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Does Bone Measurement on the Radius Indicate Skeletal Status?

Concise Communication

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Single-photon (I-125) absorptiometry was used to measure bone mineral content (BMC) of the distal third of the radius, and dual-photon absorptiometry (Gd-153) was used to measure total-body bone mineral (TBBM), as well as the BMC of major skeletal regions. Measurements were done in normal females, normal males, osteoporotic females, osteoporotic males, and renal patients. The BMC of the radius predicted TBBM well in normal subjects, but was less satisfactory in the patient groups. The spinal BMC was predicted with even lower accuracy from radius measurement. The error in predicting areal density (bone mass per unit projected skeletal area) of the lumbar and thoracic spine from the radius BMC divided by its width was smaller, but the regressions differed significantly among normals, osteoporotics, and renal patients. There was a preferential spinal osteopenia in the osteoporotic group and in about half of the renal patients. Bone measurements on the radius can indicate overall skeletal status in normal subjects and to a lesser degree in patients, but these radius measurements are inaccurate, even on the average, as an indicator of spinal state.

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Single-photon absorptiometry with I-125 (28 keV) has become a widely used method of bone evaluation (*1–3*) since instrumentation (*4*) has become commercially available. It has been demonstrated that a measurement of bone mineral content (BMC) in the radius is highly intercorrelated ($r \sim 0.9$) with the BMC at other sites in long bones, and with the total skeletal weight or total body calcium (*5–9*). Radius BMC measurements also indicate the BMC of the femoral neck with modest error—15% according to Wilson (*10*)—but are less well correlated (20–25% error) with mass or density of the spine (*11,12*). Perhaps because of the variable relationship between compact bone of the appendicular skeleton and the more trabecular organization of the axial skeleton (*13,14*), there have been difficulties using the radius BMC for diagnosis of osteoporosis (*14–17*). This report examines the relationship between radius BMC and that of other skeletal regions (using Gd-153 absorptiometry) in normal subjects and patients.

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METHODS

Single-photon absorptiometry was done with a direct-readout unit (*4*) on the shaft of the radius, at a standard site one-third of the forearm length proximal to the styloid process of the ulna. The BMC (g/cm) was divided by bone width (cm) to give an index, BMC/W (g/cm^2), that is commonly used to normalize data for bone size.

Measurements of TBBM (in g) were made by rectilinear transmission scanning over the entire body area (120 × 180 cm), as previously described (*18*), using a dual-photon source (Gd-153) with emissions at 44 and

100 keV. Count data using conventional instrumentation were collected on magnetic tape. Before further calculations, the data were corrected for (a) count loss due to deadtime, (b) beam hardening, (c) spillover from the 100-keV channel into the 44-keV channel, (d) scattered radiation from the patient, and (e) background. The TBBM measurement has been shown to measure accurately (<2% error) the actual mass of excised skeletons (*18*), and the results in vivo were very highly correlated with total body calcium by neutron activation (*19*).

The bone mineral and soft-tissue content were calculated for each pixel (5 mm × 25 mm) where soft tissue was present. Of the 8000 or so pixels in a TBBM scan, about 3000 occur with bone present, 2000 with soft tissue alone, and 3000 with only air. Computer algorithms were used to divide the skeleton into major anatomical segments (head, arms, legs, and trunk, and within the trunk, ribs, pelvis, and spine). These segments involved approximations; for example, the spine also included the sternum, the ribs contained the clavicles, and the pelvis included the sacrum and the femoral heads. The computer-generated areas were evaluated on a printout of the skeletal image, and in those cases where alignment problems had occurred, the appropriate areas were selected by entering the correct coordinates. The areal density, BMD (= BMC per unit area), was calculated for each area; similarly TBBM/AREA for the total skeleton. Areal densities minimize the influence of anatomical positioning, and they normalize for skeletal size.

Reproducibility was assessed from 142 measurements on an isolated skeleton and 12 measurements on one adult male (age 40) over a 4-yr period. For TBBM/AREA there was a precision error of 1.4% ex vivo and 2.4% in vivo. The reproducibility for limb segments and the trunk was 2% ex vivo and 4% in vivo, while reproducibility of the smaller subsegments of the trunk was 4% ex vivo and 6% in vivo. During the past 2 yr, when most of the data were collected, the precision errors were somewhat lower than over the 4-yr period, since there were fewer changes of sources, geometry, and counting equipment during the recent period.

