An Evaluation of Forearm Bone Mineral Measurement with Dual-Energy X-ray Absorptiometry

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Dual-energy x-ray absorptiometry (DEXA) has been reported to be a valuable means of bone mineral measurement of the lumbar spine and hip. In order to determine whether DEXA could be as useful for bone mineral analysis of the forearm, we compared its accuracy, precision and measurement performance to single-photon absorptiometry (SPA). There was high correlation between these techniques for integral bone mineral density in standard aluminum tubes ($r = 0.99$) and 30 adult volunteers or patients with osteoporosis ($r = 0.95$). The mean short-term precision of DEXA was 0.9% in vitro and about 1.5% in vivo. DEXA produced excellent bone images which enhance long-term in vivo precision. The measurement performance of both instruments was largely unaffected by localized fat deposits or increases in forearm thickness or proportion of fat subcutaneously. We conclude that DEXA is a clinically useful alternative to SPA for forearm bone mineral assessment.

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Noninvasive bone mineral measurement has been enhanced by recently developed techniques, notably dual-energy x-ray absorptiometry (DEXA) and quantitative computed tomography (QCT). These methods have emerged as attractive alternatives to dual-photon absorptiometry (DPA) for the lumbar spine and hip, due to some or all of the following factors: improved precision, shorter scanning time and comparable accuracy (*1–10*). The cost effective nature of DEXA has further increased the potential of this method for routine clinical practice (*5,6,8*). By comparison, QCT is currently employed in only a few dedicated laboratories and its widespread application appears limited (*11*).

Single-photon absorptiometry (SPA) has been widely used to measure forearm bone mineral. This technique enjoys considerable appeal in community screening programs as it is simple to operate, but still predicts osteoporotic fracture risk (*12–14*). However, in long-term studies, reliance on external landmarks contributes to inexact repositioning and potentially misleading results (*15*). Further, economic constraints are imposed by the requirement for periodic radioisotope source replacement (*6*). Thus, there is a need for a competitive and economically viable means of appendicular bone mineral assessment. Preliminary reports using DEXA for the radius have been promising (*16–18*), but further analysis of measurement performance under conditions encountered in clinical practice would be appropriate.

The purpose of this study was to compare a commercial DEXA device with forearm software program (QDR-1000 Hologic Inc., Waltham, MA) with a radioisotope SPA instrument constructed locally according to the principles of Cameron and Sorenson for bone mass determination (*19*). The variables investigated included accuracy and precision in aluminum tubes, cadaveric bone and patients, as well as potential limitations imposed by arm thickness, soft tissue compositions, marrow fat and localized extraosseous fat deposits.

PATIENTS AND METHODS

Instruments

The instruments used in this study have been previously described in detail (*1,5–8,19,20*). Briefly the SPA device has a collimated ^{125}I source (7.4 GBq) generating a monoenergetic photon beam of 27.5 keV. The source is mounted opposite to a collimated sodium iodide (Tl) scintillation detector with the two components rigidly coupled in a vertical C frame. The patient's forearm is positioned between the source and detector with the arm placed prone on a template and the hand restrained by a locating pin placed between the fingers. The source and detector assembly are motor driven so as to traverse the longitudinal axis of the radius in increments of 1 mm/sec. The forearm is surrounded by a rubber bag filled with water and held in position by a plastic plate under moderate pressure. Five 1-mm passes are made through the ultradistal radius, taking approximately 15 min. During the study, measurement of the photon beam attenuation through bone and soft tissue is made.

The DEXA instrument also scans in a rectilinear fashion. The subject's nondominant forearm is placed palm down on the scanning table and is imaged in air. A foam block is placed alongside the forearm in order to align the limb with the long-axis of the table and to prevent rotation. Separate low- and high-

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energy (70 and 140 kVp, respectively) transmitted photon intensity values are recorded on a pixel by pixel basis. Internal calibration is provided by a rotating disc composed of known standards. The x-ray tube source generates a significantly greater photon flux than the ^{125}I source, thereby allowing improved collimation and resolution. The distal third of the forearm can be scanned within 5 min. Subsequently, a bone mineral image of the radius and ulna is generated. A region of interest (ROI) is then placed over the desired area. A variety of measuring sites may be selected after the scan has been performed, whereas with SPA the ROI must be selected prospectively.

