

## REVIEW

## Measuring body composition\*

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Several aspects of body composition, in particular the amount and distribution of body fat and the amount and composition of lean mass, are now understood to be important health outcomes in infants and children. Their measurement is increasingly considered in clinical practice; however, paediatricians are often unsure as to which techniques are appropriate and suitable for application in specific contexts. This article summarises the pros and cons of different techniques in various clinical situations. Simple techniques are adequate for many purposes, and simple regional data may often be of greater value than "whole body" values obtained by more sophisticated approaches.

circumstances. A further important issue is that of the difficulty of validating techniques in humans, where the gold standard—chemical analysis of the carcass—is not possible. In vivo techniques do not measure body composition directly, but rather predict it from measurements of body properties. Thus all techniques suffer from two types of error: first, methodological error when collecting raw data; and second, error in the assumptions by which raw data are converted to final values. The relative magnitude of these errors varies between techniques, and this issue must be addressed when selecting methodology.

The aim of this review is to discuss available techniques for assessing body composition, together with their theoretical basis, assumptions, and advantages and disadvantages, and to suggest which techniques are most suitable in different situations.

## TECHNIQUES FOR MEASURING BODY COMPOSITION

## Simple measurements or indices

Traditionally, *skinfold thickness* measurements have been used to rank individuals in terms of relative "fatness" or to assess the size of specific subcutaneous fat depots.<sup>3</sup> Skinfold measurements have the advantage of being quick and simple to obtain in most age groups, including young infants, although toddlers can quickly become distressed. In general, intraobserver and interobserver error is low compared with between subject variability, but in obese children accuracy and precision are poorer. In addition, the commonly measured skinfolds are those in the arm (biceps and triceps) and trunk (subscapular and suprailiac), whereas the leg, which may be a significant component of body fat,<sup>4</sup> is ignored.

The best use of skinfold thicknesses is as raw values, where they act as relatively reliable indices of regional fatness. They can be converted into standard deviation score (SDS) format for longitudinal evaluations. However, whereas UK reference data for infants and toddlers up to 2 years are relatively recent,<sup>5</sup> children's reference data currently remain those of Tanner and Whitehouse from 1975, with equations for the calculation of SDSs subsequently reported.<sup>6</sup> The publication of contemporary children's skinfold reference data is therefore a current research priority, which we are addressing. Although the contemporary epidemic of obesity presents chal-

Body composition and growth are key components of health in both individuals and populations. The ongoing epidemic of obesity in children and adults has highlighted the importance of body fat for short term and long term health.<sup>1</sup> However, other components of body composition also influence health outcomes, necessitating a broader approach.

Body composition is important in two main contexts. First, it is an important determinant of disease course and outcome in the clinical setting, and is potentially amenable to intervention. In some diseases (obesity, eating disorders) body composition represents the primary symptom and therefore underpins diagnosis. Second, body composition, including the propensity to obesity, may be "programmed" by environmental factors operating in early life,<sup>2</sup> placing particular emphasis on optimal nutrition during infancy. The ontogenetic development of body composition may itself comprise the mechanism whereby early nutrition affects later health. Thus the increasing interest of paediatricians in body composition parallels their growing awareness of the importance of nutritional management during infancy and childhood. For example, body composition represents a better guide to energy and fluid requirements than body weight alone, which can often conceal abnormal levels of body fat.

The gold standard for body composition analysis is cadaver analysis, so no in vivo technique may be considered to meet the highest criteria of accuracy. Various techniques are available, varying in complexity and ease of use, and each making assumptions that may affect its suitability for different conditions. It is clear, given the disparate areas in which body composition may be important, that a single technique is unlikely to be optimal in all

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**Abbreviations:** BIA, bioelectric impedance analysis; BMI, body mass index; DXA, dual energy x ray absorptiometry; FFM, fat-free mass; FM, fat mass; TBW, total body water; TOBEC, total body electrical conductivity

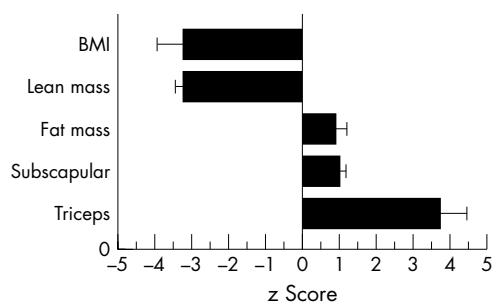
allenges for body composition reference data, whether *individual* patients are becoming more or less fat over time can only be assessed through comparison with a reference population. Such data would therefore represent a “reference” (what exists), but not a “standard” (what should exist).

The use of skinfold data in prediction equations (see below) or ratios is more problematic. From a statistical perspective, ratios adjusting one regional skinfold for another are an unsatisfactory approach for evaluating relative central fatness.<sup>7</sup> Consistent with this argument, our unpublished analyses indicate that triceps or subscapular skinfolds are better correlated with plasma lipids or blood pressure during childhood and adolescence than are either subscapular/triceps or triceps/subscapular ratios. However, no skinfold measurement can directly assess the visceral fat depot, which is most strongly associated with later health outcomes.

*Body mass index* (BMI, calculated as weight/height<sup>2</sup>) is also widely used in clinical practice as an index of relative weight, often expressed as SDS to take into account the effects of age and sex.<sup>8</sup> In adult populations, BMI is clearly predictive of clinical outcomes such as type 2 diabetes; however, its predictive value for outcome in children and adolescents is less clear. In children, BMI is a global index of nutritional status, used for example to categorise both overweight/obesity<sup>9</sup> and eating disorders in combination with psychological criteria,<sup>10</sup> but its relation with body composition per se is controversial.

Several studies have reported high correlations between BMI and per cent fat ([fat mass/weight] \* 100%).<sup>11, 12</sup> However, BMI cannot distinguish fat and lean masses, and though each of these can be correlated with BMI, there is a twofold range of variation in fatness for a given BMI value in individual children.<sup>13</sup> The relation between BMI and per cent fat varies with ethnicity,<sup>14</sup> and appears plastic within populations over time.<sup>15</sup> BMI may be particularly misleading in hospital patients, where children who are apparently “malnourished” in terms of their BMI may actually have an increase in relative body fat and a severe decrease in lean tissue when these components are individually measured (fig 1).<sup>16</sup> This could be important for their nutritional management, as the low BMI may lead to inappropriate overfeeding which will only further increase the fat mass.

*Waist circumference* is increasingly used as a simple measure of central fatness, which may be more predictive of adverse outcomes such as lipid profile or insulin resistance than total fat. In adults, the waist–hip ratio is independently associated with morbidity after adjustment for relative weight, such that the use of relative weight and body shape simultaneously gives a better estimate of risk of morbidity than either alone.<sup>17, 18</sup> Similar findings are now emerging in children.<sup>19</sup>



**Figure 1** Data from infant patients with congenital myasthenia, a condition in which the development of connective tissue is impaired. Despite extremely low BMI SDS, the patients have body fat levels higher than the average in healthy children. This paradox can be attributed to extremely low levels of lean mass.<sup>9</sup> Though the children are underweight, energy intake is not itself constraining their growth.

Reference data on waist circumference were obtained from a nationally representative sample of UK children in 1988 and are now published,<sup>20</sup> along with appropriate software for the calculation of standard deviation scores.

