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MASTER

THREE-COMPONENT BODY COMPOSITION ANALYSIS BASED ON
POTASSIUM AND WATER DETERMINATIONS*

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ABSTRACT

The two-component model of body composition is shown to be inadequate to explain the observed changes of potassium and water as a function of age. A three-component model of body composition -- adipose, muscle, and muscle-free lean -- similar to that of von Döbeln is examined using potassium concentration (meq/kg total body weight) and body water (per cent) as parameters. Input data are averages as a function of age for 2160 subjects whose potassium was determined with a 4π liquid scintillation gamma counter and whose water was calculated from literature values for similar age groups. These subjects are supplemented by a group of 38 individuals measured by gamma counting and tritium water dilution and compared with a group of 35 subjects measured by K^{42} and tritium water dilution by another laboratory. Agreement among the results is excellent.

The numerical value of fraction adipose, muscle, and muscle-free lean is regarded as tentative because of the limited analytical data on the composition of the dissected components. The variation of the potassium to water ratio is, however, logically explained by the model, and a simple picture of the aging process for males results. From age 12 to 35, the fraction of muscle mass varies little from about 27 per cent, while adipose and muscle-free lean vary reciprocally. From age 35 to 70, the development can be interpreted either as replacement of muscle by muscle-free lean with constant adipose fraction or as the replacement of a constant mixture of these three components by connective tissue.

INTRODUCTION

At least one obvious fact is becoming better appreciated as further studies of body composition provide us with an increasing number of parameters measured to a constantly improving precision: that is, the human body is a very complex mixture of many components. The history of methods of estimating body composition is basically one of finding a satisfactory and useful compromise between the implications of this complexity, on the one hand, and the requirements of a practicable method, on the other. It is a fundamental principle that, in order to specify completely a multi-component system, one must determine at least as many parameters as there are components. A number of considerations prevent carrying this logic to its extreme, not the least of which is the desirability of nondestructive methods of measurements and the requirements of practicality, especially when large numbers of subjects must be measured. It may also be noted that the fewer components which are used in specifying body composition, the better chance there is of "overdetermining" the system (that is, of measuring more parameters than there are components and thus being able to check the hypothesis of uniform composition on the basis of internal evidence).

A variety of attempts have been made, therefore, to demonstrate constant proportionality between various components of the body so that a determination of one component would permit the inference of the amounts of the related components. In its extreme form, this

approach reduces the normal body to two components only (for example, "fat" and "lean," "obesity" and "nonobesity" tissue) so that, in principle, a single determination of one component (e.g., body water, total or exchangeable potassium, or density), in addition to gross weight, would uniquely define body composition. While such methods have had varying degrees of success, particularly with "normal" subjects (perhaps best defined in this connection as subjects who give reasonable and consistent results under the chosen method of analysis), they are clearly inapplicable to abnormal situations. They will also fail when the precision of the investigation exceeds the limitations of the fundamental assumptions of the method.

The present paper discusses the limitations of the two-component system and investigates a three-component system of body composition analysis, similar to that proposed by von Döbeln (W. von Döbeln, 1962) but based on different measured parameters, which may offer an increase in accuracy and precision without an inordinate increase in experimental complexity. Our motivation for the use of a more elaborate system is the failure of the simpler model to explain potassium to water ratios.

METHODS

Experimental Data. Most of the data used here have been previously published. The 4π liquid scintillation counter method (M. A. Van Dilla and E. C. Anderson, 1962) for determining total body

potassium by gamma ray measurement has recently been discussed in detail with respect to its precision and accuracy (E. C. Anderson, 1963). Briefly, the routine procedure (200 seconds counting time per subject) gives a precision and accuracy of ± 5 grams potassium, which corresponds to 4 per cent for an average adult male subject. When computing the average potassium concentration for a group of given age, the minimum error is determined by the standard deviation of the group due to the natural variance of the individuals and the number of subjects. The former has been determined to be 10 per cent for our population samples; therefore, for a group of 100 subjects (typical), the standard error of the mean is 1 per cent if random sample statistics apply. The standard deviation of a body water determination using tritium dilution is ± 0.7 kg water.

The measurements used are:

(a) A group of healthy male and female subjects: 28 males (age range 22 to 44, average 33) and 10 females (ages 16 to 51, average 32) were studied, total potassium being determined by the 4π liquid scintillator counter and body water by tritium dilution. The data are given in Table 1 and were previously reported (T. H. Allen, E. C. Anderson, and W. H. Langham, 1960).

(b) A large population sample consisting of 2160 persons (1512 males and 648 females) who visited the Los Alamos Scientific Laboratory during the period 1956-1961 (Table 2). These data are expressed as the averages for given age groups. A portion of the data

(1590 measurements made during 1956-1958) has been previously reported (E. C. Anderson and W. H. Langham, 1959; T. H. Allen, E. C. Anderson, and W. H. Langham, 1960). The additional measurements made since are in good agreement with the first group. Figure 1 compares two independent population samples in a plot of potassium concentration (in g/kg) versus age. The lines are based on the 1956-1958 data, shifted downward an arbitrary 2 per cent, and the points are 1959-1960 data. The average of ratios for age groups of the first to second set is 1.019 for potassium and 1.026 for body weight for the age range 11 through 60 years. The standard deviation of these group ratios about their mean is 2.9 per cent. The second population was comparatively small, age groups ranging in size from 14 to 118 subjects. For this set of data, therefore, the estimated standard error of the group means (based on group size and width of the group frequency distribution curve) is 1 to 3 per cent, in agreement with the observed deviation. For the final combined population sample, age groups range in size from 53 to 421 subjects, so that the precision of a group average is expected to be from 0.5 to 1.4 per cent. (A complete tabulation of the individual measurements is available from the author on IBM punched cards and as a printed listing.)

