Selected Body Composition Methods Can Be Used in Field Studies1,2

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ABSTRACT This article provides an overview of the present status of in vivo body composition methodologies that have potential for use in field studies. The methods are divided into four general categories: anthropometric indices and skinfold, body volume measurements, body water measurements including bioelectrical methods, and imaging techniques. Among the newest technologies are air-displacement plethysmography, three-dimensional photonic scanning, multifrequency bioelectrical impedance spectroscopy and whole-body tomography using electrical impedance and magnetic induction. These newer approaches are compared with the established reference methods. The advantages and limitations of each technique as a field method are presented relative to the corresponding concepts of an ideal method. J. Nutr. 131: 1589S–1595S, 2001.

KEY WORDS: • body composition • human • noninvasive methods

Chemical analyses of human tissues have provided the basis of modern medicine and helped to form much of our knowledge of basic physiology and metabolism. The removal of small amounts of tissue from a living subject is technically rather simple, although the procedure is not comfortable or without risk. The findings from a single tissue sample may be highly informative but not necessarily indicative of the condition of the total organ, much less that of the whole body. In this article, the various techniques currently available for the noninvasive assessment of body composition in humans are examined, focusing on their applications as potential field methods. The definition of a field method can be somewhat arbitrary, but it is usually bound by the resources that are available, the level of information that is being sought and the geographical location of the study.

1 Presented at the symposium “Non- or Minimally-Invasive Technologies for Monitoring Health and Nutritional Status in Mothers and Young Children” held August 7–8, 2000 at the Children’s Nutrition Research Center, Baylor College of Medicine, Houston, TX. This symposium was sponsored by Baylor College of Medicine Office of Analysis, Nutrition and Evaluation of the Food and Nutrition Service of the U.S. Department of Agriculture. The proceedings of this symposium are published as a supplement to The Journal of Nutrition. Guest Editors for the supplement publication were Dennis M. Bier, Baylor College of Medicine, Houston, TX and D’Ann Finley, University of California, Davis, CA.

2 Supported by the U.S. Department of Agriculture, Agricultural Research Service under Cooperative Agreement 58-6250-6-001 with Baylor College of Medicine. This work is a publication of the U.S. Department of Agriculture/ Agricultural Research Service Children’s Nutrition Research Center, Department of Pediatrics, Baylor College of Medicine and Texas Children’s Hospital, Houston, TX. The contents of this publication do not necessarily reflect the views or policies of the U.S. Department of Agriculture, and mention of trade names, commercial products or organizations does not imply endorsement.

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The classic two-compartment (2-C)4 model of body composition divides body weight into fat mass and fat-free mass (FFM). The direct measurement of the body’s fat mass has never been easy and remains a significant challenge for most body composition techniques. However, if one can accurately determine the FFM, then fat mass can be defined as the difference between body weight (Wt) and FFM. Over the last 50 y, three methods that use the 2-C model have emerged, and each of these is often used as the reference method for the evaluation of newer technologies. These methods are based on measurements of body density by underwater weighing (UWW), body cell mass by whole-body potassium counting and total body water (TBW) by isotope dilution (Ellis 2000).

As more measurement techniques were developed, the basic 2-C model evolved into multicompart model of body composition (Fig. 1). Wang and colleagues (1992, 1993, 1995) collated this information into a comprehensive description of body composition. Garrow and Webster (1985) proposed that five factors should be considered when defining an ideal method for field studies: 1) initial cost, 2) training of the operator, 3) maintenance and operating costs, 4) precision and accuracy. To this list, I would add the consideration that the measured parameter can be translated into a useful biological meaning.

The selection of a model often decides the methods that are needed, depending on the type and quality of the information

4 Abbreviations used: 2-C, two-compartment; FFM, fat-free mass; UWW, underwater weighing; TBW, total body water; Wt, body weight; Ht, height; SF, skinfold thickness; BMI, body mass index; ADP, air-displacement plethysmography; BIA, bioelectrical impedance analysis; BIS, bioelectrical impedance spectroscopy; CT, computer tomography; MRI, magnetic resonance imaging; DXA, dual-energy X-ray absorptiometry; EIT, electrical impedance tomography.
Although similar charts have been used for many years for overweight and obese children (www.cdc.gov/growthcharts), new BMI charts that are recommended for use in identifying the U.S. Centers for Disease Control and Prevention released the one most commonly used (Brodie et al. 1998). Recently, developed, the body mass index (BMI), defined as \( \text{Wt}/\text{Ht}^2 \), is used to identify the centile distributions for each gender and sometimes for ethnicity. Although many different Wt-for-Ht indices have been described in the following sections are not needed. However, if the objective is to determine the body’s fat mass or its visceral component, or if there is bone loss or abnormal cellular distribution of body water such as edema or dehydration, then the more robust methods discussed below must be used.

