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THE EVALUATION OF BODY SURFACE, BODY VOLUME AND BODY COMPOSITION IN HUMAN BIOLOGY RESEARCH

ABSTRACT — Comprehensive evaluation of human physique can be approached also by the measurements of body surface, body volume and composition. A number of methods is presented characterising in this way not only morphological, but indirectly also the functional and nutritional features of the human organism. Body surface measurements have a long tradition (coating, triangulation, planimetry, prediction from major body dimensions etc.). For the evaluation of body volume water displacement, underwater weighing, helium dilution, pressure changes, geometric approach and/or predictions from body dimensions have been mostly used. Body composition from the anatomical, biochemical and/or intermediary aspect dividing therefore the human organism in various number of components has been mostly approached by anthropometry, skinfold thickness measurements, densitometry, hydrometry, kaliometry or the use of fat soluble gases; most recently by total body electrical conductivity and neutron activation analysis. Complex methodology gives most reliable results characterising thus age changes and the impact of environmental factors such as nutrition and physical activity.

KEY WORDS: Body surface — Body volume — Body composition — Methodology.

PART I.

INTRODUCTION

The measurements of body surface and body volume have become, in context with physiological and medical aspects a vital part of the expansion and transmutation of the narrowly conceived physical anthropology into what has been termed "human biology". Mentioned measurements deal with the body as a whole; the impulse for this had its roots in applied, primarily biomedical interests. Thus, for exemple, the early scientific concern with body surface was related to the effort to evaluate the number of pores in the human skin and the exchange of materials across the skin. In the 19th century the interest shifted to surface area as a common point of reference for comparing the basal energy metabolism of animals and human beings differing in size. The utilization of body surface in clinical medicine, gastroenterology, pharmacology, experimental physiology, nutritional sciences etc. serves as a criterion for drug dosage, reference standard for various physiological and medical characteristics. The same applies to body composition which found the application in many biomedical disciplines (Martin 1984, Wilmore and Fox 1984, Pařízková 1977, 1985 etc.).

Matiegka (1921) developed his approach to the assesment of body composition *in vivo* as a means for evaluating the somatic component of "fitness"; he spoke of "physical efficiency". He could not have dreamt that, within two generations, concern with the loss of muscle tissue during prolonged space flights might become a critical factor and concern in man's exploration of the universe and potential colonization of other planets. The very idea of studying body composition *in vivo* was so radically new as an approach to a quantitative study of the human physique that it largely fell on the deaf ears of his contemporaries and immediate successors. The era of explosive growth of the methods for the study of body composition and of their application was ushered in by Behnke (1941/42) and his studies on the functional significance of body composition (with emphasis on body fat) in deep sea diving, the individual differences in the fat content of healthy men (Behnke et al. 1942), and compositional characteristics of exceptional athletes (Welham and Behnke 1942). Extensive use of compositional methodology was made in the years 1944—1945 in studying the complex changes taking place during prolonged, severe food restriction and subsequent rehabilitation (Keys et al. 1950). Book-length publications adressed themselves also to compositional aspects of surgery (Moore et al. 1933), human growth (Cheek 1968), and physical fitness (Pařízková 1977; cf. also Behnke and Wilmore 1974).

Another aspect which made valid the measurements of body surface and composition are the problems of food intake and of the nutritional status as related to growth period and ageing or sex, physical activity regime, physical fitness and work performance, health and life expextancy.

Nutritional status results from the balance between energy intake and output. In conjunction with this, it is recommended to consider the level of energy turnover. E.g. a young organism has both high energy intake per kg body weight and also a high energy output first of all as a consequence of a high basal metabolic rate, and then the additional energy necessary for growth. Last but not least, also a high level of spontaneous physical activity as measured both in human subjects and other species must be taken in account. An organism which has a high level of energy output as e.g. physically very active inidividuals (athletes) have also a high level of energy input, which make them similar in this respct to younger inidividuals. On the other hand, in the advanced age both basal and above-basal metabolic rate and spontaneous physical activity are low along with lower food intake as compared to younger age categories. All this is reflected in the recommended allowances for energy and all other components of food for all inidividual age and sex categories. The same applies to body composition, especially to the proportion of lean body mass.

There exist close relationships between energy intake and output which can both change due to long-term adaptation to various levels of physical activity and work load. As mentioned above, in athletes as well as in other inidividuals with high energy output due to increased work loads in physically demanding professions there exists an adjustement of spontaneous intake of diets enabling higher level of physical performance. Also this is reflected in recommended allowances (Energy and protein requirements, FAO/WHO Expert Consultation, Rome 1981; ed. WHO, Geneva, 1985). Nevertheless, there seems to exist not only a wide range of interindividual differences, but also additional mechanisms influencing the energy efficiency resulting from the adaptation processes (especially those initiated early in life), which are important characteristics of the organism adapted to high work loads (Pařízková 1984, 1985).

Interactions between food intake and physical work load influence profoundly the human organism from the point of view of antropometrics, body surface and body composition, nutrition status, and also functional capacity as well as work performance. The latter concerns notably the cardiorespiratory and neuromuscular indicators. Different regimes of physical activity and work loads modify the food intake and the nutritional status of the organism including body composition; on the other hand, nutritional status has an important impact on the level of physical performance.

All that is reflected in a characteristic way in the changes of body size, body surface and composition, which run parallel with the adaptational changes in mentioned functional and nutritional parameters of the human organism. This has been, inter alia, one of the most important reasons of the development of methodology concerning especially body composition (Pařízková 1977, 1985, Wilmore and Fox 1984 atc.).

I. BODY SURFACE

We shall rely heavily on Boyd's (1935) monograph in tracing the early developments, going back to Leeuwenhook (1719) and Abernathy (1793). In German, a historical review of the methods for determining surface area (as well as body volume and the specific gravity of the body) was written by Reischle (1919). For systematic accounts see Sendroy and Cecchini (1954, 1955), Sendroy (1961), and Krovetz (1965).

The Frenchman Sappey (1852) removed the skin from a cadaver, pinned the pieces to a table, and let them dry; subsequently, he fitted the peices together on a metric surface and determined the size of the area that was covered. Less heroic approaches to the measurement of body surface include coating, triangulation, and the measurement of the skin surface with special planimeters. Since all of these methods are tedious, in practice the surface are came to be estimated from anthropometric data.

MEASURING BODY SURFACE

Coating

The method of coating involves covering the body with a material that can then be removed and its area measured. There have been numerous variations of this method, involving attempts to find "a non-elastic, pliable substance, preferably of uniform thickness, that can be readily applied and removed without injury or discomfort to the living persons" (Boyd 1935, p. 2).

John Abernethy (1764—1831), an English anatomist to whom Boyd's monograph is dedicated, described his technique as follows: "The surface of head, hand and foot. I computed by applying paper cut as the occasion required, over these parts: afterwards placing the separate pieces of paper, so as to form an extended plain. I measured its extent" (Abernethy 1793). It may be noted that this method was combined with the calculation of the surface area of the other parts of the body, as described in the next section of this article.

The first extensive series of measurements of the body surface was made by Meeh (1879) working under the direction of Professor Karl Vierordt. Meeh combined three approaches:

1. Covering very irregular areas (such as the auricles of the ears) by pieces of paper fitted to the contours, and determining the extent of the surface by accurately weighing the paper.
2. Covering some parts of the body (such as fingers) with strips of square-milimeter paper and counting the squares.
3. Tracing the outlines of 34 regions of the body on a transparent paper, dividing them into regular geometric figures, measuring their dimensions, and calculating their area.

Several other series have been reported, using a variety of modifications of the procedures, including those reported by DuBois and DuBois (1915, Sawyer et al. (1916), and Wörner (1923).

Boyd (1935) described in detail a method in which plaster-of-Paris cast of children served as an intermediary step and provided means for checking the reliability of the technique by repeated measurements of the surface area of an adhesive coating of the casts.

Triangulation

This procedure consists in marking off regular geometric figures, chiefly triangles, on the skin. Their areas are then calculated. The first dependable determinations of the human surface area appear to have been made by Fubini and Ronchi (1881). The triangulation method was used by very few investigators, perhaps because of the tediousness of the procedure and the questionable reproducibility of the measurements.

Planimetry (Surface Integration)

The Frenchman Roussy invented several instruments for direct measurements of the surface of the human skin (pelliplanimétrie; Roussy 1899). Other "surface integrators" were divised by Bordier (1901) and Brody and Elting (1926), and modified by others, including Bradfield (1927).

The issues of assessing the accuracy of the classical techniques for measuring the surface area of the human body were considered in detail by Boyd (1935).

Estimating Body Surface

The procedures for estimating body surface on the basis of anthropometric data fall into two categories:

1. Calculating (and then summating) the surfaces of separate parts of the body and
2. Predicting the total body surface from selected body measurements.

From Partial Areas to the Total Body Surface

In addition to measuring the geometrically complex parts of the body (head, hands, feet) by the coating method, Abernethy (1779) calculated the surfaces of the other parts (neck, trunk, arms, legs) "as if they were cylinders, the dimensions of which were ascertained". The principle was applied in a number of subsequent studies (e.g., by Quételet 1848).

In 1915 DuBois and DuBois proposed a technique that called for 21 body measurements and yielded a satisfactory estimate of the surface area as determined by the coating method; the reported avarage difference between the calculated and the measured surface area was 1.7 % of the reference value. The method has been used fairly widely for research purposes (Boyd 1935, cites 13 studies).

Haycock et al. (1978) calculated the surface of 9 body parts, viewed as geometrical analogues of cylinders (except for the head, treated as a sphere), thus simplifying the procedures used by his predecessors. The precision of the technique was checked against several criteria. In turn, the values determined by the "geometric" method were used by the authors in deriving a formula for predicting the surface area from weight and height.

Predicting Total Surface Area from Major Body Dimensions

A large number of formulae for predicting body surface have been offered. An early general formula had the form

$$S = k \times W^a, \qquad \text{(No. 1)}$$

where k = a constant
W = body weight
a = an exponent

Meeh (1879) proposed an $a = 2/3$. The procedure had several weaknesses. For one, the coefficient k depended on age, and Vierodt (1881) suggested the use of separate constants for adults (Meeh's $k = 12.31$) and for children ($k = 11{,}87$). Benedict and Talbot (1921) proposed a sliding scale for the k values, according to weight. Clearly, this makes illusory the apparent simplicity of the formula.

Efforts to improve Meeh's equation included the addition of other variables, raised to different powers. Thus Bouchard (1897, 1900) suggested using height (H) and waist circumference (T), in addition to body weight (W):

$$S = k \times W^{1/3} \times (H \times T)^{1/2}. \qquad \text{(No. 2)}$$

Disappointingly, the estimates proved to be unreliable.

The equation that proved to be most useful one had the general form

$$S = k \times W^a \times H^b \qquad \text{(No. 3)}$$

where W = body weight and H = height.

For the nine subjects studied in detail by DuBois and DuBois (1916), the equation that provided the best estimate of the surface area was

$$S = 71.84 \times W^{0.425} \times H^{0.725} \quad \text{(No. 4)},$$

where the surface area is given in square centimeters, weight in kilograms, and height in centimeters.

Numerous charts and tables were provided in order to facilitate the calculations, including nomograms that made it possible to read off the surface area knowing a subject's weight and height (Feldman and Umanski 1922).

