Part I

Causes

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Measurement and definition

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1.1 Introduction

A simple definition of obesity is an excess of body fat. However, as a definition it immediately raises questions – how is body fat measured and what cut-off is used to define 'excess'? The two questions are addressed in this chapter.

If obesity is an excess of body fat, a more neutral term is needed for the amount of body fat in the body, and here it is called adiposity. Adiposity is the amount of body fat expressed either as the absolute fat mass (in units of kilograms) or, alternatively, as the percentage of total body mass. Fat mass is highly correlated with body mass, while per cent fat mass is relatively uncorrelated with body size.

It is not only the amount but also the distribution of body fat within the body that is important in adults. The distribution or patterning of body fat is associated with later disease risk, independent of the level of obesity (Vague, 1956). Adults with central, trunk or android fat patterning, who are at greater risk (Björntorp, 1985), deposit fat preferentially around the waist, while with gynoid patterning fat is found more towards the extremes of the body.

Some obese adults were fat as children, so child fatness may be a risk factor in its own right for later disease (Power et al., 1997). This is relevant for setting a fatness cut-off. However, in assessing fatness an important distinction needs to be made between childhood and adulthood – children grow in size, so that anthropometric cut-offs for fatness have to be adjusted for age and in adolescence for maturation as well. For this reason, the assessment of adiposity in childhood and adolescence differs from its assessment in adults.

So, obesity is excess adiposity, which requires a suitable measure of body fat and a suitable cut-off. In adults, adiposity is commonly assessed using the body mass index (BMI; weight/height^2; also known as Quetelet's index), and obesity cut-offs based on mortality risk are defined in body mass index units of kilograms per metre squared (kg/m^2).

The rest of the chapter is concerned with these issues in children: Section 1.2

describes briefly the natural history of child adiposity, Section 1.3 addresses the question of how to measure adiposity in children, Section 1.4 describes the predictive value of child adiposity for later obesity, morbidity and mortality, and Section 1.5 considers the references and cut-offs needed for the definition of child obesity.

1.2 Natural history of adiposity

Body fat is made up of fat cells or adipocytes. The changes in fat mass that occur in the growing child arise in two separate ways, through changes in the number and in the mean size of adipocytes. In infancy adipocyte enlargement contributes most to the increasing fat mass, while after infancy fat mass gain arises mainly through cell proliferation (Knittle et al., 1979). As a result, fat mass rises steeply during the first year and then falls again, with a second rise in later childhood. Figure 1.1 illustrates the pattern and also shows how anthropometric indices, like the body mass index or subscapular skinfold, follow the same age-related trends. Section 3.5 gives a more detailed description of the underlying processes.

1.3 Measurement of body fat

An ideal measure of body fat should be accurate, precise, accessible, acceptable and well documented. Accuracy and precision mean that the measure should be unbiased and repeatable; accessibility relates to the simplicity, cost and ease of use of the method; acceptability refers in the broadest sense to the invasiveness of the measurement and documentation concerns the existence of age-related reference values of the measurement for clinical assessment.

No existing measure satisfies all these criteria. Highly accurate reference methods like deuterium dilution or underwater weighing are expensive, and more accessible, cheaper methods based on anthropometry are not very accurate.

1.3.1 Research methods

Several accurate and direct measures of total body fat are now available, for example underwater weighing, dual energy X-ray absorptiometry (DEXA), computer tomography or magnetic resonance imaging (MRI) (see the review by Davies & Cole (1995) for more details). They are generally noninvasive, except for the water bath in underwater weighing. As research tools they are very valuable, and are particularly useful to validate other measures based on anthropometric measurements (Ashwell et al., 1985). However, they are inappropriate for routine clinical practice because of their high cost, slow response time and limited access (the equipment is found mostly in research or tertiary referral centres).

