Fat, water and tissue solids of the whole body less its bone mineral

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ALLEN, T. H., B. E. WELCH, T. T. TRUJILLO AND J. E. ROBERTS. *Fat, water and tissue solids of the whole body less its bone mineral.* J. Appl. Physiol. 14(6): 1009–1012. 1959.—Except for bone mineral, the body is shown to belong to the same water:fat:protein system as its soft tissues. Hence, an equation verified with a variety of freshly isolated tissues can be used to estimate the body fat and the so-called total tissue solids. On the average, there are 0.784 kg of water/kg of body weight less bone mineral and fat. However, this water content probably fluctuates between extremes of 0.816 and 0.752, in accordance with the time elapsing since imbibing much water. This causes the density of the tissues in the fat-free, bone mineral-free body to range from 1.050 to 1.071. Combined simultaneous measurements of water, density and bone mineral, therefore, are required for the estimation of fat and tissue solids. Bone mineral occurs in the proportion of about one part to three parts of tissue solids, irrespective of ranges in quantities of fat and water among 30 healthy persons.

THE FIRST SUITABLE MEASUREMENTS of human body density (1) gave substantiation to postulations on the 'lean body mass' (2). Some important details pertaining thereto were described by Morales *et al.* in 1945 (3) and again in 1958 (4), in reply to questions which had been evoked by the growing interest, criticism and appreciation of Behnke's approach to body composition.

We have sought to verify the operation of the constants in the body composition equations from measurements performed on numerous tissues, including human fatty tissue (5) and bone (6). The soft tissues conform fairly well with a precise mathematical relationship between the water content and the densities, when stated on a fat-free basis. As shown below, this information can be applied to the intact human body. To do this, one first estimates the bone mineral (6), and then its effects on whole-body density and water content are removed from consideration. Thus, the bulk of the body is viewed as a mixture of soft tissues consisting of a water:fat:protein system which is shown to operate between extremes almost according to the manner deduced by Siri (7).

METHODS

The following measurements of each subject were begun within a period of 2 hours or less.

Weight and density. Body weight to the nearest 10 gm, as noted with a calibrated Plima scale, was taken when the bladder and bowels had been evacuated following an overnight fast. Weighing under water was performed three times on each subject, as described by Welch and Crisp (8), who have introduced a slight correction for the depth under water. The mean observed density was corrected further by adding 0.001 gm/ml for air judged to present in the gastrointestinal tract (9). The men were nude. The women wore undergarments, bouyant to 10 gm.

Bone mineral estimation. Height and joint diameters were noted to the nearest millimeter, the subject being erect and barefoot. The intercondylar dimensions at the elbows, wrists, knees and ankles (10) were measured with machinist's calipers, the jaws of which were fastened tightly in place and then removed and laid along a millimeter rule to sight for distance. The estimated weight of bone mineral is $m = 3.9(10^{-4})(H)(\bar{T}^2)$ where height, H, and the mean transverse diameter, $\bar{T}$, are in centimeters (6). The density of bone mineral is d = 2.8 (6).

Body water. Deuterium oxide (50 ml) and tritium-enriched water (5 ml, 3.7 mc) were ingested simultaneously and followed with 450 ml of hot tea, after which nothing was drunk for 5 hours (11). Four subjects received HTO only. The Consolidated Electrodynamics Corporation model 21-620 mass spectrometer was used to measure HDO concentrations in serum and urine water (11). HTO in urine was measured by a liquid scintillation method (12). The weight of body water was computed as that immediately prior to ingestion of the water tracers (11).

