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Performance Evaluation of a Dual-Energy X-Ray Bone Densitometer

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SUMMARY

We tested a dual-energy bone densitometer (LUNAR DPX) that uses a stable x-ray generator and a K-edge filter to achieve the two energy levels. A conventional scintillation detector in pulse-counting mode was used together with a gain stabilizer. The densitometer normally performs spine and femur scans in about 6 minutes and 3 minutes, respectively, with adequate spatial resolution (1.2x1.2mm). Total body scans take either 10 minutes or 20 minutes. The long-term (6 months, n = 195) precision of repeat measurement on an 18-cm thick spine phantom was 0.6% at the medium speed. Precision error *in vivo* was about 0.6, 0.9 and 1.5% for spine scans (L2-L4) at slow, medium and fast speeds, while the error was 1.2 and 1.5 to 2.0%, respectively, for femur scans at slow and medium speed. The precision of total body bone density was 0.5% *in vitro* and *in vivo*. The response to increasing amounts of calcium hydroxyapatite was linear (r = 0.99). The densitometer accurately indicated (within 1%) the actual amount of hydroxyapatite after correction for physiological amounts of marrow fat. The measured area corresponded exactly (within 0.5%) to that of known annuli and to the radiographic area of spine phantoms. There was no significant effect of tissue thickness on mass, area, or areal density (BMD) between 10 and 24cm of water. The BMD values for both spine and femur *in vivo* correlated highly (r = 0.98, SEE = .03 g/cm^2) with those obtained using conventional ^{153}Gd DPA. Similarly, total body BMD correlated highly (r = 0.96, SEE = .02g/cm^2) with DPA results.

KEYWORDS: bone, densitometry, osteoporosis, x-ray

INTRODUCTION

Conventional dual-photon absorptiometry (DPA) with ^{153}Gd has been widely accepted in biomedical research and clinical practice. By replacing the ^{153}Gd source with an x-ray source the precision error of measurements *in vivo* can be halved, while at the same time scans are rapid, (5 vs 20 minutes for regional areas), and have better spatial resolution (2mm vs 4mm). This x-ray method, dual-energy x-ray absorptiometry (DEXA), was initially developed using rapid switching between two energies coupled with interspersion of reference materials in the beam (1-3). That approach has been incorporated recently in a bone densitometer (4-6). We report here on a different approach in which a stable x-ray source coupled with a K-edge filter is used to generate the two requisite energies.

METHODS

We tested a commercial x-ray bone densitometer (LUNAR DPX™) that uses an x-ray tube operating at 80 kVp (0.75 mA) coupled with a K-edge filter (350 mg/cm^2 of cerium). This gave effective energies of 40 and 70 keV, which are close to optimal for bone measurement. Most regional determinations were made at the standard scan speed and step interval giving a pixel-size of 1.2x1.2mm. Total body scans have a pixel-size of 4.8x9.6mm. Standard spine and femur scans take about 350 and 200 seconds, respectively, while total body scans take about 600 or 1200 seconds at fast and medium speeds. The measured radiation dose by thermoluminescence was < 1 mrem. Additional evaluations were made of fast and slow spine scans, taking about 100 and 700 seconds respectively; and of slow femur scans (400 seconds) but no determinations were done in the high-resolution mode (0.6x0.6mm pixels). Version 1.7 software was used for spine and femur scans and Version 2.0 software for total body scans.

Accuracy errors were evaluated by measuring the bone mineral content (BMC) of known quantities of calcium hydroxyapatite (HDA) in flat plastic bags; the BMD ranged from 0.6 to 1.3 g/cm^2. The HDA also was measured together with lard to simulate the effect of marrow fat.

Bone phantoms were measured in different amounts of water to assess the influence of thickness on results. Repeated measurements were made over 6 months on a spine phantom 18 cm thick to assess precision error. The

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precision error *in vivo* was obtained by doing repeated measurements on normal subjects with repositioning.

