REVIEW ARTICLE *Nutrition* Vol. 14, No. 3, 1998

Body Composition Measurement: A Review of Hydrodensitometry, Anthropometry, and Impedance Methods

DAVID BRODIE, PHD,* VICKI MOSCRIP, MSC, HDCR,† AND ROB HUTCHEON, MSC‡

*From the *Department of Movement Science and Physical Education; the †Department of Medical Imaging; and the ‡Department of Medicine, University of Liverpool, Liverpool, United Kingdom*

Date accepted: 5 July 1997

ABSTRACT

Human body composition is an expression of genetic and nutritional factors. It can change as a consequence of exogenous influences such as training, disease, or diet and is therefore of particular interest to nutrition professionals. Two of the main methods of estimating body composition in this review (hydrodensitometry and anthropometry) have been in use for decades, but the third method (bioelectrical impedance) is more recent. The procedure, theoretical basis, assumptions, standard error of estimates, and comparisons with other techniques are presented for each of the three methods. References to general and specific populations are presented that illustrate regression equations for different ages, ethnic groups, and gender. The advantages and disadvantages of the three methods are reviewed with reference made to the alternative compartment models. Other methods (DEXA, infrared interactance) are briefly reviewed. *Nutrition* 1998;14:296–310. ©Elsevier Science Inc. 1998

Key words: body composition, hydrodensitometry, anthropometry, electrical impedance, DEXA, infrared interactance

INTRODUCTION

Body composition is of interest to nutritionists because of the impact that nutritional status, specific diet, exercise, disease, and genetics can have on the major components of the human body. These components can be considered at atomic, molecular, cellular, tissue-system, and whole body levels. As direct measurement in vivo is not possible in humans, a series of indirect estimates of body constituents have been developed. Most interest has been directed at the two-compartment model, which divides the body into fat mass and fat-free mass (FFM), largely because fat proportion is a major issue in health. However, with the advent of chemical and isotope-based methods, it has become possible to subdivide the FFM into water, mineral, and protein constituents.[1] Alternatively, the use of imaging methods has enabled a different subdivision of body compartments into fat, muscle, bone, and other soft tissue.[2]

A combination of magnetic resonance imaging (MRI) and anatomic dissection has produced serial transverse images every 1 mm through the length of the human body. Such images are internationally available on the Internet,[3] therefore providing anatomy students, teachers, and body composition scientists with a database of unparalleled precision. Such detailed information is currently only available on one male and one female subject and the cost of producing such material is, for most scientists, prohibitive. The issues of cost, availability, access, validity, portability, ethical acceptability, and intervention need to be considered in body composition research. This review will make reference to a range of methods but will concentrate on three procedures that have merit either in an epidemiological context (anthropometry and electrical impedance) or as a common criterion method (hydrodensitometry). As each of these methods is used to estimate fat mass and FFM components only, it is important to define these terms, especially as fat and lipid are often used interchangeably. Fat is the triacylglycerol family of chemical compounds, whereas lipid is a more general term including other compounds such as glycerophosphatides and sphingolipids.[4] In the chemically based two-component model, the fat compartment includes all lipids (ether-extractable) with the FFM comprising all the remaining constituents.

HYDRODENSITOMETRY

Hydrodensitometry or underwater weighing is essentially a method to measure body volume. It is regarded as the most reliable of available techniques for the estimation of body

---

Correspondence to: David Brodie, PhD, The University of Liverpool, Department of Movement Science and Physical Education, Liverpool, L69 3BX UK.

Nutrition 14:296–310, 1998

ELSEVIER
0899-9007/98/$19.00
PII S0899-9007(97)00474-7

density and alternative procedures are often judged and validated against this procedure. Accepting the assumptions stated later, it is recognized as a valid method of percentage body fat estimation. It usually involves the use of a specially constructed tank in which the subject is seated on a suspended chair or frame. Because the subject is required to exhale when submerged it requires a high degree of water confidence. This excludes approximately one-third of middle-aged women[5] and if the top of the tank is not near floor level it is extremely difficult for excessively obese, pregnant, elderly, or disabled subjects. Archimedes' principle is applied by comparing the mass of a subject in air and under water. This involves a sensitive and continuous measurement of underwater mass for which a single or multiple load cell configuration linked to a computer is ideal, as the value will fluctuate due to movement and level of exhalation. Total expiration is necessary, which takes several trials, and account is taken of the remaining residual volume, water temperature, and an estimate of gut volume. For those unable to access an appropriate tank, it is possible to construct a suitable frame within a swimming pool. Autopsy scales have been used as an alternative to electronic weighing methods, but the observer has to make rapid judgements as the scale fluctuates around a mean value. The technique has been described fully elsewhere.[6–8]

Practical considerations for this method include when and how to measure residual volume, what allowance to make for the volume of gas in the gut, and the effect of pretest nutrition and exercise. The residual gas volume accounts for about 2% of the submerged volume, and the accuracy of this value becomes critical to the calculation, where a very small change of density produces a much larger change in the predicted percentage of body fat.[9] There is an appreciable day-to-day biological variation of residual volume in any given subject and this can change the estimated body fat content by as much as 1%.[10,11] Considerable controversy occurs over whether or not to measure the residual volume while in the tank or separately. Submerging the body has been shown by some authors to increase residual volume[12,13] and by others to decrease the residual volume.[14–19] Immersion was also found by several authors to make no difference in residual volume.[20–25] The actual method depends largely on the facilities available and includes nitrogen washout[8] and oxygen dilution.[26] If residual volume cannot be measured by such direct methods Mayhew et al. (personal communication) recommend estimates from 24% of vital capacity[8] or from the anthropometric method of Polgar and Promadht.[28] Garrow et al.[29] suggested that residual volume could be measured by combining a body water displacement method with an air displacement technique for the head using a plethysmograph. This method eliminates the need for total submersion of the subject. Although the equipment is more complex than that required for hydrodensitometry, it does not require the additional equipment for measuring residual volume. The procedure requires minimal subject cooperation due to the fact that the patient stands in water to the neck level and the volume of air in the lungs and gastrointestinal (GI) tract is measured by observing the pressure changes produced by a pump of known stroke volume. Standard deviations of ± 0.3 kg were reported when replicate measures were made by this method.

The volume of gas in the intestine is usually included in the calculation as being 100 mL[30] but should be increased for large adults and decreased for children. Measurements are most reproducible if taken in the fasting state. The prior consumption of food can change the estimated body fat content by up to 1%,[31] and recent ingestion of carbonated drinks will also change the intestinal estimate.[32] When converted into body fat estimation this can increase the error by 0.5%. Food consumption has doubled this effect on body fat estimation. Changes will similarly be caused by hyperhydration[31] and dehydration.[33] These effects will become relevant if immediate previous activity caused fluid loss or when high fluid retention occurs during premenstruation. As a minimum, testing should be undertaken several hours after a meal, with the subject defecating and urinating immediately prior to measurement.[34]

Once body volume is established, whole body density is estimated from the mass in air (M_a, kg) and the weight while submerged (W_s, kg), with allowances being made for residual gas volume in the lungs (V_r) and GI gas (100 mL). Density is then calculated using the following equation

$$D_b = M_a/\{[W_a - W_s/D_w] - V_r + 0.1\}V$$

where D_w is the density of water at the temperature of submersion.

The calculation of percentage body fat from body density measures is based on the assumption that the body is composed of two homogenous components—fat and fat-free tissue—each having consistent densities. The main advantage of the two-component model is that it allows measurement of the only constituent of the fat-free body from which relative fat and fat-free body content can be estimated. Where certain assumptions hold, this approach offers a practical way to establish fat and fat-free body content. The main limitations of the two-component model approach are that separate estimates of various components of the body such as muscle and bone are not made. Individual prediction errors of fat content can be substantial, and estimates of body composition in populations other than young adult males may under- or overestimate fat content. The use of the two-component model has led to a lack of research in the development of new methods and limited the potential usefulness of various laboratory methods in estimating body composition in different populations. There has been a move away from the two-component model toward three- or four-component models with the aim of improving the prediction of body fat from body density. It is therefore necessary that new methods for accurate estimation of fat, fat-free body, and muscle and bone content are continually developed and evaluated.

Body density, however, is not the preferred value for nutritionists and other health professionals working with body composition. Percentage body fat is a measure to which more people can relate and if the density of fat and lean were consistently 0.90 and 1.1 g cm^{-3}, respectively,[35] the conversion would be relatively simple. The average value of studies that measured these densities[36–38] was 0.9168 g cm^{-3} for fat and 1.0997 g cm^{-3} for lean tissue. Even this fails to account for more individual variations such as the potential for athletes to have denser bone and muscle,[39,40] osteoporosis in the elderly,[41] and different bone mineral content in preadolescents.[42]

A variety of equations are available to estimate fat from body density.[38,43–45] The most commonly used of these are those of Brozek et al.[44]

$$\%\ \text{body fat} = \left(\frac{4.57}{D} - 4.142\right) \times 100$$

and Siri[46]

$$\%\ \text{body fat} = \left(\frac{4.95}{D} - 4.5\right) \times 100$$

The equation developed by Brozek et al.[44] for the conversion of body density to body fat was based on the chemical composition of reference man. The equation was developed from cadaver chemical analysis and was proposed to be used in a young, nonathletic, adult male population. Although the original equation has not been cross validated, it has been used in many research studies. Since its development, this equation has subsequently and frequently been applied to various populations including children, the elderly, women, athletes, and various racial groups. Bones are less dense in children, women, and older subjects of both sexes, which leads to an overestimation of body fat. Lohman[47] discussed the need to limit the use of the Brozek equation and replace the concept of reference man with population specific reference bodies leading to additional development of population specific equations. This would enable more accurate estimates of fat content from body density in these populations.

Body density is converted to a corresponding percentage of body fat based on the assumption that the body is composed of two homogenous compartments—fat and fat-free tissue—each with a constant density. However, in reality, body fat comprises a complex mixture of glycerides, sterols, phospholipids, and glycolipids. Some of these constituents are more labile than others and, therefore, the average density of fat varies between individuals and also within a given individual at different times. These complications are usually ignored in densitometric calculations.[9]

As long as the assumptions implicit in these calculations are recognized then nutritionists could present body composition values in the form of percentage fat. However, if relative values are needed it seems logical to retain the body composition data from hydrostatic weighing as densities.

The validity of the underwater weighing technique has been extensively reviewed, including the biological and technical sources of error.[48–51] The several sources of biological variation can be compounded by technical errors in the body density measurements. An estimate of the expected degree of association between fat content and density can be made by combining the technical and biological sources of variation. Biological error associated with estimating the percentage fat from body density is associated with the variability in the density and composition of the fat-free body. This error must then be added to the error associated with measuring or predicting body density to give the total error in estimation of the true percentage fat. The error associated with measuring or estimating body density is only part of the problem and the accuracy in determining body fat is ultimately limited by biological variation in the fat-free body. Lohman[42] suggested that hydrostatic weighing techniques, when used to assess the percentage of body fat, may have a standard error of estimate (SEE) as high as 2.7%, primarily because of variations in the fat-free density within specific populations.

The main sources of technical errors that have been identified in measurement of body density include variation in residual lung volume, which appears to contribute the greatest source of error, and smaller amounts of error from combined factors of variation in body mass, underwater weighing, and measurement of the water temperature.[48]

The hydrostatic method remains a somewhat fallible criterion method. Signs of this fallibility have been attributed to the fact that simple indices of obesity such as total body mass and circumference measurements have shown closer correlations with skinfold measurements than percentage body fat estimated by the hydrostatic technique.[52] The technical and biological assumptions inherent in this method clearly indicate that they are most likely to be violated at the extremes of fat percentages. Therefore, this method is most appropriate for segments of the population that do not exhibit the extremes, especially the excessively obese. Roche et al.[53] provide a review on the practicalities of estimating body volume by underwater weighing.

