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Assessment methods in human body composition

Seon Yeong Lee[a,b] and **Dymphna Gallagher**[c]

[a]Body Composition Unit, Obesity Research Center, St. Luke's-Roosevelt Hospital, Columbia University, New York, New York, USA

[b]Department of Family Medicine, Inje University College of Medicine, Sanggyepaik Hospital, Nowon-Gu, Seoul, Korea

[c]Department of Medicine and Institute of Human Nutrition, Columbia University, New York, New York, USA

Abstract

Purpose of review—The present study reviews the most recently developed and commonly used methods for the determination of human body composition *in vivo* with relevance for nutritional assessment.

Recent findings—Body composition measurement methods are continuously being perfected with the most commonly used methods being bioelectrical impedance analysis, dilution techniques, air displacement plethysmography, dual energy X-ray absorptiometry, and MRI or magnetic resonance spectroscopy. Recent developments include three-dimensional photonic scanning and quantitative magnetic resonance. Collectively, these techniques allow for the measurement of fat, fat-free mass, bone mineral content, total body water, extracellular water, total adipose tissue and its subdepots (visceral, subcutaneous, and intermuscular), skeletal muscle, select organs, and ectopic fat depots.

Summary—There is an ongoing need to perfect methods that provide information beyond mass and structure (static measures) to kinetic measures that yield information on metabolic and biological functions. On the basis of the wide range of measurable properties, analytical methods and known body composition models, clinicians and scientists can quantify a number of body components and with longitudinal assessment, can track changes in health and disease with implications for understanding efficacy of nutritional and clinical interventions, diagnosis, prevention, and treatment in clinical settings. With the greater need to understand precursors of health risk beginning in childhood, a gap exists in appropriate in-vivo measurement methods beginning at birth.

Keywords

body composition; human; *in vivo*; measurement; method

Introduction

Measuring body composition in humans is usually in response to the need to describe either deficiencies or excesses of a component that is thought or known to be related to health risk. In conditions such as obesity and osteoporosis, the levels of body fat and bone mineral density (BMD), respectively allow for clinical diagnoses with implications for formulating

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Correspondence to Dymphna Gallagher, EdD, Obesity Research Center, 1111 Amsterdam Avenue, Scrymser Basement, New York, NY 10025, USA, Tel: +1 212 523 4196; fax: +1 212 523 3416; e-mail: dg108@columbia.edu.

appropriate interventions. Nutritional assessment based on body composition in infancy and childhood can guide optimal nutrition and nutritional management during these early years. The available measurement methods range from simple to complex with all methods having limitations and some degree of measurement error. The clinical significance of the body compartment to be measured must be determined before a measurement method is selected, as the more advanced techniques are less accessible and more costly. The measurement of body composition occurs in many areas of biology and medicine when the outcome is a better understanding of nutrition and growth status assessment in disease states and their treatment in populations. The aim of this paper is to review the currently available methods for body composition assessment in humans.

Text of review

At the organizational level, a five-level model [1] was developed in which the body can be characterized at five levels thus providing a structural framework for studying human body composition that goes beyond an individual compartment or level. Each level and its components are distinct (Table 1 [2]). The two-compartment (2C) models partition the body into fat mass and fat-free mass (FFM), and are the most widely used approach to estimate body composition in adults. For example, Behnke *et al*.'s [3] 2C model assumes known and constant proportions of FFM as water, protein, and mineral. When the assumptions that form the basis for the 2C model are not met, body composition estimates will be inaccurate. This may occur systematically with characteristics such as in aging, pregnancy, maturation, weight reduction in obese people, and in various disease states. The 2C model approach is not ideal for measuring fat mass or FFM in infants and young children as the proportions of FFM as water, protein, and mineral are changing with growth. The fourcompartment (4C) model is considered a most accurate measure of body composition and is frequently used as the criterion method against which new body composition methods are compared in both children and adults. The 4C model involves the measurement of body mass or weight, total body volume, total body water (TBW), and bone mineral; however, specialized laboratory equipment is required minimizing the availability of the 4C method to many clinicians and researchers. In the following section, a brief description is given of the most commonly used body composition measurement methods many of which rely on a 2C model approach in addition to recently developed methods.

