MEASUREMENT

A critique of the expression of paediatric body composition data

J C K Wells

Abstract

There is increasing interest in body composition in paediatric research, as distinct from growth and nutritional status, as almost all diseases have adverse effects on either fatness or the fat-free mass. However, the approaches used to assess growth and nutritional status are not appropriate for separate evaluations of body fatness and lean mass. Traditional measurements such as body mass index and skinfold thickness do not measure fat in accurate quantitative terms. Various techniques have been used in recent years which divide body weight into fat mass and fat-free mass; however, the data tend not to be appropriately expressed. Body fatness is generally expressed as a percentage of weight, while fat-free mass typically remains unadjusted for size. A more appropriate approach is to normalise both body fatness and fat-free mass for height. This recommendation is relevant both to studies comparing patients with controls and to the expression of new reference data on body composition which are needed to allow informative comparisons. The same approach is appropriate for the classification of childhood obesity.

There is increasing interest in the relation between paediatric diseases and body composition,[1] which refers to the components of body weight. Various different models of body composition can be used, with the simplest differentiating the fat and fat-free components of weight. More sophisticated models can distinguish more specific components, such as water, mineral, or protein.[2] Historically, the effects of disease on children tended to be assessed in terms of growth (size) or nutritional status (a global index of health intended to identify overnutrition and undernutrition). Such indices are too crude, however, to distinguish changes in the composition of weight, and the last half century has seen rapidly growing interest in children's body composition. The current obesity epidemic has drawn attention to the development of body fatness, while growth of the fat-free mass is of increasing interest to clinicians, physiologists, and epidemiologists.

There is now a need to develop an approach whereby body composition can be assessed in cross sectional terms and can be followed over time in individuals, in the same way as is currently practised for growth. This approach requires that data be expressed as age and sex specific standard deviation scores relative to a reference.

Almost all diseases influence body composition in one way or another, and measurements are required both to characterise these effects and to assess the efficacy of treatment programmes. Until recently, such measurements were extremely difficult to make with accuracy in infants and children. Many sophisticated techniques (for example, magnetic resonance imaging, in vivo neutron activation analysis, whole body potassium counting) may not be applicable to younger subjects, while relatively more acceptable methods (hydrodensitometry; dual energy *x* ray absorptiometry; isotope dilution) rely on information concerning the relative chemical immaturity of the body. Only recently have these difficulties been overcome, through the development of multicomponent models which combine several measurement methods simultaneously and distinguish the components of the fat-free mass.[2–4] These models vary in complexity, but appropriate techniques are now available, at least for children; infants and toddlers present greater practical difficulties which are still being addressed. During the next decade we can expect, through use of such models, to see a marked improvement in our understanding of the effects of disease on paediatric body composition, especially fat mass and fat-free mass.

The renewed interest in this area, combined with awareness of the growing obesity epidemic, has resulted in calls for improved reference data for body composition.[4–6] Current United Kingdom growth reference data are presented as weight, height, and body mass index (BMI).[7 8] These variables evaluate size or nutritional status but not body composition, and are of limited value for independent comparisons of body fatness and lean mass. New reference data specifically describing body composition are therefore required.

There tends to be a tacit assumption, sometimes stated more explicitly,[6] that such data should be expressed in the form of percentage

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Accepted 20 February 2001

fat, as has already been practised in other populations.[9 10] However, the current approach to representing body composition data is at best uninformative and at worst misleading. In this paper I shall describes the limitations of conventional methods for expressing body composition data, and propose a more appropriate approach for use in all age groups. The arguments are relevant to the issue of reference data, to the classification of childhood obesity, and to most studies where body composition is being assessed.

Body mass index

The BMI, calculated as weight divided by height squared, has been widely used in paediatrics owing to the relative ease with which measurements can be made on infants and children. Nevertheless, as a measure of body composition BMI is of limited value in individuals. Both lean mass and fat mass are highly correlated with BMI, such that it acts as a proxy for both but can distinguish neither. Over short intervals of time, large changes in the BMI standard deviation score[8] can be attributed primarily to changes in fatness, so BMI can be used to follow short term changes in body composition within individuals. As an absolute measure of fatness in individuals, however, it has poor accuracy,[11 12] despite arguments to the contrary,[13 14] and it is best seen as an abstract index of nutritional status rather than as a measure of body composition.[12] Despite these shortcomings, most work on childhood obesity is based on this proxy for fatness, and validation of earlier BMI based studies using measured fatness is required if our understanding of the aetiology of this disease is to be furthered.

