Overview of BMI and Other Ways of Measuring and Screening for Obesity in Pediatric Patients

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KEYWORDS

• Body mass index • Screening • Adiposity • Measurement • Hydrodensitometry
• Air displacement plethysmography • MRI • Dual-energy x-ray absorptiometry

KEY POINTS

- Body mass index (BMI) has been as measure of adiposity for more than a century.
- While there are several other measures of adiposity, they have varying clinical usefulness and correlation to adipose tissue volume.
- No measure of adiposity assesses adipose tissue pathophysiology, thought to be a precursor to obesity-related comorbidities.
- BMI is strongly correlated to obesity-related co-morbidities.
- BMI is also a strong measure of adiposity in children less than 2 years.

HISTORY OF BODY MASS INDEX AND OTHER MEASURES OF ADIPOSITY

Although obesity has been observed in humankind for millennia, the attempt to quantify body size, specifically, weight independent of height, appears to have been initiated by Belgian scientist, Adophe Quetelet in the early 1830s.[1,2] Quetelet's goal was to better describe the periods of development; starting his quest with periods of pediatric growth, he cited the need to estimate a child's age with verifiable physical elements that could "substitute precise characters and exact data for conjectural estimates, which are always vague and often faulty."[3] So, Quetelet's investigation began

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by analyzing weight and height data from various sources beginning at birth. Body mass index (BMI) is still occasionally referred to as "Quetelet's index," by his observation of "weight of developed persons, of different heights, is nearly as the square of the stature."[3] However, it is important to recognize that, in childhood, Quetelet found dynamic changes in how children grow until the age of 25. His observations suggested that there is not one suitable ratio that describes body size during the dynamic periods of growth, with weight and height increasing both proportionally and disproportionally, throughout childhood, even concluding that "during development, the squares of weight at different ages are as the fifth powers of height."[3] Recent investigations of different ratios of weight to height during pubertal changes suggest a simple number across child and adolescent development cannot capture body fat in an accurate manner.[4]

How could such a simplistic measure of body size become the most commonly used proxy for adiposity? Independent of its ease of use, Quetelet's 19th Century discovery of BMI has been repeatedly tested against other indices for its validity as a proxy of adiposity. Ancel Keys's study of over 7000 men across 5 countries, correlating skinfold thickness to body size indices showed BMI (a term he first coined in the article) was better than weight or height ratio or weight or height[3] (also known as ponderal index or tri-ponderal index).[5] Since then, BMI has been used most commonly to capture population variation among adults and track trends over time.[6,7] The individual connections between BMI and health are complex, and guidance has focused on BMI's rightful place as a screening tool and a priority for tracking population trends. Although BMI may be the best simple, non-invasive measure of adiposity, it has significant limitations in individual phenotypes or specific pathophysiology of obesity. As focus on the pathophysiology of obesity has intensified, many other measures of adiposity have emerged. The next section focuses on alternative measures to BMI and returns to discuss BMI's advantages and disadvantages as it persists as the proxy of choice for adiposity.

MEASURES OTHER THAN BODY MASS INDEX

Understanding the pathophysiology of excess adipose tissue changes the framing of the desire for BMI as a proxy. The goal is finding a proxy that best represents disease states and differentiates between states of health. Given this goal, several more direct measures of adiposity are available. Of note, most of these measures are used in research settings due to their high cost or lack of clinical feasibility. Importantly, none of these measures directly assesses the disease state of excess adiposity; further they cannot discriminate between normally functioning adipose tissue physiology from pathologic adipose tissue.

Available Measures of Adiposity

The measurement of adiposity has long been considered difficult in humans, especially children, given the various spaces that adipose tissue develops and deposits across the body.[8,9] Adipose tissue functions as energy storage, physical protection, and metabolic signaling, among other functions, complicating associations between structure and function, particularly in the developing child.[10,11] Measuring adiposity has been attempted for many centuries; however, most measures that have been developed to date still only function as a proxy for adipose volume, not function. Additionally, adipose tissue can be quantified with imaging, but the proportion quantified as adipose tissue does not represent total body fat, and these proportions vary with age and between genders.[12]

Measures of adiposity other than BMI are listed in **Table 1** and described as follows.