The technical concerns of the hydrostatic weighing procedure, not the least water confidence, have been reduced by alternative body volume measurement such as acoustic plethysmography and air displacement. Acoustic plethysmography[54–56] has been used predominantly in pediatric research. Air displacement has also been used in infants,[57] babies,[58] and adults.[59–61] The procedure described by Gnaedinger et al.[59] was abandoned because of high sources of error from lack of control over temperature, pressure, and relative humidity in the enclosed chamber. Gundlach and Visscher[61] controlled isothermal conditions but in doing so made the procedure impractical for most subjects. More recently,[62] a method has been described that has overcome most of these problems. The BOD POD Body Composition System, which uses the relationship between pressure and volume to derive the body volume of a subject seated in a fiberglass chamber, is described in detail for inanimate objects.[62] It produced an average coefficient of variation (CV) of 0.026% over 2 d, with a SEE[62] of 0.004 L for volumes in the range 25–100 L. This new air displacement plethysmograph was compared with hydrostatic weighing in 68 adults[63] and was shown to be highly reliable and valid as a method of estimating percentage body fat. The mean difference in percentage fat (BOD POD $-$ hydrostatic weighing) was -0.3 ± 0.2 (SEM). An advantage of this method of determining body composition is that it is quick and relatively simple to operate, and able to measure populations to which hydrostatic weighing is not appropriate such as the obese, elderly, and disabled.

Hydrodensitometry has been the experimental basis for the two-component model of body composition assessment. Accurate estimates of percentage body fat can be expected provided the assumptions of proportions and densities are satisfied.[64] In subjects whose fat-free body density differs from the assumed value of 1.10 g/mL, then the two-component model will be less satisfactory. The use of isotope dilution to measure the water compartment, dual-energy x-ray absorptiometry to measure mineral content and neutron activation analysis for protein has permitted the quantification of the subdivisions of the fat-free component. This has permitted the density of subgroups such as different races, levels of body fatness, gender, and physical activity levels to be estimated more accurately, largely as a result of the varying proportions of mineral and water. Multicomponent models not only refer to chemical constituents, but can also be used to describe anatomical models, molecular models, and fluid metabolic models. A more detailed discussion of multicomponent models is found in Heyward and Stolarczyk[65] and Heymsfield et al.[66]

ANTHROPOMETRY

Anthropometric techniques for the estimation of body composition utilize measurements of skinfold thicknesses at various sites, bone dimensions, and limb circumferences. These are used in equations to predict percent body density, converted to body fat using the equations shown above. The use of skinfolds to predict body fat has become one of the most common laboratory and field anthropometric techniques in body composition and nutritional status assessment.[67] There have been numerous regression equations developed that use some combination of anthropometric measures as predictors of body density.[68] Most have used skinfold measures or some combination of skinfold and circumferences. Few have used circumferences only.

The main purpose of skinfold measurements is to estimate general fatness and the distribution of subcutaneous adipose tissue. The extent that the subcutaneous adipose layer reflects total body fat varies with age, gender, and population. This method operates on the assumption that subcutaneous adipose tissue is representative of the total body fat. This is not an unreasonable assumption but there will be individual differences which will invalidate the established regression equations. As the method relies substantially on a limited number of skinfold sites, any differences in adipose tissue distribution from the original validated equation will impact on the prediction. Therefore, any observed variation of adipose tissue distribution from the population originally used in the production of the regression equation should necessitate an alternative equation or method being used.

The accessibility of the subcutaneous fat layer and the noninvasive nature of skinfold measurement has led to many skinfold applications and derivations of formulae. These in turn have led to well over 1000 published articles that have dealt directly or indirectly with skinfold measurements. Numerous equations for the prediction of body composition have been developed, using skinfold measurements as part of the equation. There have been well over 100 equations developed that use skinfold measurements and other anthropometric dimensions in various populations ranging from athletic to sedentary and from children to the elderly.[69–75] Most of these formulae have led to estimates of body density, although some studies have attempted a direct prediction of body fat.[71–73,76] The problems associated in choosing an appropriate equation have been previously well documented. They have included excessive reliance on stepwise regression analysis, failure to consider the possible curvilinear relationship between total body fat and skinfold data, and failure to account for the effect of age on body fat distribution.[73,74]

Many of the skinfold prediction formulae developed are specific to a particular sample of the population, and are also dependent upon the age, sex, nutritional status, genetic background, and specialist activities.[77–79]

The most widely used equations are probably those of Durnin and Wormersley,[73] who tested various combinations of skinfolds to produce the following formulae for body density. These equations assumed a logarithmic relationship between obesity and the sum of bicep, tricep, suprailiac, and subscapular skinfolds. The equations met several of the earlier criticisms with regard to a fewer number of variables relative to the number of subjects; the intercorrelation of the individual skinfold reading and the curvilinearity of the relationship between density and subcutaneous fat.

Males 20–69 years

$$\mathrm{D} = 1.1765 - 0.0744(\log_{10} \textstyle\sum 4S)$$

Women 20–69 years

$$\mathrm{D} = 1.1567 - 0.0717(\log_{10} \textstyle\sum 4S)$$

where Σ is the sum of the tricep, bicep, superailiac, and subscapular skinfolds. The equation assumes a logarithmic relationship between this sum of skinfolds and adiposity.

As with many of the previous skinfold equations the variable predicted by those of Durnin and Womersley[73] is the body density rather than the percentage body fat. It is, therefore, possible for errors to occur in the calculation of predicted density and its subsequent interpretation as a fat percentage. This error of estimation has been reported to be ±3.5% in women and ±5% in men relative to the hydrostatic criterion method.[9] Shephard[9] also reported the importance of using age-specific equations because of the slope of the relationship decreasing with age.

The equations of Durnin and Womersley[73] and those of Jackson and Pollock[74] are said to be "generalized" because their development and application are from a wide range of ages and fatness. Durnin and Womersley[73] were the first to consider the development of equations that could be used with more varied populations. They published equations with a common slope but adjusted the intercept to account for aging. Jackson and Pollock[74] published generalized equations for males and females. They extended the concepts of Durnin and Womersley[73] and additionally overcame some of the limitations of population-specific equations. The equations of Jackson and Pollock[74] added age into the prediction equation to account for the potential changes in the ratio of internal to external fat and also bone density. In 1981, Lohman[48] extensively reviewed the relationship between skinfolds, body density, and fatness. He agreed with the need for such generalized equations but also stated the need for their cross-validation when applied to specialized samples. Lohman[48] formulated seven principles of cross-validation analysis including the use of comparable mean values and similar standard deviations for predicted and measured densities. It was also suggested that SEE should be reported rather than correlation coefficients because of the fact that correlation coefficients are apt to be affected by intersample variability of fatness whereas SEE is not. The other principles relate to the problems of nonlinearity of the relationship between skinfolds and body density and the need for large samples to cross-validate.

Differences in procedures and equipment selection may also contribute to systematic errors in cross-validation studies. Lohman et al.[47] showed that different caliper types may affect estimates. This problem was also addressed by Sinning and Wilson,[76] who agreed with Lohman for the need to standardize equipment. Sinning and Wilson[76] also evaluated the use of generalized equations for college-aged women. They showed that each equation had to be validated and evaluated on its own merits. In 1984, Thorland et al.[80] cross validated general curvilinear models as well as selected linear models. They also found, as did Sinning and Wilson,[76] that different curvilinear equations were not equally effective in estimating body density while some linear models were fairly accurate. These studies have all identified the need for cross-validation of such equations prior to their use on specialized samples.

Several authors also carried out log transformation of their skinfold data.[72,81] The main reasons for these transformations were skewing the data, measurement errors being greater for thicker skinfolds than for thin skinfolds, and experimentally skinfold measurements not linearly related to body density. Nonlinearity differs from sample to sample but is quite significant in the obese. It is, therefore, advisable to introduce such transformations when the population under study includes subjects of extreme body types.

The skinfold caliper has been the most frequent method of measuring subcutaneous adipose tissue thickness. The popularity of this techniques is attributed to the many advantages associated with its use. These advantages include the fact that it is a noninvasive and fairly pain-free technique and that the skinfold calipers are inexpensive, easy to maintain, and simple and convenient to use. They may be used in field testing as well as in the laboratory due to their portability and they do not require extensive training for reliable use. In order to ensure validity, proper procedures must be used when obtaining anthropometric measures. Potential sources of measurement error include caliper selection and tester reliability. Tester reliability includes inter- and intrameasurement error as well as the variance associated with selection of skinfold site. A major limitation associated with skinfold measurements is the failure to estimate simultaneously all possible sources of measurement error. Different caliper types and testers have been examined separately and it is these two major sources of error that may interact and give different degrees of error variance for different conditions.[82,83]

As with most body composition assessment techniques there are limitations associated with skinfold measurements, which may result in inappropriate estimates of the subcutaneous fat thickness and consequently total body fat. These limitations have been well documented and include factors such as the inability to palpate the fat/muscle interface and the difficulty in obtaining interpretable measurements in obese subjects.[84–86] Other problems include compression of the fatty tissue during measurement, the inability to control inter- and intrasubject variations and the fact that measurements may only be useful at certain sites.[48,87] Interoperator variability as well as the use of different types of calipers has also contributed to errors in measurement of the subcutaneous fat layer.[42]

With so many prediction equations available it is difficult to know which one to select. A full account of the merits of different equations is provided by Brodie[88]; the categories include generalized predication equations, population-specific prediction equations, equations for infants and children, and equations for athletes. The concept of population specific anthropometric regression equations for the estimation of body composition is well known and well documented. Regression formulae show that although they may meet suitable limits for reliability, their applicability to different samples is poor resulting in large errors in estimating individual values. The population specificity of body composition prediction equations can be traced largely to the use of homogenous samples that lack sufficient size. The validity of their findings rests on the assumption that for each population studied the composition of the fat-free body is similar. It is assumed that the density of the fat-free body is the same from one population to another. Womersley et al.[89] proposed that some of the differences associated with population-specific equations are due to the differences between males and females in their fat-free body density with females having a lower fat-free density. This led to the overestimation of fat content in females when the fat-free body was taken to be the same as males. Their application is, therefore, limited to specific subsamples. Validity coefficients between predicted and measured body density values range from $r = 0.72$ to 0.84 for women and 0.85 to 0.89 for men. Therefore, these formulae are said to be population specific and their use for predictive purposes must be questioned. Recently, generalized equations have been developed. This generalized approach uses large heterogeneous samples and builds a regression model to fit the data. The regression model accounts for age and the nonlinear relationship between skinfolds, fat, and body density. The major problem with population specific equations is their limited generalizability. The main advantage of the generalized approach is that one equation can replace several population-specific equations without a loss of prediction accuracy; they are valid for a greater range of age and body composition than population-specific ones. Most prediction equations are by the very nature of their data collection population-specific but scientific economy can be achieved by using generalized equations.[68] They have been cross-validated in males,[74] females,[90] and in athletes.[76,91] It is essential that equations using skinfold data are cross-validated on other samples from the same and other populations to determine its general applicability. It is not possible to be certain that equations developed on one sample will predict body density with the same degree of accuracy when applied to the data of a different sample. The cross-validation process involves testing prediction equations on samples other than the ones used in the initial derivation. This process will provide information regarding the true external validity of the equations. Several studies have compared their prediction equations with other samples and when the populations were similar in age, gender, and fatness, correlations and SEEs were found to be similar.[92–97] The strongest evidence in cross-validation of generalized equations with regard to their accuracy and validity appears to be provided by the standard error when the equation is cross-validated on the second sample. The closer the SEs are to each other the more accurate and valid is the equation. As well as reporting the SE, the SD of the predicted density value should also be reported. There is a relationship between SEE and the coefficient of determination (r^2). It involves knowing the standard deviation of the criterion variable, which for percent fat is often bigger in women, and the r^2 between the variables being measured. The SEE is calculated from the formula SEE (e.g., percentage body fat) $=$ SD $\sqrt{1.0 - r_2}$.[98] Therefore, for males with a mean and standard deviation for percent fat of 20.5 ± 7.1%, and a correlation between variables of 0.58, the SEE is 5.78%. Although SEEs are not provided for each component prediction model, Heyward and Stolarczyk[65] make the case strongly for their inclusion to evaluate the relative worth of a regression equation. Jackson et al.[90] caution the use of the generalized equations for women over 40 years of age. The validity of generalized regression equations was questioned by Norgan and Ferro-Luzzi,[99] as they found a statistically significant difference between five such equations. An alternative strategy was to combine data from other sources[70,100–102] into a single regression equation using the sum of triceps, abdomen, and subscapular skinfolds alone.