The results on humans (n=53) using the DPX were compared to those obtained using ^{153}Gd DPA (LUNAR DP3, version 8C software). Spine and femur measurements were made using DPX and DPA instruments at the University of Wisconsin (n=33) and the University of Texas, Dallas (n=20). In addition, total body scans were done at the University of Wisconsin (n=11) on both the DPX and DP4 scanners.

RESULTS

Accuracy for BMC: There was a linear increase of measured bone mineral content (BMC in g) as the amount of HDA increased (Figure 1). The standard error of estimate was 0.5g or about 0.8%. Note that the regression line for HDA alone was about 6% above the identity line. This is because the DPX system makes use of the original University of Wisconsin calibration that was based on bones impregnated with paraffin. We added progressive amounts of lard (50, 120, 185, 250g) to the HDA to examine the extent of change induced by fat. There was a decrease of about 4.5g for every 100g of lard added, or about an 9% decrease at 180g (Figure 2); the indicated BMC corresponded closely to the actual mass of HDA at this level.

The ability to obtain accuracy *in vivo* depends on the stability of results with varying thicknesses. We measured changes of BMD from 10 to 24cm of water on spine and femur phantoms using the appropriate software for each site. There was no systematic effect of thickness on either the spine or femur (Figure 3). The SD among all measurements at all thicknesses was ± .02 g/cm^2.

Accuracy for Area: We examined accuracy of area determination on a series of three annuli with diameters of 4.0, 4.5 and 5.0cm and a length of 6cm. There was almost exact correspondence of measured and actual area. The actual areas were 24.0, 27.0, and 30.0 cm^2 while the observed areas were 24.0, 27.1 and 30.1 cm^2. In addition, 10 annuli were prepared from polyvinyl chloride tubing having an actual projected area of 38.55 ± 0.13 cm^2, as determined with vernier calipers; the area measured with the DPX was 38.33 ±0.21 cm^2.

The area of the L2-L4 region was measured on nine spine phantoms, each containing three human vertebrae, using the DPX. The correlation with the actual area, measured by digitization of radiographs of the same phantoms, was 0.97. The measured and actual areas corresponded closely (Figure 4).

Precision: The long-term precision error was determined on a spine phantom 18 cm thick over six months using medium speed (n=195). The precision error was 0.6%. Long-term precision (n=50) for medium speed spine scans in one male subject was about 0.7% (Figure 5). The precision error for spine scans over 1 week was under 1% at slow and medium speeds, and 1.5% at fast speed in young subjects. A femur phantom was scanned 22 times over 1 month at medium speed with a precision error of 1.28%. In one male subject, precision at medium speed for femoral neck BMD was 1.9% over one month (n=25). The precision error of femur scans in young normal subjects over 1 week was about 1.6% and 1.2% for medium and slow speed, respectively (Table 1).

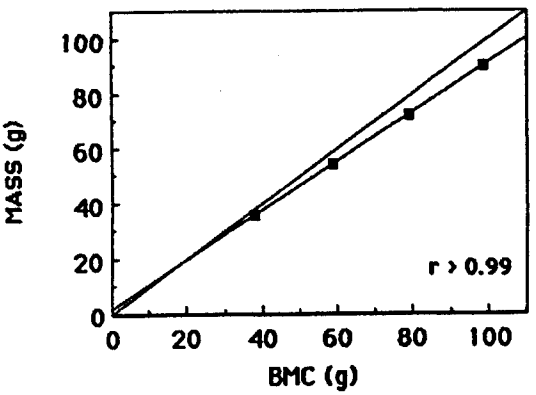

Figure 1. BMC was linearly related to actual mass of HDA (r=0.99).

