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Designing and evaluating clinical cutpoints for childhood obesity

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Designing and evaluating clinical cutpoints for childhood obesity

by

Kelly Rian Laurson

A dissertation submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of
DOCTOR OF PHILOSOPHY

Major: Kinesiology (Biological Basis of Physical Activity)

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CHAPTER 1

Introduction

The prevalence of pediatric obesity in the United States rose from approximately 5% in the 1960's to over 15% in 1999-2000 (Ogden et al., 2002) and has further increased to 18% in the past five years (Ogden et al., 2006). There are numerous potential consequences and comorbidities associated with this obesity epidemic (Must and Strauss, 1999), including type II diabetes (Pinhas-Hamiel et al., 1996), hypercholesterolemia, low high-density lipoprotein cholesterol, and hypertension (Freedman et al., 1999). Besides these immediate consequences, there is also concern for long-term consequences since pediatric weight status tracks along with the cardiovascular disease risk factors mentioned above from childhood to adolescence to adulthood (Eisenmann et al., 2004; Freedman et al., 2005; Morrison et al., 2007; Srinivasan et al., 1996). It has also been demonstrated that childhood weight status is independently related to adult mortality (Must et al., 1992). In addition to the physiological consequences, the economic (Wang and Dietz, 2002) and psycho-social (Schwimmer et al., 2003; Williams et al., 2005) consequences of childhood obesity are also well documented. Given the above mentioned medical concerns, childhood obesity are at the forefront of health research (Spiegel and Alving, 2005) and public health policy and legislation (Boehmer et al., 2007) in the United States. This epidemic is not limited to U.S. children, as it has become a global health issue (Wang and Lobstein, 2006; World Health Organization, 1998).

Considering the recent trends in the prevalence and associated health risks of childhood obesity, it is somewhat surprising that no satisfactory classification system has been identified for use in epidemiologic research and public health. In much of the current literature, the body mass index (BMI) is compared to reference centiles to categorize youth

as normal weight, overweight, or obese (Ogden et al., 2002). These risk categories were based solely on the 85th and 95th age- and sex-specific percentiles of pre-obesity epidemic BMI distributions in the United States. However, identifying a child with a BMI one to two standard deviations above the population mean may not necessarily indicate increased disease risk. In an attempt to remedy this limitation, many recent studies examining childhood obesity have used a relatively new set of international pediatric BMI cutpoints generated from six large, nationally-representative surveys from various countries wherein reference centiles are anchored to the adult values of overweight (25 kg/m²) and obesity (30 kg/m²) (Cole et al., 2000). However, both of the mentioned cutpoints are based on the BMI, a major limitation of which is the inherent inability of BMI to differentiate between fat mass and lean mass (Garn et al., 1986). Therefore, skinfold thicknesses have been recommended for use in identifying obesity and disease risk in youth (Himes and Dietz, 1994). Likewise, there are also no clear definitions or recommendations of what defines excess adiposity in children and adolescents. Using skinfold-derived percent body fat estimations, Williams et al. (1992) identified percent fat cutpoints of 25% in boys and 30% in girls that were indicative of an increased risk of being in the highest quintile for blood pressure and serum lipoproteins. In a similar study, Dwyer and Blizzard (1996) proposed a cutoff point of 20% fat for boys and 30% for girls. Neither of the two cutpoints has been cross-validated, despite the former cutpoints being widely used in FITNESSGRAM assessments (The Cooper Institute, 2007). Furthermore, both of these recommendations are static levels across childhood and adolescence. Percent body fat, like the BMI, varies by both sex and age. It is possible that these thresholds may not be crossed by overfat children until later adolescence, bypassing an opportunity for early detection, prevention, or intervention.

Identifying clinical cutpoints to accurately diagnose childhood obesity and the subsequent disease risks are essential tasks in child health care (Freedman et al., 2005; Himes and Dietz, 1994; Kimm and Obarzanek, 2002), with implications for clinicians, researchers, educators, and policy makers. In addition, limitations in the definition of childhood obesity create challenges for the surveillance of the current epidemic, theory and correlates research, and gauging the effectiveness of interventions. In contrast to creating new cutpoints, the information obtained by evaluating those in current use aids future prevention work (Swinburn et al., 2005).

Specifically related to kinesiology, obesity is a commonly used independent or dependent variable in physical activity research. Increasing physical activity is often a priority of obesity interventions (Sharma, 2006). A recent policy statement by the American Academy of Pediatrics on preventing childhood obesity through increased physical activity denotes the magnitude of influence these variables may have in healthy living for youth (Council on Sports Medicine and Fitness and Council on School Health, 2006). The aforementioned challenges with the classification of obesity are likely reasons that the relationship among physical activity, adiposity, and chronic disease remains obscure (Telford, 2007).

The series of papers to be presented in this dissertation will provide a better understanding of the development, assessment, and interpretation of clinical cutpoints associated with obesity during childhood and adolescence. To provide appropriate background for this research, a literature review on childhood body composition and clinical cutpoints for defining obesity is provided in Chapter 2. Chapters 3 and 4 will be presented in manuscript form (i.e., abstract, introduction, methods, results, discussion,

acknowledgements, and references). In Chapter 3, age-, sex-, and race-specific percent body fat reference centiles will be developed for white, black, and Mexican American youth.

Chapter 4 will describe the level of agreement between the BMI, waist circumference, and estimates of percent body fat for the previously mentioned groups also using a nationally-representative sample. The final chapter will summarize the findings herein and provide recommendations for future research in this area of study.

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CHAPTER 2

LITERATURE REVIEW

Introduction

Pediatric obesity is currently the topic of much research and discussion in contemporary society. Obesity is typically defined as an excess of body fat (Prentice and Jebb, 2001). However, this term is also synonymous with having a body mass index (BMI) greater than or equal to 30 kg/m^2 as an adult, or having a BMI as a child that projects above 30 kg/m^2 at age 18 (Cole et al., 2000). This is often confusing, as the term obesity can be used in reference to fatness or body weight. The root of this discrepancy is likely the various methods used to measure and classify obesity. Therefore, the purpose of this literature review is to summarize the various body composition assessment and screening methods commonly used in children and adolescents. This review will also encompass the current research and public health cutpoints related to childhood obesity and overfatness.

Methods of Assessing Body Composition

A number of body composition assessment tools are currently available for use in children. These tools vary greatly in cost, validity, reliability, invasiveness, and feasibility. Numerous reviews and books have been written documenting each of the methods found within this section. Hence, the focus within is not to re-summarize the numerous studies outlining the agreement with criterion methods and limitations for each methodology. Instead the approach is to provide a brief overview of what methods are most commonly used, how these tools are employed, and how these methods are currently contributing to childhood obesity assessment and classification.

Anthropometric Indices

Body Mass Index

Body mass index, or BMI, is a ratio of weight to height calculated as kg/m^2 . The ratio was originally created by Adolphe Quetelet, a Belgian statistician studying human physical characteristics and proportions (Eknoyan, 2008). Quetelet proposed that weight increased as the square of height, and this index of obesity was coined the Quetelet index until later renamed BMI by Ancel Keys in 1972 (Keys et al., 1972). Other manifestations of this weight to height ratio have been studied, such as kg/m^3 ; however, none have successfully replaced BMI over time (Roche et al., 1981).

Throughout the current pediatric obesity literature, BMI is the epidemiological classification tool most commonly used. As children grow and mature, variations are apparent in stature and body mass, and the proportions between them (Rolland-Cachera et al., 1991). For this reason the growth percentiles separate children into sex- and age-specific groups for classification. However, there are two popular classification systems for determination of weight status via BMI (Cole et al., 2000; Ogden et al., 2002). The first was created from large US surveys that took place before the current obesity epidemic (Ogden et al., 2002). The second was the Cole et al. (2000) cutpoints based on a combination of large, international datasets. The origination and differences between these two sets of cutpoints will be expanded upon later in this review.

A major limitation of BMI is the inherent inability to differentiate between fat mass and lean mass (Garn et al., 1986). Additional factors such as ethnicity, body build, and frame size can cloud the relationship between BMI and body fatness. This may potentially result in misclassification of obesity when a child may have a relatively normal level of adiposity, or an overfat child who may be classified as normal weight. Additionally, BMI offers no

indication of abdominal versus non-abdominal fat (McCarthy, 2006), leading to potential shortcomings in metabolic disease risk assessment.

Although limitations with BMI exist, it does serve as a valuable public health and epidemiological screening tool. Data from the Bogalusa Heart study have shown that 5-17 year old children with a BMI greater than the 85th percentile had an increased risk of high diastolic and systolic blood pressure, high low-density lipoproteins, high triglyceride levels, high fasting insulin, and low high-density lipoprotein cholesterol (Freedman et al., 1999). Childhood BMI is a predictor of adult mortality (Must et al., 1992) and adult coronary heart disease (Baker et al., 2007). Further, BMI tracks from childhood and adolescence into adulthood (Deshmukh-Taskar et al., 2006; Guo et al., 2000; Magarey et al., 2003). Due to these associations, and because BMI is easily calculated and extremely feasible, it is widely used to estimate obesity trends in epidemiological studies and monitor changes in large clinical populations.

Skinfold Thicknesses

Skinfold thicknesses have long been employed to estimate body composition. Skinfold thicknesses are a measurement of a double fold of skin and underlying subcutaneous adipose tissue at a given site. This provides an indirect measure of subcutaneous adipose tissue; values are often converted to body density or directly converted to whole-body fatness via a regression equation.

In 1951, Brozek and Keys (1951) found that skinfold thickness correlated with body mass and specific-gravity of college- and middle-age men, and further used this relationship to estimate body fat percentage (%BF). Since this time, various skinfold-to-%BF or skinfold-to-body density equations have been created. Commonly measured skinfolds are

the chest, subscapular, midaxillary, suprailliac, abdominal, subscapular, and thigh sites, among others. Skinfold measurements provide an inexpensive assessment of body composition, and are suited to field use due to the portability of tools and variety of population-specific equations that are available.

Although skinfold thickness measurements are widely used, limitations exist with this method. Sexual dimorphism exists in the fat patterning of youth even before puberty (Webster-Gandy et al., 2003), with females showing greater subcutaneous fat at young ages. However, these differences in regional body fatness are more pronounced throughout puberty (Deurenberg et al., 1990; Malina, 1996). Additionally, many of the conversion formulas used to convert skinfolds to body density in adults, should not be used in children and adolescents due to differences in chemical maturity. In a classic study, Moulton (1923) demonstrated that, from birth to full maturity, mammals undergo a process in which the water content of fat-free mass decreases and the protein content increases. Hence, differences between the densities of fat-free mass are apparent between adults and children, and regression equations must be created separately while taking into account the chemical maturity of the sample. In addition, ethnic variation exists in subcutaneous fat patterning. Using Bogalusa Heart Study data, it was demonstrated that black children tended to have less subcutaneous fat than white children, and white children deposited subcutaneous fat in a more uniform distribution (Harsha et al., 1980). Although few studies have focused on comparing the three major ethnic groups within the US, Hispanic children tended to be more closely related to non-Hispanic white children than black children in terms of skinfold thickness at the triceps, subscapular, suprailliac, and thigh skinfold sites (Okosun et al., 2000).

As the skinfold to %BF-estimate relationship is modified by sex, ethnicity, and maturity in children and adolescents, it is important to select the most appropriate fat-prediction equations based on these characteristics. This has led to the Slaughter equation(s) being popular in both fitness assessments and body composition research. The Slaughter equation originated from a sample of 310, 8-29 year old, white and black subjects in Illinois and Arizona (Slaughter et al., 1988). Skinfold measurements were taken at the subscapular and triceps sites and a prediction equation was created against a criterion %BF from bone mineral (single photon absorptiometry) + total body water (deuterium oxide dilution) + body density (hydrostatic weighting). In addition, the resulting prediction equations differed based on the sex, ethnicity, maturity status, and sum of skinfolds of the subjects. Maturity was assessed in the Slaughter et al. study via the Tanner Scale (Tanner, 1962) to categorize children into prepubescent (stages 1 and 2), pubescent (stage 3), postpubescent (stages 4 and 5), or adult (stage 6 and higher). However, Slaughter et al. did not state what method was used for this classification (i.e., genital development, pubic hair, breast). The resulting equations are sex-, ethnicity-, and maturity-specific. Further, males and females with a sum of skinfolds greater than 35 mm had separate equations as well:

Sum of triceps and subscapular skinfolds \leq 35 mm

White pre-pubescent males: %BF = 1.21 (sum of triceps and subscapular skinfolds (mm)) – 0.008 (sum of triceps and subscapular skinfolds (mm)²) – 1.7

Black pre-pubescent males: %BF = 1.21 (sum of triceps and subscapular skinfolds (mm)) – 0.008 (sum of triceps and subscapular skinfolds (mm)²) – 3.2

White pubescent males: %BF = 1.21 (sum of triceps and subscapular skinfolds (mm)) – 0.008 (sum of triceps and subscapular skinfolds (mm)²) – 3.4

Black pubescent males: $\%BF = 1.21 (\text{sum of triceps and subscapular skinfolds (mm)}) - 0.008 (\text{sum of triceps and subscapular skinfolds (mm)}^2) - 5.2$

White post-pubescent males: $\%BF = 1.21 (\text{sum of triceps and subscapular skinfolds (mm)}) - 0.008 (\text{sum of triceps and subscapular skinfolds (mm)}^2) - 5.5$

Black post-pubescent males: $\%BF = 1.21 (\text{sum of triceps and subscapular skinfolds (mm)}) - 0.008 (\text{sum of triceps and subscapular skinfolds (mm)}^2) - 6.8$

All Females: $\%BF = 1.33 (\text{sum of triceps and subscapular skinfolds (mm)}) - 0.013 (\text{sum of triceps and subscapular skinfolds (mm)}^2) - 2.5$

Sum of triceps and subscapular skinfolds > 35 mm

Males: $\%BF = 0.783 (\text{sum of triceps and subscapular skinfolds (mm)}) + 1.6$

Females: $\%BF = 0.546 (\text{sum of triceps and subscapular skinfolds (mm)}) + 9.7$

The Slaughter et al. equations have been employed in a number of different studies on children and adolescents. In a group of male and female adolescents ($n = 130$), the Slaughter equation was compared to dual-energy x-ray absorptiometry (DXA)-derived $\%BF$ and fat mass (Steinberger et al., 2006). Resulting correlations indicated strong associations between DXA $\%BF$ and Slaughter $\%BF$ ($r \approx 0.92$) and DXA fat mass and Slaughter fat mass ($r \approx 0.91$). Slaughter-derived $\%BF$ was found to be highly predictive of DXA $\%BF$, with residual +/- standard deviations to be 4.2% fat for boys and 3.9% fat for girls. Fat assessed by the Slaughter equation also correlated equally as well as DXA (if not better) to components of metabolic syndrome, such as blood pressure and insulin.

Although the Slaughter equation was developed on children and adolescents greater than or equal to 8 years of age, it has since been tested in wider age ranges. In an Australian sample of 265 subjects (4-26 years of age), the Slaughter equation was compared to DXA

showing strong correlations ($r > 0.80$) between the two %BF assessments (Ogle et al., 1995). Mean %BF estimates were not significantly different for boys ($15\%BF_{Sla}$ vs. $15\%BF_{DXA}$), but the Slaughter approach did underestimate %BF for girls ($20.9\%_{Sla}$ vs. $23.8\%_{DXA}$). In a study comprised of young children ($n = 75$, 3-8 years of age), the Slaughter equation was compared to %BF by DXA (Eisenmann et al., 2004). The correlation between DXA and the Slaughter equation was 0.82, although the Slaughter equations underestimated DXA by mean differences of 2.2%BF and 0.5 kg of fat mass.

More recently the Slaughter equation was compared to several other skinfold-to-fatness prediction equations (Rodriguez et al., 2005), along with DXA, that are often used in children and adolescents, such as those of Bray et al. (2001), Brook (1971), and Deurenberg et al. (1990). The sample consisted of 13-18 year old Caucasian adolescents from Spain. Mean bias for females and males when comparing Slaughter %BF to DXA %BF was 1.64% and -0.77%, respectively. Out of the more than one dozen skinfold %BF prediction equations compared with DXA, the conclusion of the authors was that the Slaughter equation demonstrated the lowest errors and showed no bias based on %BF. Therefore, it was recommended that the Slaughter equations be used for percent fat mass prediction in both males and females within epidemiological and clinical studies. This same conclusion was reached in a similar study comparing numerous skinfold prediction equations against a 4-compartment criterion method in 112 white and black female adolescents (Wong et al., 2000). The standard error of the estimate between Slaughter and the criterion was 5.0% (mean difference = 0.8%). Since the origination of the Slaughter equation in 1988, it continues to be tested and recommended for use in epidemiological studies. While skinfold %BF prediction is not as accurate as some of the methods to be mentioned later in this

chapter, this method is relatively non-invasive, portable, inexpensive, and simple to use – providing for a valuable epidemiological tool in %BF assessment.