Studies investigating the relation of waist circumference to magnetic resonance imaging (MRI) measures of abdominal fatness have shown correlations consistently in the range of 0.5 to 0.8, although the associations with total abdominal fat tend to be higher than those with intra-abdominal fat.<sup>21–23</sup> In contrast, studies reporting the association between waist–hip ratio and abdominal fat are inconsistent, and some find no significant relation.<sup>21, 24</sup> Hence waist circumference should be considered the best simple proxy for abdominal fat.

### Predictive techniques

Both skinfold thickness and bioelectric impedance measurements can be used to *predict* body composition. A generic problem with this approach is that it involves not one but two predictions. First, raw measurements are used to predict a body component or property using regression equations; second, this value is converted to final body composition data using further theoretical assumptions. In this section, we address the first of these issues. The second is then addressed in the following section, reviewing two-component body composition methods.

Several equations have been derived for the prediction of percent fat or body density from two or more skinfold thickness measurements.<sup>25–28</sup> Further equations may then be required to convert density values in order to predict the percentage fat (see below). Skinfold predictive equations have generally been derived from comparisons with two-component models (but see Slaughter *et al*<sup>27</sup>) in healthy white populations, and there is evidence that they have limited use beyond the population from which they were derived, in part due to population differences in fat patterning.<sup>29</sup> Accuracy in individuals has been found to be poor (limits of agreement  $\pm 9\%$  fat), and also to vary in relation to the magnitude of body fatness,<sup>30, 31</sup> making this approach unsuitable for longitudinal comparisons.

Prediction equations inevitably confound accurate raw values with predictive error (standard error of the estimate). Hence, for assessment of fatness, it is better to leave skinfolds in raw form or as SDS, where they act as reliable indices of regional fatness, than to attempt prediction of total fat mass. For assessment of total fat-free mass (FFM), an approach based on skinfold equations is particularly inappropriate, as no index of this component of weight is directly measured.

A simpler approach uses skinfold thickness measurements in combination with mid-upper arm circumference (MUAC) to predict the cross sectional area of fat in the arm, and hence, by difference from total area, the cross sectional area of lean mass. However, we have recently shown that the index of fatness is little more informative than skinfold values alone, as skinfold thickness values and MUAC are inevitably highly correlated. Furthermore, the index of arm lean mass shows only moderate correlations with either arm lean mass as measured by dual energy x ray absorptiometry (DXA), or total body lean mass as measured by a multi-component model.<sup>32</sup>

*Bioelectric impedance analysis* (BIA) measures the resistivity or impedance of the body to a small electric current (undetectable to the subject). BIA exploits the fact that lean tissue contains a high level of water and electrolytes and therefore acts as an electrical conductor. The generic theoretical model treats the body as a single cylinder, with measurements made between electrodes placed manually on the wrist and ankle. Adjustment of bioelectrical data for cylinder length (usually height, as a proxy) then allows estimation of cylinder volume (total body water). In practice,

this requires the empirical derivation of regression equations relating the square of height divided by impedance to total body water. These equations are then applied subsequently to predict total body water, which is converted to fat-free mass as described below.

BIA incorporates various assumptions. The simplest model, involving hand-foot or foot-foot measurements made at a frequency of 50 KHz, relies most heavily on these assumptions, and therefore provides the crudest values for body composition. The slope of regression equations relating BIA data to total body water is influenced by the age range investigated and other characteristics of the population. Published BIA equations are population specific and perform poorly in healthy individuals, with errors typically  $\pm 8\%$  fat.<sup>31</sup> Paediatric whole body equations have been derived for disease states such as obesity,<sup>33</sup> cystic fibrosis,<sup>34</sup> and HIV<sup>35</sup>; however, accuracy in individuals inevitably remains poor and measurements may be confounded by clinical status—for example, the presence of oedema (see below). Foot-foot measurements, though easier to obtain using equipment similar to bathroom scales, have slightly poorer accuracy than whole body measurements.<sup>36</sup> Replacing simple equations based on height<sup>2</sup>/impedance with others using separate terms for height, reactance, and resistance can reduce the standard error with which outcomes are predicted,<sup>37</sup> but is unlikely to resolve the problems of whole body BIA.

Despite these limitations, more sophisticated approaches to BIA have the potential both to improve accuracy and to increase the specificity of outcomes, and such progress is desirable given the ease with which measurements can be made in most age groups.

The assumption that the body represents a single cylinder is invalid, and the regional distribution of body weight does not match the distribution of impedance. For example, in children aged 8–12 years, the contributions of the arm, the trunk, and the leg to total weight are 5%, 40%, and 17%, respectively, whereas the contribution of these segments to total body impedance are 50%, 7%, and 43%, respectively.<sup>4 38</sup> This mismatch is because the limbs are relatively long thin electrical conductors that impede the current flow to a greater degree than the shorter, thicker trunk. Inconsistencies between individuals in body geometry and build therefore result in different whole body impedance even for individuals with the same overall body composition. This may be a particular problem in children of differing ages and stages of puberty, as well as in patients with altered body proportions as a result of their underlying condition.

This scenario can potentially be addressed by making BIA measurements of specific body segments. BIA data from the limbs show high correlations with fat and fat-free masses obtained by DXA, but the equivalent correlations for the trunk are poorer.<sup>4</sup> A proportion of newer BIA instrumentation is replacing the hand placed electrode approach with fixed footplates and hand grips. This segmental instrumentation has the potential to derive segment specific outcomes; however, validation studies have yet to be completed, and reference data will be required to interpret measurements in individuals.

An alternative strategy is the collection of BIA data at different frequencies, allowing the discernment of different fluid compartments. At low frequencies, electrical current cannot cross cell membranes, and hence passes through extracellular water only. At higher frequencies all lean tissue is penetrated. Theoretically, simultaneous measurements at multiple frequencies can therefore distinguish extracellular and total body water, and thus calculate intracellular water by difference. Such research in adults is proving promising,<sup>39 40</sup> and is already being explored in children. We believe that this approach is likely to develop successfully, and allow

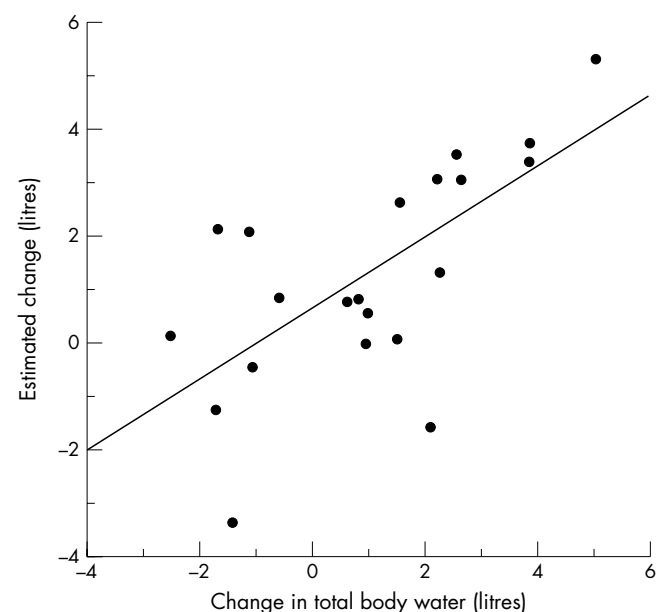
the monitoring of hydration in clinical management. However, these future benefits are separate from the current potential of BIA to predict fat and lean mass.