Both methods determine integral bone mineral. With DEXA, data are expressed as grams of ashed bone equivalent in the ROI [bone mineral content" (BMC)] or "areal" bone mineral density (BMD) in g/cm^2. Data from the SPA device are schematically depicted as counting rates across the forearm, with bone mineral determined from the area under baseline counts. BMC is expressed as gram of bone ash equivalent per unit of axial bone length or may be normalized for bone size by dividing by the diameter of bone at the scanning site (normalized BMC, g/cm^2) (Table 1 and Figure 1).

A series of experiments were conducted in order to determine the: (1) accuracy and precision of DEXA bone mineral measurements in vivo and in vitro, and (2) potential error introduced into these calculations by certain clinical variables (Table 2).

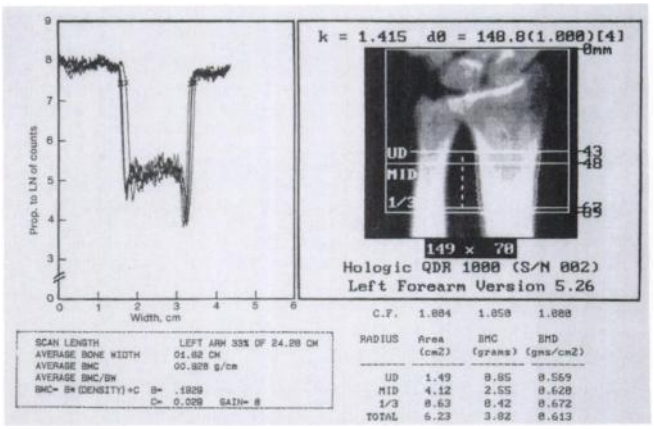

FIGURE 1. Forearm bone mineral analysis by SPA (left). Logarithm of count rate of five scans 1 mm apart plotted by analog recorder. The area under baseline is proportional to BMC. A marker (x) on the curve indicates the position of the edge corrected baseline. Results of a typical scan are shown at bottom left. DEXA printout (right) shows an image of the distal radius and ulna; the ROI in the former is indicated by UD (lines 43–48). The other regions are not used in this study. K and DO are calibration factors of the instrument.

Accuracy

Both instruments measured: (1) four standard hollow aluminum tubes (outer diameter = 1.56 cm; wall thickness range: 0.05–0.23 cm; BMD range: 0.302–0.844 g/cm^2) submerged in water and (2) the nondominant forearm of adults with proven or suspected osteoporosis (n = 20) or normal volunteers (n = 10). The accuracy of DEXA was subsequently expressed in terms of its correlation with the SPA instrument, which has previously been found to reliably predict the ash weight and bone mineral content of a dried defatted human radius (*20*) and standard aluminum tubes, respectively (*15*). For studies in human subjects a site at the ultradistal radius was selected according to the following scheme: a skin mark representing 10% of the length of the ulna from the styloid process was made on the radial side of the forearm, with a correction for skin fold thickness. The SPA device measured 5-mm centered about this mark; with DEXA, the ulna styloid process was identified on the bone image and the radius ROI was adjusted according to the above formula. This region was selected for convenience and was dissimilar to previously described ultradistal sites (*21,22*). Two scans were made with DEXA (for short-term precision in vivo) and one with SPA (for accuracy). Patients were allowed to move between studies, but were then meticulously repositioned. All subjects signed informed consent forms and the protocol was approved by the Institutional Review Board.

TABLE 1
Comparison of Features of SPA and DEXA (QD = 1000) Devices

Feature	SPA	DEXA
Method	Transmission scan	Transmission scan
Source	^{125}I	x-ray
Energy	27 keV	70,140 kVp
Source collimator (mm)	2	2
Detector collimator (mm)	3	none
Scan speed (mm/s)	1, 2	60
Line increment (mm)	1	1
Scanning time (min)	15	5
Processing time (min)	*	5
Table detector distance (cm)	19	40
Daily calibration	Aluminum tubes	Phantom
Units of measurement	BMC (g/cm), Normalized BMC (g/cm^2)	BMC (g) BMD (g/cm^2)

* Processed while scanning.