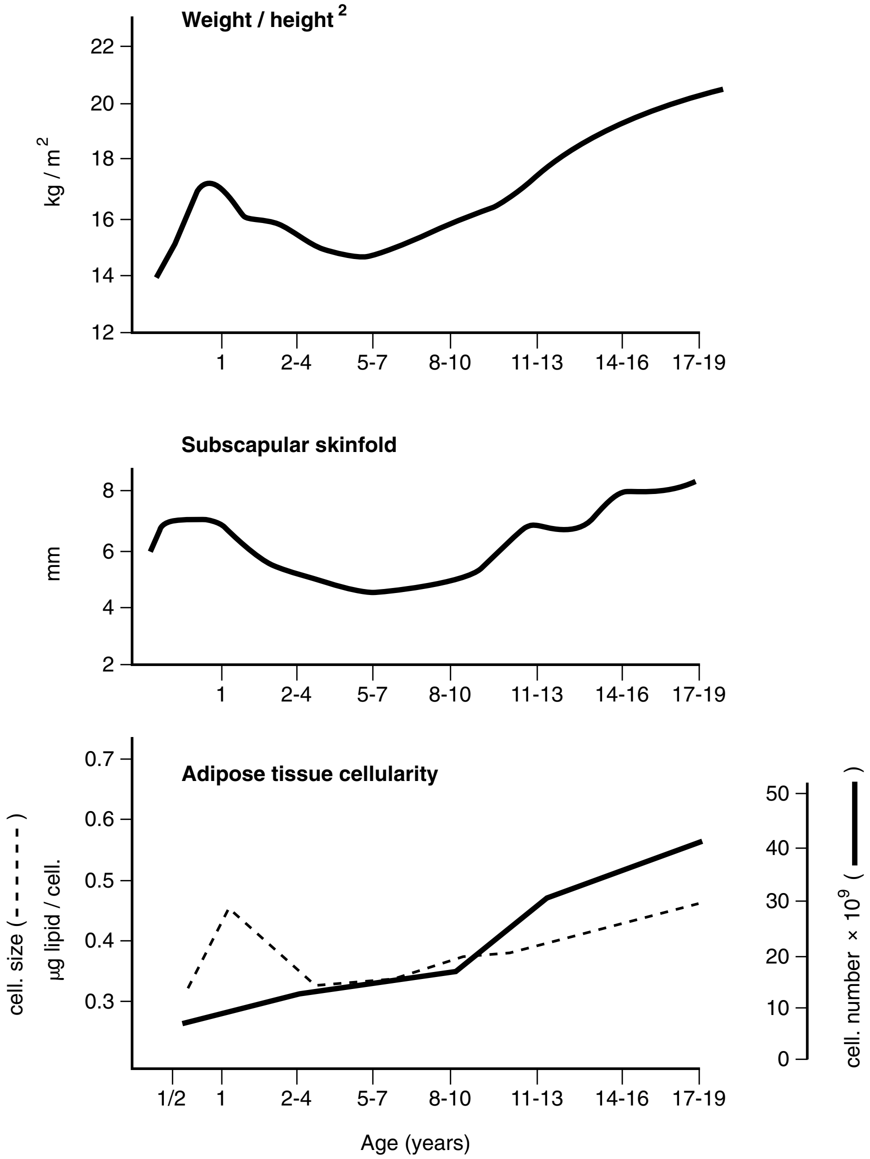

Figure 1.1 Trends in body mass index and subscapular skinfold thickness through childhood and the corresponding trends in adipose tissue cellularity (Rolland-Cachera et al., 1982; Sempé et al., 1979; Knittle, 1979).

Bioelectrical impedance analysis (BIA) is an indirect method that has become popular due to its relatively low cost (Davies & Cole, 1995). It works on the principle that body fat contains no water and, therefore, is of high electrical resistance (or impedance). Electrodes are attached to the extremities of the body, usually the hands and feet, and a small current is passed to measure the impedance between the electrodes.

The impedance is strongly correlated with body size and needs to be adjusted accordingly, usually by dividing by the square of height. There is some uncertainty as to just how much extra information BIA provides over and above simple anthropometry, but it is sufficiently popular for the latest forms of weighing scales to incorporate an impedance measurement (Jebb et al., 2000).

1.3.2 Anthropometry

Anthropometry is the single universally applicable, inexpensive and noninvasive method available to assess the size, shape and composition of the human body. It reflects both health and nutrition and predicts performance, risk factors and survival (de Onis & Habicht, 1996). The most widely used measurements to predict fatness are weight and height, skinfolds and circumferences.

Measurement technique

A common misconception with anthropometry is that it is easy to do and that no special training or supervision are required to obtain accurate and precise measurements. This is not the case if the measurements are to be of any value. For detailed information on measurement technique see, for example, Cameron (1986). Some general pointers are given here.

Children should be weighed in their underwear and for infants an adjustment should be made for any clothing. The instrument should ideally be digital or, failing that, a beam balance or, failing that, a high quality spring balance.

To measure length, at least two measurers are needed, one at the infant's head, to ensure proper contact with the headboard, and the other at the feet, to make the measurement. Use a good quality length board. For height there are several good stadiometers on the market and they should be checked and calibrated before each session. The child's head should be held in the Frankfort plane, that is with the line of vision perpendicular to the body, and the child requested to stand straight with heels, buttocks and shoulders touching the wall. There is no need to stretch the child.

