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Body Composition Methods: Comparisons and Interpretation

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Abstract

The incidence of obesity in the United States and other developed countries is epidemic. Because the prevalence of comorbidities to obesity, such as type 2 diabetes, has also increased, it is clear there is a great need to monitor and treat obesity and its comorbidities. Body composition assessments vary in precision and in the target tissue of interest. The most common assessments are anthropometric and include weight, stature, abdominal circumference, and skinfold measurements. More complex methods include bioelectrical impedance, dual-energy X-ray absorptiometry, body density, and total body water estimates. There is no single universally recommended method for body composition assessment in the obese, but each modality has benefits and drawbacks. We present here the most common methods and provide guidelines by way of examples to assist the clinician/researcher in choosing methods appropriate to their situation.

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Introduction

The recent rise in prevalence of type 2 diabetes is concomitant with the sharp rise in obesity in the United States and other developed countries.[1,2] Changes in body composition that accompany the onset and progression of obesity have a dramatic impact on metabolism and insulin sensitivity. Adipose tissue is postulated to be a key factor in regulating whole body lipid flux, thus modulating lipid and glucose homeostasis.[3] Given the role of fat and lean tissue in lipid metabolism and insulin resistance, it is clear that assessing the body's tissue composition is an important part of the management of the diabetic patient. We provide here the most common methods for assessing body composition, including anthropometry, body density, and dual-energy X-ray absorptiometry (DXA).

The human body can be quantified at several levels, depending on clinical concerns. Body composition can be assessed at the atomic level with the basic elements of carbon, calcium, potassium, and hydrogen; at the molecular level by amounts of water, protein, and fat; at the cellular level with extracellular fluid and body cell

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Abbreviations: (BIA) bioelectrical impedance analysis, (BMI) body mass index, (CDC) Centers for Disease Control and Prevention, (CT) computed tomography, (DXA) dual-energy X-ray absorptiometry, (FFM) fat-free mass, (MRI) magnetic resonance imaging, (NCHS) National Center for Health Statistics, (NHANES) National Health and Nutrition Examination Survey, (TBW) total body water

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mass; and at the tissue level for amounts and distributions of adipose, skeletal, and muscle tissues. Analysis from the atomic through the cellular levels is with direct body composition methods such as neutron activation, isotope dilution, and total body counting. Criterion methods measure a property of the body, such as its density, or describe amounts and distributions of skeletal, muscle, and adipose tissues via X-ray or magnetic imaging techniques. Criterion methods include densitometry, computed X-ray tomography (CT), magnetic resonance imaging (MRI), and DXA. Indirect methods, including anthropometry and bioelectrical impedance analysis (BIA), provide estimates or indices of body composition based on results from direct or criterion methods.[4] Indirect methods depend on biological interrelationships among direct or criterion measured body components and tissues and their distribution among normal individuals.[4] As a result, indirect methods tend to have larger predictive errors than direct methods and are affected by sample specificity and disease conditions.[5]

The following methods and associated equipment are readily available to the researcher or clinician to assess fatness and other components of body composition.[6,7] Further details on specific aspects of body composition methodology, underlying theories, and general applications, equipment, and analytical techniques can be found in several excellent texts.[6–8] Those interested in specific aspects of body composition assessment should consult these references.

It should be noted that all body composition methodologies are based on assumptions regarding the density of body tissues, concentrations of water and electrolytes, and/or biological interrelationships between body components and body tissues and their distributions among healthy individuals. Similar assumptions do not exist for obese persons or those with chronic disease, whose metabolic and hormonal problems, together with associated comorbid conditions, alter the underlying assumptions, interrelationships, and validity of body composition methods.[9] In addition, the application of body composition technology is limited among most obese adults and many older obese children because their bodies exceed the limitations of the available equipment. As a result, epidemiological and national obesity prevalence data are not based completely on direct measures of body fatness because of the difficulty of collecting such data during health surveys from sufficient numbers of obese individuals. Likewise, it is difficult to monitor and treat obesity without an easily acceptable assessment method or index and a reference population.