Waist Circumference

Regional fatness, specifically abdominal adiposity, may be a stronger overall predictor of metabolic disease than overall obesity (Savva et al., 2000). This has led to many including a measure of abdominal fat when screening for obesity and metabolic risk. While raw skinfold thicknesses can also be used to assess regional fat, or in a prediction equation to estimate intra-abdominal or subcutaneous abdominal adipose tissue (Goran, 1998), waist circumference (WC) alone may serve as a more feasible method to assess abdominal adiposity.

Because of the relationship of WC to metabolic disease, it is used as a classification component of metabolic syndrome in adults, and the World Health Organization recommends WC measurement as a screening tool in disease risk (World Health Organization, 1998). The relationship between WC and metabolic disease risks rings true in children and adolescents as well. For example, in prepubertal children, Higgins et al. (2001) found that WC was significantly associated with fasting insulin, high-density lipoprotein cholesterol, low-density lipoprotein cholesterol, triglycerides, and the ratio of total cholesterol/high-density lipoprotein cholesterol. Further, children with a WC greater than 70 cm were approximately 14 times more likely to have an adverse metabolic risk factor profile than those who had a WC lower than 70 cm. In a separate study of 3-11 year old children, those with a WC above the 90th percentile were more likely to have two or more cardiovascular disease risk factors than those with a WC under the 90th (Maffeis et al., 2001).

While WC is a simple and feasible tool for health-risk identification in children, there are potential limitations to its use. When using raw values of WC and BMI to predict disease risk in approximately 2600 white and black children and adolescents (ages 5-18 years), it was found that having both BMI and WC in the model did not increase predictive utility (Janssen et al., 2005). This was also indicated previously when receiver operator characteristic curves comparing BMI and WC to cardiovascular disease risk factors were not found to be significantly different in terms of sensitivity and specificity (Katzmarzyk et al., 2004). The failure of raw WC values to improve disease risk classification over that of BMI alone may be partially explained by the relatively strong correlation between the two variables in the previous sample ($r = 0.92-0.94$). However, it was noted by the authors that if appropriate WC cutoffs were created, BMI and WC may provide more independent contribution in prediction models. To date, a widely accepted WC classification system is absent from the childhood obesity literature.

Waist-to-Hip Ratio

Similar to WC, a ratio of WC to hip circumference, waist-to-hip ratio (WHR), provides another potentially useful anthropometric diagnostic tool. However, no WHR classification system exists for children or adolescents. Of late, this measurement has lost some appeal because it has not been shown to be advantageous over BMI or WC clinically and it is more complex both in measurement and interpretation. For example, correlations between %BF and WHR ($r \approx 0.30-0.40$) were lower than those of WC ($r \approx 0.68-0.73$) or BMI ($r \approx 0.72-0.73$) and %BF (Neovius et al., 2005). These lower correlations translated into poor diagnostic statistics when compared with WC or BMI to identify overfat adolescents based on air-displacement plethysmography. In another study comparing the ability of WC and

WHR to identify excess abdominal adiposity, WC performed significantly better than WHR (Taylor et al., 2000). Further, the benefits of using WC above that of WHR were shown in predicting intra-abdominal and subcutaneous abdominal adiposity (Goran, 1998). Therefore, in children and adolescents, it seems that WC and BMI are simpler measures that are more clinically useful than WHR for obesity classification and disease risk identification.

Bioelectrical Impedance

Another popular field method for assessing body composition is bioelectrical impedance (BIA). In BIA, low levels of electrical current are passed through the subject via electrodes placed on the skin. Body composition is estimated from the resulting resistance and reactance to the flow, allowing for determination of fat-free mass (including total body water) and fat mass (Kyle et al., 2004). Since the electric current is undetectable to the subject, the equipment is portable, technical skill required is low, and the electrode placement is usually on the wrist and ankle, this method of body composition assessment is non-invasive and potentially useful in epidemiological studies.

Considering all the benefits of BIA, much research has been conducted in an attempt to validate it for widespread use against a criterion method. However, there are mixed results with regards to the ability of whole-body analyzers to estimate %BF. For example, differences have been noted between analyzers. When comparing two BIA analyzers to DXA-assessed %BF in adolescent girls, mean differences between the BIA analyzers approximated 5% body fat, with one of the two analyzers being significantly different from DXA (Nichols et al., 2006). However, the 95% limits of agreement for the closest analyzer to DXA were -1.6 to 0.3 kg of fat-free mass and from -1.8 to 2.0% fat mass.

Other studies have also compared BIA to DXA. In a group of 10-14 year old children, BIA was highly correlated with DXA %BF, but 95% limits of agreement were large, ranging from 0.8-9.3% body fat, consistently overestimating body fat in the sample (Fors et al., 2002). In a sample of 3-8 year old children, Eisenmann et al. (2004) found relatively low correlations between DXA and BIA ($r = 0.30$), wherein BIA overestimated %BF compared to DXA, with a mean difference of 2.4% and 95% limits of agreement equal to 0.6-4.1% body fat. In prepubertal girls, Trueth et al. (2001) found that BIA accounted for 75% of the variance in DXA %BF; however, the mean difference between the methods was -7.6% with 95% limits of agreement +/- 7.6%. Both Eisenmann et al. and Trueth et al. found that skinfold thickness %BF estimation were superior to BIA compared to DXA.

One important aspect of current BIA validation research is that BIA equations are population-specific. While this is not particularly unique to field methods for body composition (recall previous skinfold equations should be based upon ethnicity, maturity, and sex), there is an exceptionally large quantity of BIA equations in the literature (Kyle et al., 2004), each created to serve in distinct subgroups of the population. A recent study in 9-11 year old Swedish children attempted to cross-validate 45 previously published BIA body composition prediction equations with DXA in a sample of 101 children (Nielsen et al., 2007). Only 2 of the 45 equations were not significantly different from DXA; hence, the authors created new BIA equations for use exclusively in prepubescent 9-11 year old European children. Additionally, it has been suggested that alternate BIA equations should be used for obese subjects (Cleary et al., 2008; Newton et al., 2005), further limiting the utility of BIA. Although BIA is an attractive tool for body composition, prediction equations are limited to narrow ranges of subjects and many have not been successfully cross-validated.

Thus, much more work is needed before BIA should be considered a viable body composition assessment method, particularly in children.

Densitometry

Hydrodensitometry

Hydrodensitometry, also known as hydrostatic weighing (HW) or underwater weighing, is a two component method of body composition assessment. HW is laboratory based, requiring the subject to be fully submerged in water and weighed in order to determine the amount of water displaced, thus providing an estimate of body volume. Body mass can then be divided by volume to determine density. This density measure can be incorporated in a prediction equation to estimate %BF and total fat mass.

In pediatrics, the HW method may not be suitable due to the requirements of the subject being fully submerged in water, while sitting still. Regardless, body density equations for children are available that attempt to account for the previously mentioned maturity-associated variation in density of fat-free mass (Lohman, 1989; Weststrate and Deurenberg, 1989). For many years, HW was recognized as the gold-standard in body composition assessment. As other methods were often compared to HW, it makes it difficult to determine the validity of this method by current standards. However, a previous study examined pig carcasses, with subsequent chemical analysis to compare DXA and HW (Elowsson et al., 1998). Variance accounted for in fat mass by three HW equations ranged from 48-60%. Comparatively, DXA accounted for 99% of the variance in bone mineral, 99% in lean mass, and 88% of the variance in fat mass. Correlation coefficients between the HW and DXA results ranged from 0.40-0.51. Considering the limitations of HW in children,

and with the advent of DXA, more suitable body composition methods are currently available for pediatric subjects.

Air Displacement Plethysmography

Air displacement plethysmography (ADP) operates on the same basic principle as HW, by estimating body volume and body density to predict fat and lean mass. However, instead of using water, air within a contained space is the medium for volume prediction. Since body density is still calculated, %BF prediction equations must remain specific to children (Lohman, 1989; Weststrate and Deurenberg, 1989). Advantages of ADP, commercially available since the 1990's as the Bod Pod (Dempster and Aitkens, 1995), relate to the ease of its use. Unlike HW, ADP requires little subject compliance, no submersion in water, and is a fairly automated process. ADP is rapid and comfortable for subjects who are not claustrophobic, making it available for use in subjects of all ages, even infants (Urlando et al., 2003).

A review comparing ADP with DXA in children found that variance accounted for by DXA in %BF by ADP ranged from 81-88% and standard error of the estimates ranged from 3.4-4.1% across three separate validation studies (Fields et al., 2002). When compared to a 4-component model, in children 9-14 years of age, ADP accounted for 90% of the variance in %BF with a standard error of the estimate of 3.2% body fat (Fields and Goran, 2000). In the latter study, ADP was found to provide better estimates than either HW or total body water. In another study, using 28 adolescent subjects to compare ADP and DXA, all ADP measures were significantly correlated with DXA, $r = 0.93-0.94$. The standard error of the estimate ranged from 3.68-3.91% fat (Radley et al., 2003). However, 95% limits of agreement were large, approximating 7% fat. ADP continues to be tested and refined for use

in children and adolescents. The relatively low subject burden in comparison to HW, as well as no radiation, makes ADP a promising method.

Imaging Tools

The imaging methods outlined below are highly sophisticated compared to methods previously described. These methods are considered by most to be more “accurate” in terms of body composition and thus used as reference methods. However, the high cost of these methods makes them prohibitive for most researchers and clinicians, especially when working with large groups. Perhaps in the future these methods will become more reasonable and their availability will increase. For example, the National Health and Nutrition Examination Survey is currently using DXA for body composition analyses and collecting data on bone density in a nationally representative sample.

Computed Tomography

Computed tomography (CT) is an x-ray based technique that creates a computer generated image of the scanned area, allowing for the separation of adipose, bone, and lean tissue. Radiation exposure and high cost usually limit this method to regional analyses instead of whole body images. Further, some scans are limited to single cross-sectional slices (Yeckel et al., 2004). However, given that metabolic diseases are associated with regional fat distribution, including visceral adiposity (Owens et al., 1998), this can be advantageous. For example, CT is one of the few body composition tools available that can determine hepatic fat content used to diagnose nonalcoholic fatty-liver disease (Kodama et al., 2007). This adverse condition (Schwimmer et al., 2003) is increasing in prevalence in obese children and adolescents (Schwimmer et al., 2006).

Dual-Energy X-ray Absorptiometry

Dual-energy x-ray absorptiometry is the gold standard and now the most widely used technique for quantifying skeletal parameters, such as bone mineral density, of specific skeletal sites (spine, hip) or whole body. DXA is the next generation technique subsequent to dual photon absorptiometry (DPA), which was based on a gadolinium-153 source that decayed over time (Blake and Fogelman, 1997). The x-ray source used in DXA is much more stable, providing more reliable measures over long periods of time. DXA measures the transmission of both a high- and low-energy x-ray beam that is pulsed through the body or specific region. By monitoring attenuation of those energies, it is possible to quantify the areal densities of the tissue. This allows for the measurement of bone mineral (hard) and soft tissue. The soft tissue can further be delineated, as adipose tissue and lean tissue have different x-ray attenuation coefficients. This not only allows for application in skeletal integrity, but overall body composition using a 3-component model (bone, non-bone lean, and adipose tissue).

Moving from DPA to DXA technology improved image resolution, precision of bone mineral density measures, lowered the radiation dose, increased the stability of the energy source, and significantly decreased scan times (i.e., from 20 minutes to 2 minutes for whole body scans). This led to the prompt replacement of DPA when commercial DXA scanners were made available in the late 1980's. However, significant improvements to the DXA have been made continually. For example, rather than the pencil beam, the fan beam was developed, further decreasing scan times and improving resolution, but decreasing precision. Although this also increased the radiation dose somewhat for spine and hip scans (from ~8 to 18 mRem/scan), the effective dose is still considered minimal for an individual subject. The radiation dose for a whole body scan is extremely low (0.5 mRem/scan).

Although DXA was originally created to measure bone mineral density (Gluer et al., 1990), specifically in clinical settings, it is now frequently used in obesity research to assess body fat and lean tissue. One of the most beneficial features of DXA is that it assesses regional fat, which other whole body techniques (such as HW or ADP) cannot accomplish. Regional adipose tissue from central regions of interest can be quantified from the whole body DXA scan using specific software from Hologic, Inc. (Bedford, MA) or algorithms imbedded in the whole body scan analysis from Lunar (Madison, WI). For example, DXA measures of total abdominal fat correlate well with CT scans ($r = 0.94-0.97$) (Clasey et al., 1999). DXA has also shown strong correlations with magnetic resonance imaging (MRI). Appendicular lean soft tissue (along with weight and height) assessed by DXA accounted for 98.6% of the variance in MRI-derived whole body skeletal muscle, with a standard error of the estimate of 0.5 kg, in 99 children ranging in age from 5-17 years (Kim et al., 2006).

Limitations of DXA are related to the constantly evolving imaging technologies and competition between the two major manufacturers (Hologic and Lunar). Differences exist between pencil- and fan-beam scanners (Soriano et al., 2004), between the different manufacturers of the DXA (Tothill et al., 1994), and also the software used to evaluate the x-ray image (Simpson et al., 2005). However, as the technology improves, researchers hope that this variability will be reduced.

Magnetic Resonance Imaging

MRI is another 3-dimensional imaging technique much like CT or ultrasound. However, unlike CT, there is no radiation exposure to the subject when using MRI. This may make MRI more appropriate for children and adolescents. During an MRI scan, radio waves are passed through the body within a magnetic field. This results in single or multiple

cross-sectional slices of tissue that can be arranged to form a 3-dimensional image. As with CT, MRI is a reference method better suited for regional body composition analysis rather than whole body scans. For example, recently MRI has been used to quantify abdominal visceral fat in a group of Chinese adults (Bao et al., 2008). Combined with metabolic syndrome risk factors, this was used to identify optimal WC cutoffs. Using advanced imaging techniques to quantify visceral and regional adipose distribution has become a popular method to study anthropometric indices, such as WC, BMI, and skinfold thicknesses for disease risk classification (Benfield et al., 2008). A recent study in 7-16 year olds found that WC explained 64.8% of the variance in visceral adipose tissue and BMI explained 88.9% of the variance in subcutaneous adipose tissue as assessed by MRI (Brambilla et al., 2006).

Classification of Childhood Weight and Adiposity Status

The number of publications, including several key position papers by the World Health Organization, American Heart Association, American Academy of Pediatrics, American Diabetes Association, and the Institute of Medicine, outlining the convincing evidence of the adverse medical, psycho-social, and economic burden of pediatric obesity identifies the magnitude and significance, of this public health epidemic in contemporary society. For this reason, early identification of at-risk children and consistent obesity classification standards are a priority clinically and epidemiologically. The majority of the obesity/adiposity classification systems currently employed are outlined below.

Body Mass Index

BMI is most commonly used as the index to identify obesity in adolescents (Barlow and Dietz, 1998). Two sets of BMI reference values are used for this purpose. The first is

the Centers for Disease Control and Prevention (CDC) growth charts for the United States (Ogden et al., 2002). The second is the Cole et al. (2000) or International Obesity Task Force (IOTF) BMI reference values, intended for international comparisons.

Originating in the US, the CDC reference values are used to categorize youth as underweight, normal weight, overweight or obese (Ogden et al., 2002). The “overweight” and “obese” categories, respectively, are based on the 85th and 95th age- and sex-specific percentiles of pre-obesity epidemic (circa 1963-1988) BMI distributions (Ogden et al., 2002). For example, if a child has a BMI between the 85th and 95th percentile, he/she is classified as “overweight”, but if the centile ranking is above the 95th, the term is “obese”. However, this tends to cause some confusion, as the percentile cutpoints at age 18 are not congruent with the adult BMI classification system using the terms “overweight” and “obesity” to correspond to BMI's $\geq 25 \text{ kg/m}^2$ and $\geq 30 \text{ kg/m}^2$, respectively. Also, identifying a child with a BMI one or two standard deviations above the population mean may not necessarily indicate increased disease risk.