Other investigators endeavored to provide additional information on the constant k and the exponents of weight and height. Thus, in order to take into account the effect of the changing body mass (weight) on the relationship between body weight and body surface, Boyd (1935) devised a "self-adjusting" formula in which the weight exponent was automatically reduced as the body weight increased. Her "best single equation for predicting surface area from other dimensions of the body" reads

$$S = 0.207 \times W^{0.7285 - 0.0188 \log W} \times H^{0.3} \quad \text{(No. 5)}$$

The formula, developed by Haycock et al. (1978) on the basis of measurements in 81 individuals ranging from premature infants to adults, reads:

$$S \text{ (in m}^2) = 0.024\,265 \times W^{0.5378} \times H^{0.3964} \quad \text{(No. 6)}$$

The formula gave a good fit for the values of the surface area from less than 0.2 m² to greater than 2.0 m². To make the information suitable for routine use, two nomograms were prepared: One for infants and one for children and adults.

II. BODY VOLUME

Much of the interest in total body volume is of a very recent origin and is related to the use of body volume in calculating body density, as an indicator of body cmposition.

Here we shall consider procedures for determning total body volume by measuring the amount of water displaced by the immersion of the body either directly or from the loss of weight upon submersion; assessing the volume from changes in the air pressure or from the concentration of an inert gas introduced into a closed, rigid chamber; and estimating the body volume anthropometricaly. It should be mentioned at the outset that we are interested not in the gross body volume but in the "tissue volume" (gross body volume less the volume of the air present in the lungs and the respiratory pathways at the time the body volume is being determined). This makes a variety of techniques for the estimation of the gross body volume inapplicable in densitometric studies on body composition.

MEASURING BODY VOLUME

Water Displacement

Conceptually simple are the approaches in which the volume of the body or its segments is determined directly in terms of the volume of water that is being displaced. But there are technical problems regarding the accuracy with which the displaced water can be measured and,most importantly, as we noted above, in obtaining simultaneously the residual air.

For some porposes, such as the study of the effects of weight reduction on the external morphology of the body, the determination of partial volume may by of interest and relevance (Carns and Glasgow 1957). The procedure involved the sequential determination of the volume of six body segments. The water raised by the immersed body segment was drawn off and its amount was determined by weighing. More sophisticated instrumentation and procedures for determining total body volume by water displacement were described by Jones (1972).

The measurements were made in triplicate, with an interval of at least 5 minutes between the measurements. Mean difference between duplicate measurements (22.6 ml) was within the range of the subject's ability to reproduce his vital-capacity measurements. To residual volume was measured by a nitrogen-dilution method, apparently prior to the measurement of body volume. Vital capacity measurement served to verify that the point of maximum exhalation has been reached.

Underwater weighing

A commonly used approach employs the Archimedes' principle, which states that an object wholly or partly submerged in water is acted upon by an upward force (buoyancy) which is equal in magnitude to the weight of the water displaced by the object; this is manifested in the "loss of weight".

A scale suspended above the tank of water or a read-out device serves to register the weight of the object in air minus the weight of the water displaced. The uncorrected (gross) volume of the body is obtained by dividing the weight of the displaced water by the density of water (at the temperature of water in the tank). To obtain a corrected value (tissue volume), the volume of the residual air present in the lungs and the respiratory passages at the time of reading the underwater weight must be subtracted (Wilmore 1969).

A detailed description of the procedure and of the instrumentation was provided by Buskirk (1961; also Keys et al. 1950, Goldman and Buskirk 1961; Katch et al. 1967). Technical improvements involve primarily the use of electronic devices. Thus the apparatus described by Akers and Buskirk (1969) utilises strain-gauge transducers ("Load cells") upon which a horizontal platform is suspended on which a subject sits when he is to be weighed under water. The subject bends forward for complete submersion. In the authors's view, a distinct advantage of using the electronic load cells rather than a dial scale for weighing subject under water is the graphic record of the weight that the system generates. The report provides also a detailed description of the method for determining the residual air, at the time of maximum exhalation, by N_2 washout. Automated gas analyser

is used to determine the nitrogen concentration in the gas collected in 7 minutes during which the subject is breathing oxygen; more exact is to wash out the air from the lungs by a certain amount of O_2 (60 l for adults, 40—50 l for chidren (Pařízková 1961, a, b, 1977).

Additional refinements, made subsequently, included the transferring of the load cells (initially mounted near the top edge of the tank on an aluminium frame) to the bottom of the tank, thereby improving the stability of the system. Furthermore, a special valve was inserted into the breathing circuit used for determination of residual air. The pneumatically operated valve reduces the changes of error that can be caused by premature inspiration when testing apprehensive subjects.

Helium Dilution

The technique for measuring body volume by helium dilution was described, in detail, by Siri (1956, 1961). It was developed in response to the need for an alternate approach, applicable to individuals for whom underwater weighing — the approach of preference — is impracticable.

The subject, wearing only a standard hospital gown, is seated in a rigid, closed chamber made out of plexiglass and is instructed to sit quietly. After the door to the chamber has been closed, about 5 to 10 minutes are required for the stabilization of the condition of the subject and the composition of the gas in the chamber. During this time, a second, previously evacuated chamber is filled with helium to slighly more than the atmospheric pressure and allowed to equilibrate with the water bath temperature. Helium is then mixed with the air in the first chamber, without altering the pressure and the total volume of the system. After equilibration, the concentration of the helium is determined using a thermal conductivity cell and the volume of the subject is calculated. A complete mixing of the helium and of the air takes less than a minute; an additional minute is allowed for the stabilization of the thermal cell unit.

The procedure involves no discomfort to the subject and does not require the subjects active participation. For all of these reasons it is well suited for work with children, aged persons, patients, and animals.

The procedure has one major disadvantage: while the principles are simple, the successful operation of the system, outside the University of California campus, at Berkeley, is a distressingly rare event. The technique was modified for use with infants by Fomon et al. (1963).

Pressure Changes

In several ways, the method in which the body volume is calculated on the basis of the changes in air pressure in a closed, rigid chamber, resulting from the injection (or removal) of known amount of air, is similar to the helium dilution method: it operates on principles that, in theory, are simple; the subject is placed in a rigid enclosure (body plethysmograph); and the method rarely if ever seems to work in other laboratories.

Strangely enough, it is one of the oldest techniques. In the early 20th century there are at least 3 papers bearing on this approach in the German literature (Pfaundler 1916; Kohlrausch 1929/30; Bohenkamp and Schnär 1931).

Other authors (Noyons and Jongbloed 1935, Jongbloed and Noyons 1938) utilized a different approach, comparable to underwater weighing (except that the "immersion medium" is air, not water): every accurate measurement of body weight in air, under two different ambient pressures, higher or lower than the atmospheric pressure, should make it possible to estimate body volume.

This work was reviewed by Lim (1961). The techniques designed to calculate body volume on the basis of changes in pressure have been largely unsuccessful, due to the failure to reduce the effects or to compensate for the thermal changes occurring with gas expansion or gas compression, and the effects of the subject's metabolism.

A recent attempt to minimize the thermal problems by the use of polyurethane foam inside the chamber was reported by Gundlach et al. (1980). The use of the polyurethane foam is said to eliminate the interference from water vapor as well. Their efforts seem to have been higly succesful, as judged by the comparisons of the values of body volume determined by underwater weighing, and plethysmographically. Should these findings be confirmed, the technique would represent a significant advance and a boom for densitometric research on body composition. The method is rapid and involves no inconvenience for the subject. Importantly, there is no need to measure the residual lung volume.

Garrow et al. (1979) reported the use of pressure-volume plethysmography in order to eliminate the need for the submersion of the head in unwilling subjects. All of the body, except for the head, is immersed in water and the weight is recorded on an electronic scale. The volume of the head (or head and neck) is determined by the pressure-volume pneumatic method. This combination of methods deserves further evaluation (Irsigler et al. 1975, Schmid and Schlick, 1976).

Estimating Body Volume

The principles for calculating and estimating body volume on the basis of body measurements are largely identical with those used for body surface, and some investigators progressed from one to the other topic. Thus Meeh, an early German anatomist, followed his studies on body surface (1879) with research on the volume of the parts of the human body and of the body as a whole (Meeh 1895).

Calculation (Geometric Approach)

As in calculating body surface, the body may be viewed as consisting of segments that approximate specific geometric shapes (cylinders, cones, spheres). Their dimensions are measured and their volumes are calculated. The partical volumes are then added to yield the total body volume. It should be reemphasized that these are gross body volumes, with undetermined air space in the lungs and the respiratory passages, and can not be used — without introducing a questionable "correction" — for the calculation of body density that has a specifiable meaning for research on body composition.

Sady et al. (1978) cite 6 earlier studies in which the geometric approach was used. In their own investigation they calculated the volume of 10 body segments. Altogether 39 measurements were made for each subject.

The calculated body volumes were compared with the values based on underwater weighing. The underwater weight was corrected for the residual volume; no such correction was apparently applied to the volume calculated from body measurements. Thus the impressive coefficient of correlation ($r = +0.98$, with $N = 63$) male subjects is seductive as a measure of validity: there was a systematic difference, with the calculated values being lower in 3 subsamples with small, medium, and large body size. For the sample as a whole, the mean values were 69.46 vs. 67,72 liters, yielding a difference of −1.74 l.

By contrast, the body volumes calculated for women ($N = 56$; Fredson et al. 1979) were substantially higher than the hydrostatically determined (criterion) values of body volume. The means were 55.48 vs. 60.94, with a difference of +5.46, indicating the presence of a large systematic error in the procedure. It should be noted that the coefficient of correlation between the two sets of data was still high ($r = +0.96$).

Prediction (Statistical Approach)

For an adult population, represented by a US Air Force personnel, Wakat et al. (1971) derived a prediction equation based on body weight (W):

$$V = 1.015W - 4.937 \qquad \text{(No. 7)}$$

where V = body volume, in liters, and W = body weight, in kg.

There is no scatter diagram of the estimated vs. hydrostatically determined values (incorporating correction for residual air). The standard error of the differences is 5.75 liters. With a mean measured value of 73.46 liters, this represents 7.8 % of the mean, indicating that the accuracy of prediction is poor. In any case, a prediction based on weight alone would imply the assumption that there are no differences in body composition in the population under consideration.

Earlier Sendroy and Cecchini (1959) provided a formula for estimating body volume, in l, from weight (W, in kg) and height (H, in cm):

$$V = W^2/(0.943H^3 + 0.989W - 0.068) \qquad \text{(No. 8)}$$

In 3 samples of subjects, apparently all adult males, with the $N0$'s of 31, 55, and 78, the standard deviations of the differences, expressed as percentages of the mean values determined by underwater weighing ranged from ±1.0 % to ±1.9 %, attesting a much higher precision.

As could be expected, "the individual deviations of the calculated (predicted) from the standard (measured) volume tend to vary in proportion to the difference of body density from average for the group" (Sendroy 1961, p. 66).

Weltman and V. Katch (1975) developed a multiple-regression equation for estimating the total body volume from circumferences. Using the 5 circumferences of the trunk and the extremities that had the highest predictive power, for a group of 24 university female students, the authors obtained a multiple $R = 0.95$, associated with a standard error of estimate of 1.69 liters (or 3.0 % of the mean of 55.57 liters).

Combining body weight (W) and thigh girth (T), Weltman and V. Katch (1978) derived the equation

$$V = 0.8719W + 0.2629T - 7.795 \qquad \text{(No. 9)}$$

In a sample of 24 college-age women, the equation yieded an extremely high R, with a standard error of estimate of 0.651 liters.

