Practical Body Composition Assessment for Children, Adults, and Older Adults

Vivian H. Heyward

This paper provides an overview of practical methods for assessing body composition of children, adults, and older adults. Three methods commonly used in field and clinical settings are skinfolds, bioelectrical impedance analysis, and anthropometry. For each method, standardized testing procedures, sources of measurement error, recommendations for technicians, and selected prediction equations for each age category are presented. The skinfold method is appropriate for estimating body fat of children (6–17 years) and body density of adults (18–60 years) from diverse ethnic groups. Likewise, bioimpedance is well suited for estimating the fat-free mass of children (10–19 years) as well as American Indian, black, Hispanic, and white adults. Anthropometric prediction equations that use a combination of circumferences and bony diameters are recommended for older adults (up to 79 years of age), as well as obese men and women.

Key Words: skinfolds, bioelectrical impedance analysis, anthropometry, near-infrared interactance, elderly

In field and clinical settings, health and nutrition professionals assess body fat levels of their clients using practical field methods such as skinfolds, bioelectrical impedance analysis, anthropometry, and near-infrared interactance. Given the choice of methods and numerous prediction equations published in the literature, it is often difficult for the clinician to select an appropriate method or prediction equation that accurately assesses each client’s body composition. This paper provides information about the development and selection of methods and equations for measuring body composition of children, adults, and older adults. For each method, assumptions, principles, and major sources of measurement error are presented, along with recommendations to ensure the accuracy of body composition assessments. Last, suitable methods and prediction equations for children, adults, and older adults are identified.

Development and Selection of Body Composition Methods and Prediction Equations

The validity of body composition field methods and the predictive accuracy of equations need to be carefully evaluated. The relative worth of prediction equations

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is established by comparing predicted scores to reference measures of body composition. According to Heyward and Stolarczyk (28), good prediction equations have several characteristics:

- Use of acceptable reference methods to obtain criterion measures of body composition
- Use of large, randomly selected samples \((N > 100)\)
- High multiple correlation between the reference measure and predicted scores \((R > .80)\)
- Small prediction error or standard error of estimate \((\text{SEE})\)
- Cross-validation of equation on additional, independent samples from the population

The predictive accuracy of field methods and equations is limited by the absence of a single gold standard method for obtaining in vivo reference measures of body composition. Although densitometry, hydrometry, and dual-energy x-ray absorptiometry are often used as reference methods, these methods provide only an indirect measure of body composition and, therefore, are subject to measurement error. In light of this limitation, Lohman (43) developed standards for evaluating prediction errors for body composition prediction equations estimating percentage body fat \((\%\text{BF})\), fat-free mass \((\text{FFM})\), and total body density \((\text{Db})\) (see Table 1). As much as 50% of the prediction error for body composition equations may be attributed to errors associated with the reference method.

**Reference Methods**

Three methods commonly used to obtain reference measures are densitometry, hydrometry, and dual-energy x-ray absorptiometry \((\text{DXA})\). This section provides a brief overview and limitations for each of these methods.

**Densitometry.** The overall density of the human body \((\text{Db})\) may be measured using either water displacement or air displacement. For years, the water displacement method, known as hydrodensitometry or hydrostatic weighing, has

<table>
<thead>
<tr>
<th>(\text{SEE } %\text{BF}) Male and female</th>
<th>(\text{SEE Db (g/cc)}) Male and female</th>
<th>(\text{SEE FFM (kg)}) Male</th>
<th>(\text{SEE FFM (kg)}) Female</th>
<th>Subjective rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>0.0045</td>
<td>2.0–2.5</td>
<td>1.5–1.8</td>
<td>Ideal</td>
</tr>
<tr>
<td>2.5</td>
<td>0.0055</td>
<td>2.5</td>
<td>1.8</td>
<td>Excellent</td>
</tr>
<tr>
<td>3.0</td>
<td>0.0070</td>
<td>3.0</td>
<td>2.3</td>
<td>Very good</td>
</tr>
<tr>
<td>3.5</td>
<td>0.0080</td>
<td>3.5</td>
<td>2.8</td>
<td>Good</td>
</tr>
<tr>
<td>4.0</td>
<td>0.0090</td>
<td>4.0</td>
<td>2.8</td>
<td>Fairly good</td>
</tr>
<tr>
<td>4.5</td>
<td>0.0100</td>
<td>4.5</td>
<td>3.6</td>
<td>Fair</td>
</tr>
<tr>
<td>5.0</td>
<td>0.0110</td>
<td>&gt;4.5</td>
<td>&gt;4.0</td>
<td>Poor</td>
</tr>
</tbody>
</table>

*Note: Data from Lohman (43).*
been considered by some experts as a gold standard method. However, this method is not error-free for a number of reasons. Accurate assessment of body density using this method requires correcting total body volume for residual lung volume. Katch and Katch (38) reported that a 600 ml difference in residual volume may affect the estimation of relative body fat (%BF) by as much as 8%. Hence, residual volume should not be predicted from age, height, body weight, or vital capacity. By comparison, errors associated with incorrect underwater weights and body weight fluctuations due to factors affecting hydration status, such as menstrual cycle stage, time of day, exercise, illness, and medications, are not as large, with a 2- to 3-kg weight fluctuation producing a change in relative body fat of only 1% (59).

Hydrostatic weighing requires much subject cooperation and therefore may not be easy to undertake with elderly or physically disabled persons or individuals with diseases that alter the relative water (e.g., malnutrition and obesity), protein (e.g., AIDS and cancer), and mineral (e.g., osteoporosis) of the fat-free body. As an alternative, total Db can be measured using air displacement plethsmography. Research demonstrates that the BodPod™, an air displacement plethsmograph, provides reliable and valid estimates of total Db compared to hydrostatic weighing (53), suggesting that this method has potential for replacing hydrostatic weighing as the standard practice in research and clinical settings. However, more research documenting the validity of this device in diverse subgroups of the population is warranted.