In an attempt to remedy these limitations, the IOTF created a relatively new set of international pediatric BMI cutpoints generated from six large, nationally-representative surveys from various countries wherein reference centiles are anchored to the adult values of overweight (25 kg/m^2) and obesity (30 kg/m^2) at age 18 (Cole et al., 2000). The purpose of the IOTF centiles was to establish cutoff values for defining childhood overweight and obesity that provide internationally comparable prevalence estimates, with the additional advantage of being based on adult reference values. Cole et al. used a complex regression technique, LMS (Cole and Green, 1992), to create and identify the BMI percentiles that

correspond to the adult values of overweight and obesity at age 18 years. Using these IOTF percentiles eliminates discrepancies between BMI indices for youth and adults.

Waist Circumference

Recently, the National Institutes of Health clinical guidelines for the identification and treatment of obesity recognized the importance of including measurements of both overall adiposity and abdominal obesity when assessing obesity-related health risks (1998). Waist circumference has been advocated as an indicator of central obesity because it is a good predictor of abdominal fat and is related to the development of cardiovascular disease (CVD) in adults and CVD risk factors in children (Maffeis et al., 2001). According to the National Institutes of Health guidelines, adult men and women with waist circumferences of >102 cm and >88 cm, respectively, are considered to be at higher risk of obesity-related disorders than are those with smaller measurements. Percentile reference standards for WC have been developed for various populations (Eisenmann, 2005; Fernandez et al., 2004; Sung et al., 2007). Recently, Jolliffe and Janssen (2007) used the previously mentioned LMS procedure to back extrapolate the adult WC cutoff values at age 18 along age- and sex-specific percentiles. The importance of WC in clinical and health screenings is noteworthy since WC is a simple, inexpensive measurement that is strongly correlated with trunk fat and has immediate and long-term implications for CVD risk factors. Thus, the assessment of WC, along with the BMI, may add to identifying children and adolescents at increased risk of atherosclerotic, metabolic, respiratory, and orthopedic complications.

Percent Body Fat

It is common for %BF recommendations to be based on expert opinion. Few studies have been conducted to empirically derive %BF cutpoints in children. A study by Williams

et al.(1992) was based on data from the well-known Bogalusa Heart Study, and included a biracial sample of 3320 children and adolescents aged 5 to 18 years. Equations developed specifically for children using the sum of subscapular and triceps skinfolds (modified Slaughter equations) were used to estimate %BF. The results demonstrated that males with %BF at or above 25% and girls with %BF at or above 30% fat were at increased risk of being in the highest quintile for blood pressure and serum lipoproteins (Williams et al., 1992). In a similar study of approximately 1500 Australian children, aged 9 or 15 years, Dwyer and Blizzard (1996) proposed a cut-off point of 30% fat for girls and 20% for boys. To date, these cutpoints have not been cross-validated. Additionally, both sets of %BF cutpoints derived to indicate disease risk are static, unchanging across age and maturation. This is a concern, possibly limiting the clinical value of the cutpoints when identifying children at risk of overfatness.

In the past few years, attempts have been made to create %BF cutpoints that are age-specific, and thus may be more appropriate for using in a pediatric sample. A recent paper proposed to refine the diagnosis of childhood obesity by creating sex-specific centile curves for body fat (McCarthy et al., 2006). In this study, body fat was measured by BIA in approximately 2000 Caucasian children aged 5-18 years from schools in Southern England. The data were collected in 1985, prior to the ongoing obesity epidemic. Smoothed centile charts were derived using the LMS method, which were designed to yield similar proportions of overweight/overfat and obese children to the IOTF BMI cutoffs. Also, Moreno et al. (2006) used skinfolds and the Slaughter equation (Slaughter et al., 1988) to create smoothed %BF reference centiles in Spanish adolescents aged 13-18 years.

Summary

Various obesity/adiposity assessment tools are available for use in pediatric samples. Although the most commonly used methods, BMI and WC, are useful, they are used as surrogate measures of the true variable of interest in obesity research – body fat. However, %BF assessment in children is also accompanied by limitations. Currently, there is no scientifically definitive, healthy range of %BF for children. Further, expert committees have recommended combining specific methods for obesity assessment, such as skinfold thicknesses and BMI (Barlow and Dietz, 1998; Himes and Dietz, 1994). A major uncertainty in clinical and epidemiological research relates to the level of uniformity between the clinical cutpoints used in conjunction with BMI, WC, and %BF. These limitations in the agreement/disagreement of these indices should be resolved, at least in part, if we hope to ascertain the most efficient method of identifying overfat children and adolescents.

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CHAPTER 3**AGE- AND SEX-SPECIFIC PERCENT BODY FAT REFERENCE CENTILES FOR
5-18 YEAR OLD WHITE, BLACK, AND MEXICAN AMERICAN CHILDREN:
NHANES 1999-2004****Abstract**

Background: To date, several studies have been published outlining reference percentiles for body mass index in children and adolescents. In contrast, there is limited reference data on percent body fat (%BF).

Objective: The purpose of this study was to derive smoothed percentile curves for %BF in a nationally-representative sample of U.S. children and adolescents.

Design: Percent fat was derived from the skinfold thicknesses of 5 to 18 year olds from 3 cross-sectional waves (1999-2000, 2001-2002, 2003-2004) of the National Health and Nutrition Examination Survey (N = 8269). The LMS regression method was used to create age-, sex-, and ethnicity-specific smoothed centile curves of %BF.

Results: Growth curves are similar between males and females through early childhood. However, as %BF peaks for males at about age 11, it continues to increase for females throughout adolescence. Median %BF at age 18 is 16.8%, 13.5%, and 19.7% for white, black, and Mexican American males, respectively. Median %BF at age 18 is 27.5%, 27.3%, and 29.5% for white, black, and Mexican American females, respectively. At age 18, females have approximately 1.5 to 2 times greater %BF than males.

Conclusions: Current information on the pediatric obesity epidemic using %BF is available based on a nationally-representative sample of U.S. children and adolescents. Using %BF instead of body mass index may offer additional information in epidemiological research and

clinical settings. Growth charts for %BF, as well as the L, M, and S values, are provided so that future research can identify appropriate cutoff values based on health-related outcomes.

Introduction

The recent increases in prevalence and secular trends of pediatric obesity have been noted in several nations (Booth et al., 2003; Janssen et al., 2005; Liu et al., 2007; Lobstein and Frelut, 2003; Ogden et al., 2006; Willms et al., 2003), as well as the adverse medical (Daniels, 2006), economic (Wang and Dietz, 2002), and psycho-social (Schwimmer et al., 2003; Williams et al., 2005) consequences of childhood obesity. A majority of studies that identify the magnitude and consequences of this health problem rely upon the classification of overweight or obesity based upon age- and sex-specific cutpoints or reference values of the body mass index (BMI) (Cole et al., 2000; Ogden et al., 2002). Although these reference values are widely used, a major limitation of BMI is its inherent inability to differentiate between fat mass and fat-free mass (Garn et al., 1986). Therefore, a direct measure of adiposity may have advantages for accurate surveillance of the current epidemic, risk association, to gauge the effectiveness of intervention, and in clinical settings.

To date, several studies have been published outlining reference values for BMI in children and adolescents (Cole et al., 1995; de Onis et al., 2007; Del-Rio-Navarro et al., 2007; Leung et al., 1998; Ogden et al., 2002). In contrast, there are limited reference data on percent body fat (%BF). Recently, centiles for bioelectrical impedance (BIA)-derived %BF in British children (McCarthy et al., 2006) and skinfold-derived %BF in Spanish adolescents (Moreno et al., 2006) have been developed. Both BIA and skinfold thicknesses are simple and feasible methods to assess adiposity. In children and adolescents, skinfold thickness values are often converted to %BF using the Slaughter equation (Slaughter et al., 1988), as in

the aforementioned study by Moreno et al. (2006). We have previously shown that the Slaughter equation correlates highly with %BF assessed by dual-energy x-ray absorptiometry in children (Eisenmann et al., 2004). Furthermore, Rodriguez et al. (2005) has also recommended the use of the Slaughter equation for male and female adolescents in epidemiological studies or clinical settings. Since skinfold thicknesses and the Slaughter equation are widely used in the pediatric literature, we derived smoothed percentile curves for %BF using LMS regression in a nationally-representative sample of white, black, and Mexican American U.S. children and adolescents.

Methods

Subjects. The National Health and Nutrition Examination Surveys (NHANES), conducted by the National Center for Health Statistics, Centers for Disease Control (NCHS/CDC), is a program of studies designed to assess the health and nutritional status of adults and children in the United States through interviews and direct physical examinations. In our study, anthropometric and body composition data of the 5 to 18 year olds from 3 cross-sectional waves of NHANES 1999-2000, 2001-2002, and 2003-2004 were included. Complete data were available for 1219 non-Hispanic white male, 1169 non-Hispanic white female, 1485 non-Hispanic black male, 1338 non-Hispanic black female, 1569 Mexican American male, and 1489 Mexican American female school-aged children and adolescents 5 to 18 years of age.

Anthropometry. Stature and body mass were measured according to standard procedures (see below). Stature was measured to the nearest 0.1 cm using a wall-mounted, digital stadiometer, and body mass was measured to the nearest 0.1 kg using a digital scale. BMI was calculated using the following equation: $\text{body mass in kg} / \text{stature in m}^2$. Skinfold

thicknesses were measured by standard procedures as a double fold of skin underlying the soft tissue on the right side of the body. All measurements described were taken by trained health technicians in the Mobile Examination Center. Furthermore, quality control checks were included throughout the data collection procedure. The training procedures, examination protocol and procedures, and quality control protocol are outlined in the NHANES anthropometry and body composition procedures manuals available at <http://www.cdc.gov/nchs/data/nhanes>. Percent body fat was calculated using the equations of Slaughter (Slaughter et al., 1988) from the triceps and subscapular sites.

Sum of triceps and subscapular skinfolds ≤ 35 mm

White pre-pubescent males: $\%BF = 1.21$ (sum of triceps and subscapular skinfolds (mm)) – 0.008 (sum of triceps and subscapular skinfolds (mm)²) – 1.7

Black pre-pubescent males: $\%BF = 1.21$ (sum of triceps and subscapular skinfolds (mm)) – 0.008 (sum of triceps and subscapular skinfolds (mm)²) – 3.2

White pubescent males: $\%BF = 1.21$ (sum of triceps and subscapular skinfolds (mm)) – 0.008 (sum of triceps and subscapular skinfolds (mm)²) – 3.4

Black pubescent males: $\%BF = 1.21$ (sum of triceps and subscapular skinfolds (mm)) – 0.008 (sum of triceps and subscapular skinfolds (mm)²) – 5.2

White post-pubescent males: $\%BF = 1.21$ (sum of triceps and subscapular skinfolds (mm)) – 0.008 (sum of triceps and subscapular skinfolds (mm)²) – 5.5

Black post-pubescent males: $\%BF = 1.21$ (sum of triceps and subscapular skinfolds (mm)) – 0.008 (sum of triceps and subscapular skinfolds (mm)²) – 6.8

All Females: $\%BF = 1.33$ (sum of triceps and subscapular skinfolds (mm)) – 0.013 (sum of triceps and subscapular skinfolds (mm)²) – 2.5

Sum of triceps and subscapular skinfolds > 35 mm

Males: %BF = 0.783 (sum of triceps and subscapular skinfolds (mm)) + 1.6

Females: %BF = 0.546 (sum of triceps and subscapular skinfolds (mm)) + 9.7

As the regression intercepts in males are based on biological maturity status (prepubescent, pubescent, or post-pubescent), and biological maturity status was not assessed in NHANES, we assumed the following based on national estimates of age of entry into different stages of secondary sex characteristics (Sun et al., 2002). Males less than 12.0 yrs were classified as pre-pubescent; males 12.0-13.99 yrs as pubescent; and males >14.0 yrs as post-pubescent.

Data analysis. Descriptive statistics by age, sex, and ethnicity were calculated using SAS v 9.1 (SAS Institute, Cary, NC). Construction of the age-, sex-, and ethnicity-specific centile curves were performed using the LMS Pro software program version 2.3 (The Institute of Child Health, London) which fits smooth centile curves to reference data using the LMS method (Cole and Green, 1992). In brief, the LMS method summarizes a changing distribution with three curves representing the median (M), coefficient of variation (S) and skewness (L), the latter expressed as a Box-Cox power. Using penalized likelihood the three curves were fitted as cubic splines by non-linear regression, and the extent of smoothing required is expressed in terms of smoothing parameters or equivalent degrees of freedom.

Results

Descriptive statistics for body size and fatness are presented in Table 1. In general, compared to national growth charts, stature for boys and girls approximated the 40-60th percentiles (Centers for Disease Control and Prevention, 2000). However, both body mass and BMI centered around the 75th percentile for both sexes. Tables 2-7 include the values

across the centiles by age for each sex- and race-specific subgroup. The corresponding centiles are graphically displayed in Figures 1-6.

In general, %BF for males increased throughout early childhood and peaked at approximately 11 years of age across all three ethnic groups. During adolescence, %BF decreased slightly, or leveled off in the mid and lower centiles, but increased again within the upper centiles. Median %BF at age 18 was 16.8%, 13.5%, and 19.7% for white, black, and Mexican American males, respectively.

Girls displayed a similar pattern of age-related changes in %BF compared to boys through early childhood. However, at the beginning and throughout adolescence, %BF for females increased across all centiles (although with varying magnitude). Median %BF at age 18 was 27.5%, 27.3%, and 29.5% for white, black, and Mexican American females, respectively. At age 18, females had approximately 1.5 to 2 greater %BF than males.

Following the 50th centile, differences between the growth curves across the children from the three ethnic groups were small. Across most centiles, white males generally had higher %BF values than did black males, and Mexican American males had the highest values overall. However, during adolescence, in the extreme centiles, the values for black males encompassed those %BF values of both white and Mexican American males (i.e., the 98th centile for black males was higher and the 2nd centile lower). This indicated greater variability in postpubescent black males as they approached adulthood and the fluctuation in %BF between ages 11 and 18 was less pronounced. For females, the 50th centile was very similar for black and white females in both shape and magnitude. The median for Mexican American females, while still following the same shape, was slightly higher. Similar to males, differences were found within the upper centiles. The 90th-98th centiles showed a

sharper increase in %BF in childhood for black females, whereas the upper centiles for black and Mexican American females tended to be larger throughout.

Discussion

To our knowledge, this is the first study to provide age-, sex-, and ethnic-specific %BF reference centiles for U.S. children and adolescents across the pediatric age range. Previously, reference curves for children in the U.K. have been provided based on data from a 1985 survey and BIA-derived %BF (McCarthy et al., 2006). Although the general shapes of the two sets of reference centiles followed those changes expected during normal growth and maturation (Malina et al., 2004), using current nationally-representative data from U.S. children provided further insight into the ongoing obesity epidemic. Figures 7 and 8 allow for a comparison between pre-obesity epidemic reference centiles from the U.K. and current data from the U.S. Large differences were found between the 95th centiles during childhood into adolescence, with %BF values for current U.S. children increasing at a greater rate (especially in males) while maintaining a similar shape. As previously recommended (Prentice and Jebb, 2001), the data provided within this study make available the average %BF levels and the range of values found within U.S. children and adolescents that were not previously available. Furthermore, using the centile curves allows one to identify differences between the sexes and among ethnic groups during growth and maturation.

Previously, Mueller et al (2004) created BIA-derived %BF centiles based on Texas children ranging in age from 8.5-17.5 years. There was little difference between studies in the shape of the 50th centiles, whereas the main difference was in the upper centiles for males. Herein, the 95th centile for white males declined during early to mid adolescence and then increased into adulthood, whereas the 95th centile from the Mueller et al. paper showed a

rather sharp decrease. However, these differences are likely due to variations within the samples, methodology of %BF estimation, and the lesser number of children ($n = 678$) in the Mueller study to estimate the centiles at the extremes.