The equation was cross-validated in 5 other samples — children, college men, a large sample of college women ($N = 242$), as well as middle - age men and women. The mean values of the predicted body volume were somewhat higher than the mean measured volumes; the differences between the means, expressed as percentages of the measured volumes, ranged from +0.9 to +2.8 %. The very high R values are interpreted by the authors as indicating that the equation is not population - specific. But do we not have to regard the systematically higher mean predicted values as reflecting a systematic error? Before any judgments about a universal validity of the prediction equation can be rendered, it is necessary to apply the procedures to non - Caucasian populations and to populations varying in the mode of life.

III. BODY COMPOSITION

General Consideration

Compositional ("somatolytic") methods provide a range of approaches to the study of the human physique, yielding quantitative portraits of the "inner man". We may speak of "anatomy without dissection" (Brožek 1955a) or "bloodless dissection" (Forbes 1985). In order to underscore both the novelty of the techniques for the study of body composition and their importance to the study of human morphology, we have referred to anthropology's "Fourth Dimension" (Brožek 1963a) — a "new world" laying below the surface of the body and beyond external body dimensions.

Human body can be analyzed as regards its compartments from different points of view — anatomical, biochemical, functional etc. The measurements of total body water (e.g. using D_2O, T_2O etc.) can be used for the calculation of lean, active body mass and depot fat. ^{40}K measurements using whole body counters can serve the same purpose. Neutron activation analysis and computer assisted tomography (CAT) have been used recently also for the measurements of body composition. Electrical conductivity principle seems also to show quite reliable results as compared to other methods when measuring body composition. There exist also other methodological approaches, c.o. somatotyping (Pařízková and Carter 1976), but we mention here just the most often used procedures during last years.

There exists always the problem of not only the reliability and reproducibility of the results, but also of the demands on the measured subjects, and last but not least the cost of such measurements as regards the apparatures, serving personel, evaluation of the data, availability of standards etc. For that reason simpler methods are still requested and widely used both under laboratory and field conditions. Especially when there is a need for the evaluation of greater population groups, when the nutritional status is measured along with other characteristics such as food intake, clinical and biochemical measurements etc., a non-invasive, simple but reliable, and last but not least also cheap procedures are requested (Pařízková 1977).

In terms of procedures, the study of the body composition *in vivo* lies at the crossroads of several disciplines. In this spirit, though in a different context Wolbach (1953) made a statement that is of direct relevance to our topic: "It seems evident that the morphologist, the biochemist and the biophysicist should all be concerned with the progress of one another in their respective fields and, whenever possible, correlation of morphological, biochemical and biophysical information be made". Anthropologists not only have a legitimate interest in this novel aspect of the human organism but can make and have made specific and important contributions to this topic.

They can proceed more anthropometric, as did Matiegka (1921), a Czech physical anthropologist well trained in human anatomy; they can add such techniques as soft-tissue roentgenography (Garn 1957, Behnke and Wilmore 1974, p. 31); and, importantly, they can collaborate with their colleagues in the relevant biomedical disciplines, in predicting whole-body components, such as body fat, from anthropometric indicators (Brožek and Keys 1951, Pařízková 1961ab, 1963, 1965, 1977).

The physical anthropologist's concern with body composition helps to make anthropometry more "dynamic" (Count 1955; Brožek 1955 ab). Focused on the "substance" of the body, the study of body composition helps to counterbalance physical anthropologist's concern with body form and external body dimensions. Importantly, it broadens its scope and brings it into a more direct contact with research on biochemical processes, physiological functions, the development of disease and a variety of applied areas, including human nutrition (Keys et al. 1950, Brožek 1953).

In part, the anthropologist's interest in body composition is tied to his concern with the large and complex topic of human variability (Brožek 1966ab), both intra-individual (including growth and aging) and inter-individual (Brožek 1954). Since the relative amount of body fat is one of the most variable body components, a heavy emphasis has been placed on this feature of body composition.

Optimally, the present account should constitute a supplement to and an update of the volume on *Techniques for Measuring Body Composition* (Brožek and Henschel 1961). Unfortunately, the volume is long out of print. More readily accessible is a detailed overview of the earlier literature on body composition (Keys and Brožek 1953), focused on the assessment of total body fat via determinations of body density and body water. However, the relevance (and limitations) of the deviations from the "standard" reverence weight, body build (somatotypes), and the subcutaneous fat measured as skinfolds and roentgenographic widths (cf. Brožek et al. 1958) were considered.

More recent surveys came from the pen of Malina (1969), Behnke and Wilmore (1974), Forbes (1976), Malina (1980), Katch and Katch (1984), and Forbes (1985). Several accounts were prepared specifically for physical anthropologists (Brožek 1960, 1961, 1963a, 1966, 1966a; Novák 1979). Information on methods as well as their application in a variety of contexts is contained in the proceedings of a number of conferences (Brožek 1956, 1963, 1965; Pařízková 1963, 1965, 1968ab, 1975, 1981, 1984—85, Meneely and Linde 1965; Agricultural Board 1968, Novotný and Titlbachová 1979).

Body Components: Nature, Assessment, Choice

In regards to their nature, the body components may be defined in terms of

1. anatomically characterized tissues (Matiegka 1921) "skin plus subcutaneous tissue", Garn's (1957) "adipose component" of body weight and its complement, "the lean body weight".
2. Chemically characterized substances (such as body water or "fat" defined as ether extract).
3. Intermediary constructs (e.g., fat-free weight"), defined as gross body weight less chemically defined fat, or "cell mass" (Moore et al. 1963).

In terms of the procedures of assessment, the body components can be grouped into 4 classes:

1. Measured (e.g., the total or extracellular water).
2. Calculated, using measurements and empirically or theoretically derived constants (such as Matiegka's — 1921 — "skeletal weight", based on the measurements of bicondylar diameters and stature, or total body fat, derived from determinations of body density).
3. Obtained by substraction. Thus the intracellular water may be obtained by substracting extracellular from the total body water.
4. Estimated on the basis of prediction equations derived statistically, by regression analysis. E.g., total body fat may be predicted from the measurements of skinfolds via the estimates of body density. This category of assessment is particularly important for the integration of the anthropometric with the biophysical (e.g. densitometry) and biochemical (hydrometry) approaches to the study of body composition.

The choice of the components and the methods for their assessment will be determined by the aims of a particular study, the technical facilities, as well as considerations of the cost (Brožek 1974).

Models — Theoretical

A comprehensive analysis of body composition may be viewed as consisting of a series of consecutive steps yielding progressively less heterogeneous "compartments". Each step involves empirical determination of a homogeneous "compartment" separated from a "residual mass" (R). In *Table 1.*, the gross body weight which constitutes the initial "compartment", is partitioned, step-wise, into body fat, extracellular water, intracellular water, body protein, and body minerals. However, the steps may be defined in other ways, as indicated in *Table 2.* When considered simultaneously (rather than sequentially), a specific set of components constitutes a theoretical model. If we consider also the operations (methods) required for the assessment of the components we may speak of a system. In illustrating the theoretical model of body composition we shall first consider model operating with anatomical constructs, to be followed by models involving chemical (and "histochemical") variables.

TABLE 1. *Step-wise partitioning of the gross body weight into body components (C) and residual masses (R_1 to R_4)*

W =	Body fat + R_1 [fat-free body mass]
R_1 =	Extracellular water + R_2 [cell mass and extracellular minerals]
R_2 =	Intracellular water + R_3 (fat-free solids]
R_3 =	Body protein + R_4 [minerals]
R_4 =	Osseous minerals + Non-Osseous minerals

TABLE 2. *Step-wise partitioning of body weight: An alternate sequence*

W =	Total body water + R_1 [water-free solids]
R_1 =	Body fat + R_2 [fat-free solids]
R_2 =	Body protein + R_3 [minerals]
R_3 =	Osseous + Non-osseous minerals

Models with Anatomically Defined Variables

These models are bi-componental, three-componental, and four-componental: Garn separated the body weight (W) into an adipose fraction (AD) and a "lean" fraction (L) : $W = AD + L$ (1957). The "adipose" fraction is estimated from the measurements of the layer of adipose tissue measured on soft-tissue roentgenograms (Garn 1957). — Anderson (1963) developed a three-componental model in which the body is partitioned into adipose tissue (AD), muscle (M), and the remainder (R) : $W = AD + M + R$. Measurements of total body water and total body potassium provided the basic empirical data.

Matiegka (1921) calculated the weight of the skeleton ("ossa", O), of the subcutaneous tissue plus the skin ("derma", D), and skeletal muscle (M). All three variables were based on athropometric data, including body weight. Adding a "residual" fraction (R), we obtain a four-componental model: $W = O + D + M + R$. The R compartment represents the weight of the "visceral mass" (plus circulating fluids).

Models with Chemically and Histochemically Defined Variables

In two-part models, the gross body weight (W) has been partioned into the "fat" and the "non-fat" (lean) component (Behnke 1941/1941). We prefer the clearer and straight-forward term "fatfree body mass", F_f. Thus, $W = F + F_f$, where F = total body fat. One of the components, be it "fat" or "fat-free", is measured; the other part is obtained by difference. In the densitometric and the hydrometric approach, we calculate body fat and the "fat-free" component is obtained as $F_f = W - F$. In the systems based on determinations of body water or body potassium (Forbes et al. 1961), one estimates the "fat-free" part and obtains f as $F = W - F_f$. — In the mid-1940s in a study on the effects of longterm, severe food restriction and subsequent nutritional rehabilitation (Keys et al. 1950) the body weight was partitioned into body fat (F), the interstitial fluid (I, defined as extracellular fluid less blood plasma), red blood cells (RBC), blood plasma (Pl), bone mineral (BM), and a large "remainder" labelled "active tissue (AT), obtained by substracting from the weight the sum of the other variables. Thus, using the symbols defined above, $W = AT + (F + I + RBC + Pl + B)$.

Models — Quantitative

Models operating with symbols might be referred to, more appropriately, as "schemata" and must be differentiated from qualitative models. A systematic account was provided elsewhere (Brožek 1966). Here we shall limit the presentation to illustrative examples.

It is necessary to stress that the equations derived for the estimation of body composition in vivo imply specific, quantitative assumptions (such as a constant density of the fatfree mass, its relative hydration or potassium concentration). It can hardly be overemphasized that in the living human beings these "constants", built into our estimation equations, apply only approximately in individual human beings, even when they belong to the same population. Matters become more complex still when the equations are applied to other ethnic populations. Thus it appears (Schutte et al. 1984) that the density of the fat-free mass is greater in blacks than in whites, reflecting a larger content of bone mineral. Consequently, using the "standard" equations for converting body density into body fat (or fat-free mass) would underestimate fatness (and overestimate the fat-free mass) in the Blacks. The authors provided a corrected formula. The consequences of the variation in the biological constants we assume as well of the imprecision with which we measure the predictor variables (such as body density) have been considered critically and in detail by Siri (1961b).

In endeavoring to provide a firmer base for research on body composition, with special references to densitometry, 3 steps were taken. They concerned the physical characteristics of body fat (defined as ether extract), the density and composition of the compositionally complex tissues that are gained or lost (referred to as "obesity tissues"), and a revised model of body composition, together with computational formulae for densitometric analysis.