Several advanced methods used for in vivo analysis in humans, such as neutron activation or gamma resonance absorption, will not be presented here because they do not lend themselves easily to field use (Chettle and Fremlin 1984, Ellis 2000, Vartsky et al. 2000). Likewise, a discussion of whole-body potassium counting is being excluded, although such instruments have been built and successfully used in field studies. The focus of this article is to examine those methods that are most likely to be used in the field for assessing body composition in large-scale epidemiological, clinical or anthropological studies. In each of these cases, weight and stature are typically recorded and compared with reference standards. If a subject’s values are in the extreme range (for example, below the third to fifth percentiles or above the 95th-97th percentiles), then a more precise body composition assay probably is not needed for screening purposes. However, for longitudinal or intervention studies, more accurate and precise body composition measures should be considered. Body composition assays are more helpful in identifying subjects before they have reached these extremes. That is, an alternate field concept for the use of body composition methods is screening for less severe conditions so that early interventions can be started.

**Anthropometry**

Anthropometry includes measurements of Wt, height (Ht), circumferences and lengths at various body regions, and skinfold thickness (SF). These data are usually presented as percentile distributions for each gender and sometimes for ethnicity. Although many different Wt-for-Ht indices have been developed, the body mass index (BMI), defined as \( \text{Wt}/\text{Ht}^2 \), is the one most commonly used (Brodie et al. 1998). Recently, the U.S. Centers for Disease Control and Prevention released new BMI charts that are recommended for use in identifying overweight and obese children (www.cdc.gov/growthcharts). Although similar charts have been used for many years for adults, the focus of this article will be on the assessment on children.

BMI is an attractive anthropometric index because it meets the first four requirements for an ideal method (Garrow and Webster 1985). The two instruments (scale and tape measure) that are required are inexpensive, require minimal training to use and are virtually maintenance-free, and repeat values can be obtained with good precision. The remaining question is the accuracy of BMI in assessing body fatness for the individual (Gallagher et al. 1996), especially for children (Ellis et al. 1999a). We have examined the relationship between BMI and body fatness (obtained using dual-energy X-ray absorptiometry [DXA]) for children; the results for boys are shown in Figure 2 (Ellis et al. 1999a). Body fatness and BMI were correlated (\( r = 0.8; P < 0.001 \)); however, BMI was not a precise predictor of the degree of fatness. When BMI was 20 kg/m\(^2\), the corresponding fat mass could range from 5% to 40% of body weight. Conversely, if the fat mass was 20% of body weight, the BMI value could be anywhere between 15 and 30 kg/m\(^2\).

When the BMI vs body fatness (measured by any number of techniques) relation is examined in adults, similar but not a dramatic disagreement is often reported. One clear advantage for using BMI in adults, however, is that height remains virtually constant during adulthood, thus longitudinal examinations based on BMI reflect mainly changes in fat mass. Although BMI has its limitations, it remains a simple measurement to obtain and is used widely in large-scale international studies for long follow-up periods to assess disease risk.

One criticism of this analysis has been that BMI should only be used to screen children for obesity, not to quantify the percentage of body fat. To test this application, we used the latest Centers for Disease Control and Prevention rating scheme for BMI to classify pubertal children; the results for girls are shown in Figure 3. It can be seen that many of the children with a normal BMI actually had an elevated percentage of body fat. Furthermore, children with an overweight BMI classification could have a normal, elevated or excess amount of body fat. When BMI was in the highest category, most of the children had body fat above 30%. Therefore, based solely on a scientific evaluation, it is recommended that use of BMI alone to assess adiposity in obese children should be replaced with other noninvasive techniques whenever available.

The second most commonly used anthropometric technique to assess body fatness is based on skinfold measurements of the subcutaneous fat layer using inexpensive mechanical calipers. The precision of the skinfold data has been shown to be highly variable and operator-dependent. The accuracy of this method has been questioned for many years when assessing body fat mass of the individual. The skinfold technique, at best, provides a measure of the subcutaneous layer covering the body. In the absence of other techniques, within a study population, SF (without the conversion to body fat estimates) can be used to monitor population changes in the subcutaneous fat layer. Unfortunately, > 100 SF prediction equations have been published, which only illustrates the population-specific limitations between SF and whole-body fat mass. However, the general nature of this relation does not seem to prevent journals from publishing new versions (Goran et al. 1996, Dezenberg et al. 1999, Wong et al. 2000).

