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Measurement Issues Related to Studies of Childhood Obesity: Assessment of Body Composition, Body Fat Distribution, Physical Activity, and Food Intake

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ABSTRACT. This article reviews the current status of various methodologies used in obesity and nutrition research in children, with particular emphasis on identifying priorities for research needs. The focus of the article is 1) to review methodologic aspects involved with measurement of body composition, body-fat distribution, energy expenditure and substrate use, physical activity, and food intake in children; and 2) to present an inventory of research priorities. *Pediatrics* **1998;101:505–518;** ***obesity, body composition, energy expenditure, physical activity, diet, methodology.***

ABBREVIATIONS. DXA, dual energy x-ray absorptiometry; SEE, standard error of the estimate; MRI, magnetic resonance imaging; CT, computed tomography; RQ, respiratory quotient; METs, metabolic equivalents.

BODY COMPOSITION

Accurate assessment of body composition is important in many areas of obesity and nutrition-related research. In addition to providing fundamental whole-body descriptive characteristics, accurate measures of body composition often are required as scaling factors to normalize physiologic variables (eg, metabolic rate, physical activity, physical fitness, etc). As described by Wang et al,[1] the composition of the human body can be thought of in terms of an atomic model (ie, oxygen, carbon, hydrogen, etc), a molecular model (ie, water, lipid, protein, minerals, and glycogen), a cellular model (ie, cell mass, extracellular fluid, etc), or a tissue model (ie, skeletal muscle, adipose tissue, bone, etc). In terms of obesity research, the most useful model is probably the molecular model, in which the body's composition is broken down into its main molecular components: lipids (includes essential and nonessential lipids), water, protein, minerals, and glycogen. Fat and fat-free mass are terms used frequently that refer to the classic two-component body composition model in which body mass is broken down into fat and nonfat tissue masses.

Measurement of the masses of the individual compartments of body mass is extremely challenging, because no direct method exists other than in vivo neutron activation analysis (very limited availability) and chemical analysis of the cadaver (useful for animal studies only). The lack of direct methods has led to development of various models and indirect methods for estimation of fat and fat-free mass, all of which are imperfect and require a number of assumptions, many of which require age-specific considerations, because the usual assumptions in multicompartmental models (eg, hydration of fat-free mass, density of fat-free mass) are known to be influenced by age and state of maturation.[2,3] In addition, practical aspects limit the availability of techniques for use in younger prepubescent children to specialized research-based techniques such as total body water,[4] dual energy x-ray absorptiometry (DXA),[5] total body electrical conductivity,[6] total body potassium,[7,8] and other more convenient and widely available techniques such as bioelectrical resistance,[4] skinfolds,[2] and other clinical anthropometric evaluations (eg, weight for height, ideal body weight, body mass index). Some of the more frequently used body composition techniques in children are discussed briefly below.

Densitometry

Densitometry is based on estimating body composition from measurement of total body density. The most widely used approach is to measure body volume by underwater weight and determine density by dividing body mass by body volume. The technique is a two-compartment model and is based on the different tissue densities of the fat and fat-free compartments of the body. If total body density and the specific densities of fat and fat-free mass are known, an equation can be generated for converting total body density to percentage of body fat based on the Archimedes principle.[9] Generally, at least in adults, the densities of fat and fat-free mass are assumed to be 0.9 g/mL and 1.1 g/mL; however, the density of fat-free mass is known to be influenced by factors such as age, gender, and ethnicity,[3] and little information exists in children.

Current limitations for applying densitometry to the pediatric population include practical problems and theoretic considerations. The technique requires climbing into a large tank of water, emptying the lungs by maximal exhalation, and sitting still underwater for several seconds. Thus, from a practical standpoint, testing adherence is extremely difficult for young children and impossible for infants. Recent developments using air rather than water displacement[10] for measurement of volume may be more practical for pediatric populations. Such a device,

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called the BodPod,[10] has been developed, and it produces an alternative method for measuring body volume that is simpler, quicker, and more practical than hydrostatic weighing.

From a theoretic standpoint, the limitations of successfully applying densitometry requires additional knowledge of the specific densities of fat and fat-free mass in children of different states of maturity, gender, and ethnicity. One previous study suggests that between birth and 22 years of age, the density of the fat-free mass increases from 1.063 to 1.102 g/mL in boys and from 1.064 to 1.096 g/mL in girls. The density of fat mass probably does not change, because it is more or less fixed by the biophysical properties of fat in vivo at a density of 0.9 g/mL.[11] Thus, as described by Lohman,[3] application of densitometry and development of accurate age-, gender-, and ethnic-specific equations requires knowledge of the density of fat-free mass for each subgroup being investigated.

DXA

Recent advances in techniques to measure body composition have provided DXA for assessment of whole-body as well as regional measurements of bone mass, lean mass, and fat mass.[12] DXA is based on the exponential attenuation resulting from absorption by body tissues of photons emitted at two energy levels to resolve body weight into bone mineral and lean and fat soft tissue masses; the theoretic considerations are reviewed elsewhere.[5] The advantages of DXA are the relatively quick scan time (≤20 minutes with newer machines equipped with a fan beam) and minimal radiation dose (<1 mSv or <1/100th of the equivalent radiation exposure of a chest x-ray). In addition, because the technique is based on a whole-body scan, additional information is collected about aspects of regional body composition. Thus, the technique is of potential use to the pediatric population.

Since the introduction of DXA, numerous studies have compared this technique with other research-based methods.[13–16] These studies have proved valuable in cross-validating and comparing the individual techniques. A general limitation of many widely used body composition techniques is the lack of true validation studies that have performed comparisons with known chemical composition. One advantage of DXA is that there are several studies that have demonstrated validity by comparison with chemical analysis of the carcass by using a pig model.[17–20]

Chemical analysis of the carcass is an ideal laboratory standard technique for comparing body composition techniques, because the whole-animal model simulates the various body composition compartments of a living organism. Because of practical and ethical issues, studies with human cadavers are limited; pigs often are used in these studies because their body-fat content is similar to that of humans. The adult[17] and pediatric[20] software of the Lunar DPX-L instrument have been cross-validated successfully against chemical analysis with pig models. One study in the pediatric body weight range[20] used 18 pigs (25.5 ± 7.0 kg; 9.9% to 32.8% body fat) and showed that carcass lean and fat content were highly correlated with DXA measurements (Pearson r values >0.98). The regression between carcass and DXA data deviate by a small but significant amount, suggesting that specific correction factors may need to be used to improve the measurement accuracy of total body composition by DXA. This approach effectively calibrates the DXA technique to the laboratory standard of carcass analysis in a pig model. The Hologic QDR-1000/W DXA instrument with pediatric whole-body software failed to measure fat mass accurately (as derived by chemical analysis) in small (~1.57 kg) and large (~6 kg) piglets.[19] In larger pigs (5 to 35 kg), the Hologic QDR-2000 using adult scan analysis also failed to measure fat mass accurately.[18]

Collectively, the validation studies of DXA suggest that the relationship between actual chemical content of the carcass and DXA estimates may be affected by factors such as the size of the animal, the equipment used, and the operation mode. These validation studies and generation of new calibration equations are important steps in development of standardized techniques to measure body composition in children.[20]

Skinfolds and Anthropometry

Estimation of fat mass from anthropometry involves development of prediction models in which anthropometric measures (eg, sum of skinfolds) are related to body-fat mass. Thus, the use of an accurate criterion method is important for development of these equations. Several prediction equations have been developed for children based on use of a multicompartmental model[2] or DXA[21] as criterion method.

Slaughter and colleagues[2] developed body composition prediction equations from data on 310 subjects (8 to 29 years of age), including 66 prepubescent children (50 boys and 16 girls). A multicompartmental model of body composition was used as a criterion method by combining measures of total body density (from underwater weight), total body water (from deuterium dilution), and bone mineral density (from photon absorptiometry) on the right and left radius and ulna. This study led to development of gender-, race-, and maturation-specific equations for estimating body fat based on measurement of either triceps plus calf (two gender-specific equations) or triceps plus subscapular skinfolds (nine equations recommended depending on gender, race, maturation state, and sum of skinfold thickness).

