RELATIONSHIP BETWEEN BONE MINERAL CONTENTS OF THE RADIUS
FEMORAL NECK, THORACIC VERTEBRAE AND OTHER SITES*

by

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ABSTRACT

The loss of bone and the increased incidence of spontaneous fractures in the femoral neck and spine during aging is a serious medical problem. However, osteoporosis is not usually diagnosed prior to the occurrence of a spontaneous fracture due to the difficulty in accurately determining in vivo the amount of bone in these areas. The monoenergetic x-ray photon absorptiometric technique for determining bone mineral content provides an accurate and precise measurement, but the method is usually limited to the appendicular bones. The relationships between the mineral contents at various sites on the radius, femoral neck and lower thoracic vertebrae of twenty-four skeletons (ages from 35 to 89 years) were examined to evaluate the ability of the radius mineral content to reflect the mineral content of the femoral neck and the spine. It was found that the radius bone mineral content was highly related to that of the femoral neck, $r = 0.87$, and moderately related to the mineral content of the thoracic vertebrae with the majority of the correlation coefficients between 0.60 and 0.70. Also regression analyses indicated that the radius mineral content and age provides a moderately accurate estimate (standard error of estimate of about 17%) of the mineral contents of the femoral neck and spine.

INTRODUCTION

The importance of the structural function of bone to the health of the individual is well known. However, in many instances there is a failure of the skeleton to provide adequate structural function throughout life. A progressive deterioration in skeletal integrity begins after maturity with the most serious loss of strength occurring in the femoral neck and spine. Fractures in these areas, associated with minimal trauma and called "spontaneous" increase markedly with age. The incidence of fracture of the femoral neck in women doubles for every five years of age after the fifth decade.¹ It has been estimated that over four million persons in the United States over 50 years old have suffered vertebral fracture or collapse.²

The load bearing capacity of a bone in vivo, whether it is a vertebra, radius, femur, etc., is dependent on the bone's form or architecture, the intrinsic strength of the bone tissue, and the amount of bone present. Aging in general produces changes in these factors which lead to a deterior-

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ation in the strength of the skeleton. However, the primary factor in the increased skeletal fragility in old age is the reduction in the total amount of bone present in the skeleton resulting from cortical thinning, increased porosity and loss of trabecular bone. It has been demonstrated in vitro that the strength of the femoral neck³ and vertebrae^{4,5} are highly related to the amount of bone present, with the deterioration in strength in these areas paralleling or even exceeding the loss of bone with age. A "spontaneous fracture resulting from the loss of bone in these areas is often defined as clinical osteoporosis. Estimates have been made that the probability of "spontaneous" failure of the spine increases greatly when the mass of bone in the vertebra is reduced to fifty percent or less than present at maturity.⁶ However the recognition of the potential osteoporotic or individual at risk is not usually possible because of the difficulty in accurately determining the amount of bone in either the femoral neck or spine in vivo.

Attempts to measure bone mass in vivo in these areas using x-ray photodensitometry of radiographic images⁷ have not been very successful. Difficulties related to the polyenergetic nature of the photon beam, the ill-defined amount of scattered radiation reaching the film, etc. contribute to a sizeable uncertainty in the measurement of bone mass using this technique. The photon absorptiometric technique developed by Cameron⁸ circumvents many of these difficulties. The amount of bone mineral is determined by measuring the transmission of a narrow monoenergetic photon beam from a radioactive source (typically ¹²⁵I) through the bone. This technique provides an accurate and precise measurement of the mineral content either in vitro or in vivo.

Although the absorptiometric technique is usually limited to the peripheral bones of the skeleton, i.e. radius, ulna, os calcis, etc., the bone mineral content of the appendicular skeleton reflects the status of the clinically significant areas of the axial skeleton. It is evident that the bone of the appendicular and axial skeleton are related since the majority of factors which influence bone such as diet, age, genetic heritage, hormonal levels, etc., are systemic. The mass of individual bones of both the axial and appendicular skeleton are interrelated and empirical formulae for estimating the masses of axial or the entire skeleton from the mass(es) of one or more of the appendicular bones have been reported.^{9, 10, 11} Smith¹² found that the radius mineral content is significantly lower in women with "spontaneous" fracture of the hip than age-matched normals of similar physique. Also Goldsmith¹³ reported that the radius mineral content was sufficiently related to standard radiographic criteria for assessing the spine to be of diagnostic value in separating normal and osteoporotic individuals. Therefore the feasibility of quantitatively estimating the amount of bone in the femoral neck and spine from the mineral content of a single or combination of locations on the appendicular skeleton and age was investigated.