The subjects consisted of 72 normal females (24 with ages 20–49 and 48 aged 50–80) and 13 normal males (aged 20–61) who were free of disease and not taking drugs causing osteopenia (anticonvulsants, corticosteroids). In addition we measured 18 older females (aged 50–74) with definite osteoporosis as judged by multiple spinal fractures and/or minimal-trauma fractures of the distal radius and ribs (but not the femoral neck). An additional 11 adult osteoporotic males who were taking corticosteroids for asthma or arthritis were measured. A detailed comparison of these groups is given in a companion report (*18*). In addition, 20 patients with renal osteodystrophy (7 F, 13 M) were measured; three of these were adolescents.

Correlation coefficients, standard deviations (s.d.), and linear regressions were calculated by standard methods. The predictive error was expressed as the standard error of estimate (s.e.e.) about a regression line. This s.e.e. was expressed as a percentage of the mean value of the dependent variable to give a relative error.

RESULTS

In normal subjects there were moderate correlations between the measurements of the radius and the skeletal values derived from Gd-153 absorptiometry (Table 1). Radius BMC predicted TBBM with an error of only 10% in normal females and 13% in males (Fig. 1, top). Osteoporotics and renal patients had lower-than-normal values for TBBM, and the relation between radius BMC and TBBM was roughly parallel to that in normals, but at any given radius BMC the TBBM was lower (Fig. 1, bottom). The s.e.e. in these patients was about 14%. In normal women the s.e.e. for predicting the bony mass of the head, arms, or legs was about 12%, but the s.e.e. in predicting spinal BMC was 15%. The regression lines in osteoporotic and renal patients fell below that for normals. The s.e.e. was about 25% in these patients (Table 1).

The predictive errors were reduced somewhat when area densities were used to normalize for skeletal size. The radius BMC/W was correlated ($r \sim 0.6$) with areal densities of the total skeleton and its regions in normal subjects. The s.e.e. was about 0.07g/cm^2 (7%) for the total skeleton (Fig. 2, top), arms, or legs; about 0.06 g/cm^2 (8%) for the trunk as a whole; and 0.10 g/cm^2 (10%) for the spine (Fig. 3, top). Moreover, a single regression equation relating BMC/W to areal densities could be used for both young and older females, and even for normal males, without appreciable error. The s.e.e. for pooled data on normal males and females was about 0.08 g/cm^2 in predicting TBBM/AREA from radius BMC/W, and was 0.11 g/cm^2 for predicting spine BMD. The variance in osteoporotic and renal patients was somewhat greater than in normal subjects, but more importantly the regression lines differed from those in normal subjects. For TBBM/AREA, the patients were about 8% lower than normal. There was little relation between BMC/W and spinal BMD in the osteoporotic patients (Fig. 3, bottom). About 60% of all patients were 2 s.d. below normal for spinal BMD, but half of the renal patients in this mixed group had normal or high-normal spinal BMD (leading to a large predictive error in this group). None of the osteoporotics was within 1 s.d. of age-matched controls.

The expected areal densities of osteoporotic women were calculated using the regression relationships, established in normal older women, between radius BMC/W and (a) TBBM/AREA or (b) spinal BMD. The osteoporotic women were 8% below their expected