It was not feasible to determine body water on these large groups; data were, therefore, taken from the literature (I. S. Edelman, H. B. Haley, P. R. Schloerb, D. B. Sheldon, B. J. Friis-Hansen,

G. Stoll, and F. D. Moore, 1952; J. D. McMurrey, E. A. Boling, J. M. Davis, H. V. Parker, I. C. Magnus, M. R. Ball, and F. C. Moore, 1958; T. H. Allen, B. E. Welch, T. T. Trujillo, and J. E. Roberts, 1959; T. H. Allen, E. C. Anderson, and W. H. Langham, 1960; E. A. Boling, W. L. Taylor, C. Entenman, and A. R. Behnke, 1962) on the average body water as a function of age for both sexes. Figure 2 is a plot of these data. For numerical analyses, the actual data points were used and not the smoothed curve.

Figure 3 shows the variation with age of the gross body weight of the combined population sample whose potassium was determined by gamma counting. Bars indicate standard error of the mean as estimated from observed variance and sample size.

(c) A third set of potassium-water data has been taken from the literature for comparison with our measurements. This is the measurement at the Naval Radiological Defense Laboratory (E. A. Boling, W. L. Taylor, C. Entenman, and A. R. Behnke, 1962)* of 35 healthy male subjects (age range 20 to 56 years, average 31 years) by K^{42} and tritium isotope dilution methods (Table 3). These data provide an independent check on our values for water and potassium and extend our data in an important respect by including a group of 7 obese males.

*We are indebted to Drs. Boling and Behnke and to the Naval Radiological Defense Laboratory for their kind permission to make rather extensive use of these excellent data.

(d) Additional age groups can be obtained by averaging the individual data of Tables 1 and 3. These are given in Table 4.

Choice of Units. As evident from the figures so far presented, we will express all data in concentration units: potassium as meq/kg, and water as per cent of gross body weight. This choice is made for two reasons. First, to the extent that biochemical factors are important in determining body composition, concentrations rather than total quantities are clearly the relevant parameters, since they are the basic driving forces in chemical equilibria and reaction rates. Second, we wish to investigate the aging process as a change in composition rather than as a change in size, so that a normalization for weight is required by the model under study. We are indebted to Professor S. M. Garn for pointing out the statistical hazards inherent in calculation of the regression of potassium concentration on water concentration as a result of the presence of a common factor on both sides of the equation. However, a statistical study of these data shows that "spurious" correlations do not contribute significantly to the following analysis, primarily because of the limited range of weight changes and the high precision of the data.

Model of Body Composition. One of the basic difficulties in determining "lean body mass" from body potassium is the large difference in potassium content of muscle compared with that of the

remainder of the lean body (W. von Döbeln, 1962; E. Oberhausen and C. O. Onstead, 1963). The classical division of the body into two parts, lean body mass and excess fat (A. R. Behnke, 1943; A. Keys and J. Brozek, 1953) or obesity and nonobesity tissue (H. Ljunggren, 1957), assumes a more or less constant composition for the two components. For analytical methods based on water or density determinations, this is a better approximation than for analyses based on potassium (either exchangeable or total). (The water content of muscle appears to be within 11 per cent of that of the remainder of lean body mass; whereas, its potassium content is 18 per cent higher.) We, therefore, choose to follow von Döbeln (W. von Döbeln, 1962) and divide the body into three components: adipose, muscle, and the remainder (difficult to characterize physiologically, since it includes skeleton, skin, nervous system, and all the internal organs), which can be termed "muscle-free lean." Figure 4 compares the three methods of analysis. Clearly, such a three-component system can only be analyzed if at least two components (in addition to total weight) are measured. Von Döbeln used potassium and skeletal measurements; the present paper will use potassium and water. These two parameters can be determined with higher precision than most others, and the measurements are fairly easy to perform.

One difficulty with this approach is that very few analytical data are available on the potassium and water content of body components. We use the direct analytical data of Forbes and Lewis (G. B.

Forbes and A. M. Lewis, 1956), although only two determinations were made, on male cadavers of ages 46 and 60 years, respectively. We have calculated the average potassium and water contents of fat-free muscle and of "lean body minus muscle" from their data, as shown in Table 5. The third component, adipose tissue, is assumed to be 70 per cent fat* and the remaining cellular mass to have the composition of muscle-free lean. Results obtained by this three-component analysis can be easily converted into Behnke's system by adding 30 per cent of adipose tissue to the sum of the other two components to give "lean body mass" and considering the remaining 70 per cent as "fat." However, lean body mass is here assumed to be of variable composition, depending on its muscle fraction. The permissible range of variation predicted by the current model is shown in Fig. 5, in which total potassium (in meq/kg) is plotted against total water (in per cent). The three points are the assumed components with hypothetical composition as given in Table 5. Any composite formed by adding arbitrary fractions of each of the three components must of necessity lie within the triangle. Even this area is, however, not entirely accessible to body composition; the actual area will be limited by such physiological requirements as may exist for minimum fraction muscle, maximum fraction adipose tissue,

*It was intended to use 62 per cent (J. Brozek and A. Keys, 1955; L. C. Johnston and L. M. Bernstein, 1955); the arithmetic error was not detected until too late to change. Changing this parameter will not affect the conclusions of this paper significantly. The main effect would be to increase the fraction of adipose by about 10 per cent of its value (that is, by about 2 per cent of gross body weight with a corresponding decrease in muscle and muscle-free lean).

etc. While it is impossible to calculate a priori the composition of the three components solely from the in vivo data on body potassium and water, an incorrect assumption as to the nature or composition of the components may be revealed by the observation of a potassium-water combination lying outside the permitted area.

