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Evaluation of Dual-Energy X-Ray Absorptiometry Bone Mineral Measurement—Comparison of a Single-Beam and Fan-Beam Design: The Effect of Osteophytic Calcification on Spine Bone Mineral Density

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Abstract. Dual energy X-ray absorptiometry (DXA) using a single-beam (SB) design is a well-established procedure for measuring bone mineral area density (BMD). Recently, fan beam (FB) techniques have become available to measure BMD. We evaluated the QDR1000 and QDR2000 densitometers with regard to precision and cross-compared values using single beam (SB) and FB techniques. To study the effect of osteoarthritic changes on bone measurement (BMC in g) and bone mineral area density (BMD in g/cm^2), both parameters were measured in patients with and without osteophytic calcifications (OC) of the lumbar spine. Precision errors for BMD *in vitro* over 1 and 6 months using the QDR2000 were 0.4% and 0.6% for SB and 0.5% and 0.7% for the three FB modes. For QDR1000 only SB is available. Using this scan mode, the BMD difference (δ = 0.1%) *in vitro* between QDR1000 and QDR2000 was not significant. The short-term (same day) reproducibility of BMD *in vivo* was 0.85% for SB mode and 1.1% for FB scan mode (n = 33). The midterm (1 month) precision errors were 0.9% for SB and 1.5% for FB (n = 11). The spine BMD of 751 patients from our outpatient clinic and department of rheumatology was 1.7% lower with FB than with SB (0.878 ± 0.137 versus 0.888 ± 0.146 g/cm^2). Lower (1.8%) BMD values were also found in the hip with FB compared to SB (0.805 ± 0.111 versus 0.821 ± 0.111 g/cm^2). There was a highly significant ($P < 0.00001$) correlation between SB and FB on the spine (r = 0.99) and hip (r = 0.98) using the QDR2000. Correlations found QDR1000 and QDR2000 were lower on the spine (r = 0.97) and hip (r = 0.93). In contrast to hip BMD, spine BMD was significantly higher in women (n = 78) with OC (FB: 0.894 ± 0.134 g/cm^2, SB: 0.900 ± 0.140 g/cm^2) than in normals (n = 148) (FB: 0.844 ± 0.130 g/cm^2, SB: 0.865 ± 0.140 g/cm^2) ($P < 0.05$). The FB mode provides reproducible data *in vitro* and *in vivo*, though not as precise as SB. FB results *in vivo* are 1–2% lower than FB results, even with identical results *in vitro*. Women with OC present with higher BMD values in spine scans than normals.

Key words: Osteophytic calcifications — DXA — Single beam — Fan beam.

Over the years a variety of techniques for determining bone mineral density has been developed and used clinically [1]. Besides single photon absorptiometry, dual photon absorptiometry (DPA), and quantitative computed tomography, dual energy X-ray absorptiometry (DXA) has been widely used. DXA is considered to be one of the most accurate and sensitive methods for assessing bone loss at different sites, especially vertebral bodies [2–4]. Most DXA systems now commercially available use single beam (SB) systems that require 2–10 minutes to measure bone mineral area density (BMD in g/cm^2) of the lumbar spine. Recently, multiple detector systems (fan beam, FB) have been developed [5] by several manufacturers (Aloka, Hologic, Lunar and Sopha) to reduce data acquisition time.

The present study was performed to evaluate some characteristics of a new DXA system working in both SB and FB modes.

Materials and Methods

Characteristic Features of the Multiple Detector DXA System with Fan Beam Design

The SB and FB designs of the QDR2000 (Hologic, Inc., Waltham, MA, USA), includes an X-ray-generator, providing continuous X-ray output at two different levels of energy (70 KVp and 140 KVp). The FB width is 10.8–15.3 cm, depending on the area measured. The apparatus can be used to determine the BMD and bone mineral content (BMC in g) of any part of the body. The principle of BMD measurement with the QDR2000 is essentially the same as that with the QDR1000. An advantage of the QDR2000 is its ability to measure rapidly. The detector array uses a line of 31 $CDWO_4$ detectors (2 cm × 1 cm in size). The source slit width and length are 0.5 × 65 mm for FB compared with 2.2 mm circular hole for SB. The corresponding width and length of the detectors are 2.0 × 43.7 cm and 2.25 × 4.2 cm, respectively. Scans of the lumbar spine and hip were analyzed using the manufacturer's standard software.

