The mammalian body can be regarded as consisting of certain major phases: fat, bone, muscle, skin, nervous and visceral tissue. To be sure there are heterogeneities within each phase, but these are negligible in comparison to the differences in individual properties of the phases. Physiological experiments on intact animals frequently depend for their success on knowledge of how much of each of these components is present. To measure the relative proportion in the intact animal requires an indirect method. The present work is concerned with the theory and use of one such method.

Theoretical Considerations—It is assumed (1) that the fat component is the one subject to wide variation, while the proportions of other components to some standard component, say bone, are relatively constant (2). In terms of the following notation,

\[ M_f \text{ and } D_f = \text{mass and density respectively of fat} \]
\[ M_b \text{ and } D_b = \text{ " " " " " " bone} \]
\[ M_m \text{ and } D_m = \text{ " " " " " " muscle} \]
\[ M_s \text{ and } D_s = \text{ " " " " " skin} \]
\[ M_n \text{ and } D_n = \text{ " " " " " nervous tissue} \]
\[ W = \text{weight of animal} \]

and it is assumed that (a) muscle, skin, and nervous tissue are (in the adult) constant fractions, \( k \), of the mass of bone, or, symbolically,

\[ M_m = k_m M_b \]  \hspace{1cm} (1)
\[ M_s = k_s M_b \]  \hspace{1cm} (2)
\[ M_n = k_n M_b \]  \hspace{1cm} (3)

* The opinions or assertions contained herein are the private ones of the writers and are not to be construed as official or reflecting the views of the Navy Department or the naval service at large.

† Lieutenant (j.g.), H(S), U. S. N. R.
‡ Lieutenant (j.g.), H(W), U. S. N. R.
§ Lieutenant H(S), U. S. N. R.
and that (b) the densities of skin and nervous tissue are approximately the same as that of muscle:

$$D_s = D_n = D_m$$  \hfill (4)

From the notation and Assumptions 1 to 4, the following equations are obtained: the total mass of the body is

$$W = M_f + M_b + M_m + M_s + M_n = M_f + M_b(1 + k_m + k_s + k_n)$$  \hfill (5)

and the average density, $G$, of the body is

$$G = \frac{W}{\frac{M_f}{D_f} + \frac{M_b}{D_b} + \frac{M_m}{D_m} + \frac{M_s}{D_s} + \frac{M_n}{D_n}} = \frac{M_f}{D_f} + M_b\left(\frac{1}{D_b} + \frac{k_m + k_s + k_n}{D_m}\right)$$  \hfill (6)

If $k_m + k_s + k_n = K$, Equations 5 and 6 are readily solved for

$$\frac{M_f}{W} = \left(\frac{1 + K}{G} - \frac{D_m + KD_b}{D_bD_m}\right)\left(\frac{1 + K}{D_f} - \frac{D_m + KD_b}{D_bD_m}\right)$$  \hfill (7)

$$\frac{M_b}{W} = \frac{1}{1 + K}\left(1 - \frac{M_f}{W}\right)$$  \hfill (8)

$$\frac{M_m}{W} = \frac{k_m}{1 + K}\left(1 - \frac{M_f}{W}\right)$$  \hfill (9)

$$\frac{M_s}{W} = \frac{k_s}{1 + K}\left(1 - \frac{M_f}{W}\right)$$  \hfill (10)

$$\frac{M_n}{W} = \frac{k_n}{1 + K}\left(1 - \frac{M_f}{W}\right)$$  \hfill (11)

Thus, the gross composition of the animal may be determined from a knowledge of (1) the weight of the animal, (2) the body density of the animal, (3) the densities of fat, muscle, and bone, and (4) the ratios of muscle, skin, and nervous tissue to bone. In what follows, Equations 7 to 11 are established, and their use in the study of human body composition is indicated.

**Fat Content of Eviscerated Guinea Pigs**—On an animal such as the guinea pig it is possible to determine the body composition directly, as well as to calculate it theoretically, thus comparing the two values for a test of the theory.

In Paper I (1), the relationship of $M_f/W$ to $G$ in hairless, eviscerated carcasses was determined by direct methods, yielding what is in effect a plot of Equation 7. Even without analysis, the plot furnishes an obvious point of justification (see Fig. 1). Equation 7 predicts that the plot of $M_f/W$
versus $G$ should be a rectangular hyperbola \(^1\) displaced from its principal $x$ axis.

![Graph](image)

Fig. 1. The abscissa, $G$, represents the body specific gravity of the guinea pig, and the ordinate, $M_f/W$, represents the ratio of fat to body weight. The equation for the statistical line was obtained as described by Rathbun and Pace (1). The equation for the theoretical line is discussed in the text.

The theoretical curve of $M_f/W$ also appears on Fig. 1, and will be discussed after consideration of other quantities necessary for the computation.