TABLE 1. THE REGRESSIONS OF RADIUS BMC AND BMC/W ON SKELETAL MEASUREMENTS

	n	r	B‡	Int.§	s.e.e.	% s.e.e.
BMC(x) · TBBM(y)						
Young females	24	0.73†	2730	297	261	9.6
Old females	48	0.70†	2165	712	253	10.0
All females	72	0.72†	2399	549	256	9.9
Osteoporotic females	18	0.72†	2262	373	297	15.1
All males	13	0.71†	2268	464	438	13.0
Osteoporotic males	11	0.80†	1657	623	297	12.3
Renal	20	0.71	1797	721	416	19.0
BMC(x) · SPINE BMC(y)						
Young females	24	0.32	193	189	59	16.3
Old females	48	0.46†	235	138	51	15.3
All females	72	0.44†	238	140	53	15.5
Osteoporotic females	18	−0.04	−16	226	54	25.4
All males	13	0.56*	278	−3	81	22.8
Osteoporotic males	11	0.45	104	76	50	26.4
Renal	20	0.54	190	100	69	27.2
BMC/W(x) · TBBM/AREA(y)						
Young females	24	0.38	0.49	0.78	0.07	6.2
Old females	48	0.66†	0.84	0.50	0.06	5.3
All females	72	0.64†	0.83	0.52	0.06	5.8
Osteoporotic females	18	0.66†	0.74	0.47	0.07	8.2
All males	13	0.56*	0.92	0.44	0.10	8.1
Osteoporotic males	11	0.92†	1.03	0.27	0.06	5.5
Renal	20	0.78	0.72	0.50	0.07	7.3
BMC/W(x) · SPINE BMD(y)						
Young females	24	0.21	0.37	0.75	0.10	10.3
Old females	48	0.48†	0.72	0.46	0.08	8.4
All females	72	0.47†	0.74	0.46	0.09	9.2
Osteoporotic Females	18	0.05	0.04	0.70	0.07	9.4
All males	13	0.55	1.39	−0.15	0.15	15.2
Osteoporotic males	11	0.83†	0.61	0.28	0.05	7.4
Renal	20	0.44	0.66	0.47	0.16	18.2

* $p < 0.05$.
† $p < 0.01$.
‡ B = slope.
§ Int = intercept.

TBBM/AREA (0.90 compared with 0.98 g/cm^2) and 15% below their expected spinal BMD (0.74 compared with 0.87 g/cm^2). Thus radius BMC/W could not be used to predict either total skeletal or spinal density in these women; that ratio even overestimated the BMD of the arms and legs (compact bone) by 3% and 7%, respectively. In osteoporotic males there was a similar overestimation of areal densities using the radius BMC/W relationships derived from the small sample of normal males. The overestimation was 6% for the total skeleton and 12% for the spine. Thus in both male and female osteoporotic patients the radius BMC/W predicted a total-skeletal status that was 6–8% higher than actual, and a spinal density that was 12–15% higher than actual. This was true also when the areal density of the four limbs was used to predict spinal status. That is, the radius BMC/W failed to predict spinal status in osteoporosis because the limbs simply did not reflect the preferential osteopenia of the spine. In renal patients the TBBM/AREA was overestimated by 9%, whereas spinal BMD was overestimated by only 4% when the regressions established on normals were applied.

