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REVIEW ARTICLE

Methodologies to assess paediatric adiposity

M. Horan · E. Gibney · E. Molloy · F. McAuliffe

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Abstract
Introduction Childhood obesity is associated with increased risk of adult obesity, cardiovascular disease, diabetes and cancer. Appropriate techniques for assessment of childhood adiposity are required to identify children at risk. The aim of this review was to examine core clinical measurements and more technical tools to assess paediatric adiposity.
Methods The online databases PubMed, CINALH and EMBASE were searched and the abstracts identified were reviewed to determine appropriate studies. Their reference lists were also searched to identify further eligible studies. Publications were included if they described childhood measurement techniques or involved validation.
Results and Discussion There are many body composition assessment tools available, none of which are direct. Each technique has limitations and a combination of methods may be used. The main clinical techniques are weight, height, body mass index (BMI) and circumferences which provide sufficient information to enable classification of overweight or obesity when growth centile charts and ratios are employed. Further investigation depends on resources available and examiner skill. Skinfold thicknesses are cost-effective but require technical training and only measure subcutaneous fat. Dual energy X-ray absorptiometry (DEXA), air displacement plethysmography (ADP), magnetic resonance imaging (MRI) and computed tomography (CT) are more costly and intensive, requiring the child to remain still for longer periods. DEXA and ADP are capable of accurately measuring adiposity but are unable to distinguish between fat depots. MRI and CT can distinguish intra-abdominal from subcutaneous adiposity and are considered gold standards, but CT is unsuitable for adiposity measurement in children due to high levels of radiation exposure. Ultrasound is a promising technique capable of measuring intra-abdominal adiposity in children but requires further validation.
Conclusion The core clinical measurements of weight, height, BMI and circumferences are sufficient to enable diagnosis of paediatric overweight and obesity while more technical tools provide further insight.

Keywords Paediatric anthropometry · Skinfold · Paediatric obesity · Body composition · Growth references · Growth standards · Childhood BMI

M. Horan · E. Molloy · F. McAuliffe (✉)
University College Dublin Obstetrics and Gynaecology, School of Medicine and Medical Science, National Maternity Hospital, Dublin 2, Republic of Ireland
e-mail: fionnuala.mcauliffe@ucd.ie

M. Horan
e-mail: mary.horan@ucdconnect.ie

E. Gibney
Institute of Food and Health, University College Dublin, Belfield, Dublin 4, Republic of Ireland

E. Molloy
Royal College of Surgeons, Dublin 2, Republic of Ireland

Introduction

Childhood obesity is becoming increasingly prevalent, particularly in developed countries where there is an obesogenic environment involving sedentary lifestyle and high intakes of energy dense foods [1, 2]. Childhood obesity is associated with increased risk of obesity in adulthood and with the metabolic syndrome as well as related diseases such as cardiovascular disease and diabetes, and with cancer. Furthermore, obese adults who were

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obese in childhood have been found to be more at risk of metabolic syndrome than obese adults who were normal weight as children [3, 4]. Childhood obesity is also predictive of premature death [5]. In light of the risks and complications associated with childhood obesity, it is essential to be able to accurately measure body composition both at individual and population levels, to assess the impact of lifestyle factors and interventions. Many different techniques are available, from relatively easy to carry out, inexpensive techniques including weight, height, body mass index (BMI), circumferences and skinfold measurements, to more expensive and technical approaches including bioelectrical impedance (BIA), dual energy X-ray absorptiometry (DEXA), air displacement plethysmography (ADP), magnetic resonance imaging (MRI), computed tomography (CT) and ultrasound (US). Each of these methods has advantages and limitations and varies in suitability depending on the characteristics of the population under study and the time and resources available. Therefore, an understanding of the techniques available is essential as is their correct application. Paediatric body composition is measured using surrogate methods; therefore, it is important that techniques used have been validated in the population under examination [6]. The online databases PubMed, CINALH and EMBASE were searched from March to October 2013. Combinations of the search terms "children", "anthropometry", "validation", "weight", "height", "BMI", "circumference", "skinfold", "centiles", "references", "standards", "bioelectrical impedance", "hydrodensitometry", "air displacement plethysmography", "DXA", "DEXA", "ultra-sound", "CT" and "MRI" were used to identify appropriate studies. The abstracts of identified studies were reviewed to determine eligibility and their reference lists were searched to source further eligible studies. Publications were included if they described childhood measurement techniques or involved validation. This is not an all-inclusive review due to the vast amount of literature available but will attempt to give an overview of the techniques available, focusing on the most clinically practical and widely available methods and their applications and limitations in paediatric populations. It will also cover more advanced and newer techniques and includes a table (Table 1) which summarises the advantages and disadvantages associated with each method including relative cost, necessary training and expertise and availability of each technique.

Weight and height

A 2009 Cochrane Review [7] stated that "at present, there is insufficient reliable information to be confident whether routine (weight and height) growth monitoring is of benefit to child health in both developing and developed country settings". However, UNICEF states that many countries have had positive outcomes with growth monitoring programs leading to the recommendation by an expert consultation [8] that weight and height/length be regularly measured, i.e. monthly until 12 months and regularly with no specifically defined frequency thereafter.