Body Fat

"Fat" is the most variable body component and its assessment is of central interest in studying differences between individuals (Keys 1049). Lindegoard (1953) spoke of "differential somatology", in parallel to William Stern's (1911) "differential psychology". Importantly, fat is significantly lighter than the other body components. Thus it is feasible, in principle, to apply the densitometric analysis to the human body. When we reviewed the available information (Keys and Brožek 1953), we found it to be meager.

Since this matter is of critical importance for the densitometric analysis of body composition, a systematic study was made of the density of body fat, defined as ether extract. Human samples of subcutaneous and intra-abdominal adipose tissue were obtained from men and women at surgery or immediately after death (Fidanza et al. 1953). At 36C, the densities of the extracted fat averaged 0.90074 g/cm³ with a narrow range (from 0.8996 to 0.9015). The differences between sites were trivial.

Obesity Tissue

The term designates a "histochemical" construct, not the anatomist's adipose tissue. The information on the fat content of the "obesity tissue" will be used in deriving the formulae for calculating total body fat on the basis of body density determinations. — We have studied the composition of the obesity tissue under three conditions:

1. As total weight gain (114.41 kg) in 10 normal-weight, middle age men in positive energy balance maintained for 6 months.

2. As a total weight loss (172.00 kg) in 10 obese young men maintained for 10 weeks on a low energy diet.

3. As the difference (29.35 kg) between 16 low-density and 21 high density young men, similar in age (with the means of 25 and 24 years, respectively) and identical stature (176.5 cm). The densities and the fat content of these three varieties of obesity tissue are given in *Table 3.* For details see Brožek et al. (1963), Keys and Brožek 1953, and Keys et al. (1955).

TABLE 3. *Density and the fat content (as % of weight) of "obesity tissue" gained, lost, or obtained as a difference between young men identical in stature but widely differing in body density.* (From BROŽEK et al. 1963, p. 131, Table 19.)

Characteristic of obesity tissue	From gain	From loss	From static diffrence
Density	0.948	0.954	0.938
Fat content, %	64	64	73

Frame of Reference

The construct "reference body" is based on the data obtained by the chemical analysis of 3 male cadavers (Brožek et al. 1963). Their average age was 35 years; height, 176.8 cm; and weight, 65.4 kg. The composition of the reference body and of its fat-free compartment is given in *Table 4.* Their densities, at 36 °C, were computed from their chemical components. This information will be used for translating both body density and total body water into total body fat.

TABLE 4. The composition, in %, and the density of the *Minnesota reference body and its fat-free mass* (From BROŽEK et al. 1963, p. 124, Table 11.)

Component	Reference Body	Fat-free mass
Water	62.4	73.8
Protein	16,4	19.4
Fat	15.3	—
Bone minerals	4.8	5.6
Non-osseous minerals	1.1	1.2
Density	1.064	1.100

Anthropometric Methods

In principle, external body dimensions can serve as indicators of body composition: body weight (expressed as % of an appropriate reference weight), circumferences, diameters (including the bicondylar widths), and skinfolds.

The skinfolds are useful indicators of fatness. Muscularity can be assessed from limb circumferences (c) using an appropriate skinfold (s) as a correction factor. We can calculate, then, the diameter (d) of the layer of muscle (plus bone) as

$$d = (c/\Pi) - s.$$

More adequate assessment of the tissues composition of the limbs can be obtained by measuring soft-tissue roentgenograms (Garn 1961). Less precise but more convenient are the ultrasound techniques (Bullen et al. 1965; Katch and Katch 1984). Several attempts were made to use body measurements for the assessment of total body composition.

Matiegka's Approach

In 1921, Matiegka proposed a system for calculating the weight of 3 body compartments: the skeleton (O, for "ossa", bones), skin plus subcutaneous tissues (D, for "derma", skin), and skeletal muscle (M).

Using the symbol R for the "remainder" we have a quadri-partite model for partitioning body weight (W):

$$W = O + D + M + R.$$

This is our equation; Matiegka did not use the concept of a remainder. The components were calculated as follows:

$$O = o^2 \times L \times k_1 \qquad D = d \times S \times k_2$$
$$M = r^2 \times L \times k_3 ,$$

where o = average of 4 biepicondylar diameters (elbow, wrist, knee, ankle), d = one-half of the average thickness of 6 skinfolds (at upper arm, forearm, thigh, calf, thorax and abdomen); r = average of 4 radii calcuated from limb circumferences measured at the same sites as the skinfolds and corrected for the layer of skin + adipose tissue. L = stature, S = body surface, calculated from stature (L) and body weight (W). The coefficient k_1 to k_3 were derived on the basis of Matiegka's experience as a quantitative anatomist and the data available in the literature. Their values were given as $k_1 = 1.2$, $k_2 = 0.13$, and $k_3 = 6.5$. These values were regarded by Matiegka as the first approximations, in need of empirical validation and refinement. Unfortunately, systematic validation as far as we are aware has not been carried out.

For years, Matiegka's work was largely neglected. In the early 1950s Trotter (1954) took Matiegka's ideas for the estimation of skeletal weight as the point of departure for her own studies (Merz et al. 1956). The appreciation of Matiegka's contribution is reflected in the dedication of Ashley Montague's (1960) Handbook of Anthropology to Jindřich Matiegka and his friend and collegue, Aleš Hrdlička, the editor of the journal in which Matiegka's 1921 paper was published (Brožek 1964). Matiegka's formula was used also in combination with densitometry for the evaluation and confrontation of body composition measurements in athletes; the correlation between the mentioned two methodological approaches in athletes (Malkovská — see Pařízková 1977):

Drinkwater and Ross (1980) acknowledged warmly Matiegka's contribution to the methodology of body composition analysis and responded creatively to Matiegka's ideas in three ways: first, they set forth to estimate directly what we call the "remainder" (R), rather than by substraction: $R = W - (O + D + M)$. They label the compartment "V" (for "vital organ" visceral mass) and, using body weight as a predictor, proposed the equation $V = W \times k$, where $k = 0.206$. More in harmony with the spirit of Matiegka's prediction equations is their alternative equation:

$$V = \left(\frac{TR + AP}{2}\right)^2 \times H \times k,$$ where TR = average of 3 transverse diameters (transverse chest, biacromial, bicristal); AP = anteroposterior chest diameter; H = height, in cm, and $k = 0.35$.

Secondly, Drinkwater and Ross redefined Matiegka's 3 original constants using a reference man ("phantom", in their parlance) whose quantitative characteristics were specified by Ross and Wilson (1974). Finally, since in their system the 4 body compartments are derived independantly, the gross body weight can serve as a criterion of validity of the estimates.

Garn's approach

The author proposed to partition the gross body weight into an "adipose" and "lean" compartment, based on regression analysis. For a population, the relationship between a fat indicator (I-such as the width of the shadow of the layer of subcutaneous adipose tissue measured a soft-tissue roentgenograph — Garn 1957a, b; 1961) and the body weight (W) can be characterized by the equation $W = a + bI$, where a = the intercept (population value of W for $I = O$) and b = the slope of the regression line. — Having obtained by mathematical analysis of a body of data the values a and b, and having measured the I for a given individual, J, and his body weight (I_J, W_J) we can calculate the compartments: "lean", $L_J = bW_J$ and, by difference, "adipose", $A_J = W_J - L_J$.

In principle, the procedure can be applied to other anthropometric indicators of fatness, such as fatfolds (skinfolds) measured by calipers. It was indicated (Brožek 1961) that there is a number of problems with this technique, involving both consistency (values of the two compartments estimated from measurements made at different sites) and precision (dependent on the size of the coefficient of correlation between a given indicator of adiposity and body weight). We have suggested the usefulness of combining several measures of a given indicator (see Pascale et al. 1956, Pařízková 1961, 1977 etc.).

Behnke's system

A. R. Behnke physiologist and a Captain of Navy devoted productive lifetime to research on body composition. He developed several approaches for arriving at the major body compartments on the basis of anthropometric data. The initial approach (Behnke et al. 1959) involved two estimates of body weight: W_A, based on circumferential measurements of the more fat-laden body parts (such as abdomen and buttocks), and W_S, estimated from bony dimensions. The differences, $d = W_A - W_S$, were taken as a measure of "excess fat". Later he preferred to operate with "modules": the stature (H), weight (W) module, designated (not particularly fortunately) as F, and the module of perimetric size, D:

$$F = \frac{W\,[\text{kg}]}{H\,[\text{dm}]} \quad \text{and}$$

$$D = \frac{\text{sum of 11 circumferences}}{100}$$

(Behnke and Wilmore 1974). The two modules are viewed as interchangeable: $D = 3F$. Thus the surface area is estimated as $S = D \times H \times k$ or $S = 3F \times H \times k$, where $k = 0.001\,762$.

In analogy to Matiegka's approach, Behnke estimated "body fat" from the sum of six radiographic shadows of the adipose layer, which we shall call ΣR, and the surface area (S): weight of fat, in kg $= \Sigma R \times S \times k$, where $k = 0.134$ (Behnke and Wilmore 1974).

The relative weight of body fat, "F %" is obtained as $\% \text{ Fat} = \frac{\text{Fat [kg]}}{\text{Weight [kg]}} \times 100$. Alternately, using the modules, the fat percentage cauld be calculated as

$$\% \text{ Fat} = \frac{\Sigma R}{3F \times k} \times 100 \quad \text{or as} \quad \frac{\Sigma R}{D \times k} \times 100, \text{ where } k = 4.71.$$

Another way to estimate % fat called for comparing the radiographic fat widths, R, with the radiographic width of the muscle (M) plus bone width of the upper arm. $\% \text{ fat} = \frac{0.94 \times R}{(M + B)}$.

Laboratory Methods

In the present context, the laboratory methods are not of interest for their own sake but as yielding data that can be integrated with anthropometry. On the basis of the published literature, three methods qualify as "primary" (basic, directly relevant): densitometry, hydrometry and kaliometry. Some of the other methods will be notified briefly.

Densitometry

Body density (D) is defined as the ratio of body weight (W [kg]) and the body volume (V [l]) corrected for the space occupied by air in the lungs and respiratory passages: $D = \frac{W}{V}$ (No. 7). Body density has been the most widely used indicator of body composition, with focus on the total body fat. The translation of body density into body fat involves specific quantitative assumptions and it is valid only when these assumptions are met or at least closely approximated. One such assumption is a normal hydration (water content) of the body. In the presence of an excess of the extracellular fluid, whether or not is manifested as visible edema, both the body weight and body volume have to be corrected before an interpretable values of body density (or specific gravity, SG = W/weight of the water displaced by the body during total submersion) can be calculated (Keys and Brožek 1953). In any system, such as the human body, knowing the densities of its two constituent parts (fat and fat-free body mass) and having determined the body density of a given individual, we can calculate the relative amounts of the two parts. Let us look, briefly, at the mathematical considerations.