Indirect Methods

Anthropometry

Anthropometric measurements are the most basic method of assessing body composition.[4] Anthropometric measurements describe body mass, size, shape, and level of fatness. Because body size changes with weight gain, anthropometry gives the researcher or clinician an adequate assessment of the overall adiposity of an individual. However, the associative power among anthropometric measures and indices is altered as weight is gained or lost.[10]

Standardized anthropometric techniques are necessary for comparisons between clinical and research studies, and video and text media describing these techniques are available.[11–13] Those interested in using anthropometric equipment and methods should consult these resources.

Weight, Stature, and Body Mass Index (BMI). Body weight is the most frequently used measure of obesity. In general, persons with high body weights typically have higher amounts of body fat. A variety of scales are available for measuring weight, and these should be calibrated regularly for accurate assessments of weight. Changes in weight correspond to changes in body water, fat, and/or lean tissue. Weight also changes with age in children as they grow and in adults as they accumulate fat. However, body weight taken without other measures of body size is misleading because a person's weight is highly related to stature (i.e., tall people are generally heavier than short people). Stature is measured easily with a variety of wall-mounted equipment. Additional methods have been developed for predicting stature when it cannot be measured directly, e.g., for the handicapped or mobility impaired.[14,15]

One way to overcome the lack of specificity in body weight is to use the body mass index. BMI is a descriptive index of body habitus that encompasses both the lean and the obese[16] and is expressed as weight divided by stature squared (kg/m^2). A significant advantage of BMI is the availability of extensive national reference data and its established relationships with levels of body fatness, morbidity, and mortality in adults.[16] BMI is particularly useful in monitoring the treatment of obesity, with a weight change of about 3.5 kg needed to produce a unit change in BMI. In adults, BMI levels above 25 are associated with an increased risk of morbidity and mortality,[17] with BMI levels of 30 and greater indicating obesity.[18] In children, BMI is not a straightforward index because of growth. However, high BMI percentile levels

based on Centers for Disease Control and Prevention (CDC) BMI growth charts and changes in parameters of BMI curves in children are linked to significant levels of risk for adult obesity at corresponding high percentile levels.[19,20] The use of BMI alone is also cautioned in athletes and persons with certain medical conditions (e.g., sarcopenia) where body weight may be altered significantly by changing proportions of muscle and fat masses.

Abdominal Circumference. Obesity is commonly associated with increased amounts of intra-abdominal fat. A centralized fat pattern is associated with the deposition of both intra-abdominal and subcutaneous abdominal adipose tissue.[21] It should be noted that abdominal circumference is an imperfect indicator of intra-abdominal adipose tissue, as it also includes subcutaneous fat deposition, as well as visceral adipose tissue. This does not preclude its usefulness, as it is associated with specific health risks.[22,23] Persons in the upper percentiles for abdominal circumference are considered obese and at increased risk for morbidity, specifically type 2 diabetes and the metabolic syndrome, and mortality.[24,25] There has been a steady increase in the prevalence of high abdominal circumference in the general population from 10 to 20% in the 1960s to between 40 and 60% in the year 2000.[26] Circumferences of other body segments such as the arm and leg are possible,[11] but there are few reference data available for comparative purposes. Furthermore, the calculation of fat and muscle areas of the arm is not accurate or valid in the obese.

The ratio of abdominal circumference (often referred to incorrectly as "waist" circumference) to hip circumference is a rudimentary index for describing adipose tissue distribution or fat patterning.[27,28] Abdomen-to-hip ratios greater than 0.85 represent a centralized distribution of fat. Most men with a ratio greater than 1.0 and women with a ratio greater than 0.85 are at increased risk for cardiovascular disease, diabetes, and cancers.[29,30]

Skinfolds. Skinfold measurements are used to characterize subcutaneous fat thickness at various regions of the body, but it should be noted that they have limited utility in the overweight or obese adult. The primary limitation is that most skinfold calipers have an upper measurement limit of 45 to 55 mm, which restricts their use to subjects who are moderately overweight or thinner. A few skinfold calipers take large measurements, but this is not a significant improvement because of the difficulty of grasping and holding a large skinfold while reading the caliper dial. The majority of national reference data available are for skinfolds at the triceps and subscapular locations. The triceps skinfold varies considerably by sex and can reflect changes in the underlying triceps muscle rather than an actual change in body fatness. Skinfolds are particularly useful in monitoring changes in fatness in children because of their small body size, and the majority of fat is subcutaneous even in obese children.[31,32] However, the statistical relationships between skinfolds and percent or total body fat in children and adults are often not as strong as that of BMI.[33] Also, the true upper distribution of subcutaneous fat measurements remains unknown because most obese children and adults have not had their skinfolds measured.

