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— REVIEW —

# Models for Human Body Composition Analysis and Basic Concepts Underlying the Generation of Predictive Equations

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## Abstract

At present, the most widely used model for body composition research is the classic two-component model, which partitions the total body mass into its lean and fat components. The lean component is referred to as the lean body mass (LBM) and other portion as the fat mass (FM). In this review, we have concentrated our discussion on this two-component model. Our discussion of two-component model begins with an overview of body composition models. We then describe the main underlying theories of body composition methods in order to demonstrate the concepts that lead to the construction of the generation of predictive equations. In summary, we consider that the measurement of bioelectrical impedance significantly improves the prediction of total body water and/or LBM, as validated in a large heterogenous group of adult and child subjects. Bioelectrical impedance analysis has many advantages over other body composition methods in that it is safe, inexpensive, portable, rapid, easy to perform and requires minimal operator training. This method should be useful in estimating the body compositions of population group, for example in epidemiologic studies, and should be recommended for such purposes.

***Key words***: two-component model, lean body mass, fat mass, predictive equation,
bioelectrical impedance analysis

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## Introduction

The human body is a marvellous machine, its composition being determined by its environment. A comprehensive model of the composition of the human body has been developed. This includes five distinct levels of increasing complexity: atomic, molecular, cellular, tissue-system and whole-body, and each level has clearly defined components that comprise the total body mass (Fig.1)[1]. The fundamental building blocks of the human body are the atoms of elements. Six elements (oxygen, carbon, hydrogen, nitrogen, calcium and phosphorus) account for over 98 % of the body mass, and one element, oxygen, constitutes over 60% of the total body mass in the Reference Man developed by Snyder et al.[2]. The 11 principal elements are incorporated into molecules that form the 100,000 chemical compounds found in the human body. The major molecular components are water, lipids, proteins, minerals and glycogen. At the cellular level, the human body can be described using three main

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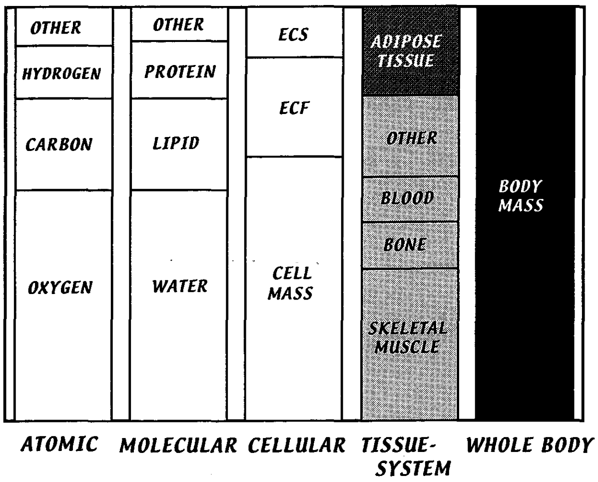

Fig. 1 The five level model of human body composition.
ECF: extracellular fluid,
ECS: extracellular solids
*Adapted from Wang et al., 1992*

compartments: cells, extracellular fluid and extracellular solids. These three compartments are further organized into tissues, organs and systems.

At present, the most widely used model for body composition research is the classic two-component model, which partitions the total body mass into its lean and fat components. The lean component is referred to as the lean body mass (LBM) or fat-free mass (FFM), and the other portion as the fat mass (FM) (Fig.2)[3)-5)].

## The two-component model

### *Fat-free mass (FFM) and Lean body mass (LBM)*

FFM encompasses the sum total of the body water, bone minerals, soft tissue minerals, proteins and glycogen. FFM is thus expressed as the combined weight of

$$W + Pro + M + G + R,$$

where W represents water, Pro proteins, M minerals, G glycogen and R residual chemical compounds.