TABLE 2
Summary of Experimental Design

Variable	Experiment
1. Accuracy	Aluminum tubes and human subjects* (both methods).
2. Short-term precision	Aluminum tube (both), cadaveric radius and human subjects (DEXA).
3. Long-term precision	Spine phantom (DEXA), aluminum tube (SPA).
4. Forearm thickness	Cadaveric radius (DEXA) or aluminum tube (SPA) in varying levels of water.
5. Fat content in forearm soft tissue	Cadaveric radius (DEXA) or aluminum tube (SPA) in varying water/oil mixture.
6. Marrow fat	Hollow aluminum tubes with and without lard (both).
7. Fat deposits around distal radius	Cadaveric radius surrounded by varying layers of porcine skin (both).

* Accuracy of SPA previously published (refs. *15,20*).

Precision

Short-term precision was assessed by scanning: (1) a cadaveric radius (DEXA), (2) an aluminum tube (both) and (3) human subjects (DEXA). The cadaveric bone and aluminum tube were each immersed in 6 cm of water, with precision determined by performing six scans of each object over an 1-hr period. Subtle bone rotation was prevented by wedging the proximal aspect of the radius between two small plastic columns located at the base of the water tank. Precision in patients was derived from duplicate scans of the non-dominant ultradistal radius (see above). The coefficient of variation (CV) was determined by division of the standard deviation by the mean. The long-term (80 day) in-vitro precision of these instruments was evaluated from results of daily or second daily measurements of a spine phantom (DEXA) and aluminum tube (SPA), respectively.

Forearm Thickness

The influence of forearm thickness on bone mineral measurement with DEXA was simulated by scanning a cadaveric radius in varying levels of water from 3 to 7 cm. The performance of the SPA device was similarly assessed by using an aluminum tube in 3–9 cm of water. All measurements were normalized to an average forearm thickness of 3 cm for DEXA and 5 cm for SPA (the latter taking into account the extra dimensions of the water filled bag). For each method, three scans were acquired at each level of water, with results subsequently expressed according to the mean.

Forearm Soft-Tissue Composition

The effect on bone mineral measurement of changing levels of fat in the bone surrounding medium was examined by scanning a cadaveric radius (DEXA) or an aluminum tube (SPA) in a variable mixture of water and vegetable oil (simulating fat). The vegetable oil was added uniformly to the water surrounding the scanned object. The combination of the 2 components was subsequently varied by progressively increasing the vegetable oil by 1 cm, with a corresponding decrease in water. Thus, the level of "bone" surrounding medium remained constant (SPA = 7 cm, DEXA = 5 cm). For each instrument, the mean of three scans was determined for each different soft-tissue composition.

Intra- and Extraosseous Fat

The effect of intraosseous (marrow) fat on bone mineral measurement acquired with SPA and DEXA was assessed by scanning three standard hollow aluminum tubes of different wall thickness in water. These were subsequently rescanned after the lumen of the tube was filled with lard (Armour Food Co., Omaha, NE) (thus simulating intraosseous fat). The effect on instrument performance of small deposits of fat located over the distal radius was evaluated by placing one and two layers of porcine skin (each 3 mm thick) circumferentially around a cadaveric radius. Measurements were obtained with both methods at baseline (0 mm thick), 3 and 6 mm.

RESULTS

Bone mineral measurements with DEXA correlated highly with SPA acquired values in vitro (r = 0.99) and in vivo (BMD: r = 0.95; BMC: r = 0.99). The results of DEXA showed a linear response over the measurement range (Figs. 2 and 3).