Bioelectrical impedance analysis and bioimpedance spectroscopy

Bioelectrical impedance analysis (BIA) is a commonly used method for estimating body composition based on a 2C body composition model. BIA measures the impedance or resistance to a small electrical current as it travels through the body's water pool. An estimate of TBW is acquired from which total body FFM is calculated using the assumption that 73% of the body's FFM is water. Single-frequency BIA (SF-BIA) is most commonly used for assessing TBW and FFM but is limited in its ability to distinguish the distribution of TBW into its intracellular and extracellular compartments. Body weight is also measured in the leg-to-leg pressure contact BIA [4].

Bioimpedance spectroscopy (BIS) or multifrequency BIA allows for the differentiation of TBW into intracellular water (ICW) and extracellular water (ECW) compartments, which is useful to describe fluid shifts and fluid balance and to explore variations in levels of hydration [5]. In addition to providing information on fat mass, multifrequency BIA (frequencies up to 300 kHz) may have an added advantage over SF-BIA (50 kHz) for evaluating leg skeletal muscle [6]. Multisegmental BIA is available in both single-frequency and multifrequency systems. The multisegmental approach assumes that the body is made up of a group of cylinders (left and right arms, the left and right legs, and the total body are measured).

The advantages of BIA include its portability and ease of use, relatively low cost, minimal participant participation required, and safety (not recommended for participants with a pacemaker), thus making it attractive for large-scale studies. Validity of BIA is also influenced by sex, age, disease state, race or ethnicity [7], and level of fatness in which TBW and relative ECW are greater in obese individuals compared with normal-weight individuals; and type of BIA system in which SF-BIA was found to have better absolute agreement than multifrequency BIA when compared with dual energy X-ray absorptiometry (DXA) as a criterion measure for fat mass and FFM estimates in overweight and obese men [8]. A study [9] involving HIV-negative and HIV-positive breast-feeding South African mothers reported that multifrequency BIA or BIS provided values that compared favorably to values obtained by dilution technique for TBW, FFM, and fat mass whereas BMI did not.

By differentiating between ECW and ICF spaces, BIS can provide an estimate of body cell mass (BCM) [5]. In normal-weight persons, there is reasonable evidence to conclude that BIS can accurately measure TBW and ECW [10,11]. In a heterogeneous study sample (Hispanic, black, and white healthy adults), percentage body fat by BIS was strongly correlated with a 4C model [12•]. SF-BIA at 50 kHz and BIS are useful for estimating TBW in the healthy elderly and in cases of water imbalance, but both methods are less reliable in estimating ECW than the isotope dilution method particularly in conditions of fluid overload [13]. BIS estimates of FFM were underestimated in normal-weight individuals and overestimated in obese individuals compared with DXA [14•].

Dual energy X-ray absorptiometry

DXA systems provide whole-body and regional estimates of three main components: bone mineral, bone-free FFM, and fat mass and the DXA technique is accepted as a noninvasive measurement method that can be applied in humans of all ages. The radiation exposure from a whole-body DXA scan ranges from 0.04 to 0.86 mrem (instrument and individual’s size dependent), which is equivalent to between 1 and 10% of a chest radiograph. The advantages of DXA include good accuracy and reproducibility, and provides for the assessment of regional body composition and nutritional status in disease states and growth disorders. Disadvantages of DXA include a small amount of radiation; the scanning bed or stretcher has an upper weight limit and the whole-body field-of-view cannot accommodate very large persons. DXA estimates of fat mass are influenced by ‘trunk thickness’ with the error increasing as the individual’s trunk thickness increases. In longitudinal studies of persons who undergo significant changes in body composition, DXA measures can be biased [15].

DXA continues to be considered the gold standard technique for the diagnosis of osteopenia and osteoporosis. Assumptions associated with DXA include: the assumed constant attenuation (R) of fat ($R = 1.21$) and of bone mineral content; minimal effects of hydration on lean tissue estimates; lack of an effect of variations in regional (e.g., chest, leg, and arm) thickness on soft-tissue estimates; and that the fat content of the area being analyzed (nonbone-containing area or pixels) is comparable with the fat content of the unanalyzed area (bone-containing area or pixels) [16]. The limitations associated with these assumptions when these assumptions are not met include errors in the estimation of fat mass, lean, and bone in both regional and whole body values. In terms of measurement error, changes in body fatness (placement of lard or exogenous fat) impacts the accuracy of DXA measures of BMC and BMD [17]. In obese and nonobese children, the measurement error of DXA for fat mass was lower for obese than nonobese children, but for lean mass, was higher for obese than nonobese children [18]. Despite these limitations, DXA is a widely used method, owing to its ease of use, availability, and low-radiation exposure.