Height is not as easy to measure as weight. In particular, to measure height velocity over time it needs highly trained observers and continuous quality control to ensure high precision. For single measurements to assess adiposity it is less critical but, even so, training is important to minimize interobserver variation.

In large-scale epidemiological studies, self-reported values of weight and height are used, but in adolescence and later they tend to be biased in opposite directions, with weight underestimated and height exaggerated, and the weight error is larger in heavier subjects.

Skinfolds are the most difficult of all measurements to make. An experienced trainer and continuous quality control are essential, as even experienced measurers disagree systematically in their skinfold measurements.

Circumferences are easier than skinfolds to measure, but the placing and tension of the tape are important. Again, quality control is recommended to minimize inter- and intraobserver variation.

Percent of median, centiles and Z-scores

Anthropometry changes with age during childhood. To assess individual children, measurements need to be adjusted to compare them with those of other children of the same age. In addition, weight may need to be adjusted for height. The adjustment is made by comparing the child's measurement with a suitable reference value, obtained either from a chart or table, though computers are now simplifying the process.

There are three different ways of expressing the adjusted anthropometry value: as a percentage of the median, as a centile and as a Z-score. The per cent of median is 100 times the measurement divided by the median or mean reference value for the child's age (or in the case of weight-for-height, weight divided by the median for the child's height). For centiles, the measurement is plotted on a growth centile chart and the child's centile interpolated from the growth curves. Z-scores are closely related to centiles and indicate the number of standard deviations the child's measurement lies above or below the mean or median reference value.

As an example, three proposed cut-offs to define overweight based on age-adjusted weight are 120% of the median, the 97th centile and +2 Z-scores respectively. These cut-offs are all similar to each other, identifying 2–3% of the reference population as being overweight.

Per cent of the median is the simplest of the three forms to calculate, and has been in use the longest (Gomez et al., 1956). Centiles are easy to read off the chart and are well understood by parents. If the measurement is normally distributed, centiles and Z-scores are interchangeable. However, often there is no known distribution by which to convert the centiles on the chart to Z-scores. This applies particularly to skew data like weight and skinfold thickness.

Recently, it has become possible to construct charts that convert between centiles and Z-scores when the data are not normally distributed, for example weight (Cole et al., 1998) and triceps skinfold (Hughes et al., 1997). For the purposes of epidemiological analysis, Z-scores are more appropriate than centiles – it is not correct for example to average centiles, as they are on a nonlinear scale. Calculations such as these should always be done on the Z-score scale.

Weight

We now turn to anthropometric measures of adiposity. Weight is the simplest and most direct index of body size, easy to measure, cheap and reproducible. It is also reasonably highly correlated with body fat (Cole, 1991). Weight-for-age tables and charts were originally used to assess undernutrition (Waterlow, 1972), and weight-for-age is currently recommended by the World Health Organization (WHO, 1995) to assess nutritional status.

However, weight is highly correlated with height, and height is only weakly correlated with body fat (Himes & Roche, 1986). So, by adjusting weight for height the relationship between weight and body fat can be strengthened, leading to a more sensitive and specific index of adiposity. Note, though, that weight–height indices do not measure fatness as such, only overweight.

Weight-for-height

There are many different forms of index based on weight and height, dating back over 150 years (Cole, 1991). One of the simplest is relative weight. It requires a table or chart of expected weight for the child's height and sex (and sometimes age and maturation as well), and the child's weight is expressed as a percentage of their expected weight (per cent of median). If the expected weight is based on just height and sex, then the index is known as weight-for-height. Weight-for-height, because it takes no account of the child's age, is useful in parts of the world where dates of birth are not recorded, but for children who are particularly tall or short for age it leads to a biased assessment in infancy and adolescence (Cole, 1985).

The World Health Organization's international growth reference weight-for-height chart (Dibley et al., 1987) is truncated at the age of 10 years for girls and 11.5 years for boys. The reason is that, past this age, weight-for-height cannot be adjusted for, although it remains age-dependent. As a result, weight-for-height is of no use at all for assessing adiposity during adolescence.

The need to adjust weight for both height and age is now widely accepted (Cole, 1979; Rolland-Cachera et al., 1982), and it has led to the study of power indices like weight/height^2 and weight/height^3.

Weight/height^p uncorrelated with height

The rationale for adjusting weight for height is to strengthen the relationship between weight and adiposity (see above). However, this has not always been the intention – weight was originally adjusted for height to give an index that was uncorrelated with height, irrespective of adiposity. These two alternative approaches lead to slightly different forms of weight–height index, one uncorrelated with height and the other maximally correlated with adiposity.