Precision of BMC and BMD in Vitro *with SB and FB-DXA*

The reproducibility of BMC and BMD determinations over 1 and 6 months were estimated with a Hologic anthropomorphic spine phantom (QDR2000). Both slow (3 minutes) and various fast (array: medium 2 minutes, fast 1 minute) scan modes were employed in FB; only one mode was employed in SB design (7–8 minutes). The BMC and BMD were determined and the coefficients of variation (CV%) were calculated dividing the standard deviation (SD) by the mean.

Furthermore, the BMD and BMC values *in vitro* of QDR1000 and 2000 (Hologic anthropomorphic spine phantom, QDR1000) were cross-compared using SB mode.

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Table 1. Precision *in vitro* of BMC and BMD (Hologic anthopomorphic spine phantom) with single and fan beam

			Single beam		Fan beam Slow, medium, fast		
	Period	QDR1000[1]	QDR2000[2]	QDR2000[1]	QDR2000[2]		
BMD	1 month	0.29%	0.42%	0.50%	0.58%	0.48%	0.49%
	6 months	0.30%	0.58%	0.59%	0.67%	0.58%	0.68%

[1] Using QDR1000 phantom
[2] Using QDR2000 phantom

Study in Vivo

Short-term precision errors of BMC and BMD measurements of the lumbar spine in FB (medium array) and SB were assessed in 33 normal individuals (mean age 54.3 ± 7.4 years) on the QDR2000. Each individual was scanned twice on the same day with repositioning between the scans. The same measurements were performed to assess midterm precision errors in 11 healthy volunteers (mean age 54.7 ± 3.5 years) once at baseline and after 4 weeks. For reliable assessment of the precision error, the 'compare' feature of the analysis software of the repeated scans was not used. The CV was calculated according to Slosman et al. [6].

Cross-comparison of QDR1000 and 2000 Scanning (SB) Hip and Lumbar Spine

The QDR1000 and QDR2000 densitometer were compared scanning 144 patients (125 women mean age 55.6 ± 6.1, 19 men mean age 51.5 ± 8.3 years from our outpatient clinic and department of rheumatology and osteoporosis) on the same day in the lumbar spine and hip using SB technique.

Comparison of SB and FB with QDR2000

To evaluate and compare SB and FB techniques, the lumbar spines of 751 patients (664 females, mean age 55.2 ± 7.2 and 77 males, mean age 54.2 ± 5.7) and the hip of 173 patients (151 females, mean age 55.2 ± 6.5 and 22 males, mean age 55.9 ± 5.3 years, from our outpatient clinic and department of rheumatology and osteoporosis) were scanned by SB and FB mode. Medium and fast array FB were used for lumbar spine and hip; slow array was available only for lumbar spine.

BMD and BMC in Normals and Patients with Osteophytic Calcification

The lumbar spine and the hip were measured in normals (n = 148 women, mean age 54.1 ± 6.1 years) and women with osteophytic calcification (OC) of the spine (n = 78 women, mean age 56.3 ± 6.1 years). These patients had anterior-posterior and lateral lumbar spine radiographs performed within several days one month of bone density measurement. In each subject, all vertebrae were identifiable. The control and the patient group had no evidence of clinical, laboratory, or radiological bone-related disease except for osteopenia or OC in the OC group. Especially, they had no fractures of the spine, hip, or wrist. Patients were assigned to the OC group by a rheumatologist and radiologist (joint session), if having osteophytic calcification (grade 1 to 3 according to Orwoll et al. [7]. Patients (n = 13) with vascular calcification > grade 1 [7] were excluded from the study. Patients with OC were also included in the SB/FB and QDR1000/QDR2000 study.

Results

Results in Vitro

Precision errors *in vitro* of BMC and BMD by FB and SB with the QDR2000 phantom are listed in Table 1. The 1 and 6 months precision errors of the SB scans were lower on QDR1000 than QDR2000 and better than FB on QDR2000. Even faster FB scan modes showed precision ≤1.0%.