Regardless of the method used to measure total Db (hydrodensitometry or air displacement plethsmography), a major potential source of measurement error for both of these methods is the formula used to convert total body density (Db) to relative body fat. For years, the classic two-component model equations of Siri (64) and Brozek et al. (6) have been the basis of hydrodensitometric estimates of %BF. Both conversion formulas were based on direct analysis of a limited number of white male and female cadavers that did not necessarily represent the entire population. The Siri conversion formula assumes that the density of fat (0.901 g/cc) and the fat-free body density (FFB density = 1.10 g/cc) are constant for all individuals. The Brozek et al. conversion formula is based on a reference body with a specified Db and assumes slightly different values for the density of fat (0.88876 g/cc) and the FFB (1.10333 g/cc).

Research documents that FFB density is not constant for all individuals but rather varies with age, gender, level of body fatness, physical activity, and ethnicity, depending on the relative proportion of water, mineral, and protein comprising the FFB (2, 43, 74). For example, the FFB density of black women (1.106 g/cc) and black men (1.113 g/cc) is greater than 1.10 g/cc because of a higher relative mineral content in the fat-free body and bone density (57, 62). Thus, relative body fatness will be systematically underestimated when two-component model equations are used to convert measured body density to %BF for black men and women. Because of these limitations, neither hydrodensitometry nor air displacement plethsmography can be considered a gold standard method.

**Hydrometry.** Hydrometry, or the measurement of total body water (TBW), is also limited when used singly to derive reference measures of body composition. With this method, the concentration of hydrogen isotopes (deuterium and tritium) in biological fluids (saliva, plasma, and urine) after equilibration is measured and used to estimate TBW (61). This method assumes that the distribution and exchange of the isotope by the body are similar to the distribution and exchange of water. However,
due to the exchange of the isotope with nonaqueous hydrogen in the body, total body water may be overestimated by 1 to 5% (49). Using this method in conjunction with the two-component model to obtain estimates of FFM, it is further assumed that the hydration of the FFM is constant for all individuals. Because total body water fluctuates greatly within and among individuals depending on age, gender, level of obesity, and disease, large errors may result when hydrometry and the two-component model are used to obtain reference measures of body composition. Siri (64) estimated that biological variability in the hydration of the FFM (2%) would produce a substantial error in the estimation of body fat (3.6% BF) for the general population.

**Dual-Energy X-Ray Absorptiometry.** Dual-energy x-ray absorptiometry (DXA) is a relatively new technology that is gaining recognition as a reference method for body composition research. This method is based on a three-compartment model that divides the body into total-body mineral, mineral-free lean, and fat tissue masses. DXA is highly reliable, and there is good agreement between %BF estimates obtained by hydrodensitometry (adjusted for relative mineral and/or water) and DXA (18, 29, 68). DXA is an attractive alternative to hydrodensitometry as a reference method because it is safe, is rapid (a total body scan takes 10 to 20 min), requires minimal subject cooperation, and most importantly, accounts for individual variability in bone mineral. Also, DXA estimates of body composition appear to be less affected by fluctuations in total body water compared to hydrodensitometry and hydrometry. Kohrt (41) estimated that a 5% difference in the relative hydration of the FFB (78 vs. 73% FFB) would produce ≤0.5 kg error in fat and fat-free mass, suggesting that hydration status has a relatively small effect on soft-tissue estimates obtained via DXA.

However, standardization of DXA technology is imperative before it can be universally accepted as a reference method. Differences between DXA and densitometric estimates of fat mass depend on the manufacturer (Holtec, Waltham, MA; Norland, Fort Atkinson, WI; and Lunar Radiation Corp., Madison, WI), the data collection mode (pencil beam vs. array beam), and the software version used to analyze the data (44). Thus, it is somewhat difficult to establish the validity of DXA for body composition assessment in comparison to other reference methods (i.e., hydrodensitometry and multicomponent models). Still, researchers are beginning to use DXA to develop and cross-validate body composition field methods (skinfold and bioelectrical impedance analysis) and prediction equations (22, 70).

In the future, it is highly likely that additional body composition prediction equations will be developed and validated using DXA as a reference method, especially for population subgroups for whom hydrodensitometry is not feasible (e.g., elderly and spinal cord injured). However, further research and standardization of technology are needed before DXA can be firmly established as a gold standard reference method (41, 60).

Because each of these reference methods (densitometry, total body water, and DXA) yields indirect estimates of body composition, none can be singled out as the gold standard for in vivo body composition assessment. In fact, many researchers have obtained more valid reference measures of body composition by using variables obtained from all three methods. There are multicomponent model approaches that adjust body density from densitometry based on total body water from hydrometry and/or total body mineral from DXA estimates of bone mineral (16, 25, 43, 64).
Body Composition Models

Regardless of the method used, reference measures of body composition for the development of field methods and prediction equations are based on theoretical body composition models, ranging from simple, whole-body, two-component models to more complex elemental, chemical, anatomic, or fluid-metabolic multicomponent models. Generally, the whole-body (fat + fat-free body) and chemical (fat + water + mineral + protein) models have been more widely used in body composition research.

As mentioned previously, the classic two-component model divides the body mass into fat and fat-free body (FFB) compartments and assumes that the densities of fat (0.901 g/cc) and the FFB (1.10 g/cc) do not vary within and among individuals. Generally, two-component model equations provide accurate estimates of %BF as long as the basic assumptions of the model are met. Using multicomponent models that take into account individual variation in the water and mineral compartments of the FFB, some researchers (16) have demonstrated surprisingly good agreement between the assumed FFB density (1.10 g/cc) and multicomponent model estimates (1.102 to 1.103 g/cc) for white males, 19 to 55 years of age, indicating that the Siri and Brozek equations can be used to accurately estimate %BF in white males.

Although the average density of the FFB for certain population subgroups may be very close to the assumed value (1.10 g/cc), there is a high degree of interindividual variation within any given subpopulation. This points to the need to use body composition prediction equations that are validated against a reference body composition measure derived from multicomponent models and a combination of technologies that account for individual differences in bone mineral content and hydration levels.