Several studies have examined the accuracy of the Slaughter equations in cross-validation studies. Janz and coworkers[22] were unable to cross-validate the Slaughter equation based on triceps and calf skinfolds in girls and boys. In 98 white children (6.6 ± 1.4 years old; 24.1 ± 5.9 kg),[21] fat mass by DXA (4.8 ± 3.0 kg) was significantly lower than fat mass by skinfolds (5.0 ± 3.1 kg) with the Slaughter equation,[2] although fat masses by these two techniques were strongly related (R^2 = 0.87; standard error of the estimate [SEE] = 1.1 kg). A possible explanation for the differences between equations for predicting fat mass may be the small sample size of young girls (n = 16) in the original study by Slaughter et al.[2]

We recently developed a series of new anthropometric prediction equations based on data from 98 white children.[21] Having previously cross-validated the DXA technique against carcass analysis in a pig model,[20] these new equations were developed relative to DXA measures. Subscapular skinfold, body weight, triceps skinfold, gender, and height^2/resistance were the strongest predictors of fat mass measured by DXA with a model R^2 of 0.91 and an SEE of 0.94 kg of fat mass, suggesting new anthropometric body composition prediction equations based on the use of DXA as a criterion method.[21] The combination of skinfolds and bioelectrical resistance was previously shown to improve the prediction of fat mass in adults.[23] In the absence of bioelectrical resistance data, subscapular skinfold, body weight, and triceps skinfold can be used to estimate fat mass. Also, simple clinical anthropometric indices (eg, triceps skinfold) can be used to estimate fat mass with prediction equations.[24]

The cross-validation and testing of anthropometric prediction equations in independent groups is of particular importance for several reasons. First, although there are standardized methods,[25] the measurement of skinfolds is by nature sensitive to interuser variability. Second, because of potential gender-, ethnic-, and maturation-related changes in body composition, the relationship between skinfold measures and body fat may vary between subgroups of the population. Thus, it is important to identify anthropometric measures that are robust to interuser variability and equally reflective of body composition in all subgroups of the population.

Bioelectrical Impedance Analysis

Bioelectrical resistance is an alternative technique for assessing body composition in clinical and population-based studies. The technique is based on measurement of electrical resistance in the body to a tiny imperceptible current. The electrical resistance is a function of body shape and the volume of conductive tissues in the body.[26] Various equations have been developed to predict total body water from height^2 and bioelectrical resistance; these and other measurement issues are reviewed elsewhere.[26] Age-specific equations have been recommended,[27] because age-related differences in electrolyte concentration in the extracellular space relative to the intracellular space may alter the relationship between bioelectrical resistance and total body water.[28]

In a study that did not include adolescents, the relationship between height^2/resistance and total body water was robust across a wide age range including infants and young children.[29] Moreover, the Kushner equation[29] for estimating total body water from height^2/resistance has been cross-validated against total body water in 4- to 6-year-old children in two independent laboratories.[4] Also, the intraclass reliability for estimates of fat and fat-free mass by using bioelectrical resistance in 26 children was >0.99.[4] Thus, the techniques appear to be reliable as well as robust to interlaboratory variation, and the Kushner equation is generally recommended in young children, although this approach has not been validated in children of different ethnic groups. In adolescents, the equations of Houtkooper[30] are recommended, although these equations have not been cross-validated widely or examined in other ethnic groups.

One of the limitations of bioelectrical resistance is that this approach provides an estimate of total body water, which then must be transformed into fat-free mass. This requires knowledge of the hydration of fat-free mass, which generally is thought to be constant in adults at 73.2%,[31] but known to vary in children.[7] Fomon and colleagues[7] published age- and gender-specific hydration constants, although the original constants may have to be modified slightly.[4]

Bioelectrical resistance has been cross-validated in children against total body water,[4] total body potassium,[8] and DXA.[22] Schaefer and coworkers[8] estimated fat-free mass from total body potassium in a sample of 112 healthy children (4 to 19 years of age) and demonstrated that fat-free mass could be estimated from bioelectrical resistance and age with an R^2 value of 0.98 and a root mean square error of 1.98 kg. In an independent cross-validation study in 98 white children (6.6 ± 1.4 years old; 24.1 ± 5.9 kg),[21] fat mass by DXA (4.8 ± 3.0 kg) was significantly lower than fat mass by bioelectrical resistance (5.7 ± 3.4 kg). Interestingly, the model R^2 (0.75) and the SEE (1.5 kg) were not as strong as for the relationship between DXA and fat mass by skinfolds, which suggests that bioelectrical resistance may have a poorer precision than skinfolds.

Body Fat Distribution

In adults, intraabdominal adipose tissue (body fat around the visceral organs) is related to negative health outcome independent of total body fat.[32,33] Thus, assessment of body fat distribution is equally as important as measurement of total body fat. Traditionally, body fat distribution has been measured by anthropometry. Recently, in vivo imaging techniques (eg, magnetic resonance imaging [MRI] and computed tomography [CT]) have allowed more accurate measures of body-fat distribution in children and adolescents.[34–36]

The early accumulation of intraabdominal adipose tissue in childhood is clinically relevant, because there is a significant relationship with adverse health, including dyslipidemia and glucose intolerance, at least in obese children.[37–39] The existence of intraabdominal adipose tissue also has been observed in healthy, nonobese children as young as 4 to 7 years of age[34] as well as in nonobese adolescents.[35,40] It is currently unclear whether the amount of visceral fat accumulation observed in children is appropriate for the pediatric body size and whether the observed extremes are related to extremes of general body fatness. For example, some studies suggest that intraabdominal adipose tissue in children increases in proportion to overall fatness,[34] as observed in adults,[36] whereas others have shown that children with extremes of body mass index have similar amounts.[35]

In 101 black and white lean and obese children (7.5 ± 1.7 years old; 33.0 ± 12.2 kg [body weight]; 30% ± 11% [body fat]), intraabdominal adipose tissue averaged 30.0 ± 23.0 cm^2 but varied greatly from 6 to 102 cm^2.[41] Subcutaneous adipose tissue averaged 101 ± 95 cm^2 (range, 8 to 372 cm^2). Intraabdominal adipose tissue area was significantly correlated with subcutaneous adipose tissue area ($r = 0.83$), total fat mass by DXA ($r = 0.79$), soft lean tissue mass by DXA ($r = 0.62$), and body weight ($r = 0.77$) but not age ($r = 0.33$). Thus, the degree to which visceral fat accumulation occurs is highly variable. The residual from the regression between intraabdominal adipose tissue and subcutaneous abdominal adipose tissue has been suggested for use as an index of visceral obesity in children that is independent of total body fat.[41]

In adults, there are gender[36] and ethnic[42] differences in intraabdominal adipose tissue area. Males have greater amounts than females, even after taking into account differences in total body fat,[36] and this difference is apparent during adolescence[35] but not in prepubescence.[41] In terms of ethnic differences, anthropometric skinfold studies have suggested a greater central fat distribution in children of African,[43] Mexican,[43] and Native-American[44] descent. This suggests that these ethnic groups may have increased visceral fat, which places them at higher risk from the negative health effects of obesity. However, in prepubertal children, intraabdominal adipose tissue in black boys and girls is actually significantly lower than in white children,[41] similar to that observed in obese adult women.[42]

CT and MRI are accurate imaging techniques for assessing body-fat distribution, but the disadvantages are cost, radiation exposure, and limited use to a research setting. Thus, other indirect indicators of body fat distribution have been used. For example, in adults, the waist-to-hip ratio or the waist circumference are used often as markers of intraabdominal adipose tissue. However, in children[34] and adolescents,[35,40] there is no significant correlation between these markers and intraabdominal adipose tissue as measured by imaging techniques. In children and adolescents, central skinfold thicknesses explain only 25% to 60% of the variation in intraabdominal adipose tissue.[34,35,40] Collectively, these studies confirm that circumferences may not be good indices of body fat distribution, whereas individual measurements of skinfold in the trunk region may be more useful but not very accurate.

The use of DXA to measure total abdominal fat may provide a stronger index, but this technique cannot resolve subcutaneous from intraabdominal adipose tissue. The combination of total abdominal fat by DXA and skinfold and anthropometry data (as an index of subcutaneous fat) has been used in adults to estimate intraabdominal adipose tissue with reasonable accuracy.[14,45] Preliminary equations have been developed and cross-validated in children with this approach (Goran MI, unpublished observations). The combination of trunk fat by DXA, total fat by DXA, and abdominal skinfold thickness predicted intraabdominal adipose tissue as measured with CT scanning with a model R^2 of 0.85 and an SEE of ± 9 cm^2. In fact, the incorporation of DXA was not essential, because abdominal skinfold thickness, ethnicity (white versus black), and subscapular skinfold predicted intraabdominal adipose tissue with a model R^2 of 0.82 and an SEE of ± 10 cm^2.