Research measures

Hydrodensitometer. Hydrodensitometry (HD), once the gold-standard for body composition assessment, is a measurement of weight underwater.[13] HD uses principles from Archimedes noting that higher fat-free mass will weigh more in water.[14,15] HD is fairly accurate; a major limitation is cost. In addition, the individual needs to be healthy, ambulatory, and able to follow very precise instructions, which limits its use in children. Second, formulae were created based on non-Hispanic white, male cadavers,[15] potentially misclassifying body composition in women and those from other races and ethnic groups.[8]

Air displacement plethysmography. Air displacement plethysmography (ADP), uses pressures and volume relationships to measure body density.[16–19] ADP was originally developed by measuring the density of inanimate objects. After recent technology allowed for the adjustment for body temperature and humidity in skin and hair,[20] several studies have shown good agreement between ADP and HD in certain populations but not in others.[19] While options exist for young infants,[21] ADP cannot be measured for most children between the ages of 6 months and 3 years.[22]

Doubly labeled water (isotope dilution methods). Isotope dilution uses a stable isotope deuterium oxide ($^{2}H_2O$) or oxygen-18 (^{18}O) labeled in water (H_2 [^{18}O]) to measure energy expenditure. A small, concentrated dose of the isotope is administered and allowed to mix effectively with the total body water pool ($\sim$4 hours). The rise in isotopic concentration is measured (through expired carbon dioxide [CO_2] or excretion in the urine) which estimates total body water, from which fat-free mass is calculated.[23] This method has been validated in all ages and is accurate within 5%.[24] Isotopes are safe and provide an option for non-invasive measures of a child's total body water.[23] While it is a gold standard for body composition for children across the age range,[25–27] it is not often used as it requires proper sampling, dosing, and storage of the isotopes.

MRI. MRI uses magnetic fields to detect radiofrequency energy emitted by hydrogen atoms from the nuclei of cells to generate images of the target organ or tissue.[28] MRI creates a three-dimensional image, allowing for volumetric measurements of adipose tissue. It is highly accurate and reliable and can measure small changes over time, but use is limited in children due to sensitivity to movement and cost.[29]

Dual-energy X-ray absorptiometry. Dual-energy x-ray absorptiometry (DEXA), projects 2 beams of different energy x-rays through different body tissues to estimate the amount of density in tissues.[30] DEXA is highly correlated to MRI and computed tomography (CT) measures of adiposity (r = 0.83 - 0.90)[31] and is preferred given the ease of use, lower cost, and relatively lower dose of radiation than CT. A major limitation is that it does not discriminate between visceral and subcutaneous fat and overestimates fat mass when body dimensions, mostly in severe obesity, violate the assumption of independence from anteroposterior depth.[32]

Clinical measures

Waist circumference. Waist circumference (WC) is an individual's measure of their waist at the level of the umbilicus or top of the iliac crest and is the preferred method of measuring central obesity. WC is age- and sex- dependent and is highly correlated to BMI[33] and to cardiovascular disease risk and type 2 diabetes.[34] It is also better correlated with fat mass than BMI.[35] Limitations include a lack of consensus on

Table 1
Measures of adiposity and their characteristics

Measure	Brief Summary of How It Measures Adiposity	Strengths	Limitations	Age Limitation	Cost
Research Measures					
Hydrodensitometer	• Estimates fat-free and fat body densities through measurement of body weight when submerged underwater and compares to body weight in air	• Was previously considered gold standard for body composition • Fairly accurate	• Densitometry equations were developed from direct analysis of white cadavers and systematically underestimates relative fatness in other races and biologic sex[15]	8 y or older (due to compliance)	$$$$
Air Displacement Plethysmorgraphy (ADP)	• Uses pressure/volume relationships to estimate body density	• Several studies that support validity and reliability	• Validity testing shows ADP less accurate in younger children	Birth and older	$$$
Doubly Labeled Water (Isotope Dilution Methods)	• Uses stable isotopes (deuterium oxide (^2H_2O) or oxygen-18 (^{18}O) labeled in water (H2 [18O]) to estimate total body water (and thus fat mass)	• Also considered gold standard for measurement of body composition in children • Fairly accurate • Isotopes are safe for children all ages (including pre-term infants)	• Is fairly labor intensive • Often difficult to administer isotope solution orally in younger children	Birth and older	$$$
MRI	• Uses magnetic fields to detect radiofrequency energy emitted by hydrogen atoms from nuclei of cells	• Creates a 3-dimensional image from which volumetric measurements of adipose tissue can be taken • Highly accurate and reliable	• High-cost • Difficulty getting children to lay still (thus may require anesthesia for younger children)	Birth and older	$$$