Currently, most of the pediatric literature relies upon BMI to identify children as overweight and obese. Although an important epidemiological and clinical tool (Reilly et al., 2000), the BMI does not distinguish between fat mass and fat-free mass with individuals of the same BMI with various degrees of fatness. In this regard, it may be advantageous to use %BF, to decrease misclassification of overweight and obesity. While there is no perfect tool for estimating %BF in epidemiological surveys, skinfold thicknesses provide some advantages and have previously been recommended for identifying obesity and health risk in youth (Himes and Dietz, 1994). Skinfold thicknesses can easily be taken in the field, are inexpensive, are relatively non-invasive, and are currently used in the U.S. in school-based health-related fitness testing programs, such as FITNESSGRAM. More specifically, the Slaughter equation is widely used in the pediatric literature. As the subscapular and triceps skinfolds are available in previous NHANES data collections, secular trends can be established with a common methodology, allowing continuous tracking of the obesity epidemic.

One current problem with using %BF in clinical or research settings is the lack of definitive cutoffs with which to base health risk estimates. Previous studies on pre-obesity epidemiologic data suggest using the 85th and 95th centiles (McCarthy et al., 2006). Although this serves as a starting point, it is recommended that clinical cutpoints be based on increased health risk rather than a population distribution. For example, Dwyer and Blizzard (1996) proposed a cutoff point of 20% fat for boys and 30% for girls based on at-risk groups

for dyslipidemia and hypertension in a group of Australian adolescents. Using a modified Slaughter equation, Williams et al. (1992) identified percent fat cutpoints of 25% in boys and 30% in girls that were indicative of an increased risk of being in the highest quintile for blood pressure and serum lipoproteins in adolescents. The Williams et al. cutpoints are now used within FITNESSGRAM, a widely used health-related fitness testing system in the U.S.

Due to the lack of clearly defined cutoffs for %BF, the L, M, and S parameters have been made available in Tables 8 and 9. For example, if one was to choose the cutpoints of Williams et al. (1992), the 77th centile corresponds with a body fat of 25% at age 18 for white males (found by calculating the standard deviation score, or z score). This centile can be back-extrapolated to indicate what %BF value at any age corresponds with a white male having a %BF greater than 25% at age 18. For reference, the 83rd centile corresponds with 25% BF at 18 years for black males and the 68th centile for Mexican American males. Also, the 63rd centile corresponds to 30% BF at age 18 for both white and black females, while the 53rd centile represents 30% fat at age 18 for Mexican American females. The z-score can be calculated from the L, M, and S values by using the following equation, where Y is the measurement value (in this case 25% for males or 30% for females) and the L, M, and S values come from the desired age in Table 8 or 9:

$$Z \text{ score} = [(Y / M)^L - 1] / (LS)$$

A strength of the current study is the use of nationally representative data to create %BF centiles that are age-, sex-, and ethnicity-specific. These centiles span the pediatric age range and allow the opportunity to use %BF instead of BMI for epidemiological research and perhaps clinical practice. A limitation of the current study is that the LMS software takes into consideration the weighting of the NHANES survey, which incorporates the different

probabilities of selection and adjustments for nonresponse and noncoverage, but not for the clustered nature of the survey in producing the growth curves. This can potentially lead to bias in the resulting curves. Although the magnitude of this potential bias is likely small, it is unknown. This specific limitation has been outlined previously in a study that used the LMS software to create growth curves for components of metabolic syndrome with NHANES data (Jolliffe and Janssen, 2007). Further information on the sampling strategy and analytic procedures for NHANES data can be found at <http://www.cdc.gov/nchs/data/nhanes>.

In summary, this study provided age-, sex-, and ethnicity-specific %BF reference centiles for U.S. children and adolescents. Using current, nationally-representative data, we have provided previously unavailable information about the magnitude of the current obesity epidemic based upon body fat assessment rather than BMI. The L, M, and S parameters have been provided so that the preferred %BF cutpoints can be identified based upon the target application. Future studies should focus on identifying health-related %BF cutpoints during growth and maturation.

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Table 1. Physical characteristics of the sample

Variable	White Males (n = 1219)	Black Males (n = 1485)	Mexican American Males (n = 1569)	White Females (n = 1169)	Black Females (n = 1338)	Mexican American Females (n = 1489)
Age (yrs)	12.0 (0.15)	11.8 (0.10)	11.7 (0.12)	11.9 (0.13)	11.6 (0.14)	11.4 (0.13)
Height (cm)	151.3 (0.82)	150.9 (0.57)	147.5 (0.63)	146.3 (0.56)	146.1 (0.64)	141.9 (0.60)
Mass (kg)	48.7 (0.73)	48.3 (0.59)	47.9 (0.60)	44.4 (0.57)	46.3 (0.63)	42.6 (0.51)
BMI (kg/m ²)	20.0 (0.16)	20.0 (0.14)	20.8 (0.14)	19.8 (0.15)	20.7 (0.16)	20.1 (0.16)
Tricep SF (mm)	12.6 (0.27)	11.3 (0.18)	13.4 (0.17)	16.0 (0.25)	15.5 (0.22)	15.8 (0.20)
Subscapular SF (mm)	9.8 (0.23)	9.9 (0.16)	11.2 (0.16)	11.7 (0.25)	12.8 (0.19)	12.7 (0.22)
Bodyfat (%)	19.2 (0.40)	16.9 (0.26)	21.1 (0.23)	23.3 (0.31)	23.7 (0.26)	24.0 (0.26)

All values are mean (standard error)

BMI = Body Mass Index, SF = skinfold

Table 2. Smoothed LMS curves for the 2nd, 5th, 10th, 25th, 50th, 75th, 85th, 90th, 95th, and 98th percentiles of percent body fat for white males in the 1999-2004 National Health and Nutrition Examination Survey.

Age (yrs)	2 nd	5 th	10 th	25 th	50 th	75 th	85 th	90 th	95 th	98 th
5	9.2	9.9	10.5	11.9	14.0	16.9	19.0	20.8	24.3	29.9
6	8.8	9.6	10.4	12.0	14.4	17.9	20.4	22.6	26.8	33.5
7	8.6	9.5	10.4	12.2	15.0	19.0	22.0	24.5	29.3	36.8
8	8.6	9.6	10.6	12.6	15.8	20.4	23.9	26.8	32.3	40.8
9	8.9	9.9	11.1	13.4	17.1	22.4	26.5	29.8	36.1	46.0
10	9.0	10.2	11.5	14.1	18.2	24.2	28.8	32.6	39.7	50.8
11	8.9	10.1	11.5	14.2	18.6	25.2	30.1	34.2	41.9	53.9
12	8.5	9.7	11.0	13.9	18.3	25.1	30.1	34.4	42.4	54.8
13	7.9	9.1	10.4	13.2	17.6	24.3	29.4	33.6	41.7	54.1
14	7.3	8.4	9.7	12.4	16.7	23.4	28.4	32.6	40.5	52.8
15	6.8	8.0	9.2	11.9	16.2	22.7	27.7	31.9	39.9	52.1
16	6.6	7.7	9.0	11.7	16.1	22.8	27.9	32.2	40.3	52.9
17	6.6	7.7	9.0	11.8	16.3	23.3	28.7	33.2	41.7	54.8
18	6.6	7.8	9.1	12.1	16.8	24.2	29.8	34.5	43.5	57.4

Age indicates whole age group, e.g., 8.0-8.99 years, etc.

Table 3. Smoothed LMS curves for the 2nd, 5th, 10th, 25th, 50th, 75th, 85th, 90th, 95th, and 98th percentiles of percent body fat for black males in the 1999-2004 National Health and Nutrition Examination Survey.

Age (yrs)	2 nd	5 th	10 th	25 th	50 th	75 th	85 th	90 th	95 th	98 th
5	8.4	8.9	9.5	10.7	12.5	15.1	17.1	18.8	22.3	28.2
6	6.9	7.5	8.1	9.3	11.3	14.3	16.7	18.9	23.2	31.5
7	6.3	7.0	7.6	9.1	11.3	14.8	17.7	20.3	25.6	35.5
8	6.6	7.4	8.2	9.9	12.8	17.2	20.9	24.1	30.8	43.1
9	6.8	7.7	8.6	10.7	14.1	19.5	23.9	27.8	35.8	50.0
10	6.8	7.7	8.8	11.1	15.0	21.1	26.1	30.6	39.6	55.3
11	6.5	7.5	8.7	11.1	15.3	22.0	27.4	32.2	41.8	58.5
12	6.1	7.2	8.3	10.8	15.1	22.0	27.6	32.5	42.5	59.5
13	5.7	6.7	7.9	10.4	14.6	21.5	27.2	32.2	42.3	59.5
14	5.4	6.4	7.5	9.9	14.1	21.0	26.7	31.7	41.9	59.3
15	5.1	6.1	7.2	9.6	13.7	20.6	26.3	31.4	41.6	59.4
16	5.0	5.9	7.0	9.4	13.5	20.4	26.2	31.4	41.9	60.3
17	4.9	5.9	6.9	9.3	13.4	20.5	26.4	31.7	42.6	61.8
18	4.9	5.8	6.9	9.3	13.5	20.6	26.7	32.2	43.5	63.6

Age indicates whole age group, e.g., 8.0-8.99 years, etc.

Table 4. Smoothed LMS curves for the 2nd, 5th, 10th, 25th, 50th, 75th, 85th, 90th, 95th, and 98th percentiles of percent body fat for Mexican American males in the 1999-2004 National Health and Nutrition Examination Survey.

Age (yrs)	2 nd	5 th	10 th	25 th	50 th	75 th	85 th	90 th	95 th	98 th
5	9.2	9.9	10.7	12.2	14.5	17.8	20.1	22.1	25.7	31.4
6	9.4	10.2	11.1	12.9	15.7	19.6	22.5	24.8	29.3	36.2
7	9.4	10.4	11.4	13.5	16.7	21.3	24.7	27.5	32.7	40.6
8	9.3	10.5	11.6	14.0	17.7	23.0	26.8	30.0	35.8	44.5
9	9.3	10.6	11.9	14.6	18.8	24.9	29.2	32.7	39.1	48.5
10	9.3	10.7	12.2	15.4	20.2	27.0	31.9	35.8	42.7	52.8
11	9.1	10.6	12.3	15.8	21.1	28.5	33.8	37.9	45.3	55.6
12	8.5	10.1	11.8	15.5	21.0	28.7	34.1	38.3	45.6	55.8
13	7.7	9.3	11.1	14.7	20.2	27.9	33.2	37.3	44.4	54.1
14	7.0	8.6	10.2	13.8	19.2	26.7	31.8	35.8	42.7	51.9
15	6.5	8.1	9.7	13.3	18.7	26.1	31.1	35.1	41.8	50.9
16	6.4	8.0	9.7	13.3	18.8	26.5	31.7	35.7	42.6	51.9
17	6.4	8.1	9.8	13.6	19.3	27.2	32.7	36.9	44.1	53.7
18	6.5	8.1	9.9	13.8	19.7	27.9	33.4	37.8	45.2	55.2

Age indicates whole age group, e.g., 8.0-8.99 years, etc.

Table 5. Smoothed LMS curves for the 2nd, 5th, 10th, 25th, 50th, 75th, 85th, 90th, 95th, and 98th percentiles of percent body fat for white females in the 1999-2004 National Health and Nutrition Examination Survey.

Age (yrs)	2 nd	5 th	10 th	25 th	50 th	75 th	85 th	90 th	95 th	98 th
5	9.7	10.5	11.4	13.2	15.8	19.4	22.1	24.2	28.2	34.2
6	9.4	10.3	11.2	13.0	15.8	19.6	22.4	24.6	28.7	34.9
7	9.4	10.4	11.4	13.4	16.3	20.4	23.3	25.7	30.0	36.2
8	9.9	11.0	12.1	14.3	17.6	22.0	25.2	27.7	32.2	38.6
9	10.6	11.8	13.1	15.6	19.2	24.2	27.6	30.3	35.0	41.5
10	11.3	12.6	14.0	16.8	20.8	26.1	29.6	32.4	37.2	43.7
11	11.8	13.2	14.7	17.7	21.9	27.4	31.0	33.8	38.5	44.8
12	12.2	13.8	15.3	18.4	22.8	28.3	31.9	34.6	39.2	45.2
13	12.7	14.3	15.9	19.2	23.6	29.2	32.7	35.4	39.7	45.4
14	13.1	14.9	16.6	19.9	24.4	29.9	33.4	36.0	40.2	45.5
15	13.6	15.4	17.2	20.6	25.2	30.7	34.1	36.6	40.6	45.6
16	14.1	16.0	17.9	21.4	26.0	31.4	34.7	37.2	41.0	45.8
17	14.7	16.6	18.5	22.1	26.7	32.2	35.4	37.8	41.5	46.1
18	15.2	17.2	19.2	22.9	27.5	32.9	36.1	38.4	42.0	46.4

Age indicates whole age group, e.g., 8.0-8.99 years, etc.

Table 6. Smoothed LMS curves for the 2nd, 5th, 10th, 25th, 50th, 75th, 85th, 90th, 95th, and 98th percentiles of percent body fat for black females in the 1999-2004 National Health and Nutrition Examination Survey.

Age (yrs)	2 nd	5 th	10 th	25 th	50 th	75 th	85 th	90 th	95 th	98 th
5	8.9	9.8	10.7	12.4	14.9	18.2	20.4	22.1	25.0	29.1
6	9.0	10.0	10.9	12.9	15.7	19.5	22.1	24.1	27.7	32.6
7	9.2	10.2	11.3	13.6	16.8	21.2	24.2	26.6	30.8	36.7
8	9.6	10.8	12.0	14.5	18.2	23.3	26.8	29.6	34.5	41.3
9	10.1	11.4	12.8	15.6	19.8	25.5	29.4	32.5	38.0	45.5
10	10.6	12.0	13.5	16.6	21.1	27.3	31.5	34.8	40.5	48.4
11	11.2	12.7	14.3	17.6	22.3	28.7	32.9	36.3	42.0	49.7
12	11.9	13.5	15.2	18.6	23.4	29.8	34.0	37.2	42.7	50.0
13	12.7	14.4	16.1	19.6	24.5	30.7	34.8	37.9	43.1	49.8
14	13.4	15.2	17.0	20.6	25.5	31.6	35.5	38.5	43.4	49.6
15	14.0	15.9	17.7	21.3	26.2	32.2	36.0	38.8	43.4	49.3
16	14.4	16.3	18.1	21.8	26.6	32.5	36.2	38.9	43.3	48.9
17	14.6	16.5	18.4	22.0	26.9	32.7	36.3	39.0	43.2	48.5
18	14.8	16.7	18.7	22.4	27.3	33.1	36.7	39.3	43.4	48.6

Age indicates whole age group, e.g., 8.0-8.99 years, etc.

Table 7. Smoothed LMS curves for the 2nd, 5th, 10th, 25th, 50th, 75th, 85th, 90th, 95th, and 98th percentiles of percent body fat for Mexican American females in the 1999-2004 National Health and Nutrition Examination Survey.

Age (yrs)	2 nd	5 th	10 th	25 th	50 th	75 th	85 th	90 th	95 th	98 th
5	9.1	10.1	11.1	13.0	15.9	19.7	22.3	24.4	28.0	33.0
6	9.6	10.6	11.7	13.8	16.9	21.0	23.8	25.9	29.7	34.9
7	10.0	11.1	12.3	14.6	17.9	22.3	25.3	27.5	31.5	36.8
8	10.4	11.7	12.9	15.4	19.0	23.6	26.7	29.1	33.1	38.5
9	10.9	12.2	13.6	16.3	20.1	25.0	28.2	30.6	34.7	40.2
10	11.4	12.9	14.4	17.2	21.3	26.4	29.7	32.2	36.3	41.8
11	12.1	13.7	15.2	18.3	22.5	27.8	31.2	33.7	37.9	43.3
12	12.8	14.5	16.2	19.4	23.9	29.3	32.7	35.2	39.4	44.6
13	13.6	15.4	17.1	20.6	25.1	30.6	34.0	36.5	40.6	45.6
14	14.3	16.2	18.1	21.6	26.2	31.7	35.1	37.5	41.4	46.3
15	15.0	16.9	18.9	22.5	27.1	32.6	35.9	38.2	42.0	46.6
16	15.6	17.6	19.6	23.3	27.9	33.3	36.5	38.8	42.4	46.7
17	16.2	18.3	20.3	24.0	28.7	34.0	37.1	39.3	42.7	46.8
18	16.8	19.0	21.0	24.8	29.5	34.7	37.7	39.8	43.1	47.0

Age indicates whole age group, e.g., 8.0-8.99 years, etc.