Unfortunately, the overwhelming majority of existing field methods and prediction equations were developed using hydrodensitometry and two-component model equations to derive reference measures of %BF and FFM. However, some skinfold and bioelectrical impedance equations have been developed using multicomponent model reference measures (2, 30, 65, 73).

Skinfold Method

The skinfold (SKF) method is widely used in field and clinical settings. This method is particularly useful for estimating body composition of children and adults. Most SKF equations use two or more SKF measures to estimate Db or %BF.

Assumptions and Principles. Because the SKF indirectly measures the thickness of subcutaneous adipose tissue, certain basic relationships are assumed (28):

- The SKF is a good measure of subcutaneous fat. Research has demonstrated that the value for subcutaneous fat assessed by SKF measurements at 12 sites is similar to the value obtained from magnetic resonance imaging (MRI) (24).
- The distribution of fat subcutaneously and internally is similar for all individuals within each gender. The validity of this assumption is questionable. Older subjects of the same gender and body density have proportionately less subcutaneous fat than their younger counterparts. Also, lean individuals have a higher proportion of internal fat, and the proportion of fat located internally decreases as overall body fatness increases (46).
Because there is a relationship between subcutaneous fat and total body fat, the sum of several skinfolds can be used to estimate total body fat. Research has established that SKF thicknesses at multiple sites measure a common body-fat factor (33). It is assumed that approximately one-third of the total fat is located subcutaneously in men and women (46). However, there is considerable biological variation in subcutaneous, intramuscular, intermuscular, and internal-organ fat deposits, as well as essential lipids in bone marrow and the central nervous system. Biological variation in fat distribution is affected by age, gender, and degree of fatness (46).

There is a relationship between the sum of SKFs (ΣSKF) and body density (Db). This relationship is linear for homogenous samples (population-specific SKF equations) but nonlinear over a wide range of Db (generalized SKF equations) for both men and women. A linear regression line, depicting the relationship between the ΣSKF and Db, will fit the data well only within a narrow range of body fatness values. Thus, using a population-specific equation to estimate the Db of a client who does not represent the sample originally used to develop that equation leads to an inaccurate estimate of your client’s Db (32).

Age is an independent predictor of Db for both men and women. Using age and the quadratic expression of the sum of skinfolds (ΣSKF²) accounts for more variance in Db of a heterogeneous population than using the ΣSKF² alone (32).

Sources of Measurement Error. The accuracy and precision of SKF measurements and the SKF method are affected by the technician’s skill, type of SKF caliper, and client factors (26). The following questions and responses address these sources of measurement error.

Is there high agreement among SKF values when the measurements are taken by two different technicians?

A major source of measurement error is differences between SKF technicians. Objectivity, or between-technician reliability, is improved when SKF technicians follow standardized testing procedures, practice taking SKFs together, and mark the SKF site (58). A major cause of low intertester reliability is improper location and measurement of the SKF sites (48).

Are the anatomical descriptions for specific SKF sites the same for all SKF equations?

In the past, for some SKF sites, the anatomical location and direction of the fold have varied. For example, Behnke and Wilmore (4) recommended measuring the abdominal SKF using a horizontal fold adjacent to the umbilicus, whereas Jackson and Pollock (35) recommended measuring a vertical fold taken 2 cm lateral to the umbilicus. Inconsistencies such as this have led to confusion and lack of agreement among SKF technicians. As a result, experts in the field of anthropometry have developed standardized testing procedures and detailed descriptions to identify and measure SKF sites (21).

How many measurements are taken at each SKF site?

Intratechnician reliability or consistency of measurements by the skinfold technician is another source of error for the SKF method. A minimum of two measurements should be taken at each site in rotational order. If the two values for any site vary from each other by more than ±10%, additional pairs of measurements
should be taken until this criterion is met. Two trials within ±10% of each other are averaged and used in the prediction equation to estimate Db and %BF.

What types of SKF calipers are available and how do these calipers differ?

When selecting an SKF caliper for use in the field, you should consider factors such as cost, durability, and degree of precision needed, as well as your skill and experience as an SKF technician. Either high-quality metal calipers or plastic calipers can be used to measure SKF thickness. The cost of SKF calipers varies, depending on the materials used in construction (metal or plastic) and the caliper's accuracy and precision throughout the range of measurement. High-quality instruments, such as Harpenden, Lange, Holtain, and Lafayette calipers, exert constant pressure (~10 g/mm²) throughout the range of measurement (0 to 60 mm). Calipers should not vary in tension more than 2.0 g/mm² over the range or exceed 15 g/mm² (15). Excessive tension and force cause client discomfort (a pinching sensation) and significantly reduce the SKF measurement (20). High-quality calipers also have excellent scale precision (0.2 and 1.0 mm for Harpenden and Lange calipers, respectively). The accuracy of the caliper should be checked periodically using a high-precision Vernier caliper or SKF calibration blocks.

Although the Harpenden and Lange SKF calipers have similar pressure characteristics, a number of researchers have reported that SKF's measured with Harpenden calipers produce significantly smaller values compared to Lange calipers (20, 47). Even though the pressure is similar for the Lange (9.3 g/mm²) and Harpenden (9.36 g/mm²) calipers, researchers have noted that the Harpenden caliper requires three times more force to open its jaws. Therefore, it is more likely that the adipose tissue will be compressed to a greater extent, resulting in smaller SKF measurements with this type of caliper.

Are plastic SKF calipers as accurate as metal SKF calipers?

Compared to high-quality calipers, plastic SKF calipers have less scale precision (~2 mm), nonconstant tension throughout the range of measurement (23), a smaller measurement scale (~40 mm), and less consistency when used by inexperienced SKF technicians (47). Despite these differences, several researchers (23, 47) reported no significant differences between SKF's measured with high-quality calipers (Harpenden, Holtain, and Lange) and plastic calipers (McGaw caliper, Ross adipometer, and Fat-O-Meter). However, SKF's measured with Harpenden, McGaw, Slim-Guide, and Skyindex calipers are significantly smaller than those measured with Lange calipers (18, 20, 23, 47, 79). Lohman et al. (47) noted that differences among instruments (Harpenden, Lange, Holtain, and Ross adipometer calipers) varied depending on the SKF technician. Differences among technicians were less for the Harpenden and Holtain calipers compared to the Lange caliper and Ross adipometer. Given that the caliper's type may be a potential source of measurement error, the same caliper should be used to monitor changes in the client's SKF thicknesses.