Skinfold thickness and other proxies for fatness

Skinfold thickness measurements are another popular traditional technique that can be applied easily to patients and healthy children in large numbers. Unfortunately, subcutaneous fatness is not necessarily strongly correlated with deeper lying fat depots. Published equations which convert raw measurements into values for total body fatness have been shown to be inaccurate, both in groups and in individuals,[4 15] which in turn is likely to detract from the accuracy of reference data based on these determinations.[9] Nevertheless, skinfold measurements themselves remain of some value to the clinician. Raw data can now be expressed as SD scores relative to the reference data of Tanner and Whitehouse,[16] allowing patients both to be compared with a reference population and to be followed over time. Skinfold standard deviation scores rank individuals in terms of fatness reasonably successfully at the extremes, but have reduced accuracy in the middle of the fatness range.

Several further drawbacks remain. First, the inaccuracy of the equations that convert skinfold measurements into quantitative measures of body fat means that data cannot be expressed reliably in absolute terms. Second, relative skinfold data refer only to fatness and not to lean mass, such that only one index of body composition can be considered. Third, the reference data of Tanner and Whitehouse were collected in 1966–7,[17] and are likely to be inappropriate for contemporary children who have different activity levels and dietary intakes. Research has already shown such bias in the first 2 years of life, with contemporary infants having significantly reduced fatness.[18]

Similar drawbacks pertain to reference data based on anthropometric circumferences, such as the waist-to-hip ratio.[19 20] Although such data may provide a reasonable index of relative fat distribution, they cannot provide absolute measures of fat mass, and hence allow only the ranking of subjects in terms of fatness, with relative lean tissue deposition being ignored.

Two component versus multicomponent models of body composition

Various techniques have now been used in paediatric research which apply a two component model dividing body weight into fat-free mass (FFM) and fat mass (FM). Examples include densitometry,[15] dual energy *x* ray absorptiometry,[21] total body electrical conductivity (TOBEC),[22] and isotope dilution,[23] although recent studies have shown that accuracy varies significantly between these techniques when used independently.[4 24]

Two-component methods rely on assumed constant properties of the fat-free mass, such as constant hydration or density. For example, if constant fat-free mass hydration is assumed, then measurement of total body water (TBW) by isotope dilution allows estimation of fat-free mass by the equation:

$$\text{FFM} = \text{TBW}/\text{FFM hydration}$$

Likewise, if constant densities of fat mass and fat-free mass are assumed, then measurement of total body density allows differentiation of the FFM and FM fractions of weight using the Archimedes principle.[2] In both cases, accuracy of the resulting data is heavily dependent on the validity of the assumption of fat-free mass constancy.

Three factors introduce variation into the properties of the fat-free mass. First, the properties are not constant even between healthy subjects of a given age and sex, although such variability is relatively low.[4] Second, between birth and adulthood, the properties change significantly owing to the normal process of chemical maturation.[25] Third, disease states may involve a variety of conditions such as overhydration or underhydration, muscle wasting, tumour growth, mineral loss, or oedema, each of which exerts effects on the properties of the fat-free mass. Each of these sources of variation reduces the validity of the two-component model of body composition.

The impact of variability in the composition of fat-free mass on the accuracy of body composition measurements in healthy children can be minimised by using appropriate reference values[25] and by using techniques which rely on fat-free mass components that are less prone to variation. For example, isotope dilution has

been shown to be a more accurate two-component approach in normal children than densitometry or dual energy *x* ray absorptiometry.[4] In disease states, however, where greater variability in the properties of the fat-free mass is expected, the only option is to use multicomponent models of body composition. Such models combine several measurements and allow some of the major sources of variability (for example, hydration and mineral content) to be quantified rather than assumed.[2–4]

Even where multicomponent models are used, the more accurate data that are obtained tend still to be expressed using a two-component model, for clinicians remain interested in the relative fatness of patients and in their lean growth. The preference of multicomponent over two component models is intended to maximise accuracy, but the outcomes of interest usually remain fat mass and fat-free mass. The value of maximised accuracy will be compromised, however, if the tradition of expressing fat mass as a percentage of weight—and leaving fat-free mass unadjusted for size—is continued.