The development of population specific equations has shown that age and gender are important sources of body density variation.[70,103,104] The effect of age has been shown to be significant when individual differences in skinfold fat are statistically controlled.[74] Substantial gender differences in body density determined by hydrodensitometry have been reported in the literature.[105] Body density differences between men and women have largely been attributed to differences in fat patterning and distribution, internal to external fat ratios, and gender specific essential fat.[48,104] Fat patterning refers to differences in the anatomical placement of adipose tissue. The pattern of subcutaneous adipose tissue is known to exhibit large variations between individuals. Garn[106] maintained that women carried a greater proportion of subcutaneous fat than men, whereas Durnin and Womersley[73] came to the opposite conclusion. Research on population specific equations has shown that age, gender, and degree of fatness need to be taken into account when estimating body density from anthropometric variables. To provide valid estimates of body composition it is, therefore, essential that equations representative of the study sample are used.

Population-specific prediction equations have been produced for college students,[72,92,93,95,103,107,108] soldiers,[109,110] male youths,[111] boys and girls separately,[81,112] obese girls,[113] and premenarcheal and postmenarcheal girls.[114] Optimizing the regression equations have included such methods as stepwise regression,[115] maximum r^2 improvement,[116] and factor analysis.[117,118]

Equations have been specially produced for infants and children. Oakley et al.[119] showed greater fat thicknesses in newborn females compared with males and concluded that skinfold levels could be a valuable indication of nutritional status in neonates. Triceps and subscapular skinfolds have been shown to be adequate predictors in older boys[120] but not in girls. Older children have been studied by various researchers,[81,120–123] and Nelson and Nelson[124] found that the best predictor of fat was a combination of triceps and subscapular. Two skinfolds were also found to be good estimates of body density in 8- to 11-y olds[122] but methodological and biological variability in children still requires additional examination.

In athletes, regression equations have been established for distance runners,[125] volleyball, hockey, synchronized swimming,[126] wrestlers,[102] baseball, track and field, football, tennis,[94] gymnasts,[127] swimmers,[126,128] male athletes,[94,102,125] and female athletes.[127–129]

An excellent example of the process to select specific regression equations for children, adults, seniors, the obese, anorexics, athletes, and different racial groups is described by Heyward and Stolarczyk.[65] For example, not only does it provide a generalized equation for white women aged 18–55 y, but the specific equation for an obese, Japanese, female group can be accessed.[130]

In addition to the choice of sites and regression equation, the experience of the tester, the type of caliper, and the subject's state of hydration all need to be considered with care. Studies in caliper type have shown that cost is not necessarily a good predictor of performance. The issue of technical characteristics of available skinfold caliper is debated fully in Brodie.[88] For practical purposes, ideally use the same caliper with an established technique after checking the experimenter's reliability and ensuring comparable test conditions. Even having taken such precautions, the measurement of extremely obese patients should proceed with caution, ensuring that the caliper remains in one position over a well-defined skinfold.

Biological variations include aspects of age, gender, overall fatness, and body size. Older people have a greater total body fat for a given skinfold thickness. Likewise, women have more fat than men as a result of a higher level of sex-specific essential fat. A greater proportion of fat is stored internally as total fatness increases. Katch et al.[131] propose that to compensate for the biological variability caused by body size that both surface area and skinfolds are included in body composition estimation.

Lohman[48] summarized the main sources of error in the prediction of body fat from skinfold data as biological variations in the proportion of subcutaneous fat (±2.5%), biological variations in the distribution of subcutaneous fat (±1.8%) and technical measurement errors (±0.5%). Each source of error is independent and so the total error is ±3.3% fat, slightly better than the figure claimed for densitometry and of similar order to that obtained by many of the more sophisticated indirect methods.

External body measurements such as diameters and circumferences can be used independently to estimate body fat or in combination with skinfolds. One of the earliest workers was Matiekga[132] who used cadaver data to develop a series of equations, using external body measurements, to estimate four body compartments of muscle, skin and subcutaneous fat, deep fat, and viscera and bone. The masses of skin and subcutaneous tissue, bone and muscle were estimated independently from a series of empirical constants and anthropometric measurements. The other component was determined by subtracting the sum of skin and subcutaneous tissue, bone, and muscle from body mass. The equations developed for estimating the four component models are:

$$\text{Skin + subcutaneous adipose tissue mass (g)} = 0.065\ \Sigma\ S/6\ A$$

where Σ S was the sum of six skinfolds and A was the body surface area (cm^2).

$$\text{Bone mass (g)} = 1.2\Theta^2 H$$

where Θ is the average diameters of the humoral and femoral condyles, the ankle, and wrist in centimeters and H is the height in centimeters.

$$\text{Muscle mass (g)} = 6.5r^2 H$$

where r is the mean of the radii calculated from the maximal circumferences of the arm, forearm, calf and thigh, and H is the height, all in centimeters.

$$\text{Deep fat and adipose tissue mass (g)} = 0.206\ M$$

where M is the body mass in grams. In each case, adipose tissue mass refers to the total mass, not the fat within adipose tissue.

This four component anatomical model has been largely neglected with the increasing popularity of the two component model, which estimates the masses of the fat and fat-free components of the body.

In 1979 Katch et al.[131] suggested that total fat mass could be estimated from skinfold thickness (ΣS), surface area (A), and a population specific constant (K), which varied with the sum of 11 girth measurements. The equation developed was:

$$\text{Fat mass (kg)} = A \times \Sigma S \times K$$

In 1980 Drinkwater and Ross[133] proposed some changes to the constants that Matiekga had used. They had found that in an athletic population the formulae of Matiegka showed errors of 8% in the prediction of total body mass. The main change to the constants by Drinkwater and Ross was in the constant used in the estimation of skin and subcutaneous fat. They used a smaller coefficient of 0.036 rather than Matiekga's original 0.065. The changes of the muscle and bone constants were smaller; muscle changed from 6.5 to 6.41 and bone from 1.2 to 1.25. Applying these new constants to their data Drinkwater and Ross predicted total body mass with an accuracy of 0.8%.

Drinkwater et al.[134] reported the results of correlations between Matiekga's original anthropometric estimates and the measurements taken from the cadaver evidence of the Brussels study. It was found that the Matiegka's formulae when applied to the cadaver data underestimated the mass of skin and subcutaneous tissue by 21.9%, the mass of muscle by an average of 8.5%, and the mass of visceral tissue by 11.6%. The mass of the bone component was overestimated by 24.8%. Based on these findings a new set of coefficients were developed for use in the original formulae. The new co-efficients overestimated the fat content of the females by 15.9% and underestimated the male fat content by 12.3%. It was evident that the results being obtained were only specific to the sample of cadavers which were relatively elderly subjects. Based on these findings, it became clear that there was a need for the development of sex-specific equations.[135] The prediction of body composition from cadaveric skinfold sites produces theoretical concerns when applied to free-living humans. One is that the body temperature of cadavers is lower, which could affect compressibility of skin, and another is the natural dehydration that occurs even in a relatively fresh cadaver. The elastic nature of skin is lost shortly after death and will contribute to skin compression variability.

Assessment of muscle volume has been performed by anthropometric methods such as circumference or girth measurements of the limb. The thigh and arm are two of the sites where these measurements have been obtained in the estimation of changes that have resulted from disuse, orthopaedic dysfunction, and exercise training. Anthropometric techniques have been useful for measuring body and limb volumes but have had a limited use in the determination of component tissue volumes. The main problem that has been identified includes the fact that anthropometric measurements are only indirect indicators of muscle volume, and girth measurements cannot differentiate between components within the circumference.[136] One additional limitation is that any circumference measurement has limited construct validity as it is determined by a combination of bone dimensions, skin thickness, body fat, and muscle volume.

The upper mid-arm circumference has been used in several nutritional studies to assess protein and energy malnutrition.[137–140] Unfortunately, a single circumference measurement confounds the relative measures of fat, muscle, and bone. In 1973 Gurney and Jelliffe,[141] proposed a formula for calculating the upper arm muscle cross-sectional area.

$$\text{Muscle cross-sectional area} = (C - \pi T)^2 / 4\pi$$

where C was the maximum arm circumference over the triceps and T was the tricep skinfold measurement. The problem with this formula is that there is no allowance made for the cross-sectional area of the bone contained in the area. In 1982, Heymsfield[142] compared the formula of Gurney and Jelliffe[141] against computed tomography measurements. They found that at the maximum circumference of the triceps the cross-sectional area of bone was 6.5 cm^2 in women (17% of the total cross-sectional area) and 10 cm^2 in men (18% of the total cross-sectional area).

In 1982 Jelliffe and Jelliffe[143] suggested that muscle volume of the upper arm could be estimated as 20% of the upper arm length multiplied by the muscle cross-sectional area from the formula of Gurney and Jelliffe.[141]

There have been several studies[108,144–148] that have used anthropometric principles to calculate regional fat, lean tissue, bone mass, and limb volumes. Segmental zone techniques have been shown to be a valid method of estimating segmental lower limb volumes in adult men and women.[145,149] These volumes have subsequently been converted to either a limb muscle volume or percentage fat content. The theoretical development of the segmental zone method for estimating total body volume and percentage fat is based on the intrinsic relationship that exists between body volume and body mass. Katch et al.[150] and Weltman and Katch[108] were the first to establish this theoretical model for the prediction of total body volume and, therefore, percentage body and lean body mass. The main reason for the development of this method was to try and overcome the problems that were associated with previous procedures that had been developed to predict body density, percentage fat, and lean body mass. They demonstrated that there was an intrinsic relationship between segmental volume, segmental circumferential measurement, and body mass, showing that it was possible to predict total body volume and percentage fat using circumference measurements, and body mass. Regression equations were found not to be population specific and associated SE of less than ±6% for predicting percentage fat in all samples of subjects were better than any previously published equation.

In general, these calculations have been restricted to the limbs, which have taken the form of four or more truncated cones, each containing concentric cylinders. The basic principle underlying this techniques is that the whole segment volume will equal the sum of its part volumes. By taking the appropriate measurements, the volume of each geometric shape can be calculated using geometric formulae.

Jones and Pearson[145] used a number of girth and height measurements taken serially along the limb and then used a mathematical model of truncated cones to calculate the volume of the thigh. They suggested that the mathematical calculation of segmental volumes could be used in place of water displacement or conventional x-ray techniques. The volume of limb segments was calculated using the formulae:

$$1/3L\ [a + b + \sqrt{(ab)}]$$

where a and b were the areas of two parallel cross-sections estimated from circumference measurements and L was the distance separating the two cross-sections. The volume of the foot was calculated using the formula:

$$1/2L\ (h.b)$$

where L was the length of the foot, h was the height from the sole of the foot to the first cross-section at the ankle, and b was the average breadth of the foot. Correlations of 0.98 in men and 0.99 in women were found when the total limb volume was compared with a water displacement criterion value. Muscle plus bone volume was calculated by taking skinfold measurements at the thigh and calf, and correcting cone dimensions for overlying fat. Fat was calculated as total limb volume, minus "muscle plus bone." Comparison of the fat with a radiographic criterion found correlations in the thigh to be 0.95 and 0.85 and in the calf 0.83 and 0.86 in men and women, respectively.