\(^1\) That the nature of the relationship between the mass of any body component and the average body density is not linear but hyperbolic is deducible from purely dimensional considerations. The per cent of any component has the dimensions $(M)/(W)$, and the average density has the dimensions $(W)/(V)$. If the relationship were linear, the constant of proportionality would have to be $(M)/(V)/(W)/(W)$, while if the relationship were hyperbolic, the constant of proportionality would then be $(M)/(V)$. In the former case, the complexity of the constant and the fact that it contains the dimensions of one of the supposed variables argue against the assumption. The second is therefore favored as the simpler and more reasonable alternative.
EXPERIMENTAL

Densities of Tissues—The density of muscle was determined (3) by matching with standard CuSO₄ solutions. The mean of determinations on thirty animals was 1.066.

By direct determination, the density of general body fat obtained by extraction was found to be 0.912. That there is no significant difference between the densities of perirenal, intermuscular, and subcutaneous fat can be inferred from the fact that the CuSO₄ method gives respectively 0.927, 0.921, and 0.921 for these composite tissues.

The average density of the entire skeleton was determined on three guinea pigs. For this purpose all the bones were dissected out and cleaned individually, and the displacement of water by the entire mass measured.

The results agreed well among themselves: 1.430, 1.441, and 1.433 (mean = 1.43), and with the data of Tsai and Lin (4) for non-cleft bone. These authors also give the density of nervous tissue as between 1.04 and 1.05, a fact which made possible Assumption 4.

Direct determination of the density of shaved skin, scraped clean of subcutaneous fat, gives 1.06, and shows that the actual amount of skin is 40.4 per cent of the "skin" (including hair) removed in the usual skinning operation. It is also of interest to note that skin density may be calculated as follows: From the data of Williams (5), and if the density of protein is assumed to be about 1.25 (6), the following composition is obtained: water 66, protein 25, fat 7, inorganic salts, etc., 2 (total 100) gm.; approximate volume, 66, 20, 8, and 0 (total 94) cc. respectively. Whence the average density is 100/94 = 1.06. This figure is in close agreement with that obtained by actual measurement and further substantiates Assumption 4.

Ratios $k_m$, $k_s$, and $k_n$—The ratio of muscle mass to bone mass, $k_m$, was determined in the same three animals referred to above. So far as was possible the entire musculature was dissected out, freed of fat, and collected for weighing. From the data of Table I, a mean value of 5.34 was obtained for $k_m$.

A value for $k_s$ can be determined from the weight of bone and of skin freed of subcutaneous fat and hair by multiplying the "skin" weight by 0.404 as stated above. The mean was found to be 1.95.

$k_n$ defies simple, direct determination; consequently, its value was obtained by indirect means. Judging from a comparison between the diameters of peripheral nerves and the girth of the cord, it is estimated that the peripheral nervous system is about two-thirds the mass of the cord. Thus, one may arrive at an estimate of the mass of the entire nervous

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2 For this calculation, we are indebted to Lieutenant (j.g.) R. E. Eakin, II(S) U. S. N. R.
system. The data of Donaldson (7) give the ratio mass of spinal cord per mass of brain as 0.36; whence it follows that the entire nervous system is about 1.6 times the mass of the brain (for this order). From an allometric determination on the data of Crile and Quiring (8) for the guinea pig, brain weights for our animals (Table II) have been estimated.

**Table I**

*Ratio of Mass of Muscle and Skin to Bone*

<table>
<thead>
<tr>
<th>Guinea pig No.</th>
<th>Weight</th>
<th>Muscle</th>
<th>&quot;Skin&quot;</th>
<th>40.4 per cent &quot;Skin&quot;</th>
<th>Bone</th>
<th>k_m</th>
<th>k_a</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>572</td>
<td>172.1</td>
<td>150</td>
<td>60.6</td>
<td>32.3</td>
<td>5.47</td>
<td>1.88</td>
</tr>
<tr>
<td>2</td>
<td>639</td>
<td>164.6</td>
<td>196</td>
<td>79.2</td>
<td>35.8</td>
<td>4.76</td>
<td>2.21</td>
</tr>
<tr>
<td>3</td>
<td>699</td>
<td>222.4</td>
<td>175</td>
<td>70.7</td>
<td>40.0</td>
<td>5.80</td>
<td>1.77</td>
</tr>
</tbody>
</table>

**Table II**

*Ratio of Mass of Central Nervous System to Bone of Guinea Pig*

<table>
<thead>
<tr>
<th>Weight</th>
<th>Brain</th>
<th>Nervous system</th>
<th>Bone</th>
<th>k_m</th>
</tr>
</thead>
<tbody>
<tr>
<td>gm.</td>
<td>gm.</td>
<td>gm.</td>
<td>gm.</td>
<td></td>
</tr>
<tr>
<td>572</td>
<td>4.2</td>
<td>6.72</td>
<td>32.3</td>
<td>0.210</td>
</tr>
<tr>
<td>639</td>
<td>4.3</td>
<td>6.88</td>
<td>35.8</td>
<td>0.197</td>
</tr>
<tr>
<td>699</td>
<td>4.4</td>
<td>7.04</td>
<td>40.0</td>
<td>0.176</td>
</tr>
</tbody>
</table>

**DISCUSSION**

*Test of Equations*—There are two ways of combining the results in testing Equation 7. First, a plot of Equation 7 may be compared with a statistical fit to the data (Fig. 1). The parallelism between the two curves in the range 0 to 100 per cent fat is interpreted as a substantiation of the theoretical equations. The consistent error in the direction of yielding low values of G may well be due to the adherence of air bubbles to the animal’s surface and within its ears. A volume of air of about 2 cc. would cause the experimental curve to coincide with the theoretical. At present experiments are in progress to check this question by other specific gravity methods.