Weight and height are the most commonly used techniques for assessing childhood overweight or obesity. They are neither time consuming nor costly, and the only equipment required is a stadiometer and regularly calibrated weighing scales. Weight should be taken with the child in light clothing without shoes, ensuring that there is nothing in the pockets and that, if present, their nappy is dry. Ideally the child's bladder should also be empty. Recumbent length is used for infants under 2 years of age while standing height is used thereafter. Recumbent length is on average 0.5 cm greater than standing height; however, this difference has little impact on anthropometric calculations [9] and is taken into account by growth centile charts [10]. Measurement of recumbent length involves lying the child on an infantometer and ensuring that the head is in the Frankfort plane, i.e. that the imaginary line between the hole of the ear and the bottom of the eye socket is perpendicular to the platform of the infantometer, and that the child's shoulders, hips and feet are in line and knees are straight. Length should be measured from the flat sole of the child's foot rather than toes which may be naturally pointed [11]. For height measurement, the child should stand in bare feet with heels together and touching the back of the stadiometer or wall if the stadiometer is wall-mounted. The child's buttocks, upper back and head should also touch the stadiometer. However, if the child is obese, the buttocks and/or back may touch the stadiometer but not necessarily the child's head or heels. This is acceptable as long as the child remains standing as straight as possible but should be documented [12]. The child's head should be in the Frankfort plane, i.e. perpendicular to the stadiometer and parallel to the floor [11]. Height measurement should be taken at the child's tallest stature which can be obtained by asking the child to take a deep breath and hold it until their height measurement has been recorded.

Surrogate measurements for height are available in the event that a child is unable to stand fully or straight, e.g. in the case of scoliosis for example: knee height (measurement from the bottom of the foot to above the knee when the leg is bent at a right angle), ulna length (the distance from the olecranon process, i.e. the point of the elbow, to the styloid process, i.e. the prominent bone of the wrist), demi-span (the distance from the supra-sternal notch of the clavicle to the base of the middle and ring fingers when the arm is stretched out at a right angle to the body) or full arm-span (the distance from the tip of the middle finger of

Table 1 A summary of the advantages and disadvantages of the various body composition measurement techniques

Method	Advantages	Disadvantages	References
SF thickness with prediction equations	Quick Convenient Inexpensive Valuable for research	Must choose from a range of predictive equations Large systematic and random error Bias which increases with adiposity and is affected by age Contention over which side of the body to take measurements from Considerable expertise and training necessary Callipers not generally available in clinical setting Not suitable for general clinical practice	Reilly et al [68] Moreno et al. [84]
SF thickness—raw data compared with references or standards	Quick Convenient Inexpensive Good for ranking at the extremes of fatness Valuable for research	References based on norms during 1970s—newer references impossible to create due to prevalence of overweight and obesity Not useful for individual measurements Less useful for ranking in less extreme body fatness Does not describe lean body mass Contention over which side of the body to take measurements from Considerable expertise and training necessary Callipers not generally available in clinical setting Not suitable for general clinical practice	Wells [76] Moreno et al. [84]
BMI	Quick Convenient Inexpensive Minimal training required Can be used at all ages Increases in sensitivity with increasing adiposity WHO Growth standards represent children's full growth potential WHO Growth standards encourage breastfeeding Equipment available in clinical setting Suitable for general clinical practice and research	Does not take lean body mass or stunting into account Affected by ethnicity Less sensitive in thinner children Should not be used alone to characterise adiposity WHO growth standards do not represent formula-fed or premature infants Growth standards for children >5 years more controversial—creation from new measurements not feasible	Freedman and Sherry [30] Prentice and Jebb [28] WHO [10] Michaelsen, [36]
Circumferences	Quick Convenient Inexpensive Minimal training required WC indicative of central obesity Centile charts available WC almost as effective as BMI at determining excess adiposity Waist-to-height ratio >0.5 effective in all children Head circumference can be compared with WHO standards for children up to age of 5 years Equipment available in clinical setting Suitable for general clinical practice and research	No standard recommendation for WC as it depends on age, ethnicity, gender and height WC inaccurate in some illnesses, e.g. constipation/ascites Peripheral measurements must also be taken to ensure whole body fat distribution is taken into account	Gläβer et al. [39] McCarthy et al. [42] McCarthy and Ashwell M [49] Motil [61] WHO [10]

Table 1 continued

Method	Advantages	Disadvantages	References
BIA	Quick	Difficult to ensure children are fasted and adequately hydrated	Ellis et al. [89]
	Convenient	Child may need to lie supine for up to 10 min prior to measurement	de Beer et al. [92]
	Non-invasive	Need for standardisation of techniques, e.g. placement of electrodes	Shafer et al. [93]
	Cost varies depending on machine used but can be relatively cost-effective	Relies on prediction equations	
		Machines that supply raw data are expensive	
	Equipment may be available in clinical setting	Greater natural error of TBF than LBM	
	Minimal training required	Underestimates TBF in leaner children and overestimates in obese children	
	Suitable for general clinical practice if equipment is available	Greater inaccuracy at higher BMI	
	Valuable for research		
DEXA	Differentiation of bone and soft tissue	Relies on algorithms	Sopher et al. [98]
	Measures BMD	Lack of compatibility between machines	Toombs et al. [97]
	Good precision	May overestimate body fat in heavier and underestimate in lighter individuals	Wells et al. [99]
	Able to measure weight changes	Some children may exceed size limits of scanner	
	Minimal radiation exposure	Bias worsened with pubertal progression	
	DEXA scanner may be available in clinical setting	Expensive equipment	
	Valuable for research	Radiation safety training necessary	
		Moderate level of training and expertise needed	
		Not suitable for general clinical practice except for bone health or in specialised cases	
HD	Gold standard in density measurement	Difficult to perform with children due to submersion and maximal inhalation	Fields and Goran [114]
	Used for specialist research	Estimation of respiratory volume results in largest variability	
		Expensive	Holmes et al. [111]
		Moderate–high level of training and expertise needed	
		Equipment not available in clinical setting	
		Not suitable for general clinical practice	
ADP	Does not require submersion unlike HD, therefore more acceptable for children	Not validated for use between 6 months and 2 years	Fields and Allison [107]
		Relies on algorithms	
	Minimal training needed	Thoracic volume measured vs estimated	Holmes et al. [111]
	Valuable for research	Validation studies conflicting, possibly due to experimental methods	Wells et al. [103]
		Hydration status affects accuracy	Jensky-Squires et al. [117]
		May overestimate body fat in heavier and underestimate in lighter individuals	
		Expensive equipment	
		Expensive extra attachment necessary for children between 6-month and 6-year old	
		Equipment unlikely to be available in clinical setting	
		Not suitable for general clinical practice—may be used in specialised cases	