Relative weight is weight adjusted for height and so is, by definition, uncorrelated with height. The same principle applies to indices like weight/height^p – the power of height, p, can be chosen to make the index uncorrelated with height. If the adjustment is done ignoring the age of the individual child, the optimal whole-number value for p throughout childhood is 2 (Cole, 1991).

However, it is important to adjust for age and, to achieve this, the calculation to optimize p is done in narrow age groups (Rolland-Cachera et al., 1982) or else weight and height are adjusted for age first (Cole, 1979). In early childhood p is near 2, so the best index is weight/height^2 (Cole et al., 1981; Gasser et al., 1995). The value of p increases during childhood and peaks during adolescence, reaching a value of 3 or more (i.e. weight/height^3), and then drops back to 2 in adulthood (Rolland-Cachera et al., 1982; Cole, 1986). So, earlier in childhood the body mass index (or BMI), weight/height^2, is optimal, while during adolescence Rohrer's index, weight/height^3, is better.

Weight/height^p highly correlated with adiposity

An alternative is to choose the index weight/height^p explicitly for maximal correlation with body fat, rather than zero correlation with height. The two criteria lead to the same index only if, after adjusting for age, height and body fat are uncorrelated.

In practice, body fat, like the body mass index, is weakly positively associated with height in adolescence (Himes & Roche, 1986; Lazarus et al., 1996), and the two correlations tend to cancel out. This means that in adolescence, though body mass index is correlated with height, it is also more strongly correlated with adiposity than alternative indices like Rohrer's index. For this reason, body mass index is generally accepted as the optimal weight–height index of child and adolescent adiposity.

Body mass index

The interdependence between weight, height, body mass index and body fat is often insufficiently well understood. The body mass index is sometimes criticized because of its association with height (O'Dea & Abraham, 1995; Lazarus et al., 1996), yet this is only a flaw if the index is required to be uncorrelated with height. From a broader perspective the association is actually an advantage, as it flags the greater fatness of tall children during adolescence. Recent studies (Daniels et al., 1997; Pietrobelli et al., 1998) have shown high correlations between BMI and per cent body fat measured by DEXA.

Equally it is important to realize that the body mass index cannot be used to demonstrate an association between adiposity and height in adolescence – body mass index does not measure adiposity directly. To investigate the correlation

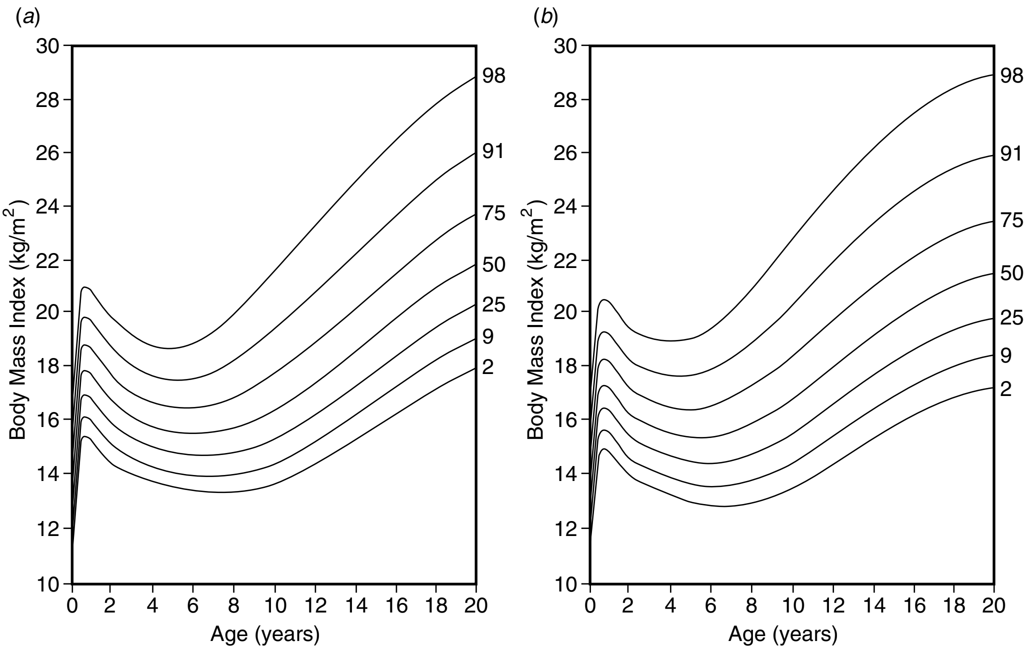

Figure 1.2 Centiles of body mass index for British boys (*a*) and girls (*b*) in 1990. The seven centiles are spaced two-thirds of a Z-score apart, i.e. the 2nd, 9th, 25th, 50th, 75th, 91st and 98th centiles.

between adiposity and height a direct measure of body fat, for example by DEXA, should be used.