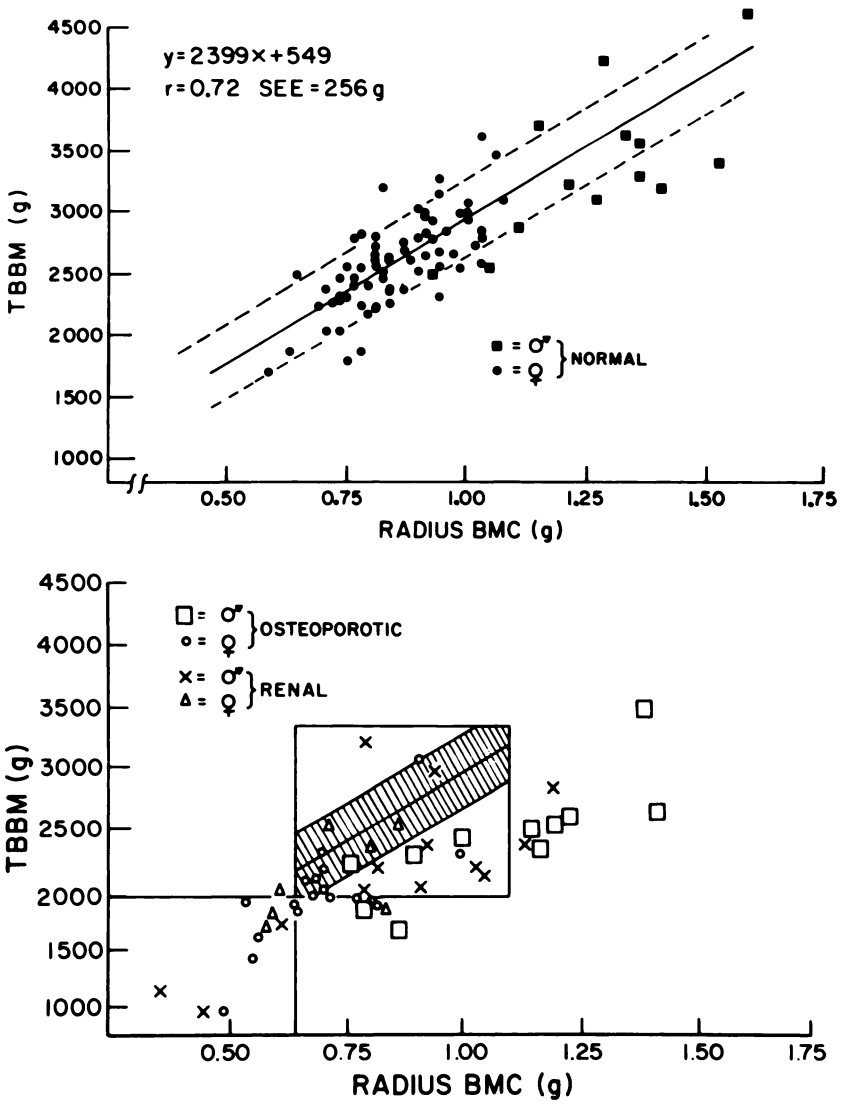

FIG. 1. Upper: Relation between radius bone-mineral content (BMC) and total-body bone mineral (TBBM). Regression line for normal females is shown (±1 s.e.e.). Lower: Data from osteoporotic and renal patients are shown, superimposed on regression for normal females (shaded area). Rectangle marks ±2 s.d. limits.

There was a good correlation in normal females (r = 0.78) and in the total sample (r = 0.80) between TBBM/AREA and spinal BMD (Fig. 4, top). The regression equation for 72 normal females (y = 0.96x − 0.07, % s.e.e. = 6.5%) was very similar to that for the entire sample (y = 0.94x − 0.07, % s.e.e. = 10.5%, n = 134). The plotted data (Fig. 4, bottom) show that the regressions actually differed in the various patient subgroups. For any given TBBM/AREA, the osteoporotic men had a lower-than-expected spinal BMD, whereas the renal patients tended to have a spinal BMD higher than normal.

DISCUSSION

In normal males and females there was a relatively small error (6–10%) in estimating the status of the total skeleton—or of its subregions, including the spine—from bone-mineral measurements on the radius. This was expected from a number of previous studies ex vivo and in vivo (*5–9*). It has even been shown that properly normalized radius measurements in normal subjects correlate very highly (r = 0.95) with the density of samples from the iliac crest (*20*). Consequently, noninvasive measurements, such as absorptiometry, seem to be appropriate for epidemiologic investigations in normal populations. They could be used to examine the role of diet, exercise, and sunlight in influencing growth and age-related changes of the skeleton. However, in metabolic bone diseases or during immobilization, where preferential alterations of trabecular bone do occur, measurements at appendicular sites are inappropriate for clinical management (our osteoporotic patients were 1.3 s.d. below normal for the limbs, 1.7 s.d. below normal for the total skeleton, and 2.0 s.d. below normal for the spine). Our results show that this is not due simply to an increased variation about the regression line relating the limbs and the spine (and the total skeleton), but rather to changes in that regression slope itself.

The existence of only moderate correlations (r ~ 0.7) between long-bone measurements and spinal measurements has been recognized over the past decade, and