A more conventional representation of body composition as a ternary system is on the basis of a diagram such as that shown in Fig. 6. (For an elementary discussion of the properties and use of ternary diagrams, see S. Glasstone, 1946.) In this diagram, the vertices of the equilateral triangle represent each of the "pure" components: adipose, muscle, and muscle-free lean. The fractional composition in terms of these components of a point within the triangle is given by the relative lengths of the perpendiculars from the point to the three sides of the triangle. Each of the three edges is calibrated in the per cent of one of the components. The illustrative point corresponds to 35 per cent adipose, 65 per cent muscle-free lean, and 20 per cent muscle. Three components are present, but there are only two independent variables; the amount of the third is 100 per cent minus the sum of the other two. This type of diagram will be used later to illustrate the change in body composition as a function of aging.

An interesting conclusion regarding the relation of water and potassium to composition can be drawn from the ternary diagram as illustrated in Fig. 7. In this figure, the contours of constant

potassium and constant water have been drawn using the data of Forbes and Lewis (G. B. Forbes and A. M. Lewis, 1956), and the scales on two edges of the triangle now refer to potassium and water concentrations, respectively. (The scales for adipose, muscle, and muscle-free lean have been omitted but are the same as in Fig. 6.) The water contours are nearly parallel to the right side of the triangle (that is, to lines of constant adipose concentration). Variations in muscle to muscle-free lean ratio have little effect on it. This explains the excellence of the water method for determining adipose. For example, along the 55 per cent water contour, the maximum observed variation in potassium for male subjects corresponds to a range in adipose concentration of 23 to 29 per cent, and an error of only ± 3 per cent will result if an average potassium is assumed.

The potassium contours, on the other hand, are nearly perpendicular to the lines of constant muscle-free lean fraction. This means that potassium is determined by the muscle to adipose ratio (or vice versa) and is insensitive to the fraction of muscle-free lean. A potassium determination alone will, therefore, give the muscle to adipose ratio accurately but will not determine the actual fractions of either unless an additional assumption is made. The quantitative details of these conclusions depend on the concentrations of potassium and water in the three components and are, therefore, subject to modification if these data are changed.

Derivation of Composition Equations. We use the following symbolism:

K = total body potassium (meq/kg)

W = total body water (per cent)

M, fraction muscle; k_M , w_M , potassium and water content of muscle

L, fraction muscle-free lean; k_L , w_L , potassium and water content of MFL

A, fraction adipose; k_A , w_A , potassium and water content of adipose

$$K = k_M \cdot M + k_L \cdot L + k_A \cdot A \quad (\text{Eq. 1})$$

$$W = w_M \cdot M + w_L \cdot L + w_A \cdot A \quad (\text{Eq. 2})$$

In solving for M, L, and A, it is first convenient to express all concentrations of potassium and water as the excess above that corresponding to adipose tissue and to represent these new quantities by primes, i.e.:

$$K' = K - k_A \quad k'_L = k_L - k_A \quad k'_M = k_M - k_A$$

$$W' = W - w_A \quad w'_L = w_L - w_A \quad w'_M = w_M - w_A$$

(Graphically, this corresponds to moving the origin of the coordinate system of Fig. 5 to the point corresponding to the composition of adipose tissue.) The equations can now be solved:

$$M = \frac{W' - K' \frac{w'_L}{k'_L}}{w'_M - k'_M \frac{w'_L}{k'_L}} \quad (\text{Eq. 3})$$

$$L = \frac{K'}{k'_L} - \frac{k'_M}{k'_L} \cdot M \quad (\text{Eq. 4})$$

$$A = 1 - (L + M) \quad (\text{Eq. 5})$$

Substituting numerical values calculated from Table 5 (remembering that the primes refer to differences from the adipose concentrations):

$$\text{Per cent muscle} = 100 M = 3.15 K' - 2.36 W' \quad (\text{Eq. 6})$$

$$\text{Per cent muscle-free lean} = 100 L = -3.77 K' + 5.06 W' \quad (\text{Eq. 7})$$

$$\text{Per cent adipose} = 100 A = 100 + 0.62 K' - 2.70 W' \quad (\text{Eq. 8})$$

where $K' = K - 14.6$ and $W' = W - 19.4$. These equations do not predict a unique relationship between potassium and body water; within certain limits, these two parameters can vary independently. In fact, it is

the experimental observation of such an apparent variation which is one of the principal motivations for abandoning the simple two-component models and turning to a three-component system.