The inadequacy of per cent fat as an index of fatness

The rational for dividing fat mass by body weight is the normalisation of fatness for body size. Clearly larger individuals tend to have greater fat mass, so the derivation of percentage fat is intended to adjust for this trend. However, the exercise ignores between subject variation in fat-free mass. Individuals will differ in percentage fat either if they have identical fat-free mass but different fat mass, or if they have identical fat mass but different fat-free mass. Percentage fat, like BMI, therefore contains information about two different aspects of body composition and cannot distinguish effectively between them. This defect is less noticeable, though still important, in the general population, where major differences in body weight are likely to be due to fat. However, many diseases may influence the fat and lean components of weight separately, and in such circumstances the use of percentage fat as the outcome variable may mask important effects. A further problem with the percentage fat approach is that lean mass, if considered at all, tends to be left unadjusted for body size, which hinders comparisons between patients and controls. In many diseases, growth as well as body composition is affected, and the fact that patients are shorter or taller than age matched controls needs to be taken into account.

This failing of the percentage fat approach is responsible for our poor understanding of the development of, and sources of variation in, lean body mass in childhood. Variation between healthy individuals in fat-free mass is consistently two thirds that in fat mass, after adjusting for height, in both infants and children,[12] and such variation is likely to be even greater in disease states. Equally, the use of percentage fat to define obesity risks allocating individuals to obese or non-obese status partly on the basis of their relative lean deposition. Thus both fat-free mass and fat mass must be normalised for body size if useful comparisons are to be undertaken.

Normalising for height

The defects of the percentage fat approach were realised in 1990, when van Itallie and colleagues recommended that fat-free mass and fat mass should each be normalised separately for height.[26] Both fat-free mass and fat mass can be divided by height squared, to give the fat-free mass index (FFMI) and the fat mass index (FMI). Such a model allows independent evaluation of both fat-free mass and fat mass relative to body size. This approach was subsequently adopted by Hattori *et al*,[27] who devised an extremely informative chart by plotting FFMI on the x axis and FMI on the y axis (fig 1). Diagonal lines then represent BMI and percentage fat. The graph allows simultaneous independent analysis of fat-free mass and fat mass on the respective axes, while also allowing comparison of BMI and percentage fat. It has proved ideal for comparing body composition in adults, taking into account both sources of variation.

However, application of Hattori's chart to infants and children reveals significant differences between the sexes in the relative deposition of fat mass and fat-free mass during different periods of growth. Figure 1 illustrates differences between male and female children in fat mass and fat-free mass deposition between the ages of 1 and 10 years, using data from the reference child.[25] During growth, as this analysis demonstrates, FFMI and FMI change naturally. Infancy and adolescence are periods of high fat deposition, whereas during mid-childhood fat deposition is reduced and children, especially boys, gain primarily fat-free mass. This means that while the chart is a good way to compare individuals of a single age, it is confusing when the sample varies by age, and adjusting for height squared will only normalise data effectively if the same stage of growth is being considered.

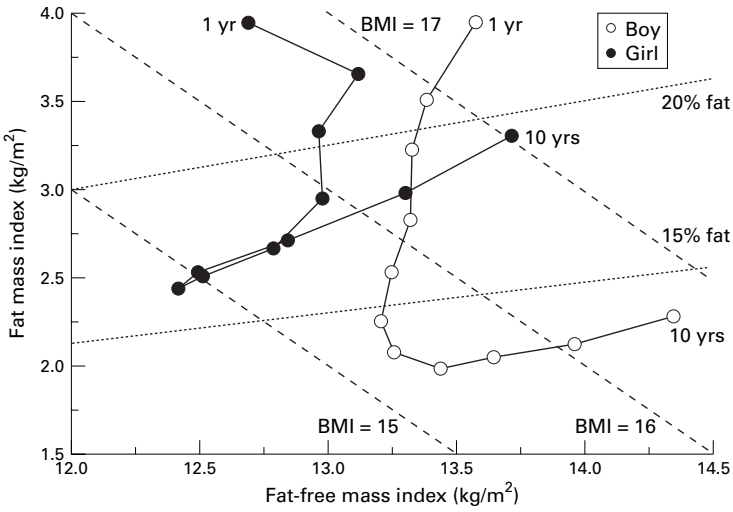

Figure 1 Hattori graph of the reference child for both sexes, plotting fat-free mass (x axis) and fat mass (y axis), both divided by height squared. Diagonal lines indicate body mass index (BMI) and percentage fat. Sequential data points are at 1 year, 1.5 years, and then yearly from 2 to 10 years. Reproduced with permission of the International Journal of Obesity, reference 12.