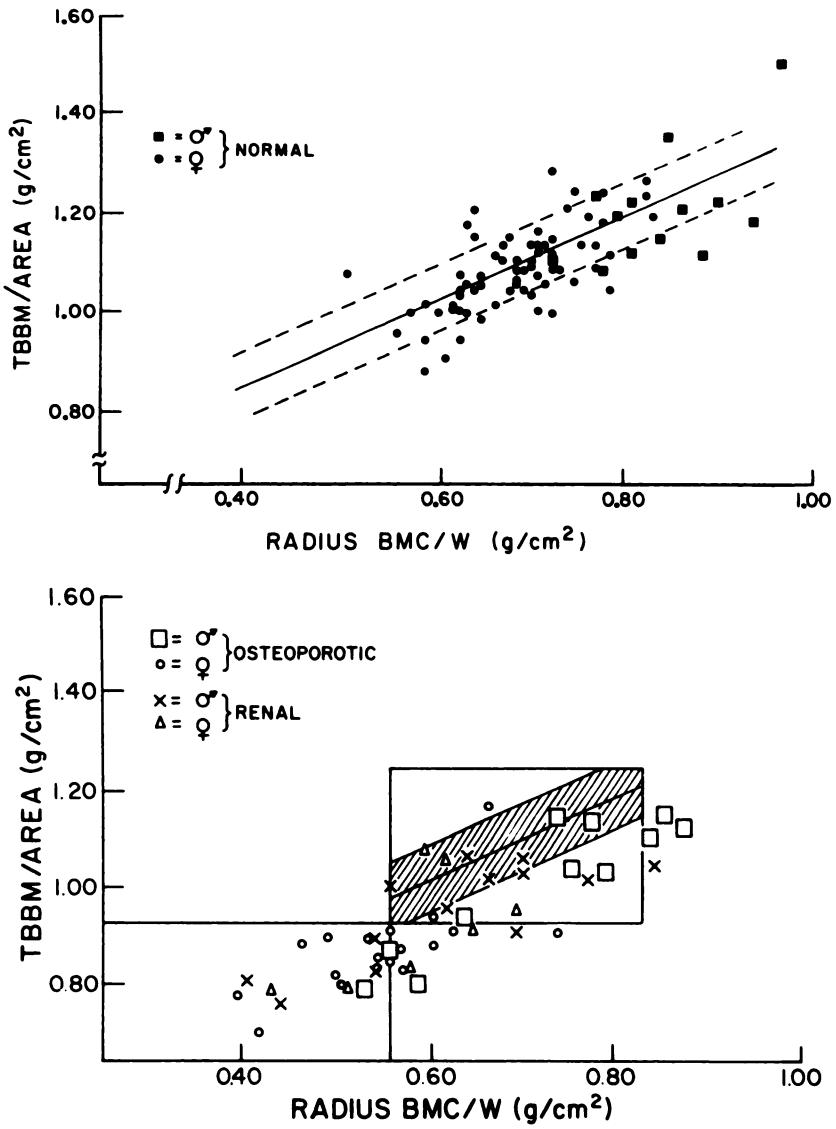

FIG. 2. Upper: Relation between radius BMC/W and TBBM/AREA, with regression line for normal females (±1 s.e.e.). Lower: Data from osteoporotic and renal patients are shown, superimposed on regression for normal females (shaded area). Rectangle marks ±2 s.d. limits.

there is evidence that this relationship becomes more tenuous in bone disease as a result of preferential changes in trabecular bone (*12–14*). Seeman et al. (*13*) demonstrated that the nature and extent of the relationship between appendicular and axial bone differ in several metabolic bone diseases. One study in osteoporotic patients even showed a negative association between limb measurements and iliac-crest biopsies (*21*). The present results show that there is a systematic shift in the relationship between the limbs and both the spinal and the total skeletal state in senile osteoporosis and in corticosteroid osteoporosis. In the latter condition there is preferential trabecular osteopenia that results in the overestimation of TBBM/AREA by 8%, and of spinal BMD by twice that amount. All osteoporotic patients, both male and female, were more than one standard deviation below controls for spinal BMD, and 72% (21/29) had values below the fifth percentile for older women. Riggs et al. (*14*) found that 45% of his osteoporotic patients were below this level for spinal BMD (76% when noncrushed vertebrae were used), yet there was substantial overlap for radius BMC. Preferential spinal osteopenia probably explains the poor diagnosis of osteoporosis based on forearm measurements (*14–17*). In the present study 19 of 48 normal older women were within one standard deviation of the average BMC/W for osteoporotic women, and four of 18 (22%) osteoporotic women were within one standard deviation of controls. All studies to date have shown at least this degree of overlap in long-bone measurements. Less overlap has been seen for normalized total-body calcium by neutron activation than for radius BMC/W (*22*). TBBM/AREA reflected spinal BMD better than did radius BMC/W in both normal and patient groups, though it was still rather inexact (Fig. 4, bottom).