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TABLE 1. *Estimates of Bone Mineral and Kilogram Quantities of Water, Fat and Dry Solids**

m	M_1	D_1	W_{HDO}	W_{HTO}	F†	F‡	M_2†	M_2‡	M_3†	M_3‡
					Men					
3.64	52.82	1.018	34.4	(36.8)	10.4	(7.2)	42.4	(45.6)	8.0	(8.8)
3.16	60.76	1.006	34.4	35.9	17.6	16.5	43.2	44.3	8.8	8.4
3.89	61.94	1.014	39.5	41.3	13.4	12.1	48.5	49.8	9.0	8.5
3.35	59.50	1.014	37.5	36.6	13.2	13.9	46.3	45.6	8.8	9.0
4.12	64.79	1.015		41.8		13.5		51.3		9.5
3.75	61.00	1.016	36.8	37.8	14.5	13.7	46.5	47.3	9.7	9.5
3.31	60.57	1.018	35.2	37.5	15.1	13.4	45.6	47.2	10.4	9.7
3.12	52.34	1.033		32.2		9.8		42.5		10.3
3.78	65.73	1.018	39.2	40.8	15.7	14.5	50.0	51.2	10.8	10.4
3.47	71.30	1.007	37.6	38.8	22.5	21.6	48.8	49.7	11.2	10.9
3.64	71.49	1.010	40.3	40.8	20.1	19.7	51.4	51.8	11.1	11.0
3.22	61.25	1.025	36.0	36.9	13.9	13.2	47.4	48.1	11.4	11.2
3.10	62.57	1.022	35.8	37.0	15.4	14.5	47.2	48.0	11.4	11.1
4.29	79.91	1.000	39.9	42.3	28.3	26.5	51.6	53.4	11.7	11.1
3.89	70.48	1.017	42.6	41.9	16.5	17.0	54.0	53.5	11.4	11.6
3.82	61.65	1.034	41.4	40.5	8.9	9.5	52.8	52.2	11.4	11.7
4.24	65.11	1.037	44.2	44.3	8.6	8.5	56.5	56.6	12.3	12.3
4.14	73.71	1.017	41.7	41.5	19.4	19.5	54.3	54.2	12.6	12.7
4.43	87.56	1.006	46.0	49.1	28.0	25.7	59.6	61.9	13.6	12.8
4.16	73.65	1.025	43.1	45.1	16.8	15.4	56.9	58.3	13.8	13.2
4.42	93.53	1.005	46.9	52.5	31.8	27.6	61.7	65.9	14.8	13.4
4.51	74.40	1.038	49.6	50.4	10.3	9.7	64.1	64.7	14.5	14.3
3.63	118.01	0.991	(48.2)	55.8	(52.3)	46.7	(65.7)	71.3	(17.5)	15.5
					Women					
2.72	53.67	1.005		28.6		17.0		36.7		8.1
2.85	56.27	1.010	33.7	32.7	14.3	15.1	42.0	41.2	8.3	8.5
2.63	54.80	1.008	30.3	29.2	16.1	16.9	38.7	37.9	8.4	8.7
2.83	58.81	1.009	32.8	32.1	17.0	17.5	41.8	41.3	9.0	9.2
2.99	61.49	1.006	33.0	31.7	19.1	20.1	42.4	41.4	9.4	9.7
3.25	68.05	1.002	35.4	36.3	22.7	22.0	45.4	46.1	10.0	9.8
3.15	66.96	1.016		37.4		18.1		48.9		11.5

* In 30 men and women, on the basis of relation between M_1, D_1 and W by HDO and HTO methods. Parentheses enclose results believed to be dubious because of possible error in W. † Using D_1 and W by HDO. ‡ Using D_1 and W by HTO.

Equations. The body weight consists of bone mineral, fat, water and a residual mass. $M = m + F + W + M_3$. Other masses are defined as: $M_1 = M - m$; $M_2 = M_1 - F$; $M_3 = M_2 - W$. Having noted the density of the whole body, the density of the body less bone mineral is clearly $D_1 = (M - m)/(V - v)$ which can be rewritten:

$$D_1 = \frac{dDM_1}{dM - Dm} \qquad (1)$$

Studies of isolated tissues showed that the major constituents of the body resemble a physical system of simple admixture. The following equation was derived and verified:

$$F = M_1 \left(\frac{2.516}{D_1} - 1.793 \right) - 0.740\ W \qquad (2)$$

where the numerical values of the constants are based on the densities of fat, water and a dried, defatted residual mass (5).