Quantitative computed tomography

Quantitative computed tomography (QCT) has the potential to measure true volumetric BMD and has the advantage of distinguishing between trabecular and cortical components but with substantially higher-radiation exposure than DXA. Peripheral QCT (pQCT) allows for the measurement of the compartment-specific density and geometry-based parameters of cortical bone although the usefulness of pQCT remains controversial, as few studies have used it [19]. Recently, three-dimensional high-resolution pQCT (HR-pQCT) measures important components of bone quality including BMD, microarchitectural morphology and bone mechanics [20••,21].

Dilution techniques

Water is an important constituent in the body. Changes in the body's TBW will impact body composition, especially when body composition estimates are acquired on the basis of TBW assumptions. Deuterated (^{2}H), tritated (^{3}H), or oxygen-labeled (^{18}O) water can be used to determine TBW by dilution [2]. These isotope dilution techniques allow for the evaluation of fat mass and FFM in which it is assumed that the hydration of FFM is stable (i.e., TBW/FFM = 0.73). The tracer sodium bromide (NaBr) can be used for the measurement of ECW space. Administration of these tracers and collection of samples are easy but these methods are impractical for large-scale studies and studies in very small children, particularly newborns. Fat mass is calculated in the TBW method as body weight devoid of FFM. The hydration of FFM although regarded constant at 0.73 may be influenced by several health factors thus limiting its use for quantification of excess fluid [22•].

Air displacement plethysmography

The air displacement plethysmography (ADP) method for measuring body volume and hence fat mass is an alternative to the underwater weighing (UWW) method requiring no water submersion and therefore is better tolerated by individuals. ADP as determined by the BODPOD (Life Measurement Inc., Concord, California, USA) measures the volume of air displaced by the individual. Reliability was high for percentage body fat and body density in adults [23,24]. Davis *et al*. [25] reported that BODPOD's functional residual lung capacity measurement in healthy adults was both reliable and valid. When fixed amounts of water (1, 2, and 4 liter) were placed with an individual in the BODPOD, the ADP underestimated FFM and overestimated fat mass in the individuals [26•]. ADP compared favorably to UWW for body volume and density in spinal cord-injured adults [27]. Although there is a tendency for an overestimation of fat mass by ADP compared with DXA and 4C model, ADP is considered a valid measurement method in the healthy elderly [28]. Body volume and therefore body fat measures in infants (<6 months of age or <7 kg body weight) can be acquired using the PEAPOD (Life Measurement Inc., Concord, California, USA). In validation studies, the PEAPOD was found to have high reliability and accuracy for determining percentage body fat in infants and therefore this method is used for monitoring changes in body composition during infant growth in both the research and clinical settings [29••]. The principles of measurement are similar to the BODPOD. The advantages of the ADP methods include noninvasive, fast, no radiation exposure, and no individual sedation required.

Three-dimensional photonic scanner

The need for accurate measurements of body shape and body dimensions has resulted in the development and application of a digitized optical method to generate a three-dimensional (3D) photonic image of an object and individual. This approach generates values for total and regional body volumes and dimensions. Wang *et al*. [30] evaluated the accuracy of the three-dimensional photonic scanner (3DPS) system for the measurement of body volume, circumferences, lengths, and percentage body fat compared with UWW and tape measures. The values obtained with 3DPS were slightly but significantly greater than those obtained with UWW for body volume and those obtained with a tape measure for circumferences, but the values for percentage body fat were not significantly different between 3DPS and UWW. The values obtained with 3DPS were significantly greater than those obtained by UWW and a tape measure for clothed mannequins, but the values were not uniformly significantly different for the mannequin without clothing. The 3DPS system has been used to investigate the relationship between shape and BMI and to examine associations between age, sex, and shape in the UK National Sizing Survey [31••]. BMI was significantly associated with chest and waist in men and with hips and bust in women. In early adulthood, the sexes differed significantly in shape; however, these sex differences declined with increasing age. Whereas male shape remained highly stable throughout adulthood, upper body girths, particularly waist, increased in women, but thigh decreased. After adjustment for other girths, waist was significantly and inversely associated with height, particularly in men. Waist varied widely in both sexes for a given BMI value. The 3DPS system offers a novel approach for epidemiologic research into associations between body shape and health risks and outcome.