Error Analysis. The magnitude of the error in the calculation of each of the components resulting from a given error in determining the parameter potassium or water can be calculated by differentiating Eqs. 6 to 8. For the sake of a concrete numerical example, we assume that the experimental errors in potassium (milli-equivalents) and in body water (kg) are both 2 per cent. For a subject whose composition is 50 meq K/kg and 56 per cent body water (an average 35-year-old male), these errors correspond to 1 meq/kg and 1 per cent (of gross body weight), respectively. The resultant errors in the components are given in Table 6 and range from 2 to 4.5 per cent of gross body weight. If the total errors are expressed in terms of per cent of the mass of the component present, they are 9, 11, and 9 per cent, respectively. The error in determining the masses of the components are, therefore, 4 to 6 times the experimental errors in the water and potassium determinations, expressed in per cent of the amount present. This indicates the need for high precision measurements in this analysis.

The error in adipose is determined almost entirely by the error in the water determination. This is another way of saying that water alone is sufficient to determine adipose as indicated earlier. Water also largely determines the muscle-free lean; this was evidenced

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are in excellent agreement with the 7 obtained by isotope dilution, thus showing that there is no consistent discrepancy between these two methods for obese subjects as has been suggested for another gamma counting system (A. P. Remenchik, P. J. Talso, and C. E. Miller, 1963). Agreement is also excellent for the normal males: for the 26 non-obese males measured by gamma counting, body water averaged 58 per cent and total potassium 52.1 meq/kg, while for the 28 non-obese NRDL subjects, water was 58.4 per cent and exchangeable potassium 51.2 meq/kg. Exchangeable potassium is, therefore, 98.3 per cent of total potassium. This is not significantly different from unity, since two different populations are compared. (The accuracy of an average of 27 determinations should be 0.7 per cent for the counting method, assuming no sampling errors, but the latter are 1.9 per cent if the population standard deviation is 10 per cent.) Five of the NRDL subjects were later measured at LASL; for this group, the average ratio of exchangeable to total potassium was 0.964 (E. C. Anderson, 1963).

The least squares fit of a straight line to the two sets of data gives the results shown in lines 1 and 2 of Table 7 for the values of the constants a and b in the equation $K = a + b W$, where K is the potassium concentration in meq/kg of gross body mass (GBM) and W is the fraction of body water. The standard deviation of fit is calculated from the square root of the sum of the squares of the deviations of the measured K values from those calculated by substituting

the measured water in the least squares equation. This standard deviation is about 6 per cent for the total potassium data and 5 per cent for the exchangeable potassium data. Since gamma counting error is 4 per cent for a single determination on an individual, about half of the scatter can be accounted for on the basis of measurement error. The fact that the constant a is not significantly different from zero indicates that these data, on the average, show a constant potassium to water ratio compatible with the simple lean-fat model. However, the scatter of the data beyond experimental error casts some doubt on this for individual cases.

The data on female subjects are too limited to justify detailed analysis. As previously noted (T. H. Allen, E. C. Anderson, and W. H. Langham, 1960), women have a consistently lower potassium to water ratio than men, and there is also a suggestion of a steeper slope. The broken line in Fig. 8 is based on the female population average (to be discussed below) and is given here only to indicate that the meager individual data are consistent with the more detailed population averages.

We turn now to the data of Tables 2 and 4, referring to averages rather than to individuals. The averaging process removes a great deal of the scatter in the data, a fact having both advantages and disadvantages. The principal advantage is that, by eliminating individual variations (which may be due to experimental error or to

random secondary effects), averaging permits the observation with higher precision of secular trends applying to the population as a whole. The disadvantage is that the individual variations thus eliminated may be important clues to the general problem of body composition and certainly have to be reckoned with when one comes to study the individual subjects.

Figure 9 presents all the averaged data as determined by both methods for male and female age groups; the number beside each point gives the average age of the group. The statistical parameters of linear regression for these data are given in Table 7, items 5 through 8. The three lines in the figure are items 5, 7, and 8. A necessary requirement of the two-component model is that the constant a be zero. This is true only for item 7, male averages below age 42, in agreement with the results for individual males (items 1, 2, and 3). For this population group, the two-component model is not eliminated, but for females and for males older than 42, a is not zero but is respectively 7.3 and 4.0 times its standard deviation. Note that when one attempts to fit a single regression through all the data (item 6), the value of a is 7.3 times its standard deviation. For the male population, a similar break between two linear portions occurs in the same age range when total potassium is plotted against total water, proving that the break is not an artifact introduced by use of concentrations. From the non-zero a's and the three discrete classes, it is concluded that the two-component model is not

confirmed; the required simple proportionality between potassium and water is not observed. There does, however, appear to be a simple linear relation between these parameters within each of the three classes, the standard deviation of fit as given in the last column of Table 7 being 2.3, 1.2, and 1.4 per cent of the average potassium concentrations for the female, young male, and old male groups, respectively.

One should note in Fig. 9 the excellent agreement in the averages derived from different methods. Once again, very similar results are obtained by K^{42} exchange or by gamma counting, by simultaneous determination of body water and potassium, or by the use of independently measured population averages of these two parameters. This agreement increases one's confidence that the results are not artifacts due to a consistent error in one of the several techniques.