Alternative, high-technology methods have been developed to replace the use of the mechanical calipers for the measurement of the subcutaneous fat layer. Such methods include ultrasound, infrared interaction and photon backscatter (Conway et al. 1984, Moller et al. 1994, Moller et al. 2000). The use of these devices has automated the analysis and reduced the operator-dependent errors, but there are still limi-
limitations associated with extrapolation to the body's total fat mass. In general, there has not been sufficient evaluation of the usefulness of these devices for the individual (Thomas et al. 1997).

**Body volume measurements**

The UWW technique for the measurement of body volume was developed in the 1940s based on a 2-C model, where \( W_t \) is divided into fat and FFM. UWW has become a standard reference assay for many laboratories. These instruments are priced moderately but they require high maintenance and a well-trained operator. The major technical difficulty with UWW is that the subject must be completely submerged under water and must exhale the air in his/her lungs to correct for residual lung volume (Buskirk 1961, Siri 1961). A second limitation of the basic UWW method is that the density of the FFM is assumed to be constant, whereas it well known that the composition of the FFM varies with gender, ethnicity, growth, sexual maturation, physical activity and aging (Ellis 2000).

Over the years, the difficulty of performing the UWW measurement has shown that this method is not suited for field studies.

However, two new techniques measuring body volume have been developed that have the potential to become field methods. One instrument (Dempster and Aitkens 1995, McCrory et al. 1995), based on air-displacement plethysmography (ADP), consists of two chambers; the subject sits in one chamber, while the other serves as a reference (Fig. 4). The volumes of the two chambers are varied slightly and the difference in air pressure is recorded. The subject’s body volume is calculated using corrections for isothermal properties of the air in the lungs and near the skin’s surface. The most...
obvious advantage is that the subject does not have to be submerged under water; although the subject still needs to wear a swimsuit and cap, the measurement time is only a few minutes. Preliminary studies using ADP have shown very good agreement with the UWV method in healthy adults and children (McCrorry et al. 1998, Lockner et al. 2000).

The second novel technique for the measurement of body volume is based on a three-dimensional reconstructed image of the body's surface contours using photon scanning (Wells et al. 2000). Application of this technology to the study of body composition is new and only a few subjects have been examined. Figure 5 illustrates the type of reconstructed body image that can be obtained and the general design of the scanner. The obvious advantages of this technique are that the subject does not have to be submerged under water or sit in a closed small-volume chamber. Furthermore, the whole-body scan time is only ~15 s. Currently, the precision for a body volume estimate is ~3%, which is too high to be translated into a meaningful assay for body fatness. The accuracy of the method remains unknown. However, if the precision could be improved to ~1% and the accuracy to < 5%, this method would be comparable to UWV. An added advantage of this method is that it may also allow for the possibility of monitoring changes in the body’s contour, which may reflect changes in the subcutaneous fat layer. This technology is new and clearly holds much promise for the future and has the potential to become a standard for field measurements of body composition.

Body water and bioelectrical impedance methods

For healthy adults and older children, the water content of FFM is relatively constant: 0.732 L per kg (Wang et al. 1999). Thus, any measurement technique based on the assay for TBV indirectly provides an estimate for FFM (Ellis 2000). The body’s percentage of fatness can be defined as %Fat = 100 × (Wt − FFM)/Wt. The first methods used a radioactive isotope of water; today this assay is based on stable isotopes (deuterium, 18O) of water. In one technique, called the dilution isotope of water; today this assay is based on stable isotopes (Wt

\[ \text{Wt} \]

of the fluid sample (Blagojevic et al. 1990, Aslani and Hansen 2000), can be used as an alternative analytical technique in place of the more costly mass spectroscopy approach. In addition to the cost benefits, the results can be obtained relatively quickly, typically within a few hours after giving the oral tracer dose. However, no commercial instrument designed specifically to measure body water has been marketed.