In two part system, the weights and the volume of the parts add up to the weight (W) and volume (V) of the whole:

$$W = W_1 + W_2 \quad \text{(No. 8)}$$

$$V = V_1 + V_2 \quad \text{(No. 9)}$$

— thus density,

$$D = \frac{W_1 + W_2}{V_1 + V_2}. \qquad \text{(No. 10)}$$

The next step involves introducing the concept of proportional weights, w_1 and w_2:

$$w_1 = \frac{W_1}{W} \qquad \text{(No. 11)}$$

and

$$w_2 = \frac{W_2}{W}. \qquad \text{(No. 12)}$$

Consequently,

$$w_1 + w_2 = 1 \qquad \text{(No. 13)}$$

and

$$w_2 = (1 - w_1). \qquad \text{(No. 14)}$$

The next step call for replacing volumes by the ratios of weights and densities. Since $D = W/V$, $V = W/D$. More specifically,

$$v_1 = \frac{w_1}{d_1} \qquad \text{(No. 15)}$$

and

$$v_2 = \frac{w_2}{d_2} = \frac{1 - w_2}{d_2}. \qquad \text{(No. 16)}$$

Using these symbols,

$$D = \frac{1}{\frac{w_1}{d_1} + \frac{1 - w_1}{d_2}}. \qquad \text{(No. 17)}$$

Solving for w_1, we can write:

$$w_1 = \frac{d_2 - d_1}{D(d_2 - d_1)} - \frac{d_1}{(d_2 - d_1)},$$

where, to repeat, w_1 is the weight of the first component, expressed as a fraction of the whole weight. As we know, $w_2 = (1 - w_1)$.

In the densitometric analysis (Minnesota system) of body composition the two components of body weight (W), i.e.

$$W = O + R \qquad \text{(No. 18)}$$

are defined as follows: "O" represents the obesity tissue. For the sake of the economy of space, here we shall consider only the tissue complex defined as accounting for the difference in the body weight of young men closely similar in age, identical in stature, but with a low and high body density. Such a tissue complex has a density $d_O = 0.938$ and a fat content of 73 %; "R" denotes the part identical in density and in composition with the characteristics of the "reference man", with a density $R = 1.064$ and a fat content of 15.3 %.

Calculating obesity tissue, as a fraction of the body weight, from equation No. 17, we can write:

$$o = \frac{1}{D_B} \times \frac{1.064 \times 0.938}{(1.064 - 0.938)} - \frac{0.938}{(1.064 - 0.938)} = \frac{7.921}{D_B} = 7.444. \quad \text{(No. 19)}$$

In analogy to equations No. 13 and No. 14, $o + r = 1$ and $r = 1 - o$.

Total fat content of the body, $f_B = f_O + f_R$, i.e. the sum of fat in the o-fraction and the r-fraction.

Since $f_O = 0.73o$ and $f_R = 0.153r$, we can write

$$\begin{aligned} f_B &= 0.73o + 0.153r \quad \text{(No. 20)} \\ &= 0.73o + 0.153\,(1 - o) \\ &= 0.73o + 0.153 - 0.153o \\ &= 0.577o + 0.153. \end{aligned}$$

Replacing "o" by equation No. 19, the total fat as a fraction of the body weight,

$$f_B, \text{ is } f_B = 0.577\,(7.921/D_B - 7.444) + 0.153 =$$
$$= \frac{4.570}{D_B} - 4.142. \qquad \text{(No. 21)}$$

Using the simplest model, the body weight is partitioned into body fat, F_B, and the fat-free mass, F_{free}:

$$W = F + F_{\text{free}}. \qquad \text{(No. 22)}$$

The $d_F = 0.9007$ at 36C and the density of the fat-free mass of the reference body is 1.100. Using the equation No. 17, we can obtain the fat fraction of the body, f_B, as:

$$f_B = \frac{1}{D_B} \times \frac{1.100 \times 0.9007}{(1.100 - 0.9007)} -$$
$$- \frac{0.9007}{(1.100 - 0.9007)} = \frac{4.971}{D_B} - 4.519. \quad \text{(No. 23)}$$

In *table 5.* the fat equivalent of body densities, obtained by using equations No. 17 and No. 23 are compared over a wide range of densities. In the middle range of the body densities the estimated fat values are very similar (and, for the density of the reference body, identical). Equation No. 17 slightly overestimated the fat content at very high densities. There is no independent evidence for the assessment of the validity of the fat estimates based on very low body densities (*Table 5*).

TABLE 5. *The fat fractions of the body estimated from Equation No. 21 and equation No. 23 at different levels of body density*

Body Density	$f_B = (4.570/D) - 4.142$	$f_B = (4.971/D) - 4.519$
1.020	0.338	0.355
1.064	0.153	0.153
1.100	0.013	0.000

Hydrometry

A large number of substances have been suggested and used as test solutes for the estimation of total body water on the dilution principle, such as deuterium tritium or urea (Keys and Brožek 1953, Forbes 1985 etc.). The basic theoretical assumption underlying the use of the procedure for the assessment of body composition specifise that body water (A), is a fixed fraction of the fat-free body mass (F_f):

$$\frac{A}{F_f} = k. \qquad \text{(No. 24)}$$

Expressing the weights of A and F_f as fractions of the body weight (a, f_f),

$$f_f = \frac{a}{k}. \qquad \text{(No. 25)}$$

With f = total body fat, as a fraction of body weight,

$$f + f_f = 1. \qquad \text{(No. 26)}$$

Consequently,

$$f = 1 - f_f \qquad \text{(No. 27)}$$

$$\text{i.e.} = 1 - \frac{a}{k} = 1 - \left(\frac{1}{k} \times a\right).$$

In the "Minnesota reference man", in fractional terms,

$$k = \frac{0.6243}{0.8469} \quad \text{and} \quad \frac{1}{k} = \frac{0.8469}{0.6243} = 1.3566.$$

Thus the calculational formula may be written

$$f = 1 - 1.3566a \qquad \text{(No. 28)}$$

where a = total water expressed as a fraction of body weight. For $a = 0.6243$ (the value for the reference body), $f = 1 - (1.3566 \times 0.6243)$, i.e. $= 1 - 0.8469$, and thus 0.153.

The k-value for the reference body, $k = 0.7372$, is close to the values reported in the literature (Key and Brožek 1953).

Kaliometry

The amount of potassium contained in the body may be determined by several techniques (Forbes 1985). One of them is the isotopic dilution of ^{42}K, administered intravenously. This yields the "exchangeable" K" (K_e), a value that is somewhat lower than the total body potassium. Forbes (1985) cites the figure of 90—95 %, the difference being due to incomplete exchange of the isotope in the red blood cells and in the brain.

A non-invasive technique involves the determination of the body content of the naturally isotope of

TABLE 6. *Composition of Fat-free Body Mass. Body Water (%), Potassium (meq./kg), and Density (g/ml) In Males and Females Differing in Age* (From FORBES 1985, Table 5.)

AGE and SEX	H_2O	K	Density
Fetus, 24 wk. combined	89	40	—
Fetus, 32 wk. combined	86	46	—
Birth, male	81	49	1.063
female	81	49	1.064
5 yr. male	77	64	1.078
female	78	62	1.073
10 yr. male	75	67	1.085
female	77	64	1.075
18.5 yr. male	73.6	—	1.093
Young adult male	73	68.1	1.100
female	73	64.2	

potassium ^{40}K, using sodium iodide crystals and plastic or liquid scintillation counters (Miller and Remenchik 1963; Remenchik et al. 1968).

In principle, the approach based on the assessment of body potassium as an indicator of body composition corresponds to that of hydrometry in that it assumes a constant proportion between body potassium and the fat-free weight:

$$\frac{\text{total } K}{\text{fat-free weight}} = c. \qquad \text{(No. 29)}$$

Forbes et al. (1961) proposed to use a $c = 68.1$. Thus, expressing the potassium in milliequivalents and the fat-free weight (F_f) in kilograms,

$$F_f = \frac{\text{measured total } K}{68.1}. \qquad \text{(No. 30)}$$

The total body fat (F, in kg) is obtained as a difference between the body-weight (W) and the fat-free weight (F_f):

$$F = W - F_f. \qquad \text{(No. 31)}$$

The value of the "constant", c, exhibits age changes in parallel to other indications of body composition. The values for selected parameters are reproduced in *Table 6.*

PART II.

INTRODUCTION

Human physique is a complex phenomenon and its comprehensive description, in quantitative terms, requires a combination of diverse methods; like that more proper characteristics of the human organism can be given. The selection and combination of necessary methods depends on the purpose of the study, size of the examined sample, qualification of the examiners and so forth. The measurements in large population samples e.g. in epidemiological studies requires reliable, simple and reproducible methods which could give an adequate information on human physique and physical performance (Matiegka 1921).

Combinations of the "classical" methods for the study of body composition may serve two goals:

a) to reduce errors of measurements, and

b) to produce a more comprehensive description of body components. These issues have been considered systematically by Siri (1961b).

Some aspects of the relationship between anthropometric data and the information obtained by the laboratory techniques were considered by Johnston (1982); the paper may serve as the source of additional references to publications dealing with the topic.

Fat from density and body water

Instead of partitioning the gross body weight into body fat and the fat-free body mass, we can use a tri-partite model:

$$W = A + F + R \qquad \text{(No. 1)}$$

where W = body weight, in kg, A = body water, F = body fat, and R is the "remainder", consisting of protein, bone mineral, and the nonosseous mineral. At the mean body temperature of 36—37 °C, the densities of water, $d_A = 0.9973$ and of fat, $d_F = 0.9007$. But what is the density of the remainder, d_R? There has been substantial uncertainty about its value (Keys and Brožek 1953). New information for its computation was provided in re-examining the quantitative assumptions of densitometry (Brožek et al. 1963), yielding $d_R = 1.5687$.

Expressing the 3 parts as fractions of body weight (a, f, r), so that

$$w = a + f + r \qquad \text{(No. 2)}$$
$$= 1$$

so that

$$r = 1 - a - f \qquad \text{(No. 3)}$$

and replacing volumes by ratios of weight and density, we can write the formula for body density as

$$D_B = \frac{1}{\dfrac{a}{d_a} + \dfrac{f}{d_f} + \dfrac{(1 - a - f)}{d_r}}. \qquad \text{(No. 4)}$$

Solving for "f",

$$f = \frac{\dfrac{d_r}{D_B} - a\left(\dfrac{d_r}{d_a} - 1\right) - 1}{\left(\dfrac{d_r}{d_f} - 1\right)}. \qquad \text{(No. 5)}$$

Replacing symbols by the numerical values of d_a, d_f and d_R and carrying out the computations, we obtain the estimation equation

$$f = (2.1153/D_B) - 0.7802a - 1.3484 \quad \text{(No. 6)}$$

For $D_B = 1.064$, the density of the Minnesota reference body and $a = 0.6243$,

$$\begin{aligned} f &= 1.9881 - 0.4871 - 1.3484 \\ &= 0.1526 \doteq 0.153 \end{aligned}$$

Beyond Fat and Water

Multicomponental models were discussed previously on body composition, and we shall return to them in the closing section on the integration of the anthropometric and laboratory methods. Here we shall consider, briefly, the work of Moore et al. (1963).

The simplest model with "body cell mass" (BCM) as the central construct is tripartite:

$$W = BCM + F + R_1 \qquad \text{(No. 7)}$$

where W = body weight, F = total body fat, and R_1 = a remainder. The body cell mass is calculated from the information on exchangeable potassium, obtained from ^{42}K measurements: BCM (in grams) = $= K_e(mEq) \times 8.33$. Total body fat is estimated as a difference between the total body weight and the fat-free body mass; the latter is calculated on the assumption that water constitues 73.2 % of the weight of the fatfree mass.