In Fig. 8, one female subject fell outside the range of potassium to water composition permitted by the model. In Fig. 9, the age 70 female group is likewise outside. These cases correspond to a slightly negative muscle content, as can be seen in the sixth column of Tables 1 and 2. They suggest that either the ternary model used is erroneous or that the compositions used for the three components are not all correct. Additional evidence for the latter conclusion is provided by plotting the primary Forbes and Lewis data (G. B. Forbes and A. M. Lewis, 1956) from which the components were

derived. The asterisks in Fig. 9 represent the gross and "lean body mass" compositions for the two cadavers. It is clear that the potassium to water ratios for these points are considerably higher than those of the present data. If the Forbes and Lewis data were arbitrarily normalized to bring them onto the in vivo data, the negative results would be eliminated. Such a normalization appears to be unjustified, in view of the large uncertainty in the cadaver data. This discrepancy means that the compositions calculated from the present model, while probably qualitatively correct in terms of trends, patterns, and range of variation, are likely to have consistent errors and are subject to revision when better dissection data are available.

DISCUSSION

In Figs. 8 and 9, the data on the potassium and water content of our subjects are presented directly as measured, and it was concluded that a two-component model was inadequate. We now turn to a more speculative interpretation of the primary data on the basis of the ternary composition hypothesis; that is, we now use the primary potassium and water concentrations in conjunction with Eqs. 6, 7, and 8 to calculate body composition in terms of adipose, muscle, and muscle-free lean. The numerical results will be found in the last three columns of the body composition tables (Tables 1 through 4).

Figure 10 shows the results for the population averages as a function of age from Table 2. (Only the lower right portion of the ternary diagram of Fig. 6 is used to provide an expanded presentation.) The other averages (from Table 4) are not graphed; the much smaller group size for these averages increases the error of the mean and the probability of a systematic sampling error.

The surprising regularity and simplicity of the male results tempt one to conclude that the model used corresponds closely to physiological reality. Such a conclusion is probably premature, in view of the uncertainties in the composition of the three components. However, it is interesting to outline the nature of the changes in body composition deduced from the model. From age 12 to 35, the muscle fraction of the average male varies little from about 27 per cent, although there appears to be an increase near age 20. Adipose and muscle-free lean vary from 24.4 per cent and 48.8 at age 35 to 7.9 per cent and 64.7 at age 16. Above age 35, development follows a completely different line, approximating constant adipose of 24.7 per cent (range 24.4 to 26.6 per cent). (The similarity of this trend to a constant water line is indicated by the 55 per cent water contour.) Muscle and muscle-free lean vary from 26.8 and 48.8 per cent at age 35 to 8.2 and 66.9 per cent at age 70. This is the same two-line structure noted in Fig. 9, but the transformation of coordinates has accentuated the effect and gives it a more definite physiological implication.

The trend of the female results is perhaps simpler than that of the males in that a single straight line may represent the entire age span. It is interesting that the observed weight increase of the female population sample can account quantitatively for the difference in the two aging trends for mature subjects. If the females age at constant weight and adipose fraction, as do the males in our population sample, then at 70 years the average weight would be 57.1 kg and the adipose fraction 32.2 per cent. Assuming muscle fraction to be small, the remaining 67.8 per cent would be mostly muscle-free lean. Now add to this the 7.4 kg which our female population gained in weight by age 70 and assume this to be all adipose. The composition resulting is 40 per cent adipose and 60 per cent muscle-free lean, in good agreement with the observed composition. Thus, one could say that aging beyond maturity in both males and females occurs by the replacement of muscle by muscle-free lean at constant adipose but that the females also add another 7 kg adipose.

It is clear that the averaging by age in Fig. 10 is much coarser than could be desired and that significant fine structure may be concealed thereby. A finer division in age would require a larger population sample, which would be easy for the potassium determination but more difficult for the body water.

If theories postulating the significant increase in connective tissue with age are correct, then the ternary system will require modification. According to the data of Forbes and Lewis (G. B. Forbes and A. M. Lewis, 1956), skin (which may be taken to roughly approximate connective tissue) has a potassium-to-water ratio of 76 meq/kg, which is very similar to our assumption of 75 meq/kg for muscle-free lean. However, both potassium and water in skin are only 82 per cent of their values in muscle-free lean, so that connective tissue is significantly different in terms of the composition diagram. In Figs. 9 and 10, the potassium and water content of connective tissue would place it near the intersection of the male aging line with the edge of the triangle. However, accumulation of connective tissue is certainly not responsible for the major portion of the male potassium and water change beyond age 35. To produce this change by replacement of a constant muscle to adipose to muscle-free lean mixture with connective tissue alone would require that the 70-year male be two-thirds connective tissue and one-third everything else. Nevertheless, significant accumulations of connective tissue may have to be considered in an accurate model of the composition of the elderly body.

Finally, it may be noted that our results are not in good agreement with von Döbeln's analysis (W. von Döbeln, 1962) based on body potassium and lean body mass as estimated from skeletal measurements. In his analysis, water is not used and a rather different potassium content is assumed for muscle and muscle-free lean. Table 8 compares the results. Since von Döbeln did not report the ages of his subjects but reported them as "U. S. Army Personnel and German Students," we have selected an average age of 35 for the comparison female group (chosen partly on the basis of giving the same average potassium concentration) and 16 and 26 for the male group. It was not possible to obtain potassium agreement at a reasonable age for the males. The principal discrepancy between the two methods is on muscle, for which our values are consistently lower. In view of the occasional negative muscle concentration which we obtain and the apparent tendency of the Forbes and Lewis potassium data to be systematically higher than ours, one is led to the conclusion that our model consistently underestimates muscle concentration.