MRI and magnetic resonance spectroscopy

Imaging methods are considered to be among the most accurate approaches for the in-vivo quantification of body composition. Specifically, MRI and computed tomography (CT) allow for the estimation of adipose tissue, skeletal muscle, and other internal tissues and organs. Their primary application has been in quantifying the distribution of adipose tissue into visceral, subcutaneous, and more recently intermuscular depots [32], the application of these depots to understanding cardiovascular disease risk [33•], and the volumetric assessment of epicardial adipose tissue [34••,35]. A further application of MRI has been to dissect the FFM compartment for the quantification of specific high metabolic rate organs *in vivo* (e.g., liver, kidneys, heart, spleen, pancreas, and brain) with application to improving our understanding of resting energy expenditure [36] and as a diagnostic tool in cancer staging [37]. The limitations of MRI include high costs owing to scan acquisition and after processing of data, claustrophobic persons cannot be scanned, and large individuals cannot fit within field-of-view. Neither MRI nor CT is capable of accommodating very large persons (BMI >40 kg/m^2), as the field-of-view for most MRI scanners is limited to 48 × 48 cm. The latter is a significant limitation when the need arises to image persons before treatments such as bariatric surgery, which typically involves persons who have BMI’s greater than 40 kg/m^2.

Conventional MRI is not useful for determining lipids or water in skeletal muscle. Chemical shift imaging techniques have been developed that separate water and fat signals. Imaging techniques including proton magnetic resonance spectroscopy (^{1}H-MRS) and ^{31}P-MRS are being used to help elucidate the quantity of lipid in specific tissues with implications for better understanding precursors to the development of insulin resistance. ^{1}H-MRS quantifies lipid content in the liver and muscle at early stages of disease in adults and children. ^{1}H-MRS has also been used to compare intramyocellular lipid (IMCL) changes during exercise in adults and to report on age-related changes in IMCL [38,39••]. IMCL plays an important role in the study of metabolism *in vivo*. Therefore, a precise measurement of body fat distribution together with the quantification of ectopic fat deposition provides a powerful tool by which to determine, at an early stage, individuals at risk of reduced insulin sensitivity and development of type 2 diabetes [40]. Ectopic fat accumulation within and around the myocardial wall has been implicated in the pathogenesis of cardiovascular disease and type 2 diabetes in obesity. Myocardial fat percentage can be quantified in the septum by ^{1}H-MRS [41]. In young men with increased fatty liver measured by ^{1}H-MRS, fat was found to have accumulated in the epicardial area and despite normal left ventricular morphological features and systolic and diastolic functions, individuals had abnormal left ventricular energy metabolism [42••].

Quantitative magnetic resonance

The quantitative magnetic resonance (QMR) methodology has recently been developed for body composition measurement application in humans although it has been in use in small animals for a few years. The QMR system from EchoMRI (Echo Medical Systems, Houston, Texas, USA) uses the differences in the nuclear magnetic resonance properties of hydrogen atoms in organic and nonorganic properties to fractionate signals originating from fat, lean tissue, and free water [43]. Just one study [44••] to date has reported on the validity of the QMR compared with a 4C model for whole-body fat and lean mass measurements in humans. The findings were: QMR underestimated fat mass and overestimated lean mass; the extent of difference increased with body mass such that the SD of repeated measurements increased with increasing adiposity, from 0.25 kg (fat) and 0.51 kg (lean) with BMI less than 25 kg/m^2 to 0.43 and 0.81 kg, respectively with BMI more than 30 kg/m^2. This initial study has shown shortcomings in absolute accuracy and specificity of fat mass measures in humans. However, using canola oil and water for the purpose of simulating body composition changes in fat and lean tissues, respectively, the QMR detected accurately and with high precision the additional quantities. QMR provides a simple and noninvasive method for measuring body composition that is convenient for the individuals and can be performed quickly (<3 min).

