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EFFECT OF SUBCUTANEOUS FAT ON BONE MINERAL CONTENT MEASUREMENTS WITH THE 'SINGLE-ENERGY' PHOTON ABSORPTIOMETRY TECHNIQUE

by

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The 'single-energy' photon technique of CAMERON et coll. (1963, 1968) is presently used by a considerable number of laboratories for the measurement of bone mineral content in humans (Proceedings of bone measurement conference 1970). The expression used in this determination of bone mineral content is generally of the form

$$M = K \left[\delta \sum_{i=1}^{n} ln \left(\frac{I_0^*}{I} \right)_i \right]$$

δ is the distance traversed in an integration interval, K a proportionality constant,

$$\left[\delta \sum_{i=1}^{n} ln \left(\frac{I_0^*}{I} \right)_i \right]$$

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called the integral value represents the absorption of roentgen rays by bone, I_0* and I are the intensities transmitted respectively through 'soft tissue' (including tissue equivalent material) and through 'soft tissue' plus bone (CAMERON & SORENSON 1963) and n is the number of integration intervals.

The proportional relationship of mineral content and absorption depends on the presence of a two component system consisting of bone mineral and non-bone mineral which absorbs as 'soft tissue'. The linear absorption coefficient of the material used to obtain a constant absorbing thickness over the traversed area is chosen very close to that of 'soft tissue' to maintain the two component model (CAMERON & SORENSON).

The linear absorption coefficient for 27.4 keV roentgen rays of fat or adipose tissue is only about 65 per cent that of muscle or 'soft tissue' (SPIERS 1946). Thus, the presence of a fat component in a constant thickness 'soft tissue' absorbing path should increase the transmitted beam intensity over that for the same thickness of soft tissue. SORENSON & MAZESS (1970) have estimated the errors involved in ignoring the fat component in both the 'single-energy' photon and 'dual-energy' measurement of bone mineral content. From the data reported here, it is estimated that the mineral content calculated for the forearm bones of an obese individual, with the 'single-energy' photon technique can be in considerable error, depending on the method employed to determine the I_0* value. However, the reproducibility of the bone mineral measurement on an individual with this technique is generally in the order of 2 per cent.

Materials and Methods

An instrument similar to that first described by CAMERON & SORENSON, the details of which are reported elsewhere (ZEITZ & FREED 1970), was used to obtain the direct photon absorption data reported here. The photon source consisted of either 200 or 400 mCi ^{125}I with a tin filter (from Atomic Energy of Canada, Ltd., Quebec, Canada).

A scan across a fat-free phantom human left forearm was compared to the left forearm scans of individuals of varying degrees of obesity. The individuals chosen were all females since their scans showed evidence of a larger fat component than did males. The fat-free phantom consisted of dried human forearm bones, tissue equivalent liquid (TEL) (GOODMAN 1969), and a thin plastic enclosure whose cross section approximated that of a normal arm. All scans on humans were obtained with the forearms rigidly held in a plastic box 9.3 cm thick containing Super Stuff (Wham-O-Mfg. Co., San Gabriel, Calif.) as tissue equivalent material or in 8.3 cm of water. The Super Stuff has a density close to