The Remainder, R_1, into extracellular water, A_e (measured in the system of Moore et al.) as the dilution space of ^{82}Br (corrected for the penetration of the red blood cell); the red blood cells, RBC, from the dilution of the red blood cells tagged with ^{52}Cr: and another, smaller remainder, R_2. Thus

$$W = BCM + F + A_e/RBC + R_2 \qquad \text{(No. 8)}$$

The remainder, R_2, may be partitioned into the weight of dry bone (the matrix plus mineral, estimated from the measurements of total body water and ^{42}K) and the remainder, R_3, which represents the solids contained in the extracellular fluid and in connective tissues (dermis, tendons, fascias).

Beyond this model, Moore et al. are interested in body hydration (extracellular and intracellular water), plasma and blood volume, and the amount of exchangeable ions other than potassium (sodium, chloride).

Other Methods

There is a large number of other methods, both older and newer (Garron 1982), designed to improve on the existing techniques, provide alternatives to the "classical" methods of body-composition analysis (Jenin et al. 1975), or as means for determining additional body components (cf. Peppler and Mazess 1981).

Fat-soluble Indicators (Gases)

Theoretically, the dilution principle is aplicable to determinations of total body fat, using materials that are soluble solely or preferentially in fat. Since nitrogen is about 5 times more soluble in body fat than in water, efforts have been made to estimate body fat from the body nitrogen washed out be breathing oxygen (Behnke et al. 1935; Behnke 1945). Cyclopropane is one of the gases substantially more soluble in fat than is nitrogen. The use of this gas was adapted to human studies, and other gases have been explored as potential fat indicators, such as krypton (Lesser and Zak 1963; cf. Lesser et al. 1971). The most apealing aspect of this approach is that it is independent of the assumptions incorporated into the use of the other laboratory methods and thus can be used, in principle, for their validation.

Total Body Electrical Conductivity

The fundamental observation on which the method is based is that the electrical conductivity of lean tissues is substantially greater than the conductivity of fatty tissues (Presta et al. 1983a), due to the higher electrolyte content of the lean tissues. It is a non-invasive technique, safe, simple, rapid, and convenient.

The measurements involve the change in the impedance of a large solenoidal coil (designed to accomodate a living human body, in supine position, within its interior) from when the coil is empty to when a subject is placed within its interior.

The aim of the procedure is to provide an estimate of the fatfree fraction of the body weight (and thus, as a complement, of the total body fat). The data on electrical conductivity correlated highly with the densitometrically estimated fat-free body mass in a sample of 32 men and women, 20 to 53 years of age (Presta et al. 1983b).

Neutron Activation

The technique is designed to make possible an *in vivo* analysis of body elements. Of special interest for the study of body composition is K, Ca, and N. The underlying principle specifies that these elements can be made radioactive by neutron irradiation of a subject and that the induced radiation can serve as an indicator of the amount of the particular element present in the body. The development of the technique since 1957 was traced by Cohn (1981). The uses of the aproach are illustrated by the measurement of the extracellular space (Yasumura et al. 1983) and of body protein (Mc Neill et al. 1979).

Cohn (1981) is outspoken on the merits of the technique: "*In vivo* neutron activation has provided investigators with a most powerful tool for research on body composition... New possibilities for modeling of the human body have thus become available with this technique."

Comparison of the Techniques

In assessing the "precision" of the various techniques, Forbes (1985) took into consideration both the errors of measurement (variability associated with the technique) and the biological variability of the "constants" that are built into the models of body composition. A tabular comparison is provided (Forbes – Table 3, 1985).

A concise "buyer's guide to body composition techniques" was provided by Garrow (1982), reproduced below. We have omitted the techniques using fat-soluble gases, since the author felt that not enough information is available. We have replaced Garrow's system of stars (from one "worth" to 4 "best") by numbers (*Table 1*).

TABLE 1. *Rating of methods for the study of body composition, from 1 = "worst" to 4 = "best"*. After Garrow (1982, Table 2)

Method	Cost	Convenience	Accuracy
Water ^2H or ^{18}O	2	2	3 (for fat)
^3H	3	2	2
Potassium ^{40}K	2	3	3
Neutron activation			
N, Ca	1	3	2
Conductivity	2	4	3
Skinfold thickness	4	3	2
Muscle metabolites	4	3	?
Density by immersion	3	1	3
by plethysmograph	2	2	4

Comprehensive Characterisation of Human Physique

The multi-parameter approach will be illustrated in reference to a multidisciplinary study on the effects of severe caloric restriction, associated with about one quarter of the initial body weight, and subsequent nutritional rehabilitation (Keys et al. 1950).

The following methods were used to study the changes in the external and internal (tissue) morphology:

a) Ratings and measurements of whole body photographs (3 views: frontal, dorsal, and lateral).

b) External body measurements (standing and sitting height, 6 diameters, 5 circumferences) and body weight.

c) Analysis of body composition, including densitometric estimates of total body fat and determinations of thiocyanate-dilution space (as an indicator of the volume of extracellular fluid), blood plasma volume, and erythrocyte volume.

d) Roentgenographic assessment of bone mineralization.

Analysis of Photographs

Three full-length photographs of the body, in the nude, and close-ups of the face were taken at different points in the study. Here we shall consider only two periods: end of control period and end of semistarvation (six months later). The photographs document, vividly, the dramatic changes in appearance dominated by decreases of the soft tissues and the resulting prominence of the bones (ribs, scapula, facial bones) (*Table 2*).

TABLE 2. *Average somatotype ratings (range 1 to 7) based on photographs taken prior to and at the end of 6 months of semistarvation* (From Keys et al. 1950, p. 153.)

Period	Endomorphy	Mesomorphy	Ectomorphy
Control	3,47	3,94	3.42
End of semi-starvation	1,82	2.81	5,71
Difference	–1.64	–1.13	+2.29

A systematic analysis of the photographs was carried out in the Harvard Anthropometric Laboratory (Cambridge, MA) in the Sheldonian framework of "somatotypes" (Sheldon et al. 1940; cf. Hooton 1946, Keys et al. 1950). Three aspects of human physique are rated on the scales ranging from 1 (very low) through 4 (intermediate) to 7 (very high): endomorphy (soft roundness), mesomorphy (predominance of muscle and bone), and ectomorphy (linearity and fragility). Clearly, the characteristics of somatotypes represent a mixture of relatively permanent, "constitutional", and modifiable, "compositional" features. The results, summarized in *Table 2*, indicate a marked decrease in endomorphy, a lesser decrease in mesomorphy, and a marked increase in ectomorphy. The changes in the ratings reflect the large decrement of body fat and a less marked losses of muscle tissues, documented by anthropometric and laboratory techniques.

For the sake of completeness it should be noted that the same set of photographs was analyzed metrically by Lasker (1947, Keys et al. 1950), retaining the same terminology and scales from 1 to 7. Surprisingly enough, the same average decrement (–1.72, was reported for both endomorphy and mesomorphy.

Data for the 17 dimensions measured by Lasker are of interest in themselves, without reference to any typological scheme. For the most part, the dimensions showed an average decrement at the end of the semistarvation period. The largest decrements were registered in the thickness of the upper arm (–27.0 %) and upper-thigh breadth (–25.4 %). For many dimensions the losses were in the range from 12 to 15 %. Importantly, some "bony" dimensions, particularly the breadth of the ankle, showed increases in some individuals and thus documented the presence of edema. This represents a specific methodological and factual contribution of photography in general and of photogrammetry in particular (cf. Keys et al. 1950).

Direct Body Measurements

External body measurements (ibid.) showed no difference between the control and the semistarvation value in the bicristal diameter, measured with pressure on the tips of the spreading calipers. The other "bony" diameters (bitrochanteric, thorax anteroposterior, biacromial) showed minimal changes (–2 % or less) while the bideltoid diameter, a substantial part of which consists of soft tissues, decreased by 9 %.

The limb circumferences showed large decrements: 24 % for the upper arm, 19 % for the thigh, and 12 % for the calf; the change in that calf reflects two phenomena, opposite in direction: losses of fat and muscle vs. increased water content.

Since there are problems, related to the issue of the range of potential changes in different dimensions (problem of the "biological zero"), in the use of percentages for comparing the magnitude of change, we chose to apply a different mathematical approach. The delta scores were defined as

$$\Delta = \frac{\bar{x}_S - \bar{x}_C}{SD_C}. \qquad \text{(No. 9)}$$

where $\bar{x}_C$ = average value for the control period
$\bar{x}_S$ = average value for the end of starvation
SD_C = standard deviation of the measurements in the control period.

For the upper arm, the thigh, and the calf the delta scores were –4.08, –3.21, and –1.65 respectively.

The presence of marked differences in the relative losses in different regions is confirmed, and it is large. This fact is not and can not be demonstrated with the laboratory methods for the study of the composition of the body as a whole. However, the laboratory methods provide critical information for the interpretation of changes in body dimensions, especially the body weight.

Laboratory methods

Using a subsample of the 32 subjects, for whom measurements were available from the control period (*C*) through the semistarvation phase (*S*) of 24 weeks to the 58th week of rehabilitation (*R*), we obtain the following values for the gross body weight, expressed as % of the control weight: at the end of semistarvation (*S*24), 79.6; at *R*6, 78.2; at *R*12, 85.1; at *R*33, 106.8; at *R*58, 103.0 %.

However, the gross body weight proved to be an "impure" indicator of the actual tissue loss: It was subject to a biological "error of measurement", due to the increase in the relative hydration of the body, manifested in the expansion of the extracellular fluid (the volume of which was estimated from the thiocyanate-dilution space). The phenomenon and its magnitude is documented in *Table 3*.

TABLE 3. *Extracellular fluid (= 0.7 thiocyanate-dilution space) under control conditions, at the end of the semistarvation period (S24), and at specified weeks (R 5, R 19, R 33—58) of nutritional rehabilitation. The values are averages and represent the weight of the extracellular fluid expressed as percentages of the total body weight.* (*The* basic data are presented in Keys et al. 1950, p. 278).

Variable	Period				
	C	S24	R5	R19	R33—58
Extracellular fluid, % of body weight	16.55	23.79	19.58	16.62	16.46
Difference from control	—	+7.24	+3.03	+0.07	—0,09

By the end of the starvation period, the excess hydration represents about 7 % of the body weight. Applying this value to the mean body weight obtained at the end of the starvation period (*S*24) for the 32 men (52.6 kg), the excess extracellular fluid accounts for about 3.7 kg. This yield 48.9 kg as the weight of the body free of excess hydration. As percentage of the control weight (69.4 kg), the value is 70.5 % (versus 75.8 %, when gross body weight is considered).

In terms of weight loss, the values are 24.2 vs. 29.5 %. It is the latter figure that reflects the actual tissue loss. Such a correction would not be feasible without the combination (integration) of the anthropometric and the laboratory methods.

Using a combination of methods, it was feasible to partition the whole-body weight into 6 parts. Four of these are based on measurements: total body fat (estimated densitometrically), plasma volume, interstitial fluid (obtained as the thiocyanate dilution space less plasma volume), and the red blood cells (erythrocytes). Body mineral was estimated as 4 % of the normal (control) body weight; this figure was used throughout, since quantitative radiological measurement of bone density (Keys et al. 1950) did not demonstrate changes in bone mineralization. The large component designated "active tissues" was obtained by difference (as the total body weight less the sum of the other 5 components).

Effects of Moderate Weight Loss

Having measured, on soft-tissue roentgenograms, the width of the "fat" shadow at 9 sites, Garn (1957b) characterized the pattern of the distribution of subcutaneous fat by calculating *z*-scores:

$$z = \frac{(X_i - \bar{X})}{SD_X} \qquad \text{(No. 10)}$$

where X_i = a measurement made in a given individual (*i*) at a specified site
$\bar{X}$ = the mean of such measurements in a group
SD_X = a standard deviation of the measurements in the group.