Does the client's hydration level affect skinfold measurements?

SKF measurements may also be affected by compressibility of the adipose tissue and hydration levels of clients. Martin, Drinkwater, and Clarys (51) reported that variation in SKF compressibility may be an important limitation of the SKF method. In addition, an accumulation of extracellular water (edema) in the subcutaneous tissue caused by factors such as peripheral vasodilation or certain diseases may increase skinfold thicknesses (39). This suggests that SKFs should not be
measured immediately after exercise, especially in hot environments. Also, most of the weight gain experienced by some women during their menstrual cycles is caused by water retention (7). This could increase SKF thicknesses, particularly on the trunk and abdomen. However, there are no empirical data to support or refute this hypothesis.

**Should SKFs be measured on the right or left side of the body?**

Although there are only small differences (1 to 2 mm) between SKF thicknesses on the right and left sides of the body for the typical individual, there is disagreement as to which side of the body SKF measurements should be taken. In the United States, researchers and practitioners take these measurements on the right side of the body, as recommended in the *Anthropometric Standardization Reference Manual* (48). On the other hand, the general practice in Europe and developing countries is to measure SKF on the left side of the body, as recommended by the International Biological Programs (52).

**Should the SKF method be used to assess the body composition of obese clients?**

It is difficult, even for highly-skilled SKF technicians, to accurately measure the SKF thickness of extremely obese individuals. Oftentimes, the client's SKF thickness exceeds the maximum aperture of the caliper, and the jaws of the caliper may slip off the fold during the measurement. Therefore, SKF should not be used to measure body fat of extremely obese clients.

**Recommendations for SKF Technicians.** To ensure accuracy and reliability of SKF measurements, standardized procedures need to be closely followed (21). Experts have made the following recommendations for increasing one's skill as an SKF technician (34, 48, 58):

- Be meticulous when locating the anatomical landmarks used to identify the SKF site, measuring the distance, and marking the site.
- Read the dial of the caliper to the nearest 0.1 mm (Harpenden or Holtain), 0.5 mm (Lange), or 1 mm (plastic calipers).
- Take a minimum of two measurements at each site. If the two values at any site vary from each other by more than ±10%, take additional pairs of measurements until this criterion is met.
- Take skinfold measurements in a rotational order (circuits) rather than consecutive readings at each site.
- Take the SKF measurements when the client's skin is dry and lotion-free.
- Do not measure SKFs immediately after exercise, because the shift in body fluid to the skin tends to increase the size of the SKF.
- Practice taking SKFs on 50 to 100 clients.
- Avoid using plastic calipers if you are inexperienced; use metal calipers instead.
- Train with skilled SKF technicians, and compare your results.
- Use SKF training videotape that demonstrates proper techniques (45).
- Seek additional training at workshops held at state, regional, and national conferences.

**SKF Prediction Equations.** The SKF method may be used to estimate body composition of children and adults from diverse ethnic groups. Each of the recommended equations in Table 2 meets the selection criteria previously discussed. The
<table>
<thead>
<tr>
<th>SKF sites</th>
<th>Population subgroups</th>
<th>Gender</th>
<th>Age</th>
<th>Equation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Σ7SKF Chest + abdomen + thigh + triceps + subscapular + suprailiac + midaxilla</td>
<td>Black or Hispanic</td>
<td>Women</td>
<td>18–55</td>
<td>$Db (g/cc)^a = 1.0970 - 0.00046971 (Σ7SKF) + 0.00000056(Σ7SKF)^2 - 0.00012828(AGE)$</td>
<td>Jackson et al. (37)</td>
</tr>
<tr>
<td>Σ7SKF Chest + subscapular + thigh + midaxilla</td>
<td>White</td>
<td>Men</td>
<td>34–84</td>
<td>$%BF^a = 0.486 (Σ4SKF) - 0.0015 (Σ4SKF)^2 + 0.067 (AGE) - 3.83$</td>
<td>Williams et al. (73)</td>
</tr>
<tr>
<td>Σ4SKF Triceps + subscapular + abdomen + calf</td>
<td>White</td>
<td>Women</td>
<td>34–84</td>
<td>$%BF^a = 0.428 (Σ4SKF) - 0.0011 (Σ4SKF)^2 + 0.127 (AGE) - 3.01$</td>
<td>Williams et al. (73)</td>
</tr>
<tr>
<td>Σ3SKF Triceps + suprailiac + thigh</td>
<td>White or anorexic</td>
<td>Women</td>
<td>18–55</td>
<td>$Db (g/cc)^a = 1.0994921 - 0.0009929(Σ3SKF) + 0.0000023(Σ3SKF)^2 - 0.0001392(AGE)$</td>
<td>Jackson et al. (37)</td>
</tr>
<tr>
<td>Σ3SKF Chest + abdomen + thigh</td>
<td>White</td>
<td>Men</td>
<td>18–61</td>
<td>$Db (g/cc)^a = 1.109380 - 0.0008267(Σ3SKF) + 0.0000016(Σ3SKF)^2 - 0.0002574(AGE)$</td>
<td>Jackson &amp; Pollock (35)</td>
</tr>
<tr>
<td>Σ2SKF Triceps + calf</td>
<td>Black or white</td>
<td>Boys</td>
<td>6–17</td>
<td>$%BF = 0.735(ΣSKF) + 1.0$</td>
<td>Slaughter et al. (65)</td>
</tr>
<tr>
<td></td>
<td>Black or white</td>
<td>Girls</td>
<td>6–17</td>
<td>$%BF = 0.610(ΣSKF) + 5.1$</td>
<td>Slaughter et al. (65)</td>
</tr>
</tbody>
</table>

*Note. ΣSKF = sum of skinfolds (mm).*
*Use population-specific conversion formulas to calculate %BF from Db (see Heyward and Stolarczyk, 28).  These equations for older adults need to be cross-validated on additional samples from this population.*
Slaughter et al. (65) equations were developed using hydrodensitometry and a multicomponent model to obtain reference measures of %BF for children. These equations are useful to estimate the %BF of black and white children, aged 6 to 17 years. Jackson and colleagues (35, 37) developed generalized equations to estimate the Db of adults varying greatly in age (18 to 60 years), ethnicity (black, white, and Hispanic), and levels of body fatness (up to 45% BF). These equations also account for the effect of age on the distribution of subcutaneous and internal fat. Williams et al. (73) developed SKF equations for older men and women, 60 to 84 years. Although these equations were based on multicomponent models that adjusted Db for bone mineral content and total body water, cross-validation of these equations on additional samples is needed to verify their predictive accuracy for older adults.