Table 1 continued

Method	Advantages	Disadvantages	References
MRI and CT	Examines body fat distribution	CT requires radiation exposure	Samara et al. [126]
	Can differentiate between different fat depots	Expensive equipment	
	Equipment available in clinical setting	Require children to remain still for extended periods	
	Valuable for research	Radiation safety training required for CT	
		High level of training and expertise needed	
		Equipment often in high demand in clinical setting	
		Not suitable for general clinical practice	
Ultrasound	Less time consuming and strenuous than MRI or CT	Preperitoneal fat used as an approximation of visceral fat	Mook-Kanamori et al. [128]
	Moderately expensive equipment	High level of training and expertise needed for accuracy	
	Equipment available in clinical setting	No universal guidelines for measurement of adipose tissue	
	Valuable for research	Not suitable for general clinical practice	

one hand to the tip of the middle finger of the other when arms are stretched outwards at right angles to the body) [11]. These surrogate measurements can be inputted into equations to calculate approximate height [11] and have been found to be accurate and precise predictors of height in children [13, 14].

Measurement of a child's weight and height in the clinical setting is essential as Scholtens et al. [15] found that at 4 years of age, the higher a child's BMI, the more parents underreported the child's weight and that similarly parents of children with low BMIs tended to over-report weight. Children [16] and adolescents [17, 18] have also been found to be unreliable reporters of weight and height with height tending to be over-reported by adolescents.

Weight and height growth references and standards

Several indices for assessment of child growth based simply on weight and height exist, i.e. weight-for-age, height-for-age and weight-for-height. These indices are based on population references or standards. Weight-for-age is a measure of a child's weight in relation to other children of the same age and can be used to track a child's weight longitudinally. However, this index does not take height into account and therefore may define taller than average children as overweight and shorter children as underweight. It provides no information on whether underweight is due to wasting or to stunting [9]. Height-for-age on the other hand gives no information on adiposity and is simply a measure of the child's height in comparison to other children of the same age. Height-for-age is useful in identifying stunting [9]. Parental height should also be taken into account when examining height-for-age to rule out stunting. References which take mid-parental height (i.e. the average of the child's father's and mother's height) into account are available [19] and should be consulted where there is concern about a child's height as these standards provide greater clarity in classifying adequacy of a child's growth according to height-for-age. Weight-for-age and height-for-age indices should be used together to determine whether a child's weight is abnormal and whether its height is also affected. However, the commonly used rule of thumb that if the child's weight-for-age is not over two centiles greater or less than his/her height-for-age, the child's weight and height are in proportion has been found to be unreliable. Research by Cole [20] has found that this comparison is a poor measure of weight-for-height and its use is not advised. BMI-for-age or weight-for-height should instead be used. Weight-for-height is a composite of both absolute weight and absolute height and can identify both wasting and excess adiposity. It involves plotting weight on the *y*-axis and height on the *x*-axis to

identify a child's weight-for-height centile. However, it does not take age into account and can therefore fail to identify stunting. Due to the limitations of each of these indices, it is recommended that all three be used in conjunction to comprehensively assess a child's growth and adiposity [9]. It may also be beneficial to calculate percentage weight-for-height in certain disease states or disorders to identify acute or chronic malnutrition using the Waterlow classification of malnutrition [21]; however, further discussion of this technique is outside the scope of this review. The WHO child growth standards were developed in 2006 based on children from Ghana, Brazil, India, Norway, Oman and the USA under optimal conditions, i.e. full-term, single-term, breastfed, healthy children whose mothers did not smoke before or after delivery. Therefore, the WHO growth standards describe ideal growth rather than growth references which are simply growth centile charts derived from measurement of a representative sample of a population [10]. Country-specific growth reference centile charts as well as WHO growth standards are available and will be explained in more detail in the next section. In Ireland, there are no national growth references for children below 5 years; however, national growth references exist from cross-sectional and longitudinal data compiled by Hoey et al. [22] in 1987 on children from 5 to 19 years of age. These centile charts require calculation and plotting of decimal age to determine an individual child's growth centile. The UK uses a combination of the WHO growth standards and UK growth references for children aged 2 weeks to 18 years. On the recommendation of the Irish National Development and Implementation group for New Growth Charts in Ireland, the current official policy in Ireland is to use these UK-WHO child growth centile charts until age 4 for all children born from 2013 onwards [23]. Growth centile charts for children over the age of 4 years will be introduced at a later date and the UK growth centile charts should be used in the interim [23]. It should also be noted that in addition to the growth centile charts for the general population, there are specific growth centile charts for many genetic syndromes and other conditions, such as joint UK and Irish growth centile charts for Down syndrome [24] and US growth centile charts for cerebral palsy [25, 26].

BMI growth references and standards

Body mass index is a measure of weight-for-height expressed as kg/m^2. Unlike adults who have norms for BMI ranges, children have no such norms or standard ranges but rather healthy BMI depends on age and gender. Children's BMI is difficult to categorise due to growth and changing body composition as well as natural fluctuations in adiposity such as the adiposity rebound; therefore, BMI centiles and z scores or measures of standard deviation should be used to determine BMI status for age up to 18 years [10, 20, 27]. It is important to note that BMI is a simple measure of weight-for-height and is a surrogate measure of body fatness but not a measure of the composition of the body compartments and does not take into account the impact of muscle mass or bone mineral density [28]. Ethnicity also affects BMI due to different natural body composition, i.e. Africans and Polynesians have been found to have a proportionately lower fat mass than Caucasians of the same BMI whereas Asians, particularly Indians, have a higher fat mass [29]. BMI also overlooks the issue of stunting as weight-for-height may be normal while height-for-age is below the normal range. Furthermore, it has been found that BMI in children increases in sensitivity and specificity, as a measure of body fatness, with increasing adiposity making it a better measure in children above the 95th percentile of the reference population but less accurate in "thinner" children [30]. Therefore, BMI should not be used as a single measure of fatness but other factors such as lean body mass (LBM) and height-for-age must be considered, perhaps with the use of supplementary methods of measuring body fat such as bioelectrical impedance (BIA) [28].