What can BIA currently offer the paediatrician? We suggest that conventional BIA analysis is inherently unsuited to the prediction of body fatness in individuals, given that it measures properties of the fat-free mass only. Conventional single frequency BIA does have high precision, providing electrode placement is consistent, and hence could be suitable for assessing short term *changes* in total body water (TBW) within individuals. Given that children's body build is relatively consistent over short time periods, such measurements could in turn indicate the *direction* of changes in fat-free mass, but are unlikely to quantify their *magnitude* with accuracy. BIA measurements are sensitive to numerous factors that influence fluid distribution, such as whether the subject has recently consumed fluid or undertaken exercise, and even the time of day. The less control there is over such factors, the greater the likelihood of error, especially when evaluating longitudinal changes. For example, fig 2 shows measured versus predicted (using BIA) change in body water over 6 months in obese children, using an equation developed for this population. The error in individuals is large, and the technique would not demonstrate change in fatness successfully. These issues should be borne in mind as reference data for BIA data become available.

At present, the value of BIA is primarily as an epidemiological technique, where it is the only predictive technique that estimates lean mass (providing it is validated in the population where it is applied). It could fulfil two functions in clinical paediatrics: first, the prediction of segmental tissue masses; and second, the monitoring of fluid distribution. In both cases, further work is required before routine clinical application is recommended.

### Two-component techniques and models

Two-component methods divide the body into fat mass (FM) and fat-free mass. They avoid two of the difficulties mentioned above, addressing both components of weight



**Figure 2** Change in total body water either measured (using deuterium dilution), or predicted using bio-electrical impedance analysis. The subjects were 21 obese patients measured 6 months apart. Body water was predicted from height and impedance using an equation generated by ourselves in 80 obese children.

and avoiding the need to predict total masses from regional or superficial proxies. However, they remain dependent on theoretical assumptions, such as constancy of the composition of fat-free mass. Between birth and adulthood, chemical maturation of lean mass occurs, whereby the relative proportions of the three main components (water, protein, and mineral) change with age and pubertal status. In two-component techniques, these changes are addressed by assuming constant lean mass characteristics for a given age and sex. Such assumptions may largely hold true for healthy subjects but are more problematic in patients who may have deranged body composition or hydration. Various methods are available.

### Dual energy x ray absorptiometry

DXA was introduced as a technique for measuring bone mass, primarily in order to screen for and monitor osteoporosis in adults. Bone mineral mass is calculated from the differential absorption of x rays of two different energies. However, this calculation requires allowance for (and hence quantification of) overlying soft tissue. Using algorithms that are specific to the manufacturer and instrument model, values of fat and fat-free mass are also calculated for whole body scans.

DXA has the advantage of being fairly quick and acceptable to children down to about 4 years of age. It can also be employed in small infants. It uses ionising radiation, but the effective dose equivalents of contemporary instrumentation are below background levels, making it acceptable for use even in healthy children. However, although this method is now widely accepted and used as a measure of body composition, particularly in the USA, problems with accuracy have received insufficient attention. Bias in the measurement of fat mass varies with age and fatness and, in some cases, underlying disease state.<sup>41</sup> Comparisons between groups are likely to identify the direction of changes, but fail to quantify the difference accurately, while the accuracy with which changes can be quantified within individuals gaining/losing weight is likewise liable to be confounded by the change in weight status. Variability in hydration has also been identified as a source of error, though of moderate magnitude.<sup>42</sup> Thus, although DXA studies increasingly



**Figure 3** A child sitting inside the measurement chamber of the whole body air displacement plethysmograph, known as the Bodpod (Life Measurements Inc, California). The measurement involves air being gently blown around the subject during two 1 minute measurement periods, while the subject breathes normally. Written permission was obtained from the child's parents for the publication of this photograph.

contribute to the evidence base for clinical paediatrics, such studies should be interpreted with caution.

The limitations of DXA vary according to body geography. The technique only estimates the relative proportions of fat and lean tissue in pixels containing no bone. In the limbs, this allows the majority of pixels to undergo soft tissue analysis, but in the trunk, the pelvis, spine and ribs obscure substantial numbers of pixels. In such cases the composition of soft tissue overlying bone is predicted from adjacent pixels that do not contain bone; however, in lean individuals few such bone-free pixels are available. Thus trunk composition involves substantial prediction rather than measurement, and soft tissue estimation in this area is less accurate than in the limbs.

DXA may provide useful information on relative fat and lean masses as a single measurement in an individual, particularly with respect to limb lean mass. However, such assessments are currently hampered by the lack of normal reference data for fat and fat-free mass during childhood. This issue is being addressed, and age and sex specific fat and fat-free mass SD scores will be available shortly. In contrast to the limitations of DXA for measurement of body composition, measurement of bone mass is relatively precise and accurate, although values vary according to instrumentation.<sup>43</sup> These values are used in the four-component model (see below).

### Densitometry

The densitometric approach uses Archimedes' principle to distinguish the fat and fat-free components of weight, assuming specific densities of these two tissues,<sup>44</sup> and therefore requires the measurement of total body density (body mass/body volume). While the density of fat is indeed relatively constant, that of fat-free mass varies according to the relative proportions of water, mineral, and protein. This variability is partly explained by the process of chemical maturation that occurs before adulthood,<sup>45</sup> and can be taken into account using age and sex specific equations for the conversion of body density to final body composition values. Two such sets of equations have been published, and provide relatively similar results<sup>46-47</sup> owing to the fact that both rely heavily on the estimations of fat-free mass density proposed in the reference child.<sup>45</sup> Subsequent research has shown that these values are biased in contemporary children, and also that interindividual variability is significant even in healthy children.<sup>31</sup>

Traditionally, body volume was measured by hydrodensitometry; however, this approach is clearly unsuitable for many children, especially patients. A new alternative is whole body air displacement plethysmography or the "Bodpod" (Life Measurement Inc, Concord, USA; fig 3). The technique measures the volume of air displaced by the subject, using pressure changes induced by an oscillating diaphragm according to Boyle's laws of the relations between the volume, pressure, and temperature of gases. Raw data are corrected for thoracic gas volume and surface area artefact using appropriate prediction equations for children.<sup>48-50</sup> The technique has better precision than hydrodensitometry in children,<sup>49-51</sup> and is acceptable in children as young as 4 years. An infant plethysmograph (PeaPod) has also become available, allowing measurement of body volume during the first 6 months of life.<sup>52-53</sup>

The main sources of measurement error are movement artefacts during the measurement period, and the approach used to measure or predict lung volume. Movement artefacts can be resolved by obtaining repeat measurements to screen for rogue values.<sup>54</sup> Many paediatric researchers predict rather than measure lung volume. Measurements of lung volume and body volume are not simultaneous; hence any advantage

**Table 1** Summary of assumptions underlying different techniques, their availability, and their main advantages and disadvantages