The bone mineral content at sites on the radii, ulnae, humeri, fibulae, tibiae, femurs, and thoracic vertebrae of 24 skeletons were measured using the photon absorptiometric technique. Single and multiple regressions were calculated to evaluate the accuracy of estimating the mineral content of the femoral neck and thoracic vertebrae from the bone mineral content of the radius, the bone mineral content of the radius and age, and the bone

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mineral contents of the radius with other scan sites and age. Correlation coefficients between the mineral contents at sites on the same bone and between different long bones were also calculated.

METHODS AND MATERIALS

Partial skeletal remains consisting of the radii, ulnae, humeri, tibiae, fibulae, femurs, and the eighth through eleventh thoracic vertebrae of 24 cadavers were obtained from the University of Wisconsin Department of Anatomy. The cadavers, 17 males and 7 females ranging in age from 35 to 89 years, were acquired by the University of Wisconsin from hospitals and nursing homes around the state and information as to the cause of death, race, and length of confinement to bed prior to death was lacking. Prior to scanning, most of the soft tissue adhering to the long bones was removed. The eighth through eleventh vertebrae were separated and the intervertebral discs were removed. The lumbar vertebrae could not be obtained because the dissection techniques used by the anatomy students destroyed these vertebrae. All bones were stored at 0° C and measures were taken to prevent dehydration.

The BMC* of the long bones were measured at positions corresponding to 25, 50, and 75 percent of the total length of the bone measured from its distal end using the photon absorptiometric technique. These scan sites will be referred to as D, M, and P, corresponding to distal, midshaft, and proximal, respectively. In addition to these sites the radius and ulna were also scanned at 33 percent of the length from the distal end, the distal third site or DT. The BMC of the femoral neck was measured at the narrowest portion of the neck. The size and shape of the neck varies in the region between the trochanter and the femoral head and there are differences in the shape of the femoral neck between individuals. Thus it is difficult to measure the corresponding anatomical site on different femurs. Sets of four or five consecutive scans across the femoral neck were repeated three or more times with the femur repositioned after each set in order to reduce anatomical variations. The coefficient of variation in the BMC of the four or five scans in a set was typically less than one percent, and the coefficient of variation of the mean BMC on the femoral neck was about five percent. The mineral content, width and height of the individual thoracic vertebrae were obtained by scanning each vertebra through its maximum width with the vertebra in positions. Both scans were made in the coronal plane through the maximum width. The beam was perpendicular to the disc along the first scan path; for the second path the vertebra was rotated 90° about an axis perpendicular to the plane of the first scan path. The portion of the vertebral body scanned in both paths was the same and the BMC in the two cases agreed to within less than five percent.

The BMC at each site on the long bone and vertebrae was obtained by averaging four or five consecutive scans. The coefficients of variation in the BMC and the sites were between one and two percent. The "mineral" of an Al bar standard was measured at various times each day to monitor the performance of the equipment. Table 1 gives the mean coefficients of variation of the BMC of the midshaft site of some long bones, the ninth thoracic vertebra, and the Al standard.

*Bone Mineral Content

RESULTS

The correlation coefficients (r) between the bone mineral content (BMC) at sites on the same bone and between different bones were calculated. Table 2 illustrates the magnitude of the coefficients between sites on the same bone; $p \leq 0.001$ in all cases. Coefficients of similar magnitude were found between sites on contra-lateral pairs of bones. The interrelation between the BMC at scan sites on different long bones were also high, with r typically greater than 0.85. Table 3 gives the coefficients between the BMC at sites on the radius and sites on the ulna, humerus, tibia, fibula, and femur. The coefficients between the BMC at sites on the radius and sites on the lower extremities are slightly lower than those between the former and sites on the humerus and ulna. This is due probably to the greater difficulty in scanning the corresponding anatomical sites on each of the lower bones. The magnitude of the correlation coefficients between the mineral contents of the eighth through eleventh thoracic vertebrae were slightly less than those found between scan sites on the long bones (Table 4). There is a fair degree of correlation between the vertebral bodies with r -values typically greater than 0.80 and p -levels less than or equal to 0.005.