The short-term precision of SPA and DEXA in an aluminum tube were 0.4% and 0.9%, respectively. In cadaveric bone, the precision of DEXA was equivalent to 1.2%. In human subjects, the mean CV of DEXA was 1.7% (range: 0.2%–4.6%) in volunteers and 1.5% (range: 0.2%–3.3%) in osteoporotic patients respectively (Table 3).

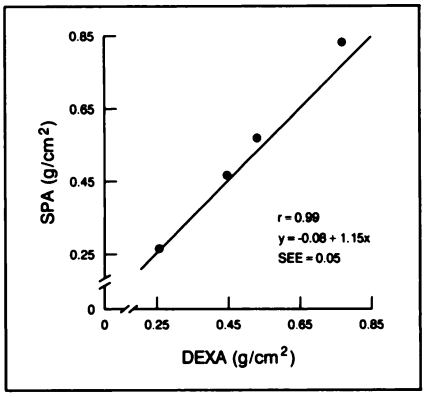

FIGURE 2. BMD of four standard aluminum tubes, determined by single measurement with DEXA and plotted against results obtained with SPA. Correlation coefficient, r = 0.99.

The long-term (80 day) in-vitro precision of both SPA and DEXA showed an effective slope of 0, indicating no change in measurement performance over this time (Fig. 4).

For DEXA, increases in absorber thickness of 2–4 cm over a baseline forearm thickness of 3 cm (imitated by water) produced corresponding changes in measured BMD of 1.3%–2.3%, respectively. For SPA, similar increments in absorber thickness over baseline (5 cm) produced decreases in calculated BMD of 1.5%–2.5%, respectively (Fig. 5).

Bone mineral measurement with both DEXA and SPA were insensitive to large increases in the proportion of "fat" (vegetable oil) in bone surrounding soft tissue. In a "5-cm forearm," the calculated BMD with DEXA was inaccurate only when the level of fat was ≥ 4 cm. Significant inaccuracy in SPA measurements of a "7 cm forearm" were encountered only when the level of fat was ≥ 6 cm (Fig. 6).

Little change was noted with either instrument when porcine skin was placed circumferentially around the distal

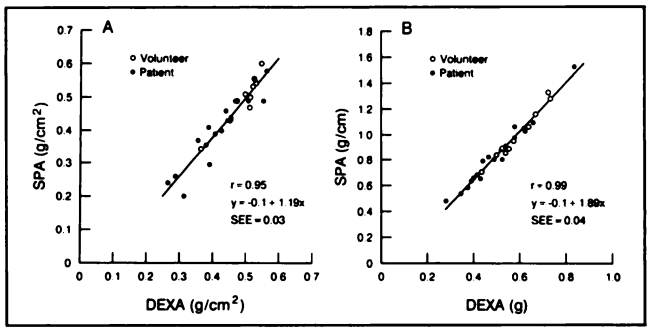

FIGURE 3. Areal BMD (A) or BMC (B) of 30 human subjects with DEXA and plotted against diameter normalized BMC (A) or BMC (B) with SPA. Correlation coefficient, r = 0.95 (A) and 0.99 (B), respectively.

TABLE 3
Short-term Precision of SPA and DEXA

	SPA	DEXA
Aluminum tube	0.467 ± 0.002 (0.4%)	0.435 ± 0.004 (0.9%)
Cadaveric bone	ND	0.347 ± 0.004 (1.2%)
Normal volunteers	(1%–2%)*	(1.7)
Patients	ND	(1.5)

Results indicate mean BMD ± s.d. Values in parentheses indicate coefficient of variation.
ND = Not done.
* Previously published (ref. *24*).

radius; with a 6-mm thick layer, the measured BMD was 0.3% and 0.8% above baseline value for DEXA and SPA, respectively (Fig. 7). However, when several standard aluminum tubes were packed with fat (lard), the calculated BMD was falsely reduced with both instruments. The degree of change was exaggerated at lower bone mineral values (13.9% and 10.1% for SPA and DEXA, respectively); the underestimation at higher bone mineral values was proportionately less (5.2% and 3.9% for SPA and DEXA, respectively) (Fig. 8).