Table 8. L, M, and S parameters for the calculation of z-scores in males

Age (yrs)	White Males			Black Males			Mexican American Males		
	L	M	S	L	M	S	L	M	S
5	-1.052	13.959	0.255	-1.212	12.513	0.252	-0.858	14.509	0.275
6	-0.853	14.379	0.293	-0.994	11.313	0.313	-0.726	15.679	0.305
7	-0.699	14.960	0.326	-0.817	11.309	0.362	-0.596	16.748	0.335
8	-0.587	15.802	0.354	-0.678	12.758	0.403	-0.472	17.708	0.364
9	-0.509	17.064	0.379	-0.568	14.088	0.440	-0.355	18.848	0.391
10	-0.453	18.170	0.400	-0.484	14.959	0.472	-0.249	20.190	0.416
11	-0.410	18.621	0.419	-0.422	15.269	0.499	-0.155	21.084	0.438
12	-0.376	18.333	0.437	-0.380	15.051	0.522	-0.078	20.999	0.458
13	-0.347	17.587	0.453	-0.354	14.587	0.539	-0.020	20.232	0.475
14	-0.322	16.746	0.467	-0.340	14.090	0.554	0.020	19.228	0.488
15	-0.302	16.161	0.480	-0.334	13.693	0.565	0.045	18.663	0.500
16	-0.284	16.054	0.492	-0.332	13.494	0.574	0.059	18.847	0.508
17	-0.268	16.332	0.503	-0.334	13.448	0.582	0.067	19.319	0.516
18	-0.253	16.810	0.514	-0.335	13.473	0.589	0.073	19.684	0.522

Age indicates whole age group, e.g., 8.0-8.99 years, etc.

Table 9. L, M, and S parameters for the calculation of z-scores in females

Age (yrs)	White Females			Black Females			Mexican American Females		
	L	M	S	L	M	S	L	M	S
5	-0.753	15.773	0.286	-0.453	14.922	0.280	-0.438	15.857	0.305
6	-0.654	15.783	0.301	-0.410	15.732	0.306	-0.377	16.886	0.309
7	-0.562	16.332	0.312	-0.367	16.807	0.330	-0.316	17.950	0.313
8	-0.472	17.554	0.321	-0.324	18.248	0.350	-0.254	18.994	0.315
9	-0.381	19.236	0.325	-0.281	19.778	0.362	-0.193	20.073	0.316
10	-0.296	20.776	0.325	-0.237	21.138	0.366	-0.132	21.262	0.315
11	-0.218	21.887	0.323	-0.194	22.331	0.361	-0.070	22.542	0.310
12	-0.146	22.760	0.318	-0.151	23.430	0.349	-0.009	23.856	0.304
13	-0.078	23.600	0.311	-0.108	24.490	0.333	0.052	25.115	0.295
14	-0.013	24.398	0.303	-0.065	25.470	0.318	0.113	26.225	0.285
15	0.050	25.167	0.294	-0.021	26.183	0.306	0.175	27.149	0.276
16	0.111	25.954	0.286	0.022	26.609	0.298	0.236	27.938	0.266
17	0.168	26.744	0.278	0.065	26.897	0.293	0.297	28.697	0.257
18	0.223	27.532	0.270	0.108	27.299	0.290	0.359	29.478	0.248

Age indicates whole age group, e.g., 8.0-8.99 years, etc.

Figure Captions and Figures

Figure 1. Smoothed LMS curves for the 2nd, 5th, 10th, 25th, 50th, 75th, 85th, 90th, 95th, and 98th percentiles of percent body fat for white males in the 1999-2004 National Health and Nutrition Examination Survey.

Figure 2. Smoothed LMS curves for the 2nd, 5th, 10th, 25th, 50th, 75th, 85th, 90th, 95th, and 98th percentiles of percent body fat for black males in the 1999-2004 National Health and Nutrition Examination Survey.

Figure 3. Smoothed LMS curves for the 2nd, 5th, 10th, 25th, 50th, 75th, 85th, 90th, 95th, and 98th percentiles of percent body fat for Mexican American males in the 1999-2004 National Health and Nutrition Examination Survey.

Figure 4. Smoothed LMS curves for the 2nd, 5th, 10th, 25th, 50th, 75th, 85th, 90th, 95th, and 98th percentiles of percent body fat for white females in the 1999-2004 National Health and Nutrition Examination Survey.

Figure 5. Smoothed LMS curves for the 2nd, 5th, 10th, 25th, 50th, 75th, 85th, 90th, 95th, and 98th percentiles of percent body fat for black females in the 1999-2004 National Health and Nutrition Examination Survey.

Figure 6. Smoothed LMS curves for the 2nd, 5th, 10th, 25th, 50th, 75th, 85th, 90th, 95th, and 98th percentiles of percent body fat for Mexican American females in the 1999-2004 National Health and Nutrition Examination Survey.

Figure 7. The 95th percentile of percent body fat for white, black, and Mexican American males in the 1999-2004 National Health and Nutrition Examination Survey and 1985 White males from the UK. UK data from McCarthy et al. (2006).

Figure 8. The 95th percentile of percent body fat for white, black, and Mexican American females in the 1999-2004 National Health and Nutrition Examination Survey and 1985 White females from the UK. UK data from McCarthy et al. (2006).