RESULTS

The observed densities and content of body water in 30 human beings are plotted in figure 1 along the dashed curve. When extended to the abscissa, this curve fails to describe the fatty tissues (5), and far too low a value is obtained for d_f, the density of fat. What causes the whole body not to match its fatty tissues? Obviously, the body contains a material of high density and low water content, whereas this material is absent from the soft tissues. Bone mineral can be corrected for as proposed above. Once this is removed from consideration, the body water is contained in a mass, smaller by 2.5–4.5 kg and of lower density. The data points corresponding to these corrected water content and densities are scattered along the curve which can be seen to describe both fatty tissue (5) and the body less bone mineral. This curve was drawn by utilizing *equations 3* and *4* of the preceding study (5) and also the mean δ value of the present subjects. The acceptance of this δ value accomplishes a weighting of the δ and D_2 values of the body's individual soft tissues, which values lie along the curve ranging between d_w and d_s. The intersection of the two curves gives the weighted values of the water content and density of the healthy body when free of fat and bone mineral. Note, when the water content is zero, the density, d_f, is that of neutral fat as shown by the intercept on the density axis.

Some quantitative aspects are given (table 1) under headings which show that estimates of fat differ to the extent by which there is variation between the measurements of body water by either method (11, 12). This also holds for M_2, which is the size of the body less its bone mineral and fat. When, from the later, the measured weights of water are deducted, the M_3 sizes usually agree to within a few tenths of a kilogram. Although the esthetic concept of a youthful lean body is lacking, it is interesting that M_3 is like a dried-out, defatted mass of protein together with traces of body solutes, glycogen, etc. This mass in the 30 human beings tested necessarily has a mean density of 1.40, as shown in the preceding report (5).

In 24 of the subjects the δ value, being the ratio of W to M_2 (5), is similar with either the HDO or the HTO methods. Among the entire 30 subjects the degree of hydration is also similar, as judged from a mean $\delta = 0.784$, with $\sigma_\delta = 0.016$. These healthy men and women therefore have a mean D_2 value of 1.061 (*eq. 3* (5)) which is the density of the body less bone mineral and fat. However, body density varies inversely with body water content (fig. 2) and appears to fluctuate in accordance with water intake and output. To show this, let us double the σ_δ and let it operate about a body-water size of 40 kg, whereupon ± 1.6 kg would be the fluctuation. Some would refuse this as being much too large a draught, yet, during a single day twice this quantity is usually drunk and taken with food. While the body maintains its average daily water balance, δ could fluctuate between extremes of 0.816 and 0.752 and cause D_2 to range from 1.050 to 1.071.

DISCUSSION

Actual determinations of density, water and fat in tissues were shown to permit the accurate estimation of

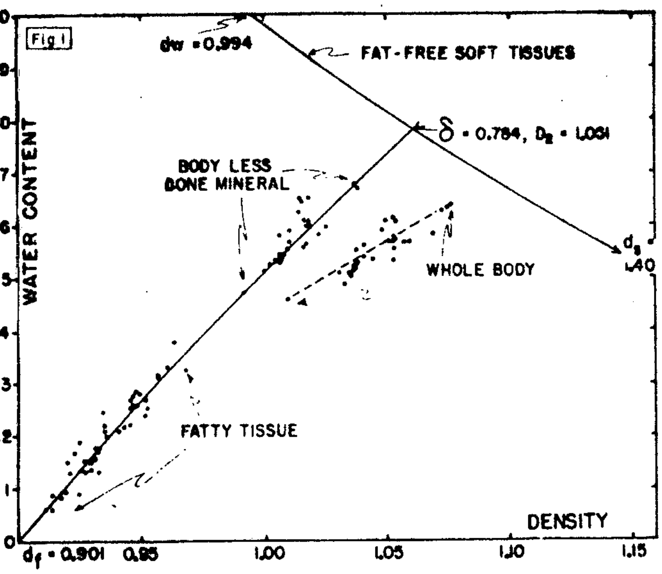

FIG. 1. Showing, once effect of bone mineral is removed, that a water:density system can be defined in terms of mean water content of the body's fat-free soft tissues. This water content of 0.784 gm/gm occurs at a fat-free, bone mineral-free density of 1.061 gm/ml, which is the intersection with the curve of fat-free soft tissues ranging between the density of water and the density of the so-called tissue solids.