Lipids can be classified physiologically as essential and nonessential[2)]. Essential lipids, such as sphingomyelin and phospholipids, serve important functions such as the formation of cell membranes. Nonessential lipids, largely in the form of triglycerides, provide thermal insulation and a storage depot of mobilizable fuel. In the *Reference Man*, about 10% of the total body lipid is essential and 90% is nonessential[2)]. Although essential and nonessential lipids are structurally and physiologically different, their solubilities in organic solvents are similar and it is difficult to separate them completely even *in vitro*[6)7)]. As a result, the small essential lipid component is usually ignored, or is grouped into a miscellaneous or residual mass component, in body composition research. However, the LBM takes these essential lipids into account, consisting of the FFM plus the essential lipid substances present in the bone marrow, spinal cord, brain and certain organs. It is therefore expressed as the combined weight of

$$Le + W + Pro + M + G + R,$$

where Le represents essential lipids. Figure 3 shows the LBM and its respective components for the 70-kg *Reference Man*[2)]. However, the LBM does not usually distinguish between

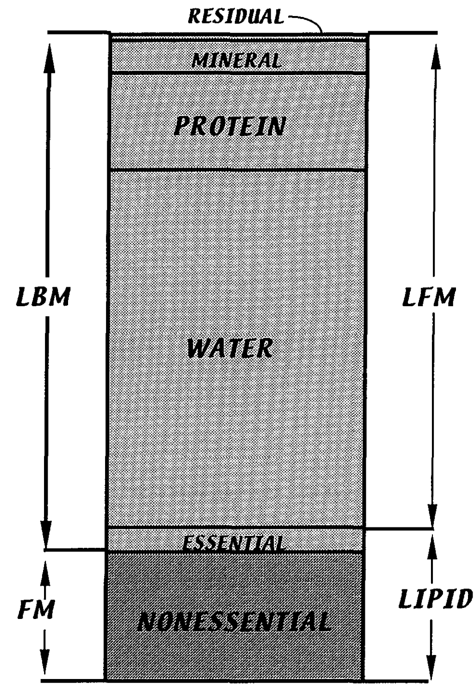

Fig. 2 Two-component model
LFM; lipid-free body mass
*Adapted from Wang et al., 1992*

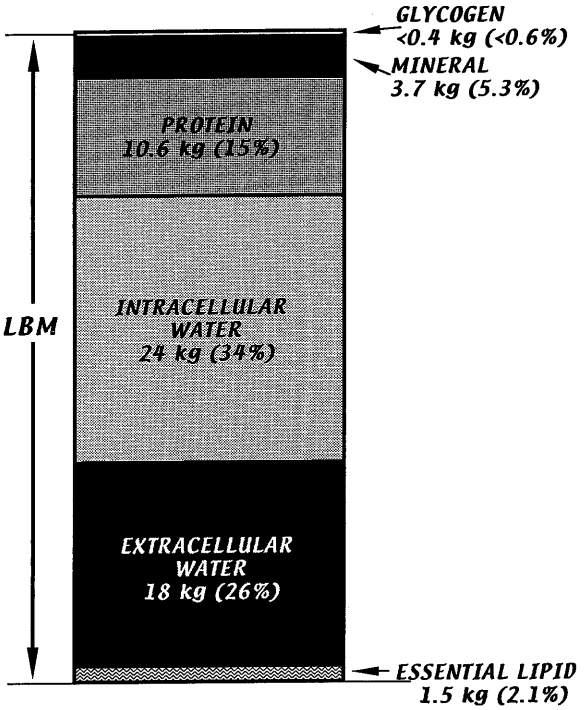

Fig. 3 LMB and their respective components (percent of body mass) for the 70-kg Reference Man
*Adapted from Snyder et al., 1984*

Pro, M, G and R, which may be required in body composition research. Nevertheless, as explained in later sections, there are many mathematical models that describe the relationships between these different components in healthy subjects. This formula indicates that there are quantitative associations that can describe the relationships between compartments in equilibrium.

The most abundant chemical compound in the human body is water, which comprises 60% of the body mass in the Reference Man[2]. Total body water (TBW) can be divided into intracellular (ICW) and extracellular water (ECW). TBW can be measured using the dilution principle. The ratio of TBW to LBM is assumed to be constant (0.732)[8] and LBM can be calculated from TBW as

$$\mathrm{LBM} = \mathrm{TBW} / 0.732$$[8][9].