Bioelectrical Impedance Analysis

Bioelectrical impedance analysis (BIA) is a rapid, noninvasive, and relatively inexpensive method for evaluating body composition in field settings. With this method, a low-level electrical current is passed through the client's body, and the impedance (Z), or opposition to the flow of current, is measured with a BIA analyzer. The individual's total body water (TBW) can be estimated from the impedance measurement because the electrolytes in the body's water are excellent conductors of electrical current. When the volume of TBW is large, the current flows more easily through the body with less resistance (R). The resistance to current flow will be greater in individuals with large amounts of body fat, because adipose tissue is a poor conductor of electrical current due to its relatively low water content. Because the water content of the fat-free body is relatively large (73% water), fat-free mass (FFM) can be predicted from TBW estimates. Individuals with large FFM and TBW have less resistance to current flowing through their bodies, compared to those with a smaller fat-free mass.

Assumptions and Principles. Since the volume of the body's FFM or TBW is indirectly estimated from bioelectrical impedance measures, certain basic assumptions about the geometric shape of the body and the relationship of impedance to the length and volume of the conductor are made (28):

- The human body is shaped like a perfect cylinder with a uniform length and cross-sectional area. Of course, this assumption is not entirely true. Because the body segments are not uniform in length or cross-sectional area, resistance to the flow of current through these body segments will differ.
- Assuming the body is a perfect cylinder, at a fixed signal frequency (e.g., 50 kHz), the impedance (Z) to current flow through the body is directly related to the length (L) of the conductor (height) and inversely related to its cross-sectional area (A): \( Z = \frac{pL}{A} \), where \( p \) is the specific resistivity of the body's tissues and is assumed to be constant. To express this relationship in terms of Z and the body's volume, instead of its cross-sectional area, the equation is multiplied by \( L/L \): \( Z = \frac{pL^2}{V} \). A \( \times \) L is equal to volume (V), so rearranging this equation yields \( V = \frac{pL^2}{Z} \). Thus, the volume of the FFM or TBW of the body is directly related to \( L^2 \), or height squared (HT^2), and indirectly related to Z.
- Biological tissues act as conductors or insulators, and the flow of current through the body will follow the path of least resistance. Because the FFM
contains large amounts of water (~73%) and electrolytes, it is a better conductor of electrical current than fat. Given that fat is anhydrous and a poor conductor of electrical current, total body impedance, measured at the constant frequency of 50 kHz, primarily reflects the volumes of the water and muscle compartments comprising the FFM and the extracellular water volume (42).

- **Impedance is a function of resistance and reactance, where** $Z = \sqrt{(R^2 + Xc^2)}$. Resistance (R) is a measure of pure opposition to current flow through the body; reactance (Xc) is the opposition to current flow caused by capacitance produced by the cell membrane (42). Typically, R is more than 10 times larger than Xc (at a 50 kHz frequency) when whole-body impedance is measured; therefore, R alone provides an accurate approximation of Z. For this reason, the resistance index (HT²/R), instead of HT²/Z, is often used in many BIA models to predict FFM or TBW (42, 43).

**Sources of Measurement Error.** The accuracy and precision of the BIA measurements are affected by instrumentation, technician skill, client factors, and environmental factors (26). The following questions and responses address these sources of measurement error.

**Can different types of bioimpedance analyzers be used interchangeably?**

Two commonly used impedance analyzers are the RJL™ System (Detroit, MI) and Vahalla Scientific™ (San Diego, CA). Research demonstrates that the whole-body resistances (hand to foot) measured by different brands of single-frequency analyzers differ by as much as 36Ω (19). For example, the average %BF estimated for men from one BIA equation differed by 6.3%BF using the Valhalla™ and Bioelectrical Sciences™ (BES, La Jolla, CA) analyzers to measure R. In general, the Valhalla analyzer produced significantly higher resistances (~16 to ~19Ω) than the RJL analyzer for men and women, causing a systematic underestimation of FFM (19). To control for this potential source of measurement error, the same instrument should be used when monitoring changes in a client’s body composition.

Recently, less expensive bioimpedance analyzers have been marketed for home healthcare. The Tanita™ analyzer measures lower body resistance between the right and left legs as the individual stands on the analyzer’s electrode plates, whereas the OMRON™ analyzer is hand-held and measures upper body resistance between the right and left arms. The upper body and lower body resistances measured by these analyzers will be larger than whole-body resistance (right arm–trunk–right leg) because of the relatively smaller volumes of these body segments compared to the trunk. There are no published reports verifying the validity and applicability of equations programmed into these newer analyzers for assessing body composition of diverse subgroups of the population.

**Does eating or being dehydrated affect bioimpedance measures?**

A major source of error for the BIA method is intraindividual variability in whole-body resistance due to factors that affect the client’s state of hydration. Eating, drinking, and dehydration alter the individual’s hydration state, thereby affecting total body resistance and the estimate of FFM. Taking resistance measures 2 to 4 hr after a meal decreases R and is likely to overpredict FFM by almost 1.5 kg (13). On the other hand, dehydration, produced by restricting fluid and food intake, increases resistance (~40Ω), resulting in a 5.0 kg underestimate of FFM (50).
Will bioimpedance test results be affected if I measure my client immediately after exercise?