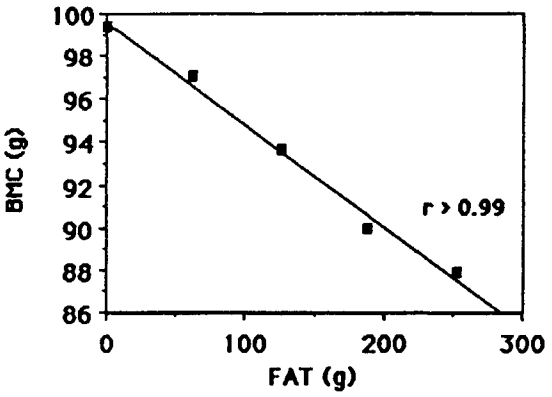

Figure 2. BMC decreased with increasing fat content; the measured BMC corresponded to the actual mass when the fat content was twice the hydroxyapatite mass.

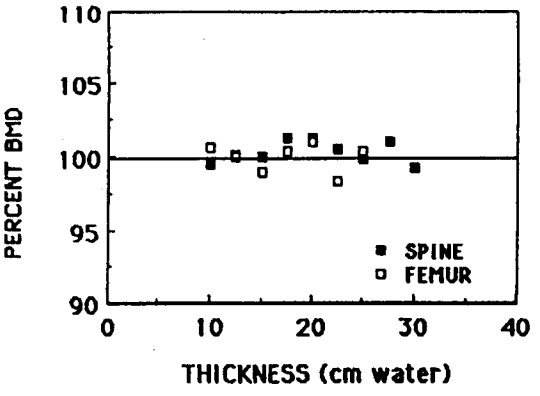

Figure 3. There was no significant change of values using spine or femur software with water thickness.

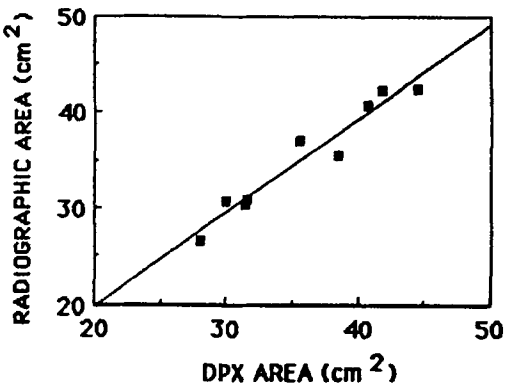

Figure 4. The relation between radiographic and DPX area on 9 spine phantoms; r = 0.97, SEE = 1.5 cm^2.

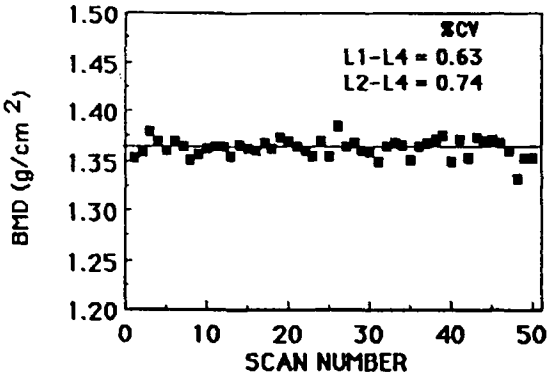

Figure 5. Precision of BMD measured on 1 young male subject twice daily (morning, afternoon) for 25 days.

	Time (sec)	Obs	Cases	Obs/Cases	Precision (%)
Spine	100	40	8	5.0	1.53
Spine	350	40	6	6.7	0.90
Spine	700	15	3	5.0	0.64
Femur	200	45	9	5.0	1.65
Femur	400	30	6	5.0	1.22
Total	600	10	2	5.0	0.35
Total	1200	20	4	5.0	0.49

TABLE 1. Short-term precision (1 week) of DPX measurements *in vivo* on the lumbar spine (L2-L4), the femoral neck, and total body.