In cooperation with Dr. Garn (1957a, 1955), the procedure was applied in a study of the effects of maintaining a group of young male volunteers on survival rations for 24 days. This regimen resulted in the loss of 11 % of the initial body weight. It was interesting to find that, at this level of moderate weight loss, the "profiles" of the z-scores obtained in the control period and on the 24th day of maintenance on the experimental dietary regimen, obtained by connecting the *z*-scores, tended to be parallel to each other, i.e., the "profiles" were similar (Brožek 1955).

Effects of Aging

In a study carried out in the early 1950s and focused on age-related differences in human physique, 83 clinically healthy women between 18 and 67 years of age were examined.

Qualitative morphological observations were made by Božo Škerlj, who has been long interested in the body build of women and the phenomenon of the "physiological fatness" of women (1930, 1938). His descriptive system, based on anthroposcopy (systematic inspection), included 3 principal characteristics

TABLE 4. *General characteristics of the sample of clinically healthy women, mean body density, and the corresponding values of total body fat (as % of gross body weight)*

N	23	19	20
Age range, years	18 to 30	31 to 45	46 to 67
Mean age, years	24.2	39.1	56.0
Relative body weight, % of standard	95.3	97.3	95.3
Body density	1.040	1.026	1.016
Fat, as % of body weight	25.2	31.2	35.6

referred to as "vectors": overall leanness-fatness, the relative development of soft tissues on the trunk above and below the waist, and the size of the fat depots on the trunk vs. the extremities. In the Minnesota study these constructs were quantified (Škerlj et al. 1953).

The total body fat was assessed densitometrically (Brožek et al. 1953; Brožek 1962). The data are presented in *Table 4.* with the fat percentages recalculated using the conversion formula for fat, as percentage of weight = $(4.570/D - 4.142) \times 100$. The data indicate a substantial and progressive — within the age limits of the sample — decrease of body density with age, reflecting an increase in body fat (as % of weight- *Table 4.*).

Skinfolds were measured at 10 sites, using calipers with a low pressure (about 5.4 g/mm of the contact surface): under the chin (1), on the upper trunk (3), on the lower trunk (2), and the extremities (1 site on the upper arm, 2 on the upper leg, 1 on the calf). The age — related changes in the distribution of the subcutaneous adipose tissue (and of the fat contained in these tissues) may be examined in reference to

a) comparisons between the size of the depots of adipose tissue in different regions, and

b) a comparison of the trends in the calculated "outer" (subcutaneous) and the "inner" fat.

Data in *Table 5.* indicate a trend toward a continuing increase in the upper region (skinfolds below the chin, on the upper arm, at 3 sites on the upper trunk, plus 1/2 of the waist skinfold) vs. the lower region (1/2 of waist skinfold plus skinfolds thicknesses measured at the abdomen, at mid-thigh, above the knee, and on the calf).

Similarly, the relative contribution of the skinfolds measured on the trunk and on the chin (the ("axial" area) was increasing, vs. a decrease registered for the extremities (*Table 5*).

TABLE 5. *Subtotals of skinfolds, expressed as % of the total sum of 10 skinfolds, in groups of clinically healthy women differing in age* (From Brožek et al. 1953, p. 591).

Age groups	18 to 30	31 to 45	46 to 67
N	31	25	28
Upper body region vs.	39.6	43.5	45.7
Lower body region	60.4	56.4	54.4
Trunk and chin vs.	46.6	50.1	53.5
Extremities	53.4	49.8	46.6

Effects of physical activity regimes

The impact of the work load both induced by professional and/or leisure activities have a significant impact on body surface, volume and body composition as regards the absolute and relative amounts of lean, active body mass and depot fat. In the subjects who are adapted to a high degree of physical activity and exercise a relatively great body surface as related to body weight, and mostly a high body density indicating great lean body mass in absolute and relative terms at the expense of depot fat can be found. Static work loads increase the absolute amount of lean body mass; mostly depot fat decreases after dynamic exercise. Thus morphological characteristic runs parallel with a high level of functional capacity evaluated from numerous points of view.

By functional capacity and fitness we understand first of all the ability to perform physical work which depends mostly on the efficiency of the cardiovascular, respiratory and neuromuscular systems as related to the function of all other systems of the human organism. Among the measurements of health, and thus also of the nutritional status these functional parameters have an important place. They belong to the most important characteristics of the human organism, its level of development, growth and maturation, as well as ageing. Their reduction or impairment can be often a first sign of illness, malnutrition or any other pathological state, before the changes of the morphological indicators (Pařízková 1984, 1985). They can characterize not only normality, but also "positive health"; their importance from the point of view of well-being and economic productivity (especially for physical workers in developing countries) is evident (Pařízková 84). As often commented, it is more important to be healthy and fit, then to achieve certain bodily dimensions (WHO 1985).

Similarly as in other physical traits there exists in humans a wide variability of fitness and functional capacity which depends both on genetic and/or environmental factors. Similarly as in morphological parameters, the adaptational processes can modify significantly the capacity to perform physical work in all age categories: the impact of systematic work load, which has a sufficient intensity, but is within the adaptation limits of the organism, can markedly increase the work performance along with changes of body composition, i.e. mostly the increase of lean body mass ratio at the expense of fat (Pařízková 1963, 1965, 1968, 1972, 1975, 1984, 1985 etc., Wilmore and Freund 1984 etc.). This applies especially for growth period, when an appropriate stimulation helps to develop an optimal level of all bodily systems involved in physical work.

For the measurements of the functional capacity and fitness there exist many methods; from the practical point of view they are classified as laboratory and/or clinical, half-field and field methods, according to the aim and circumstances of the study in question. A battery of tests was adopted for e.g. International Biological Programme (IBP — Weiner and Laurie 1969, see Pařízková 1984, 1985). It is recommendable to use these tests ad there exist already many data which can serve as norms for comparison; however, expecially as regards laboratory research, a substantial development from the technical point of view has occurred since. Nevertheless, for field measurements many of these tests are still useful.

There exist relationships between selected morphological parameters especially the proportion of lean body mass, the high value of which is mostly paralleled by a high aerobic power and physical performance (Pařízková 1977, 1984 etc.). Also some indices relating e.g. bicristal and biacromial breadths, body mass index (BMI), selected circumferential measurements (e.g. of the chest, abdomen, hips; arm contracted and relaxed etc.) and their mutual relationships give an information on muscular development, body build and thus also indirectly on the level of performance capacity.

Predicting Body Composition from Anthropometric Data

The task and the procedures for predicting body components and body compartments from body measurements constitute an important facet in the "integration" of anthropometry and the laboratory methods. The latter yield such fundamental indicators of body composition as body density, total body water, and total body potassium from which in a bi-partite model, we can estimate total body fat and the fatfree body mass.

The antropometric predictors include weight and height (as well as body surface, calculated from weight and height), circumferences and diameters, and — importantly — "skinfolds". We shall begin with the semi-quantitative ratings of body build.

From Somatotype Ratings to Total Body Fat

We shall consider the relationship between the ratings of "endomorphy" and the hydrostatically estimated total body fat (Dupertuis et al. 1950/51). The ratings were made by the senior author, an antropologist, on 81 men (primarily naval personnel) averaging 26.6 years of age. Their average fat content was estimated at 15 % of body weight. In the selection of the subjects effort was made to include a wide range of body build.

TABLE 6. *Specific gravity (Body Density / Density of water in the tank), body fat (as % of weight), and ratings of endomorphy (range, 1 to 7).* (From Dupertuis et al. 1950/1951, p. 677.)

N	Range of spec. gr.	Mean spec. gr.	Body fat, %	Mean rating
24	1.022 to 1,059	1.050	24.3	4.42
23	1.060 to 1.074	1.066	16.1	3.65
34	1.075 to 1.100	1.068	7.4	2.50

The men were placed into one of the 3 categories of specific gravity. *Table 6.* shows that with an increase in specific gravity (parallel to a decrease of the fat content estimated from specific gravity) the ratings of "endomorphy" tent to decrease. Utilizing the data for all the 81 men, the coefficient of correlation between the endomorphy ratings and specific gravity is $r = -0.853$. The regression equation for estimating specific gravity (Y) from the endomorphy rations (X) reads:

$$Y = 1.094 - 0.119X \qquad \text{(No. 11)}$$

From Bony Diameters to "Lean Body Mass"

Usirg Behnke's (1939) data, Hechter (1959) derived a multiple — regression equation for predicting "lean body weight" (L) from height and 7 diameters (biacromial, transversal thoracic, biiliac, bitrochanteric, wrist, ankle, and knee). The dependent variable (L) was determined hydrostatically. With a negligeable loss of precision, the predictor variables could be reduced to 3 measures: stature (H), transverse thoracic diameter (T), and waist diameter (M, for "manus"). Using S predictor variable, the coefficient of multiple correlation $R = 0.85$; with 3 variables, $R = 0.84$.

In the logarithmic form the prediction equation reads:

$$\log L = \log (519 \times 10^{-5}) + 1.18 \log H = 0.75 \log T + 0.43 \log M \qquad \text{(No. 12)}$$

From subcutaneous adipose tissue to body density

The thickness of the subcutaneous layer of adipose tissue may be assessed as skinfolds (using calipers), fat shadows on the soft-tissue roentgenograms, and from ultrasonic measurements.

An early (and perhaps the earliest) report on predicting the specific gravity of the body from skinfold measurements (made at 5 sites: abdomen, lateral chest, below scapula, upper arm above triceps, thigh) and relative body weight (as % of reference standard) dates from 1951 (Brožek and Keys). Later (Brožek 1954) the prediction equations were recast in term of body density.

In this particular study, made in a large group of young men ($N = 116$, mean age = 22 years) an average value of the residual lung volume rather than individually determined values were used, thus decreasing the precision of the procedure. Nevertheless, the coefficients of multiple correlation were substantial: $R = 0.876$ when all 6 predictors were used and $R = 0.871$ for 3 selected variables (abdominal, chest, and upper-arm skinfold). For a large group of older men ($N = 214$, mean age = 49) the coefficients were lower; using all six variables, $R = 0.744$; this may have been due to a greater interindividual variability in the actual residúal lung volume in the group of the older men.

Since in the studies reported in 1981 the pressure at the contact surface of the calipers was higher (about 35 g/mm²) than the pressure of 10 g/mm², later accepted internationally as the standard pressure, and there was some increase in the pressure as the jaws of the calipers opened more widely, it was highly desirable to repeat the studies. For a group of young soldiers ($N = 88$, mean age 22.1 year) this was done by Pascale et al. (1956). Using calipers with standard pressure (10 g/mm²), the authors measured skinfolds at 11 sites. Residual lung volume was measured in individual subjects. Using only 3 sites that contributed significantly to prediction efficiency, the following equation was derived for predicting body density (D):

$$D = 1.088\,468 - 0.007\,123\,X_1 - 0.004\,834\,X_2 - 0.005\,513\,X_4$$

where X values refer to skinfold thickness, in cm, measured at the following sites: X_1, thorax, at the midaxillary line, at the level of the xyfoid; X_2 = chest, in the juxta-nipple position; X_4, dorsum of the upper arm, at mid-point. The coefficient of multiple correlation ($R = 1.85$), based on the 3 skinfolds, yielded a standard error of estimate $SEE = 0.0064$ body density units.