ASSESSMENT OF ENERGY EXPENDITURE AND SUBSTRATE USE

Energy expenditure is typically measured in humans by either direct or indirect calorimetry. Direct calorimetry involves measurement of heat production directly. This approach is technically demanding, especially in human studies, and is now infrequently used. Indirect calorimetry measures energy production by respiratory gas analysis. This approach is based on measurement of oxygen consumption and carbon dioxide production that occurs during the combustion (or oxidation) of protein, carbohydrate, fat, and alcohol. Respiratory gas analysis can easily be achieved in humans either over short measurement periods at rest or during exercise with a face mask, mouthpiece, or canopy system used for gas collection, and over longer periods of 24 hours or more by having subjects live in a metabolic chamber. Indirect calorimetry has the added advantage that the ratio of carbon dioxide production to oxygen consumption (the respiratory quotient [RQ]) is indicative of the type of substrate (ie, fat versus carbohydrate) being oxidized; for example, carbohydrate oxidation has an RQ of 1.0, and fat oxidation has an RQ close to 0.7. Finally, carbon dioxide production rates can be measured directly and used to estimate energy expenditure over extended free-living periods of 7 to 14 days with stable isotope methodology and double-labeled water.[46,47]

There are three main components of energy expenditure that need to be considered. The largest component is resting metabolic rate, which is the energy expended to maintain the basic physiologic function of the body (eg, heart beat, muscle function, respiration). Resting metabolic rate occurs in a continual process throughout the day. Resting metabolic rate is typically measured by indirect calorimetry under fasted conditions, while subjects lie quietly at rest in the early morning for 30 to 40 minutes. In addition to resting metabolic rate, there is an increase in metabolic rate in response to food intake. This increase in metabolic rate is often referred to as the thermic effect of a meal (or meal-induced thermogenesis) and is the energy that is expended to digest, metabolize, and store ingested macronutrients. The thermic effect of a meal is typically measured by continuous indirect calorimetry for 3 to 4 hours after consumption of a test meal of known caloric content. The third component of energy expenditure is the increase in metabolic rate that occurs during body movement (includes exercise as well as all forms of physical activity). This metabolic rate is primarily the energy expended for muscular contractions. The energy expended in physical activity can be measured under laboratory conditions by indirect calorimetry during standard activities. Free-living physical activity-related energy expenditure over extended periods of up to 2 weeks can be measured by the combination of double-labeled water to measure total energy expenditure and indirect calorimetry to measure resting energy expenditure and the thermic effect of a meal.

Indirect Calorimetry

Indirect calorimetry can be performed easily in children by using standard commercial equipment as performed in adults. There are no special assumptions or theoretic considerations in children. However, there may be important considerations for measurement conditions before and during measurement of metabolic rate to achieve the need for having subjects lie still and quiet for 30 minutes. For example, basal metabolic rate is often understood to encompass measurements performed after a 10- to 12-hour fast in a nonaroused state, with minimal muscular movement. These conditions are often met in adults when measurements can be performed immediately on awakening after the subject has slept in the laboratory or clinical research center.[48] This approach is viable and reproducible in young children,[49] but may not always be possible. The terms *basal metabolic rate* and *resting metabolic rate* are often used interchangeably. Resting metabolic rate implies a resting but nonbasal state and may include the increase in metabolic rate associated with arousal. In children, a relaxed and quiet state can be achieved in younger children by allowing them to watch television or standardized cartoons[50] or by measurement in a nonfasting state,[50] although this approach should be used with careful control over pretest food consumption.

One of the limitations of using indirect calorimetry to measure resting metabolic rate is that measurements can be performed over only a very short time (usually 30 minutes). Measurements over 24 hours can be achieved by having subjects live in a metabolic chamber. This approach has been used successfully in children as young as 4 years of age (Figueroa-Colon R, unpublished observations). An additional advantage of this approach is that activity and food intake can be monitored and controlled. The disadvantage is that the chamber environment is not habitual, especially because movement and physical activity may be restricted.

Double-labeled Water

The double-labeled water technique is the first truly noninvasive means to measure total daily energy expenditure accurately in free-living humans. The technique was first introduced by Lifson and colleagues[51] in the 1950s as an isotopic technique for measuring carbon dioxide production rate in small animals. Unfortunately, it was not possible to apply the technique to humans, because the dose required was cost-prohibitive given the relatively poor sensitivity of isotope ratio mass spectrometry at that time. It was not for another 20 years that Lifson and coworkers[52] described the feasibility of applying the technique to measure free-living energy expenditure in humans, an application that was recognized later by Schoeller et al.[53] Schoeller et al[54] and Speakman and colleagues[55] provide equations for calculating energy expenditure from double-labeled water data.

The major advantages of the double-labeled water method are that 1) the technique is noninvasive and unobtrusive; 2) measurements are performed under free-living conditions over extended periods (7 to 14 days); and 3) the technique can be used to estimate activity energy expenditure when combined with measurement of resting metabolic rate. The major disadvantages include the following: 1) the cost of ^{18}O (~$200 for a 30-kg child); 2) the need for an isotope ratio mass spectrometer for sample analysis; 3) the method provides a direct measure of CO_2 production and not energy expenditure (the food quotient of the diet is required for generating estimates of energy expenditure); 4) the method gives an integrated measure of activity energy expenditure over 14 days and does not provide any qualitative information on physical activity pattern; and 5) the technique is not really suitable for large-scale epidemiologic studies.

The double-labeled water technique has been validated in humans in several laboratories around the world by comparison with indirect calorimetry in both adults and infants, as described previously.[56] These studies generally show the technique to be accurate to within 5% to 10% relative to data derived by indirect calorimetry for subjects living in metabolic chambers. There are no special considerations or limitations in applying the technique to children. The theoretic precision of the double-labeled water technique is 3% to 5%,[57] although the experimental variability is ±12% in free-living adults because of fluctuations in physical activity levels[58] and ± 8% under more controlled sedentary living conditions.[59] The accuracy and reasonable precision of the technique therefore allow the double-labeled water method to be used as a standard measure of free-living energy expenditure in humans with which other methods can be compared.

ASSESSMENT OF PHYSICAL ACTIVITY

Physical activity is a broadly used term, and its heterogeneous nature makes it extremely difficult to characterize and quantify. Physical activity can be defined by any physical movement that is a result of skeletal muscle contraction. Physical activity is often measured in terms of caloric cost, but this may not be appropriate because the benefits and health effect of physical activities using a high-energy expenditure (eg, running at a certain intensity) versus a low-energy expenditure (eg, strength training) may not be related to the caloric cost of the physical activity. Thus, quantification and description of physical activity should probably consider all aspects, including the following: 1) type and purpose of physical activity (eg, recreational or obligatory, aerobic or anaerobic, occupational); 2) intensity (strenuousness); 3) efficiency; 4) duration (ie, time); 5) frequency (ie, times per week); and 6) specific energy cost of the activity performed. It is also important to consider that physical activity and exercise may not be synonymous. Exercise typically refers to structured activities that are performed for the purpose of improving physical fitness and well-being. This distinction is of particular relevance in children.

An additional difficulty with the development of rigorous techniques for measuring physical activity is the lack of an ideal standard with which to validate the data, thus making it difficult to truly validate any given technique. Standard techniques that are available include measurement of specific energy costs of different activities in a laboratory setting by indirect calorimetry and measurement of free-living physical activity-related energy expenditure with double-labeled water. Various methods are available for assessing physical activity in children, including questionnaires, accelerometry or pedometry, double-labeled water for assessment of free-living physical activity-related energy expenditure, and heart-rate monitoring. Use of these techniques in children has been reviewed previously[60–62] and is briefly described below.

Activity Energy Expenditure With Double-labeled Water

As described above in the section on energy expenditure, the combination of double-labeled water (to measure total energy expenditure) and indirect calorimetry (to measure resting energy expenditure) can be used to estimate physical activity-related energy expenditure by difference. Thus, the major advantage of this approach is the quantification of physical activity-related energy expenditure under free-living conditions over extended periods. However, the technique does not describe physical activity patterns, nor does it differentiate between different types of physical activity (eg, playing outside at a low intensity for 2 hours vs riding a bike for 30 minutes). In addition, although the 14-day period is generally considered long-term relative to other metabolic studies, this window of time actually might be quite short when considered relative to the time scale for development of obesity.