Weight-for-height, a similar index to BMI, has already been mentioned. The benefit of using BMI over this index is that the calculated BMI value can be plotted against age giving BMI-for-age centiles or z scores. This is useful as BMI fluctuates during childhood increasing steeply in infancy, decreasing during preschool age children until the adiposity rebound occurs at approximately age 5–6, and increasing again as the child gets older, reaches adolescence and then adulthood [31]. An additional advantage of the BMI-for-age index is that BMI centile charts can be smoothed into adulthood allowing an individual's progress to be tracked along the centile lines all throughout life.

The WHO BMI standards define the ideal BMI and use z scores based on distance from the median to determine BMI classification, i.e. 1 z score above the mean classifies a child as "at risk of overweight", 2 = "overweight" and 3 = "obese". These standards have been adopted rapidly and are being used worldwide. However, there are several issues associated with their use, i.e. they are based on breastfed babies that have a different growth pattern early on with a slowing of growth velocity and a reduction in overall weight compared with formula-fed babies. While growth patterns differ in formula-fed infants, the WHO BMI standards may in fact encourage breastfeeding which is the ideal method of infant feeding for health [10]. Another issue with the WHO BMI standards is that they are based on values from a number of countries and so may not represent the paediatric population of a particular country

as well as nationally derived centiles might. Several European countries have developed their own BMI growth centile reference charts [31–35]; however, discussion of each of these references is beyond the scope of this article. The ideal conditions used to develop the WHO standards reflect growth patterns of infants and children who have reached their full growth potential, and the use of populations of differing average stature means that these standards should be appropriate for use in different countries. The WHO BMI standards currently remain the best tool for use up to age 5 years and have been widely accepted [10]. Some countries are using a combination of the WHO BMI standards and nationally derived data, e.g. the UK where the WHO data are used from 2 weeks to 4 years of age and the UK data for preterm infants and from 4 years on because there is no information available in the WHO BMI standards on preterm infants, and UK birthweights are higher than the mean WHO birthweights but normalise after the first 2 weeks of life [36]. There are no Irish-specific BMI growth centile charts at present and the reference charts from Hoey et al. [22] do not include BMI-for-age centiles; therefore, similarly to growth reference centiles, the official policy in Ireland is to use the UK-WHO combination BMI-for-age centile charts until age 4 for all children born from 2013 onwards. Newer BMI centile charts are to be introduced for children older than 4 years at a later date and the UK BMI centile charts are to be used in the interim [23]. Current measurement data in children over 5 years are unsuitable for growth standard derivation as the obesity epidemic would result in normalisation of overweight and obesity, and there would be great difficulty in exerting optimal environmental control in older age groups. Therefore, further WHO BMI centile charts have been developed from modification of the 1977 National Centre for Health Statistics data using supplementary literature and statistical techniques [27]. However, these BMI centile charts are not as widely used due to differing growth patterns of populations as a result of differences in age of pubertal onset, final height and overweight and obesity [36] and many countries opt to use their own references for children over 5 years of age.

There are a number of different cut-offs used to define childhood overweight and obesity. The European Childhood Obesity Group recommends that country-specific cut-offs be used clinically while prevalence studies should use a variety of cut-offs to allow international comparison [37]. Overweight is classified as BMI above the 85th centile and obesity as BMI above the 95th centile in the annual Health Survey for England but in clinical practice in the UK these cut-offs are above the 91st and 95th centile, respectively [38]. In Ireland, overweight is classified as BMI above the 91st centile and obesity as BMI above the 98th centile on the UK-WHO BMI centile charts with the recommendation that children above the 91st centile on two or more occasions (2 weeks apart if under 3 months of age, 4 weeks apart if over 3 months of age or 3 months apart if over 1 year of age) be considered for further evaluation or specialist referral [23]. It is important to note that while country-specific references are more nationally representative, they were created using a past reference population of children. The secular increase in childhood overweight and obesity in later years has resulted in an upward skewing of BMI in modern children, and therefore plotting these children on the original BMI reference centile charts results in increased diagnosis of overweight and obesity regardless of the cut-offs used [30].

Circumferences

Due to the limitations of BMI in determining true overweight/obesity in children, circumferences can be used as supplementary measures of adiposity with waist circumference (WC) being used as an indicator of central obesity to identify children at risk of obesity-related morbidity later in life [39]. Circumferences are also very useful as a simple measure of the efficacy of interventions which include physical activity as although weight, and consequently BMI, may not change following such an intervention, fat mass may decrease and muscle mass increase which will be reflected in a reduction in circumference measurements [40].