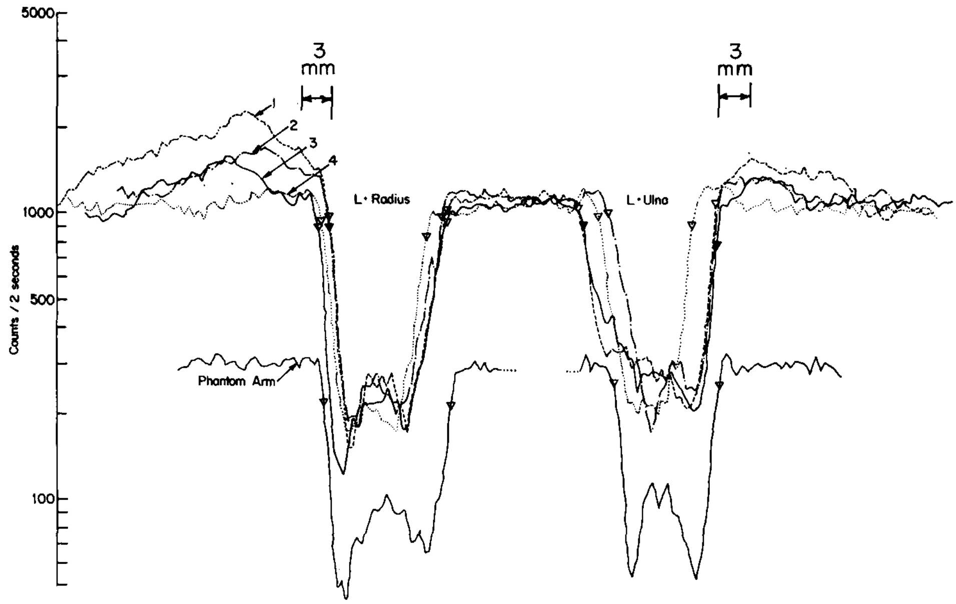


Fig. 1. Midshaft scans of human phantom left arm and the left arms of individuals with varying degrees of adipose tissue. Weight, height and Ponderal Index are: (1) 105.8 kg, 1.7 m, 10.888; (2) 80.4 kg, 1.62 m, 11.339; (3) 60.8 kg, 1.52 m, 11.725; (4) 49 kg, 1.55 m, 12.809. The measurements are taken with the arm rigidly clamped in a plastic box containing Super Stuff. The scans of the four individuals are adjusted vertically so that the scans in the region between the radius and ulna approximately downward and the ulna is artificially placed to the right of its actual scan position to avoid confusing the various scans.

1.0 and its linear absorption coefficient as measured with rays from a tin filtered ^{125}I source (ca 27.4 keV) differs by no more than 2 per cent from that for the TEL. Linear scans across the forearm were carried out at about 1/3 the distance up from the distal to the proximal end of the radius. The long term precision in per cent standard deviation for measuring integral values in human forearm bones was found to be about ± 2 per cent (ZEITZ).

An estimate of the error involved in ignoring the fat component was made by determining the integral value for scans of a bone reference standard kindly supplied by CAMERON's Laboratory (WITT et coll.; Fig. 3) with and without varying configurations of subcutaneous fat in the path. The coefficient of variation in measuring the integral value of the standard in water was less than 1 per cent. The bone standard plus fat were always immersed in 8 cm of water. The dimensions and absorptance of the large simulated bone in the standard approxi-