Several studies have used this approach to measure physical activity-related energy expenditure in children under free-living conditions.[63–65] These studies show that the energy expended in physical activity is ~400 kcal/day in young children. This low level of physical activity energy expenditure is consistent with several studies showing that children spend only a small fraction of their active time in high-intensity activities.[66,67] Thus, although children often appear to be very active, the combined energy cost of these activities is not that high. In addition, physical activity energy expenditure is related only weakly to fat-free mass ($r = 0.32$) and body weight ($r = 0.28$ to 0.29). These observations may appear counterintuitive because the energy cost of physical activity is usually thought to be a function of body weight (at least for weight-bearing exercise). However, the physical activity being measured combines all physical activities throughout the day (including exercise and spontaneous and obligatory physical movement) and is a combination of weight-bearing and nonweight-bearing activities.

It is important to note that activity energy expenditure estimated from the difference between total and resting energy expenditure may be an imprecise measure. There are no test/retest studies of physical activity energy expenditure in children, but precision can be estimated by a propagation-of-error approach.[58] The projected error in total energy expenditure minus resting energy expenditure approaches 50% when the ratio of these two components to one another is 1.4 to 1.6, as observed in several studies in young children.[64,65] Because of this limited precision, values of total and resting energy expenditure can be corrected for their true score; this approach improves the precision of an estimate that is derived from the difference between two independent measures.[68] In addition, repeat measures of physical activity energy expenditure should be performed to improve precision. Despite the many limitations discussed above, measurement of physical activity energy expenditure by double-labeled water is available as a standard technique that can be used to verify the combined energy cost of physical activity derived by other techniques.

Questionnaires

Questionnaires may be useful for large-scale epidemiologic studies. However, this approach is fraught with many difficulties. The major difficulty with the questionnaire approach is that it relies on the ability of the subject (or the parent) to recall behavioral information accurately. Also, it is difficult to translate qualitative information on physical activity (eg, playing for 30 minutes) to quantitative data (ie, kcal per exercise session). Although many different types of questionnaires exist, very few (if any) have been developed specifically and validated for use in children.

As described in more detail by Montoye et al,[62] the most frequently used questionnaires in adults include the Minnesota, Paffenberger, Five-City 7-Day Recall, Baecke, and Framingham questionnaires as well as dozens of others that have been described in the literature. Although some validity and reliability studies have been performed, the lack of use of strong criterion methods makes it difficult to interpret the true validity of these tools. Furthermore, only a few questionnaires have been designed specifically for children, and these have not been tested rigorously.

In children, the problems of recall with questionnaires and interview techniques are confounded. Another difficulty is that the source and type of physical activities observed in children are very different than those in adults (ie, no occupational activity, different types and intensities of habitual activity). Also, there is very limited information available on the specific energy costs of different activities in children, making it difficult to translate activity information to energy expenditure. Finally, it has been shown that children are able to recall only ~50% of the previous week's physical activities.[69]

Despite these limitations, several physical activity and behavior questionnaires have been designed specifically for children. The Netherlands Health Education Questionnaire[70] rates the response to eight questions relating to physical activity behavior on a scale of 1 to 5 and computes an average rating. The questions refer to preferences for aspects such as 1) playing alone or with other children; 2) playing quiet or vigorous games; 3) like or dislike of gymnastics; and 4) like or dislike of reading. The questionnaire of Kriska and colleagues[71] is an interview that obtains information on hours spent sleeping, napping, watching television, playing, and performing specific types of activities according to an inventory list. The outcome index is rated in hours of activity per day. The Amsterdam Growth Study questionnaire[72] obtains information on types, intensities, and duration of physical activities related to school (eg, transportation to school, physical education classes), organized activities (eg, organized sports participation), and other unstructured activities.

These questionnaires have been subjected to limited validity and reliability studies. For example, the Kriska questionnaire[71] has a reliability of 0.35 (Spearman rank-order correlation for test/retest) and a validity of 0.8 (by correlation with the Caltrac accelerometer). In most cases, the questionnaires are examined for validity by comparing with other techniques of unknown validity. Thus, although these questionnaires are used widely, their accuracy has not been rigorously examined relative to strong criteria methods to check for validity and reliability.

Only one published study has compared activity data by questionnaire in children with physical activity-related energy expenditure by double-labeled water.[73] In 101 white children, hours of physical activity per week with the Kriska questionnaire[71] was not related to free-living physical activity-related energy expenditure. The reason for this disparity is likely explained by the fact that the two instruments being compared actually measure quite different things. The activity index derived by the questionnaire is simply a reflection of time devoted to recreational activities. It is not dependent on factors such as intensity or efficiency. Activity energy expenditure by double-labeled water reflects time and intensity of all physical activities and also has a built-in efficiency factor. Thus, physical activity behavior by questionnaire may not be synonymous with physical activity-related energy expenditure. This is because time spent in different physical activities may not be representative of the daily energy expended by children in physical activity. Thus, future development of physical activity instruments may need to consider quantitative as well as qualitative information on physical activity.

One of the major difficulties in interpreting questionnaire techniques is the difficulty in translating qualitative information on physical activity to energy use. This conversion relies on the use of activity factors or intensity factors called metabolic equivalents (METs) for specific activities. METs are multiples of resting energy expenditure (eg, walking for pleasure = 3.5 METs, meaning that when a person is walking, the energy expenditure is three times resting energy expenditure). Also, it is assumed that 1 MET = 1 kcal/minute, so that 60 minutes of walking at 3.5 METs is assumed to be equivalent to 210 kcal; an alternative approach is to base the calculations on the assumption that energy is expended at a rate of 1 kcal per hour per kilogram of body weight per MET.

Thus, the conversion of qualitative questionnaire-derived information on physical activity to quantitative data is based on the following assumptions: 1) the energy intensity of specific activities can be explained as METs; 2) that resting energy expenditure = 1 kcal/minute in all subjects or that the energy cost of physical activities is directly proportional to body weight; 3) that intensity is constant among individuals; 4) that intensity is constant within individuals for different activities; and 5) that physical activity-related energy expenditure can be accounted for by set periods of defined physical activity. These assumptions never have been examined rigorously in children, and additional consideration of the following factors is warranted: measurement of the energy cost of specific activities; incorporation of the relationship between energy cost of activities and resting energy expenditure, fat-free mass, and weight to increase the specificity and sensitivity of the calculations; assessment of variation in intensity; and identification, definition, and quantification of the energy cost of physical activities not related to defined periods of exercise.

Heart-Rate Monitoring

One technique that has been examined rigorously in children is the heart-rate method.[63] Some of the limitations of this technique are that it is time-consuming, that it requires close cooperation from the subjects, and that there is some concern that heart rate may vary independently of energy expenditure. However, a study by Livingstone et al[63] in children suggests that the heart-rate method may yield accurate group assessment of physical activity. Heart rate was measured continuously for 2 to 3 days in 36 children (7 to 15 years old) and compared with total energy expenditure over 14 days by double-labeled water. The method relies on the individual laboratory calibration of the relationship between heart rate and oxygen uptake, as measured during standardized activities in the laboratory. Also a flex value for heart rate is identified that represents the heart rate unique to each person that distinguishes rest from exercise. During the period when heart rate falls below the flex value, energy expenditure is assumed to be equivalent to resting energy expenditure. In the entire group, total energy expenditure was estimated to within ± 20% from heart-rate data when compared with double-labeled water, and the correlation between the two techniques was 0.91.[63]

Techniques Based on Movement and Accelerometry

One of the most basic approaches to measuring physical activity involves direct observation and analysis of motion. This classic approach has been used frequently in children,[74] but it is time-consuming and expensive. Also, the observations are restricted to specific locations and may not reflect actual free-living conditions. An alternative approach, the Children's Activity Rating Scale, was developed by Puhl and coworkers[75] for 3- to 5-year-old children. This is a five-level scale designed to evaluate physical activity involvement during periods of investigator observation. The five-point incremental scale is based on observed intensity of activity (ie, stationary through very fast movement). Children are observed for 6 to 12 hours per day, and activity is scored according to the five-point scale. This technique has been examined closely for various aspects of precision and reliability in an ethnically diverse group of 180 children 3 to 4 years of age, and it has an intraclass reliability >0.7 for most aspects of assessment.[76]

Because of the limitation of assessing movement by observation, several portable devices have been developed (eg, motion counters and accelerometers). The advantages of this type of approach include low cost and generation of information on physical activity patterns. Some of the general limitations of this approach include practical issues with obtaining reliable information from children, especially with regard to ensuring that the portable device is worn at all times and is not tampered with. Also, there are issues that relate to converting the movement information to energy expenditure.

Pedometers were designed to record the number of steps taken by an individual. However, laboratory tests show that the pedometer is not reliable for measuring free-living activity because of its inaccuracy at slower and faster walking speeds. More recent developments with accelerometry may be more useful. Accelerometry is based on the theoretic relationship between muscular force and body acceleration that occurs during discrete physical movements.