The ability to estimate the BMC of the femoral neck from the BMC at sites on the long bones was investigated by calculating the regression relations between the BMC of the femoral neck and the BMC of sites on the radius or femur and a combination of sites on the radius and femur. These regressions were also calculated with age included as another independent variable. In all cases there was no significant gain in predictive accuracy using the multiple regressions over the single regression with only the radius bone mineral as the independent variable. There were also no marked differences in the predictive accuracy of single regressions between different sites on radius or femur and the BMC of the femoral neck. Figure 1 is a scattergram between the BMC of the DT site on the radius and the femoral neck. The regression equation, standard error of estimate (SEE), and correlation coefficients are given in the figure. The open dots represent females.

The correlation coefficients between the BMC at scan sites on the radius and the thoracic vertebrae are given in Table 5. There is a weak correlation between the radius sites and the mineral content of the individual vertebrae. Most coefficients are significantly different from zero at a p -level less than 0.005. Figure 2A is a scattergram of the mineral content of the ninth thoracic vertebra versus the BMC at the distal third (DT) site on the radius, $r = 0.68$; this scattergram is typical of those between the radial BMC and the thoracic vertebrae. Averaging the mineral contents of the four vertebrae, however, increased the interrelation between the BMC of the radius and the axial skeleton. Figure 2B is the scattergram of the BMC at the DT site on the radius and the average mineral content of the four thoracic vertebrae. The regression line and the standard error of estimate are shown. In comparison to Figure 2A the scatter appears to have been reduced and while the correlation coefficient, $r = 0.69$, is not significantly greater than that between the BMC of the DT site on the radius and the mineral content of the individual thoracic vertebrae, most of the variation is due to the two cadavers which lie approximately two standard deviations above the line. When these were omitted this correlation coefficient was considerably increased, i.e. $r = 0.85$.

Single regression equations were calculated between the average thoracic mineral content (dependent variable) and the BMC at different sites on the radius of ulna. Multiple regressions were calculated between the average thoracic mineral content and the following: the BMC at sites on the radius and the ulna; the BMC at sites on the radius and age, and the BMC at sites on the ulna and age. The latter two were also calculated with another site on the radius or ulna included as a third independent variable. There was no significant difference between the predictive accuracy of the regression equation, either single or with age, using different sites on the same bone or on different bones. Any radial scan site was as good as any other radius or ulna scan site. Also multiple regressions using the BMC at two scan sites were not statistically better than regressions using a single scan site. This was expected due to the high interrelation between the BMC at sites on the long bone. There was, however, a slight increase in predictive accuracy when age was included as a second independent variable with the BMC at a radius or ulna scan site. For example, the SEE in the predicted average vertebral mineral (PVMC) from the BMC of the radial midshaft alone was 18.6 percent while it was 16.8 percent when the radial BMC and age were used in the regression. Figure 3 is the scattergram of the predicted versus observed vertebral mineral content, the predictive equation is given on the figure.

CONCLUSIONS

While it is evident that the bone of the appendicular and axial skeleton are related the degree of relationship is not clear, and the question of whether the BMC at a scan site on the radius or ulna could be used to estimate the BMC at other appendicular locations, the femoral neck, and spine was investigated.

The high degree of correlation between the BMC at scan sites on the same long bone and on different long bones indicates the possibility of predicting the BMC at a site on the same or different bones. Regression equations between the BMC on the radius and other locations on the appendicular skeleton, although not given, were calculated. The standard error of estimates were typically less than 10 percent indicating a fair degree of uniformity in the mineral content throughout the appendicular skeleton. These results are in agreement to those previously reported by Mazess.¹⁰

Of greater interest is the relatively high correlation ($r = 0.87$) between the radius and femur mineral content and the possibility of using the radius bone mineral for assessing the likelihood of hip fractures. As was mentioned before, Smith⁹ reported that the mean radius BMC of women with hip fractures is significantly lower than age-matched controls with no fractures. Using a discriminant value of 0.68 gm/cm he found that about 80% of the fracture group had a radial mineral content below and 80% of the normals had a mineral content above 0.68 gm/cm. Substituting this discriminant value, 0.68 gm/cm, into the predictive equation in Figure 1 indicates that a femoral neck with a BMC of less than 1.55 gm/cm would have a high risk of fracture. Five of the skeletons present in the investigation (four females and one male) had a radial BMC, DT scan site of less than 0.68 gm/cm. Of these five, two showed evidence of past