The degree to which test results are affected depends on intensity and duration of the exercise workout. Although dehydration due to fluid restriction increases resistance, researchers have reported that fluid loss, resulting from sweating during jogging and cycling at moderate intensities (~70% \( VO_{max} \)) for 90 to 120 min, substantially decreases resistance (50 to 70\( \Omega \)), resulting in a large overestimate of FFM (~12 kg) (40, 50). The decrease in resistance after strenuous exercise most likely reflects the relatively greater loss of body water in the sweat and expired air, compared to the loss of electrolytes. This increases the electrolyte concentration in body fluids, thereby lowering resistance values (13). In addition, increases in core body temperature and skin temperature contribute to the sharp decline in resistance after exercise, because increased skin temperature (33.4 °C compared to 24 °C) decreases resistance (11).

Are bioimpedance measures affected by the menstrual cycle?

Although the menstrual cycle alters total body water, the ratio of extracellular to intracellular water, and body weight (56), there are only small changes in bioimpedance measures (Z and R) between the follicular and premenstrual stages (~5 to 8\( \Omega \)) and between menses and the follicular stage (~7\( \Omega \)) (13, 17). In women experiencing relatively large body weight gains (2 to 4 kg) during the menstrual cycle, a large part of this weight gain is due to an increase in total body water (7). Until there are more conclusive data on this issue, BIA measurements should be taken at a time during the menstrual cycle when the client perceives that she is not experiencing a large weight gain. This practice should minimize error and yield a more accurate estimate of FFM.

Is there a high degree of agreement in bioimpedance values when measurements are taken by two different technicians?

Technician skill is not a major source of measurement error for the BIA method. There is virtually no difference in resistance measurements taken by different technicians, provided that standardized procedures for electrode placement and client positioning are closely followed (37). The proximal sensor electrodes, in particular, need to be correctly positioned at the wrist and ankle. For example, a 1-cm displacement of the sensor electrodes may result in a 2% error in resistance. Also, as a standard practice, bioimpedance measures are taken on the right side of the body.

**Recommendations for BIA Technicians.** The accuracy of the BIA method is highly dependent on controlling factors that may increase measurement error. Therefore, it is important to determine whether your client follows all BIA pretesting guidelines:

- Do not eat or drink within 4 hr of the test.
- Do not exercise within 12 hr of the test.
- Urinate within the 30 min preceding the test.
- Do not consume alcohol within 48 hr of the test.
- Do not take diuretics within 7 days of the test.

Female clients who perceive they are retaining water due to their menstrual cycle should not be tested.
In addition, standardized testing procedures for the BIA method need to be closely followed:

- Take bioimpedance measures on the right side of the body with the client lying supine on a nonconductive surface in a room with normal ambient temperature (~22°C or 72 °F).
- Clean the skin at the electrode sites with an alcohol pad.
- Place the sensor (proximal) electrodes (a) on the dorsal surface of the wrist so that the upper border of the electrode bisects the head of the ulna and (b) on the dorsal surface of the ankle so that the upper border of the electrode bisects the medial and lateral malleoli. Use a measuring tape and surgical marking pen to mark these points for electrode placement.
- Place the source (distal) electrodes at the base of the second or third metacarpal–phalangeal joints of the hand and foot. Make certain there is at least 5 cm between the proximal and distal electrodes.
- Attach the lead wires to the appropriate electrodes. Red leads are attached to the wrist and ankle and black leads to the hand and foot.
- Make certain that the client’s legs and arms are abducted approximately 45° to each other. There should be no contact between the thighs and between the arms and the trunk.

**BIA Prediction Equations.** Commonly used, population-specific, and generalized BIA equations for children and adults are presented in Table 3. The Houtkooper et al. (30) equations were developed using hydrodensitometry and a three-component model that adjusts Db for TBW to obtain reference measures of FFM. These equations accurately estimate the FFM of boys and girls, aged 10 to 19 years. The fatness-specific equations developed by Segal et al. (63) have excellent predictive accuracy for individuals (17 to 62 years) from diverse ethnic groups (American Indian, black, Hispanic, and white) (1, 66, 69). However, one limitation of these fatness-specific equations is that a two-component model was used, in conjunction with hydrodensitometry, to derive reference measures of FFM. Baumgartner et al. (2) developed an age-specific BIA equation to assess the body composition of very elderly women and men (65 to 94 years). Although this equation was developed using a multicomponent model to correct Db for total body water and body mineral, cross-validation on additional samples is needed to substantiate the predictive accuracy and applicability of this equation.