The Caltrac is an accelerometer that measures movement in a single plane only. The device is a small portable unit worn around the waist. The basis of the technique is that a transducer records any body acceleration and a charge is produced that is proportional to force of movement. In studies performed in children, there are reasonable correlations ($r = \sim 0.7$ to 0.9) between registered counts and energy expenditure during specific activities performed under laboratory conditions.[60,77] However, there are no studies that have compared the Caltrac to free-living energy expenditure in children.

One of the major limitations of the Caltrac is that movement registration is limited to recording of vertical movement only. Thus, accelerometers have been designed to record movement in three dimensions.[78,79] These units compare well with energy expenditure during specified laboratory tests and free-living energy expenditure in adults,[78] but they remain to be examined in children.

Assessment of Physical Inactivity

Epidemiologic studies suggest that physical inactivity exerts a strong influence on the development of obesity in children.[80] In addition, it has been shown that hours of activity per week in children is inversely related to body fat mass, whereas physical activity-related energy expenditure over 14 days by double-labeled water is not.[73] Thus, sedentary lifestyle behavior in general may be more important in the etiology of obesity, which suggests that measurements of physical inactivity may be an important consideration. Such measures of physical inactivity could include hours watching television or playing computer games per day and are likely to be extracted from questionnaire data and other techniques as discussed above.

ASSESSMENT OF FOOD INTAKE

Measurement of habitual food intake remains one of the most challenging aspects of human obesity research. Dietary intake techniques in children tend to suffer from the general limitation that they involve an interview approach and, thus, they often rely on the child's parent or teacher to recollect daily intake accurately. Thus, as with physical activity questionnaires, the accuracy of these food intake methodologies in children is confounded because of the reliance on a third person to recollect a subject's intake. An additional limitation of studies examining children's intake is the possibility of recall bias, and the mother's capacity to complete the questionnaire is affected by memory failure, level of nutrition knowledge, and motivation to complete the form accurately.[81] Memory errors may play a major role in the disparity between estimated intake by semiquantitative food frequency questionnaire and actual intake. Sources of memory error consist of memory failure and elaboration or confusion with current diet.[81] Additionally, the inability of the parent to correctly appraise serving sizes, the degree of the perceived value of the food items to be recalled, and the fact that children tend to better remember preferred foods as larger portions than nonpreferred foods augments the amount of error.[81] The amount of time the parent spent observing the child during the recall diet period also may be reflected in the elaboration of the answers.

Also, development of new techniques for dietary intake has been hindered by the inability to cross-validate instruments with any known standard technique. With the advent of double-labeled water as a means to check the internal consistency by way of measuring total energy expenditure, several advances have been made, and several such studies have been performed in children. This approach is based on the concept that in subjects who are in energy balance, energy intake must be equivalent to total energy expenditure as measured by double-labeled water. Data from several studies suggest that bias in energy intake techniques does not occur systematically across all age groups or across different dietary methods. A limitation of the double-labeled water validation approach is that it does not provide any sense of validity of macro- or micronutrient intake. With the double-labeled water validity check, previous studies in adults have shown that most food intake methods underestimate actual intake,[82] and that this bias is more pronounced in women and in obese individuals. In children, previous studies with double-labeled water used as a standard have shown that the food frequency questionnaire overestimates total calorie intake by ~50%,[83] whereas repeated 24-hour recalls[84] and weighed diet records[85] provide reasonably accurate group mean values for intake, although the values are not accurate on an individual basis.

Food Frequency Questionnaires and Diet History

Food frequency questionnaires and diet history assess type and amount of food consumption in a semiquantitative manner. Many of the questionnaires frequently used do not take into account the smaller portions consumed by children and thus may overestimate intake.[83] The food frequency questionnaire was designed to measure typical patterns of food intake and was not necessarily intended to provide accurate quantitative measures of energy intake on an individual basis. The aforementioned techniques have not been widely assessed for their validity in measuring energy intake. However, the few studies that have been conducted in children suggest that both diet histories and food frequency questionnaires overestimate energy intake. In a small group of 3-year-old children ($n = 8$), energy intake by diet history (1414 ± 132 kcal/day) overestimated energy intake based on total energy expenditure (1258 ± 163 kcal/day) by 14%.[85]

In 4- to 6-year-old children,[83] energy intake obtained from a semiquantitative food frequency questionnaire (2145 ± 535 kcal/day) was 53% higher than total energy expenditure by double-labeled water (1403 ± 276 kcal/day; $P < .001$). The magnitude of this overestimation was not influenced by gender or body composition. In addition, the food frequency questionnaire is known to produce estimates of energy intake that are significantly higher than those obtained from 24-hour recalls.[86] Nonetheless, because the diet history and food frequency questionnaire were not designed to reflect accurately and precisely true energy intake, these techniques still may permit classification of subjects into categories of intake for epidemiologic research, but are clearly not very useful for determining individual differences in energy requirements.

Self-reported weighed diet records provide estimates of actual food intake and require a high degree of subject cooperation. Subjects are instructed to weigh or measure individual food and beverage items to provide detailed information on portion sizes. In 7- ($n = 12$) and 9-year-old ($n = 12$) children,[85] there was good agreement between energy intake estimated from a weighed 7-day diet record (1959 ± 517 kcal/day in 7-year-old children; 2022 ± 325 kcal/day in 9-year-old children) and total energy expenditure from double-labeled water (1823 ± 330 kcal/day in 7-year-old children; 2100 ± 301 kcal/day in 9-year-old children). With adolescents, however ($n = 34$; 12- to 18-year-old children), a systematic negative bias was evident,[33] because the diet record estimates (2210 ± 588 kcal/day) were significantly lower than measurements of total energy expenditure (2829 ± 616 kcal/day). Other investigators confirmed this finding in a cohort of 28 nonobese and 33 obese 12- to 18-year-old adolescents by using 2-week diet records in which reported energy intake was underestimated by 19% in nonobese adolescents and by 41% in obese adolescents.[85]

Given the aforementioned limitations, the question that follows is whether food frequency and diet history questionnaires can be modified by adjusting the serving sizes for age and whether an appropriate correction factor can be applied so that energy intake can be measured accurately. Previous research findings in adults were inconclusive when serving sizes were adjusted on a food frequency questionnaire. Flegal and Larkin[87] found that errors in classification were primarily attributable to errors in frequency estimation instead of to errors in serving size estimates. Therefore, modification of serving sizes would not necessarily affect the quality of information obtained. On the other hand, Block and coworkers[88] found that correlations between the modified food frequency questionnaire and 16 days of dietary record were improved significantly with the addition of age-specific portion sizes. The role of modifying serving sizes to improve the accuracy of estimating energy intake in children with the food frequency questionnaire warrants additional investigation.

24-Hour Recall Method

The 24-hour recall method has been widely used in children, and reported energy intake with this technique compares well with total energy expenditure in young children when the multiple-pass interview technique is used. The multiple-pass approach was developed to overcome the dilemma of underreporting that is known to exist with interview techniques.[84] The multiple-pass approach involves three distinct stages of an interview: 1) a quick listing of food consumed, 2) a more detailed description of the specific items, and 3) a review of the information. Food portion sizes are determined by using two-dimensional food models. When applied in triplicate in 24 young boys and girls,[84] total reported mean intake (1553 ± 435 kcal/day) was not significantly different than total daily energy expenditure averaged over 14 days by double-labeled water (1607 ± 492 kcal/day). Thus on a group basis, the 24-hour reported intake reflected energy intake accurately. However, the correlation between individual expenditure and reported intake was not significant, indicating that the recall technique was not precise enough to estimate actual energy intake on an individual basis. The degree of misreporting of energy intake was not influenced significantly by gender, age, or body-fat content in children.[84]

One of the limitations of the 24-hour recall is that several recalls are needed to overcome daily fluctuations in intake pattern. Taking into account inter- and intraindividual variation in young subjects, Nelson et al[89] estimated that 10 days of recall would be required to achieve an r value of 0.9 between measured and actual average intake. Collection of numerous recalls and multiple dietary analysis would be cumbersome and time-consuming.

In summary, weighed diet records and repeated multiple-pass 24-hour recalls may provide accurate group mean estimates of energy. However, this does not hold up across other age groups, because a systematic negative bias in the underreporting of energy intake has been noted in the adolescent years and continues throughout the lifespan; it is complicated further by the additional effect of gender and obesity. Weighed food diaries and direct observation of intake may provide a more accurate picture of intake in children. However, these techniques are more cumbersome to implement and are labor-intensive and invasive for the subjects. In addition, these constraints may influence reporting and lead to a behavioral modification that may influence the data.