Bioelectric Impedance Analysis

The analysis of body composition by bioelectrical impedance produces estimates of total body water (TBW), fat-free mass (FFM), and fat mass by measuring the resistance of the body as a conductor to a very small alternating electrical current.[34,35] Bioelectrical impedance analyzers do not measure any biological quantity or describe any biophysical model related to obesity. Rather, the impedance index [stature squared divided by resistance (S^2/R) at a frequency, most often 50 kHz] is proportional to the volume of total water and is an independent variable in regression equations to predict body composition.[36–38] Bioelectrical impedance analyzers use such equations to describe statistical associations based on biological relationships for a specific population, and as such the equations are useful only for subjects that closely match the reference population in body size and shape. BIA has been applied to overweight or obese samples in only a few studies[39,40]; thus, the available BIA prediction equations are not necessarily applicable to overweight or obese children or adults. The ability of BIA to predict fatness in the obese is difficult because they have a greater proportion of body mass and body water accounted for by the trunk, the hydration of FFM is lower in the obese, and the ratio of extracellular water to intracellular water is increased in the obese.[39,41]

Bioelectrical impedance analysis validity and its estimates of body composition are significant issues even for normal weight individuals. BIA is useful in describing mean body composition for groups of individuals, but large errors for an individual limit its clinical application, especially among the obese. The large predictive errors inherent in BIA render it insensitive to small improvements in response to treatment.[42] Commercial bioelectrical impedance analyzers are popular and widely available to the public, but it is important to remember that these units contain all of the problems associated

with this methodology. Recent BIA prediction equations have been published[43] along with body composition mean estimates for non-Hispanic whites, non-Hispanic blacks, and Mexican-American males and females from 12 to 90 years of age.[44] However, these equations are not recommended for obese individuals or groups.

Direct Methods

Total Body Water

Total body water is easy to measure because it does not require undressing or any real physical participation. Water is the most abundant molecule in the body, and TBW volume is measured by isotope dilution. Water maintains a relatively stable relationship to FFM; therefore, measured water/isotope-dilution volumes allow prediction of FFM and fat (i.e., body weight minus FFM) in normal weight individuals. As with the other methods mentioned earlier, the TBW method is limited in the obese. The major assumption is that FFM is estimated from TBW based on an assumed average proportion of TBW in FFM of 73%, but this proportion ranges from 67 to 80%.[44,45] In addition, about 15 to 30% of TBW is present in adipose tissue as extracellular fluid, and this proportion increases with the degree of adiposity.[46] These proportions tend to be higher in women than in men, higher in the obese, and therefore produce underestimates of FFM and overestimates of fatness.[41] Importantly, variation in the distribution of TBW as a result of disease associated with obesity, such as diabetes and renal failure, affects estimates of FFM and TBF further.[47]

Total body water is a potentially useful method applicable to the obese but there are details that need to be considered. The several analytical chemical methods used to quantify the concentration of TBW (and extracellular fluid) have errors of almost a liter. Equilibration times for isotope dilution in relation to levels of body fatness are unknown because, theoretically, it might (and should) take longer for the dilution dose to equilibrate in an obese person as compared with a normal weight individual. Also, a measure of extracellular space is necessary to correct the amount of FFM in an obese person.[46] Such data could also be very useful in the treatment of end-stage renal disease.