Waist circumference may be taken in the standing position either at the umbilicus or at the midpoint between the lower rib and top of the iliac crest making sure that the measuring tape runs parallel to the floor and at the same level all around [11]. Central adiposity in children is associated with higher fasting glucose and insulin concentrations and altered lipid profiles [41]. Waist circumference is also age and sex dependent and has been found to be almost as effective in determining excess adiposity as BMI [39]. Due to its dependence on age, sex and height, there is no standard recommendation for WC values in children and instead centile charts may be used [42–48]. A possible solution to the age, sex and height influences on WC is the use of an ideal waist circumference to height ratio of no more than 0.5 for all children and adults, which relies on the concept of proportionality. Values above 0.5 have been found to reflect the 95th centile for boys and 97.5th for girls using the 1977/1987 UK waist circumference data in children [49]. There has been great interest in waist-to-height circumference in recent years and it has been found to accurately predict central adiposity [50–52]. Interestingly, it appears that there has been a greater secular rise in WC than BMI in recent years, possibly reflecting the increased propensity for the upper body to

accumulate excess fat mass in young people and to the concomitant decrease in muscle mass and increase in fat mass that has accompanied a decrease in physical activity over the same period [44]. Waist circumference to height ratio has been found in a recent study by Brambilla et al. [52] to be a better predictor of adiposity than WC or BMI. Although further studies are necessary to validate the use of waist to height ratio for use in children, it has been found in adults to be a better predictor of adverse outcomes including diabetes, hypertension and cardiovascular disease, than either WC or BMI [53]. This relationship has not yet been completely explained but is thought to be due in part to the metabolic and inflammatory effects of visceral abdominal fat depots, and to the ability of height to reflect genetic and epigenetic influences and early-life exposures which may result in phenotypic programming towards short stature and elements of metabolic syndrome [53]. Waist circumference to height ratio has also been found to be capable of identifying both normal-weight and overweight/obese children with increased cardiometabolic risk factors which has great implications for clinical practice with many studies [50, 51, 54, 55] finding it to be a better identifier of cardiovascular disease risk than BMI. Some studies have found that while waist-to-height ratio is capable of identifying children with increased metabolic risk factors, BMI is a better predictor of systolic blood pressure. However, these children have been found to have taller stature and therefore their increased systolic blood pressure is height-appropriate rather than representing cardiovascular risk [51, 56].

Another option is to use the waist–hip circumference ratio (WHR) which also gives an estimation of central adiposity. Hip circumference is measured in a standing position around the widest part of the hips and buttocks, again keeping the measuring tape parallel to the floor and level all the way around as with any circumference measurement [11]. WHR decreases with age due to the natural increase in pelvic size, particularly in girls. However, a great disadvantage of WHR is that individuals who have higher BMI may have a similar WHR to those of lower BMI, provided excess fat is evenly distributed and weight loss may not result in a change in WHR despite a reduction of cardiovascular disease risk factors [57]. Therefore, while WHR has been found to correlate with intra-abdominal fat to some extent, WC has been found to be better correlated and waist–height ratio has been found to better predict visceral fat and mortality [47, 58–60].

Other circumferences commonly used in children are mid-upper arm circumference and thigh circumference. MUAC is measured around the midpoint of the upper arm with the arm relaxed by the side. The midpoint of the upper arm is located by placing the arm across the body with the hand towards the opposite shoulder and measuring the halfway point between the flat ridge called the acromion process of the scapula and the olecranon process of the ulna, i.e. the point of the elbow [11]. Thigh circumferences provide additional information on peripheral fat distribution and it is important to include them when taking upper-body anthropometric measurements to avoid introducing error in assessment of muscle and fat distribution [61]. Thigh circumference can be measured in the standing position either at the widest part of the thigh or at the midpoint between the top of the iliac crest and the knee [11]. MUAC and thigh circumferences are more commonly used to estimate changes that may occur due to malnutrition, limb disuse, orthopaedic issues or to exercise interventions but are less useful in identification of childhood overweight or obesity [62].

For most clinicians, this is the extent to which growth and adiposity assessment will be necessary and, as long as done correctly, can be very effective in identifying and classifying the extent of paediatric overweight and obesity. However, there are situations and settings when more accurate and/or intensive methods will be necessary, for example in specialist obesity or endocrinology clinics or research studies. In these situations, use of the following techniques may be explored.

Skinfold thickness

Skinfold thickness measurement is the measurement of the thickness of two layers of subcutaneous fat pinched together. Skinfold thickness can be measured at a multitude of sites, the most common of which are the biceps (front of the mid-upper arm), triceps (back of the mid-upper arm), subscapular (below the shoulder blade), suprailiac (the midpoint between the bottom rib and top of iliac crest) and thigh (mid-upper thigh). Skinfolds for all except subscapular are taken by holding the skin between the index finger and thumb 2 cm above the measurement site so that the fold of skin grasped is perpendicular to the floor. The subscapular skinfold is taken at a 45° angle to the spine along the natural line of the scapula. Skinfolds should be pulled away from the body ensuring that they have been separated from the underlying muscle. The skinfold should continue to be held in this way while the calliper is applied perpendicular to the skinfold and full tension applied for 3 s before a reading is taken from the calliper dial [11, 12]. Skinfold measurement is relatively inexpensive with the only cost involving purchase of the skinfold calliper. However, skinfold measurement requires considerable measurement expertise and researchers or clinicians should undergo training in this technique before carrying it out as reliability and accuracy of measurements are essential [63].

Skinfold thickness measurement and the use of standardised equations, while involving some limitations, have been validated as a good method for calculating body fat percentage in adults [64–67] and are widely used to calculate adiposity in children also. However, there is little information on the validity of equations used in childhood. A validation study by Reilly et al. [68] comparing five such prediction equations [69–73] with body fat measured in pre-pubescent children using hydrodensitometry found these equations to be biased and associated with large random and systematic errors. Bias was particularly increased by increasing fatness and was affected by age. Therefore, these equations may be better suited for use as indices or for groups rather than absolute measures of adiposity in individuals [74]. Obesity has also been found to result in increased variability in tissue compressibility and increased inter-individual variability [75]. Another solution is to avoid inputting skinfold thicknesses to prediction equations and to simply use them as stand-alone measurements [76]. This method allows raw data to be expressed as standard deviation scores using population reference values such as those for children by Tanner–Whitehouse [19] or for newborn infants [77]. However, these values are based on a reference population measured in the 1970s and therefore may not be comparable to today's paediatric population [76]. The comparison of raw data SD with reference values has also been found to most accurately rank children at the extremes of fatness with reduced accuracy for less extreme fatness and an inability to ascertain absolute fatness, while lean body mass is not described [76].