The precision of total body scans was assessed over 20 days (n = 46) on the excised skeleton of an osteoporotic woman with a total body calcium of about 500 g. The error was .004 g/cm^2 (0.50%) for total body BMD and 1.0 to 1.5% for major subregions (arms, legs, spine). The precision error of total body calcium in four subjects at normal speed averaged 12g or 1.08%, but normalizing for area to give total body BMD gave a precision error of .005 g/cm^2 or 0.49%. Preliminary results showed faster scans did not compromise precision.

Comparison to DPA: Spine BMD *in vivo* (n = 50) using the DEXA was closely correlated to prior DPA scans (Figure 6). Similarly, femoral neck BMD (n = 14) was closely correlated using DEXA and DPA (Figure 7). There was almost exact correspondence of DEXA and DPA values. Only 11 subjects had total body BMD measured by both DPA and DEXA; again, the correlation was very high (Figure 8).

DISCUSSION: The DPX scanner showed the linearity of response for both BMC and area measurements that is conventional with absorptiometric instruments (7-9). The system is initially calibrated to provide accurate BMC measurements *in vivo*, including (a) a calibration adjusted for moderate marrow fat, and (b) an insensitivity to thickness differences. The indicated BMC corresponded exactly to the mass of HDA when the fat content was approximately twice that of the HDA. This is the normal ratio of fat to bone ash *in vivo* (10). Based on the observed relationship, the HDA would be overestimated by about 5% at the lowest levels of fat while at higher levels (300 mg/cm^3) the HDA would be underestimated by 5%. A calibration for any device (QCT, DPA, or DEXA) used to measure the spine that does not take into account the average offset induced by marrow fat will have an average systematic inaccuracy (14). For DPA and DEXA, this would be about a 10% error at normal fat levels and a 15% error in the elderly and osteoporotic patients. However, a calibration that includes compensation for the average amount of fat will not correct for individual variations, including the large variations that may be associated with aging, osteoporosis, or corticosteroid use. The corresponding uncertainty for single-energy QCT at 120 kVp is about 10% for a change of 100 mg/cm^3 in fat (11-14). This is double the magnitude of the effect seen with DEXA.

There was little effect of tissue thickness on accuracy results up to 24cm of water. This level of water is equivalent to a patient thickness of about 27cm given that patients of this thickness contain fat, which is less attenuating than muscle, and are not 100% "lean" as is water. Above this thickness level, both accuracy and precision are compromised. It remains to be demonstrated if the slower scans available with the DPX can produce accurate and precise results above this level of thickness.

The observed precision error *in vitro* was close to that expected based on quantum statistics (15). The precision *in vivo* for total body BMD (0.5%) and for spinal BMD (0.9%) were only slightly higher than both expected results and those observed *in vitro*. However, it must be recognized that precision results *in vivo* are not always directly reflected by precision *in vitro*. While the latter is determined by quantum statistics, i.e. radiation flux or dose, the former can be affected by patient positioning and by the ability of software algorithms to accurately relocate regions-of-interest. One DEXA scanner that has 3X the radiation dose of the DPX instrument does give comparable 0.5% precision on spine phantoms at equivalent 18-cm thickness (4-6), yet has a precision on normal subjects of 1.4% on the spine and 2.3% on the femur (5). The

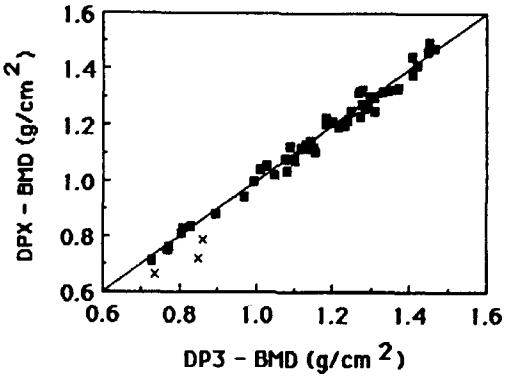

Figure 6. Relationship of spine BMD between DPX and DP3 *in vivo* (n = 50). The regression was congruent with the identity line (r = 0.98, SEE = .026 g/cm^2). Three cases with errant DP3 densities (X) were excluded due to abnormally small bone areas.