In body composition research, the term '*protein*' is usually taken to mean almost all compounds containing nitrogen, ranging from simple amino acids to complex nucleoproteins. Total body protein (TBPro) can be calculated from total body nitrogen (TBN) as

$$\mathrm{TBPro} = 6.25 \times \mathrm{TBN}$$[10].

The term '*mineral*' describes a category of inorganic compounds containing a wide range of metallic (*e.g.* calcium, sodium and potassium) and nonmetallic (*e.g.* oxygen, phosphorus and chlorine) elements. The classic approach to measuring LBM is the total body potassium (TBK) approach. TBK can be determined directly by whole-body $^{40}$K counting. The first step is to measure the decay of the natural $^{40}$K found in human tissue by measuring gamma-ray emissions, because there are known constant ratios between the gamma-ray counts and $^{40}$K, and between $^{40}$K and TBK[11]. The next step is the calculation of LBM from TBK. A relatively stable ratio exists between TBK and LBM (TBK/LBM = 68.1 mmol/kg = 0.00266 kg/kg). Accordingly,

$$\mathrm{LBM\ (kg)} = \mathrm{TBK\ (kg)} / 68.1.$$

The primary storage form for carbohydrates is glycogen (G), which is found in the cytoplasm of most cells but is especially abundant in skeletal muscle and the liver. Indeed, glycogen accounts for over 1% and 2.2% of the respective wet weights of these tissues[2][12]. The small G component is usually ignored in body composition research.

## *Total body fat mass (FM)*

The nonessential lipid component is synonymous with fat as it consists almost entirely of triglycerides. The storage fat mass has therefore become virtually synonymous with FM. Although FM is a compartment of major interest, there are no practical methods for directly evaluating the fat compartment *in vivo*. All of the presently used methods are indirect and are based on direct measurements of the LBM; for example:

1) FM = body mass − TBK (mmol) / 68.1; and
2) FM = body mass − TBW / 0.732.

Thus,

$$\mathrm{FM} = \text{body mass} - \mathrm{LBM}.$$

The storage fat is the fat accumulated in adipose tissue. Adipose tissue can be classified as visceral (internal or deep) or subcutaneous (external or outer). Computerized tomography (CT) and magnetic resonance imaging (MRI) are the primary tools used in the study of visceral adipose tissue (VAT) and subcutaneous adipose tissue (SAT), which are most often measured in the abdominal region. However, there is no consensus as to which methods best define and describe adipose tissue mass.

As FM accounts almost entirely for the total storage fat (total body nonessential lipid), then

$$\mathrm{FM} = \mathrm{SFM} + \mathrm{IFM}$$

where SFM is subcutaneous fat mass, and IFM is internal fat mass. Figure 4 shows the FM and its respective components for the 60-kg Japanese *Reference Man*[13].

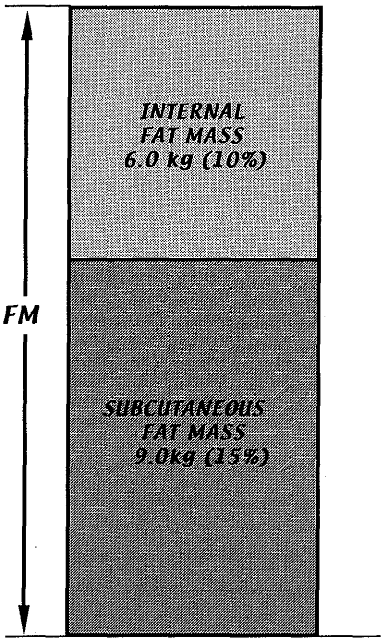

Fig.4 FM and their respective components (percent of body mass) for the 60-kg Japanese Reference Man
*Adapted from Komiya, 1997*