The conclusions presented here are not advanced without reservations and should be accepted as hypotheses to be tested by further experiments rather than as firm conclusions. The basic potassium and water measurements used are believed to be accurate enough to justify calculations which are this detailed and precise. The independent variation of these two parameters is firmly established; the

interpretation of this variation in terms of body composition is speculative except that it seems to require a "lean body mass" of variable composition. The following principal difficulties may be noted with the present treatment:

(a) The three components chosen for the analysis (adipose, muscle, and muscle-free lean) may not be -- in fact, are probably not -- the most desirable. This is especially true of the third one which is neither chemically, physically, nor physiologically an attractive entity.

(b) The data used for the potassium and water content of the components are extremely limited. Further data are needed to extend the samples with respect to age and sex and to increase the number of measurements. It is here assumed that potassium and water contents of the components are the same for all ages and sexes; this is to be proved.

(c) The large population samples used here are essentially uncontrolled and unscreened. A better population selection is desirable.

(d) Determinations of potassium and water on the same subjects are clearly superior to combining averages from different population samples. The few data used here, which were of this sort, appear to confirm the other results, but it would be highly desirable to obtain more measurements of this type.

While speculations of this type may be fruitful in suggesting future experimentation, they must be accepted only as tentative hypotheses. It is tempting, and often profitable, to look for the simplest pattern or mechanism which will explain a set of observations; this is the basic principle of economy of hypothesis. It must be constantly realized, however, that this approach may have a Procrustean effect on the data, and the prime objective must be to formulate means of further testing the assumptions. Since we do not plan to continue experiments on body composition at Los Alamos, we hope one of our colleagues elsewhere will be stimulated (or irritated, which is almost the same thing) to prove, disprove, or modify this hypothesis.

LEGENDS TO FIGURES

Fig. 1. Potassium concentration (in g/kg) as a function of age for two large population samples. The solid curves are drawn for the 1956-1958 sample, displaced downward by 2 per cent, and the points are the 1959-1960 repetition.

Fig. 2. Body water as a function of age. Average values were taken from the literature.

Fig. 3. Total body weight as a function of age for the composite population sample (1956-1961).

Fig. 4. Models of body composition used by various investigators.

Fig. 5. Potassium-water composition of von Döbeln's three components on the basis of the Forbes-Lewis data and the compositions accessible to bodies built on this model.

Fig. 6. Ternary composition diagram of body composition model.

Fig. 7. Potassium and water contours in relation to ternary composition diagram (based on the data of Forbes and Lewis).

Fig. 8. Potassium-water concentrations in individual subjects measured by dilution and by gamma counting. Dotted lines represent limits predicted by ternary model.

Fig. 9. Average potassium-water concentrations for age groups studied by various methods and suggested lines of aging.

Fig. 10. Ternary composition diagram for age groups drawn from large population sample and suggested lines of aging. Contours of 50 and 55 per cent water and of 50 meq K/kg are also given.

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TABLE 1

BODY COMPOSITION OF INDIVIDUALS AS DETERMINED BY GAMMA COUNTING AND TRITIUM EXCHANGE

Subject	Age	Weight (kg)	Total Body Water (Per cent of Weight)	Total Body Potassium (meq/kg)	Calculated Body Composition		
					Muscle (Per cent)	Muscle-Free Lean (Per cent)	Adipose (Per cent)
MALES							
WCR	22	59.1	64.4	64.3	50.4	38.7	10.9
PN	23	87.8	57.8	51.1	24.4	55.5	20.1
AR	24	61.2	61.3	51.3	16.7	72.6	10.7
DWL	25	80.0	62.5	59.8	40.7	46.2	13.1
CEC	25	71.4	62.1	55.8	29.0	59.4	11.6
FK	26	66.8	60.4	50.0	14.7	72.9	12.4
HFG	26	123.0	42.2	33.9	7.0	41.9	51.1
BEW	28	65.5	56.9	50.7	25.2	52.6	22.2
ALF	28	63.2	58.6	51.8	24.7	56.8	18.5
GIB	29	84.1	65.3	65.4	51.7	39.3	9.0
WHS	30	65.9	55.2	44.6	10.0	67.1	22.9
JMI	31	85.0	48.3	42.0	18.1	42.1	39.8

TABLE 1 (continued)

RLS	32	75.6	53.7	47.6	23.1	48.0	29.9
JBS	33	68.6	63.2	58.2	33.9	56.1	10.0
KTW	33	79.1	54.0	51.6	34.9	34.5	30.6
VER	35	60.0	64.6	60.6	38.2	54.0	7.8
PSH	35	85.0	53.7	48.1	24.6	46.2	29.2
JFS	36	55.9	57.6	51.7	26.7	52.3	21.0
WRW	36	75.2	55.4	51.6	31.6	41.6	26.8
ECA	36	65.0	56.0	50.2	25.7	50.0	24.3
LJB	36	59.6	58.9	48.8	14.5	69.9	15.6
JFM	39	99.1	50.2	44.7	22.1	41.5	36.4
CCL	40	75.4	50.6	45.9	25.0	38.8	36.2
CEP	40	75.0	58.3	55.7	37.7	40.5	21.8
JEF	42	65.5	59.7	53.4	27.1	56.5	16.4
OSJ	42	64.1	54.9	47.9	21.1	52.0	26.9
THA	42	92.3	51.6	46.8	25.4	40.6	34.0
WHL	44	57.5	61.9	51.8	16.9	73.5	9.6