Weltman and Katch[108] extended the technique of Jones and Pearson to calculate segmental volumes of the arm and hand, thigh and leg, the feet and the head and neck. They found segmental volumes could be accurately predicted from circumference measurements at the arm, thigh, and leg sites. They, therefore, suggested that circumference measurements were good predictors of total body density and percentage body fat.

Shephard et al.[148] proposed the following formulae for the estimation of limb volume, limb fat, limb muscle, and limb bone:

$$\text{Limb volume (mL)} = (\Sigma c^2)\ L/62.8$$

where Σc^2 was the sum of the square of five circumference measurements (cm) and L was the length of the limb (cm).

$$\text{Limb fat (mL)} = (\Sigma c/5\ (\Sigma s/2n)\ L$$

where Σc was the sum of the five limb circumferences (cm), Σs was the sum of skinfolds measured over the limb (cm), n was the number of skinfolds taken over the limb, and L was the length of the limb (cm).

$$\text{Limb bone (mL)} = 3.14R^2L$$

where R was the average bone radius of the limb, and L was the length of the limb (cm).

In validation of proposed equations, Shephard et al.[148] demonstrated good correlation between maximum oxygen intake and muscle volume in the lower limb, while the percentage of fat that was calculated in the limbs coincided closely with percentage fat estimated by the skinfold method.

Sady et al.[151] and Freedson et al.[152] suggested that total body volume could be approximated from anthropometric measurements made on 10 body segments using three geometric shapes. Coefficients of correlation with hydrostatic weighing were high (0.96 in females, 0.98 in males) but there were substantial systematic and random sources of error relative to the criterion, which suggests that the accuracy of their methods is too low to provide useful body composition information (5.46 ± 1.86 L in women; 1.74 ± 1.88 L in men).

The many technical difficulties associated with the accurate measurement of skinfolds have resulted in studies that have used circumference measurements as an additional means of predicting body fat or as a means of adding precision to skinfold predictions.[95,153–156] There have been different prediction equations developed using circumference measurements on each sex and different age groups. Although these equations have been cross-validated on different samples with good results, they still appear to be population specific and should not be used in the prediction of body fat in individuals who appear extremely obese or extremely thin.[157]

The circumference-based prediction equations have been found to be useful in ranking individuals within a group according to their relative fatness. Katch et al.[164] presented a series of equations and constants for young and older men and women that could be used in the prediction of percentage body fat. They reported the error in the prediction of body fat associated with the circumference equations to be ± 2.5–4.0%. In view of these relatively low errors, they suggested that the equations could be particularly useful in circumstances where there is no access to laboratory facilities.

It has been shown that the reliability of moderately trained observers is substantially greater for circumference measurements rather than skinfold measurements.[9] Nevertheless, the greater construct validity of skinfold data has been found to outweigh the negative impact of poor measurement reliability, and skinfold predictions have been found to be more accurate than those based on circumferences.[74,122]

There appear to be no studies that have used circumference measurements to predict the volume of a body segment and compare the calculated circumferential segmental volume with volumes obtained from a water displacement technique.

BIOELECTRICAL IMPEDANCE

Bioelectrical impedance analysis (BIA) is based upon the relationship between the volume of the conductor (i.e., the human body), the conductor's length (i.e., the subject's height), the components of the conductor (i.e., fat or FFMs) and its impedance (Z). Impedance itself reflects frequency-dependent opposition to the flow of an alternating electric current, and comprises of resistive (R) and reactive capacitive (Xc) components, defined as the square root of the sum of the squares of the resistance and reactance ($Z = [R^2 + Xc^2]$).[159] Both R and Xc components are found in biological systems, although Xc is usually very small relative to Z at lower frequencies ($<4\%$),[160] so R and Z are often reported interchangeably. The distinction between Z and R becomes more important with the advent of multifrequency analyzers, as Xc may no longer remain so small as frequency increases.

BIA assumes that the volume of a conductor can be deducted from measurements of its length (L) and resistance. This stems from Ohm's Law, which states that between two points of a conductor, $R = V/I$, where R is measured in ohms, V is measured in volts and I, (current) in amperes. In a symmetrical isotropic conductor, R is directly proportional to its length (L, cm), and inversely proportional to its cross-sectional area (A, cm^2), $R = \rho L/A$, where ρ is the specific resistivity measured in ohm centimeters. As volume (ν) equals $L \times A$, algebraic rearrangement shows that $\nu = \rho L^2/R$. Stature (S) is used as an index of the length of the body, and S^2/R or S^2/Z forms the basis for predicting FFM or total body water. This estimation assumes that the conductor is a perfect cylinder with a uniform cross-sectional area, whereas, in reality, there are five cylinders (excluding the head). Each cylinder has a different cross-sectional area and, therefore, contributes a different resistance.[161] Additionally, the differences in cross-sectional area are not proportional to the differences in percentage body mass. The trunk, for example, may comprise 46% of body mass, but has little influence (3%) on whole body resistance when measured conventionally, the main influencing factors being the arm and the leg.[150] Variations in body proportions may, therefore, enhance the error associated with percentage body fat predictions. Differences in structure also affect the conduction of the current. The human body as a conductor is highly anisotropic, especially in the trunk, which additionally leads to an indication that the relationship between whole body resistance and the conductor volume with its electrolytic concentration is not strictly linear. FFM predictions at the extremes of body fatness are less accurate,[162] as prediction equations tend to overestimate fat mass in the lean and underestimate fat mass in the obese. Electrical conduction in biological systems is mainly ionic,[159] and proportional to fluid volume and the number of free electrolytic ions.[163] It is also inversely related to temperature.[164] This infers that the bioelectric resistance is affected by changes in body geometry, volume, temperature, and electrolytic concentration, and these effects should be taken into consideration.

The overall conductivity of the human body is closely related to lean tissue and has been validated with criterion methods such as hydrodensitometry and skinfold measurement.[165,166] The technique involves attaching adhesive surface electrodes to specific sites on the dorsal surface of the hand and anterior surface of the ipsilateral foot of the subject who lies flat on a nonconducting surface with legs abducted, preferably with the thighs not touching, although this may not be possible in extremely obese subjects. It is important that there is no metal close to the subject that may influence impedance readings (such as a metal frame on a hospital bed, metallic jewelry) as it may exert an influence on high frequency measurements,[167] and that these standard test conditions are maintained. The applied current is usually in the order of 500 μA for single (50 kHz) frequency machines, or 500 μA to 1 mA for multifrequency machines (5 kHz to 1 mHz), and tests times may last from a few seconds for a single frequency scan to several minutes for a full frequency scan. The raw outputs are generally visible immediately on the analyzer (resistance and reactance), and subsequently transmitted to a host computer whereby dedicated software processes the data. To maintain regression data accuracy, interchanging processing software from difference manufacturer analysers should be avoided.

It has been used in a range of specific groups including the elderly,[168] children and adolescents,[169–175] the overweight,[176–178] middle-aged,[179] malnourished,[180–182] dialysis patients,[183–190] infants,[191,192] for nutritional analysis,[193,194] during growth,[195] in eating disorders,[196] for cancer patients,[197] in ethnic groups,[198,199] and in patients with cystic fibrosis.[200]

Bioelectrical impedance has been used to assess lean-body mass in HIV-infected men,[201] showing no statistically significant results between the mean lean-body mass estimate by total body electrical conductivity and those measured by BIA or a prediction equation on the basis of body mass index. Ott et al.[202] reported that phase angle alpha was the best single predictive factor for survival in a 3-y study of patients with AIDS, and Kotler et al.[203] reported more accurate predictions of body cell mass using reactance rather than the values reported from the BIA. Kotler et al.[203] found that modeling equations derived after logarithmic transformation of height, reactance, and impedance were more accurate predictors than equations using $height^2$/resistance. Others have found that BIA measurements within these patient groups is greatly dependent upon the prediction equations used, with reported variations in the FFM content of weight loss ranging from 55% by total body water, 57% from skinfold thickness, 60% from dual energy x-ray absorptiometry, to 65% and 78% using two different prediction equations using BIA.[204] The use of gender-dependant equations also affects accuracy. Body composition within AIDS patients using in vivo neutron activation analysis has shown high reliability with 0.99 for total body chloride to 0.84 for total body phosphorous.[205,206]

It is recognized that the measurement of bioelectrical impedance is influenced by other factors that should either be controlled or reported. These include electrode configuration such as bipolar or tetrapolar,[207–209] the menstrual cycle,[210,211] skin temperature,[212] use of oral contraceptives,[213] exercise-induced dehydration,[33] prior food,[214] and different body positions.[215] If such features are controlled the prediction errors to calculate body fat are 3–5%. Most studies report that the impedance method is reliable and valid,[165,166,216–219] although some report caution in the use of a single frequency device in a clinical setting,[220] and others found that body mass alone estimated FFM as accurately as any of the bioelectrical equations in lean males.[221] The single frequency machine may be replaced by multiple frequency analyzers that are able to differentiate between total and extracellular fluid compartments in the body.[222–224] This is based on the current flow at low frequencies (5 kHz) passing primarily through extracellular fluids and at higher frequencies ($>$200 kHz) penetrating all body tissues. This will increase the value for assessing clinical and nutritional status considerably. Multifrequency analysers have been shown to produce significant improvements in the prediction of body water[225–229] and improves the standardization of the method over the single frequency approach.[215] It should be of particular value when hydration states need to be monitored such as in renal dialysis,[230] or in the management of lymphoedema.[231] A comparison between the single frequency and multiple frequency approaches yield similar results.[215] Comparisons with different single frequency devices shows that some models record a lower impedance value than others.[240] It is interesting to note that cost does not seem to be a major factor, mean differences of only 0.6%,[232] between machines.

Bioelectrical impedance is used to estimate total body water (TBW) measured by isotopic dilution techniques. In this instance, the standard error of the estimate of TBW, under carefully controlled conditions, is <2 L of water. This is less than a 4% error for an adult comprising of 50 L of TBW. Prediction errors for young adults, based on the coefficient of variation, have for FFM been reported at 4% or less. Errors in the measurement of height and weight, error in BIA measurement, error of measurement of the criterion method, and errors from the prediction equation all sum to produce this prediction error.

Although the standard error of estimates is at best reported as 2.5% in humans,[233] its advantages such as speed of operation, safety, portability and lack of intrusion make it an ideal tool for epidemiological investigations.

Validation studies have generally involved healthy adults. The elderly, youth, children, and neonates provide far more limited data. Ethnic minority groups are less commonly reported than Caucasian. Individuals who differ substantially from the reference population will limit validity as will the accuracy of the measurement of the criterion variable. Specific validation would be necessary for any individuals who did not conform to the basic assumptions applying to BIA measurement. These would include any conditions causing asymmetry or producing localized changes in tissue atrophy or perfusion.[234]

Baumgartner's contribution[53] reviews the assumptions, applicability, equipment, measurement procedure, precision, and accuracy of the BIA method and is highly recommended.

Clinicians value knowledge of body composition in health and illness because of the additional information provided compared with height, mass and derived measures such as body mass index. TBW's predictive value is only valid in disease when the central and peripheral body components are affected similarly. This is likely to apply in moderate obesity, many noninflammatory diseases, and in early HIV infection. In these and others, nutritional status is likely to be the main use of the technique. Haemodialysis is a probable area for BIA investigation as is any disturbance of the intracellular/extracellular water ratio as in protein malnutrition, injury, or inflammation. This whole area is, to date, poorly researched and will need to be cautiously investigated as critically ill patients will have variable ratios of TBW to FFM. Measurement of nutritional replenishment for malnourished patients may be a more productive line of investigation.