Technique	Assumptions made	Reference data	Availability*	Advantages/disadvantages
Skinfolds – raw	Constant skin protein content	Y	+++	For: simple measure of regional fat Against: no information on lean mass
Skinfolds – equations	Skinfolds $\propto$ whole body fat	N	+++	For: simple and quick Against: population specific, poor accuracy in individuals and groups
Body mass index	Var weight = var fat	Y	+++	For: simple and quick Against: measures nutritional status not body composition
Waist circumference	Waist $\propto$ central fat	Y	+++	For: simple, quick, robust measure of abdominal fat Against: not so accurate as measure of internal visceral fat
Impedance	Conductivity $\propto$ body water	N	++	For: simple and quick Against: population specific; poor accuracy in individuals and groups
DXA	Constant attenuations of FFM and F	N	++	For: accurate for limb lean and fat Against: radiation exposure; whole body bias ?size, sex, fatness
Densitometry†	Constant $D_{\text{ffm}}$ and $D_{\text{f}}$	N	+	For: acceptable two-component technique Against: effects of disease on lean mass reduce accuracy
Isotope dilution	Constant $H_{\text{ffm}}$	N	+	For: only technique acceptable in all age groups Against: delayed results; inaccurate if disease affects $H_{\text{ffm}}$
MRI	Electromagnetic properties	N	+	For: accurate for regional AT Against: expensive, limited availability, measures AT not fat
TOBEC	Conductivity $\propto$ body water	N	+	For: acceptable two-component technique Against: rarely available, accuracy unknown
TBK	Constant K in cell mass	N	+	For: measures functional component of body composition Against: rarely available, poor accuracy for fatness
Multicomponent models	Constant $D_{\text{prot}}$ and $D_{\text{min}}$ , constant mineral composition	N	+	For: most accurate approach, all measurements acceptable Against: expensive, specialist research approach

\*Availability: +, low; ++, medium; +++, high.

†Densitometry by air displacement plethysmography (Bodpod)

AT, adipose tissue;  $D_{\text{f}}$ , density of fat;  $D_{\text{ffm}}$ , density of fat-free mass;  $D_{\text{min}}$ , density of mineral;  $D_{\text{prot}}$ , density of protein; F, fat; FFM, fat-free mass;  $H_{\text{ffm}}$ , hydration of fat-free mass; K, potassium; Var, variability.

of measurement over prediction is offset by possible inconsistency of the subject between the periods. The protocol requires the subject to exhale forcibly into a tube, which many children find difficult. Finally, values for lung volume (functional residual capacity plus half tidal volume) are multiplied by 0.4 before being applied in corrections to body volume, so any error from either approach is similarly reduced in magnitude. Lung volume prediction equations in children have relatively high accuracy, and may introduce less error than direct measurement. Until recently, it was necessary to predict functional residual capacity and tidal volume from different equations.<sup>55–56</sup> However, new equations are now available for children aged over 5 years (57). In practice, measuring and predicting lung volume have been shown to give similar body composition data.<sup>58</sup>

In general, densitometry is unsuitable for application as a two-component technique in patients where the composition of lean mass may be abnormal. Typical effects of disease are excess fluid retention and undermineralisation; both decrease the density of lean mass and hence lead to the overestimation of fatness. The main role of densitometry in children is likely therefore to be in multicomponent models, although the value of the infant version remains to be researched. However, in relative terms, densitometric errors are smaller in larger individuals. Recent studies have shown that childhood obesity is associated with increased hydration and mineralisation of fat-free mass<sup>59</sup>; however, these effects appear relatively stable over time. Thus densitometry may prove useful for monitoring changes in body composition over time in overweight or obese individuals, and its accuracy is less likely to be confounded by longitudinal changes in fatness, in contrast to DXA.

### Isotope dilution (hydrometry)

Deuterium dilution can be used to measure total body water (TBW), allowing the estimation of fat-free mass. A dose of water labelled with deuterium (a non-radioactive stable isotope of hydrogen) is given and, following equilibration, the enrichment of deuterium in the body water pool is measured using samples of either saliva, urine, or blood. Samples are generally analysed by isotope ratio mass spectrometry; however, clinical services could be based on a substantially cheaper but more labour intensive spectrophotometric technique.<sup>60</sup>

Blood samples are rarely required, with saliva optimal for children, and urine preferable in infants. In most age groups, a single post-dose sample is required to calculate total body water. However, in infants with rapid water turnover it is necessary to account for fluid intake during the equilibration period. This is most easily achieved by collecting post-dose samples over several days and calculating maximum post-dose enrichment through back extrapolation.<sup>61</sup> Ideally, correction for water intake during the equilibration period is also undertaken when measuring children, by recording fluid intake. In most children, four hours is sufficient for equilibration in saliva; however, six hours is recommended for obese individuals. Equilibration in urine takes longer, and this approach is unsatisfactory as it is difficult to predict the time when bladder urine content accurately reflects body water enrichment. For calculating TBW, it is assumed that the deuterium dilution space overestimates total body water by a factor of 1.044,<sup>62</sup> although in infancy this factor varies in relation to age.<sup>63</sup>

An alternative isotope, 18-oxygen (<sup>18</sup>O), can also be used. It is regarded as a slightly more accurate tracer for body

water, the magnitude of overestimation being 1.01.<sup>62</sup> Otherwise the protocol is identical to that for deuterium; however, <sup>18</sup>O is rarely used as the isotope is substantially more expensive.

Estimation of fat-free mass from total body water requires an assumed value for the hydration of fat-free tissue. Published reference values are relatively consistent with measured values in healthy infants and children,<sup>50</sup> with between-individual variability also relatively low.<sup>31–64</sup> However, in disease states variability in fat-free mass hydration may be substantially higher, owing to either overhydration or underhydration. In future, BIA may be used to assess whether hydration is abnormal or not; however, for now isotope dilution is best used in populations where the normality of hydration is known or can be assumed.

Isotope dilution is simple to perform and requires minimal subject cooperation. It has proved particularly valuable in infants and toddlers owing to the low compliance required, and can easily be used in field studies. In healthy subjects, body composition measurements obtained using deuterium dilution are accurate relative to multicomponent models, both in individuals and groups,<sup>31–36</sup> but it should be used with caution as a two-component method in disease states. Nevertheless, it could prove a useful clinical tool for individuals where normal hydration can be assumed. It has an essential role in multicomponent models (see below) when it enables quantification of relative hydration.

### Total body electrical conductivity

Total body electrical conductivity (TOBEC) is based on similar theoretical principles to BIA, using electrical conductivity of the body to predict its composition.<sup>65</sup> The subject is either placed within, or passed through, a large coil of wire termed a solenoid. Changes in the electromagnetic field induced by this current indicate the conductivity of the tissues, and are proportional to the amount of water. Raw conductivity data are converted into actual values for total body water and hence fat-free mass using equations determined empirically.<sup>66</sup>

Recent TOBEC instrumentation is less bulky than previously, and child specific versions are available. Although the technique remains rare, it is relatively easy and quick to use. However, it is influenced by environmental factors such as temperature and humidity, and its accuracy is poor when the subject is overhydrated or underhydrated. Most accurate results are obtained after a six hour fast, which reduces its routine applicability in paediatrics. Its agreement with other techniques is also poor, making it dependent on reference data specific to this method. Reference data have been published for Dutch infants,<sup>67</sup> but are not currently available for children.

### Total body potassium

Total body potassium (TBK) scanning is a technique based on the emission of <sup>40</sup>K by the body cell mass, and hence estimates this component of body composition. Subjects are scanned motionless and supine over a period of approximately 15 minutes. The technique is relatively non-invasive, although younger subjects may experience claustrophobia in some instruments, or may fail to comply with the protocol.

As an outcome, body cell mass has advantages over fat-free mass, as it reflects more directly the functional component of weight. In a few hospitals, it is measured routinely in the monitoring and treatment of paediatric patients—for example, discerning the nature of weight gain in the treatment of eating disorders. However, the equipment is expensive, bulky, and only available in specialised centres. It is less reliable than most two-component techniques in the

estimation of fat-free mass, due to uncertainty as to the potassium content of lean mass in younger age groups, and is hence unsuitable as a method for assessing fat mass. The lack of UK paediatric reference data is a particular drawback, given that this technique measures neither fat-free mass nor fat mass. Nevertheless, this method has the potential to guide clinical practice in various contexts should it become more widely available.