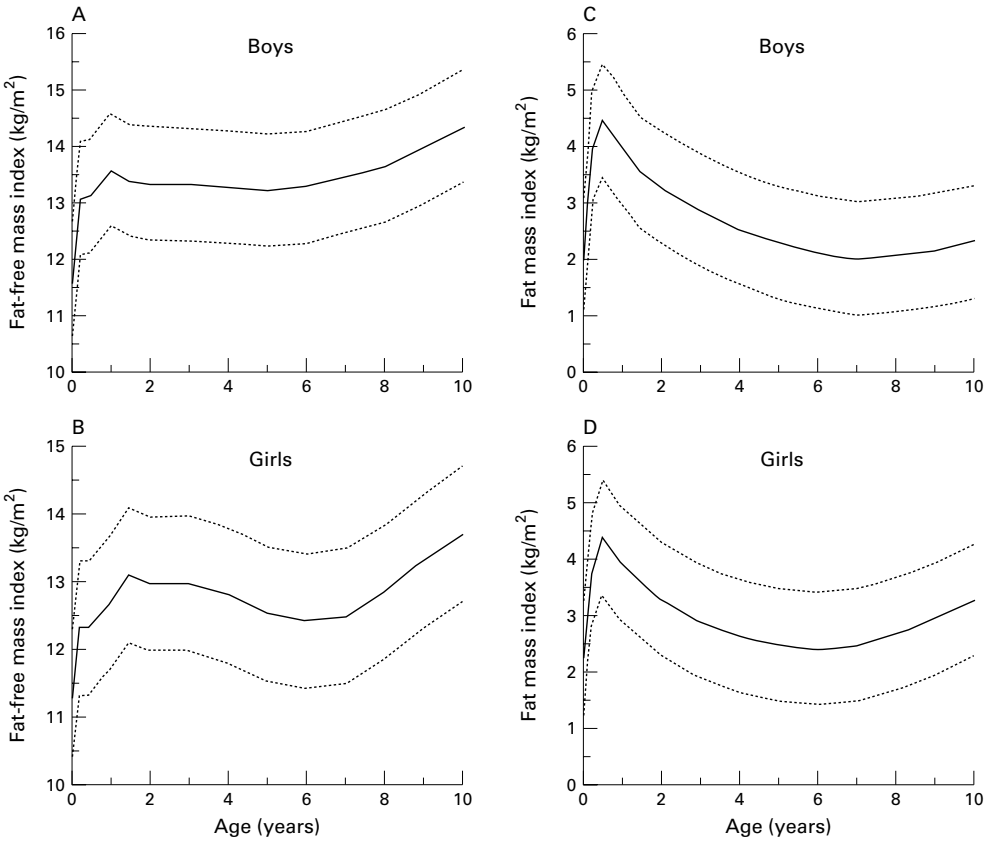

Figure 2 Fat-free mass index and fat mass index plotted against age for each sex, based on data from the reference child.[27] The power to which height has been raised is 2 in all cases, and the standard deviation has been assumed to be 1 kg/m².

Separate evaluations of FFMI and FMI

The optimum way to compare individuals is therefore by splitting Hattori's graph back into its two components and considering the changes in FFMI and FMI against age separately. It is then possible to evaluate fatness per unit height, and relative lean deposition per unit height, against age and sex specific reference data.

The indices FFMI and FMI can be calculated throughout the human age span, but the optimum power by which height should be raised will not necessarily always be 2. The rationale behind BMI is that is highly correlated with weight, while being minimally correlated with height. Although this is true to a reasonable degree throughout the human age span,[28] the optimum power for height in the index (weight/height^n) deviates from 2 in early infancy[29] and during puberty.[28 30] This variation reflects cross sectional changes in the relation between weight and height, probably arising from changes in the coefficient of variation of either weight or height (Cole TJ, personal communication).