OTHER METHODS

A full review of techniques of body composition[79] and a critique on the variability in the measures of body fat[235] are outside the scope of this article and have been undertaken elsewhere. It is, however, valuable to consider just two alternative approaches briefly as they are gaining current popularity for body composition assessment. The first is near-infrared interactance, which is based on the principle of light absorption and reflection. An infrared light beam is placed over the biceps muscle and reflected energy from the fiberoptic probe is monitored by an optical detector. It compares the light absorption properties of two wavelengths and in combination with other anthropometric data predicts body composition utilizing an appropriate regression equation. It has been shown to be reliable[236–238] and has been validated with ethnic groups,[239] in the middle aged,[238] women of varying ages,[240] and in children and adults.[239] Standard errors of estimate were in the range 4.9–5.5%,[237] and it was found that the method underestimated the percentage body fat of obese women.[238,240] This was considered to be related to the bigger differences between skinfold and optical density values in sites of higher fat depths.[240] It is generally considered that additional work needs to be undertaken with infrared interaction to demonstrate its utility. More studies should be completed to cross-validate the technique for general and specific populations. Its appeal, not unlike impedance, is its lack of intrusion, its speed, and portability.

The final method to consider is that of dual energy x-ray absorptiometry (DEXA). Originally developed for bone content analysis, especially the clinical study of osteoporosis, it is now being heralded as a potential criterion method for body composition. Compared with MRI, it is currently more widely available as a research tool and is likely to be less expensive to operate and maintain. DEXA has the advantage of being able to partition the body into three components; namely bone mineral, fat and lean tissue. This division is somewhat based on assumptions incorporated into the manufacturer's software but the results when compared with hydrodensitometry compare well, providing errors in the equation used to calculate percent fat from density are accepted. Additional support for DEXA as a method of body composition measurement comes from the sum of the three components that is within 1% of the actual body mass. The technology of DEXA is reviewed by Nord and Payne[241] and validation studies have been undertaken against potassium-40,[242,243] total body water using deuterium dilution,[243,244] skinfolds,[245–247] hydrodensitometry,[245,246,248–251] bioelectrical impedance,[245,247] and even compared with lard as a soft tissue substitute.[252] It was also found to have satisfactory short-term reproducibility.[253] The general conclusions are that DEXA is a safe method for routine use in humans,[254] is precise with a low standard error of estimate[247] and has initial promise as a method for estimating body composition.[255–257] It has already been used widely in addition to postmenopausal women,[258–260] by such groups as children,[261–266] young women,[267,268] the newborn,[269,270] men,[271] athletes,[256] and growth hormone deficient adults.[272] Nonetheless, it is important to appreciate within-manufacturer variability, which can be as high as 15% for the mass of bone mineral.

Any user of DEXA for fat mass must remember that estimated fat is lipid (the chemical component) not adipose tissue (the anatomical component). Nonetheless, once validated against an imaging criterion such as MRI, DEXA may prove to be a useful addition to the body composition options. Any validation would need to take account of the theoretical differences in the imaging modalities.

SUMMARY

The range of options available for body composition measurement includes chemical, electrical, physical, and anthropometric. A number of these are restricted to research institutes that have committed high capital investment such as whole body counters or computer tomography scanners. Many nutritionists will find low-cost systems that can be applied rapidly and noninvasively a useful adjunct to their clinical experience. Body composition using hydrodensitometry, surface anthropometry, bioelectrical impedance, or infrared interactance provides evidence for fat and fat free components, which is becoming increasingly popular in the literature and in practice. This article provides an overview of the current literature and gives a basis for future research, for purchase of equipment or for making decisions to include body composition as part of nutritional activity.

REFERENCES

1. Boileau RA, Lohman TG. The measurement of human physique and its effect on physical performance. Orthop Clin North Am 1977;8: 563
2. Roberts N, Cruz-Orive LM, Reid NMK, et al. Unbiased estimation of human body composition by the Cavalieri method using magnetic resonance imaging. J Microsc 1993;171:239
3. Hawkes N. Executed killer reborn as ‘visible man’ on Internet. The Times, 29th November 1994
4. Gurr MI, Harwood JL. *Lipid biochemistry,* 4th ed. London:Chapman and Hall, 1991
5. Brodie DA, Slade PD. Dietary versus healthy life style interventions in the treatment of obesity: resultant changes and the prediction of outcome. Psychol Health 1990;4:319
6. Katch F, Michael E, Horvath S. Estimation of body volume by underwater weighing: description of a simple method. J Appl Physiol 1967;23:811
7. Luft VC, Cardus D, Lim TPK, et al. Physical performance in relation to body size and composition. Ann N Y Acad Sci 1963;110:807
8. Wilmore JA. A simplified method for determination of residual volumes. J Appl Physiol 1969;27:96
9. Shephard RJ. *Body Composition in biological anthropology.* Cambridge:Cambridge University Press, 1991
10. Mendex J, Lukaski HC. Variability of body density in ambulatory subjects measured on different days. Am J Clin Nutr 1981;34:78
11. Marks C, Katch V. Biological and technological variability of residual lung volume and the effect on body fat calculations. Med Sci Sports Exerc 1986;18:485
12. Brandom JL, Boileau RA, Lohman TH. Comparison of two procedures employed in measuring body density in children. Med Sci Sports Exerc 1981;13:122
13. Girandola RN, Wisewell RW, Mohler JG, et al. Effect of water immersion on lung volumes: implications for body composition analysis. J Appl Physiol 1977;43:276
14. Agostini E, Gurnter G, Torri G, et al. Respiratory mechanics during submersion and negative pressure breathing. J Appl Physiol 1966; 21:251
15. Bondi KR, Young JM, Bennett RM, et al. Closing volumes in man immersed to the neck in water. J Appl Physiol 1976;40:736
16. Jarrett JS. Effect of immersion on intrapulmonary pressure. J Appl Physiol 1965;20:1261
17. Ostrove SM, Vaccaro P. Effect of immersion on RV in young women: implications for measurement of body density. Int J Sports Med 1982;3:220
18. Robertson CH, Engle CM, Bradley ME. Lung volumes in man immersed to the neck: dilution and plethysmographic techniques. J Appl Physiol 1978;44:679
19. Sawka MN, Weber HR, Knowlton RG. The effect of body submersion on residual lung volume and body density measurements in man. Ergonomics 1978;21:89
20. Arborelius M, Balldin UI, Lila B, et al. Regional lung function in man during immersion with the head above water. Aerospace Med Biol 1972;43:701
21. Craig AB, Ware DB. Effect of immersion in water on vital capacity and residual volume of the lungs. J Appl Physiol 1967;23:423
22. Dahlback GO, Lundgren CE. Pulmonary air-trapping induced by water immersion. Aerospace Med Biol 1972;32:768
23. Etheridge GL, Thomas TR. The effect of body position and water immersion on lung volumes of women. Med Sci Sports Exerc 1978; 19:61
24. Prefaut C, Lupi HE, Anthonisen NR. Human lung mechanics during water immersion. J Appl Physiol 1976;40:320
25. Sloan AW, Bredwell GAG. A comparison of two simple methods of determining pulmonary residual volume. Hum Biol 1973;45:23
26. Wilmore JH, Vodak PA, Parr RB, et al. Further simplification for a method for determination of residual lung volume. Med Sci Sports Exerc 1980;12:216
27. Mayhew JL, Piper FC, Douglas W. Effect of residual volume estimates on calculations of body density in adolescent athletes. Unpublished abstract, AAHPERD National Meeting, Detroit, MI, 1980
28. Polgar G, Promadht V. *Pulmonary function testing in children: techniques and standards.* Philadelphia:WB Saunders, 1971:123
29. Garrow JS, Stalley S, Diethelm R, et al. A new method for measuring body density of obese adults. Br J Nutr 1979;42:173
30. Buskirk ER. Underwater weighing and body density: a review of procedures. In: Brozek J, ed. *Technique for measuring body composition.* Washington DC, 1963
31. Girandola RN, Wisewell RA, Romero G. Body composition changes resulting from fluid ingestion and dehydration. Res Q Exerc Sport 1977;48:299
32. Durnin JVGA, Satwanti K. Variations in the assessment of the fat content of the human body due to experimental technique in measuring body density. Ann Hum Biol 1982;9:221
33. Brodie DA, Eston RG, Coxon AY, et al. Effect of changes of water and electrolytes on the validity of conventional methods of measuring fat-free mass. Ann Nutr Metab 1991;35:89
34. Noble B. *Physiology of exercise and sport.* St. Louis:Mosby, 1986
35. Schemmel R. Assessment of obesity. In: Schemmel R, ed. *Nutrition, physiology and obesity.* Boca Raton, FL:CRC Press Inc., 1980
36. Chien S, Peng MT, Chen KP, et al. Longitudinal measurements of body volume and essential body mass in human subjects. J Appl Physiol 1975;39:818
37. Pace N, Rathburn EN. Studies on body composition III: the body water and chemical combined nitrogen content in relation to fat content. J Biol Chem 1965;158:685
38. Siri W. *Body Composition from fluid spaces and density.* Report 19. Berkeley, CA:University of California Press, 1956
39. Adams J, Mottola M, Bagnall KM, et al. Total body fat content in a group of professional football players. Can J Appl Physiol 1982;7:36
40. Macdougal JK, Wenger JA, Green HJ. *Physiological testing of the elite athlete.* Toronto: Canadian Sports Science, 1983
41. Weredin EJ, Kyle LH. Estimation of the constancy of the fat-free body. J Clin Invest 1960;39:626
42. Lohman TG. Research progress in validation of laboratory methods of assessing body composition. Med Sci Sports Exerc 1984;16:596
43. Behnke AR. The absorption and elimination of gases of the body in relation to its fat and water content. Medicine 1945;24:359
44. Brozek J, Grande F, Anderson JT, et al. Densiometric analysis of body composition: revision of some quantitative assumptions. Ann N Y Acad Sci 1963;110:113
45. Keys A, Brozek J. Body fat in adult man. Physiol Rev 1953;33:245
46. Siri WE. *The gross composition of the body.* 1956;4:239
47. Lohman TG, Slaughter MH, Boileus RA, et al. Bone mineral measurements and their relationship to body density in children, youth and adults. Hum Biol 1984;56:667
48. Lohman TG. Skinfolds and body density and their relation to fatness: a review. Hum Biol 1981;53:181
49. Pollock M, Jackson AS. Research progress in validation of clinical methods of assessing body composition. Med Sci Sports Exerc 1984;16:606
50. Bakker HK, Struidenkamp RS. Biological variability and lean body mass estimates. Hum Biol 1977;49:187
51. Buskirk ER. Body composition analysis: the past, present and future. Res Q Exerc Sport 1987;58:1
52. Murray S, Shephard RJ. Possible anthropometric alternatives to skinfold measurements. Hum Biol 1988;60:273
53. Roche AF, Heymsfield SB, Lohman TG, eds. *Human body composition.* Champaign, IL:Human Kinetics Publishers, 1992:366
54. Valerio Jiminex OS, Moon JK, Jensen CL, et al. Pre-term infant volume measurements by acoustic plethysmography. J Biomed Eng 1993;15:91
55. Deskins WG, Winder DC, Sheng HP, et al. An acoustic plethysmograph to measure total infant body volume. J Biomed Eng 1985;197: 304
56. Shen HP, Adolph AL, O’Brian Smith E, et al. Body volume and fat-free mass determinations by acoustic plethysmography. Pediat Res 1988;24:85
57. Taylor A, Aksoy Y, Scopes JW, et al. Development of an air displacement method for whole body volume measurement of infants. J Biomed Eng 1985;7:9
58. Falkner F. An air displacement method of measuring body volume in babies: a preliminary communication. Ann N Y Acad Sci 1963; 110:75