Total Body Counting and Neutron Activation

In addition to total body water, two other direct methods of body composition assessment are available to the researcher/clinician: total body counting and neutron activation. Total body counting (also called whole body counting) measures the amount of naturally radioactive potassium 40 (40K) in the body. Because potassium is found almost entirely within cell bodies, measuring potassium can provide an estimate of body cell mass. Fat-free mass can then be estimated once total body potassium is known, assuming a constant concentration of potassium in FFM.[48] There are only a few of the detectors required for this technique currently in use in the United States, which precludes its use in most research. For further details regarding total body counting, readers are encouraged to consult Ellis.[48]

Neutron activation techniques have been reported to be highly accurate for tissue-specific body composition,[49] with a typical body scan occupying up to 1 hour. After subject exposure to a neutron field, gamma output can be measured as the cell nucleus relaxes and goes back to its pre-exposed state. Gamma output can be measured immediately upon activation ("prompt gamma neutron activation") or at a somewhat delayed period ("delayed gamma neutron activation"). Using this technique, many elements in the body can be measured, including carbon, nitrogen, sodium, and calcium.[48] Body nitrogen quantified by this method has been used to predict the amount of protein in the body to further analyze components of FFM.[50] A significant concern with this technique is that it involves high levels of neutron radiation exposure and therefore has not been used in large-scale population research.

Criterion Methods

Body Density

Hydrodensitometry (commonly called "underwater weighing") is a technique that estimates body composition using measures of body weight, body volume, and residual lung volume. Historically, body density was converted to the percentage of body weight as fat using the two-compartment models of Siri[45] or Brozek *et al.*,[51] but more recently, a multicompartment model is used to calculate body fatness.[52] The multicompartment models combine body density with measures of bone density and total body water to calculate body fatness[43] and are more accurate than two-compartment models.

Hydrodensitometry is highly reliant upon subject performance. This is particularly problematic in children or obese subjects because it is difficult, if not impossible, for them to submerge completely under water. Weight belts reduce buoyancy, but cannot compensate for all aspects of performance problems.

Air displacement plethysmography[53–55] works under many of the same assumptions as hydrodensitometry and affords some advantages over it (e.g., subject compliance does not involve breath holding or aversions to being under water). Air displacement devices do make assumptions regarding tissue density, much like other methods of body composition assessment.[8] Thus, caution should be taken when applying these methods to persons suspected to have alterations in the density of fat-free mass tissues, such as the elderly and children.[8] Unfortunately, body density methodologies (hydodensitometry and air displacement plethysmography) are rarely applied to obese subjects, as most overweight and obese persons are reluctant to put on a bathing suit and participate in body density measurements.

Dual-Energy X-ray Absorptiometry

Dual energy X-ray absorptiometry is the most popular method for quantifying fat, lean, and bone tissues. The two low-energy levels used in DXA and their differential attenuation through the body allow the discrimination of total body adipose and soft tissue, in addition to bone mineral content and bone mineral density. DXA is fast and user-friendly for the subject and the operator. A typical whole body scan takes approximately 10 to 20 minutes and exposes the subject to <5 mrem of radiation. Mathematical algorithms allow calculation of the separation components using various physical and biological models. The estimation of fat and lean tissue from DXA software is based on inherent assumptions regarding levels of hydration, potassium content, or tissue density, and these assumptions vary by manufacturer.[56,57]

Dual energy X-ray absorptiometry estimates of body composition are also affected by differences among manufacturers in the technology, models, and software employed, methodological problems, and intra- and intermachine differences.[56,58] There are physical limitations of body weight, length, thickness and width, and the type of DXA machine, i.e., pencil or fan beam. Most obese adults and many obese children are often too wide, too thick, and too heavy to receive a whole body DXA scan, although some innovative adaptations have been reported.[59] Additionally, some studies indicate that DXA may not be as reliable in extreme populations, including the obese.[60] Although specific manufactures and models have been tested and found to have certain biases that may overestimate FFM,[61] DXA is a convenient method for measuring body composition in much of the population and is currently included in the ongoing National Health and Nutrition Examination Survey (NHANES).

Computed Tomography and Magnetic Resonance Imaging

The other imaging modalities, such as CT and MRI, are gaining in popularity and represent important new techniques for body composition assessment. Unfortunately, these methods are often not practical for obese individuals. CT is able to accommodate large body sizes but has high radiation exposures and, as such, is inappropriate for whole body assessments, but it has been used to measure intra-abdominal fat. In many instances, MRI is not able to accommodate large body sizes but can be used for whole body assessments in normal weight or moderately overweight individuals. Both these methods require additional time and software to provide whole body quantities of fat and lean tissue.