SUMMARY AND RESEARCH PRIORITIES

Body Composition and Fat Distribution

Current techniques for assessing body composition and fat distribution in children are summarized in Table 1, which includes a listing of priorities for methodologic research. In addition to the development of new methods, there is also a need to incorporate a more unified approach in the interpretation and use of existing techniques so that different equations and methods can be compared between laboratories and across studies. Additional studies with direct measures by in vivo neutron activation analysis during growth and development are warranted. In addition to the methodologic issues listed in Table 1, there are a number of other priorities important for interpretation of body composition. Probably one of the most important needs is to reach a consensus on choice of reference data and standards to assess body fat and fat distribution throughout childhood. Thus, there is a need to develop normative data for body composition and fat distribution throughout the maturation process and across all ethnic groups. Moreover, additional studies are needed to examine 1) the relationship between body fat and fat distribution and health risk in children of different ethnic backgrounds, and 2) how this risk changes through maturation and the lifespan. In addition, there is a need for studies aimed at understanding the factors contributing to variation in body fat and fat distribution during the growth process.

Energy Expenditure and Substrate Use

The double-labeled water technique has provided the long-sought-after means for measuring total energy expenditure under free-living conditions. However, the technique is expensive and limited to specialized research facilities. Thus, there is a need to develop prediction equations with biomarkers (eg, fat-free mass, physical fitness) that can be used to estimate total energy expenditure from more simply measured variables, as is used routinely for prediction of resting metabolic rate in children from weight and gender.[90] In addition, an alternative isotopic technique with labeled bicarbonate has been described for measuring whole-body CO_2 production over periods of days or less.[91,92] This technique has not been explored widely for its potential to assess energy expenditure (and potentially physical activity); additional studies in children are warranted.

Summary Priorities for Research for Assessment of Physical Activity

The status of current techniques for assessing physical activity in children, including current research priorities, is summarized in Table 2. The development of new techniques for the assessment of physical activity is probably one of the most emergent needs that could benefit from incorporation of advanced technology. Clearly, there is a strong need for the development and testing of specific questionnaires for use in children, although given the constraints of this approach in general, the questionnaire approach may not be a suitable approach for assessing physical activity in children. The accuracy of any new questionnaire will always be limited by the ability of the subject (or the ability of his or her parents) to recall information accurately and without bias. Thus, as suggested previously by Baranowski,[69] additional improvements in questionnaire accuracy depend on greater understanding of the processing of information retrieval from memory. Therefore, in-

TABLE 1. Summary of Body Composition Techniques in Children

Method	Advantages	Limitations	Research Needs
Densitometry	Direct measure of total body density	Two-compartment model of fat and fat-free mass; underwater weight may not be practical; expensive equipment ($30 000); research based	Use of air displacement; determine variability in density of fat-free mass
DXA	Quick and simple; separates bone tissue; data on fat distribution; accuracy versus known standards has been established	Different machines and software for different subjects; expensive equipment ($70 000); research based	Undetermined
Skinfolds and anthropometry	Quick and simple; inexpensive; useful for large studies; information on fat pattern	Need different equations to transform data to body composition	Development and cross-validation of equations for different ethnic groups and states of maturation
Bioelectrical resistance	Quick and simple; inexpensive; useful for large studies	Estimates body water, so need to have information on hydration of fat-free mass	Use of multifrequency resistance; development and cross-validation of equations for different ethnic groups
CT/MRI scanning	Measures tissue area in specific anatomic locations	CT involves radiation; expensive and limited availability; research based	Verify representative anatomic sites; develop alternative prediction equations to avoid use of expensive equipment

TABLE 2. Summary of Methods for Assessment of Physical Activity in Children

Technique	Advantages	Limitations	Research Needs
Double-labeled water	Free-living; unobtrusive; includes all nonresting energy expenditure; long-term (14 days)	No information on activity pattern or acute periods of activity; expensive; limited to measurement of energy expenditure; research based	Development of alternative prediction equations to avoid use of expensive isotopes and provide availability to large scale studies
Questionnaires	Cheap; useful for large-scale studies	Behavioral bias; relies on memory and recall; conversion to energy use	Calibration against energy expenditure; energy costs of different activities; define activity inventories in different groups; methods for converting qualitative information to energy expenditure
Heart rate	Small and inexpensive; assesses patterns; validated against double-labeled water	Factors other than activity affect heart rate; invasive and obtrusive; potential for subjects to tamper with a mechanical device; not useful for very large studies; potential for behavioral bias	Assessment of optimal collection period
Accelerometry	Small and cheap; assesses patterns; triaxial accelerometry measures movement in three planes	Invasive and obtrusive; potential for subjects to tamper with a mechanical device; not useful for very large studies; behavioral bias	Calibration of counts against caloric cost for different activities; assessment of optimal collection period; calibration and validation of triaxial accelerometry in children

terview instruments should incorporate cognitive contextual cues to assist in the recollection of accurate information. In addition, because of the complex nature of physical activity, new techniques should provide information on quantitative as well as qualitative aspects.

Validation of existing technology such as three-dimensional accelerometry in children under a variety of conditions is also warranted. Such studies rely greatly on assessing duration, type, energy cost, efficiency, and intensity of habitual free-living activity as well as specific activities performed routinely by children. Laboratory measures of fitness and economy should be examined for their capability of predicting free-living habitual activity. Alternative noninvasive measures of muscle function and metabolism can be examined for their potential in predicting habitual physical activity. In addition, assessment of physical activity should consider the strong likelihood of intraindividual variation[93] because of seasonal fluctuations, behavior factors, and the highly volitional nature of physical activity. Therefore, it is important to identify the optimal period and timing of data collection.

Food Intake

The status of current techniques for assessing physical activity in children, including current research priorities, is summarized in Table 3. Current methodology is severely lacking in sophistication, which compromises the impact of current research with respect to food intake. Thus there is a great need for development of more sophisticated approaches for assessing dietary intake, including identifying biomarkers for specific nutrient consumption and incorporating a cognitive approach into questionnaires to improve recall, as described above for physical activity questionnaires. By its very nature, the use of interview techniques also leads to the potential for recall bias; additional studies with modeling and specific screening criteria need to be developed to identify erroneous data. The use of sophisticated computer and scanning technology has not been exploited widely for its potential in measuring habitual food intake.

CONCLUSIONS

Many recent developments have led to the availability of good measurement techniques for body

TABLE 3. Summary of Food Intake Methodologies in Children

Method	Advantages	Limitations	Research Needs
24-Hour recall	Can use alternative interview approaches to maximize the accuracy of subject recall; has been validated for group mean energy intake	Multiple recalls are required to overcome daily variability	Continue to improve interview techniques to maximize accuracy and diminish bias
Food-frequency and diet history	Mail-in forms can be used for large population studies	Questionnaires lack information on portion sizes for children; data are more qualitative in nature	Incorporate portion sizes into questionnaires; develop specific questionnaires for children
Weighed records	More thorough recording of information; has been validated for group mean energy intake	Invasive technique that may change habitual behavior; demanding for research subjects	Use of more sophisticated technology to record intake

composition and energy expenditure, although some additional work is required (Table 1). In addition, additional research is needed to identify a more unified approach for the assessment and interpretation of body composition and energy expenditure in children. This will provide a more useful approach for comparing and combining data. The highest priority in terms of method development is for techniques related to assessment of physical activity and food intake. The lack of strong techniques in this area is severely limiting research progress into the causes, treatment, and prevention of childhood obesity. Direct observation approaches appear to offer a strong possibility for overcoming measurement issues, particularly in younger children, for whom the chances of behavioral bias might be reduced. Because of the complex and heterogeneous nature of dietary intake and physical activity, it is important to examine the individual components. For example, for dietary intake, the individual components of interest include frequency of consumption, availability, portion size, specific food type and pattern of intake, and macronutrient composition. For physical activity, the individual components of interest include type of activity, duration, frequency, intensity, and efficiency.

The development and assessment of new methodology also should consider whether the techniques have the necessary precision. Current body composition and energy expenditure techniques have a precision of ~5% to 10% in children,[20,21,49,50,93] whereas current techniques for assessment of physical activity and food intake might have a considerably poorer precision. Some techniques might be limited in their application to population assessment and may not have adequate resolution for individual measures. In view of the fact that the development of obesity over time represents the end result of an energy imbalance of 2% of daily energy flux (assuming that the process of obesity development occurs gradually over time),[94] existing techniques might not have adequate resolution to pinpoint the important etiologic factors.