59. Gnaedinger RH, Reineke EP, Pearson AM, et al. Determination of body density by air displacement, helium dilution, and underwater weighing. Ann N Y Acad Sci 1963;110:96
60. Gundlach BL, Nijkrake GM, Hautvast JGAJ. A rapid and simplified plethysmographic method for measuring body volume. Hum Biol 1980;52:22
61. Gundlach BL, Visscher GJW. The plethysmographic measurement of total body volume. Hum Biol 1986;58:783
62. Dempster P, Aitkins S. A new air displacement method for the determination of human body composition. Med Sci Sports Exerc 1995;27:1692
63. McCrory MA, Gomez TD, Bernauer EM, et al. Evaluation of a new air displacement plethysmography for measuring human body composition. Med Sci Sports Exerc 1995;27:1686
64. Lamb DR. *Physiology of exercise: responses and adaptations.* New York:Macmillan, 1984
65. Heyward VH, Stolarczyk LM. *Applied body composition assessment.* Champaign, IL:Human Kinetics Publishers, 1996
66. Heymsfield SB, Wang S-M, Withers RT. Multicomponent molecular level models of body composition analysis. In: Roche AF, Heymsfield SB, Lohman TG, eds. *Human body composition.* Champaign, IL:Human Kinetics Publishers, 1996:129
67. Moscrip V. Ultrasonic estimation of adipose tissue volume in young adult females. Unpublished MSc dissertation, University of Liverpool, 1995
68. Jackson AS, Pollock ML. Steps towards the development of generalised equations for predicting body composition of adults. Can J Appl Sports Sci 1982;7:189
69. Keys A, Brozek J. Body fat in adult man. Physiol Rev 1953;33:245
70. Sloan AW. Estimation of body fat in young men. J Appl Physiol 1967;23:23
71. Fletcher RF. The measurement of total body fat with skinfold calipers. Clin Sci 1962;22:33
72. Durnin RVGA, Rahaman MM. The assessment of the amount of fat in the human body from measurements of skinfold thickness. Br J Nutr 1967;21:681
73. Durnin JVGA, Womersley J. Body fat assessed from total body density and its estimation from skinfold thicknesses: measurements on 481 men and women aged 16 to 72 years. Br J Nutr 1974;32:77
74. Jackson AS, Pollock ML. Generalised equations for predicting body density of men. Br J Nutr 1978;40:497
75. Martin AD, Ross WD, Drinkwater D, Clarys JP. Prediction of body fat by skinfold caliper: assumptions and cadaver evidence. Int J Obesity 1985;9(suppl)1:31
76. Sinning WE, Wilson JW. Validity of “generalized” equations for body composition analysis in women athletes. Res Q Exerc Sport 1984;55:153
77. Jackson AS. Research design as analysis of data procedures for predicting body density. Med Sci Sports Exerc 1984;16:616
78. Slaughter MH, Lohman TG, Boileau RA, et al. Influence of maturation on relationship of skinfolds to body density: a cross-sectional study. Hum Biol 1984;56:681
79. Brodie DA. Measurement of body composition (Part 2). Sports Med 1988;5:74
80. Thorland WG, Johnson GO, Tharp GD, et al. Validity of anthropometric equations for the estimation of body density in adolescent athletes. Med Sci Sports Exerc 1984;16:77
81. Parizkova J. Total body fat and skinfold thicknesses in children. Metabolism 1961;10:794
82. Sloan AW, Shapiro M. A comparison of skinfold measurements with three standard callipers. Hum Biol 1972;44:29
83. Lohman TG, Pollock ML, Slaughter MH, et al. Methodological factors and the prediction of body fat in female athletes. Med Sci Sports Exerc 1984;16:92
84. Brozek J, Kinsey W. Age changes in skinfold compressibility. J Gerentol 1960;15:45
85. Himes JG, Roche AF, Siervogel RM. Compressibility of skinfolds and the measurement of subcutaneous tissue thickness. Am J Clin Nutr 1979;37:1734
86. Fanelli MR, Kuczmarski RJ. Ultrasound as an approach to assessing body composition. Am J Clin Nutr 1984;39:703
87. Burkinshaw L, Jones PRM, Krupowics DW. Observer error in skinfold thickness measurements. Hum Biol 1973;45:273
88. Brodie DA. Techniques of measurement of body composition: part one. Sports Med 1988;5:11
89. Wormersley J, Durnin JVGA, Boddy D, et al. Influence of muscular development obesity and age on the fat free mass of adults. J Appl Physiol 1976;41:223
90. Jackson AS, Pollock ML, Ward A. Generalized equations for predicting body density of women. Med Sci Sports Exerc 1980;12:175
91. Sinning WE, Dolney DG, Little KD, et al. Validity of “generalized” equations for body composition analysis in male athlete. Med Sci Sports Exerc 1985;17:124
92. Wilmore JH, Behnke AR. An anthropometric estimation of body density and lean body weight in young men. J Appl Physiol 1969: 27:25
93. Wilmore JH, Behnke AR. An anthropometric estimation of body density and lean body weight in young women. Am J Clin Nutr 1970;23:267
94. Forsyth HL, Sinning WE. The anthropometric estimation of body density and lean body weight of male athletes. Med Sci Sports Exerc 1973;5:174
95. Katch FI, McArdle WD. Prediction of body density from simple anthropometric measurements in college-age men and women. Hum Biol 1973;45:445
96. Pollock ML, Laughridge E, Coleman B, et al. Prediction of body density in young and middle-aged women. J Appl Physiol 1975;38: 745
97. Pollock ML, Hickman T, Kendrick Z, et al. Prediction of body density in young and middle-aged men. J Appl Physiol 1976;40:300
98. Lohman TG. *Advances in body composition assessment.* Champaign, IL:Human Kinetics Publishers, 1992
99. Norgan NG, Ferro-Luzzi A. The estimation of body density in men: are general equations general? Ann Hum Biol 1985;12:1
100. Boileau RA, Buskirk D, Horstman H, et al. Body composition changes in obese and lean men during physical conditioning. Med Sci Sports Exerc 1971;3:181
101. Lohman TG, Slaughter MH, Selinger A, et al. Relationship of body composition to somatotype in college age men. Hum Biol 1978;5: 147
102. Sinning WE. Body composition assessment of college wrestlers. Med Sci Sports Exerc 1974;6:139
103. Young CM, Kerr Martin ME, Tensuan R, et al. Predicting specific gravity and body fatness in young women. J Am Diet Assoc 1962; 40:102
104. Edwards DAW. Differences in the distribution of subcutaneous fat with sex and maturity. Clin Sci 1951;10:305
105. Baumgartner JA, Jackson AS. *Measurement and evaluation in physical education.* 2nd ed. Dubeque: WC Brown Company, 1982
106. Garn SM. Fat weight and fat placement in the female. Science 1957;12:1092
107. Brozek J, Keys A. The evaluation of leanness-fatness in man: norms and interrelationships. Br J Nutr 1951;4:194
108. Weltman A, Katch VL. Preferential use of casing (girth) measures for estimating body volume and density. J Appl Physiol 1975;38:560
109. Haisman MF. The assessment of body fat content in young men from measurements of body density and skinfold thickness. Hum Biol 1970;42:679
110. Pascale LR, Grossman MI, Sloane HS, et al. Correlations between thickness of skinfolds and body density in 88 soldiers. Hum Biol 1956;28:165
111. Katch FI, Michael EC. Densitometric validation of six skinfold formulas to predict body density and percent body fat of 17 year-old boys. Res Q Exerc Sport 1969;40:712
112. Brook CGD. Determination of body composition of children from skinfold measurements. Arch Dis Child 1971;46:182
113. Seltzer CC, Goldman RF, Mayer J. The triceps skinfold as a predictive measure of body density and body fat in obese adolescent girls. Pediatrics 1965;36:212
114. Young CN, Sippin SS, Roe DA. Body composition of pre-adolescent and adolescent girls. I. Density and skinfold measurements. J Am Diet Assoc 1968;53:25
115. Johnston FE. Relationships between body composition and anthropometry. Hum Biol 1982;54:221
116. Mukherjee D, Roche AF. The estimation of percent body fat, body

density and total body fat by maximum R^2 regression equations. Hum Biol 1984;56:79