### Magnetic resonance imaging

MRI is an imaging technique that estimates the volume rather than the mass of adipose tissue. By analysing the absorption and emission of energy in the radio frequency range of the electromagnetic spectrum, the technique produces images based on spatial variations in the phase and frequency of the energy absorbed and emitted. It primarily addresses hydrogen nuclei, located either in water or fat, and uses these data to discern tissue types in “imaging slices” which can then be summed to calculate regional tissue volumes.

Despite the high quality of imaging data obtained by MRI, there are difficulties in comparing results with those obtained by other techniques. First, in order to derive fat mass, it is necessary to assume the fat content of adipose tissue and the density of fat. While the latter is relatively invariable, the former is not. However, few studies have been conducted to date and there are inadequate data. A second problem is that fat mass discerned by MRI is only that present in adipose tissue. Thus techniques such as densitometry, hydrometry, or multicomponent models quantify a different entity from MRI, total fat mass versus adipose tissue mass.

The main advantage of MRI over other techniques is its capacity for estimation of regional body composition, and it is currently the only accurate and viable approach for the estimation of intra-abdominal adipose tissue. Its main disadvantage is its relatively high cost and limited availability. Also, although infants and older children can be scanned without difficulty, it is unsuitable for younger children, who cannot comply with the measurement protocol. Where MRI cannot be used, recent studies support the use of waist circumference as a robust index of abdominal fat and a useful index of visceral fat.<sup>68</sup>

An alternative imaging technique is computed tomography (CT), based on  $x$  rays as opposed to radio waves. Its ability to differentiate tissue properties is superior to that of MRI, and in adults it is better at discerning visceral fat.<sup>69</sup> However, the high radiation dose per imaging slice makes it essentially unsuitable for routine paediatric use, although radiation exposure could be decreased if pixel resolution were likewise reduced.

### Multicomponent models

The value of multicomponent models lies in minimising the assumptions made in simpler models. Total body water and bone mineral are measured by techniques specifically designed for that purpose. Overall, this results in a greater degree of accuracy in the calculation of body composition (for example, fat mass, fat-free mass), as well as a variety of outcomes. Whereas two-component models assume key body properties, multicomponent models measure them, and can provide data on the hydration, density, and mineralisation of fat-free mass. In the absence of carcass analysis, these models are regarded as the gold standard for body composition measurement. However, owing to the lack of an alternative reference method they have not been directly validated. Because of the complex nature of the measurements and the equipment required, they are only suitable for use in research, and along with MRI for fat distribution should be regarded as the optimum approach for acquiring the evidence base to underpin clinical practice.

**Table 2** Illustration of the advantages and disadvantages of different techniques for measuring body composition in clinical practice. The patient is a 14 year old girl referred for assessment and management of obesity with associated type 2 diabetes. Which measurements might be useful in terms of baseline assessment and monitoring of body composition during weight loss?

Technique	Advantages	Disadvantages
<b>Simple measurements</b>		
Skinfold thickness	–	Poor accuracy and precision in obesity
BMI	Useful as a simple baseline and longitudinal measurement of relative weight	Will not allow assessment of fat and lean masses and changes in fat which may be more relevant in terms of metabolic risk
Waist circumference	Useful baseline and longitudinal measurement. Centile charts are available, and central fatness is of greater relevance to metabolic risk	
<b>Predictive measurements</b>		
Skinfold thickness equations predicting FM and FFM	–	Poor precision and accuracy—any error will be magnified by the use of prediction equations not derived from a comparable (obese) population
Whole body BIA	Could provide information on the direction of longitudinal changes in lean mass	Poor accuracy in absolute terms. Changes in body weight, the relative proportions of trunk and limbs, or FFM hydration with treatment could introduce further errors
<b>Two-component techniques</b>		
DXA	Could be used to measure regional (limb) lean mass which could provide information on whether weight loss is accompanied by changes in lean mass as well as fat mass	Limited use for measuring baseline fat mass or longitudinal changes in fat mass with weight loss, since measurements are known to be biased by body size (thickness)
Densitometry (BodPod)	Could provide longitudinal data on both lean and fat mass since its accuracy is less likely to be affected by changes in fatness.	Does not provide regional data
Deuterium dilution	Could estimate whole body lean mass	Results may be affected by the small differences in FFM hydration in obesity, but these have been quantified and could be adjusted for. Small differences in FFM hydration would introduce minor errors in the short term*

\*Multifrequency BIA could provide informative data on hydration in the future.  
 BIA, bioelectric impedance analysis; BMI, body mass index; DXA, dual energy x ray absorptiometry; FFM, fat-free mass; FM, fat mass.  
**Conclusions:** In practical terms, the techniques most useful in this patient are BMI and waist circumference for monitoring nutritional status and central fat distribution. If available, DXA could be used for assessing changes in limb lean mass, and densitometry or deuterium could also provide longitudinal data for both fat and lean mass.

**Table 3** Illustration of the advantages and disadvantages of different techniques for measuring body composition in clinical practice. The patient is a 10 year old boy with chronic renal failure on peritoneal dialysis. Which measurements might be useful in terms of baseline assessment and monitoring of body composition? In this child, measurement of lean mass would be potentially useful as a guide for basing nutritional requirements or drug doses, but measurements may be complicated by oedema or variation in fat-free mass hydration or both

Technique	Advantages	Disadvantages
<b>Simple measurements</b>		
Skinfold thickness	Useful index of regional fatness	Poorer accuracy and precision in obese/oedematous individuals
BMI	Useful as a simple baseline and longitudinal measurement of relative weight	Will not allow assessment of fat and lean masses and changes in fat which may be more relevant in terms of nutritional/drug requirements and metabolic risk
Waist circumference	Useful baseline and longitudinal measurement. Centile charts are available, and central fatness is of greater relevance to metabolic risk	Value may be limited in this child who is on peritoneal dialysis
<b>Predictive measurements</b>		
Skinfold thickness equations predicting FM and FFM	–	Poor precision and accuracy—any error will be to magnified by the use of prediction equations not derived from a comparable population
BIA	Could provide information on the direction of longitudinal changes in lean mass	Poor accuracy in absolute terms. Changes in body weight, the relative proportions of trunk and limbs, or FFM hydration will introduce further errors*
<b>Two-component techniques</b>		
DXA	Could be used to measure regional (limb) lean mass which could provide information on which to base nutritional requirements or drug doses	Limited use for measuring baseline fat mass or longitudinal changes in fat mass, since measurements are known to be biased by body size (thickness). In this child, skinfold thicknesses may already provide information on regional fatness
Densitometry (BodPod)	Could provide longitudinal data on both lean and fat mass since its accuracy is less likely to be affected by changes in fatness	Variations in the hydration (and therefore density) of FFM in this child will invalidate assumptions of constant density
Deuterium dilution	Could estimate whole body lean mass if hydration known, and could potentially aid calculation of dialysis fluids*	Results for both TBW and FFM may be affected by variation in hydration in this child*

\*Multifrequency BIA could provide informative data on hydration in the future.  
 BIA, bioelectric impedance analysis; BMI, body mass index; DXA, dual energy x ray absorptiometry; FFM, fat-free mass; FM, fat mass; TBW, total body water.  
**Conclusions:** In practical terms, the techniques most useful in this patient are BMI ± skinfold thickness measurement for monitoring fat mass and distribution. If available, DXA could be used for assessing changes in (limb) lean mass, which might be more relevant for nutritional requirements and drug doses. This technique will be of greater use in practice once reference data are available.