## Basic concepts underlying the generation of predictive equations

Methods of quantifying the composition of body components *in vivo* can be organized as suggested by the general formula

$$\mathrm{C} = f(\mathrm{Q}) \quad (1)$$

where C represents an unknown component, Q a measurable quantity and $f$ a mathematical function relating Q to C[14]. The quantity (Q) can be one of three things. Firstly, it may be a directly measurable property, such as body volume (BV), TBW or electrical resistance (R). For example, TBW can be measured using the dilution principle. About one-half of body composition components can now be quantified using property-based methods. Secondly, Q may be a fixed component. In this case, the fixed component must have been quantified using a property-based method. An example is the calculation of LBM from TBW, in which the ratio of TBW to LBM is assumed to be constant. Finally, there is a third category in which the measurable quantity used in general formula (1) is a combination of both a directly measurable property and a fixed component. An example is the calculation of FM from two measurable properties (BV and body mass) and a measurable component (TBW)[5]. Once Q has been determined for the particular subjects under study, regression analysis is used to establish the mathematical function ($f$) and thus develop an equation that will predict the unknown component from the measurable property or the fixed component.

If certain assumptions are made about the composition of the LBM, the LBM of the human body can be calculated using densitometry (BV), hydrometry (TBW), whole-body counting of potassium-40 ($^{40}$K), or bioelectrical impedance (R). Subsequently, FM can be calculated as the difference between body mass and LBM. Other techniques developed for epidemiological surveys, such as anthropometry and skinfold thickness measurements, are less reliable predictors of body composition.

### *Densitometry*

The hydrodensitometry method was originally proposed by Behnke et al.[15] and was derived from the BV model (BV = FM / 0.9007 + LBM /

1.100). Using the values for the densities of LBM (1.100 kg /L) and FM (0.9007 kg /L at 36 ℃), the formula becomes

$$\text{LBM (kg)} = 4.519 \times \text{body mass (kg)} - 4.971 \times \text{BV (L)} \quad (2)$$

and

$$\text{FM (kg)} = 4.971 \times \text{BV(L)} - 4.519 \times \text{body mass (kg)}. \quad (3)$$

The FM equation can be rewritten to express FM as a fraction of body mass,

$$\text{FM / body mass} = 4.971 / D_b - 4.519 \quad (4)$$

where $D_b$ is the body density (= body mass / BV [kg / L]) and the percentage body fat (%BF) is (FM / body mass) × 100. For example, the density of FM at 37 ℃ is 0.9000[16], so if this temperature is chosen the formula becomes

$$\text{FM / body mass} = 4.95 / D_b - 4.50^{17)}. \quad (5)$$

The method of Brozek et al. (1963) uses the concept of the "reference man" (D = 1.064), to which FM is added or subtracted ($D_{FM}$ = 0.9007) to yield the following:

$$\text{FM / body mass} = 4.570 / D_b - 4.142^{3)}. \quad (6)$$

The differences in the calculated %BF values between formulae 4, 5 and 6 are fortunately not very great.

### *Hydrometry*

Water is the largest compositional component of the body[18)-20)]. Most of the water in the body is in the lean tissue, so the measurement of TBW provides a means for estimating LBM. On the other hand, adipose tissue is relatively nonaqueous. The calculation of LBM from TBW depends on the assumption that the LBM is consistently hydrated. The measurement of TBW is based on two principles of isotope dilution. Firstly, certain substances will dilute or distribute themselves evenly throughout a fluid space in the body, and secondly, the degree of dilution of a known amount of substance, such as an isotope tracer, administered into an unknown volume, will enable the calculation of the unknown volume, after correction for excretion or exhalation of the isotope. Thus,

$$C_1 V_1 = C_2 V_2 \quad (7)$$

where $C_1$ and $V_1$ are the known concentration and volume of the isotope tracer before dilution (*i.e.*, before administration), and $C_2$ and $V_2$ are the concentration and volume of the tracer after mixing (*i. e.*, after administration). Hence, the unknown volume of dilution can be calculated as follows:

$$V_2 = (C_1 V_1) / C_2 \quad (8)$$

Finally, the concentration of the isotope in urine, serum or saliva ($C_2$) is measured. Thus,

$$\text{TBW} = (A - E) / C \quad (9)$$

where A is the amount of isotope administered, E is the amount of isotope excreted, and C is the concentration of the isotope in the sample. Then, assuming that the percentage of water in the LBM is constant in healthy subjects, LBM is estimated. The most commonly used hydration constant is 0.732, which was first recommended by Pace and Rathbun[8)]. LBM is estimated as follows:

$$\text{LBM} = \text{TBW} / 0.732 \quad (10)$$

and FM is estimated by subtraction.