Skinfolds have been found to accurately reflect adiposity in children but studies vary depending on the sites measured with multiple sites found to be superior to measurement of one site [78]. A study by Gutin et al. [79] found that two-site skinfold equations were equivalent to those using multiple sites. However, since skinfold thickness measurements are measures of subcutaneous fat, they are unable to quantify intra-abdominal or visceral adiposity which is well established as a mediator of metabolic syndrome [80]. Therefore, skinfold thickness measurements have been found to no better predict cardiovascular risk factors than BMI [30, 81, 82]. Subscapular-to-triceps skinfold ratio measurement has been suggested as a method of overcoming this problem as, while not a direct measurement of intra-abdominal fat, it has been found to be reflective of central adiposity in children and correlates well with BMI and waist circumference [83, 84]. Different studies have used combinations of different skinfold measurement sites and there appears to be no gold standard site for this type of measurement at any age group.

There is some contention over which side of the body skinfold and circumference measurements should be taken from with the original convention being the use of the left side which is generally used in Europe and in children [19, 85, 86], whereas the US Centre for Disease Control (CDC) advise use of the right side of the body [12] as is the convention in North America [84]. Another method is to use the non-dominant side. A study by Moreno et al. [84] found that in children aged 7–9 years, there was no significant difference found whether skinfold thicknesses and circumferences were taken on the left or right and that differences found were lower than the technical error of measurement. Authors state that there may be a difference in adolescents and adults and that more studies are needed to reach a convention. As one side must be chosen, Moreno et al. [84] suggest the use of the non-dominant side in the absence of evidence to the contrary.

Due to the training needed and the issues with reliability and accuracy, as well as the fact that they change too slowly to capture acute weight loss or gain, skinfold thickness measurements are not regularly used in clinical practice [87].

Bioelectrical impedance (BIA)

Bioelectrical impedance involves passing an alternating electric current through the body and measuring the resistance to its flow by the body fat mass. The voltage drop between electrodes is called the impedance. Body fat and bone are resistant to electrical currents whereas lean body mass (LBM) contains most of the fluid and electrolytes which are good conductors [88]. Impedance is a combination of the resistance of body tissues to the flow of the electric current plus the reactance due to the capacitance of non-ionic substances and cell membranes [89]. Therefore, BIA actually measures total body water (by measurement of the amount of current that has been conducted) and allows calculation of lean body mass and fat mass [90]. However, certain assumptions must be made, i.e. LBM contains a particular proportion of fluid and potassium, that the subject is not dehydrated or the intracellular:extracellular water ratio remains constant, that reactance is negligible and that prediction equations are valid for the population in question [89]. Therefore, it is preferable to use a BIA machine that provides the raw data on conductivity to select the appropriate equation unless the proprietary equation used by the machine has been previously validated for use in a similar population. In addition, methodological errors may occur as it is important that the equations used are suitable for the population examined and that electrodes are placed precisely in the same positions, that subjects are fasted (as absorption and digestion of a meal result in electrolyte and fluid distribution changes leading to an underestimation of body fat mass [91]) but

not dehydrated, that subjects empty their bladder before measurement, that the temperature is ambient and, ideally, that patients are supine for approx. 10 min although some machines operate on upright subjects. There is a great need for standardisation of techniques to allow comparison of research studies and paediatric populations [89, 92].

BIA may involve single- or multiple-frequency or whole body or segmental approaches. Single-frequency whole body BIA assumes that the body is a cylinder with a constant resistivity throughout whereas multiple-frequency segmental BIA defines the body as five different cylinders with different resistivities, i.e. two arms, two legs, and a trunk which allows calculation of the percentage body fat in each body compartment. Therefore, multiple-frequency BIA machines are required to examine central obesity and fat distribution [93]. BIA measurement may also be carried out using hand-to-foot BIA machines or foot-to-foot BIA machines. Hand-to-foot machines run an electrical current from arm to foot via the trunk whereas foot-to-foot run the electrical current from one foot up to the hips and back down though the other foot bypassing the upper body and trunk in the process. Foot-to-foot BIA has been found to be useful in classification of overweight and obesity in children at a group level but has been found to inaccurately measure individual children with overweight or obesity [94, 95]. This may be due to the disproportionately higher resistance of the legs to the electrical current in comparison to the trunk. It may also be contributed to by the use of prediction equations which assume a particular body fat distribution that may differ in some children with overweight and obesity [95]. Therefore, hand-to-foot BIA machines are preferable for use in measurement of overweight and obese children [94].

Since BIA is a measure of total body water, BIA will always more accurately predict LBM and there will be more natural error of percentage fat [89, 92]. Validation studies have found that BIA generally underestimates body fat percentage in leaner subjects, overestimates it in obese subjects and may become less accurate at higher BMI [93]. A recent systematic review by Talma et al. [96] found that BIA is subject to considerable measurement error and there are conflicting validity study results in children. Therefore, Talma et al. [96] state that BIA cannot accurately assess paediatric body composition. The benefits of BIA are that it is safe, non-invasive and portable, provides rapid results and does not require extensive operator training [88]. Therefore, BIA is a good supplementary method to skinfold thickness provided an appropriate machine is used [92], but further improvements in devices and prediction equations are necessary to improve accuracy and reliability [96]. BIA may be used in the clinical setting depending on availability of equipment; however, its use is not yet widespread outside of clinically specialised areas.