DEXA	• Uses x-ray beams of different energy levels to pass through different body tissues • Estimates amount of density in tissues transmitted in low vs high energy x-ray	• Highly correlated to MRI measures of adiposity • Easier to use compared to other research methods	• Limited availability • Uses radiation, which can have health sequelae	Birth and older (although used in older children given radiation	$$
Clinical Measures					
Waist Circumference	• Measures individual waist at level of umbilicus or top of iliac crest	• Low cost • Ease of use • Favorable safety profile • Can assess all body shapes/sizes	• Cutoff points vary with sex and ethnic groups. • No consensus on the best anatomic location	Birth and older	$
Waist to Hip Ratio	• Ratio of waist circumference to hip ratio (widest part of the hips and buttocks) measured in the standing position	• Low cost • Ease of use • Favorable safety profile	• Measurements may be similar across body mass index (BMI) ranges due to changes in pelvic size • Unable to accurate measure change in distribution of adipose tissue	2 y and older	$
Skinfold Thickness	• Measure of thickness of 2 layers of subcutaneous fat pinched together • Common locations include bicep, tricep, subscapular, and suprailiac	• Low cost • Ease of use • Favorable safety profile • Can assess all body shapes/sizes	• Fairly uncomfortable for patient • Validation data in children is limited compared to adults • Requires considerable training to achieve reliable and accurate measurements • Does not quantify visceral adiposity	2 y and older	$

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Table 1
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Measure	Brief Summary of How It Measures Adiposity	Strengths	Limitations	Age Limitation	Cost
Bioelectrical Impedance	• Uses low-voltage alternating current to measure total body water and estimate lean and fat body mass	• Relatively low cost • Safe, non-invasive • Portable • Rapid results • Less extensive operator training	• Estimation of fat mass based on hydration status • Prediction equations not validated in all ages, sexes, or race/ethnic groups	Birth and older	$$
Body Mass Index	• Is a ratio of weight to height squared	• Relative low-cost • Easy to measure and calculate • Several studies show correlation between BMI and future cardiovascular risk	• BMI oversimplifies differences in body composition • Not well-validated in non-White children	Children 2 y and older	$

Legend: Cost is estimated. Range represented by "$", ranging from $ - $$$$.

how to best measure waist circumference. Additionally, because of its dependence on age, sex, and height, there are no standards for WC values in children. Finally, it requires training to ensure accuracy, reliability, and measured in way that avoids stigma.

Waist-to-hip ratio. Waist-to-hip (WHR) uses the ratio of WC to hip circumference, measured as the widest part of the hips and buttocks while standing. WHR is correlated with intra-abdominal adipose tissue; however, its association to morbidity and mortality is inferior to WC and waist-to-height ratio.[36–39] WHR may be similar across BMI due to changes in pelvic size (especially in females) and changes in the distribution of adipose tissue and muscle mass, thus, it should be interpreted with caution.[9]

Skinfold thickness. Skinfold thickness is the measure of thickness of 2 layers of subcutaneous fat measured between a set of calipers.[9] It is often measured at the bicep or tricep of the mid-upper arm, the mid-upper thigh, or at the midpoint between the bottom rib and top of the iliac crest (suprailiac). Skinfold thickness is relatively inexpensive and has been well-correlated with body fat percentage in adults. Although used in children,[40] validation data for skinfold thickness is limited;[41–43] it is invasive, with potential for stigma, and considerable training is required.[44] It also lags when an individual losses weight.[9,45] Finally, it does not appear to improve on BMI in predicting cardiovascular risk[46–48]

Bioelectrical impedance. Bioelectrical impedance (BIA) induces an alternating current (<0.25 V) into the body and measures electrical differences in tissue water content.[9,49–51] Lean body mass and fat mass are estimated based on several assumptions including the hydration status of the individual. BIA may involve single or multiple frequency approaches and whole-body versus segmental approaches.