DISCUSSION

Our study indicates that DEXA is a precise technique with comparable accuracy to SPA in vivo and in vitro. Further, bone mineral measurement is relatively insensitive to potential limitations introduced by changes in forearm thickness, soft-tissue composition and small deposits of fat over the distal radius. Current DEXA forearm software and bone images impart several advantages over SPA including: (1) ROI selection based on anatomical rather than surface landmarks; (2) the ability to retrospectively analyze alternate regions should this become necessary; and (3) recognition of unsuspected bone lesions which would otherwise contribute to inaccurate results. Thus, DEXA can be used in clinical practice to determine forearm BMD and is a suitable alternative to SPA.

SPA was first described in 1963 by Cameron and Sorenson (*19*) and forms the basis of most commercially available devices. These instruments are relatively inexpensive to purchase, simple to operate and widely used in research applications. Appendicular bone measurement with SPA has also been used to predict skeletal fracture risk (*12–14*). The accuracy of SPA was initially reported as 4%–11%, however, technical modifications have led to improved results (*23*). The SPA device used in our experiments has been repeatedly found to predict to within 3% the bone mineral content of excised bone samples and precision engineered aluminum tubes (*20*). In our study, the correlation of DEXA with SPA was excellent in vitro (r = 0.99) and in vivo (BMD: r = 0.95; BMC: r = 0.99). These results were achieved over a wide range of values, indicating that DEXA is a technically suitable alternative for forearm bone mineral measurement. Further, in contrast to a previous report in which DEXA BMD values of the lumbar spine were about 10% less than achieved with DPA (1), no such discrepancy with SPA was noted in the current study. BMC values were also highly correlated. The greater difference between SPA and DEXA values in

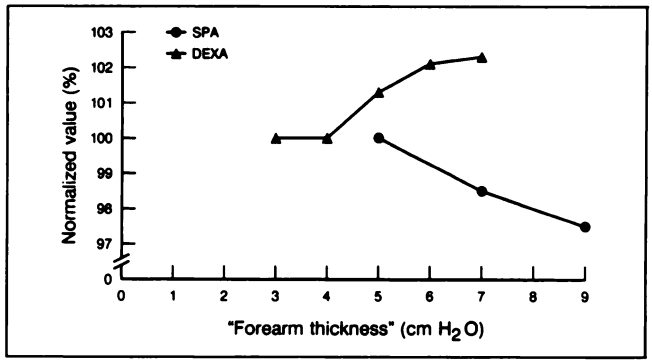

FIGURE 5. Compared to a normalized forearm thickness of 3 cm, increases of 1, 2, 3 and 4 cm over baseline produced increases 0%, 1.3%, 2.1%, and 2.3%, respectively, in bone mineral density (DEXA). For a normalized value of 5 cm for SPA, measurements at 7 cm and 9 cm created an underestimation of BMD of 1.5% and 2.5%, respectively.

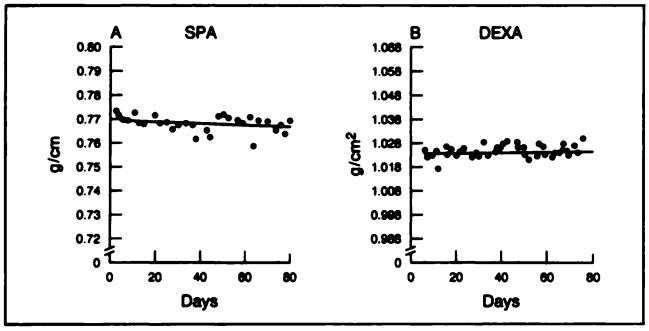

FIGURE 4. The long-term in vitro precision of SPA (A) and DEXA (B) indicated an effective slope of 0.