The comparison of 1 month precision errors of the two densitometers resulted in mean (±SD) BMD of 1.033 g/cm² ± 0.03 (CV: 0.29%) on the QDR1000 and 1.032 g/cm² ± 0.05 (CV: 0.5%) on the QDR2000 densitometer (δ = 0.1%). The 6 months SB precision error of BMD was 0.30% for QDR1000 and 0.59% for QDR2000 (Table 1).

Table 2. Linear regression predicting FB from SB with correlation coefficients (r) and standard errors of estimate (SEE) for spine of 751 and the hip BMD of 173 subjects

Site	Scan mode	r	SEE	Intercept	Slope
Spine	Slow	0.96	0.041	0.081	0.90
	Medium	0.99	0.019	0.033	0.95
	Fast	0.95	0.043	0.059	0.92
Hip	Medium	0.98	0.019	0.007	0.97
	Fast	0.99	0.019	0.012	0.95

Results in Vivo

The short term reproducibility of BMD values was 0.85% for SB and 1.10% for FB scan mode (medium array) of the lumbar spine L2–L4. There was a significant ($P < 0.05$) difference in midterm precision errors for SB and FB (0.9% versus 1.5%).

Spine BMD and BMC for 166 subjects in SB mode were not significantly ($P > 0.05$) different (δ = 0.9%) for QDR2000 (BMD: 0.903 ± 0.18 g/cm²) and QDR1000 (BMD: 0.911 ± 0.17 g/cm²) (BMC: QDR2000 42.7 ± 10.7, QDR1000 42.9 ± 10.5 g). The BMD of the total hip was similar with the two densitometers (QDR2000: 0.900 ± 0.137 g/cm², QDR1000: 0.910 ± 0.130 g/cm²) using SB design also.

We found a significant correlation ($r = 0.97$, $P < 0.001$) between spine BMD measured by QDR1000 and QDR2000 in SB mode. Again, this was also true for the BMD measurements of the total hip ($r = 0.93$, $p < 0.001$) in SB mode.

The comparison of SB and FB in 751 patients (664 women and 77 men) resulted in significantly ($P < 0.05$, δ = 1.7%) higher spine BMD (0.888 ± 0.146 g/cm², BMC: 41.7 ± 9.1 g) for SB than for FB (0.878 ± 0.137 g/cm², BMC: 40.6 ± 9.2 g, slow scan mode). Again, similar differences (δ = 1.8%) were obtained for the total hip (SB: 0.821 ± 0.111 g/cm², BMC: 30.8 ± 7.1; FB (0.805 ± 0.111 g/cm², BMC: 29.7 ± 6.6 g, medium array).

Values of femoral neck, trochanteric and Ward's triangle were consistently lower for FB than for SB.

There were highly significant correlations (lumbar spine $r = 0.99$, $P < 0.00001$, for both women and men; hip $r = 0.98$,

Table 3. BMD of BMC (QDR 2000) of L2–L4 spine and total hip in patients with (n = 78) and without (n = 148) osteophytic calcification (OC)

	Spine		Hip	
	SB	FB	SB	FB
BMD (g/cm^2) in patients without OC	0.865 ± 0.14	0.844 ± 0.13	0.805 ± 0.11	0.792 ± 0.11
BMD (g/cm^2) in patients with OC	0.900 ± 0.14[a]	0.894 ± 0.13[a]	0.820 ± 0.09	0.804 ± 0.08

[a] $P < 0.05$ significant differences in BMD and BMC between patients with and without OC

$P < 0.00001$) of BMD of all patients measured with SB and FB (medium array) (Table 2). Again, significant correlations of SB and FB were also found for faster scan modes of FB in the lumbar spine (r = 0.95, $P < 0.00001$) and hip (r = 0.99, $P < 0.00001$).

Spine BMD and BMC were significantly ($P > 0.05$) higher in women (n = 78) with OC (SB: 0.90 ± 0.140 g/cm^2, 42.7 ± 8.0 g; FB: 0.894 ± 0.134 g/cm^2, 41.4 ± 8.1) than in normals (n = 148) (SB: 0.865 ± 0.140 g/cm^2, 39.2 ± 8.0; FB: 0.844 ± 0.130 g/cm^2, 38.1 ± 8.2) (Table 3).