Figure 1

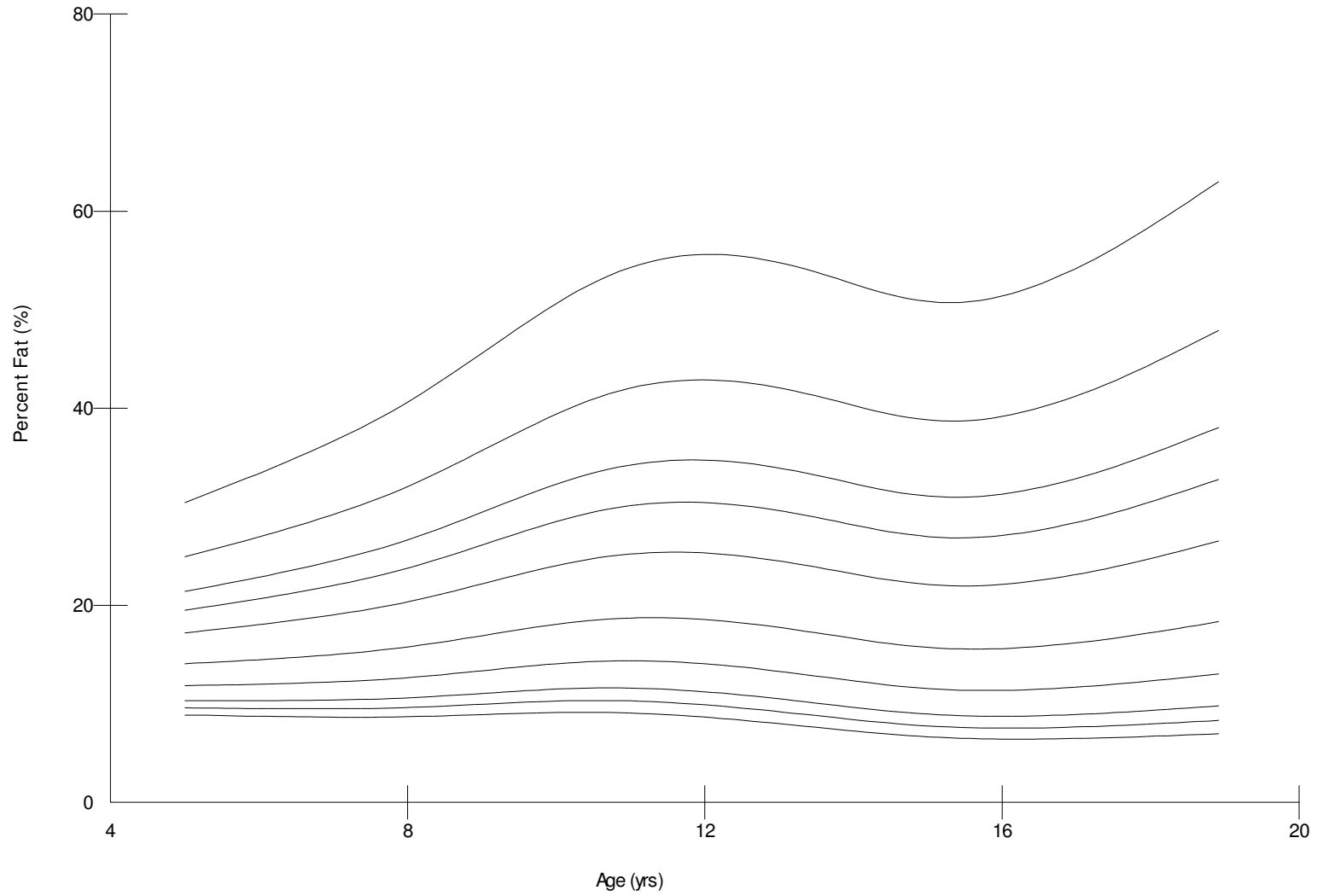


Figure 2

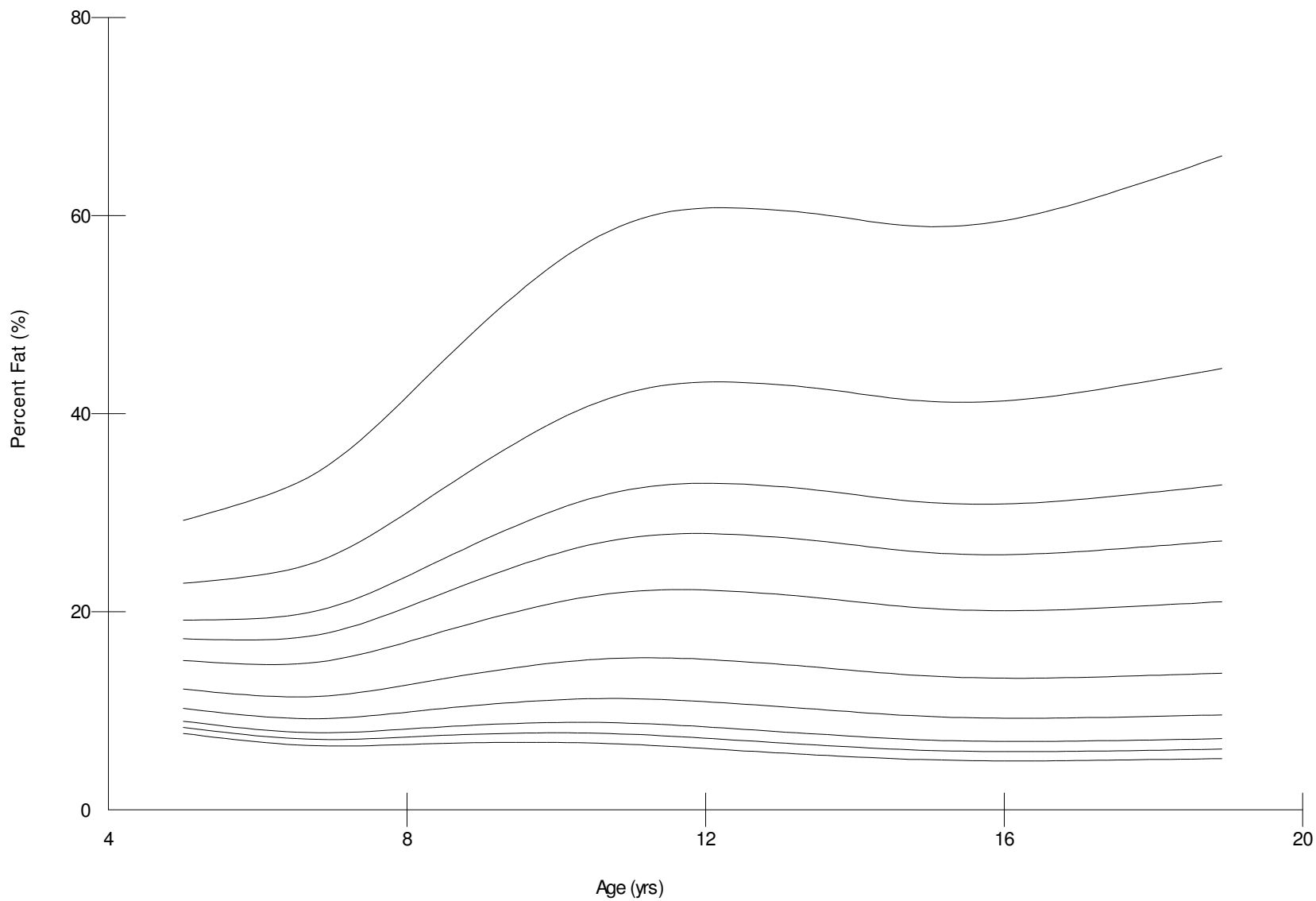


Figure 3

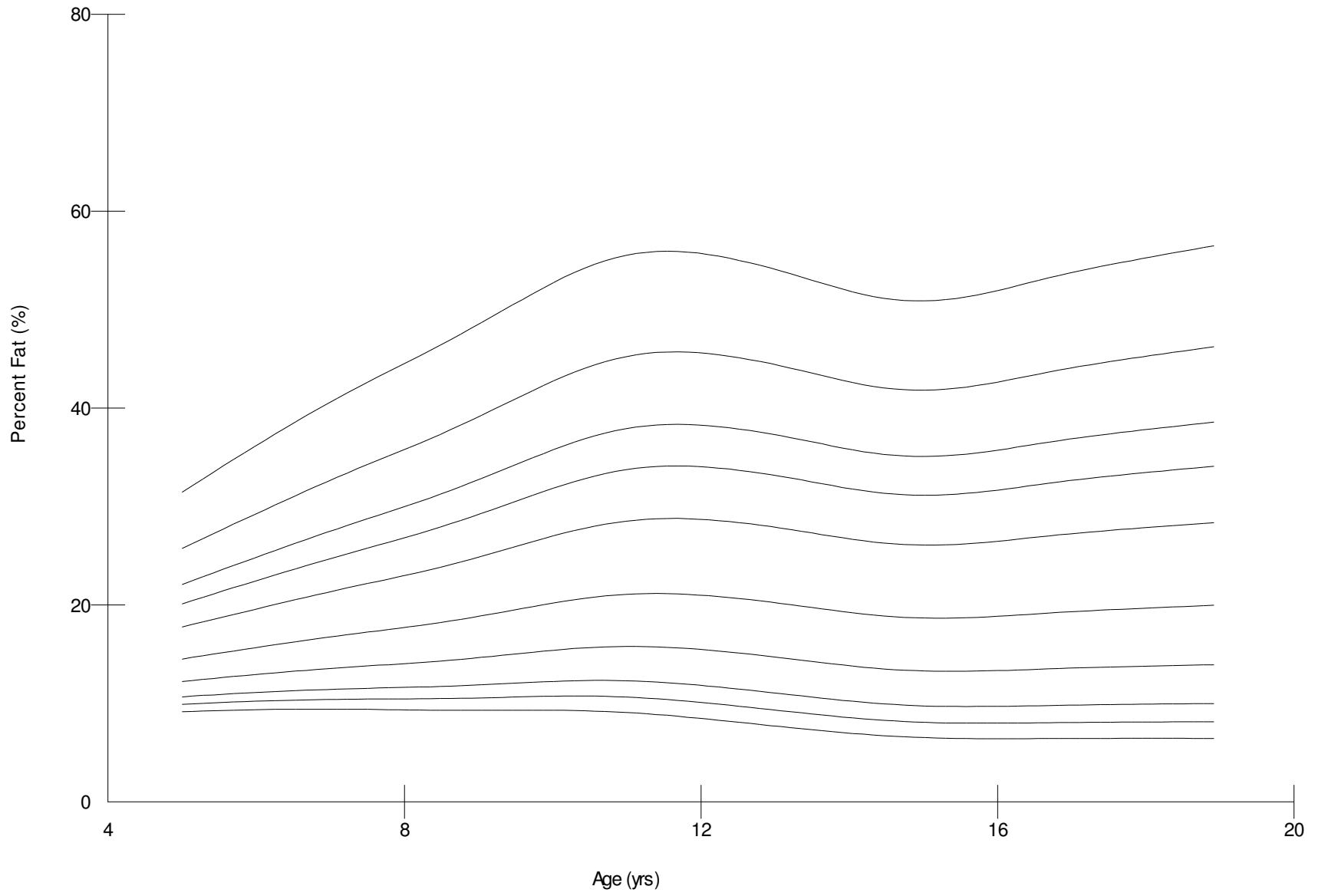


Figure 4

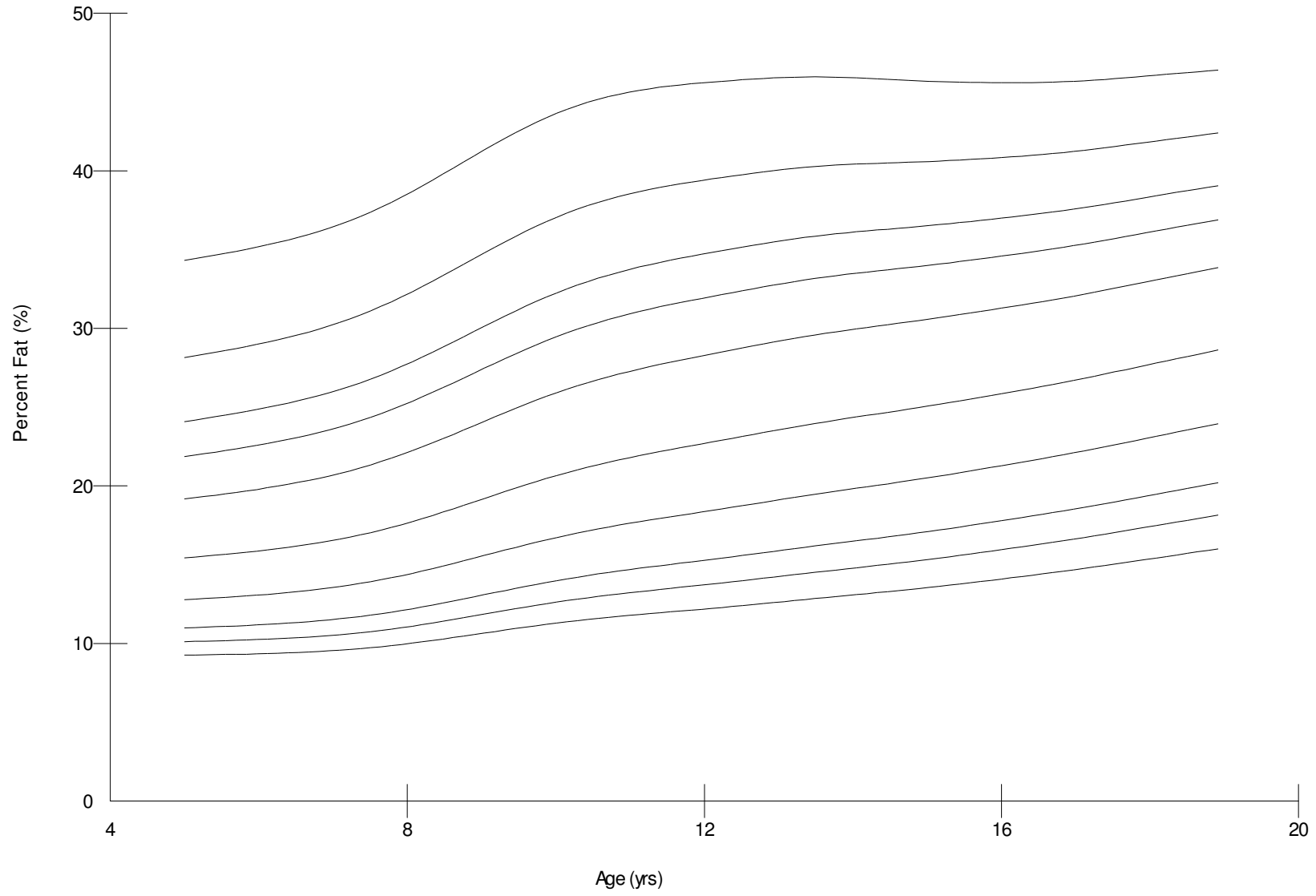


Figure 5

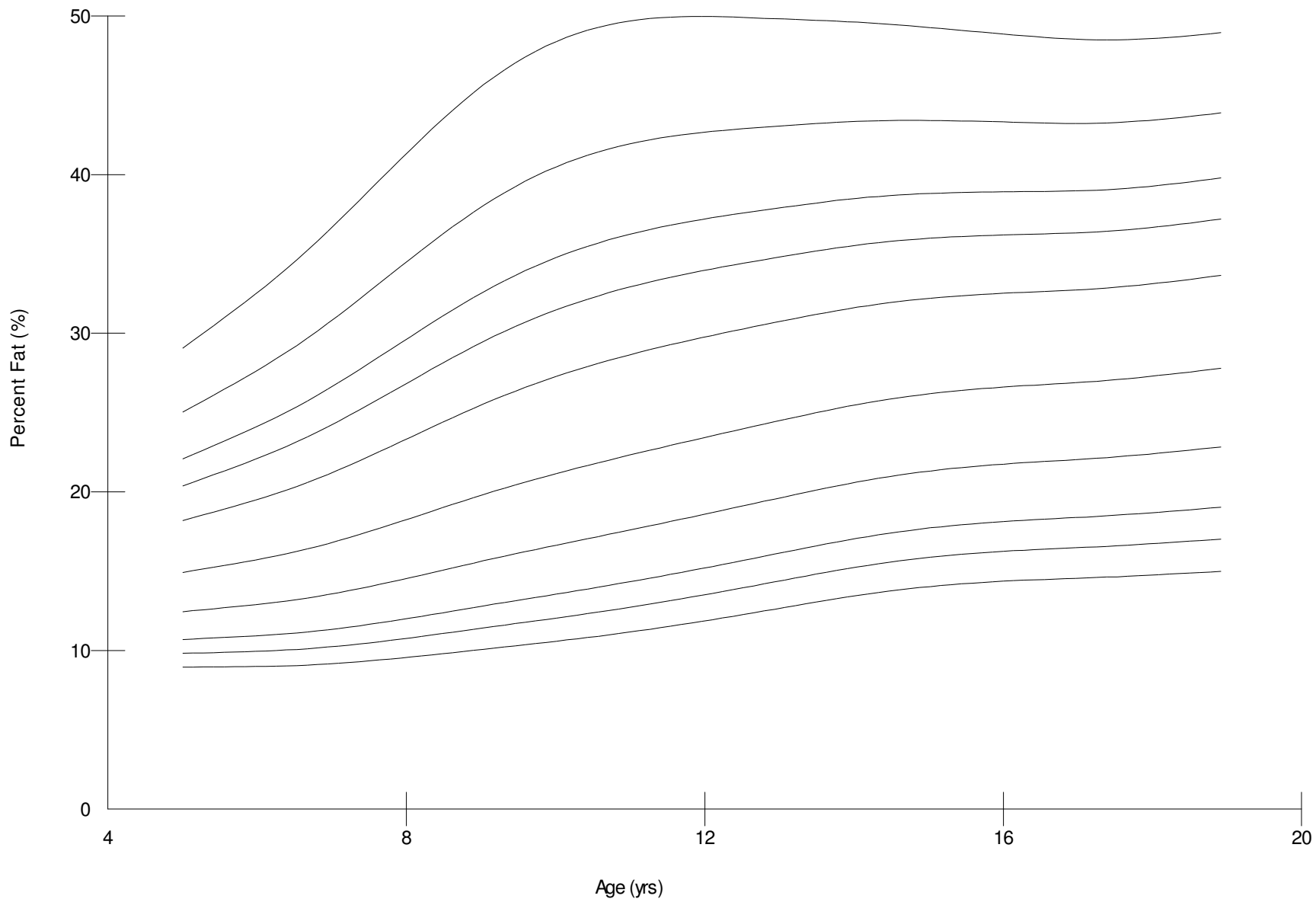


Figure 6

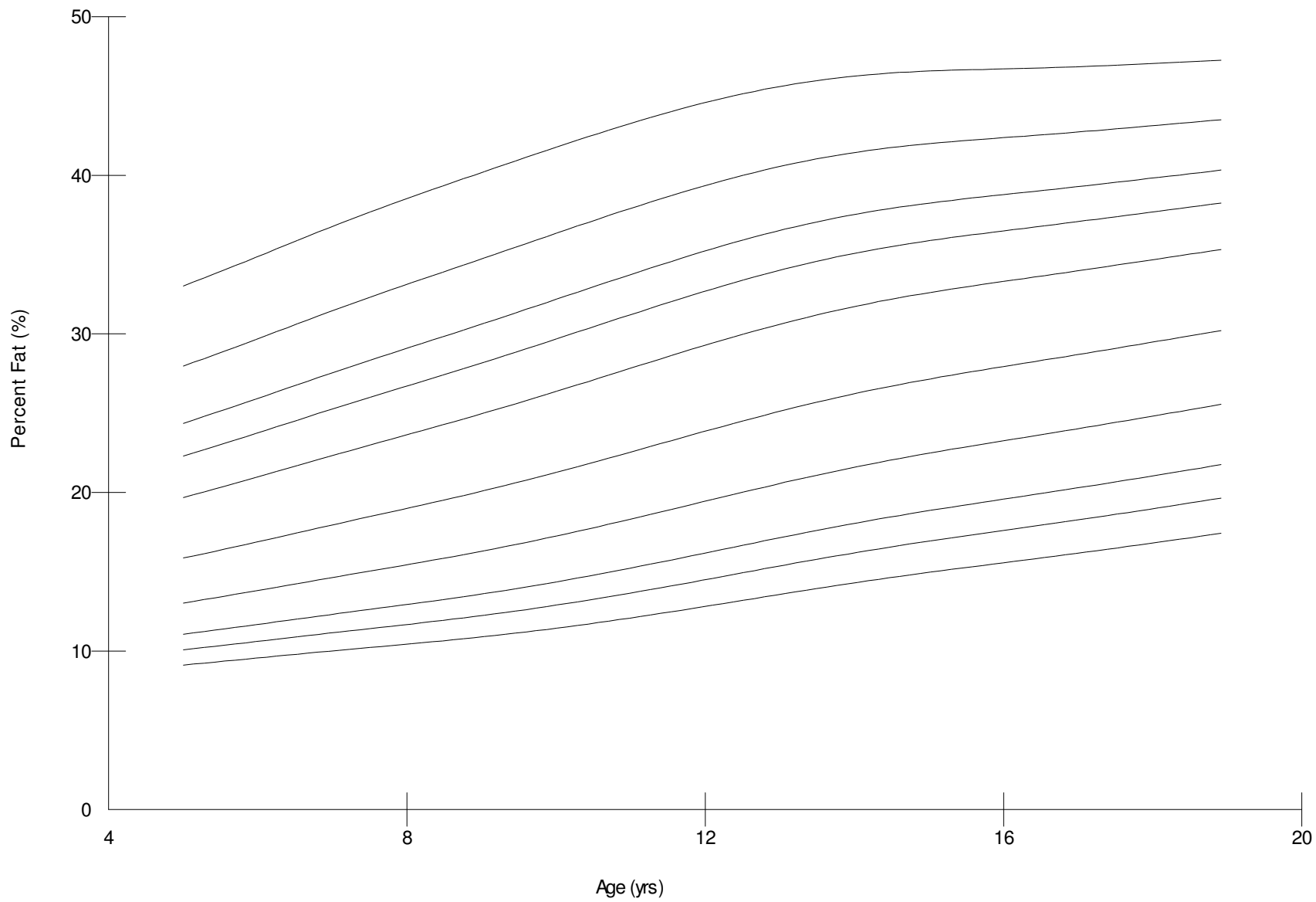


Figure 7

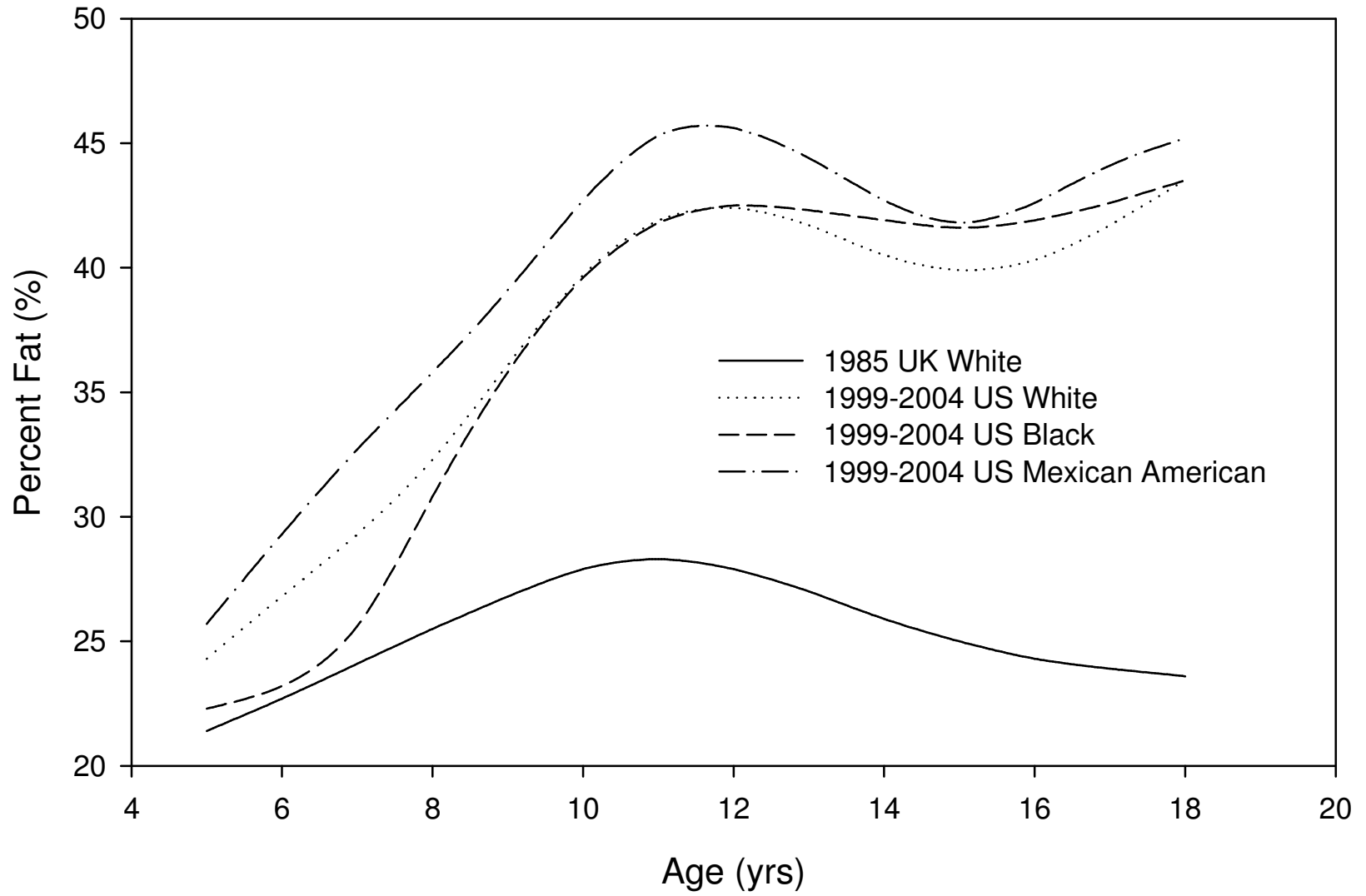
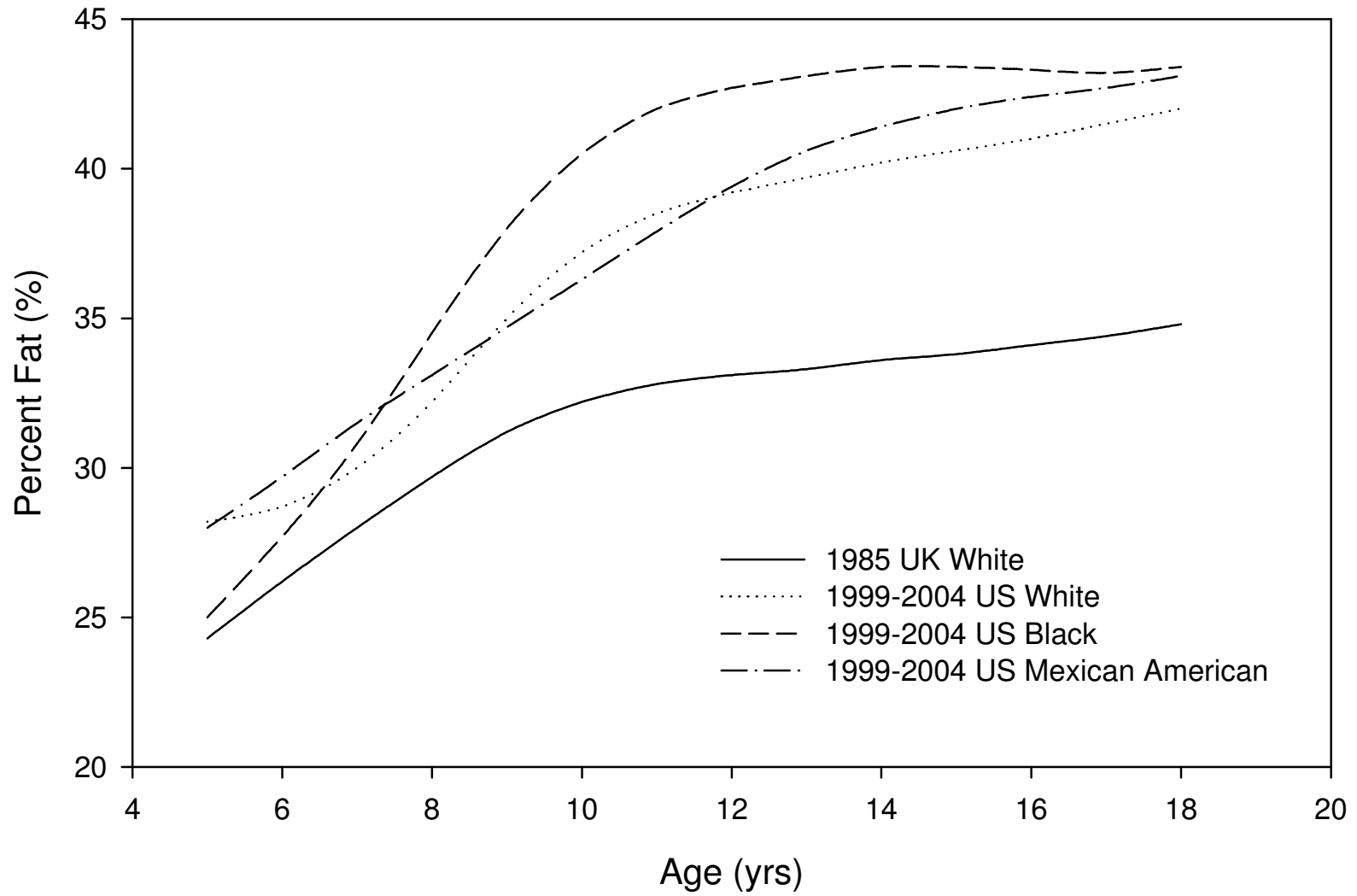