For optimum accuracy, then, it could be argued that both FFMI and FMI should be independently normalised in relation to height^n, where age and sex specific values for n are derived from separate evaluations of the relation between height and fat-free mass or fat mass in the population, as considered by Cole for growth.[29 30] In practice, however, the simpler approach of Van Itallie,[26], where weight is first normalised for height and then split into its fat and fat-free components, is likely to be adequate for most purposes. Just as BMI is a valid index of weight adjusted for height throughout childhood, despite showing a low correlation with height at certain age points, so FFMI and FMI will be able to distinguish the relative fat and lean proportions of BMI. The presentation of body fatness and relative lean size in identical units will also aid interpretation of the results.

Figure 2 illustrates the format that could be taken by graphs of FFMI and FMI against age, based on the reference child, for the mean values and assumed standard deviation values of 1 kg/m² derived from unpublished data (Wells JCK, Davies PSW, Cole TJ). Both aspects of body composition have been normalised for height squared, and a normal distribution has been assumed. In practice, differences in skewness would be expected between the sexes and between body fatness and lean size, and centiles would need to incorporate these patterns,[31] as already practised for growth[7] and nutritional status.[8]

Such graphs would benefit both clinical evaluations and population studies of obesity. Currently, childhood obesity (excess body fat) remains defined with poor accuracy on the basis of BMI (relative weight) centiles—an approach that risks the possibility that children with high body fatness but low lean mass will appear in the normal range of the population. Children in the United Kingdom are increasingly less active for a number of reasons relating to changes in mobility and leisure pur-

suits, and lean mass deposition is likely to be reduced compared with previous decades, as exercise stimulates muscle growth.[32] Accurate evaluations of the prevalence of obesity and the success of treatment programmes require that both lean mass and fatness be taken into account, and that fatness relative to size be quantified independently of lean mass. The definition of obesity therefore requires normalisation of fatness for size but not for weight.

The need for new reference data

There is increasing awareness of the need for new reference data for paediatric body composition against which disease states and in particular obesity can be compared. Currently, reference data suffer from various inadequacies. The reference child of Fomon and colleagues[25] refers to American children measured in the 1960s and 1970s, and presents only the average for each sex. Although a landmark paper, most values in the reference child were predicted, and actual measurements (combined from several studies) were made only in infancy and at 9 years, all data being smoothed onto the NCHS 50th centile.

More recent reference data describing inter-individual variability are based on proxy fat measures[9 10 33] and do not present the data in a form that allows adjustment of both fatness and lean mass for size. The most extensive and reliable data are those derived from 423 infants in the first year of life using TOBEC.[34] In that study, results are presented for percentage fat, fat mass, and fat-free mass plotted against weight, length, and age. However, the format still precludes effective comparison between groups and individuals, as none of these approaches normalises body composition indices appropriately for body size.

Ruxton and colleagues point out that a representative sample of contemporary children would inevitably incorporate the effects of the current obesity epidemic.[6] For this reason, new reference data may need to be matched to trends in weight and height dating from an earlier period, such as the data used to construct the 1990 United Kingdom growth reference.[7 8] The issue is of great importance for both fat and fat-free components of weight. Although obesity is defined as an excess of body fat, it is associated with extra lean tissue which is required to support the excess body weight. To provide valid reference data on lean size, the effects of excess fatness must therefore be excluded.

Summary

In this paper I have discussed the limitations of the traditional approach to evaluating body composition in children, and proposed a new approach which for the first time would allow equal consideration both of body fatness and lean growth. For many purposes, evaluations of growth or nutritional status are adequate, and existing reference data will be sufficient. For more detailed investigations of the effect of disease on body composition, however, nutritional status and growth are not sufficiently informative to detect the relevant changes. For example, we have recently shown that young patients with congenital myasthenia have low BMI SD scores, suggesting malnutrition, but have high FMI and skinfold thickness values, indicating that it is poor lean mass deposition that accounts for their low BMI values.[35]

The proposed approach, recommending independent evaluation of fatness and relative lean size, is relevant to many areas of paediatric research and clinical practice. First, for studies comparing patients before and after treatment, or comparing patients with controls, the approach should be more robust in sizing the differences caused by growth between groups or between time points. Second, the expression of reference data in the suggested format will allow population changes in excess body fat to be distinguished from changes in relative lean size arising from differences in activity level. Third, the same approach is also appropriate for the definition of childhood obesity, which remains classified on the basis of relative body weight despite the disease being defined as excess body fat.

I am very grateful to Professor Tim Cole, of the Institute of Child Health, London, for his comments on the manuscript.

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