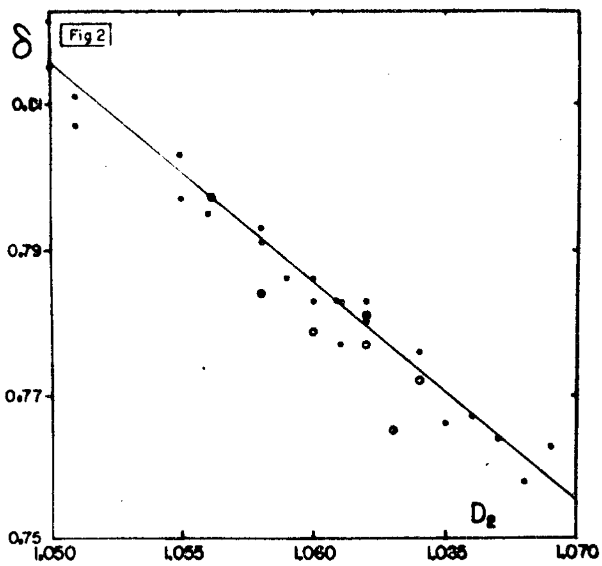

FIG. 2. Curve showing relationship between water content and body density on the bone mineral-free, fat-free basis. 23 men, *filled circles*; 7 women, *circles*.

fat from measurements of tissue density and water (5). The present results on human beings extend the tissue studies and show that correction for the high density of dry bone mineral (6) allows the body to match its soft tissues as to water, fat and solids. To predict a person's quantity of fat, therefore, requires measurements of bone mineral, body water and body density. The measurements of water and density should be done at the same time to avoid fluctuations in density caused by variation in body water, as from drinking and eating. Ideally, when the densitometry has been completed the water tracer is then taken. Although more than 3 hours often elapse before the HDO or HTO is thoroughly mixed, it is easy to state the weight of body water just prior to taking the water tracer (11). Behnke and Siri (13) are believed to be the only others reporting all of the necessary dimensions, including joint diameters from x-ray films. Although they measured the body density and water at different times when the body weight was not the same, their 22 sailors can be shown to have a mean $\delta = 0.784$ in exact agreement with our subjects. However, the variation is larger, as expected; σ_δ, being 0.029, is almost twice that presently observed.

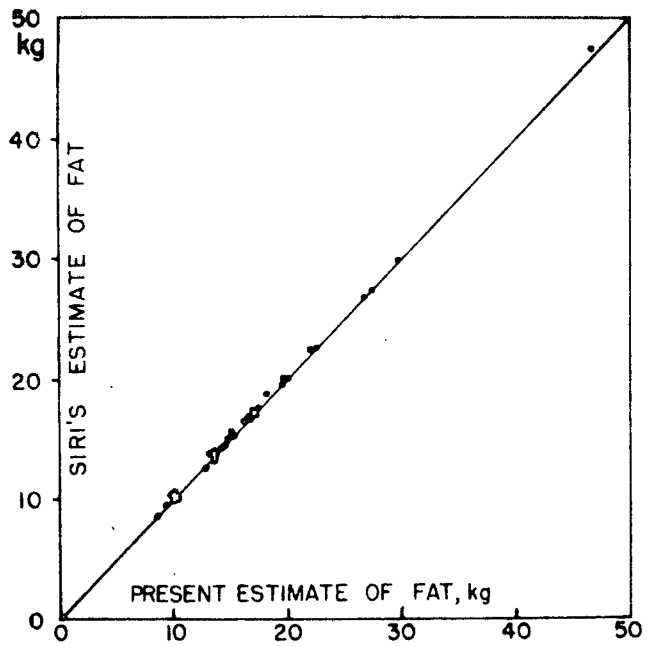

FIG. 3. Siri's equation is based on an assumed constancy between bone mineral and protein, whereas in our equation an actual estimate of bone mineral is introduced. However, good agreement occurs in the prediction of fat.