BIA has several advantages: it is relatively low cost, does not require extensive training, and is instantaneously measured.[52] BIA likely overestimates body fat percentage in individuals with higher BMI[53–55] and are more inaccurate in children since current prediction equations have been developed from previous population studies.[56]

Body Mass Index

Given the complexity of the measures detailed mentioned earlier, it is understandable that a simple measure using just weight and height has attracted criticism as an oversimplification. In fact, there is considerable discussion about improving measures that are associated with health outcomes,[57] understanding more about the heterogeneity of obesity,[1] and acknowledging that BMI alone will not measure body fat nor disease risk on an individual basis. Further, none of these measures assesses physiologic function, an important factor in disease that is partially independent of volume of adipose tissue.[58–60] The American Medical Association recently passed a resolution discouraging the use of BMI alone to make medical decisions and encouraging the use of BMI "in conjunction with other valid measures of risk."[61]

Echoing the historic lack of representation, the source data with which BMI-for-age assessment is categorized will not reflect every population, and similar to many sources of pediatric health data, it tends to overemphasize white children from families with fewer resource and education limitations. Moreover, BMI oversimplifies population-specific differences in visceral fat, fat-free masses, and adipose pathophysiologies that may lead to very different health outcomes. For example, the World Health Organization (WHO) has acknowledged that Asian populations have higher risk of metabolic and cardiovascular disease at lower BMI thresholds compared to European populations.[62] Indeed, attempts have been made to refine BMI cutoffs for adults across sex, race, and ethnicity categories that better reflect risk for comorbidities such as hypertension, dyslipidemia, and diabetes.[63] Acknowledging these differences in BMI are important for pediatric care given the persistence of elevated childhood BMI into adulthood.[64–66]

The ability of BMI to reflect adiposity during childhood varies by age,[67] degree of BMI,[46] and by race and ethnicity.[68] Comparing BMI to total and percent fat mass with DEXA, BMI Z-score appears to be an excellent predictor of total fat mass in children over the age of 9, but may not predict fat mass as well under the age of 9.[67] Others looking at populations with a lower mean BMI have shown that BMI is well-correlated with total and percent fat mass in children as young as 5.[69] BMI is a worse predictor of adiposity as the degree of adiposity decreases. Especially among children with a BMI under the 85% for age, Freedman found that the sensitivity of BMI as a measure of fat mass decreases as BMI-for-age becomes lower. Particularly for children with a BMI less than 85% for age and sex, differences in BMI are more likely to be attributed to differences in fat free mass. This can be contrasted with the 70% to 80% sensitivity of BMI for adiposity in children with obesity as defined as a BMI over the 95% for age.[46]

Similar to differences seen in racial and ethnic groups in adults, BMI tends to slightly overestimate adiposity among black children and slightly underestimate adiposity among Asian children. Given a similar level of BMI-for-age, black children had approximately 3% less body fat as measured by DEXA and Asian children had 1% more body fat. These differences highlight the limitations of equating BMI with adiposity at an individual level, and suggest that BMI cutoffs for the overall population may not be suited for specific risk stratification.

A meta-analysis of the diagnostic validity of BMI for obesity in children aged between 4- and 18-years tested against an array of reference standards including skinfold thickness, BIA, DEXA, ADP, and HW, showed a pooled sensitivity of 73% and specificity of 93%.[70]

BODY MASS INDEX SCREENING

In pediatric populations, rapid changes in the development of adipose tissue in the first years of life create both a peak in adiposity during infancy and a nadir during early childhood, around the time of school entry. The corresponding peak and trough of BMI during this time, and additional rapid changes in adipose physiology during puberty, mean BMI does not increase monotonically. Public health agencies and clinical societies recommend using sex- and age-specific BMI percentiles. These BMI-for-age percentiles have been a linchpin of pediatric routine care. Screening for obesity is a Grade B recommendation from the United States (US) Preventive Services Task Force starting at age 6 years[71] and recommended by the American Academy of Pediatrics starting at age 2 years.[72]