In addition to the measurement issues described above, there are a number of other areas important for the study of obesity in children. In terms of health and disease, the major reason for studying obesity in children is the long-term risk for conditions such as cardiovascular disease and noninsulin-dependent diabetes mellitus. Thus, studies of childhood obesity also should focus on the relationship with these conditions; other measurement issues related to assessment of dyslipidemia and insulin action also are important. Additional studies are needed to identify microassays to screen for lipid profile, assess insulin action, and determine cardiovascular health. These techniques should potentially be applicable in large groups for routine screening and monitoring of general health status related to obesity.

This review also has identified a number of other general issues that are important considerations in development and application of methodology for obesity research in children. These include the development of population-based normative values for the measurements described. In many cases, population-based studies have not included data collection in the pediatric population; this trend should be reversed. It is important to consider intraindividual variability in relation to the optimal data collection period. Also, from the discussion presented, it is apparent that there is a strong need to appreciate measurement issues related to ethnicity, gender, and state of maturation. The etiology of obesity is likely to involve a complex interaction of diet, metabolic, physical activity, and genetic-related factors; therefore, studies are needed that incorporate a combination of sophisticated techniques that can address these issues. Alternative modeling techniques are required to separate interacting and covarying effects of the aforementioned factors.

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REFERENCES

1. Wang Z-M, Pierson RN Jr, Heymsfield SB. The five-level model: a new approach to organizing body-composition research. *Am J Clin Nutr.* 1992;56:19–28
2. Slaughter MH, Lohman TG, Boileau RA, et al. Influence of maturation on relationship of skinfolds to body density: a cross-sectional study. *Hum Biol.* 1984;56:681–689
3. Lohman TG. Applicability of body composition techniques and constants for children and youths. *Exercise Sports Sci Rev.* 1986;14:325–357
4. Goran MI, Kaskoun MC, Carpenter WH, Poehlman ET, Ravussin E, Fontvieille AM. Estimating body composition in young children using bioelectrical resistance. *J Appl Physiol.* 1993;75:1776–1780
5. Pietrobelli A, Formica C, Wang Z, Heymsfield SB. Dual-energy x-ray absorptiometry body composition model: a review of physical concepts. *Am J Physiol.* 1996;34:E941–E951
6. Fiorotto ML, Cochran WJ, Funk RC, Sheng H, Klish WJ. Total body electrical conductivity measurements: effects of body composition and geometry. *Am J Physiol.* 1987;252:R794–R800
7. Fomon SJ, Haschke F, Ziegler EE, Nelson SE. Body composition of reference children from birth to age 10 years. *Am J Clin Nutr.* 1982;35:1169–1175
8. Schaefer F, Georgi M, Zieger A, Scharer K. Usefulness of bioelectric impedance and skinfold measurements in predicting fat-free mass derived from total body potassium in children. *Pediatr Res.* 1994;35:617–624
9. Siri WE. Body composition from fluid spaces and density: analysis of methods. In: Brozek J, Henschel A, eds. *Techniques for Measuring Body Composition.* Washington, DC: National Academy Press; 1961:223–244
10. Dempster P, Aitkens S. A new air displacement method for the determination of human body composition. *Med Sci Sports Exercise.* 1995;27:1692–1697
11. Fidanza F, Keys A, Anderson JT. Density of body fat in man and other animals. *J Appl Physiol.* 1953;6:252–256
12. Mazess RB, Barden HS, Bisek JP, Hanson J. Dual-energy x-ray absorptiometry for total-body and regional bone-mineral and soft-tissue composition. *Am J Clin Nutr.* 1990;51:1106–1112
13. Johansson AG, Forslund A, Sjödin A, Mallmin H, Hambraeus L, Ljunghall S. Determination of body composition—a comparison of dual-energy x-ray absorptiometry and hydrodensitometry. *Am J Clin Nutr.* 1993;57:323–326
14. Svendsen OL, Hassager C, Bergmann I, Christiansen C. Measurement of abdominal and intra-abdominal fat in postmenopausal women by dual energy x-ray absorptiometry and anthropometry: comparison with computerized tomography. *Int J Obes.* 1993;17:45–51
15. Van Loan MD, Mayclin PL. Body composition assessment: dual-energy x-ray absorptiometry (DEXA) compared to reference methods. *Eur J Clin Nutr.* 1992;46:125–130
16. Pritchard JE, Nowson CA, Strauss BJ, Carlson JS, Kaymakci B, Wark JD. Evaluation of dual energy x-ray absorptiometry as a method of measurement of body fat. *Eur J Clin Nutr.* 1992;47:216–228
17. Svendsen OL, Haarbo J, Hassager C, Christiansen C. Accuracy of measurements of body composition by dual energy x-ray absorptiometry in

