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, 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.

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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 multicompartiment models 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 field method: 1) accuracy, 2) precision, 3) ease of use, 4) initial cost, 5) maintenance and operating costs.

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 Wt/Ht^2, is centile distributions for each gender and sometimes for eth-

Anthropometry includes measurements of Wt, height (Ht), circumference and lengths at various body regions, and skinfold thickness (SF). These data are usually presented as per-
centile distributions for each gender and sometimes for ethnic-

ty. The second most commonly used anthropometric tech-
nique 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 subcutane-
ous 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). The use of these devices has automated the analysis and reduced the operator-dependent errors, but there are still lim-

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 Wt 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 is 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

FIGURE 2 Relationship between BMI (Wt/Ht²) and %fat (via DXA) for boys ages 5–18 y (Ellis et al. 1999a).

FIGURE 3 Distribution of %fat values for three BMI classifications for prepubertal girls. The dashed line is at a fixed %fat value of 25%; the dotted line is at 30%.

FIGURE 4 Diagram of the basic components of an ADP device (BodPod instrument; Life Measurement Instruments, Concord, CA).
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 UWW method in healthy adults and children (McCroy 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 UWW. 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 TBW indirectly provides an estimate for FFM (Ellis 2000). The body’s percentage of fatness can be defined as %Fat = 100 × (Wt − FFM / TBW)/Wt. The first methods used a radioactive isotope of water; today this assay is based on stable isotopes (deuterium, 1H2O) of water. In one technique, called the dilution principle, a tracer dose of isotope is administered orally, allowed to mix with the body’s water for several hours and then the tracer concentration in plasma, saliva or urine is measured (Schoeller 1991, Sheng and Huggins 1979). For field use, the major limitations are the administration of a precise amount of the tracer dose, collection of the fluid sample, proper storage of the sample and analytical processing of the sample before shipment to a central laboratory, where it is usually assayed using mass spectroscopy. Attention to detail at each step is required; thus, well-trained technicians or nurses are necessary. The major costs are for the isotopes and the mass spectroscopy analysis. Also, the results are not immediately available; therefore, this assay is not very helpful if prompt health care decisions are required.

If a small loss in precision and accuracy can be tolerated, then Fourier transformed infrared analysis, with ultrafiltration of the fluid sample (Blagoev et al. 1996, Askani 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 TBW, 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 (Ht / R) is assumed to be proportional to the volume of TBW. 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 (Xr) 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 = arctangent (Xr / 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

A) Scan configuration  B) Reconstructed surface image

FIGURE 5 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 cap-

![Image](https://example.com/image1.png)

**A) total body**

**B) upper body**

**C) lower body**

**FIGURE 6** Configuration of electrodes and path of the electrical current for bioelectrical impedance analysis: total body (A), upper body region (B) and lower body region (C).

![Image](https://example.com/image2.png)

**FIGURE 7** DXA images of the whole body, lumbar spine and femur (Hologic QDR-2000 instrument; Hologic, Bedford, MA).
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 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. Eddy currents are induced in the body, 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.

## 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

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### LITERATURE CITED


Buskirk, E. R. (1961) Underwater weighing and body density; a review of pro-

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**Table 1**

<table>
<thead>
<tr>
<th>Body composition variable method</th>
<th>Measurement</th>
<th>Minimum detectable change amount</th>
<th>%</th>
<th>% of adult</th>
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</thead>
<tbody>
<tr>
<td>TBW</td>
<td>D_2O dilution</td>
<td>1–2</td>
<td>2 L (5)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BIA/BIS</td>
<td>2–4</td>
<td>4 L (10)</td>
<td></td>
</tr>
<tr>
<td>FFM</td>
<td>UWW</td>
<td>1–2</td>
<td>2 kg (4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ADP</td>
<td>1–2</td>
<td>2 kg (4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DXA</td>
<td>1.5</td>
<td>1.5 kg (2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BIA/BIS</td>
<td>2–4</td>
<td>4 kg (7)</td>
<td></td>
</tr>
<tr>
<td>Fat mass</td>
<td>UWW</td>
<td>2–3</td>
<td>2 kg (11)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ADP</td>
<td>2–3</td>
<td>2 kg (11)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DXA</td>
<td>&gt;5</td>
<td>2 kg (11)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BIA/BIS</td>
<td>&gt;8</td>
<td>4 kg (22)</td>
<td></td>
</tr>
</tbody>
</table>

1 D_2O = 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.

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**Supplement**

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). We thank L. Loddeke for editorial assistance.
cures. In: Techniques for Measuring Body Composition (Brozek, J. & Hen-
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