Several alternative methods for the assay of body water have been developed based on the electrical properties of tissues. The most common method, and probably the most practical for field use, is called bioelectrical impedance analysis (BIA). This technique is based on the premise that when an electrical current is passed through the body, the voltage drop between two electrodes is proportional to the body’s fluid volume in that region of the body. Although measurements can be performed at any frequency, 50 kHz has become the standard for commercial instruments. The cost of a bioelectrical impedance instrument is relatively inexpensive (~$1/30 of a mass spectroscopy instrument), its operation does not require highly trained personnel and the results (obtained immediately) have good reproducibility. The accuracy of BIA results and their biological interpretation should be used with caution (National Institutes of Health 1996, Ellis et al. 1999a, Ellis et al. 1999b).

The BIA measurement is performed by attaching a pair of electrodes at the wrist and at the ankle (Fig. 6A) so that a weak alternating current (800 μAmp) can be passed through the body. The voltage drop is measured and the resistance (R) calculated, while the current is kept constant. To estimate the volume of TBV, three assumptions are used: the whole body acts like a cylindrical conductor, the conductor’s length is proportional to the subject’s height and the reactance component of the voltage signal can be disregarded. Under these conditions, the impedance index \( \text{Ht}^2/R \) is assumed to be proportional to the volume of TBV. Activities performed within 4 h before the measurement, such as moderate to vigorous exercise, consumption of excessive alcohol or excessive sweating, can substantially alter the reading.

Other investigators have taken an alternate approach by using both resistance (R) and reactance (Xc) components of the measured impedance. The reactive component is assumed to be produced by the capacitive properties of cells, which shift the voltage and current out of phase. In electrical terms, this phenomenon is defined by the phase angle (ϕ), where \( ϕ = \arctan(Xc/R) \). In healthy adults, the phase angle at 50 kHz is typically above 8°; in clinical conditions, it can be as low as 2–3° (Piccoli et al. 1994, Piccoli et al. 1996).

As noted above, the actual measurement procedure for the subject is relatively easy and can be performed within a few minutes. The major concern with BIA is that the proportion of the current that passes through cells at 50 kHz is unknown (National Institutes of Health 1996). To overcome this uncertainty, bioelectrical impedance spectroscopy (BIS) was developed (Cornish et al. 1993, Mathie et al. 1998). The resistance and reactance values are recorded for a wide frequency range (5 kHz to 1 MHz) and are mathematically fit to

\[ \text{location of the scanning elements for the instrument (left) and reconstructed body surface image (right (Hamamatsu Bodyline Scanner, Hamamatsu, Japan).} \]
a parallel resistance model that is used to derive estimates for TBW and extracellular water. Although a BIS instrument (Xitron, San Diego, CA) is slightly costlier than a single-frequency BIA device, the operating cost, training of the operator and the portability of the instrument for field use are virtually the same as those for any single-frequency BIA device. A weakness of both BIA and BIS is that they are indirect methods and must be calibrated with a reference assay (Ellis et al. 1999b). Furthermore, the number of BIA calibration equations that have been developed is approaching the level observed for the skinfold method.

Another interesting aspect of the BIA technology is that it is probably the only body composition technique that has been direct-marketed to the general public. Two of these devices, as illustrated in Figure 6, are designed for upper body (B) and lower body (C) measurements. Although their daily precision is good, their accuracy for the assessment of an individual’s body fatness remains unclear. There are also issues as to whether a partial body assessment will be representative of the whole body, independent of body size proportions.

**Imaging methods**

Three major techniques are used for imaging of the body: computer tomography (CT), magnetic resonance imaging (MRI) and dual-energy X-ray absorptiometry (DXA). In general, these techniques cannot be considered as field methods for body composition analysis because of the high initial cost.
ital investment, the need for a highly trained technical staff and the high annual maintenance and service costs, especially for CT and MRI. Furthermore, only the DXA manufacturers have developed standard software that can routinely assay for body composition (Fig. 7). Many scientists consider these methods as the standards for precision and accuracy for body composition measurements, matched only by that obtained using neutron activation analysis (Chettle and Fremlin 1984, Ellis 2000). The main applications of CT and MRI are for tumor detection and evaluation of abnormal or damaged anatomical structure. The sheer size and complexity of these whole-body instruments rule them out as field methods. However, smaller devices have been built for measurements involving only the arms or legs, and these are increasingly used in physicians’ offices. DXA instruments, in fact, are used in the field, if one considers the ongoing National Health and Nutrition Examination Survey as a field study at multiple sites across the United States. In addition, there are a number of mobile clinics around the country that perform DXA scans as a part of screening for osteoporosis. In the future, triple-energy X-ray absorptiometry (Kotzki et al. 1991, Swanpalmer et al. 1998) may displace DXA, if some of the problems with the latter are not resolved (Van Loan 1998).