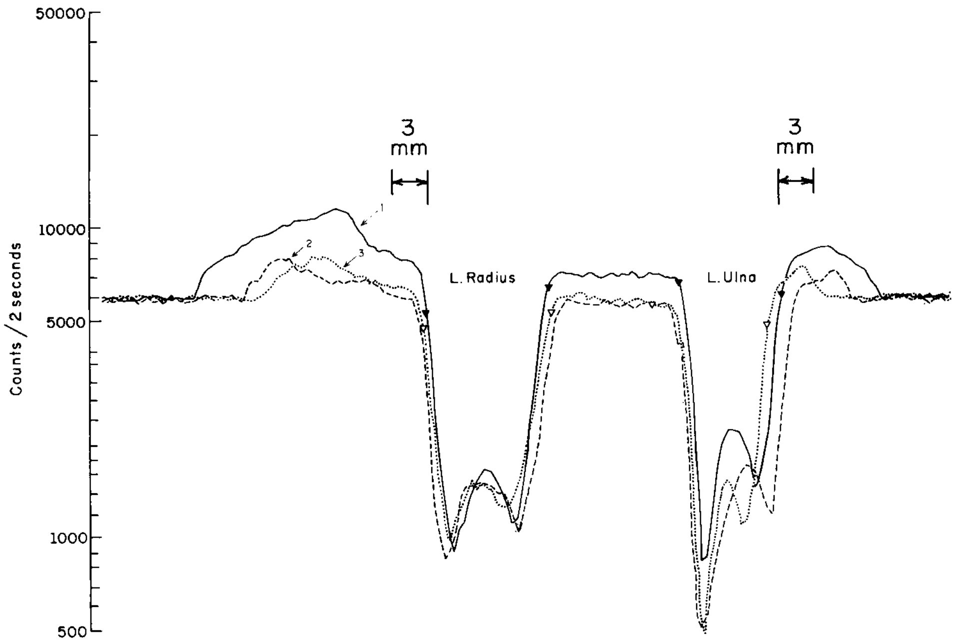


Fig. 2. Midshaft left arm scans of the individual designated (1), (2) and (3) of Fig. 1. The measurements are taken with arm immersed in water. The scans are plotted directly from the data with no displacement as in Fig. 1.

mates those of the midshaft radius. The beef fat employed in these studies was found difficult to accurately shape or measure. Therefore, the shapes and the dimensions of fat configurations are only approximate.

Results

A comparison of the scan of a fat-free phantom arm to several human arms in Fig. 1 shows an increased transmitted intensity toward the arm edges which can be seen to be larger the smaller the ponderal index (HUBER 1969) *R*o, where

$$Ro = \frac{\text{height in cm,}}{\sqrt[3]{\text{weight in kg}}}$$

and a low ponderal index indicates greater obesity. Subjects 2 and 3 in Figs 1 and 2 have approximately the same increase in transmitted intensity over the I_0^* level. There is no significant change in transmitted intensity when the beam enters the phantom arm from the tissue equivalent material (Super Stuff) until the bone is reached.

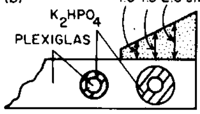
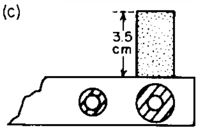
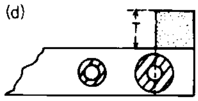
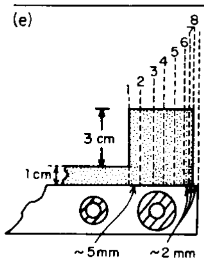
CONFIGURATION OF FAT	Io* BASED ON THE MEAN OF SIX VALUES: BETWEEN BONES[a]	REGION BEYOND EXTERNAL EDGE[b]	REGIONS ON BOTH SIDES OF BONE[c]
(a) APPROXIMATELY UNIFORM THICKNESS OF 2.5 cm	+1	+1	+1
(b) 	−9	+3	−3
(c) 	−32	−32	−32
(d)  T (cm) 1	−6	+2	−2
(d) T (cm) 2	−9	+5	−1
(d) T (cm) 4	−15	+15	+1
(e)  POSITION OF FAT STEP 1			+1
POSITION OF FAT STEP 2			−7
POSITION OF FAT STEP 3			−4
POSITION OF FAT STEP 4			+3
POSITION OF FAT STEP 5			+8
POSITION OF FAT STEP 6			+7
POSITION OF FAT STEP 7			+10
POSITION OF FAT STEP 8			+1

Fig. 3. Per cent error in the determination of the integral value for different arbitrarily chosen configurations of fat. The bone standard plus fat are immersed in 8 cm of water.

Scans with the arms immersed in water (Fig. 2) show that the fractional increases in transmitted intensity at the edges of the arm were approximately the same, while the shape of the 'hump' of increased transmission was slightly different, for the two cases. This suggests that the distribution of fat in soft tissue of the arm is the primary cause for a greater transmission than is expected for soft tissue plus tissue equivalent material. The replacement of each centimeter of water by subcutaneous beef fat resulted in a 20 per cent increase in transmitted intensity. Based on these data, we estimate that individual 1 in Figs 1 and 2 has a peak thickness of a little less that 4 cm of fat lateral to the radius and a thickness of about 1 cm between the radius and ulna. These estimates are to be accepted as very approximate and are used only as a guide in selecting fat thicknesses to be used in the examinations outlined in Fig. 3.