In contrast, BMD and BMC of the total hip in patients with OC (SB: 0.820 ± 0.087 g/cm^2, 30.09 ± 5.016 g; FB: 0.804 ± 0.080 g/cm^2, 28.8 ± 4.7 g) did not differ significantly from normals (SB: 0.805 ± 0.108 g/cm^2; 29.6 ± 6.7 g, FB: 0.792 ± 0.109 g/cm^2, 28.64 ± 6.6 g). Corresponding data were obtained for BMD of the femoral neck, trochanter, and Ward's triangle in patients with OC and normals.

Analyzing women with OC yielded significant correlations of spine BMD and hip (r = 0.53, SB r = 0.53 FB $P <$ 0.001).

Patients without OC showed much better correlations between BMD of the total hip and spine (SB: r = 0.63, FB: r = 0.62, $P < 0.001$). Some better correlations were provided between femoral neck and the lumbar spine (SB: r = 0.66 and FB: r = 0.64, $P < 0.0001$) in those patients. Again, this correlation was lower (r = 0.55, $P < 0.0001$) for patients with OC. In contrast to patients with OC, spine BMD of women without OC correlated ($P < 0.001$) inversely with age (SB: r = −0.37, FB: r = −0.35).

Discussion

FB design was introduced to facilitate a faster performance of bone densitometry. Precisions errors of BMC and BMD *in vitro* were comparable for SB and FB with all errors ≤1.0% including fast scan. Previous studies [10] have shown precision errors *in vitro* in the same range.

The short and midterm precision errors *in vivo* of FB or SB are suitable for control measurements, too. However, FB scans have significantly poorer precisions than SB scans. One possible alternative is to slow FB scans to achieve better precisions, but our results *in vitro* did not show better precisions with slower scans. Furthermore, it would obviate the advantage of the FB design and may increase X-ray exposure from about 30 to 45 mrem (1.8 to −2.9 μS) [11].

Important for follow-up measurements is the difference between FB and SB design, presenting with lower values of spine BMC and BMD both in phantoms, normals, and patients with OC. Corresponding results were seen in BMD of the total hip as well as femoral neck, Ward's triangle, and trochanter. Beside this systematic difference, highly significant correlations were found between SB and FB (medium array) BMD of patients with and without OC both for lumbar spine and hip (fast scan modes included). The standard error of estimate (SEE) (SB, FB medium of spine and hip) was in the same range as reported by Harper et al. [12].

As the QDR2000 densitometer offers both SB and FB design, a cross-calibration of QDR1000 and QDR2000 with SB was evaluated showing significant correlations for lumbar spine and hip. These correlations were not as high as those from upgrading QDR1000/w to QDR2000 or comparing both machines, as reported by Faulkner et al. [10] and Blake et al. [13], respectively.

The systematic difference between mean BMD of both densitometers was in the same range as reported [10, 14], showing slightly lower mean BMC and BMD total values for QDR2000 also. Although the BMD results with SB on either QDR1000 or QDR2000 were nearly identical on both phantoms and similar *in vivo*, we observed higher precision errors for QDR2000 compared with QDR1000 using SB. Short and mid-term reproducibility of QDR1000 confirmed previous studies [15].

Some of our results are slightly worse than reported by others, as patients with degenerative spine disease were included in our (SB/FB-QDR1000/2000) study cohort. The analysis procedure of these patients is more difficult than in normals.

Furthermore, our data confirm the effect of OC on BMD and BMC resulting in higher mean values of the lumbar spine [16]. The dependence of osteoarthritic changes and bone density has also been described by others [3, 17, 18]. However, our normals and patients with OC had mean BMC and BMD levels of the hip and their mean age was not significantly different. This is in accordance with data of Orwoll et al. [7] who reported higher spinal BMD levels in patients with osteophytes, without significant BMD differences in hip density also. In addition, the relationship between age and bone density was also obscured in their patients with OC. Ito et al. [8] reported a missing relationship between BMD and age in patients with large osteophytes. Experimental data of this relationship [9] proposed the use of MRI to contribute to the assessment of bone quality.

The reduction in scan time with FB may contribute to more convenient routine clinical use and allows for mass screening of a large number of subjects. However, poorer precision errors of FB compared with SB can potentially affect longitudinal assessment. The slower FB scans *in vitro* did not show better precision errors, but increased radiation dose. At a given level of hip BMD, spine BMD was significantly ($P < 0.05$) higher in women with OC than in normals both for SB and FB.

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