TABLE 1 (continued)

FEMALES

BR	16	48.2	48.8	39.0	7.5	55.9	36.6
GAT	27	71.6	52.2	42.9	11.7	58.5	29.8
VJB	29	55.9	57.1	51.2	26.3	51.7	22.0
CFB	29	65.5	49.4	38.2	3.5	62.1	34.4
PCS	31	72.0	49.9	40.8	10.5	54.8	34.7
JMW	31	59.1	56.2	43.3	3.6	77.0	19.4
BSR	34	57.5	49.8	41.1	11.8	52.9	35.3
IUB	34	57.2	51.7	38.3	-1.5	73.1	28.4
CWC	35	62.7	52.0	40.7	5.3	65.7	29.0
EKH	51	83.2	43.4	33.9	4.2	47.9	47.9

TABLE 2

BODY COMPOSITION OF A POPULATION SAMPLE AVERAGED BY AGE GROUPS

Age Range	Average Weight (kg)	Average Body Water (Per cent)	Average Total Body Potassium (meq/kg)	Calculated Body Composition		
				Muscle (Per cent)	Muscle-Free Lean (Per cent)	Adipose (Per cent)
MALES						
10-14	39.3	57.6	52.5	27.6	53.0	19.4
14-18	61.2	63.6	56.2	27.4	64.7	7.9
18-22	72.3	61.5	56.5	32.6	53.8	13.6
22-30	75.1	58.5	52.6	27.1	53.8	19.1
30-40	76.5	56.1	50.6	26.8	48.8	24.4
40-50	77.1	55.6	48.8	22.6	52.8	24.6
50-60	77.3	54.4	46.9	19.5	53.9	26.6
60-80	77.2	54.1	42.8	8.2	66.9	24.9

*Taken from I. S. Edelman, H. B. Haley, P. R. Schloerb, D. B. Sheldon, B. J. Friis-Hansen, G. Stoll, and F. D. Moore, 1952; J. D. McMurrey, E. A. Boling, J. M. Davis, H. V. Parker, I. C. Magnus, M. R. Ball, and F. C. Moore, 1958; E. C. Anderson and W. H. Langham, 1959; T. H. Allen, B. E. Welch, T. T. Trujillo, and J. E. Roberts, 1959; T. H. Allen, E. C. Anderson, and W. H. Langham, 1960; E. A. Boling, W. L. Taylor, C. Entenman, and A. R. Behnke, 1962.

TABLE 2 (continued)

FEMALES

10-14	39.2	56.1	50.8	27.4	48.2	24.4
18-22	57.4	52.2	43.6	15.8	53.5	30.7
22-30	56.8	51.1	43.9	18.8	47.4	33.8
30-40	60.6	51.1	41.3	10.3	57.7	32.0
40-50	59.7	49.0	39.6	9.5	54.0	36.5
50-60	62.3	47.8	37.0	3.6	58.4	38.0
60-80	64.5	46.2	33.7	-3.0	62.7	40.3

TABLE 3

BODY COMPOSITION OF INDIVIDUALS AS DETERMINED BY POTASSIUM⁴² AND TRITIUM EXCHANGE AT NRDL

Subject	Age	Weight (kg)	Total Body Water (Per cent of Weight)	Exchangeable Potassium (meq/kg)	Calculated Body Composition		
					Muscle (Per cent)	Muscle-Free Lean (Per cent)	Adipose (Per cent)
NORMAL MALES							
NW	20	64.3	58.5	55.0	35.0	44.3	20.7
GC	21	62.7	62.4	52.3	17.3	74.2	8.5
JS	21	74.1	59.8	51.0	19.4	65.9	14.7
JD	22	81.8	61.1	53.8	25.1	61.9	13.0
DF	22	73.6	58.4	52.5	27.4	53.2	19.4
EH	22	83.4	61.9	59.4	40.8	44.9	14.3
NS	23	77.6	62.9	55.5	26.1	64.8	9.1
MK	24	79.5	52.4	46.5	22.6	45.7	31.7
KJ	24	94.6	60.8	54.9	29.2	56.4	14.4
DJ	25	77.7	55.7	47.1	16.7	60.2	23.1
JF	25	70.9	64.2	60.2	37.9	53.4	8.7

TABLE 3 (continued)

EBK	26	74.3	58.4	54.0	32.1	47.5	20.4
TC	26	79.3	62.7	58.1	34.8	53.8	11.4
CR	27	83.6	54.8	49.8	27.4	45.2	27.4
KF	28	89.5	58.5	51.1	22.7	59.1	18.2
OS	29	67.6	57.4	49.0	18.7	61.5	19.8
MSH	30	87.0	53.8	45.8	17.1	55.4	27.5
JH	30	78.6	67.4	58.8	25.9	75.0	-0.9
BV	32	73.6	52.7	45.9	20.0	49.5	30.5
AY	34	85.4	57.4	46.9	12.0	69.6	18.4
TCA	34	81.2	55.4	47.2	17.7	58.3	24.0
LG	35	74.8	62.2	57.2	33.2	54.7	12.1
SF	36	69.0	55.6	48.9	22.6	52.8	24.6
HC	37	58.2	65.3	51.9	9.2	90.3	0.5
MS	43	52.4	58.4	46.4	8.2	76.3	15.5
MO	45	82.2	54.4	48.4	23.9	48.6	27.5
ALS	45	75.4	53.0	44.0	13.3	58.2	28.5
ARB	56	93.6	51.8	45.3	20.2	47.4	32.4