The three component model divides the body into fat, water, and remaining fat-free dry tissue. It avoids the assumption of constant hydration or density of fat-free mass, but assumes a constant ratio of protein to mineral. The model requires measurements of body weight, body volume (by plethysmography), and body water (by deuterium dilution). Taking into account the assumed densities of the components and the constant ratio of protein to mineral, fat mass is calculated as follows:

$$FM \text{ (kg)} = [(2.220 \times \text{body volume}) - (0.764 \times \text{TBW})] - (1.465 \times \text{body weight})$$

where volume is in litres, TBW in litres, and weight in kg.<sup>70</sup>

The four component model further divides fat-free dry tissue into protein and mineral, by measuring total body mineral (by DXA). This avoids the assumption of a constant protein to mineral ratio, but still assumes a constant ratio of bone mineral to total mineral. The mass attributed to protein also contains various other matter, including glycogen, free amino acids, and nucleic acids. Fat mass is calculated as follows:

$$FM \text{ (kg)} = [(2.747 \times \text{body volume}) - (0.710 \times \text{TBW})] + [(1.460 \times \text{BMC}) - (2.050 \times \text{body weight})]$$

where BMC is bone mineral content in kg.<sup>70</sup>

Studies increasingly demonstrate the greater accuracy of multicomponent models in quantifying fat and fat-free mass—for example, indicating an error of >1 kg in fat mass when using two-component techniques in obese children.<sup>59</sup> Studies also show the impact of paediatric diseases on hydration and mineralisation, which are important issues in their own right. The principal functional component of lean mass, protein mass, can only be quantified with accuracy if the water content of lean mass is measured.

The advantages and disadvantages of the various techniques, their availability, and the existence of reference data are summarised in table 1.

### NORMALISATION OF BODY COMPOSITION DATA

Although this review is concerned mainly with the measurement of body composition, it is relevant to discuss the use of the data obtained. This has been addressed in detail previously.<sup>71</sup> However, we briefly summarise this argument to emphasise the importance of data expression when measuring paediatric body composition.

Body composition measurements in children require normalisation for body size if comparisons within and between individuals or populations are to be meaningful. Traditionally, fat mass has been normalised by expressing it as a percentage of body weight, whereas fat-free mass tends to be expressed in absolute units unadjusted for body size. However, percentage fat remains influenced by the relative amount of fat-free tissue in body weight and, like BMI, is not an independent index of fatness. The pitfall of this approach is apparent in the patients in fig 1—these patients have high percentage of fat (40%), but this can be attributed more to low lean mass than to high fat mass. The natural alterations that occur in per cent fat over the course of development likewise reflect changes in fat-free mass as well as fat mass,<sup>13</sup> while the variable percentage of fat conceals the absolute increase in adiposity that occurs with excess weight gain.<sup>7</sup>

To resolve these issues, both fat mass and fat-free mass can be separately normalised for height. For most purposes, a simple approach is adequate, involving the calculation of *fat mass index* (fat mass/height<sup>2</sup>) and *fat-free mass index* (fat-free mass/height<sup>2</sup>). These discrete indices are analogous to BMI, being in the same units of kg/m<sup>2</sup>.<sup>72</sup> Plotting the two indices against each other illustrates clearly that, once height has been taken into account, individuals can vary in both their relative fat mass and their relative lean mass.<sup>73</sup> For certain analyses, it is more appropriate to adjust fat and fat-free mass

for height using multiple regression analysis. Nevertheless, we have argued previously that reference data for paediatric body composition should be presented as fat-free and fat mass indices,<sup>70</sup> as has recently been done for adults.<sup>74</sup> Using this approach, we suggest that variability in lean mass will for the first time be given the same emphasis as that already directed to fatness. This is an important point, as fat-free mass and its constituents may in many paediatric disease states be a more important determinant of health.

To some extent, the most appropriate normalisation for fat and fat-free mass depends on the question being asked. Moreover, the relative predictive value of different body composition indices for outcomes such as cardiovascular or diabetes risk has currently not been determined in children. At this stage it is therefore important to appreciate that the use of different methods for normalising and presenting data can have major effects on results and conclusions.

### RECOMMENDATIONS WITH CASE STUDIES

The value of measuring body composition in paediatric clinical practice is increasingly emphasised by research associating fatness, fat distribution, and lean mass with clinical outcomes. Selecting appropriate measurements depends on several factors, including age, vulnerability, and disease state. As the above review highlights, measurement of body composition *in vivo* is an imperfect process, subject to various constraints, and yet the outcome has clinical value. We believe technological advances are now sufficient to justify the measurement of body composition in paediatric clinical practice, and offer the following recommendations.

- Simple techniques should not be rejected because they appear unsophisticated. Skinfold measurements and waist circumference provide a simple, easy, and quick yet highly informative assessment of fatness in most paediatric patients before more sophisticated investigations are done. DXA is unlikely to improve substantially on this simple assessment, given the difficulty in estimating trunk fatness by this technique. For the assessment of whole body lean mass, both skinfold measurements and BIA have limitations. Application of the combination of these methods may reduce the likelihood of misdiagnosis of high or low lean mass, but will be least successful when applied to disease states where regional tissue distributions differ from those of healthy children.
- Though BIA has potential utility in measuring regional body composition and hydration, its value in routine clinical paediatrics is at present limited. Predictive error in individuals is high, even when using population specific equations. If used to monitor individuals over time, it can indicate the direction, but not the magnitude, of changes in lean mass, provided a rigorous protocol is observed. However, such data are difficult to interpret in the absence of reference data.
- Whole body data may appear the optimum assessment, but in practice regional data may be more informative about clinical condition, as well as more accurate. Many disease states exert disproportionate effects on particular body regions, such as the central fat in obesity, the lipodystrophy in HIV patients treated with retroviral drugs, and the reduced limb muscle mass of bed-bound patients. In obesity, the main concern is central adiposity, so monitoring of waist circumference may provide a better indication of health risk, and response to treatment, than whole body fatness. Whole body lean mass is difficult to measure with simple methods, but DXA is a relatively accurate technique for quantifying limb lean mass. Its value in this role will increase once reference data for these outcomes are published. Whole body data are most useful



for estimating energy requirements, or the dose size for drug treatment and dialysis.

- Two-component models are ideal where the aim is to quantify fat or fat-free mass with greater accuracy than that permitted by the simplest methods. However, this approach is only justified if the technique can be assumed to be relatively robust to likely derangements in fat-free mass composition. Furthermore, while two-component techniques are of great value in research, they may have less value in many aspects of routine clinical management as they conceal important regional variability within a global whole body value. Where appropriate, however, their clinical application may be improved in the future through prior use of multifrequency BIA to identify potential abnormal hydration.
- Multicomponent models and MRI are ideal for detailed analyses but remain unfeasible in most contexts. Their main value lies in the quality of their evidence in supporting treatment approaches, rather than in routine practical application.
- The value of any approach is greatly enhanced by the availability of reference data. The acquisition of such data is a current priority, being addressed by several research groups.

These recommendations are illustrated using two case studies (tables 2 and 3).