### *Whole-body potassium counting*

Potassium occurs naturally in three isotopic states: $^{39}$K, $^{41}$K and $^{40}$K. It is mostly found within cells, especially in muscle tissue. It is assumed that the proportion of potassium in the LBM is constant. There are also known constant ratios between $^{40}$K and total body potassium (TBK) ($^{40}$K / TBK = 0.000118) (Forbes, 1987). Hence, measurement of the concentration of potassium in the body can provide an estimate of LBM. This is done by measuring the concentration of $^{40}$K with a highly sensitive detection instrument called a whole-body counter, which counts the gamma emissions of naturally occurring potassium. The calculation of TBK from the $^{40}$K count is straightforward:

$$\text{TBK} = \text{Cfi} \times {}^{40}\text{K counts} \quad (11)$$

where Cfi is a calibration factor derived from a body mass versus stature matrix established for Cfi relative to the body size. A relatively stable ratio exists between TBK and LBM (TBK/LBM = 68.1 mmol/kg = 0.00266 kg/kg). Accordingly,

$$\text{LBM (kg)} = 376 \times \text{TBK (kg)}. \quad (12)$$

FM is then derived by subtraction.

While laboratory methods such as densitometry, hydrometry and whole-body counting are accurate, they are expensive and are not suitable for field studies. There is therefore a need for rapid, safe, noninvasive total body composition measurement techniques that are accurate and convenient enough to permit use in the clinical setting and in epidemiological studies. The methods outlined below were developed with these aims in mind.

### *Bioelectrical impedance*

Bioelectrical impedance analysis (BIA) involves the application of a localized 50-kHz current. Tissues that contain a lot of water and electrolytes, such as cerebrospinal fluid, blood or muscle, are highly conductive whereas fat, bone and air-filled spaces such as the lung are highly resistive or dielectric tissues. An applied electric current will always follow the path of least resistance; in the human body, this means that it will flow preferentially through the extracellular fluid, blood, muscle and other conductive tissues that comprise the majority of the LBM. The volume of these tissues can therefore be deduced from measurements of their combined resistances. BIA makes use of the fact that impedance to the electrical flow of an applied current is related to the volume of the conductor (in this case, the human body) and the square of the conductor's length (*i.e.*, the subject's height). For a cylindrical, isotropic conductor such as a wire, the resistance (R) is directly proportional to its length (L [cm]) and inversely proportional to its cross-sectional area (A [cm$^2$]), or $R = \rho L/A$. Since volume (V) equals $L \times A$, algebraic rearrangement shows that $V = \rho L^2 / R$. Hence, the volume of a conductor can be deduced from measurements of its length and resistance. This principle was demonstrated by Hoffer et al.[21], who observed that TBW and LBM correlated strongly with stature$^2$/ R when body resistivity or impedance was measured using a tetrapolar electrode method. Several subsequent studies[22)-24)] confirmed strong correlations between BIA results (either stature$^2$/ resistance measured by BIA, or LBM and TBW predictions derived from BIA using equations provided by the equipment manufacturer), TBW (measured by isotope dilution) and LBM (determined densitometrically). However, these studies usually included small or heterogeneous samples, and the reproducibility of this method between laboratories has not been determined by means of cross-validation studies.

### *Skinfold thicknesses*

When laboratory facilities are unavailable, simpler alternative procedures can be used to predict the body fat content. The measurement of skinfold thicknesses requires relatively inexpensive equipment; however, it suffers from a lack of precision. The most common areas for measuring skinfold thicknesses are the triceps, subscapular, suprailiac, abdominal and upper thigh sites. All measurements are taken on the right side of the body with the subject standing. The use of this method for estimating body fat content is based on two assumptions: first, that the thickness of the subcutaneous fat mantle reflects the total amount of fat in the body, and second, that the sites chosen for the measurements, either singly or in combination, represent the average thickness of the entire mantle. Neither assumption has been proven true. Nevertheless, skinfold thickness measurements can provide meaningful information concerning body fat and its distribution. Their first useful application is in conjunction with mathematical equations designed to predict body density or %BF. These equations are population-specific, and predict fat content fairly accurately for subjects who are similar in age, gender, state of training, fatness and race to those in whom the equations were derived. When these criteria are met, the predicted value of the fat content of an individual is usually within 3 to 5 % of the FM assessed by hydrodensitometric weighing. Secondly, skin thickness scores can be summed to obtain an indication of regional fatness among individuals.