These findings have implications for diagnostic procedures in bone disease. Widely used noninvasive measurements that focus on compact bone (photodensitometry, I-125 absorptiometry, radiogrammetry, x-ray TCT of long bones) will be far less useful in osteoporosis

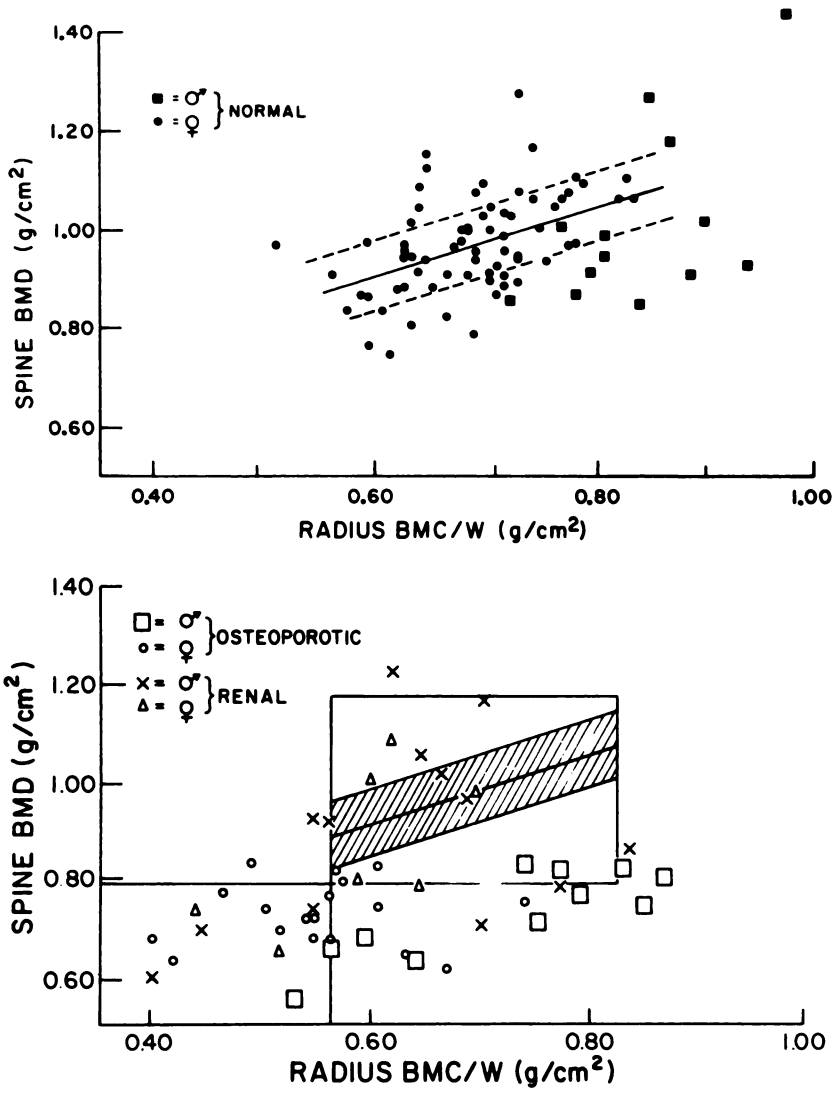

FIG. 3. Upper: Relation between radius BMC/W and spinal BMD, with regression line for normal females (±1 s.e.e.). Lower: Data from osteoporotic and renal patients are shown, superimposed on regression for normal females (shaded area). Rectangle marks ±2 s.d. limits.

than measures of trabecular bone. The compact-bone measures may even have shortcomings in diseases that involve the appendicular skeleton (renal osteodystrophy). Our renal patients averaged about 20% below normal in limb measurements but only 10% below normal for the trunk as a whole. The radius BMC/W did reflect total skeletal state (TBBM/AREA), but the regression for normal subjects overestimated the actual value in renal patients by 9%. Thus, the radius BMC/W would be limited diagnostically in renal osteodystrophy but could be used for monitoring changes in a given individual.