TABLE 3 (continued)

OBESE MALES

RR	26	124.6	42.1	35.1	11.2	36.5	52.3
JD	28	104.2	48.3	41.5	16.5	44.1	39.4
JBE	28	122.3	44.9	38.5	15.1	38.2	46.7
FF	31	111.9	44.2	37.6	14.0	37.9	48.1
KT	35	115.0	46.7	41.5	20.3	36.0	43.7
TA	39	98.6	48.6	40.0	11.1	51.1	37.8
JB	41	130.7	46.7	40.4	16.9	39.9	43.2

TABLE 4

BODY COMPOSITION OF GROUPS OBTAINED BY AVERAGING DATA FROM TABLES 1 AND 3

No. of Data	Average Age	Average Weight (kg)	Average Body Water (Per cent)	Average Body Potassium (meq/kg)	Calculated Body Composition		
					Muscle (Per cent)	Muscle-Free Lean (Per cent)	Adipose (Per cent)
TABLE 1 (Gamma Counting)							
Males							
9*	26	71.0	61.0	55.6	31.0	54.7	14.3
12	34	72.8	55.9	49.6	24.2	51.5	24.3
6	42	71.6	56.2	50.2	25.3	50.9	23.8
Females							
7	31	63.5	52.4	42.6	10.3	60.6	29.1
TABLE 3 (Potassium ⁴² Exchange)							
Normal Males							
13	23	76.4	60.0	53.9	28.0	56.0	16.0
11	32	77.1	58.3	51.1	23.3	58.1	18.7
3	44	70.0	55.2	46.2	15.0	61.1	23.9
Obese Males							
7	33	115.3	45.9	39.2	15.0	40.5	44.5

*Omitting HFG.

TABLE 5
ASSUMED COMPOSITION OF THREE COMPONENTS OF THE BODY*

Tissue	Water (Per cent)	Total Potassium (meq/kg)
Adipose Tissue	19.4	14.6
Muscle	73.7	87.1
Remainder = "muscle-free lean"	64.6	48.5

* Calculated from the data of Forbes and Lewis (G. B. Forbes and A. M. Lewis, 1956) for two male cadavers (ages 46 and 60 years), except for adipose which was assumed to be 70 per cent fat and 30 per cent muscle-free lean.

TABLE 6
 ERRORS IN BODY COMPOSITION RESULTING FROM 2 PER CENT ERROR
 IN POTASSIUM AND WATER FOR 35-YEAR-OLD MALE

Component	Per cent of GBW	Error in Per cent of Gross Body Weight		
		Due to Potassium	Due to Water	Total
Adipose	24.3	-0.37	+2.20	+2.2
Muscle	26.2	+2.26	-1.93	+3.0
Muscle-free lean	49.5	-1.89	+4.13	+4.5

TABLE 7

COEFFICIENTS FOR LEAST SQUARES LINEAR REGRESSION OF POTASSIUM ON WATER [K/GBM (meq/kg) = a + b W]

Item	Data Source	No. of Data	$a \pm \sigma_a$ (meq/kg)	$b \pm \sigma_b$ (meq/kg)	Standard Deviation of Fit (meq/kg)
1	Table 1, Individual Males (Gamma counting)	28	-6.03 ± 6.36	100.4 ± 11.1	3.13
2	Table 3, Individual Males (Potassium ⁴² exchange)	35	-4.98 ± 3.50	96.3 ± 6.2	2.31
3	Tables 1 and 3, Individual Males (Both methods)	63	-5.84 ± 3.31	98.8 ± 5.8	2.74
4	Table 2, Population Average, Males, All Ages (Gamma counting)	8	-20.58 ± 12.2	124.0 ± 21.0	1.88
5	Table 2, Population Average, Females, All Ages (Gamma counting)	8	-41.28 ± 7.72	163.6 ± 15.2	1.23
6	Tables 2 and 4, Population Average, Males and Females, All Ages (Both methods, except obese males)	22	-27.85 ± 3.84	136.9 ± 6.9	1.44
7	Tables 2 and 4, All Male Averages (Ages 12-42)	10	-3.10 ± 6.23	95.1 ± 10.6	0.82
8	Tables 2 and 4, All Male Averages (Age above 34)	7	-114.6 ± 31.2	293.6 ± 56.4	1.15

TABLE 8
COMPARISON OF RESULTS OF TWO METHODS OF TERNARY COMPOSITION ANALYSIS

	Males			Females	
	von Döbeln	LASL		von Döbeln	LASL
Number of Subjects	154	226	162	73	74
Average Weight (kg)	72	75.1	61.2	64	60.6
Average Age (years)	--	26	16	--	35
Potassium (meq/kg)	56.5	52.6	56.2	41.8	41.3
Adipose	14%	19%	8%	40%	32%
Muscle	46%	27%	27%	25%	10%
Muscle-Free Lean	40%	54%	66%	35%	58%
Assumed Concentrations (meq/kg) of Potassium in:					
Adipose	18	14.6			
Muscle	81.8	87.1			
Muscle-Free Lean	40.9	48.5			

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