Figure 8



CHAPTER 4**AGREEMENT BETWEEN BODY MASS INDEX, WAIST CIRCUMFERENCE, AND
PERCENT BODY FAT IN CHILDREN AND ADOLESCENTS****Abstract**

Background: A major uncertainty in clinical and epidemiological research relates to the level of uniformity between the clinical cutpoints used in conjunction with body mass index (BMI), waist circumference (WC), and percent body fat (%BF).

Objective: The purpose of this study was to examine the diagnostic performance of BMI and WC in relation to an estimate of %BF in children and adolescents.

Design: Percent fat was derived from the skinfold thicknesses of 5 to 18 year olds from 3 cross-sectional waves (1999-2000, 2001-2002, 2003-2004) of the National Health and Nutrition Examination Survey (n = 8228). Stature and body mass were used to calculate BMI. WC was also measured. Receiver operator characteristic (ROC) analysis was employed to determine optimal cutpoints between the various adiposity indices.

Results: The optimal %BF values associated with an overweight BMI in boys ranged from 14%-23% across the age range in all ethnicities. The corresponding values for girls were slightly higher and covered a larger range (16%-33%). For both sexes, the 85th centile corresponded with slightly lower %BF values for black youth. However, at the 95th percentile, the values for boys were almost identical, ranging from 17%-28% fat, whereas black girls displayed lower %BF values than either white or Mexican American girls.

Conclusions: Single-value %BF cutoffs are not appropriate for use across the pediatric age range. Instead, using %BF centiles may improve diagnostic agreement, especially for

females. The optimal cutoffs are provided for each adiposity index, based on the sum of sensitivity and specificity.

Introduction

Although the recent trends in the prevalence of childhood obesity and its associated health risks are well documented (Freedman et al., 2001; Freedman et al., 2005; Must et al., 1992; Ogden et al., 2006), there are limitations regarding the various indices used in the clinical setting and epidemiologic research to diagnose childhood obesity. Currently, the body mass index (BMI) is widely used to classify youth as underweight, normal weight, overweight, or obese based on age- and sex-specific reference centiles (Cole et al., 2000; Ogden et al., 2002). In addition to BMI, there is recent interest in the assessment of waist circumference (WC) as a proxy for abdominal adiposity, given its link with the metabolic syndrome (McCarthy, 2006). WC reference percentiles are also available to characterize childhood abdominal adiposity (Fernandez et al., 2004). Although both of these anthropometric indices (BMI and WC) are useful, they are essentially surrogate measures of the true outcome of interest in obesity research – body fat. However, using assessment of percent body fat (%BF) in children carries limitations as well. Currently, there is no definitive, healthy range of %BF identified for children. Using skinfold-derived %BF estimations, Williams et al. (1992) identified %BF cutpoints of 25% in boys and 30% in girls that were indicative of increased risk of being in the highest quintile for blood pressure and serum lipoproteins. However, neither the WC nor %BF cutpoints have been cross-validated, despite the former cutpoints being widely used in FITNESSGRAM assessments (The Cooper Institute, 2007). Furthermore, the %BF recommendations assume static levels of %BF across childhood and adolescence, despite the age-associated variation in %BF. Therefore,

these thresholds may not be appropriate and may cause clinicians to bypass an opportunity for early detection, prevention, or intervention.

A major uncertainty in clinical and epidemiological research relates to the level of uniformity between the clinical cutpoints used with BMI, WC, and %BF. For example, if a child is categorized as overweight based on BMI, would this child also be considered overweight based on %BF and/or have an elevated WC? Furthermore, are these relationships stable between the sexes and among ethnicities? Given the issues raised herein, the purpose of this study is to examine the diagnostic performance of BMI and WC in relation to an estimate of overfatness in children and adolescents. Also, we desired to determine the level of agreement between these often used indices of childhood obesity.

Methods

Subjects. The National Health and Nutrition Examination Surveys (NHANES), conducted by the National Center for Health Statistics, Centers for Disease Control (CDC), is a program of studies designed to assess the health and nutritional status of adults and children in the United States through interviews and direct physical examinations. Publically available anthropometric and body composition data of 5 to 18 year olds from 3 cross-sectional waves of NHANES 1999-2000, 2001-2002, and 2003-2004 were combined for the current analysis. Complete data were available on 1207 non-Hispanic white male, 1161 non-Hispanic white female, 1478 non-Hispanic black male, 1332 non-Hispanic black female, 1565 Mexican American male, and 1485 Mexican American female school-aged children and adolescents 5 to 18 years of age.

Anthropometry. Stature was measured to the nearest 0.1 cm (wall-mounted, digital stadiometer) and body mass was measured to the nearest 0.1 kg (Toledo Digital Scale). BMI

was calculated using the equation: body mass in kg/stature in m². Weight status was categorized as normal weight (BMI < 85th percentile), overweight (BMI ≥ 85th and < 95th percentile), and obese (BMI ≥ 95th percentile) based upon age- and sex-specific percentiles using the 2000 CDC growth charts (Ogden et al., 2002). WC was measured using a constant tension tape. Since individual percentiles could not be calculated for each child in the current study, children were grouped according to the six age- and sex-specific centile categories: WC < 10th percentile, WC ≥ 10th and < 25th percentile, WC ≥ 25th and < 50th percentile, WC ≥ 50th and < 75th percentile, WC ≥ 75th and < 90th percentile, and WC ≥ 90th percentile (Fernandez et al., 2004). Tricep and subscapular skinfold thicknesses were measured by standard procedures as a double fold of skin underlying the soft tissue on the right side of the body. %BF was calculated using the equations of Slaughter et al. (1988) from the triceps and subscapular sites.

Sum of triceps and subscapular skinfolds ≤ 35 mm

White pre-pubescent males: %BF = 1.21 (sum of triceps and subscapular skinfolds (mm)) – 0.008 (sum of triceps and subscapular skinfolds (mm)²) – 1.7

Black pre-pubescent males: %BF = 1.21 (sum of triceps and subscapular skinfolds (mm)) – 0.008 (sum of triceps and subscapular skinfolds (mm)²) – 3.2

White pubescent males: %BF = 1.21 (sum of triceps and subscapular skinfolds (mm)) – 0.008 (sum of triceps and subscapular skinfolds (mm)²) – 3.4

Black pubescent males: %BF = 1.21 (sum of triceps and subscapular skinfolds (mm)) – 0.008 (sum of triceps and subscapular skinfolds (mm)²) – 5.2

White post-pubescent males: %BF = 1.21 (sum of triceps and subscapular skinfolds (mm)) – 0.008 (sum of triceps and subscapular skinfolds (mm)²) – 5.5

Black post-pubescent males: $\%BF = 1.21 (\text{sum of triceps and subscapular skinfolds (mm)}) - 0.008 (\text{sum of triceps and subscapular skinfolds (mm)}^2) - 6.8$

All Females: $\%BF = 1.33 (\text{sum of triceps and subscapular skinfolds (mm)}) - 0.013 (\text{sum of triceps and subscapular skinfolds (mm)}^2) - 2.5$

Sum of triceps and subscapular skinfolds > 35 mm

Males: $\%BF = 0.783 (\text{sum of triceps and subscapular skinfolds (mm)}) + 1.6$

Females: $\%BF = 0.546 (\text{sum of triceps and subscapular skinfolds (mm)}) + 9.7$

Since the intercept in males is based on biological maturity status (prepubescent, pubescent, or post-pubescent) and biological maturity status was not assessed in NHANES, we assumed the following based on national estimates of age of entry into different Tanner stages (Sun et al., 2002): Males less than 12.0 yrs were pre-pubescent; males 12.0-13.99 yrs pubescent; and males >14.0 yrs post-pubescent.

Males and females were dichotomized into overfat and normal fat groups based upon %BF using the cutpoints of 25% and 30% for males and females, respectively, derived by Williams et al. (1992). Further, using the LMS-values derived previously (see Chapter 3), children were assigned a percentile score based upon their position in age-, sex-, and ethnicity-specific distributions.

All measurements described were taken by trained health technicians in the Mobile Examination Center. Furthermore, quality control checks were included throughout the data collection procedure. The training, examination protocol, and quality control procedures are outlined in the NHANES anthropometry and body composition procedures manuals available at <http://www.cdc.gov/nchs/data/nhanes>.

Data analyses. All statistical analyses were performed in SAS v 9.1 (SAS Institute, Cary, NC). ROC analysis was used to determine optimal cutoff values and to provide an evaluation of the global performance of the BMI and WC to discriminate between adiposity status based on skinfold-derived %BF (e.g., overfat and normal fat). ROC analysis evaluates the performance of any continuous variable to discriminate between two mutually exclusive states of disease (Greiner et al., 2000). By using ROC amongst these three adiposity indices, information about the agreement of the tests will be provided along with suggested cutpoints. ROC provides measures of sensitivity (Se), specificity (Sp), and the area under the ROC curve (AUC). Se can be defined as the probability of a positive test outcome in an overfat individual (true-positive) and Sp as the probability of a negative test outcome in a non-overfat individual (true-negative). Se and Sp are inversely related, depending on the cutpoint, and indicate local performance of the recommended cutpoint. The optimal cutoff can be identified as the value where the sum of Se and Sp are maximized.

ROC analysis involves the plotting of a curve representing the diagnostic Se (true positive rate) and $1 - Sp$ (false-positive rate) across a wide range of cutoff values using a diagnostic test (in this case, based on adiposity status). The area under this curve can be a measure of the global accuracy of a diagnostic test (Greiner et al., 2000). More specifically, AUC relates to the overall ability of using the BMI or WC to discriminate between normal fat and overfat children. In this analysis, AUC can be considered equivalent to the probability that a randomly drawn individual from the overfat reference has a higher BMI or is in a higher WC percentile group than a child randomly drawn from the normal-fat sample. Swets (1988) suggested that the AUC be interpreted according to the following guidelines: non-informative/test equal to chance ($AUC = 0.5$), less accurate ($0.5 < AUC \leq 0.7$),

moderately accurate ($0.7 < \text{AUC} \leq 0.9$), highly accurate ($0.9 < \text{AUC} \leq 1.0$), and perfect discriminatory tests ($\text{AUC} = 1.0$).

First, we examined the ROC performance of BMI centiles and WC groups to evaluate which was the best indicator of excess body fat with the sample stratified by sex. Se and Sp of the optimal cutpoint and the AUC demonstrated the agreement between these two indices and overfatness derived by skinfolds using the cutpoints of 25% in males and 30% in females. Then, we reversed the ROC analysis since %BF changes during growth and maturation. We used the CDC percentiles to create two new dichotomies of children: 1) BMI centile $< 85^{\text{th}}$ centile vs. $\geq 85^{\text{th}}$ centile (overweight), 2) BMI centile $< 95^{\text{th}}$ centile vs. $\geq 95^{\text{th}}$ centile (obesity). By using the %BF centiles in the ROC analysis as a continuous marker of adiposity, we were able to identify the %BF centile that best discriminated between the two sets of BMI groupings, and the associated Se, Sp, and AUC values for each sex and ethnic group. The end result of these analyses provided information about how well the BMI centiles and WC groupings discriminated between overfat and normal fat based on static cutpoints and also provided information about how well the newly created %BF centiles discriminated between the CDC categories of overweight and obesity.

Results

The results determining the optimal BMI percentile and WC grouping versus the Williams et al. (1992) cutpoints of 25% and 30% fat are shown in Table 1. The optimal BMI centile for boys was the 85^{th} centile, which in this case is the CDC BMI cutpoint for overweight. For girls, the 80^{th} BMI centile was identified as the cutpoint that maximized the sum of Se and Sp. For both boys and girls, the selected WC grouping was a $\text{WC} \geq 75^{\text{th}}$ percentile $< 90^{\text{th}}$ percentile. Sensitivity, specificity, and AUC for the cutpoints were slightly

higher for boys compared to girls, indicating better agreement between the indices.

However, AUC values between BMI and WC indicate that neither diagnostic test is superior to the other when compared to %BF via skinfolds.

The results of the ROC analysis using the 85th BMI centile to dichotomize boys into groups and the %BF centiles as the continuous marker of adiposity are presented in Table 2. The %BF centile that maximized the sum of Se and Sp was used to identify age- and ethnicity-specific %BF values. AUC values were similar for all three ethnic groups. The selected centile for black boys had the lowest Se but also the highest Sp. The %BF values were highest for Mexican American boys; however, they were similar to those values identified for white boys. The corresponding analysis for girls is presented in Table 3. The cutpoint for Mexican American girls had the highest Se but lowest Sp. Again, %BF values were highest for Mexican American girls. As age increased, the optimal %BF corresponding to the BMI cutpoints changed. In boys, the %BF cutpoints increased from age 5, peaked near 11-12 years of age, and then slightly decreased and leveled off through the remainder of adolescence. In girls, the optimal %BF cutpoints increased throughout the pediatric age-range.

The %BF values from the ROC analysis using the 95th BMI centile to dichotomize boys into groups and the %BF centiles as the continuous marker of adiposity are presented in Table 4. The %BF centile that maximized the sum of Se and Sp was used to identify age- and ethnicity-specific %BF values. Se of the cutpoint between all three ethnicities was similar. In contrast, Sp for the %BF centile for black boys was higher than for white or Mexican American boys. However, %BF values were similar across all ethnicities. The corresponding analysis for girls is presented in Table 5. AUC values for all three ethnic

groups were similar. Se values were higher for white and black girls, although the cutpoint for black girls had the lowest Sp. Black girls displayed slightly lower %BF values in reference to the CDC overweight cutpoint than did white or Mexican American girls.

Discussion

BMI, WC, and %BF as determined by skinfolds are three inexpensive and feasible indices that can be used to classify adiposity status in large groups of children. As these indices are commonly used by clinicians, epidemiologists, and interventionists, it is important to determine the level of concordance among the three indices. The results of this study demonstrated reasonable agreement among the CDC BMI centiles, WC centiles, and %BF cutpoints of 25% for boys and 30% for girls. AUC values were approximately 0.95 for boys and 0.90 for girls. BMI and WC were more accurate when compared to the single-value %BF thresholds in boys compared to girls.