Table

Integral values (mm) for radius and ulna using different methods to obtain I_0. Forearm constraint and tissue equivalent material*

Invidual in Figs 1 and 2	1			
	SS/PB*		WI**	
	Radius	Ulna	Radius	Ulna
Method employed to obtain I_0*:				
a) Mean between radius and ulna	17.7 −12 %	18.5 −9 %	17.7 −7 %	12.5 −7 %
b) Mean of six successive counting intervals starting on the third interval from the edge of the radius (ulna) away from the ulna (radius)	22.9 +14 %	22.5 +11 %	20.2 +6 %	14.7 +9 %
c) Mean of six intervals, three on each side of radius (ulna) starting on the third interval from the edges of the bone	20.1	20.3	19.0	13.5
d) Value taken at a point outside the bone 3 mm from the edge of the radius (ulna) away from the ulna (radius)	23.3 +16 %	22.6 +11 %	20.5 +8 %	14.7 +9 %
e) Value taken at a point outside the bone 3 mm from the edge of the radius (ulna) toward the ulna (radius)	17.5 −13 %	18.9 −7 %	17.7 −7 %	12.6 −7 %

* Super Stuff in plastic box
** Water immersion

The errors resulting from the presence of the different configurations of fat shown in Fig. 3 were determined. The maximum fat thickness used was less than that estimated to be present in the individual designated 1 in Figs 1 and 2. The integral values obtained for the scans of the various fat configurations are dependent on the manner in which the I_0* values are determined. The I_0* was determined in three different ways. The method designated 'between bones' used 6 intervals starting from the third from the edge of the large simulated bone going toward the smaller simulated bone, that designated 'region beyond external edge' uses six intervals on the opposite side starting with the third from the edge and 'regions on both sides of the edge' refers to the mean of six intervals three on each side starting on the third interval from the edges. The distance traversed in one counting interval was 0.549 mm.

Table *(cont.)*

2				3			
SS/PB*		WI**		SS/PB*		WI**	
Radius	Ulna	Radius	Ulna	Radius	Ulna	Radius	Ulna
20.3 −1 %	17.7 −6 %	18.1 −3 %	16.4 −6 %	16.7 −8 %	14.9 −5 %	16.2 −6 %	12.8 −8 %
21.3 +4 %	20.5 +8 %	19.8 +6 %	19.1 +9 %	19.7 +8 %	16.6 +6 %	17.8 +3 %	15.0 +8 %
20.5	18.9	18.6	17.5	18.2	15.7	17.2	13.9
20.9 +2 %	21.2 +12 %	19.7 +6 %	19.0 +9 %	19.8 +9%	16.4 +4 %	17.7 +3 %	15.5 +12 %
20.0 −1 %	18.3 −3 %	18.1 −3 %	16.5 −6 %	16.8 −8 %	14.1 −10 %	16.6 −3 %	12.6 −9 %

The per cent error was determined from the ratio of the integral values obtained with the fat present to that obtained when water replaces fat. The integral values for the standards immersed in water agree with those reported by other laboratories for the same type of standards (Zeitz & Freed, Witt et coll.). The errors obtained for configurations (b) and (d) of Fig. 3 are found to be a minimum when the I_0^* is based on the average of the transmitted intensity immediately adjacent to the two edges of the bone. For this reason only this averaging method of obtaining the I_0^*, which for future reference will be called double-edge averaging, was used to investigate the error for the different configurations of (e) in Fig. 3. The errors found in (a) of Fig. 3 show that a uniform thickness of fat introduces no appreciable error with the different methods used to determine I_0^*. For a fat configuration similar to that of (c) of Fig. 3 which is unlikely to occur in a human forearm, the large error found is independent of the manner in which the I_0^* is determined. For a step type configuration, which may be close to what occurs in some humans' arms as suggested in the scan of individual 1 (Fig. 2), even the method of double-edge averaging which results in a minimum error still gives a value which deviates considerably from the actual or true integral value for certain positions of the step.

The integral values were determined for the radius and ulna of individuals 1, 2 and 3 (Figs 1, 2) on the basis of five different methods for obtaining I_0*. The integral values for the arm in Super Stuff and in water are not directly comparable since the scans in the two cases were inadvertently at slightly different positions on the arm.