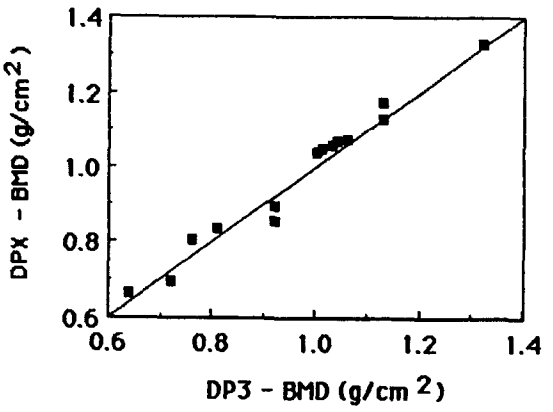

Figure 7. Relationship of femur BMD between DPX and DP3 *in vivo* (n = 14). The regression line coincided with the identity line (r = 0.98, SEE = .030 g/cm^2).

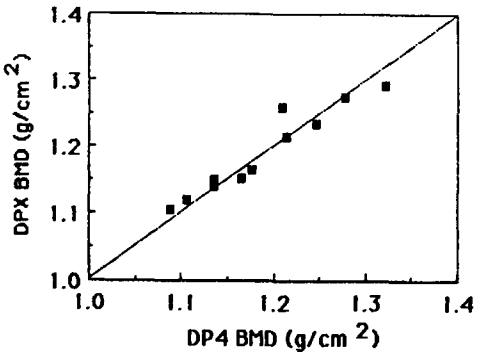

Figure 8. Relationship of total body BMD between DPX and DP4 *in vivo* (n = 11). The regression line coincided with the identity line (r = 0.96, SEE = .02 g/cm^2).

precision we observed *in vivo* with the DPX scanner constitutes a halving of the conventional precision error for DPA (< 1% vs 2% for spine and about 1.5% vs 3% for femur). It should be noted, that we use precision for the L2-L4 region of the spine and the neck region of the femur to characterize performance since these are the diagnostically significant sites. Precision for larger regions (L1-L4; neck plus trochanter) will be smaller. On the other hand, most of our studies were done on normal young subjects. Since the precision error in g/cm^2 is fairly constant with density, the coefficient of variation (%) can be expected to be higher in patients with lower BMD values.

Our preliminary results with DEXA (16, 17) showed a high correlation (r = 0.94, SEE = .04 g/cm^2) between results on individual vertebrae versus BMD values obtained with DPA. However, the precision error for an individual vertebra was high and compromised the assessment. The present spine results show an even higher correlation (r = 0.98) and a lower SEE (about .03 g/cm^2) because a series of three vertebrae (L2-L4) was measured rather than individual vertebrae. Still, part of this smaller error is due to the contribution of precision errors in DPA; the SEE might be even lower if the average from a series of DPA scans were used in regression analysis. On the other hand, most of our spine data were collected in normal subjects and the correlation in osteoporotic patients could be worse. The DPX scanner seems to give better spine values in low density patients than does DPA so there may be a departure from direct BMD correspondence and a poorer correlation in such subjects. Additional data are needed on the femur and for total body BMD over a large range of densities to confirm the relationship we observed in our small samples. Confirmation of these results is needed. Our results suggested that data collected with the DPX scanner should correspond well to published data using LUNAR DPA scanners allowing previous studies (at least of normal subjects) to be directly applicable to this new instrument. This is not unexpected since very similar algorithms have been used in both types of scanners. Results with DPA and DEXA scanners from other manufacturers seem to produce results that average about 15-20% lower for spine BMD due to differing calibration and/or algorithms (4-6). Results from such scanners may not be able to be clinically cross-calibrated, despite the high correlation of results, since the SEE may be more than .06 g/cm^2 (4, 5).

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