**Anthropometric Methods**

Circumferences and skeletal diameters may be used to assess total body and regional body composition. In addition, anthropometric indexes, such as body mass index (BMI) and waist-to-hip circumference ratio, are used to identify individuals at risk for disease. Compared to SKF measures, these anthropometric methods are relatively simple, are inexpensive, and do not require a high degree of technical skill and training. Although some anthropometric equations have prediction errors (SEE ≤3.5% BF) similar to those reported for SKF and BIA equations (67, 71, 72), these equations were developed against two-component model reference measures of body composition.
<table>
<thead>
<tr>
<th>Ethnicity</th>
<th>Gender</th>
<th>% BF level (Age)</th>
<th>Equation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>American Indian, Hispanic, or white</td>
<td>Men^</td>
<td>&lt;20% (17–62)</td>
<td>$\text{FFM (kg)} = 0.00066360(\text{HT}^2) - 0.02117(\text{R}) + 0.62854(\text{BW}) - 0.12380(\text{AGE}) + 9.33285$</td>
<td>Segal et al. (63)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>≥20% (17–62)</td>
<td>$\text{FFM (kg)} = 0.00088580(\text{HT}^2) - 0.02999(\text{R}) + 0.42688(\text{BW}) - 0.07002(\text{AGE}) + 14.52435$</td>
<td>Segal et al. (63)</td>
</tr>
<tr>
<td>American Indian, black, Hispanic, or white</td>
<td>Women^</td>
<td>&lt;30% (17–62)</td>
<td>$\text{FFM (kg)} = 0.0006646 (\text{HT}^2) - 0.014 (\text{R}) + 0.421 (\text{BW}) + 10.4$</td>
<td>Segal et al. (63)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>≥30% (17–62)</td>
<td>$\text{FFM (kg)} = 0.00091186 (\text{HT}^2) - 0.01466 (\text{R}) + 0.29990 (\text{BW}) - 0.07012 (\text{AGE}) + 9.37938$</td>
<td>Segal et al. (63)</td>
</tr>
<tr>
<td>White</td>
<td>Women</td>
<td>(65–94)</td>
<td>$\text{FFM}^p (\text{kg}) = 0.28 (\text{HT}^2/\text{R}) + 0.27 (\text{BW}) + 0.31 (\text{Thigh C}) - 1.73$</td>
<td>Baumgartner et al. (2)</td>
</tr>
<tr>
<td></td>
<td>Men</td>
<td>(65–94)</td>
<td>$\text{FFM}^p (\text{kg}) = 0.28 (\text{HT}^2/\text{R}) + 0.27 (\text{BW}) + 0.31 (\text{Thigh C}) - 2.768$</td>
<td>Baumgartner et al. (2)</td>
</tr>
<tr>
<td>White</td>
<td>Boys and girls</td>
<td>(8–15)</td>
<td>$\text{FFM (kg)} = 0.62 (\text{HT}^2/\text{R}) + 0.21 (\text{BW}) + 0.10 (\text{Xc}) + 4.2$</td>
<td>Lohman (43)</td>
</tr>
<tr>
<td></td>
<td>Boys and girls</td>
<td>(10–19)</td>
<td>$\text{FFM (kg)} = 0.61 (\text{HT}^2/\text{R}) + 0.25 (\text{BW}) + 1.31$</td>
<td>Houtkooper et al. (30)</td>
</tr>
</tbody>
</table>

^For clients who are obviously lean, use the <20% BF (men) and <30% BF (women) equations. For clients who are obviously obese, use the ≥20% BF (men) and ≥30% BF (women) equations. For clients who are not obviously lean or obese, calculate their FFM using both the lean and obese equations and then average the two FFM estimates (Stolarczyk et al., 66).

^These equations for older adults need to be cross-validated on additional samples from the population.
**Assumptions and Principles.** There are basic principles associated with using anthropometric measures such as BMI, circumferences, and skeletal diameters to estimate body composition (28):

- **Circumferences are affected by fat mass, muscle mass, and skeletal size; therefore, these measures are related to fat mass and lean body mass.** Jackson and Pollock (33) reported that circumference and bony diameter measures are markers of lean body mass (muscle mass and skeletal size); however, some circumferences are also highly associated with the fat component. These findings confirm that circumference measures reflect both the fat and fat-free body components of body composition.

- **Skeletal size is directly related to lean body mass.** Behnke (3), proposing that lean body mass could be accurately estimated from skeletal diameters, developed equations for predicting lean body mass. Cross-validation of these equations yielded a moderately high relationship \( r = .80 \) and closely estimated the average lean body mass obtained from hydrodensitometry (75, 76). Behnke's hypothesis was also supported by the observation that skeletal diameters, along with circumference measures, are strong markers of lean body mass (33).

- **To estimate total body fat from weight-to-height indexes, the index should be highly related to body fat but independent of height.** Based on data from two large-scale epidemiological surveys (National Health and Nutrition Examination Surveys I and II), Miccozzi et al. (55) reported that body mass index (body weight divided by height squared) is not significantly related to height of men and women; however, BMI is not totally independent of height, especially in younger children (<15 years old). Although BMI is directly related to skinfold thickness and the estimated fat area of the arm in adults, the relationship of BMI to total body fat varies with age, gender, and ethnicity (14, 70). This results in large prediction errors (>5% BF) when BMI is used as a single predictor of body fatness (14). Thus, BMI should not be used to estimate the body fatness of your clients.

**Sources of Measurement Error.** The accuracy and reliability of anthropometric measures are potentially affected by equipment, technician skill, and client factors (9). The following questions and responses address these sources of measurement error.

*Can any type of tape measure be used to measure body circumferences?*

An anthropometric tape measure should be used to measure circumferences. The tape measure should be made from a flexible material that does not stretch with use. Plastic-coated tape measures can be used if an anthropometric tape measure is not available. Some anthropometric tapes have a spring-loaded handle (i.e., Gullick handle) that allows constant tension to be applied to the end of the tape during the measurement.

*How much skill and practice are required to ensure accurate circumference and skeletal diameter measurements?*

Compared to the SKF method, technician skill is not a major source of measurement error in anthropometric measurements. However, practice is needed to perfect measurement technique and identify measurement sites. Experts recommend practicing on at least 50 people and taking a minimum of three measurements for each site in rotational order (9). Standardized testing procedures should be
closely followed for locating measurement sites, positioning the anthropometer or tape measure, and applying tension during the measurement.

Is there good agreement in circumference and skeletal diameter values when the measurements are taken by two different technicians?

Variability in circumference measurements taken by different technicians is relatively small (0.2 to 1.0 cm), with some sites differing more than others (9). Skilled technicians can obtain similar values, even when measuring circumferences of obese individuals (5).

Are the circumferences of obese clients more easily measured than skinfolds?

As with the SKF method, it is more difficult to obtain consistent measurements of circumference for obese compared to lean individuals (5). However, circumferences are preferable to SKFs when measuring obese clients for several reasons. First, circumferences of obese individuals can always be measured regardless of the individuals’ size, whereas the maximum aperture of the SKF caliper may not be large enough to allow measurement of some people. Second, circumferences require less technician skill, and third, differences between technicians are smaller for circumferences compared to SKF measurements (5).

Is it possible to accurately measure bony widths of heavily muscled and obese clients?

Accurate measurement of bony diameters in heavily muscled or obese individuals may be difficult because the underlying muscle and fat tissues must be firmly compressed. Bony anatomical landmarks may not be readily identified and palpated, leading to error in locating the measurement site.

Recommendations for Anthropometric Technicians. Practice is necessary to become proficient in measuring skeletal diameters and circumferences. Following standardized procedures increases the accuracy and reliability of measurements (9, 77).

