QDR 4500/A). Br J Radiol 70:728–739
4. Blake GM, Parker JC, Buxton FMA, Fogelman I (1993) Dual x-ray absorptiometry: a comparison between fan beam and pencil beam scans. Br J Radiol 66:902–906
5. Bouyoucef SE, Cullum ID, Ell PJ (1996) Cross-calibration of a fan-beam x-ray densitometer with a pencil-beam system. Br J Radiol 69:522–531
6. Franck H, Munz M, Scherrer M (1997) Bone mineral density of opposing hips using dual energy x-ray absorptiometry in single-beam and fan-beam design. Calcif Tissue Int 61:445–447 DOI: 10.1007/s002239900365
7. Ellis KJ, Shypailo RJ (1998) Bone mineral and body composition measurements: cross-calibration of pencil-beam and fan-beam dual-energy x-ray absorptiometers. J Bone Miner Res 13:1613–1618
8. Bland JM, Altman DG (1986) Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1:307–310
9. Mazess RB, Chesnut CH III, McClung M, Genant H (1992) Enhanced precision with dual-energy x-ray absorptiometry. Calcif Tissue Int 51:14–17
10. Mazess RB, Barden HS, Bisek JP, Hanson HA (1990) Dual-energy x-ray absorptiometry for total-body and regional bone-mineral and soft-tissue composition. Am J Clin Nutr 51:1106–1112
11. Pocock NA, Noakes KA, Majerovic Y, Griffiths MR (1997) Magnification error of femoral geometry using fan beam densitometers. Calcif Tissue Int 60:8–10 DOI: 10.1007/s002239900177
12. Fuerst T, Genant HK (1996) Evaluation of body composition and total body bone mass with the Hologic QDR-4500. Osteoporos Int 6(suppl):202
13. Visser M, Fuerst T, Lang T, Salamone L, Harris TB (1999) Validity of fan-beam dual-energy x-ray absorptiometry for measuring fat-free mass and leg muscle mass. J Appl Physiol 87:1513–1520
14. Modlesky CM, Evans EM, Millard-Stafford ML, Collins MA, Lewis RD, Cureton KJ (1999) Impact of bone mineral estimates on percent fat estimates from a four-component model. Med Sci Sports Exerc 31:1861–1868
15. Diessel E, Fuerst T, Njeh CF, Genant HK (1998) In vitro studies of the effect of fan beam geometry on DXA body composition. Osteoporos Int 8:511