It is possible that radius BMC/W could be used in osteoporosis for screening purposes, even without providing a clear diagnosis. Subjects with a low radius BMC tended to have a low TBBM, while a low radius BMC/W (<0.56 g/cm²) did indicate a low spinal density (Fig. 3, bottom). However, as pointed out by Kruse et al. (*17*), subjects with entirely normal radius values may well be osteoporotic. Therefore screening using radius BMC/W could identify otherwise occult abnormality in undiagnosed cases but would not exclude such abnormality in subjects with normal values. It also should be recognized that patients with fractures of the femoral neck, who were not included here, have a greater diminution of compact bone than patients with crush fracture, so radius measurements may be more pertinent for the former group.

To answer the question posed in the title of this report:

(a) radius measurements indicate total skeletal state, and even spinal state, with moderate accuracy (~10%) in normal subjects;

(b) in osteoporotic (crush-fracture) and renal patients the accuracy for either the total-body or the spinal state is poorer, and the relationships differ from those in normal subjects; and

(c) direct measurement of trabecular bone is required for either diagnosis or long-term monitoring of bone disease.

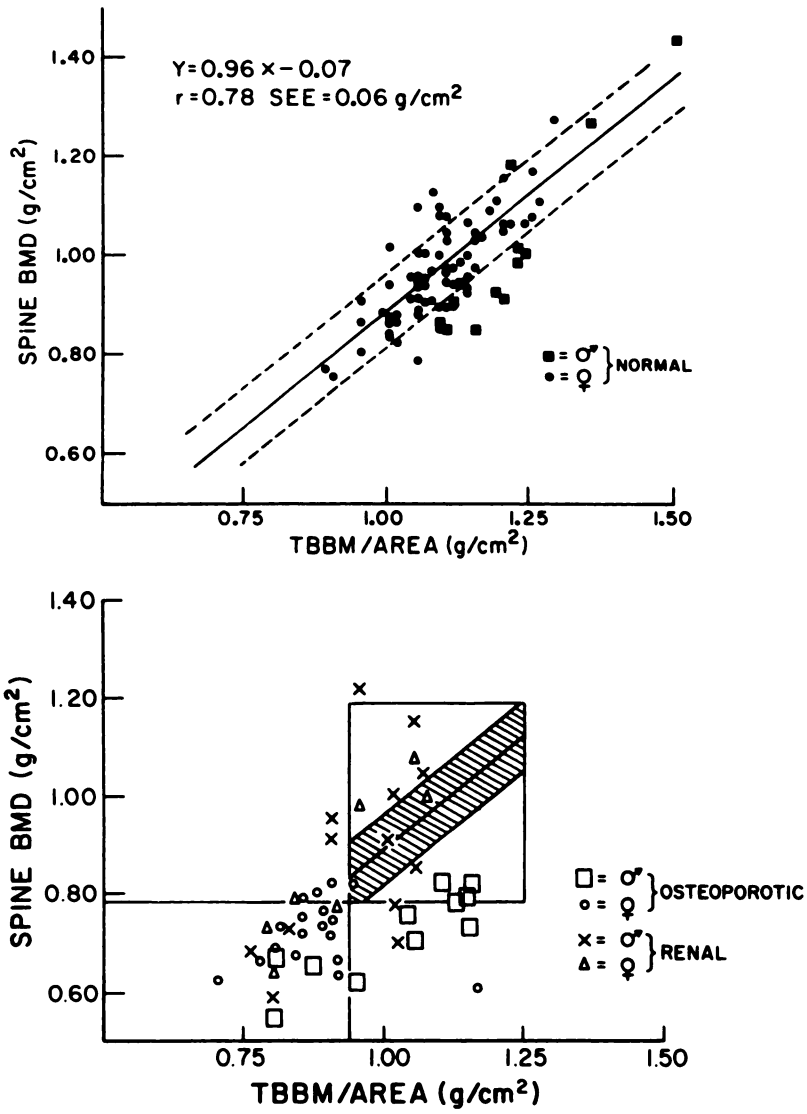

FIG. 4. Upper: Relation between TBBM/AREA and spinal BMD, with regression line for all normal subjects. Lower: Data from osteoporotic and renal patients are shown, superimposed on regression for all normal subjects (shaded area). Rectangle marks ±2 s.d. limits.

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