Positron emission tomography

With the use of fluorodeoxyglucose positron emission tomography (FDG-PET) combined with CT, brown adipose tissue (BAT) depots have now been found in the supraclavicular, the neck regions, paravertebral, mediastinal, paraaortic, and suprarenal localizations in humans [45•] negating the commonly held belief that BAT is lost postnatally. BAT has the potential to be of metabolic significance for normal human physiology as well as to become pharmaceutically activated in efforts to combat obesity. The use and validation of the [^{18}F]FDG-PET method was reported [46] and provides depotspecific measurements of insulin-stimulated regional glucose uptake in subcutaneous and intraabdominal adipose tissue, and skeletal muscle. In abdominal obese persons, insulin-stimulated glucose uptake rate was found to be markedly reduced in skeletal muscle and in all fat depots, and these reductions were reciprocally related to the amount of intraabdominal fat.

Conclusion

Table 2 summarizes the advantages and disadvantages of the body composition measurement methods discussed in this review. The measurement of body composition allows for the estimation of body tissues, organs, and their distributions in living persons without inflicting harm. It is important to recognize that there is no single measurement method that allows for the measurement of all tissues and organs and no method is error free. Furthermore, bias can be introduced if a measurement method makes assumptions related to body composition proportions and characteristics that are inaccurate across different populations. The clinical significance of the body compartment to be measured should first be determined before a measurement method is selected, as the more advanced techniques are less accessible and more costly.

Acknowledgments

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Additional references related to this topic can also be found in the Current World Literature section in this issue (pp. 676-677).

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Table 1
Representative multicomponent models at the five-body composition levels

Level	Body composition model	Number of components
Atomic	BM = H + O + N + C + Na + K + Cl + P + Ca + Mg + S	11
Molecular	BM = FM + TBW + TBPro + Mo + Ms + CHO	6
	BM = FM + TBW + TBPro + M	4
	BM = FM + TBW + nonfat solids	3
	BM = FM + Mo + residual	3
	BM = FM + FFM	2
Cellular	BM = cells + ECF + ECS	3
	BM = FM + BCM + ECF + ECS	4
Tissue-organ	BW = AT + SM + bone + visceral organs + other tissues	5
Whole body	BW = head + trunk + appendages	3

AT, adipose tissue; BCM, body cell mass; BM, body mass; CHO, carbohydrates; ECF, extracellular fluid; ECS, extracellular solids; FFM, fat-free mass; FM, fat mass; M, mineral; Mo, bone mineral; Ms, soft-tissue mineral; SM, skeletal muscle; TBPro, total body protein; TBW, total body water. Reproduced with permission [2].

Table 2

The advantages and disadvantages of available noninvasive methods for measuring body composition in humans

Method	**Primary measurements**	**Advantages**	**Disadvantages**
BIA/BIS	TBW, extracellular and intracellular fluid spaces	Inexpensive, portable, simple, safe, quick	Population specific, poor accuracy in individuals and groups
DXA	Total body fat, lean mass and regional body fat and lean mass, bone mineral content and BMD	Easy to use, low radiograph radiation exposure, accurate for limb lean and fat	Bias: body size, sex, fatness, expensive equipment and specialized radiology technician required to operate
QCT	Specific regional bone density	High accuracy and reproducibility	High-radiation exposure, expensive equipment
Dilution techniques	TBW and extracellular fluid	Acceptable in all age groups, easy to administer isotopes	Inaccurate if diseases, expensive equipment and labor for analyses
Air displacement plythsmography	Total body volume and total body fat	Relatively high accuracy, fast	Reduced accuracy if used in disease states, expensive equipment
Three-dimensional photonic scanning	Total and regional body volume	Can accommodate extremely obese persons, easy to use, suitable for both research and clinical applications	Few scanners available thus far.
Quantitative magnetic resonance	TBW and total body fat	Easy to use, safe, fast	Expensive equipment, few systems available thus far
MRI/MRS	Total and regional adipose tissue (visceral, subcutaneous, and intermuscular), skeletal muscle, organs (liver, heart, kidney, pancreas, and spleen), lipid content in liver and muscle	High accuracy and reproducibility for whole-body and regional adipose tissue and skeletal muscle	Expensive

BIA, bioelectrical impedance analysis; BIS; bioimpedance spectroscopy; BMD, bone mineral density; DXA, dual energy X-ray absorptiometry; MRS, magnetic resonance spectroscopy; QCT, quantitative computed tomography; TBW, total body water.