Another promising area of technology that is being developed for imaging is based on the electrical and magnetic properties of tissues and cells (Riu et al. 1999). Three of these new imaging approaches look quite promising for translation into field use: electrical impedance tomography (EIT), magnetic induction tomography and magnetic impedance tomography. In conducting EIT measurements, contact electrodes are equally spaced around the surface of the body on the same transverse plane. A current is injected into one electrode, and the voltage developed on the surface of the body at the other electrodes is measured. The procedure is repeated with the injection of current rotated among the set of electrodes. The EIT current is very weak, nondetectable by the subject, and presents no harm; the data are obtained rapidly. The EIT instrumentation is relatively inexpensive (comparable to BIS and UWW); however, the technician must be well trained, and the algorithms used to reconstruct the images are inferior to those used with MRI or CT. In addition, the position of the electrode array around the body produces a cross-sectional image only at that location, so multiple measurements would be needed for the whole body. In contrast, magnetic impedance tomography uses only two electrodes (Tozer et al. 1999). The basis of this technique is that as the current is passed through the body, a weak magnetic field is generated outside the body. The major difficulty is the detection of this signal above the ambient magnetic background. In addition, the mathematical reconstruction algorithms needed to convert the externally induced magnetic field to an image have not been solved. The second magnetic technique uses magnetic induction (Griffiths et al. 1999). In this case, the body is placed in an external oscillating magnetic field. Eddies currents are induced in the body, which then produce a small perturbation of the external magnetic field. Preliminary studies have been performed and the initial results are promising, but the reconstruction algorithms are still very primitive. The advantages of this technique are that nothing is attached to the body, and it should take only a few seconds or minutes to perform a whole-body scan. Again, the major difficulty is to detect the small perturbations in the magnetic field around the body.

### Table 1

<table>
<thead>
<tr>
<th>Body composition variable method</th>
<th>Measurement</th>
<th>Minimum detectable change amount</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Precision</td>
<td>Accuracy</td>
</tr>
<tr>
<td>TBW</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>D2O dilution</td>
<td>2–4</td>
<td>1.5 L</td>
</tr>
<tr>
<td>BIA/BIS</td>
<td>2–4</td>
<td>1.5 L</td>
</tr>
<tr>
<td>FFM</td>
<td>2–4</td>
<td>1.5 L</td>
</tr>
<tr>
<td>UWW</td>
<td>2–3</td>
<td>2 kg (4)</td>
</tr>
<tr>
<td>ADP</td>
<td>2–3</td>
<td>2 kg (4)</td>
</tr>
<tr>
<td>DXA</td>
<td>2–3</td>
<td>1.5 kg (2)</td>
</tr>
<tr>
<td>BIA/BIS</td>
<td>2–3</td>
<td>1.5 kg (2)</td>
</tr>
<tr>
<td>Fat mass</td>
<td>&gt;5</td>
<td>2 kg (11)</td>
</tr>
<tr>
<td>UWW</td>
<td>&gt;5</td>
<td>2 kg (11)</td>
</tr>
<tr>
<td>DXA</td>
<td>&gt;5</td>
<td>2 kg (11)</td>
</tr>
<tr>
<td>BIA/BIS</td>
<td>&gt;5</td>
<td>4 kg (22)</td>
</tr>
</tbody>
</table>

1 D2O = deuterium.  
2 Reproducibility for repeat measurements.  
3 Accuracy for absolute mass or volume estimate.  
4 Value in (%) is percentage change based on 70-kg adult with 25% fat.

### Selection of a field measurement for body composition

The precision and accuracy errors reported for the various measurement techniques that could be used as field methods are presented in Table 1. Estimates of the minimal detectable change for an individual adult are included. To detect smaller changes as statistically significant, population studies would have to be used (Hassager and Christiansen 1995). Improving the measurement’s precision or reducing the biological variability of the population can also improve the chance of a small change being significant. However, the population size is often fixed and the biological variability is not easily manipulated; therefore, the selection of the right measurement technique is critical. A second consideration relates to the selection of the time interval between repeat measurements. This is crucial, for if the time interval is too short, then it may not be physiologically possible to achieve the required change for it to be significant. Alternately, if the period is too long, the normal physiological changes in body composition may mask the effect that is being studied. The quality of the field assessment will be directly reflected by the choice of methods. In the best of worlds, one would select the most precise and accurate method, but realistically this choice often must be weighed against the cost.

### ACKNOWLEDGMENT

We thank L. Loddeke for editorial assistance.

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