Dual energy X-ray absorptiometry

Dual energy X-ray absorptiometry involves the use of X-ray beams with different photon energies to determine body composition. High density material, i.e. bone, most greatly attenuates the X-ray beam whereas lower density material allows more photons to pass through, thereby allowing differentiation of bone and soft tissue. Lean body mass and fat mass are differentiated in a similar manner. Algorithms are then used to assess body composition [97]. DEXA is most commonly used clinically to measure bone mineral density. Comparison of body composition between research studies and machines has shown disagreement as newer machines use improved technology and algorithms, while different brands of machine also use different algorithms [97]. DEXA has never been validated against body composition using human cadavers but animal cadavers have been examined. DEXA has been found to have good precision and ability to measure intra-individual weight changes, although some studies have found that it underestimates body fat percentage in healthy, weight stable individuals particularly with decreased adiposity and may overestimate adiposity in obese individuals [97]. DEXA has been found to have similar limitations in paediatric populations and some children may also exceed the size limit for DEXA scanning as, although adult machines are used, the width of the scanning area varies machine to machine and is approximately 60 cm which must also include the child's arms [98, 99]. In addition, there may be added difficulty when comparing paediatric populations longitudinally as a study by Wells et al. [99] found that measurement bias increased as individuals progressed through puberty. Advantages of DEXA scanning in children include a low level of radiation exposure, i.e. 10 % that of a chest X-ray, the ability to examine body fat distribution, its non-invasiveness, allowing children to wear light clothing during scanning, and the short duration that children must remain still. Young children and infants may also be swaddled to help them remain still during scanning [100]. It is also important to note that while DEXA scanning involves low levels of radiation exposure, repeated measurements, for example in monitoring growth or weight-management interventions, result in increased cumulative radiation exposure. Further research and development of scanners and algorithms are necessary improve the accuracy of DEXA scanning for assessment of body composition in children as study results have been conflicting [99, 101]. DEXA appears to be a useful tool for assessing overweight and obesity at group level but has been found to be inaccurate at individual level [99] and is unable to distinguish visceral adipose tissue depots [102]. A recent study has found that DEXA is more accurate than skinfold measurements when assessing paediatric body

composition using newly made reference values compiled for several different body composition measurements [103, 104].

Air displacement plethysmography: ADP/BOD POD

BOD POD consists of a test and reference chamber separated by a diaphragm which oscillates between the chambers causing a change in volume of the same magnitude in each chamber, and therefore a change in pressure between them. The ratio of the pressures of the two chambers is a measure of the volume of the test chamber, derived using Boyle's law [105]. Temperature is not controlled but the air in the chambers compresses and expands adiabatically, i.e. is allowed to freely gain and lose heat as it is compressed and expanded resulting in no net change. Air trapped in the lungs or in body hair or clothing maintains a constant temperature and such isothermal air is compressed more easily than adiabatic air resulting in underestimation of body volume. To minimise this effect, tight swimwear and cap are recommended and the average thoracic volume during normal tidal breathing is either measured or estimated and corrected for, as is skin surface area [105].

ADP can be used to measure body composition at any age. The PEA POD may be used for infants weighing between 1 and 8 kg. The PEA POD has been found to accurately and reliably assess body fat in infants [80] and has been used to create percentage body fat centiles for birth [106]. A paediatric option accessory may be used in conjunction with the adult BOD POD for children from age 6 months to 6 years to limit movement and aid safety [107]. BOD POD has been validated for use in children aged 2–6 years since the development of this attachment [107]. Fields and Allison [107] found that the BOD POD with paediatric attachment was accurate, precise, reliable and unbiased in estimating percentage fat. ADP allows the longitudinal measurement of body composition from birth to adulthood with a gap between age 6 months and 2 years where ADP has not yet been validated.

The original standard for density measurement in humans is hydrostatic weighing (HW) which is essentially a method of underwater weighing where an individual is first weighed as normal and then weighed again while completely submerged underwater. Bone and muscle are more dense while fat is less dense than water; therefore, an individual with a higher percentage body fat will weigh relatively less underwater than an individual with a higher muscle mass. HW relies on the principle that if an individual is weighed before submersion and while underwater, the difference, corrected for the water density, equals the volume of the individual and therefore density can be calculated [108]. This method is very difficult to perform with children due to the need for underwater submersion but has been used for ADP validation studies. ADP validation studies in children have provided conflicting results. An early review by Fields et al. [105] found that ADP agreed with other methods of body fat measurement to within 1–3 % body fat with a tendency to underestimate. Since this review [105], there have been several ADP validation studies [109–113]. One study [113] found that ADP significantly underestimated fat mass while three [110–112] found no significant difference between body density measured using ADP or HW. Two studies [109, 110] found that ADP may overestimate percentage body fat in leaner children and underestimate it in those with increased adiposity, and a study by Moon et al. [112] found that constant error was higher using ADP than HW.

Studies have found ADP to be acceptably accurate, precise and without bias [101, 114]. However, while inter-individual limits of agreement have been found by many studies to be wide, this disagreement can be largely attributed to intra-individual biological differences in tissue hydration and possibly chemical composition [113, 115] and to air pressure, moisture and movement of children in the machines [114]. Other methodical issues include carrying out HW before ADP, estimation vs measurement of thoracic gas volume, use of a separate weighing scale to the one incorporated into the BOD POD for HW, small "narrowly defined" sample sizes and the use of adult prediction equations [113, 115]. Recently, a validation study found that there was no significant difference in body density as measured by ADP in comparison with HW irrespective of whether thoracic volume was estimated or measured [111]. However, a significant difference was observed between body densities as calculated using estimated or measured thoracic volume within the same technique (i.e. ADP estimated vs ADP measured), indicating the need for standardisation [111]. A further issue is the use of assumed densities of lean and adipose tissues in children [103]. Studies have shown that tissue composition may differ for obese and normal-weight children [49, 116]. Such differences may be responsible for the observed overestimation of body fat in overweight and obese children and underestimation in leaner children observed in ADP, DEXA and BIA [117]. Potentially more accurate predictive paediatric body composition equations based on body density have recently been developed by Wells et al. [103] explaining 33 % of the variance in body density.