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#### REFERENCES

- 1 Reilly JJ, Methven E, McDowell ZC, *et al.* Health consequences of obesity. *Arch Dis Child* 2003;**88**:748–52.
- 2 Lucas A. Programming by early nutrition in man. In: Bock GR, Whelan J, eds. *The childhood environment and adult disease*, CIBA Foundation Symposium No 156. Chichester: John Wiley, 1991:38–55.
- 3 Tanner JM, Whitehouse RH. Revised standards for triceps and subscapular skinfolds in British children. *Arch Dis Child* 1975;**50**:142–5.
- 4 Fuller NJ, Fewtrell MS, Dewit O, *et al.* Segmental bioelectrical impedance analysis in children aged 8–12 years. 2. The assessment of regional body composition and muscle mass. *Int J Obes* 2002;**26**:692–700.
- 5 Paul AA, Cole TJ, Ahmed EA, *et al.* The need for revised standards for skinfold thickness in infancy. *Arch Dis Child* 1998;**78**:354–8.
- 6 Davies PS, Day JM, Cole TJ. Converting Tanner-Whitehouse reference triceps and subscapular skinfold measurements to standard deviation scores. *Eur J Clin Nutr* 1993;**47**:559–66.
- 7 Wells JCK, Victora CG. Indices of whole-body and central adiposity for evaluating the metabolic load of obesity. *Int J Obes* 2005;**29**:483–9.
- 8 Cole TJ, Freeman JV, Preece MA. Body mass index reference curves for the UK, 1990. *Arch Dis Child* 1995;**73**:25–9.
- 9 Cole TJ, Bellizzi MC, Flegal KM, *et al.* Establishing a standard definition for child overweight and obesity worldwide: international survey. *BMJ* 2000;**320**:1240–3.
- 10 World Health Organisation. *ICD-10 classification of mental and behavioural disorders: clinical descriptions and diagnostic guidelines*. Geneva: WHO, 1992.
- 11 Chan YL, Leung SSF, Lam WWM, *et al.* Body fat estimation in children by magnetic resonance imaging, bioelectrical impedance, skinfold and body mass index: a pilot study. *J Paediatr Child Health* 1998;**34**:22–8.
- 12 Pietrobelli A, Faiith MS, Allison DB, *et al.* Body mass index as a measure of adiposity among children and adolescents: a validation. *J Pediatr* 1998;**132**:204–10.
- 13 Wells JCK. A Hattori chart analysis of body mass index in infancy and childhood. *Int J Obes* 2000;**24**:325–9.
- 14 Daniels SR, Khoury PR, Morrison JA. The utility of body mass index as a measure of body fatness in children and adolescents: differences by race and gender. *Pediatrics* 1997;**99**:804–7.
- 15 Wells JCK, Coward WA, Cole TJ, *et al.* The contribution of fat and fat-free tissue to body mass index in contemporary children and the reference child. *Int J Obes* 2002;**26**:1323–8.
- 16 Wells JCK, Mok Q, Johnson AW. Nutritional status in children. *Lancet* 2001;**357**:1293.
- 17 Rimm AA, Hartz AJ, Fischer ME. A weight shape index for assessing risk of disease in 44,820 women. *J Clin Epidemiol* 1988;**41**:459–65.
- 18 Walton C, Lees B, Crook D, *et al.* Body fat distribution, rather than overall adiposity, influences serum lipids and lipoproteins in healthy men independently of age. *Am J Med* 1995;**99**:459–64.
- 19 Savva SC, Tornaritis M, Savva ME, *et al.* Waist circumference and waist-to-height ratio are better predictors of cardiovascular disease risk factors in children than body mass index. *Int J Obes* 2000;**24**:1453–8.
- 20 McCarthy HD, Jarrett KV, Crawley HF. The development of waist circumference percentiles in British children aged 5.0–16.9 y. *Eur J Clin Nutr* 2001;**55**:902–7.
- 21 de Ridder CM, de Boer RW, Seidell JC, *et al.* Body fat distribution in pubertal girls quantified by magnetic resonance imaging. *Int J Obes* 1992;**16**:443–9.
- 22 Fox K, Peters D, Armstrong N, *et al.* Abdominal fat deposition in 11-year-old children. *Int J Obes* 1993;**17**:11–16.
- 23 Owens S, Litaker M, Allison J, *et al.* Prediction of visceral adipose tissue from simple anthropometric measurements in youths with obesity. *Obes Res* 1999;**7**:16–22.
- 24 Brambilla P, Manzoni P, Sironi S, *et al.* Peripheral and abdominal adiposity in childhood obesity. *Int J Obes* 1994;**18**:795–800.
- 25 Brook CGD. Determination of body composition of children from skinfold measurements. *Arch Dis Child* 1971;**46**:182–4.
- 26 Johnston JL, Leong MS, Checkland EG, *et al.* Body fat assessed from body density and estimated from skinfold thickness in normal children and children with cystic fibrosis. *Am J Clin Nutr* 1988;**48**:1362–6.
- 27 Slaughter MH, Lohman TG, Boileau RA, *et al.* Skinfold equations for estimation of body fatness in children and youth. *Hum Biol* 1988;**60**:709–23.
- 28 Deurenberg P, Pieters JLL, Hautvast JGA. The assessment of the body fat percentage by skinfold thickness measurements in childhood and young adolescence. *Br J Nutr* 1990;**63**:293–303.
- 29 Wells JCK. Predicting fatness in US vs UK children. *Int J Obes* 1999;**23**:1103.
- 30 Reilly JJ, Wilson J, Durnin JVG. Determination of body composition from skinfold thickness: a validation study. *Arch Dis Child* 1995;**73**:305–10.
- 31 Wells JCK, Fuller NJ, Dewit O, *et al.* Four-component model of body composition in children: density and hydration of fat-free mass and comparison with simpler models. *Am J Clin Nutr* 1999;**69**:904–12.
- 32 Chomtho S, Fewtrell MS, Jaffe A, *et al.* Evaluation of arm anthropometry for assessing pediatric body composition: evidence from healthy and sick children. *Pediatr Res* (in press).
- 33 Wabitsch M, Braun U, Heinze E, *et al.* Body composition in 5–18-y-old obese children and adolescents before and after weight reduction as assessed by deuterium dilution and bioelectrical impedance analysis. *Am J Clin Nutr* 1996;**64**:1–6.
- 34 Puiman PJ, Francis P, Buntain H, *et al.* Total body water in children with cystic fibrosis using bioelectrical impedance. *J Cystic Fibrosis* 2004;**3**:243–7.
- 35 Arpadi SM, Wang J, Cuff PA, *et al.* Application of bioimpedance analysis for estimating body composition in prepubertal children infected with human immunodeficiency virus type 1. *J Pediatr* 1996;**129**:755–7.
- 36 Parker L, Reilly JJ, Slater C, *et al.* Validity of six field and laboratory methods for measurement of body composition in 10–14 year old boys. *Obes Res* 2003;**11**:852–8.
- 37 Kotler DP, Burastero S, Wang J, *et al.* Prediction of body cell mass, fat-free mass, and total body water with bioelectrical impedance analysis: effects of race, sex, and disease. *Am J Clin Nutr* 1996;**64**:489–975.
- 38 Fuller NJ, Fewtrell MS, Dewit O, *et al.* Segmental bioelectrical impedance analysis in children aged 8–12 years. 1. The assessment of whole-body composition. *Int J Obes* 2002;**26**:684–91.
- 39 Sartorio A, Malavolti M, Agosti F, *et al.* Body water distribution in severe obesity and its assessment from eight-polar bioelectrical impedance analysis. *Eur J Clin Nutr* 2005;**59**:155–60.
- 40 Dewit O, Ward L, Middleton SJ, *et al.* Multiple frequency bioimpedance: a bed-side technique for assessment of fluid shift patterns in a patient with severe dehydration. *Clin Nutr* 1997;**16**:189–92.
- 41 Williams JE, Wells JC, Wilson CM, *et al.* Evaluation of Lunar Prodigy dual-energy X-ray absorptiometry for assessing body composition in healthy individuals and patients by comparison with the criterion four-component model. *Am J Clin Nutr* 2006;**83**:1047–54.
- 42 Pietrobelli A, Wang Z, Formica C, *et al.* Dual-energy X-ray absorptiometry: fat estimation errors due to variation in soft tissue hydration. *Am J Physiol* 1998;**274**:E808–16.
- 43 Tothill P, Avenell A, Reid DM. Precision and accuracy of measurements of whole-body bone mineral: comparisons between Hologic, Lunar and Norland dual-energy X-ray absorptiometers. *Br J Radiol* 1994;**67**:1210–17.
- 44 Siri WE. Body composition from fluid spaces and density: analysis of methods. In: Brozek J, Henschel A, eds. *Techniques for measuring body composition*. Washington DC: National Academy of Sciences, 1961:223–44.
- 45 Fomon SJ, Haschke F, Ziegler EE, *et al.* Body composition of reference children from birth to age 10 years. *Am J Clin Nutr* 1982;**35**:1169–75.
- 46 Weststrate JA, Deurenberg P. Body composition in children: proposal for a method for calculating body fat percentage from total body density or skinfold-thickness measurements. *Am J Clin Nutr* 1989;**50**:1104–15.
- 47 Lohman TG. Assessment of body composition in children. *Paediatr Exerc Sci* 1989;**1**:19–30.
- 48 Dempster P, Aitkens S. A new air displacement method for the determination of human body composition. *Med Sci Sports Exerc* 1995;**27**:1692–7.
- 49 Dewit O, Fuller NJ, Fewtrell MS, *et al.* Whole-body air-displacement plethysmography compared to hydrodensitometry for body composition analysis. *Arch Dis Child* 2000;**82**:159–64.