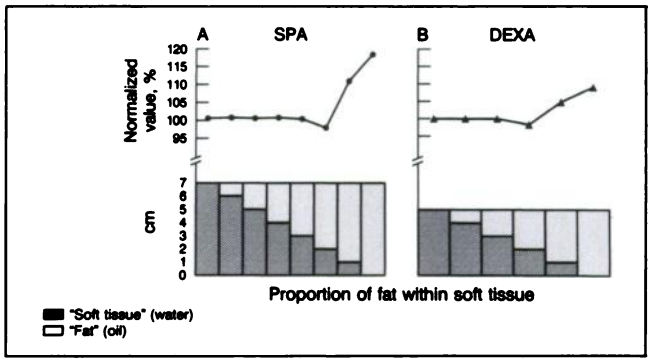

FIGURE 6. SPA (A) and DEXA (B) devices were insensitive to large increases in the proportion of fat in bone surrounding medium. However, bone mineral values were significantly overestimated when the fat level exceeded 6 cm in a 7 cm thick "forearm" (SPA) and 4 cm in a 5 cm "forearm" (DEXA).

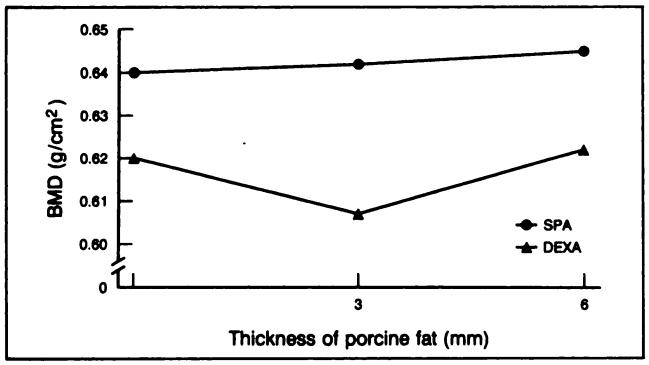

FIGURE 7. Illustration indicating the effect on measured BMD of small localized deposits of porcine skin over the distal aspect of a cadaveric radius. A 6-mm thick layer of porcine fat produced no significant change in calculated BMD with either instrument.

patients (Fig. 3B) when compared to aluminum tubes (Fig. 2) is probably due to differences in the edge detection algorithm and calibration. Conversion of BMD and BMC data from SPA to DEXA will introduce an error and should be avoided in longitudinal studies.

In our study, the short-term precision of DEXA in aluminum tubes and cadaveric bone were 0.9% and 1.2%, respectively. Results in human subjects were similar, with a mean of 1.5% and 1.7% in patients and volunteers, respectively. The SPA instrument used in our series was also precise in aluminum tubes (0.4%). Early studies of SPA from our institution reported a short-term in-vivo precision of 3%–4% for this instrument (*20*). However, the recent employment of multiple scanning paths has increased precision to 1%–2% in humans (*24*). Results from another group have also indicated a short-term precision of about 2% for aluminum tubes and patients, respectively (*25*). Thus, the short-term reproducibility in vivo and in vitro of DEXA is similar to previous findings with SPA.

The long-term precision in vitro of SPA and DEXA in our study showed an effective slope of 0. In human subjects, results with SPA have been reported to vary as much as 7% possibly due to changing source strength and difficulty with repositioning according to external landmarks (*26*). The latter may be overcome by employing a bone detection algorithm which automatically identifies the gap between radius and ulna (*21,22*). With DEXA, high resolution bone mineral images facilitate placement of appropriate ROI based on anatomical landmarks, thus contributing to better precision. In addition, the region analyzed is chosen after inspection of the bone image, thereby avoiding unsuspected local abnormalities such as deformity or old fracture which would otherwise confound bone mineral measurement. These factors increase the potential of this procedure for conducting longitudinal studies. Precision may also be improved by obtaining a mean of two measurements on each visit, since scanning time is short and radiation dose relatively low (*1*).