The natural history of body mass index is similar to that for body fat, a steep rise during infancy with a peak at 9 months of age, followed by a fall until age 6 years and then a second rise, which lasts until adulthood. The earliest published charts of body mass index were for French children (Rolland-Cachera et al., 1982), and more recently charts have appeared for North American, British, Swedish, Hong Kong and Dutch populations (Hammer et al., 1991; Must et al., 1991; Rolland-Cachera et al., 1991; Cole et al., 1995; Lindgren et al., 1995; Leung et al., 1998; Cole & Roede, 1999; He et al., 2000; Kuczmarski et al., 2000). Figure 1.2 shows the British centiles for body mass index (Cole et al., 1995). It shows broadly the same age and sex trends as other national centile charts, with body mass index rising more steeply in boys than girls during puberty.

Indices based on weight centile and height centile

It has long been standard practice to plot children's weights and heights on centile charts, and some have treated the difference between the two centiles as a measure of over- or underweight. Hulse & Schilg (1996), for example, have suggested that a

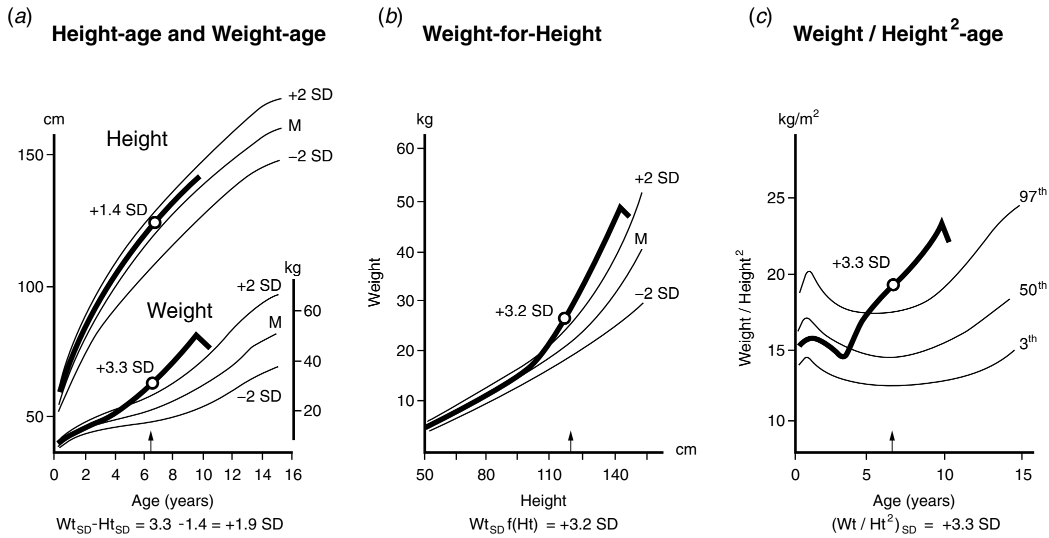

Figure 1.3 **Comparison of three methods for assessing weight adjusted for height: weight centile compared to height centile (*a*), weight-for-height Z-score (*b*) and body mass index Z-score (*c*).**

weight centile more than three centile channels above the height centile is an indicator of obesity. This is a simple but crude index, which is biased for children who are fairly tall or short for their age (Cole, 1997). Mulligan & Voss (1999) have shown that in obese children, the difference between their weight and height centiles depends on their age and height.

Figure 1.3 compares the index with two alternative indices, weight-for-height and the body mass index centile. In the example, a tall and very heavy child appears only marginally overweight with the weight centile–height centile index (Z-score = 1.9), whereas weight-for-height and BMI rate the child as obese, with a Z-score exceeding 3.

Because of the link between centiles and Z-scores, the centile–centile index is equivalent to the difference between weight Z-score and height Z-score. A better index is weight Z-score *adjusted* for height Z-score, which depends on the correlation between weight and height, typically 0.7 (Cole, 1997). This leads to the index (1.4 × weight Z-score − height Z-score) which has a standard deviation of 1, and is a Z-score of weight-centile-adjusted-for-height-centile. So, the correct way to compare weight and height centiles is to convert them to Z-scores, multiply the weight Z-score by 1.4 and subtract the height Z-score (Cole, 1994). Applying this formula to the example in Fig. 1.3 gives a Z-score of 3.2, agreeing closely with the other two indices.

Generally this form of Z-score is similar to the body mass index Z-score, which