In addition to its imaging capabilities, CT can also distinguish body tissues based on signal attenuation. This technique is especially useful for assessing non-adipose fat or the fatty infiltration of skeletal muscle or liver tissue.[62,63] These lipid stores may play a substantial role in the development of insulin resistance in type 2 diabetes patients.[64]

Reference Data

Body composition references are available from national survey data collected by the CDC National Center for Health Statistics (NCHS). These surveys are recognized for their multiple methods of data collection, including interviews, physical examinations, physiological testing, and biochemical assessments from large, representative samples of the U.S. population. Mean values and distribution statistics for stature, weight, selected body circumferences, breadths, and skinfold thicknesses and plots of means for TBW, FFM total, and percent body fat of children and adults from the third National Health and Nutrition Examination Survey (NHANES III) are available by gender and race.[44] More recent data are available on the CDC NCHS site (*www.cdc.gov/nchs/*). These body composition measurements follow techniques for corresponding measurements in the "Anthropometric Standardization Reference Manual"[11] and are similar across other national surveys.

Conclusion

The ability to monitor, diagnose, and treat obesity and associated comorbidities such as type 2 diabetes is an important aspect of both research endeavors and clinical patient care. This ability is limited, in part, by our capacity to assess the tissue composition of the body, specifically

body fatness. There is no universally recommended method for measuring or quantifying obesity, and current methods are limited in their utility in the obese for a variety of reasons. The growing epidemic of obesity in the United States and other developed countries creates a pressing need for an accurate assessment of body composition in this heavier population. As we have noted, current methods are powerful tools for assessing normal weight and overweight individuals, but there remain significant shortcomings for each. With knowledge of the utility and limitations of available methods, the clinician or researcher must choose the best-suited method for assessing body composition based on the patient population and specific characteristics desired for interpretation.

As the questions under consideration vary across research or clinical settings, criteria for choosing a method for body composition assessment must be tailored to the given situation. For example, weight loss is a common clinical recommendation for the type 2 diabetic patient in order to reduce comorbid conditions.[10] The researcher/clinician following serial changes in body composition during such a weight loss program will want to choose a method distinguishing between weight lost as fat versus weight lost as muscle and/or bone. Anthropometry may not be the first choice for this situation, as this method cannot make tissue-specific inferences. Direct methods such as those described may provide a good option as each tissue can be evaluated individually. Additionally, criterion methods such as DXA or other imaging techniques (CT, MRI) would also prove useful in these circumstances. In weight change studies, the clinician/researcher must also consider methods minimizing error due to hydration and, therefore, may want to avoid BIA techniques, which are heavily reliant on assumptions of hydration.

Similarly, investigations of individuals with end-stage renal disease, experienced by many type 2 diabetic patients, may also want to avoid body composition assessments reliant upon assumptions of hydration, as the fluid/electrolyte balance is likely to be altered significantly in these patients.[47] In these types of studies the timing of body composition assessments also becomes important. If follow-up assessments are important to the research/clinical question, the best time to make these assessments is during the "dry" stage, after the patient is off dialysis.[47] This timing is also important for comparisons between individuals as well. It is important to note that under these conditions most body measurements (anthropometry and circumferences) are valid, as is DXA, although caution should be used when evaluating persons known to have altered hydration.

As not all body composition investigation occurs within a single office or laboratory setting, additional criteria for choosing a body composition assessment method include understanding the available resources. For example, a field researcher traveling to remote locations for assessments will want to choose a method involving only portable, or highly mobile, equipment. This type of work would, therefore, rely heavily on indirect methods such as anthropometry, skinfolds, circumferences, or a combination thereof. However, large-scale studies coordinating multiple research centers or clinics for data collection will want to consider methods that involve equipment producing consistent results across centers. An example of this type of study is the NHANES, where DXA and BIA are used to establish population norms and reference samples.

Because obesity presents several challenges in body composition assessment, multiple assessment techniques used in combination may afford the investigator/clinician greater power in examining and characterizing adiposity in these populations, e.g., the use of anthropometry in conjunction with bioelectrical impedance. Improvements in, and the addition of new, technology and body composition techniques will continue to improve our ability to assess and monitor individuals suffering from consequences and comorbidities associated with obesity.

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