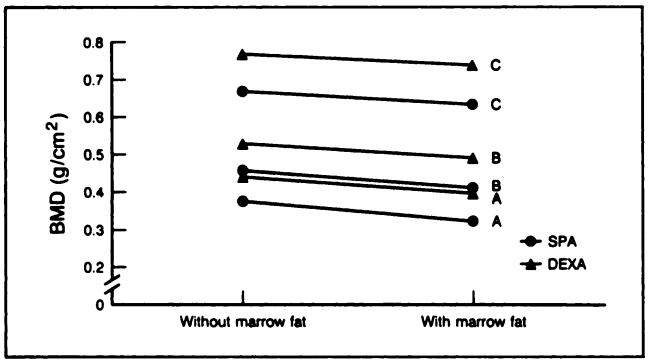

FIGURE 8. Illustration revealing the underestimation of BMD by both devices when standard hollow aluminum tubes were filled with lard. The percentage difference between baseline and filled states for SPA and DEXA were −13.9% and −10.1% (tube A), −10.1% and −7.2% (tube B), and −5.2% and −3.9% (tube C), respectively.

Our data indicate that bone mineral measurement of the radius with DEXA can be acquired without significant error when forearm thickness remains within the 3–6 cm range. These limits are within the range usually encountered in clinical practice and parallel the magnitude of change found with the SPA device. Further, the DEXA instrument was largely unaffected by an increase in the proportion of fat in soft tissue surrounding bone. By contrast, "intraosseous marrow fat" produced a significant underestimation of BMD by both devices. However, the volume of marrow fat used in our study exceeded previous "normal" estimates for the radius (*2*).

In our study, layers of porcine skin up to 6 mm in thickness did not compromise BMD evaluation by either SPA or DEXA. Sorenson et al. (*27*) reported statistically significant increases in BMD measured by SPA with layers of paraffin over the radius. However, the thickness of these layers (0.5–1.5 cm) was greater than in our study. Thus, it is likely that small deposits of fat over the distal radius do not interfere with the accuracy of bone mineral measurement of DEXA or SPA.

SPA is an established method for forearm scanning. However, this device requires an expensive radioisotope source change every 2 mo and additional room to house the instrument. DEXA incorporates technology with wide applications and excellent performance characteristics. As a result, this technique is being increasingly adopted for routine clinical practice. In many departments, the utilization of DEXA for forearm bone mineral measurement would allow retirement of the SPA device, thus offering some economic advantage.

An important limitation of SPA and DEXA is the inability to discriminate between cortical and trabecular bone mineral (*3*). QCT can measure trabecular bone separately with precision ≤ 1% (*2,4,9*). This technique therefore, may convey some advantages in the assessment of bone loss and therapeutic effect of newly developed drugs. However, QCT is expensive and currently not widely used (*11*).

In conclusion, we have demonstrated that:

1. DEXA can be calibrated to provide almost identical BMD and BMC results in the radius to SPA.
2. DEXA's short-term precision is similar to results with SPA.
3. Measurement performance is largely unaffected by clinical variables such as forearm thickness, localized fat deposits and increased fat subcutaneously.
4. Scanning time is short.
5. Images of the forearm are of excellent resolution which enhances long-term precision in vivo.

These factors indicate that DEXA is a clinically satisfactory alternative to SPA for forearm bone mineral measurement. Since DEXA is being increasingly used in routine practice for bone mineral measurement at other skeletal sites, many centers may find it convenient and economically beneficial to expand its application to the radius, thus replacing the SPA instrument.