It would have been useful to have prediction equations based on the upper arm skinfold (over triceps) and the subscapular skinfold, since these are the sites recommended by the expanded Committee on Nutritional Anthropometry (Food and Nutrition Board, National Research Council, USA, 1936).

Practical purposes are served by nomograms for predicting body fat, as % of weight (rather than density), from selected skinfolds. Such nomograms were prepared by Sloan and Weir (1960), based on earlier studies on young Caucasian women ($N = 50$, age range 17 to 25 years: Sloan et al. 1962) and men ($N = 50$, age range 18 to 26 years; Sloan 1967). Unfortunately, the optimal pairs of skinfolds were different for the two groups: for women, the best predictors were a vertical skinfold over the iliac crest in the mid-axillary line and a skinfold over the triceps in mid-axillary line; for men, a vertical skinfold at mid-thigh in the anterior mid-line and the subscapular skinfold.

The use of sums of skinfolds (cf. Pařízková 1961a, b, 1963, Pařízková and Bůžková 1971) to predict the fat content of the body represents a simple and rapid procedure but it is not as effective as when the fat values are calculated from regression equations in which the individual skinfolds are weighted optimally. For the measurements of big population groups two skinfolds (triceps and subscapular) can be sufficient (Pařízková 1977).

Roentgenographic soft-tissue analysis was introduced in the USA by pediatricians (Stuart et al. 1950). A bibliography dealing with different aspects of the technique was provided by Garn (1961) who described in detail the roentgenogrammetric procedures.

Brožek et al. (1958) provided equations for predicting body density from the radiographic fat-shadow measurements made in a group of middle-aged men (average, 57 years) at 4 sites (bideltoid insertion, upper arm, forearm, and calf). The correlation were disappointingly low, ranging from $r = 0.58$ for the calf (at the level of the maximal width) to $r = 0.75$ for the upper arm and $r = 0.76$ for the forearm. However, it should be noted that the measurements of body density were obtained 4 years before the collection of the radiographic data. This has depressed, to an unknown degree, the size of the ceofficients of correlation.

Ultrasound Depth Measurements were used in parallel with skinfolds at 7 sites by Sloan (1967). The coefficients of correlation with body density turned out to be slightly but systematically lower for the ultrasound measurements. For multiple R's based on pairs of the best predictor, the R based on ultrasonic measurements in front of the thigh and at iliac crest, $R = 0.822$; for skinfolds, measurement made at mid-thigh and below the scapula, $R = 0.845$.

From a Battery of Body Measurements to Body Density

Correlations between body density and a comprehensive set of body measurements — skinfolds, circumferences, diameters — were examined by Katch and McArdle (1973; cf. also Katch and Michael 1968, Michael and Katch 1968). The correlations between diameters and density were low to very low, and at times the sign of the coefficient of correlation varied in direction (as one could expect).

The r's between skinfolds and density were uniformly negative and substantial; they varied, in young men, from −0.67 (thigh) to −0.82 (below scapula); in young women the r's were consistently lower than in men, with a range from −0.53 (triceps) to −0.71 (below scapula). Thus the skinfold measured below the scapula proved to be the best single predictor of body density in both men and women.

For the circumferences, the r's varied widely. In men, the highest value was obtained for the umbilical circumference of the abdomen (−0.77) in women, for the thigh circumference (−0.68).

What are the optimal combinations of the body measurements? For men the highest coefficient of multiple correlation ($R = 0.89$, with the standard error of estimate $SEE = 0.0066$ g/ml) was obtained using two skinfolds (triceps and below scapula) and two circumferences (forearm and abdomen). For women, the most efficient combination of body measurements as predictors of body density were 2 skinfolds (subscapular and iliac), the thigh circumference, and the elbow diameter ($R = 0.84$, with $SEE = 0.0086$ g/ml) or body fat of ± 3.7 % of body weight. When measuring ten skinfolds, the prediction of fat percentage and body composition is more reliable (Pařízková 1961b, 1977) for all population groups.

The appearance of the elbow diameter among the "best" predictors for women is likely to represent an accidental, "idiosyncratic" result, not to be confirmed in other samples of the same population. Johnston (1982) stressed that cross-validation of the prediction equations is a very important but an easy task (cf. Boileau et al. 1981).

Height and weight as predictors of body composition

Combining the data for age groups ranging from infants to young adults, Mellits and Cheek (1970) obtained impressively looking coefficients of correlation between weight and total body water: for males, $r = 0.964$; for females, $r = 0.985$. The relationship between height and total body water was not linear and the analysis was carried out for the older (i.e. taller) and the younger (shorter) subjects separately; the R's were still very high.

Johnston (1982) points out that since the predictor variables (weight and height) increase markedly between infancy and early adulthood — as do the dependent, predicted variables (body water, body fat "a significant proportion of the variance (of body water and body fat), apparently explained (by the anthropometric predictors) is simply due to the confounding effects of age".

Watson et al. (1980) limited their sample to adults but the age ranges were large: 17 to 86 years for males (mean age = 39 years, $N = 458$) and 17 to 84 years for females (mean age = 38 years, $N = 265$). In men, body weight accounted for 61.7 % of the variance of total body water; for females, the figure is 71.7 %. Height was a dramatically weaker predictor, with the percentages of the variance of body water being reduced to 28.0 % for men and 8.6 % for women.

Combining height with weight increases the percentages of the variance explained to 68.9 % for men, 73.6 % for women.

Age is a puzzling variable: In men, age explained 15.8 % of the variance of body water while in women there was essentially no correlation between age and body water. In men adding age to weight and height as predictor of body weight improves slightly the prediction efficiency (raising the "percentage of variance explained" to 70,4 %) while it apparently reduced the value substantially in women (decreasing it to 63.8 %).

Nomograms for estimating total body water are available. The prediction efficiency justifies using the prediction equation for group means. In individual subjects we do substantially better in measuring directly the volume of total body water.

Body Surface and Body Composition

Measurements of body surface have received little attention in research on body composition. What appears as an impressive coeficient of correlation ($r = 0.067$) between the anthropometrically estimated fat-free mass and the body surface, reported by Delwaide and Crenier (1973), is in part an artifact due to the use of the same variable (specifically, the height) in calculating both the surface area and the fat-free body mass.

Burmeister (1980) is one of the very few investigators concerned with the relationships between body composition and the surface area (SA). He summarizes for the newborn, the infant, as well as for male and female adults the ratios of selected body components (body cell mass and its two components — muscle cell mass and non-muscle cell mass, body fat) to surface area. Additional components (extracellular fluid, total body water) are considered in the text and estimation equations are provided. Thus for extracellular fluid $ECF = 6.04\ SA$.

From Body Measurements to Total Body Potassium

In young adults Burkinshaw et al. (1971) explored various combinations of body measurements with reference to the precision with which the total amount of body potassium could be predicted. The approach is oriented empirically and practically. When gross body weight is used as a predictor, the standard deviation from regression is about 7 % of the mean potassium value determined by means of a whole-body radiation counter. Adding an indicator of the muscle mass (width of the thigh muscle) and total body fat (from skinfolds via density) reduces the value of the standard error of estimate to about 5 % — a figure that is close to the precision (±4 %) of the technique with which the total body potassium was being measured. Consequently, little further increase in prediction efficiency could be expected.

Delwaide and Crenier (1973) were concerned with a problem that is of critical methodological importance for the kaliometric approach to the study of body composition, namely, the concentration of potassium in the fat-free body mass. As in the study by Burkinshaw et al. (1971), the total body potassium was measured on the basis of the gamma radiation emitted by K, the natural isotope of potassium present in the body. This counter, of special design (Delwaide 1969), made it possible to reduce the counting period to less than 5 minutes. The variability of the potassium measurements made on the same day was about 3 % of the mean, and about 5 % for measurements made once a day during one month.

The fat-free body weight was calculated using the equations derived, separately for male and female subjects, by Crenier (1966). In these equations the author included four, biologically appropriate body measurements: circumferences of the upper arm and the thigh (corrected for subcutaneous adipose layer) and two bony dimensions (stature and the biacromial diameter). For males, the ratio of total potassium (in mEq) to the anthropometrically estimated fat-free body weight was 62.8, for females, 56.7.

The dependability of the anthropometric estimate of the fat-free body mass was confirmed by comparing the results with those obtained on the basis of total body water (assuming that water accounts for 72 % of the fat-free body mass). The ratios of total body potassium to the hydrometrically estimated fat-free weight were 62.6 for the adult males and 56.7 for adult females. Thus the two sets of values of this important "biological constant" are remarkably similar.

Closing comment

In his critique of equations for predicting whole-body parameters from anthropometric data, Johnston (1982) addresses 3 classes of flaws:

1. The use of the step-wise regression analysis in which the prediction variables are entered, in sequence, beginning with the variable that accounts for the greatest proportion of the variance of the predicted parameter of body composition, and proceeding in that fashion until the addition of the next predictor variable fails to increase significantly the percentage of the variance that is being statistically "explained" (accounted for). Johnston (1982) notes that while such a procedure yields the best linear combination (and weighting) of the predictor variables for a given sample, it also "capitalizes on chance" (Mosteller and Tukey 1977) in drawing upon the particular, unique characteristics of the intercorrelation matrix of that particular sample.
2. Failure to validate the equations developed for one sample on another, independent sample, using the size of the error of estimate as the criterion of validity of an equation (cf. Lohman 1981). This failure is widespread, indeed.
3. Questionable sampling of the predictor variables, in reference to the number of measurements, the reliability of the techniques, and accessibility of the sites, at which the measurements are made, under field conditions.

To the third category one could add the biological appropriateness of a predictor, and list other issues bearing on the use of body measurements in the context of the study of body composition. Thus the biological significance of skinfolds may be site-specific, making it risky or inappropriate to generalize from measurements made at one site to the fat content of the body as a whole; e.g. Johnston and Beller (1976) found differences between male and female neonates in regard to the skinfolds over the triceps but not for the subscapular site. Similarly, Blacks and Whites were found to differ in the average thickness of skinfolds at the triceps site but not at the subscapular site (Johnston et al. 1974).

One can look at this kind of findings from two different points of view: On the one hand one may be impressed (or depressed) by the fact that generalizing from the thickness of the adipose layer measured at one site to the body as a whole is "problematic" — which it is. On the other hand, these findings may serve as a stimulus for a more comprehensive assessment of the merits and limitations of the anthropometric and the laboratory approaches to the analysis of body composition, and of the possibilities and usefulness of their integration also with other characteristics of the human organism.

Accumulation of experimental and clinical evidence seems to prove the importance of the measurements of body composition along with functional capacity also as measures of the nutritional status and health. Numerous methods are available for the evaluation of these characteristics of the human organism not only for the laboratory conditions, but also under field conditions. A battery of tests can be selected for the mentioned purpose, as mentioned above, viz. measurements of at least two skinfolds (triceps and subscalupar) and the estimation of body composition, then testing of the cardiorespiratory efficiency (e.g. step test modified for various population groups), and finally some strength and skill tests. Greatest problem at the present time is that the methodology is not yet fully unified; mentioned parameters were measured in some countries, but very rarely indentical procedures using also identical apparatures were applied. Therefore, the most important task for the nearest future would be to recommend selected methods and instruments which would be used — similarly as it succeded in the framework of the International Biological Programme — by the majority, or better, all scientists.

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