117. Mueller NH, Stallones L. Anatomical distribution of subcutaneous fat: skinfold site choice and construction of indices. Hum Biol 1981;53:312
118. Jackson AS, Pollock ML. Factor analysis and multivariate scaling of anthropometric variables for the assessment of body composition. Med Sci Sports Exerc 1976;8:196
119. Oakley JR, Parsons RJ, Whitelawe AGL. Standards for skinfold thickness in British newborn infants. Arch Dis Child 1977;52:287
120. Corbin CB, Zuti WB. Body density and skinfold thicknesses of children. Am Corrective J 1982;36:50
121. AAHPERD. *Health related physical fitness test manual.* Am Ass Health, Phys Ed Reston: Recreation Dance. 1980
122. Boileau RA, Wilmore JH, Lohman TG, et al. Estimation of body density from skinfold thicknesses, body circumferences and skeletal widths in boys aged 8 to 11 years: comparison of two samples. Hum Biol 1981;53:575
123. Lohman TG, Boileau RA, Massey BH. Prediction of lean body mass in young boys from skinfold thickness and body weight. Hum Biol 1975;47:245
124. Nelson JK, Nelson KR. Skinfold profiles of black and white boys and girls ages 11-13. Hum Biol 1986;58:379
125. Pollock ML, Jackson A, Ayres J, et al. Body composition of elite class distance runners. Ann N Y Acad Sci 1977;301:361
126. Hall LK. Anthropometric estimations of body density of women athletes in selected athletic activities. Doctoral dissertation. Columbus:Ohio State University, 1977
127. Sinning WE. Anthropometric estimation of body density, fat and lean body weight in women gymnast. Med Sci Sports Exerc 1978; 10:243
128. Meleski BW, Shoup RF, Malina RM. Size, physique and body composition of competitive female swimmers 11 through 20 years of age. Hum Biol 1982;54:609
129. Mayhew JL, Clark BA, McKeown BC, et al. Accuracy of anthropometric equations for estimating body composition in female athletes. J Sports Med Phys Fitness 1985;25:120
130. Tanaka K, Nakadomo F, Watanabe K, et al. Body composition prediction equations based on bioelectrical impedance and anthropometric variables for Japanese obese women. Am J Hum Biol 1992;4:739
131. Katch FI, Behnke AR, Katch VL. Estimation of body fat from skinfolds and surface areas. Hum Biol 1979;51:411
132. Matiekga RJ. The testing of physical efficiency. Am J Phys Anthrop 1921;4:223
133. Drinkwater DT, Ross WD. Anthropometric fractionation of body mass. In: Ostyn M, Beunen G, Simons J, eds. *Kinanthropometry II.* Baltimore:University Park Press, 1980;178
134. Drinkwater DT, Martin AD, Ross WD, et al. Validation of cadaver dissection of Metiekga's equations for the anthropometric assessment of anatomical body composition in adult humans. In: Day JAP, ed. *Perspectives in kinanthropometry.* Champaign:Human Kinetics Publishers, 1986:221
135. Shephard RJ, Kofsky PR, Harrison JE, et al. Body composition of older female subjects: new approaches and their limitations. Hum Biol 1985;57:671
136. Doxey GE. The association of anthropometric measurements of thigh size and B-mode ulstrasound scanning of muscle thickness. J Orth Sports Phys Ther 1987;8(9):462
137. Gray GE, Gray LK. Anthropometric measurements and their interpretation: principles, practices and problems. J Am Diet Assoc 1980;77:534
138. Jelliffe DB. The assessment of the nutritional status of the community. Monograph 53, Geneva, WHO, 1966
139. Wolanski N. An approach to the inheritance of systolic and diastolic blood pressure. Gen Pol 1969;10:263
140. Bertrand HA, Stacey C, Masoro E, et al. Plasticity of fat cell number. J Nutr 1984;114:127
141. Gurney SM, Jelliffe DB. Arm anthropometry in nutritional assess: nomogram for rapid calculation of muscle circumference and cross-sectional muscle areas. Am J Clin Nutr 1973;26:912
142. Heymsfield SB. Anthropometric measurement of muscle mass: reused equations for calculating bone free muscle area. Am J Clin Nutr 1982;680
143. Jelliffe DB, Jelliffe EFP. *Assessment of nutritional status.* Oxford: Oxford University Press, 1982
144. Standard KL, Wills VG, Waterlow JC. Indirect indicators of muscle mass in malnourished infants. Am J Clin Nutr 1959;7:271
145. Jones PRM, Pearson J. Anthropometric determination of leg fat and muscle plus bone volumes in young male and female adults. J Physiol 1969;204:63
146. Katch VL, Katch FI. A simple anthropometric model for calculating segmental leg volumes. Res Q Exerc Sport 1975;45:211
147. Anderson P, Saltin B. Maximal perfusion of skeletal muscle in man. J Appl Physiol 1985;366:233
148. Shephard R J, Bouhlel E, Vandewalle H, et al. Muscle mass as a factor limiting physical work. J Appl Physiol 1988;64:1472
149. Katch VL, Michael ED, Amuchie FA. The use of body weight and girth measurement in predicting segmental leg volume of females. Hum Biol 1973;45:293
150. Katch VL, Weltman A, Gold E. Validity of anthropometric measurements and the segment-zone method for estimating segmental and total body volume. Med Sci Sports Exerc 1974;6:271
151. Sady S, Freedson P, Katch VL, et al. Anthropometric model of total body volume for males of different sizes. Hum Biol 1978;50:529
152. Freedson P, Sady S, Katch V, et al. Total body volume in females: validation of a theoretical model. Hum Biol 1979;51:499
153. Zuti WB, Golding LA. Equations for estimating percent fat and body density of active adult males. Med Sci Sports Exerc 1973;5:262
154. Jackson AS, Pollock ML, Gettman LR. Intertester reliability of selected skinfolds and circumference and percent fat estimates. Res Q Exerc Sport 1978;49:546
155. Sinning WE, Hackney AC. Body composition estimation by girths and skeletal dimensions in male and female athletes. In: Day JAP, ed. *Perspectives in kinanthropometry.* Champaign, IL:Human Kinetics Publishers, 1986:239
156. Tran AV, Weltman A. Predicting body composition from girth measurements. Hum Biol 1988;60:167
157. Katch FI, McArdle WD. Validity of body composition prediction equations for college men and women. Am J Clin Nutr 1975;25:105
158. Katch FI, Katch VL, McArdle WD. *Exercise Physiology: Energy, Nutrition and human performance.* Philadelphia:Lea & Febiger, 1981
159. Ackmann JJ, Seitz MA. Methods of complex impedance measurements in biologic tissue. Crit Rev Biomed Eng 1984;11:281
160. Baumgartner RN. Electrical impedance and total body electrical conductivitiy. In: Roche AF, Heymsfield SB, Lohman TG, eds. *Human body composition.* Champaign:Human Kinetics 1996:79
161. Baumgartner RN, Chumlea WC, Roche AF. Estimation of body composition from segmental impedance. Am J Clin Nutr 1989;50: 221
162. Segal KR, Van Loan MD, Fitzgerald PI, et al. Lean body mass estimated by bioelectrical impedance: a four site cross validation study. Am J Clin Nutr 1988;47:7
163. Khaled MA, McCutcheon MJ, Reddy S, et al. Electrical impedance in assessing human body composition: the BIA method. Am J Clin Nutr 1988;47:789
164. Geddes LA, Baker LE. The specific resistance of biological material: a compendium of data for the biomedical engineer and physiologist. Med Biol Eng Compu 1989;5:271
165. Keller B, Katch FI. Validity of bioelectrical resistive impedance for estimation of body fat in lean males. Med Sci Sports Exerc 1985; 23:811
166. Lukaski HC, Johnson PE, Bolonchuk WW, et al. Assessment of fat-free mass using bioelectrical impedance measurements of the human body. Am J Clin Nutr 1985;41:810
167. Roos AN, Westendorp RGJ, Frolich M, et al. Tetrapolar body impedance is influenced by body position and plasma socium concentration. Eur J Clin Nutr 1992;46:53
168. Chumlea WC, Guo SS, Kuczmarski RJ, et al. Bioelectric and anthropometric assessments and reference data in the elderly. J Nutr 1993;123:449
169. Wu YT, Neilson DH, Cassidy SL, et al. Cross-validation of bioelectrical impedance analysis of body composition in children and adolescents. Physical Therapy 1993;73:320

170. Eston RG, Cruz A, Fu F, et al. Fat-free mass estimation by bioelectrical impedance and anthropometric techniques in Chinese children. J Sports Sci 1993;11:241
171. Goran MI, Kaskoun MC, Carpenter WH, et al. Estimating body composition of young children by using bioelectrical resistance. J Appl Physiol 1993;75:1776
172. Iwata K, Satou Y, Iwata F, et al. Assessment of body composition measured by bioelectrical impedance in children. Acta Paediatr Jpn 1993;35:369
173. Danford LC, Schoeller DA, Kushner RF. Comparison of two bioelectrical impedance analysis models for total body water measurement in children. Ann Hum Biol 1992;19:603
174. Schaefer F, Georgi M, Zieger A, et al. Usefulness of bioelectric impedance and skinfold measurements in predicting fat-free mass derived from total body potassium in children. Pediatr Res 1994;35:617
175. Houtkooper LB, Going SB, Lohman TG, et al. Bioelectrical impedance estimation of fat-free body mass in children and youth: a cross-validation study. J Appl Physiol 1992;72:366
176. Saunders NH, Zeibak S, Ryde SJ, et al. The composition of weight loss in dieting obese females by electrical methods. Int J Obes 1993;17:317
177. Battistini N, Brambilla P, Virgili F, et al. The prediction of total body water from body impedance in young obese subjects. Int J Obes 1992;16:207
178. Gray DS, Bray GA, Gemayel N, et al. Effect of obesity on bioelectrical impedance. Am J Clin Nutr 1989;50:255
179. Helenius MYT, Albanes D, Micozzi MS, et al. Studies of bioelectric resistance in overweight, middle-aged subjects. Hum Biol 1987:59:271
180. Kabir I, Malek MA, Rahman MM, et al. Changes in body composition of malnourished children after dietary supplementation as measured by bioelectrical impedance. Am J Clin Nutr 1994;59:5
181. Royall D, Greenberg GR, Allard JP, et al. Critical assessment of body-composition measurements in malnourished subjects with Crohn's disease: the role of bioelectric impedance analysis. Am J Clin Nutr 1994;59:325
182. Ott M, Lembeke B, Fischer M, et al. Early changes of body composition in human immunodeficiency virus-infected patients: tetrapolar body impedance analysis indicates significant malnutrition. Am J Clin Nutr 1993;57:15
183. Schmidt RJ, Dumler F. Bioelectrical impedance analysis: a promising predictive tool for nutritional assessment in continuous ambulatory peritoneal dialysis patients. Perit Dial Int 1993;13:250
184. Bergia R, Bellini ME, Valenti M, et al. Longitudinal assessment of body composition in continuous ambulatory peritoneal dialysis patients using bioelectric impedance and anthropometric measurements. Perit Dial Int 1993;13:S512
185. Stefandis C, Michelakaki H, Koulieri A, et al. Nutritional status and growth in children less than 12 kg treated with continuous ambulatory peritoneal dialysis. Perit Dial Int 1993;13:S251
186. Rammohan M, Aplasca EC. Caliper methods versus bioelectrical impedance analysis for determining body fat in patients undergoing chronic dialysis and in health individuals. J Am Diet Assoc 1992;92:1395
187. Pastan S, Gassensmith C. Total body water measured by bioelectrical impedance in patients after hemodialysis: comparison with urea kinetics. Trans Am Soci Artif Intern Organs 1992;38:M186
188. Spotti D, Librenti MC, Melandri M, et al. Bioelectrical impedance in the evaluation of the nutritional status of hemodialyzed diabetic patients. Clin Nephrol 1993;39:172
189. Spence JA, Baliga R, Nyboer J, et al. Changes during hemodialysis in total body water, cardiac output and chest fluid as detected by bioelectrical impedance analysis. Trans Am Soc Artif Intern Organs 1979;25:51
190. Jebb SA, Elia M. Assessment of changes in total body water in patients undergoing renal dialysis using bioelectrical impedance analysis. Clin Nutr 1993;10:81
191. Wilson DC, Baird T, Scrimgeour CM, et al. Total body water measurement by bioelectrical impedance in the extremely low birth weight infant. Basic Life Sci 1993;60:185
192. Gartner A, Maire B, Delpeuch F, et al. The use of bioelectrical impedance analysis in newborns. The need for standardization. Basic Life Sci 1993;60:165
193. Sluys TE, van der Ende ME, Swart GR, et al. Body composition in patients with acquired immunodeficiency syndrom: a validation study of bioelectric impedance analysis. JPEN 1993;17:404
194. Robert S, Zarowitz BJ, Hyzy R, et al. Bioelectrical impedance assessment of nutritional status in critically ill patients. Am J Clin Nutr 1993;57:840
195. Gordon CL, Webber CE. Body composition and bone mineral distribution during growth in females. Can Assoc Radiol J 1993;44:112
196. Hannon WJ, Cowen SJ, Freeman CP, et al. Can bioelectrical impedance improve the prediction of body fat in patients with eating disorders? Eur J Clin Nutr 1993;47:741
197. Catalano G, Della-Vittoria-Scarpati M, De-Vita F, et al. The role of "bioelectrical impedance analysis" in the evaluation of the nutritional status of cancer patients. Adv Exp Med Biol 1993;348:145
198. Stolarczyk LM, Heyward VH, Hicks VL, et al. Predictive accuracy of bioelectrical impedance in estimating body composition of Native American women. Am J Clin Nutr 1994;59:964
199. de Waart FG, Li R, Deurenberg P. Comparison of body composition assessments by bioelectrical impedance and by anthropometry in premenopausal Chinese women. Br J Nutr 1993;69:657
200. Azcue M, Fried M, Pencharz PB. Use of bioelectrical impedance analysis to measure total body water in patients with cystic fibrosis. J Pediatr Gastroenterol Nutr 1993;16:440
201. Risser JM, Rabeneck L, Foot LW, et al. A comparison of fat-free mass estimates in men infected with the human immunodeficiency virus. JPEN 1995;19:28
202. Ott M, Fischer H, Polat H, et al. Biolectrical impedance analysis as a predictor of survival in patients with human immunodeficiency virus infaction. J Acquir Immune Defic Syndr Hum Retrovirol 1995;9:20
203. Kotler DP, Burastero S, Wang J, et al. Prediction of body cell mass, fat-free mass, and total body water with bioelectrical-imedance analysis: effects of race, sex and disease. Am J Clin Nutr 1996;64:489
204. Paton NI, Macallan DC, Jebb SA, et al. Longitudinal changes in body composition measured with a variety of methods in patients with AIDS. J Acquir Immune Defic Syndr Hum Retrovirol 1997;14:119
205. Wang Z M, Visser M, Ma R, et al. Skeletal muscle mass: evaluation of neutron activation and dual-energy x-ray absorptiometry methods. J Appl Physiol 1996;80:824
206. Ma R, Kotler DP, Wang J, et al. Reliability of in vivo neutron activation analysis for measuring body composition: comparisons with tracer dilution and dual-energy x-ray absorptiometry. J Lab Clin Med 1996;127:420
207. Ross R, Leger L, Boulier A. Comparison of tetra- and bipolar impedance to assess body composition. Communication to Kinanthropometry IV Conference. J Sports Sci 1990;8:172
208. Patterson R, Ranganatha C, Engel R, et al. Measurement of body fluid volume change using multisite impedance measurements. Med Biol Eng Comput 1988;26:33
209. Lukaski HC. Comparison of promimal and distal placements of electrodes to assess human body composition by bioelectrical impedance. Basic Life Sci 1993;60:39
210. Gleichaug CN, Roe DA. The menstrual cycle's effect on the reliability of bioimpedance measurements for assessment body composition. Am J Clin Nutr 1989;50:903
211. Mitchell CO, Rose J, Familoni B, et al. The use of multifrequency bioelectrical impedance analysis to estimate fluid volume changes as a function of the menstrual cycle. Basic Life Sci 1993;60:189
212. Caton J, Mole PA, Adams WC, et al. Body composition analysis by bioelectrical impedance: effect of skin temperature. Med Sci Sports Exerc 1988;20:489
213. Chumlea WC, Roche AF, Guo S, et al. The influence of physiologic variables and oral contraceptives on bioelectrical impedance. Hum Biol 1987;59:257
214. Fogelholm M, Sievanen H, Kukkonen-Harjula K, et al. Effects of meal and its electrolytes on bioelectrical impedance. Basic Life Sci 1993;60:331
215. Pinilla JC, Webster B, Baetz M, et al. Effect of body positions and splints in bioelectrical impedance analysis. JPEN 1992;16:408