With regards to BMI, the results are supported by those found in 17 year-olds participating in the Stockholm Weight Development Study (Neovius et al., 2004), in which several BMI classification systems were found to be highly specific with low sensitivity and more accurate for boys than girls when compared to static %BF thresholds. In this study, a Se of 0.55 (95% CI, 0.51-0.60) and a Sp of 0.97 (95% CI, 0.96-0.98) was found when comparing the 95th centile of BMI to 25% BF in boys. In girls, a Se of 0.42 (95% CI, 0.38-0.46) and a Sp of 0.97 (95% CI, 0.96-0.98) was found when comparing the 95th centile to 30% BF. The high Sp and low Se of the CDC BMI classification system was also previously demonstrated in 6-12 year old Swiss children (Zimmermann et al., 2004). This may create confusion, as in many cases a child would be diagnosed as overfat based on skinfolds, but would not be obese based on BMI (e.g. BMI < 95th centile). If better agreement between the

two indices is desired, using the 85th centile for boys and the 80th centile for girls would maximize Se and Sp and perhaps reduce misclassification. However, the optimal BMI cutpoints found in the present study still indicate Se and Sp values below 0.90, meaning misclassifications may occur. For example, approximately 16% of girls with a %BF above 30% would not be identified as obese using the optimal BMI cutpoint in girls (80th centile). Further, 20% of girls with a %BF < 30% would incorrectly be classified as obese. Hence, limitations exist between the agreement of BMI or WC centiles and the %BF cutpoints of 25% and 30%.

A major premise of the current study was to examine closely the currently used FITNESSGRAM cutpoints of 25% and 30% BF for males and females, respectively. A major reason for this scrutiny is that these %BF cutpoints are static; thus, they essentially ignore the age-related changes in body composition across the pediatric age range. The %BF cutoffs for overfatness used in the present study were based on these single-values. In contrast, the BMI and WC centiles do account for growth and maturation as they are age- and sex-specific. Therefore, it is probable that some misclassifications were due to this discrepancy (Table 1). In contrast, perhaps these misclassifications can be reduced by using the LMS values and %BF growth reference centiles. Since health-based %BF cutoffs have not been tested that account for maturational changes in %BF, it is currently uncertain which %BF centiles indicate increased disease risk. Lower values for %BF might be more optimal, but this conclusion would need to be based upon health-related evidence from the literature. However, it is possible to identify %BF centile curves that correspond to established BMI thresholds. Tables 2-5 indicate the %BF values that are linked to the 85th and 95th BMI

centiles. Moreover, this type of analysis has provided novel information about how BMI and %BF agree among ethnicities throughout childhood and adolescence.

Overall, the optimal %BF centiles found using the 85th age- and sex-specific CDC centile in boys identified %BF ranging from 14%-23% across the age range studied in three ethnicities. As expected, the corresponding values for girls were slightly higher and covered a larger range (16%-33%). For both sexes, the 85th centile corresponded with slightly lower %BF values for black youth. However, at the 95th percentile, the values for boys were almost identical ranging from 17%-28%BF. Similar AUC values indicate that the BMI cutoff-%BF relationship was similar across all ethnicities. Likewise, Se, Sp, and AUC values were similar in both sexes when using the %BF centiles, which is an important improvement over those values reported in Table 1. It should be noted that at the younger ages, the CDC BMI centiles would identify children as overweight, whereas a static 25% or 30% fat would not classify them as overfat. This age-related pattern in %BF illuminates a limitation of single-value %BF cutpoints when applied to a wide age-range of children. Using a similar methodology but with the International Obesity Task Force (IOTF) BMI cutoff system (Cole et al., 2000), Taylor et al. (2002) identified %BF values of 24%-36% in white boys and 26%-42% in white girls that corresponded to the IOTF obesity cutpoint. Although differences in the age-specific values of %BF between the two studies could be due to methods of %BF estimation, sample characteristics, different BMI classification systems, or various statistical analyses tests, the current study supports the conclusion of Taylor et al. in that a single %BF cutpoint should not be used to diagnose excess adiposity across the pediatric age range.

Although the %BF values that corresponded to the 85th and 95th age- and sex- specific BMI centiles were similar for all ethnicities, there was a trend for slightly lower values to be identified for black children. These data confirm the results of the previous study by Ellis et al. (1999), in which black children had lower %BF than white or Mexican American children at corresponding BMI values. In the current study, this was especially true in females. Future research is required to investigate differences in the relationship between the BMI and %BF among ethnicities, since ethnicity-specific BMI cutoffs may increase the agreement of the two assessment indices.

In conclusion, this study used ROC curves from a large, multi-ethnic, nationally-representative sample to explore the diagnostic agreement among clinical cutpoints for the BMI, WC, and %BF. Overall, there is a reasonable amount of concordance among BMI, WC, and current %BF standards. However, further improvement is needed to decrease misclassification among the three indices and increase the accuracy of current and future disease risk prediction. It is also clear that static %BF cutpoints can be a source of error when compared to age-dependent BMI/WC diagnostic tools, especially in younger children, as cutpoints such as 25% in boys and 30% in girls do not account for changes due to normal growth and maturation. In the future, we hope to use a measure of disease risk (e.g., metabolic syndrome), %BF centiles, and ROC curves to identify a %BF that corresponds with increased risk of clinical outcome and is also sensitive to maturation.

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Tables

Table 1. Optimal body mass index centile and waist circumference group cutoffs for detecting overfatness in boys and girls in the 1999-2004 National Health and Nutrition Examination Survey.

Group and Index	Optimal Cutoff	Sensitivity (95% CI)	Specificity (95% CI)	AUC
Boys – 25% Fat				
BMI	85 th Centile	0.89 (0.86-0.92)	0.85 (0.83-0.87)	0.95
WC	75 th Centile	0.91 (0.89-0.95)	0.84 (0.82-0.87)	0.94
Girls – 30% Fat				
BMI	80 th Centile	0.84 (0.81-0.87)	0.80 (0.78-0.83)	0.89
WC	75 th Centile	0.78 (0.75-0.82)	0.81 (0.78-0.83)	0.89

BMI = Body Mass Index Centiles, WC = Waist Circumference Groups, AUC = Area Under Curve

Table 2. Optimal percent body fat values for detecting ‘Overweight’ as determined by body mass index in males from the 1999-2004 National Health and Nutrition Examination Survey.

Age and Variable	White	Black	Mexican American
5	16.1	14.7	15.5
6	16.9	13.9	16.9
7	17.9	14.3	18.2
8	19.2	16.5	19.3
9	21.0	18.7	20.7
10	22.6	20.2	22.3
11	23.3	20.9	23.4
12	23.2	20.9	23.4
13	22.4	20.4	22.6
14	21.5	19.9	21.6
15	20.9	19.5	21.0
16	20.9	19.3	21.2
17	21.4	19.4	21.8
18	22.1	19.5	22.3
Sensitivity (95% CI)	0.87 (0.83-0.91)	0.81 (0.78-0.85)	0.86 (0.83-0.89)
Specificity (95% CI)	0.88 (0.86-0.91)	0.93 (0.91-0.95)	0.89 (0.87-0.92)
AUC	0.95	0.94	0.96

AUC = Area Under Curve

Table 3. Optimal percent body fat values for detecting 'Overweight' as determined by body mass index in females from the 1999-2004 National Health and Nutrition Examination Survey.

Age and Variable	White	Black	Mexican American
5	18.0	15.8	18.6
6	18.2	16.8	19.9
7	18.9	18.0	21.1
8	20.4	19.6	22.4
9	22.3	21.3	23.6
10	24.1	22.8	25.0
11	25.3	24.1	26.4
12	26.3	25.2	27.8
13	27.1	26.2	29.2
14	27.9	27.2	30.3
15	28.7	27.9	31.2
16	29.5	28.3	31.9
17	30.2	28.6	32.6
18	31.0	29.0	33.3
Sensitivity (95% CI)	0.92 (0.90-0.95)	0.91 (0.89-0.94)	0.84 (0.81-0.86)
Specificity (95% CI)	0.82 (0.80-0.85)	0.83 (0.81-0.86)	0.90 (0.88-0.92)
AUC	0.95	0.94	0.93

AUC = Area Under Curve

Table 4. Optimal percent body fat values for detecting ‘Obesity’ as determined by body mass index in males from the 1999-2004 National Health and Nutrition Examination Survey.

Age and Variable	White	Black	Mexican American
5	18.2	17.2	17.5
6	19.5	16.8	19.3
7	20.9	17.8	21.0
8	22.6	21.0	22.6
9	25.0	24.0	24.4
10	27.1	26.3	26.5
11	28.3	27.6	28.0
12	28.3	27.8	28.1
13	27.5	27.4	27.3
14	26.5	26.9	26.1
15	25.9	26.5	25.5
16	26.0	26.4	25.9
17	26.7	26.6	26.7
18	27.7	26.9	27.3
Sensitivity (95% CI)	0.90 (0.85-0.96)	0.90 (0.87-0.93)	0.90 (0.85-0.93)
Specificity (95% CI)	0.89 (0.86-0.92)	0.94 (0.93-0.95)	0.86 (0.84-0.89)
AUC	0.97	0.97	0.94

AUC = Area Under Curve

Table 5. Optimal percent body fat values for detecting ‘Obesity’ as determined by body mass index in females from the 1999-2004 National Health and Nutrition Examination Survey.

Age and Variable	White	Black	Mexican American
5	20.8	17.9	20.6
6	21.0	19.2	22.0
7	21.9	20.8	23.4
8	23.7	22.9	24.8
9	26.0	25.0	26.1
10	27.9	26.8	27.6
11	29.3	28.1	29.1
12	30.2	29.3	30.6
13	31.0	30.2	31.9
14	31.8	31.1	33.0
15	32.5	31.7	33.8
16	33.2	32.1	34.5
17	33.9	32.3	35.2
18	34.6	32.7	35.8
Sensitivity (95% CI)	0.96 (0.92-0.99)	0.96 (0.94-0.98)	0.88 (0.83-0.92)
Specificity (95% CI)	0.87 (0.85-0.89)	0.83 (0.81-0.85)	0.88 (0.85-0.90)
AUC	0.96	0.95	0.95

AUC = Area Under Curve

CHAPTER 5

SUMMARY AND RECOMMENDATIONS

Summary

This dissertation consists of a series of papers which focused on creating age-, sex-, and ethnicity-specific body fat centiles and the concordance of those centiles with other commonly used childhood obesity indices (e.g., BMI and WC). A major strength of this work was that anthropometric and body composition data of the 5 to 18 year olds were taken from a large, multi-ethnic, nationally-representative sample participating in one of three cycles (1999-2000, 2001-2002, and 2003-2004) of the National Health and Nutrition Examination Surveys (NHANES). In brief, %BF was calculated using tricep and subscapular skinfold measurements within the commonly used Slaughter equations. This equation was selected because it is sex-, ethnicity-, and maturity-specific as outlined in Chapter 2.

The development of age-, sex-, and ethnicity-specific %BF cutpoints was the aim of Chapter 3. This study described the variation in %BF across the pediatric age range and the current distribution of %BF values in children and adolescents within the United States. Body fat centiles were created using LMS regression, a technique that summarizes a changing distribution with three curves representing the median (M), coefficient of variation (S), and skewness (L). Previously, variations of the LMS methodology were used to create the current BMI reference charts for the diagnosis of obesity. Results from this study showed that %BF for males increased throughout early childhood and peaked at approximately 11-12 years of age across all three ethnic groups. During adolescence, %BF decreased slightly, or leveled off in the mid and lower centiles, but increased within the upper centiles. Girls displayed a similar pattern of age-related changes in %BF to boys through early childhood.

However, during adolescence, %BF for females increased across all centiles (although with varying magnitude). An important contribution of this study was that individual LMS values were provided so that future researchers can identify children based on these reference data.

Currently, the health-based %BF cutoffs used in many school-based fitness assessments, like FITNESSGRAM, are single values (e.g., 25%BF for boys and 30%BF for girls) that do not account for normal growth and maturation. Given the description of age-related changes in fat shown in Chapter 3, these static cutpoints may not be suitable for use in a wide age-range of children, and may actually create misclassification when compared to other adiposity indices, such as BMI and WC. For this reason, the purpose of Chapter 4 was to examine the concordance of the single-value body fat cutpoints, the LMS-derived %BF centiles from Chapter 3, CDC BMI centiles, and WC centiles. It was found that BMI and WC centiles demonstrated a reasonable level of agreement with the single-value %BF cutpoints of 25% and 30% in boys and girls, respectively. However, current CDC BMI cutpoints for obesity have low sensitivity and high specificity when compared to these values. Using these %BF and BMI cutpoints in the same sample to diagnose obesity would result in many overfat children being incorrectly diagnosed as normal weight based on BMI. Further, BMI and WC centiles agreed more consistently with single-value %BF cutpoints in boys than girls.

In addition, receiver operator characteristic (ROC) curves indicated that the LMS-derived %BF centiles corresponded consistently with currently used BMI cutpoints for overweight and obesity. Furthermore, the values of sensitivity, specificity, and area under the ROC indicated no large discrepancies between the sexes or among ethnic groups. The optimal %BF values identified at younger ages were well below the single-value %BF

cutoffs of 25% and 30% fat. Given the information presented in Chapters 3 and 4, it is clear that static %BF cutpoints do not adequately account for the common growth and variability in %BF that occurs during normal maturation. The LMS-derived %BF centiles can be used to improve agreement between %BF measures and current BMI classification systems.

Throughout this dissertation, attention has been given to refining the approach to creating and evaluating clinical cutpoints. LMS regression is a more robust technique of developing reference centiles in children and adolescents. More specifically, LMS accounts for the growth-related changes in physical variables like BMI, WC, and %BF during childhood. LMS regression also allows one to describe these changes with cross-sectional data, summarizing the sample and corresponding centiles with L, M, and S parameters that can be used to calculate z-scores and percentile values for individual children. Once reference distributions have been developed, ROC analysis can be used to identify optimal cutoff values. ROC analyses allows one to describe the local performance of a cutoff value (as sensitivity and specificity), as well as the global performance (area under the ROC curve) of a continuous diagnostic test to discriminate between two mutually-exclusive disease states. ROC analysis is not reliant on normally-distributed data, and essentially evaluates every possible cutoff value in reference to identifying disease.

Finally, the sample for all analyses in this dissertation was the nationally-representative NHANES dataset. NHANES purposefully over-samples certain sections of the population, such as low-income individuals, minorities, and adolescents. This allows for a balanced representation of all individuals and large sample sizes for subgroup analyses. However, care must be taken when using this dataset for those sampling reasons. The appropriate sample weights, clustering, and stratification were applied when possible in all

analyses. The use of this type of dataset in creating and evaluating clinical cutpoints is critical, as it enhances the generalizability of the results.

Recommendations for Future Research

Although this dissertation has added insight into our understanding of anthropometric indices commonly used in obesity research and clinical practice, additional research is needed in the following areas:

- Given the maturity-related variation in body composition particularly during puberty, it may be more appropriate to use a measure of maturation instead of age when creating LMS centiles. Since assessing maturity status has various limitations, it may be necessary to use a non-invasive method of maturity, such as the maturity-offset or percentage of predicted adult stature. This may further limit misclassification.
- %BF, BMI, and WC centiles should be linked to clinical outcomes, such as hypertension, insulin resistance, or metabolic syndrome.
- Longitudinal research is required to identify health-based outcomes of meeting or not meeting selected fat, BMI, and WC cutpoints.
- Serial and parallel diagnostic testing can be used to alter sensitivity and specificity of adiposity indices. Further research is required to determine if different combinations of simple anthropometric measurements may provide meaningful improvements over a single index in the diagnosis of childhood obesity.
- The LMS centiles provided in this dissertation should be used in conjunction with other obesity risk factors and obesity candidate-genes to determine if certain factors alter the growth trajectory of fat-mass.

- Future research should investigate the %BF, BMI, and WC relationship among ethnicities to determine if ethnicity-specific indices are required.
- The basic methodology used in this dissertation, creating reference centiles with LMS regression and then ROC analyses to determine optimal cutoff values, should be used to establish other clinical values for measures, such as maximal oxygen uptake, bone density, and accelerometer-based physical activity levels.