- Take all circumference and bony diameter measurements of the limbs on the right side of the body.
- Carefully identify and measure the anthropometric site; meticulously locate anatomical landmarks used to identify the measurement site.
- Take a minimum of three measurements at each site in rotational order.
- When measuring bony widths, apply firm pressure to the point at which the measurement no longer continues to decrease, to ensure that the underlying muscle, fat, and skin are compressed.
- Use an anthropometric tape measure to measure circumferences, and apply tension to the tape so that it fits snugly around the body part but does not indent the skin or compress the subcutaneous tissue.

Anthropometric Prediction Equations. Anthropometric equations may be used to assess body composition of adults and older adults (Table 4). The generalized equation of Tran and Weltman (67) uses abdominal and hip circumferences, in combination with age and height, to estimate Db of women aged 15 to 79 years. Using hydrodensitometry and two-component model estimates of body fatness, Weltman et al. (71, 72) developed equations to assess %BF of obese women (20 to 60 years) and obese men (24 to 68 years). Anthropometric equations for children still need to be developed.
Table 4  Circumference and Skeletal Diameter Prediction Equations

<table>
<thead>
<tr>
<th>Ethnicity</th>
<th>Gender</th>
<th>Age</th>
<th>Equation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>White</td>
<td>Women</td>
<td>15–79</td>
<td>Db (g/cc) = 1.168297 − 0.002824(Abdom C) + 0.0000122098(Abdom C)² − 0.000733128(HIP C) + 0.000510477(HT) − 0.000216161(AGE)</td>
<td>Tran &amp; Weltman (67)</td>
</tr>
<tr>
<td></td>
<td>Men</td>
<td>18–40</td>
<td>FFM (kg) = 39.652 + 1.0932(BW) + 0.8370(BI-ILIAC D) + 0.3297(AB₁ C) − 1.0008(AB₂ C) − 0.6478(KNEE C)</td>
<td>Wilmore &amp; Behnke (75)</td>
</tr>
<tr>
<td>White</td>
<td>Obese women</td>
<td>20–60</td>
<td>% BF = 0.11077 (Abdom C) − 0.17666 (HT) + 0.14354 (BW) + 51.033</td>
<td>Weltman et al. (71)</td>
</tr>
<tr>
<td></td>
<td>Obese men</td>
<td>24–68</td>
<td>% BF = 0.31457 (Abdom C) − 0.10969 (BW) + 10.834</td>
<td></td>
</tr>
</tbody>
</table>

*Use a population-specific conversion formula to calculate %BF from Db (see Heyward and Stolarczyk, 28). *Abdom C (cm) is the average abdominal circumference measured at two sites: (1) anteriorly midway between the xiphoid process of the sternum and the umbilicus and laterally between the lower end of the rib cage and iliac crests, and (2) at the umbilicus level.
Near-Infrared Interactance Method

Compared to the skinfold and bioelectrical impedance methods, which have been validated and refined through years of research, near-infrared interactance (NIR) is still in the developmental stage. Although NIR has been proposed and marketed as a viable alternative to SKF and BIA methods, much more research is needed to fully evaluate the potential of NIR for body composition assessment.

Near-infrared spectroscopy has been used since 1968 to measure the protein, fat, and water content of agricultural products. In 1984, Conway et al. (12) applied this technology to study human body composition using a high-precision (6 nm), expensive, computerized spectrophotometer. Based on results from a small (N=17) cross-validation sample, these researchers concluded that this method “successfully predicted % body fat” (p. 1129). However, their NIR prediction equation systematically overestimated relative body fat (%BF) for 10 of the 11 females in the cross-validation sample, indicating that different equations may need to be developed for men and women.

Shortly thereafter, less expensive, commercial NIR analyzers (Futrex-5000™ and Futrex-1000™) were marketed based on the results of Conway et al.’s (12) work. The Futrex 5000 analyzer estimates %BF from optical density (OD) measured at the biceps site. Cross-validation of the manufacturer’s equations indicates that these equations have poor validity and unacceptable prediction errors (SEE = 3.7 to 6.3% BF). Many studies show that the Futrex-5000™ equations systematically underestimate %BF of adults and overestimate %BF of children (10, 26, 27, 31, 54, 78). Therefore, these equations are not recommended for body composition assessment.

Closing Remarks

Selecting an appropriate method and prediction equation to accurately assess the body composition of individuals from diverse subgroups of the population is a challenging task for health and nutrition professionals. To evaluate the relative worth of prediction equations, use the following selection criteria:

1. An acceptable method (e.g., densitometry, hydrometry, DXA, or a combination of these methods) was used to derive reference measures of body composition for developing and cross-validating the prediction equation.
2. A multicomponent body composition model, instead of a two-component model, was used to obtain reference measures of %BF or FFM.
3. The size of the validation sample was adequate (N = 100–400), and the ratio of sample size to predictor variables in the equation was at least 10–20 subjects per predictor variable.
4. The size of the multiple correlation coefficient was acceptable (R^2 ≥ .80).
5. The prediction error (SEE) for the validation sample was “good” to “ideal” (see Table 1).
6. The physical characteristics (i.e., age, gender, race, and level of body fatness) of the validation sample are similar to those of the individuals for whom you intend to apply the equation.
7. The equation was cross-validated on an independent sample from the population.
8. The size of the cross-validated coefficient was acceptable (r_{cv} ≥ .80).
9. The prediction error (SEE) for the cross-validation sample was “good” to “ideal” (see Table 1).

10. There was no significant difference ($p > .05$) between the average predicted score and the average reference score for the cross-validation sample (evaluate paired $t$-test results).

As new technologies are developed and refined, it is highly probable that additional equations will become available; thus, it is important to apply these criteria in order to evaluate the relative worth of these equations as well as their applicability to individuals from various population subgroups. In the meantime, the prediction equations recommended for the SKF and BIA methods should yield fairly accurate estimates of body composition for children (6 to 18 years) and adults (18 to 62 years). Also, selected anthropometric prediction equations are suitable for estimating body composition of older adults (60 to 80 years) as well as obese women and men.

References


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