It is of interest to compare the estimates of fat by the present method with that using Siri's equation (7). As shown in figure 3 the agreement is remarkably good in healthy persons of either sex with quantities of fat in kilograms ranging from 8 to 48. On the average, his method estimates 40 gm more fat than ours; the variation between the two methods has a $\sigma = 287$ gm. Thus, Siri's original simplifying deductions can be shown to hold throughout a wide range in variation of the bone mineral:fat:water:solids of healthy persons. This occurs despite his using 3 instead of 2.8 for the density of bone mineral (6), 1.34 instead of 1.40 for the density of tissue solids (5) and a ratio of 5/12 for bone mineral to tissue solids.

It should be pointed out that M_3 is so defined as to include the soft tissue solids contained within the skeleton (6), which amounts to several kilograms of dry, fat-free solids. This lowers m/M_3 from 5/12, as implied by Siri, to 1/3, as can be noted from table 1. Is it also possible that bone mineral is a fairly uniform proportion of the fat-free body? Keys and Brozek (14), in citing analyses of a few admittedly poor specimens of cadavers, were led to believe that about 7% of the fat-free body is ash. This agrees with the present results. The fat-free body is $L = M_2 + m = M_3 + \delta M_2 + m = M_3/(1 - \delta) + m = m/\gamma(1 - \delta) + m$. Hence, $m/L = \gamma(1 - \delta)/[1 + \gamma(1 - \delta)]$. Where $\gamma = m/M_3 = 0.337$ and $\delta = W/M_2 = 0.784$, the ratio of $m/L = 0.0679$. Therefore, it is reasonable to accept 6.8% of the normally hydrated, fat-free body as being composed of bone mineral, realizing that the 2-σ range lies between 5.7 and 7.9%.

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REFERENCES

1. BEHNKE, A. R., B. G. FEEN AND W. C. WELHAM. *J.A.M.A.* 118: 495, 1942.
2. BEHNKE, A. R. *Harvey Lect.* 37: 198, 1941-1942.
3. MORALES, M. F., E. N. RATHBUN, R. E. SMITH AND N. PACE. *J. Biol. Chem.* 158: 677, 1945.
4. MORALES, M. F. AND A. R. WILLIAMS. *J. Appl. Physiol.* 12: 225, 1958.
5. ALLEN, T. H., H. J. KRZYWICKI AND J. E. ROBERTS. *J. Appl. Physiol.* 14: 1005, 1959.
6. ALLEN, T. H. AND H. J. KRZYWICKI. *Human Biology.* In press.
7. SIRI, W. E. *Advanc. biol. med. Phys.* 4: 239, 1956.
8. WELCH, B. E. AND C. E. CRISP. *J. Appl. Physiol.* 12: 399, 1958.
9. BUSKIRK, E. R. *Human Biology.* In press.
10. TROTTER, M. E. *Am. J. Phys. Anthropol.* 12: 537, 1954.
11. WENTZEL, A. D., J. M. IACONO, T. H. ALLEN AND J. E. ROBERTS. *Phys. in Med. Biol.* 3: 1, 1958.
12. LANGHAM, W. H., W. J. EVERSOLE, F. N. HAYES AND T. T. TRUJILLO. *J. Lab. & Clin. Med.* 47: 819, 1956.
13. BEHNKE, A. R. AND W. E. SIRI. U.S. Navy Research and Development Technical Report TR-203 NS 080-001, Dec. 1, 1957.
14. KEYS, A. AND J. BROZEK. *Physiol. Rev.* 33: 245, 1953.