Second, Equation 7 may be solved for G(0), i.e., the value of G for \( M_f/W = 0 \), giving,

\[
G(0) = \frac{(1 + K)D_mD_b}{D_m + KD_b} \tag{12}
\]

Substituting the experimental results in Equation 12, we obtain the following:

\[
G(0) = \frac{(1 + 5.34 + 1.95 + 0.2)(1.066)(1.43)}{(1.066) + (5.34 + 1.95 + 0.2)(1.43)} = 1.099
\]
an intercept value which is practically coincident with an experimentally measured mean specific gravity value of 1.098 obtained on whole animal aliquot samples rendered fat-free by extraction as described in Paper I (1).

On the grounds of the agreement between theory and experimental data, two useful applications follow.

Composition of Whole Guinea Pigs—To this point, both the theoretical application and the experimental data have referred to eviscerated carcasses rather than to the intact animal. For reasons of technical convenience, the data of Paper I (1) were obtained on the eviscerated preparation.

However, there is no theoretical obstacle to an extension which includes the viscera. Thus, introducing $M_v$, $D_v$, and $k_v$ as the mass, density, and bone ratio respectively of the viscera, one has on solution a set of equations identical with Equations 7 to 11, except that now one defines

$$K = k_m + k_v + k_a + k_n$$  \hspace{1cm} (13)

Extrapolating the plot of visceral fat fraction versus visceral density to zero fat fraction gives 1.06 for visceral density. Furthermore, comparison of bone weights (obtained by multiplying the weight of the eviscerated carcass by the factor of Equation 8) with the weights of fat-free viscera (1)
yields a set of values for $k_v$ whose mean is 1.62. If this $k_v$ is combined with previous $k$ values and substituted in Equation 13, it is found that for the hairless intact animal $K = 9.11$. When this value of $K$ is used in Equations 7 to 11, a final result for the body composition of intact, hairless guinea pigs as a function of body density is expressed by the equations

$$M_f/W = 5.501 \, (1/G) - 5.031, \quad M_b/W = 0.5965 - 0.5440 \, (1/G), \quad M_m/W = 3.1840 - 2.9045 \, (1/G), \quad M_s/W = 1.1640 - 1.0617 \, (1/G), \quad M_v/W = 0.1193 - 0.1088 \, (1/G),$$

and is depicted graphically in Fig. 2.

**Application to Man**—As remarked above, the importance and merit of any indirect method of body analysis lie chiefly in its applicability to the living human being. Of the four requisites for the application of the equations it is clear that three can be readily met by the data. The weight and body density of human subjects are accurately determinable quantities (2). In the absence of any facts to the contrary, the composite (e.g. muscle with slight amounts of fat) tissue densities for man are the same as those for the common experimental mammals. The technical problem, therefore, reduces to the determination of the $k$ values. It may be possible to obtain three out of four ($k_m, k_s, \text{and} k_v$) directly from roentgenographs; $k_v$ can be estimated with comparative ease from measurements on cross-sections of human skin and from body surface areas by calculation with empirical formulae (e.g. that of DuBois). The substitution of the various values in Equations 7 to 11 can then be expected to yield gross composition of the human body with reasonable precision. Further work along these lines is in progress. However, even at the present stage of investigation it is possible to deduce a useful provisional equation which gives human fat content as a function of body density. If Equation 7 is written in terms of Equation 12, the following is obtained.

$$\frac{M_f}{W} = \frac{D}{G(0)} - 1 \left( \frac{G(0)}{G} - 1 \right) \tag{14}$$

The density of human fat is given as 0.918 in tables such as those of Hodgman (9). In view of the fact that the range of $G$ for guinea pigs (1) is virtually identical to that for man (2, 10), it may be assumed that $G(0)$ for man is very close to $G(0)$ for the guinea pig, i.e. in the neighborhood of 1.10. Substituting for $D_f$ and $G(0)$ in Equation 14, we obtain for man $M_f/W = 5.548 \, (1/G) - 5.044$. For purposes of comparison, the graph of this equation is shown in Fig. 2. Calculation of other components awaits further experimental data.

It is a pleasure to acknowledge the generous collaboration and counsel of Lieutenant I. Gersh, H(S), U. S. N. R., and the Pathology Facility of the Naval Medical Research Institute.
SUMMARY

By treating the body as a five phase system, equations are developed which give the amount of each tissue component as a function of body weight and average body density.

These equations are based on the assumption that there is a lean body mass in the guinea pig and in man of relatively uniform composition. Fat is regarded as the only component that exhibits appreciable relative variation. The quantitative data obtained on these guinea pigs substantiate this assumption.

In man, values for specific gravity comparable to those of the guinea pig have been obtained. On the basis of available data, therefore, the relationship between fat and body density as determined for the guinea pig appears to be directly applicable to man.

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