femoral fracture, i.e. one had a healed fracture and the other had an orthopaedic pin in the femoral neck. The third showed no past hip fracture, however there was radiographic evidence of abnormal bone growth in the neck region. The femoral necks of the remaining two were broken and the heads of the femurs were missing. It was not possible to ascertain whether these breaks had occurred before death or during removal of the femurs from the cadavers and subsequent handling. The femoral necks of these two skeletons were clearly weaker than normal, since none of the skeletons with radial BMC greater than 0.68 gm/cm possess femurs broken in this fashion. Of all the intact femurs which could be measured only one was found to have a femoral neck BMC less than 1.55 gm/cm and in this case the contra-lateral femur had been fractured in vivo. Also only one of the skeletons (a 61 year old male) which had a radial BMC greater than 0.68 gm/cm had evidence of a hip fracture. Due to the lack of medical histories it was not known if any of the fractures were "spontaneous" or the result of major trauma. Therefore it appears that the radial BMC is a fair predictor of the femoral neck BMC and that it may be of use in the identification of individuals in danger of suffering spontaneous hip collapse.

In the case of the estimation of the vertebral mineral content from the age and BMC of the radius, the relationships between these factors does not allow a precise estimation of the vertebral mineral content. However, the degree of relationship would appear to be sufficient to be of use in assigning individuals to one of several broad classes related to the amount of their vertebral mineral content.

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TABLE 1. MEAN COEFFICIENTS OF VARIATION IN BMC.

<u>Location</u>	<u>Coefficient of Variation (%)</u>	<u>Number of Observations</u>
Radius	1.25	24
Ulna	1.53	24
Femur	1.33	24
Ninth Thoracic Vertebra	1.40	18
Aluminum Bar Standard	1.38	125

TABLE 2. CORRELATION COEFFICIENTS BETWEEN BMC AT SCAN SITES ON THE
SAME BONE (n = 24)

	Radius					Ulna			
	D	DT	M	P		D	DT	M	P
D	-				D	-			
DT	.99	-			DT	.98	-		
M	.97	.96	-		M	.96	.98	-	
P	.97	.98	.96	-	P	.93	.94	.96	-

	Humerus				Tibia		
	D	M	P		D	M	P
D	-			D	-		
M	.97	-		M	.90	-	
P	.94	.97	-	P	.94	.90	-

	Fibula				Femur		
	D	M	P		D	M	P
D	-			D	-		
M	.94	-		M	.94	-	
P	.90	.88	-	P	.86	.94	-

TABLE 3. CORRELATION COEFFICIENTS BETWEEN BMC AT SCAN SITES ON THE RADIUS AND OTHER LONG BONES

	Ulna				Humerus			Tibia			Fibula			Femur		
	D	DT	M	P	D	M	P	D	M	P	D	M	P	D	M	P
D	.91	.93	.94	.91	.94	.95	.94	.88	.85	.89	.90	.87	.78	.89	.83	.72
DT	.93	.93	.95	.93	.95	.95	.95	.90	.86	.91	.91	.88	.80	.91	.84	.73
M	.91	.92	.94	.93	.95	.91	.90	.84	.84	.88	.89	.88	.76	.84	.81	.71
P	.94	.95	.95	.90	.96	.94	.94	.88	.85	.91	.85	.85	.78	.88	.83	.73

TABLE 4. CORRELATION COEFFICIENTS BETWEEN THE BMC OF THE THORACIC VERTEBRAE. (n = 18 - 20)

	Eighth	Ninth	Tenth	Eleventh
Eighth	-			
Ninth	.92	-		
Tenth	.78	.92	-	
Eleventh	.76	.78	.84	-

TABLE 5. CORRELATION COEFFICIENTS BETWEEN THE BMC AT SCAN SITES ON THE RADIUS AND THE THORACIC VERTEBRAE. (n = 18 - 20)

	Thoracic Vertebrae			
	Eighth	Ninth	Tenth	Eleventh
D	.66	.70	.63	.50
DT	.67	.68	.61	.50
M	.67	.69	.60	.42
P	.67	.69	.60	.48

Figure 1 Scattergram between the BMC of the femoral neck and the BMC at the DT scan site on the radius. The regression equation is given; PFMC is the predicted femoral neck mineral content and RMC is the BMC at the DT site on the radius.

Figure 2 Scattergrams between: (A) Mineral content of the ninth thoracic vertebra and the BMC at the DT scan site on the radius; (B) Average thoracic mineral content of the eighth through eleventh vertebrae and the BMC at the DT site on the radius.

Figure 3 The average vertebral mineral content predicted from the regression equation based on the BMC at the M scan site on the radius and age, plotted versus the observed vertebral mineral content, $r=0.76$. The line of unity slope is drawn.