The double-edge averaging technique for obtaining I_0* results in a calculated value which is closest to the true integral value but even this value could be off by 3 per cent or considerably more from the true value for possible configurations of fat in obese individuals. Let us assume that double-edge averaging results in the most accurate determination of bone mineral content in obese individuals. Calculated per cent deviations from this 'best integral value' can be determined and are given under the integral values of the Table.

Discussion

It is clear from the Table that the method employed for determining I_0* has a considerable effect, and whether compression is or is not used on the arm has some slight effect, on the value obtained for the bone mineral content of the arm of obese individuals. Using water immersion, where there is no compression of the arm, does not in all cases diminish the deviations from the 'best integral value' for the different techniques used to obtain I_0*. It does for the radius measurement of individual 1, but increases it slightly in the cases of the radius of individual 2 and the ulna of individual 3.

The data given in the Table suggest that considerable variation in the bone mineral content measurement of human arms is possible with a 'single-energy' photon absorptiometric bone mineral analyzer if different techniques are used to determine I_0*. The magnitude of this variation could be evaluated by measuring the bone mineral content on the same obese individual with two instruments which use the two different techniques for determining I_0*, i.e., the double-edge averaging and the method designated (d) in the Table. The latter technique is presently being used in the Norland—Cameron bone mineral analyzer employed in some laboratories.

The 'single-energy' photon absorptiometric technique gives a precision in determining the integral value of about ±2 per cent (ZEITZ) for forearm bones for all individuals regardless of degree of obesity. Therefore, the method of photon absorptiometry is a very useful tool for serial examinations of bone mineral content of the forearm bones. Further work is required if one is to determine the accuracy of serial examinations on individuals where there is a drastic change in the subcutaneous fat content of the arm in the course of the investigation.

With relatively large differences in results possible with different instruments for obese individuals, it would seem advisable in reporting results to explicitly and carefully define the method employed to obtain the integral value and to give the proportionality factor used to obtain the absolute bone mineral determination from the integral value.

We are presently considering possible approximate corrections related to the obesity of the individual as well as attempting to determine if there is an obesity index level below which the error in the determination of bone mineral content remains below a fixed preassigned value such as 2 or 3 per cent.

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SUMMARY

Investigations of bone phantoms with fat configurations suggest that mineral content measurements of the forearm bones by the 'single-energy' photon absorptiometric technique could be in appreciable error for certain marked fat configurations. Actual profiles of transmitted intensity for the mid-forearm of obese individuals indicate that the bone mineral content determinations on these individuals could differ for different absorptiometric instruments. Because of these possible differences, it is suggested that the method employed to obtain the integral value be explicitly and carefully defined.

ZUSAMMENFASSUNG

Untersuchungen von Knochenphantomen mit Fettkonturen lassen vermuten, dass Messungen des Mineralgehaltes mit der 'monoenergetischen' Photonen-Absorptionstechnik für gewisse ausgeprägte Fettkonturen mit einem wesentlichen Fehler behaftet sein können. Aktuelle Profile der durchgelassenen Intensität vom mittleren Unterarm fetter Personen deuten darauf hin, dass Bestimmungen des knöchernen Mineralgehalts dieser Personen mit verschiedenen Absorptionsinstrumenten unterschiedliche Ergebnisse geben können. Wegen dieser möglichen Differenzen wird daran erinnert, dass die verwendete Methode, mit der der Integralwert erhalten wird, ausführlich und sorgfältig präzisiert werden soll.

RÉSUMÉ

Des recherches faites sur des fantomes osseux entourés de masses graisseuses font penser que les mesures du contenu minéral des de l'avant-bras par la technique absorptiométrique de photons 'd'une seule énergie' pourraient donner une erreur appréciable pour certaines masses graisseuses volumineuses. Les profils d'intensité transmise pour le milieu de l'avant-

bras d'individus obèses montrent que les mesures du contenu minéral de l'os chez ces individus peut différer suivant les différents instruments absorptiométriques. En raison de ces différences possibles l'auteur propose que la méthode employée pour obtenir la valeur intégrale soit explicitement et soigneusement définie.

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