- 50 **Wells JCK**, Fuller NJ, Wright A, *et al.* Evaluation of air-displacement plethysmography in children aged 5–7 years using a three-component model of body composition. *Br J Nutr* 2003;**90**:699–707.
- 51 **Nunez C**, Kovera AJ, Pietrobelli A, *et al.* Body composition in children and adults by air displacement plethysmography. *Eur J Clin Nutr* 1999;**53**:382–7.
- 52 **Urlando A**, Dempster P, Aitkens S. A new air displacement plethysmograph for the measurement of body composition in infants. *Pediatr Res* 2003;**53**:486–92.
- 53 **Ma G**, Yao M, Liu Y, *et al.* Validation of a new paediatric air-displacement plethysmograph for assessing body composition in infants. *Am J Clin Nutr* 2004;**79**:653–60.
- 54 **Wells JCK**, Fuller NJ. Precision of measurement and body size in whole-body air-displacement plethysmography. *Int J Obes* 2001;**25**:1161–7.
- 55 **Zapletal A**, Paul T, Samanek M. Normal values of static pulmonary volumes and ventilation in children and adolescents. *Cesk Pediatr* 1976;**31**:532–9.
- 56 **Rosenthal M**, Cramer D, Bain SH, *et al.* Lung function in white children aged 4 to 19 years: II – single breath analysis and plethysmography. *Thorax* 1993;**48**:803–8.
- 57 **Fields DA**, Hull HR, Chelone AJ, *et al.* Child-specific thoracic gas volume prediction equations for air-displacement plethysmography. *Obes Res* 2004;**12**:1797–804.
- 58 **Murphy AJ**, Buntain HM, Wong JC, *et al.* The use of air displacement plethysmography in children and adolescents with cystic fibrosis. *Eur J Clin Nutr* 2004;**58**:985–9.
- 59 **Haroun D**, Wells JCK, Williams JE, *et al.* Composition of the fat-free mass in obese and non-obese children: matched case-control analyses. *Int J Obes* 2005;**29**:29–36.
- 60 **Jennings G**, Bluck L, Wright A, *et al.* The use of infrared spectrophotometry for measuring body water spaces. *Clin Chem* 1999;**45**:1077–81.
- 61 **Davies PSW**, Wells JCK. Calculation of total body water in infancy. *Eur J Clin Nutr* 1994;**48**:490–5.
- 62 **Racette SB**, Schoeller DA, Luke AH, *et al.* Relative dilution spaces of  $^2\text{H}$ - and  $^{18}\text{O}$ -labeled water in humans. *Am J Physiol* 1994;**267**:E585–90.
- 63 **Wells JCK**, Ritz P, Davies PSW, *et al.* Factors affecting the  $^2\text{H}$ -to- $^{18}\text{O}$  dilution space ratio in infants. *Pediatr Res* 1998;**43**:467–71.
- 64 **Butte NF**, Hopkinson JM, Wong WW, *et al.* Body composition during the first 2 years of life: an updated reference. *Pediatr Res* 2000;**47**:578–85.
- 65 **Fiorotto ML**, Cochran WJ, Klish WJ. Fat-free mass and total body water of infants estimated from total body electrical conductivity measurements. *Pediatr Res* 1987;**22**:417–21.
- 66 **Bargmann RN**. Electrical impedance and total body electrical conductivity. In: Roche AF, Heymsfield SB, Lohman TG, eds. *Human body composition*. Champaign, IL: Human Kinetics, 1996:79–108.
- 67 **De Bruin NC**, van Velthoven KA, de Ridder M, *et al.* Standards for total body fat and fat-free mass in infants. *Arch Dis Child* 1996;**74**:386–99.
- 68 **Brambilla P**, Bedogni G, Moreno LA, *et al.* Crossvalidation of anthropometry against magnetic resonance imaging for the assessment of visceral and subcutaneous adipose tissue in children. *Int J Obes* 2006;**30**:23–30.
- 69 **Seidell JC**, Bakker CJ, van der Kooy K. Imaging techniques for measuring adipose-tissue distribution – a comparison between computed tomography and 1.5-T magnetic resonance. *Am J Clin Nutr* 1990;**51**:953–7.
- 70 **Fuller NJ**, Jebb SA, Laskey MA, *et al.* Four-component model for the assessment of body composition in humans: comparison with alternative methods, and evaluation of the density and hydration of fat-free mass. *Clin Sci* 1992;**82**:687–93.
- 71 **Wells JCK**. A critique of the expression of paediatric body composition data. *Arch Dis Child* 2001;**85**:67–72.
- 72 **Van Itallie TB**, Yang M-U, Heymsfield SB, *et al.* Height-normalised indices of the body's fat-free mass and fat mass: potentially useful indicators of nutritional status. *Am J Clin Nutr* 1990;**52**:953–9.
- 73 **Hattori K**, Tatsumi N, Tanaka S. Assessment of body composition by using a new chart method. *Am J Hum Biol* 1997;**9**:573–8.
- 74 **Kyle UG**, Schutz Y, Dupertuis YM, *et al.* Body composition interpretation. Contributions of the fat-free mass index and the body fat mass index. *Nutrition* 2003;**19**:597–604.