Screening for obesity and obesity related comorbidities are a recommended part of routine preventive care for children.[72] Data from children growing prior to the increase in obesity prevalence several decades ago provides the nationally-representative growth references developed by the Centers for Disease Control and prevention (CDC).[73] These clinical growth charts represent age- and sex-specific distributions of BMI among children in the US without any specific exclusion. Data were collected through multiple waves of the National Health and Nutrition Examination Survey (NHANES) and were smoothed to create curves for practical clinical use. Given the significant rightward shift in BMI distribution since these data were collected (ie, BMIs have increased), limited data were available at the upper end of the BMI distribution, and the reliability of plotting BMI above the 97th percentile has been challenged.[74] Given this limitation, additional metrics to assess and monitor BMI status have been suggested and include: BMI Z-scores; percent above the 95th percentile; and both sex- and age-adjusted and unadjusted BMI units or percent from the median.[73] Importantly, additional data from 8777 children with BMI above the 95th percentile measured in 1999 to 2016 waves of NHANES were used to develop "extended" BMI-for-age percentile and Z-score reference curves that replaced previous curves based on statistical extrapolation. These curves, newly published at the end of 2022, should be most helpful in distinguishing changes in BMI Z-score over time and provide the ability to track percentiles and Z-scores continuously across the BMI distribution.

According to survey data, under 20% of pediatric clinicians used BMI charts for routine monitoring in the early 2000s,[75] yet BMI charts are better than separate height and weight charts for flagging obesity risk.[76] This percentage of providers who use BMI charts increased in the last 2 decades alongside the implementation of electronic health records, which hold promise to improve the routine screening and diagnosis of obesity.[77,78] Enhancements to the display of BMI that address low health literacy and numeracy and engage caregivers have been shown to improve understanding.[79] One specific adaptation of the BMI reference into a poster used in clinic examination rooms increased dialogue between caregivers and clinicians and improved caregivers understanding of BMI and healthy behaviors when tested in a randomized trial (**Fig. 1**).[80]

CONSIDERATIONS IN CHILDREN UNDER 2 YEARS OF AGE

Risk for obesity and comorbidities accumulates before the age of 2, prompting a desire to use BMI or other similar measures to provide an ability to stratify risk prior to toddlerhood.[81,82] Body composition measurement in infants has also been advancing.[21,83,84] Diagnostic validity studies comparing BMI, weight-for-length (WFL), and more direct measures of adiposity suggest that BMI performs well.[85,86] BMI has a stronger association than WFL with fat mass and percent fat mass in infants measured with ADP.[85] BMI during infancy also has a high sensitivity and specificity for predicting childhood obesity. Infants with a BMI and WFL greater than or equal to 85th percentile in the first 18 months of life have a 3-fold increased risk of being obese by age 6.[86] Both the timing and magnitude of BMI during its physiologic peak during infancy has been shown to predict obesity after age 2.[87–89]

Despite the ability of BMI to better predict fat mass than WFL, the CDC continues to promote the use of WFL as a screening tool in children less than 2 years of age. Ongoing epidemiologic surveillance reports "high WFL," and defines this as a WFL greater than the 97.7% of the WHO growth standards for age and sex.[90] There are substantial methodologic differences precluding direct comparison of BMI by WHO growth standards before age 2 years to BMI-for-age references used after age 2 years. Most importantly, while neither source data are planned for update, the NHANES-based CDC data represent the distribution of weight, length, and BMI among infants and children during specific "pre-epidemic" decades in the US. The WHO methodologies aimed to exclude restrictions on normal physiologic growth to create a globally-representative sample of ideal growth. With this goal, the WHO methodology excludes infants born prior to 37 weeks gestational age, includes only breastfed infants, and excludes infants born to mothers with significant comorbidities, who smoked, or who lived in socioeconomic settings that might limit the healthy growth potential of their children. Additional methodologic distinctions are highlighted in a report by the CDC that also notes the availability, but discourages the use, of BMI under the age of 2 years.[91]