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REFERENCES

1. Wahner HW, Dunn WL, Brown ML, Morin RL, Riggs BL. Comparison of dual-energy x-ray absorptiometry and dual-photon absorptiometry for bone mineral measurements of the lumbar spine. *Mayo Clin Proc* 1988;63:1075–1084.
2. Hangartner TN, Overton TR. Quantitative measurement of bone density using gamma ray computed tomography. *J Comput Assist Tomogr* 1982;6:1156–1162.
3. Orphanoudakis SC, Jensen PS, Rauschkolb EN, Lang R, Rasmussen H. Bone mineral analysis using single-energy computed tomography. *Invest Radiol* 1979;14:122–130.
4. Isherwood I, Rutherford RA, Pullan BR, Adams PH. Bone mineral estimation by computer-assisted transverse axial tomography. *Lancet* 1976;2:712–715.
5. Cullum ID, Ell PJ, Ryder JP. X-ray dual photon absorptiometry: a new method for the measurement of bone density. *Br J Radiol* 1989;62:587–592.
6. Sartoris DJ, Resnick D. Dual-energy radiographic absorptiometry for bone densitometry: current status and perspective. *AJR* 1989;152:241–246.
7. Mazess R, Collick B, Trempe J, Barden H, Hanson J. Performance evaluation of a dual-energy x-ray bone densitometer. *Calcif Tissue Int* 1989;44:228–232.
8. Kelly TL, Slovik DM, Schoenfeld DA, Neer RM. Quantitative digital radiography versus dual-photon absorptiometry of the lumbar spine. *J Clin Endocrinol Metab* 1988;67:839–844.
9. Genant HK, Block JE, Steiger P, Glueer CC, Smith R. Quantitative computed tomography in assessment of osteoporosis. *Semin Nucl Med* 1987;17:316–333.
10. Hansen MA, Hassager C, Overgaard K, Marslew U, Riis BJ, Christiansen C. Dual-energy x-ray absorptiometry: a precise method of measuring bone mineral density in the lumbar spine. *J Nucl Med* 1990;31:1156–1162.
11. Wahner HW, Riggs BL. Methods and application of bone densitometry in clinical diagnosis. *CRC Crit Rev Clin Lab Sci* 1986;24:217–233.
12. Hui SL, Slemenda CS, Johnston CC. Age and bone mass as predictors of fracture in a prospective study. *J Clin Invest* 1988;81:1804–1809.
13. Ross PD, Wasnich RD, Vogel JM. Detection of prefracture spinal osteoporosis using bone mineral absorptiometry. J Bone Min Res1988;3:1–11.
14. Hui SL, Slemenda CW, Johnston CC. Baseline measurement of bone mass predicts fracture in white women. *Ann Intern Med* 1989;111:355–361.
15. Moore R, Wahner H. The measurement of bone mineral. *App Radiol* 1974;3:63–67.
16. Otsuka N, Fukunaga M, Satoh M. Dual-energy x-ray absorptiometry system for the determination of bone mineral density in distal radius: its fundamental and clinical study. *Third International Symposium on Osteoporosis*, October 14–18, 1990.
17. Kollerup G, Sorensen HA. Bone mass in the forearm by dual-energy x-ray densitometry. *Third International Symposium on Osteoporosis*, October 14–18, 1990.
18. Nelson D, Feingold M, Kleerekoper M. Comparison of SPA and QDR for measurement of the radial midshaft. *Third International Symposium on Osteoporosis*, October 14–18, 1990.
19. Cameron JR, Sorenson J. Measurement of bone mineral in vivo: an improved method. *Science* 1963;142:230–232.
20. Wahner HW, Riggs BL, Beabout JW. Diagnosis of osteoporosis: usefulness of photon absorptiometry at the radius. *J Nucl Med* 1977;18:432–437.
21. Hilas L, Borg J, Gotfredsen A, Christiansen C. Comparison of single- and dual-photon absorptiometry in postmenopausal bone mineral loss. *J Nucl Med* 1985;26:1257–1262.
22. Awbrey BJ, Jacobsen PC, Grubb SA, McCartney WH, Vincent LM, Talmage RV. Bone density in women: a modified procedure for measurement of distal radius density. *J Orthop Res* 1984;2:314–321.
23. Cameron JR, Mazess RB, Sorenson JA. Precision and accuracy of bone mineral determination by direct photon absorptiometry. *Invest Radiol* 1968;3:141–150.
24. Wahner HW, Dunn WL, Riggs BL. Assessment of bone mineral. Part 2. *J Nucl Med* 1984;25:1241–1253.
25. Christiansen C, Rodbro P, Hensen H. Bone mineral content in the forearm measured by photon absorptiometry. *Scand J Clin Lab Invest* 1975;35:323–330.
26. Goodwin PN. Methodologies for the measurement of bone density and their precision and accuracy. *Semin Nucl Med* 1978;17:293–304.
27. Sorenson JA, Cameron JR. A reliable in-vivo measurement of bone mineral content. *J Bone Joint Surg* 1967;A49:481–497.