## Recommendations for improving predictive equations

Methodological problems limit the validity of the commonly used body composition assessment methods. However, it seems likely that using a combination of densitometry, total body water (bioelectrical impedance) and skinfold thickness measurements would increase the accuracy of body composition status estimations, since each of these methods focuses on a different component of the body composition. The more accurately each component of the body can be measured, the more accurately the body composition status can be estimated. On the other hand, densitometry and hydrometry (TBW) are of limited use in body composition studies due to difficulties with access to the necessary instruments, cost, and the time required to obtain the measurements, while skinfold thickness measurements are less reliable predictors of body composition. Thus, there is a need for a safe, noninvasive technique that is rapid, convenient and can provide adequately accurate and reliable estimates of human body composition outside the laboratory. BIA is an approach that may meet this need.

BIA has many advantages over other body composition methods in that it is safe, inexpensive, portable, rapid, easy to perform and requires minimal operator training. BIA could be used to estimate TBW by applying a predictive equation based on the measured bioelectrical impedance (Z) of the subject. Using height (ht) as a measure of the conductor length, Hoffer et al.[19] showed that the impedance index ($ht^2/R$) was a good predictor of $^3H_2O$-derived TBW ($r = 0.92$). Subsequent regression analyses by several investigators have also demonstrated that the $ht^2/R$ yields larger correlation coefficients than weight or stature alone when used as predictors of TBW, densitometrically determined LBM or total body potassium[22][24].

More recently, Kushner et al.[25] used data from neonates, preschool children, prepubertal children and adults to derive one universal equation for estimating TBW from $ht^2/R$ that would be applicable across a wide age range. They concluded that the $ht^2/R$ is a significant predictor of TBW and that the prediction of TBW can be improved somewhat by including a body mass term (BM):

$$\mathrm{TBW} = 0.59\ ht^2/R + 0.065\ \mathrm{BM} + 0.04 \quad (SEE = 1.67\ \mathrm{kg}). \tag{13}$$

However, there is a limitation that should be borne in mind when using bioelectrical resistance to estimate body composition: bioelectrical resistance is only able to predict TBW. Goran et al.[26] overcame this limitation by using constants for the hydration of LBM to transform the equation for predicting TBW into one capable of predicting LBM:

$$\mathrm{HLBM}\,(\%) = 76.9 - (0.25 \times \mathrm{age}) - (1.9 \times \mathrm{gender}) \tag{14}$$

where HLBM is the degree of hydration of the LBM, age is measured in years, and the gender is 0 for females and 1 for males.

The Kushner equation (13) can thus be transformed into equations for estimating LBM by using the age- and gender-specific constants for the hydration of LBM in equation (14), and an equation for estimating LBM can be derived by dividing the Kushner equation (13) by equation (14):

$$\mathrm{LBM(kg)} = \{(ht^2/R)0.59 + (\mathrm{BM} \times 0.065) + 0.04\} / \{0.769 - (0.0025 \times \mathrm{age}) - (0.019 \times \mathrm{gender})\} \tag{15}$$

where height (ht) is measured in cm, resistance (R) in ohms (Ω), body mass (BM) in kilograms and age in years, and the gender is 0 for females and 1 for males[26].

Another limitation of BIA is that no constant for the hydration of the LBM has been determined for Japanese subjects. Nevertheless, using the constants for the hydration of the LBM recommended by Goran et al.[26], the difference in the calculated LBM between Japanese and Caucasian subjects is not very great.

In summary, we consider that the measurement of bioelectrical impedance significantly improves the prediction of TBW and/or LBM, as validated in a large heterogenous group of adult and child subjects. This method should be useful in estimating the body compositions of population groups, for example in epidemiologic studies, and should be recommended for such purposes.

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