216. van Marken-Lichtenbelt WD, Westerterp KR, Wouters L, et al. Validation of bioelectrical-impedance measurements as a method to estimate body-water compartments. Am J Clin Nutr 1994;60: 159
217. Heitmann BL. Impedance: a valid method in assessment of body composition? Eur J Clin Nutr 1994;48:228
218. Maughan RJ. An evaluation of bioelectrical impedance analyser for the estimation of body fat content. Br J Sports Med 1993; 27:63
219. Kushner RF, Schoeller DA, Fjeld CR, et al. Is the impedance index (Ht^2/R) significant in predicting total body water? Am J Clin Nutr 1992;56:835
220. Tagliabue A, Cena H, Tretani C, et al. How reliable is bioelectrical impedance analysis for individual patients? Int J Obes 1992;16:649
221. Eckerson JM, Housh TJ, Johnson GO. Validity of bioelectrical impedance equations for estimating fat-free weight in lean males. Med Sci Sports Exerc 1992;24:1298
222. Chumlea WC, Guo SS. Bioelectrical impedance and body composition: present status and future directions. Nutr Rev 1994;52:124
223. Thomas BJ, Cornish BAH, Ward LC. Bioelectrical impedance analysis for measurement of body fluid volumes: a review. J Clin Eng 1992;17:505
224. Espejo MG, Neu J, Hamilton L, et al. Determination of extracellular fluid volume using impedance measurement. Crit Care Med 1989; 17:360
225. Cornish BAH, Ward LC, Thomas BJ. Measurement of extracellular and total body water of rats using multiple frequency bioelectrical impedance analysis. Nutr Res 1992;12:657
226. Cornish BAH, Ward LC, Thomas BJ. Alteration of the extracellular and total body water volumes measured by multiple frequency bioelectrical impedance analysis (MFBIA). Nutr Res 1994;14:717
227. Pullicino E, Coward WA, Elia M. The potential use of dual frequency impedance in predicting the distribution of total body water in health and disease. Clin Nutr 1992;11:69
228. Van Loan MD, Mayclin PL. Use of multifrequency bioelectrical impedance analysis for the estimation of extracellular fluid. Eur J Clin Nutr 1992;46:117
229. Cornish BAH, Thomas BJ, Ward LC. Improved prediction of extracellular and total body water using impedance loci generated by multiple frequency bioelectrical impedance analysis. Phys Med Biol 1993;38:337
230. Katzarski K, Charra B, Laurent G, et al. Multifrequency bioimpedance in assessment of dry weight in haemodialysis. Nephrol Dial Transplant 1996;11:20
231. Ward LC, Cornish BAH, Thomas BJ. Multifrequency bioelectrical impedance augments the diagnosis and management of lymphoedema in post-mastectomy patients. Eur J Clin Invest 1992; 22:751
232. Smye SW, Sutcliffe J, Pitt E. A comparison of four commerical systems used to measure whole-body electrical impedance. Physiol Meas 1993;14(4):473
233. Lukaski HC, Bolonchuk WW, Hall CB, et al. Validation of tetrapolar bioelectrical impedance method to assess human body composition. J Appl Physiol 1986;60:1327
234. National Institute of Health. *Bioelectrical impedance analysis in body composition measurement.* Bethesda, MD:US Department of Health and Human Services, 1994
235. Martin AD, Drinkwater DT. Variability on the measures of body fat. Sports Med 1991;11:277
236. Nielsen DH, Cassady SL, Wacker LM, et al. Validation of the Futrex 5000 near-infrared spectrophotometer analyzer for assessment of body composition. J Orthop Sports Phys Ther 1992;16:281
237. Cassady SL, Nielsen DH, Janz KF, et al. Validity of near-infrared body composition analysis in children and adolescents. Med Sci Sports Exerc 1993;25:1185
238. Franssila-Kallunki A. Comparison of near-infrared light spectroscopy, bioelectrical impedance and tritiated water techniques for the measurement of fat-free mass in humans. Scand J Clin Lab Invest 1992;52:879
239. Wilson WL, Heyward VH. Validation of the near-infrared interactance method for native Indian, black, Hispanic and white men 19 to 57 years. Basic Life Sci 1993;60:389
240. Quatrochi JA, Hicks VL, Heyward VH. Relationship of optical density and skinfold measurements: effects of age and level of body fatness. Res Q Exerc Sport 1992;63:402
241. Nord RH, Payne RK. Body composition by DEXA-a view of the technology. Asia Pac J Clin Nutr 1994;3:15
242. Slosman DO, Casez JP, Pichard C, et al. Assessment of whole-body composition with dual-energy x-ray absorptiometry. Radiology 1992;185:593
243. Jensen MD, Kanaley JA, Roust LR, et al. Assessment of body composition with use of dual-energy x-ray absorptiometry: evaluation and comparison with other methods. Mayo Clin Proc 1993;68: 867
244. Wellens R, Chumlea WC, Guo S, et al. Body composition in white adults by dual-energy x-ray absorptiometry, densitometry, and total body water. Am J Clin Nutr 1994;59:547
245. Pritchard JE, Nowson CA, Strauss BJ, et al. Evaluation of dual energy x-ray absorptiometry as a method of measurement of body fat. Eur J Clin Nutr 1993;47:216
246. Clark RR, Kuta JM, Sullivan JC. Prediction of percent body fat in adult males using dual energy x-ray absorptiometry, skinfolds, and hydrostatic weighing. Med Sci Sports Exerc 1993;25:528
247. Hansen NJ, Lohman TG, Going SB, et al. Prediction of body composition in premenopausal females from dual-energy x-ray absorptiometry. J Appl Physiol 1993;75:1637
248. Snead DB, Birge SJ, Kohrt WM. Age-related differences in body composition by hydrodensitometry and dual-energy x-ray absorptiometry. J Appl Physiol 1993;74:770
249. Johansson AG, Forslund A, Sjodin A, et al. Determination of body composition-a comparison of dual-energy x-ray absorptiometry and hydrodensitometry. Am J Clin Nutr 1993;57:323
250. Going SB, Massett MP, Hall MA, et al. Detection of small changes in body composition by dual-energy x-ray absorptiometry. Am J Clin Nutri 1993;57:845
251. Hicks VL, Heyward VH, Baumgartner RN, et al. Body composition of Native American women estimated by dual-energy x-ray absorptiometry and hydrodensitometry. Basic Life Sci 1993;60:89
252. Svendsen OL, Haarbo J, Hassager C, et al. Accuracy of measurements of body composition by dual-energy x-ray absorptiometry in vivo. Am J Clin Nutr 1993;57:605
253. Chilibeck P, Calder A, Sale DG, et al. Reproducibility of dual-energy x-ray absorptiometry. Can Assoc Radiol J 1994;45:297
254. Lukaski HC. Soft tissue composition and bone mineral status: evaluation by dual-energy x-ray absorptiometry. J Nutr 1993;123(suppl): 438
255. Martin A. Dual-energy x-ray absorptiometry: the new gold standard for body composition? Kinanthreport 1994;8:2
256. Withers RT, Smith DA, Chatterton BE, et al. A comparison of four methods of estimating the body composition of male endurance athletes. Eur J Clin Nutr 1992;46:773
257. Haarbo J, Gotgreden A, Hassager C, et al. Validation of body composition by dual-energy x-ray absorptiometry. Clin Physiol 1991;11:331
258. Herd RJ, Blake GM, Parker JC, et al. Total body studies in normal British women using dual-energy x-ray absorptiometry. Br J Radiol 1993;66:303
259. Compston JE, Bhambhani M, Laskey MA, et al. Body composition and bone mass in post-menopausal women. Clin Endocrinol 1992; 37:426
260. Rico H, Revilla M, Hernandez ER, et al. Four-compartment model of body composition on normal elderly women. Age Ageing 1993;22: 265
261. Chan GM. Performance of dual-energy x-ray absorptiometry in evaluating bone, lean body mass, and fat in pediatric subject. J Bone Miner Res 1992;7:369
262. Ellis KJ, Shypailo RJ, Pratt JA, et al. Accuracy of DXA-based body composition measurements for pediatric studies. Basic Life Sci 1993; 60:153
263. Faulkner RA, Bailey DA, Drinkwater DT, et al. Regional and total body bone mineral content, bone mineral density, and total body tissue composition in children 8-16 years of age. Calcif Tissue Int 1993;53:7
264. Rico H, Revilla M, Hernandez ER, et al. Bone mineral content and body composition in postpubertal cyclist boys. Bone 1993; 14:93

265. Rico H, Revilla M, Villa LF, et al. Body composition in children and Tanner's stages: a study with dual-energy x-ray absorptiometry. Metabolism 1993;42:967
266. Kooh SW, Noriega E, Leslie K, et al. Bone mass and soft tissue compartments in adolescents with anorexia nervosa. Basic Life Sci 1993;60:173
267. Lloyd R, Rollings N, Andon MB, et al. Determinants of bone density in young women. I. Relationships among pubertal development, total body bone mass, and total body bone density in premanarchal females. J Endocrinol Metab 1992;75:383
268. White CM, Hergenroeder AC, Klish WJ. Bone mineral density in 15- to 21 year old eumenorrheic and amenorrheic subjects. Am J Dis Child 1992;146:31
269. Venkataraman PS, Ahluwalia BW. Total bone mineral content and body composition by x-ray densitometry in newborns. Pediatrics 1992;90:767
270. Brunton JA, Bayley HS, Atkinson SA. Validation and application of dual-energy x-ray absorptiometry to measure bone mass and body composition in small infants. Am J Clin Nutr 1993;58:839
271. Van-Loan MD, Mayclin PL. Body composition assessment: dual-energy x-ray absorptiometry (DEXA) compared to reference methods. Eur J Clin Nutr 1992;46:125
272. Orme SM, Sebastian JP, Oldroud B, et al. Detection of small changes in body composition by dual-energy x-ray absorptiometry. Clin Endocrinol 1992;37:453