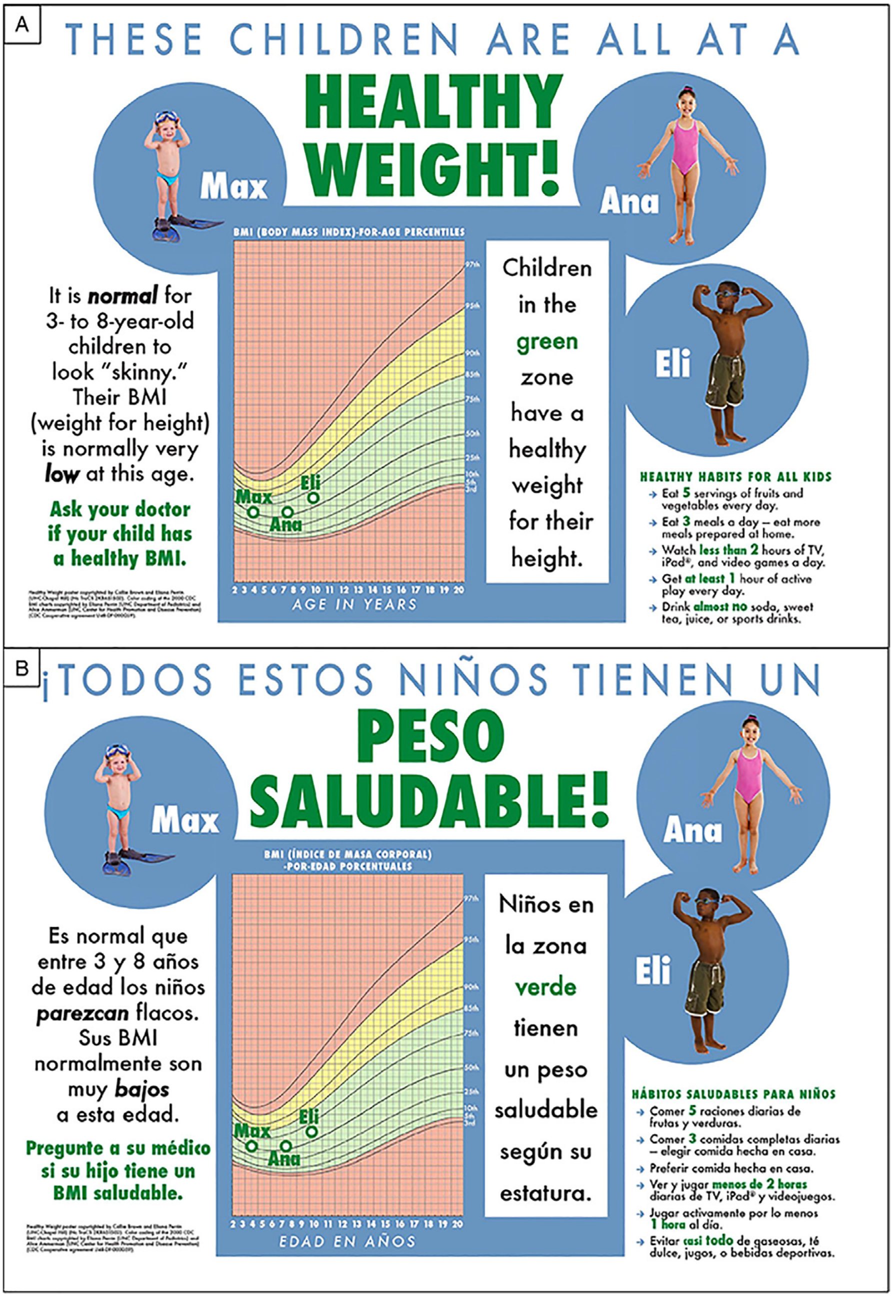

Fig. 1. Practical body mass index (BMI) chart for clinical use.

Advances Beyond Body Mass Index

The use of BMI as a screening tool has become pervasive in primary care and public health settings, and many studies have shown an association between BMI and intermediate markers of disease,[92] morbidity, and mortality.[93,94] Clinical decision support tools can improve uptake of BMI screening and linking BMI to efficient screening for comorbidities. Still, use of a given BMI in 1 individual at 1 time may not provide the information necessary to appropriately assess pathophysiology. Fortunately, there is still active and creative dialogue around the usefulness and simplicity of BMI as a proxy for body size and adiposity.[1] Although adjusting BMI based on race, ethnicity, sex, and height has been utilized,[63,73,95] newer technologies to measure body shape,[96] personalized indices,[97] and serum biomarkers of adipose pathology[98] may emerge. With advances in computer power and diagnostics, we are likely to encounter better, more personalized measures to screen for obesity in the 21st Century. While BMI remains an accurate, clinically-relevant measure, we should continue to understand the possible pitfalls of using 1 measure and the value of patient-reported outcomes related to its proper and improper use in the care of children.

CLINICS CARE POINTS

- Knowing that health care providers and health care settings are contributors to weight stigma, measurements should be performed in a way that minimizes weight stigma and centers the patient.
- BMI remains the most accurate and clinically-feasible proxy measure for adiposity.
- Routine measurement of BMI is recommended, but individualized discussion of limitations to BMI is encouraged.

DISCLOSURE

The Authors have nothing to disclose.

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