Magnetic resonance imaging (MRI)

Hydrogen atoms are abundant in the tissues of the body, and normally their single proton orbits the nucleus. MRI generates a magnetic field resulting in alignment of these

protons creating a magnetic vector. This alignment is then shifted by addition of a radio-wave and returns to the vector orientation when the radio-wave is removed creating another radio-wave. The time taken to return to vector orientation and to original orbiting state is thereby measured, and multiple pulses are used to create body images and differentiate between tissues [118]. MRI does not expose subjects to radiation and is therefore very suitable for use in children; however, it requires children to stay still for prolonged periods. Sedation is inappropriate for use in research for ethical reasons. MRI analysis may involve whole body imaging which is time consuming and expensive or simpler single-slice scanning which has been found to be less accurate [119, 120]. Single-slice MRI scanning is more practical and its accuracy can be improved by scanning above the L4–L5 levels to estimate visceral adipose tissue and in research settings by increasing subject number by up to 12 % to reach equivalent powering to whole body MRI [119–121]. Single-slice MRI has not however been found to be an accurate measure of visceral or subcutaneous tissue changes during weight loss and is therefore inadequate for use in weight loss interventions [122]. Due to their smaller size, infants are measured using contiguous MRI scanning rather than slices which usually takes only 10 min and may be achievable without sedation in certain age groups [102, 123, 124]. Premature infants can also undergo MRI scanning due to the development of MRI-compatible incubators [125]. MRI is accepted as a gold standard for measurement of adiposity and differentiation of body fat depots and is often used to validate other measures of body composition in adults and children. A recent review by Samara et al. [126] explored the use of MRI and CT in the assessment of paediatric body composition. These techniques are mainly used to examine body fat distribution and accurately differentiate between types of fat depots, i.e. visceral, ectopic and subcutaneous. Subcutaneous or abdominal MRI can be used to predict future metabolic risk and correlates well with BMI [126].

Computed tomography

Computed tomography uses a similar principle to DEXA or 2D X-ray, i.e. the variable resistance of different tissues to beams of radiation. However, it is capable of encircling any body part, providing cross-sectional and volumetric images, and is much more sensitive to attenuation allowing differentiation and measurement of different depots of fat [127]. CT is unsuitable for routine clinical paediatric assessment or research due to the radiation dose required, particularly as children are more radiation-sensitive, and due to its cost and the necessity for children to remain still for prolonged periods [128]. However, it correlates well with WC [126] and has allowed description of paediatric fat distribution patterns throughout maturation and serves as a gold standard for comparison of measurement techniques for intra-abdominal and subcutaneous fat [129].

Ultrasound

Ultrasound or sonography involves exposure of the body to high-frequency sound waves which reflect off the structures and tissues of the body and are detected by a transducer. A scanner uses the amplitude, velocity and frequency of these reflected sound waves to convert them into real-time images of the interior of the body. Due to the disadvantages of MRI and CT in children, US has been examined as a method of paediatric body composition measurement. The advantages of US are that it is a non-invasive, portable, quick and readily available technique in most clinical settings. It also has the ability to distinguish between visceral and subcutaneous fat which is not possible while using anthropometric measurements [130]. However, interpretation of US images requires technical skill and practice, and there are no universal guidelines for ultrasound measurement of adipose tissue [131]. US can measure subcutaneous and preperitoneal fat using electronic callipers. Preperitoneal fat provides good approximation of visceral fat in adults and more recently has been correlated with visceral fat in children as measured by CT although agreement was found to be limited indicating that this method may have limited use in individual measurement [128, 132]. Validation studies of US against the gold standard methods CT and MRI have given conflicting results however. A recent study by Koot et al. [133] found that internal abdominal (visceral) adiposity as quantified by MRI was better correlated with waist circumference than with US in severely obese children and adolescents with the authors concluding that ultrasound is unsuitable for use in such populations. A similar comparison of ultrasound with MRI in infants found that US was accurate, acceptable to parents, reliable and reproducible [130]. Ultrasound has also been found to be correlated with skinfold thicknesses, BMI and waist circumference in children and to show less variability in obesity than skinfold thicknesses [75]. US appears to be a promising technique but further research is necessary to fully validate its use in children.

Conclusion

There are a great number of anthropometric measurement techniques available for use in children, none of which are direct measures of adiposity and as such rely on predictive

equations and/or references. These techniques are summarised in Table 1. Due to the surrogate nature of these techniques, it is impossible to make absolute assumptions of accuracy in children. It is also important to understand that even when the greatest care has been taken to choose the most appropriate technique, each technique has its limitations and a combination of methods may assist in characterisation of paediatric body composition [74]. The main clinical techniques are weight, height, BMI and circumferences which generally provide sufficient information to enable measurement of adiposity and diagnosis of overweight or obesity when growth centile charts and ratios such as waist-to-height ratio are employed. Further investigation will depend on resources available and examiner skill, e.g. skinfold thicknesses, DEXA, ADP, MRI, CT and US. Skinfold thicknesses are the most cost-effective method of measuring body fat but require a high standard of technical training and only measure subcutaneous fat while DEXA and ADP, MRI and CT are more costly and intensive analyses, requiring the child to remain still for longer periods. DEXA and ADP are capable of measuring adiposity with good accuracy; however, they are unable to distinguish between different fat depots in the body and it is important to note that measurements using each technique are not equivalent and therefore should not be directly compared [134]. MRI and CT, on the other hand, can distinguish internal abdominal or visceral adiposity from subcutaneous adiposity and are considered the gold standard for body composition assessment but CT is unsuitable for body composition analysis in children due to high levels of radiation exposure. Ultrasound is a promising area in body composition analysis which is capable of measuring intra-abdominal adiposity in children but requires further research and validation before its use can become widespread.

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