vivo. *Am J Clin Nutr.* 1993;57:605–608

18. Ellis KJ, Shypailo RJ, Pratt JA, Pond WG. Accuracy of dual-energy x-ray absorptiometry for body-composition measurements in children. *Am J Clin Nutr.* 1994;60:660–665
19. Brunton JA, Bayley HS, Atkinson SA. Validation and application of dual energy x-ray absorptiometry to measure bone mass and body composition in small infants. *Am J Clin Nutr.* 1993;58:839–845
20. Pintauro S, Nagy TR, Duthie C, Goran MI. Cross-calibration of fat and lean measurements by dual energy x-ray absorptiometry to pig carcass analysis in the pediatric body weight range. *Am J Clin Nutr.* 1996;63:293–299
21. Goran MI, Driscoll P, Johnson R, Nagy TR, Hunter GR. Cross-calibration of body composition techniques against dual-energy x-ray absorptiometry in young children. *Am J Clin Nutr.* 1996;63:299–305
22. Janz KF, Nielson DH, Cassady SL, Cook JS, Wu YT, Hansen JR. Cross-validation of the Slaughter skinfold equations for children and adolescents. *Med Sci Sports Exercise.* 1993;25:1070–1076
23. Goran MI, Khaled MA. Cross-validation of fat-free estimated from body density against bioelectrical resistance: effects of obesity and gender. *Obes Res.* 1995;3:531–541
24. Caan B, Armstrong MA, Selby JV, et al. Changes in measurements of body fat distribution accompanying weight change. *Int J Obes.* 1994;18:397–404
25. Lohman TG, Roche AF, Martorell R. *Anthropometric Standardization Reference Manual.* Champaign, IL: Human Kinetics; 1988
26. National Institutes of Health. Bioelectrical impedance analysis in body composition measurement. National Institutes of Health Technology Assessment Conference Statement, 1995
27. Deurenberg P, van der Kooy K, Paling A, Withagen P. Assessment of body composition in 8–11 year old children by bioelectrical impedance. *Eur J Clin Nutr.* 1989;43:623–629
28. Deurenberg P, Kusters CSL, Smit HE. Assessment of body composition by bioelectrical impedance in children and young adults is strongly age-dependent. *Eur J Clin Nutr.* 1990;44:261–268
29. Kushner RF, Schoeller DA, Fjeld CR, Danford L. Is the impedance index (ht^2/R) significant in predicting total body water. *Am J Clin Nutr.* 1992;56:835–839
30. Houtkooper LB, Going SB, Lohman TG, Roche AF, Van Loan M. Bioelectrical impedance estimation of fat-free body mass in children and youth: a cross-validation study. *J Appl Physiol.* 1992;72:366–373
31. Pace N, Rathburn EN. Studies on body composition. III. The body water and chemically combined nitrogen content in relation to fat content. *J Biol Chem.* 1945;158:685–691
32. Bjorntorp P. Abdominal fat distribution and disease: an overview of epidemiological data. *Ann Med.* 1992;24:15–18
33. Bjorntorp P. Abdominal fat distribution and the metabolic syndrome. *J Cardiovasc Pharmacol.* 1992;20(suppl 8):526–528
34. Goran MI, Kaskoun MC, Shuman WP. Intra-abdominal adipose tissue in young children. *Int J Obes.* 1995;19:279–283
35. Fox K, Peters D, Armstrong N, Sharpe P, Bell M. Abdominal fat deposition in 11-year-old children. *Int J Obes.* 1993;17:11–16
36. Lemieux S, Prud'homme D, Bouchard C, Tremblay A, Després J-P. Sex differences in the relation of visceral adipose tissue accumulation to total body fatness. *Am J Clin Nutr.* 1993;58:463–467
37. Brambilla P, Manzoni P, Sironi S, et al. Peripheral and abdominal adiposity in childhood obesity. *Int J Obes.* 1994;18:795–800
38. Caprio S, Hyman LD, Limb C, et al. Central adiposity and its metabolic correlates in obese adolescent girls. *Am J Physiol.* 1995;269:E118–E126
39. Caprio S, Hyman LD, McCarthy S, Lange R, Bronson M, Tamborlane WV. Fat distribution and cardiovascular risk factors in obese adolescent girls: importance of the intraabdominal fat depot. *Am J Clin Nutr.* 1996;64:12–17
40. de Ridder CM, de Boer RW, Seidell JC, et al. Body fat distribution in pubertal girls quantified by magnetic resonance imaging. *Int J Obes.* 1992;16:443–449
41. Goran MI, Nagy TR, Treuth MT, et al. Visceral fat in Caucasian and African-American pre-pubertal children. *Am J Clin Nutr.* 1997;65:1703–1708
42. Conway JM, Yanovski SZ, Avila NA, Hubbard VS. Visceral adipose tissue differences in black and white women. *Am J Clin Nutr.* 1995;61:765–771
43. Greaves KA, Puhl J, Baranowski T, Gruben D, Seale D. Ethnic differences in anthropometric characteristics of young children and their parents. *Hum Biol.* 1989;61:459–477
44. Goran MI, Kaskoun MC, Martinez C, Kelly B, Carpenter WH, Hood VL. Energy expenditure and body fat distribution in Mohawk Indian children. *Pediatrics.* 1995;95:89–95
45. Treuth MS, Hunter GR, Kekes-Szabo T. Estimating intra-abdominal adipose tissue by dual energy X-ray absorptiometry. *Am J Clin Nutr.* 1995;62:527–531
46. Schoeller DA, Fjeld CR. Human energy metabolism: what have we learned from the doubly labeled water method. *Annu Rev Nutr.* 1991;11:355–373
47. Goran MI, Poehlman ET, Johnson RK. Energy requirements across the life span: new findings based on measurement of total energy expenditure with doubly labeled water. *Nutr Res.* 1995;15:115–150
48. Berke EM, Gardner AW, Goran MI, Poehlman ET. Resting metabolic rate and the influence of the pretesting environment. *Am J Clin Nutr.* 1992;55:626–629
49. Figueroa-Colon R, Franklin FA, Goran MI, Lee JY, Weinsier RL. Reproducibility of measurement of resting energy expenditure in prepubertal girls. *Am J Clin Nutr.* 1996;64:533–539
50. Goran MI, Nagy TR. Effect of the pre-testing environment on measurement of metabolic rate in children. *Int J Obes.* 1996;20:83–87
51. Lifson N, Gordon GB, McClintock R. Measurement of total carbon dioxide production by means of $D_2{}^{18}O$. *J Appl Physiol.* 1955;7:704–710
52. Lifson N, Little WS, Levitt DG, Henderson RM. $D_2{}^{18}O$ (deuterium oxide) method for CO_2 output in small mammals and economic feasibility in man. *J Appl Physiol.* 1975;39:657–664
53. Schoeller DA, van Santen E. Measurement of energy expenditure in humans by doubly labeled water method. *J Appl Physiol.* 1982;53:955–959
54. Schoeller DA, Ravussin E, Schutz Y, Acheson KJ, Baertschi P, Jequier E. Energy expenditure by doubly labeled water: validation in humans and proposed calculation. *Am J Physiol.* 1986;250:R823–R830
55. Speakman JR, Nair KS, Goran MI. Revised equations for calculating CO_2 production from doubly labeled water in humans. *Am J Physiol.* 1993;264:E912–E917
56. Goran MI. Application of the doubly labeled water technique for studying total energy expenditure in young children: a review. *Pediatr Exercise Sci.* 1994;6:11–30
57. Schoeller DA, Taylor PB. Precision of the doubly labelled water method using the two-point calculation. *Hum Nutr Clin Nutr.* 1987;41C:215–223
58. Goran MI, Beer WH, Poehlman ET, Wolfe RR, Young VR. Variation in total energy expenditure in young, healthy free living men. *Metabolism.* 1993;42:487–496
59. Goran MI, Poehlman ET, Danforth EJ. Experimental reliability of the doubly labeled water technique. *Am J Physiol.* 1994;266:E510–E515
60. Freedson PS. Electronic motion sensors and heart rate as measures of physical activity in children. *J School Health.* 1991;61:220–223
61. Saris WH. Habitual physical activity in children: methodology and findings in health and disease. *Med Sci Sports Exercise.* 1986;18:253–263
62. Montoye HJ, Kemper HCG, Saris WHM, Washburn RA. *Measuring Physical Activity and Energy Expenditure*. Champaign, IL: Human Kinetics; 1996
63. Livingstone MBE, Coward WA, Prentice AM, et al. Daily energy expenditure in free-living children: comparison of heart-rate monitoring with the doubly labeled water (${}^2H_2{}^{18}O$) method. *Am J Clin Nutr.* 1992;56:343–352
64. Fontvieille AM, Kriska AM, Ravussin E. Decreased physical activity in Pima Indian compared to Caucasian children. *Int J Obes.* 1993;17:445–452
65. Goran MI, Carpenter WH, McGloin A, Johnson R, Hardin M, Weinsier RL. Energy expenditure in children of lean and obese parents. *Am J Physiol.* 1995;268:E917–E924
66. Bailey RC, Olson J, Pepper SL, Porszasz J, Barstow TJ, Cooper DM. The level and tempo of children's physical activities: an observational study. *Med Sci Sports Exercise.* 1995;27:1033–1041
67. Gilliam TB, Freedson PS, Geenen DL, Shahrary B. Physical activity patterns determined by heart rate monitoring in 6–7 year-old children. *Med Sci Sports Exercise.* 1981;13:65–67
68. Crocker L, Algina J. *Introduction to Classical and Modern Test Theory*. Fort Worth, TX: Harcourt Brace Jovanovich College Publishers; 1986
69. Baranowski T. Validity and reliability of self report measures of physical activity: an information-processing perspective. *Res Q Exercise Sport.* 1988;59:314–327
70. Saris WCM, Doesburg WH, Lemmens WAJG, Reingis A. Habitual physical activity in children: results of a questionnaire and movement counters. 1974;III79–III92. Abstract
71. Kriska AM, Knowler WC, LaPorte RE, et al. Development of questionnaire to examine relationship of physical activity and diabetes in Pima Indians. *Diabetes Care.* 1990;13:401–411
72. Kemper HCG. *The Amsterdam Growth Study: A Longitudinal Analysis of Health, Fitness and Lifestyle*. Champaign, IL: Human Kinetics; 1997
73. Goran MI, Hunter G, Nagy TR, Johnson R. Physical activity related

energy expenditure and fat mass in young children. *Int J Obes.* 1997;21: 171–178

74. Bullen BA, Reed RB, Mayer J. Physical activity of obese and nonobese adolescent girls appraised by motion picture sampling. *Am J Clin Nutr.* 1964;14:211–223
75. Puhl JS, Greaves K, Baranowski T, Gruben D, Seale D. Descriptions and calibration of a children's activity rating scale (CARS). *Res Q Exercise Sport.* 1990;61:459–477
76. Durant RH, Baranowski T, Puhl J, et al. Evaluation of the children's activity rating scale (CARS) in young children. *Med Sci Sports Exercise.* 1993;25:1415–1421
77. Melanson EL Jr, Freedson PS. Validity of the Computer Science and Applications, Inc (CSA) activity monitor. *Med Sci Sports Exercise.* 1995; 27:934–940
78. Bouten CVC, Westertrep KR, Verduin M, Janssen JD. Assessment of energy expenditure for physical activity using a triaxial accelerometer. *Med Sci Sports Exercise.* 1994;26:1516–1523
79. Matthews CE, Freedson PS. Field trial of a three-dimensional activity monitor: comparison with self report. *Med Sci Sports Exercise.* 1995;27: 1071–1078
80. Dietz WH, Gortmaker SL. Do we fatten our children at the television set? Obesity and television viewing in children and adolescents. *Pediatrics.* 1985;75:807–812
81. Baranowski T, Sprague D, Baranowski JH, Harrison JA. Accuracy of maternal dietary recall for preschool children. *J Am Diet Assoc.* 1991;91: 669–674
82. Schoeller DA, Bandini LG, Dietz WH. Inaccuracies in self-reported intake identified by comparison with the doubly labelled water method. *Can J Physiol Pharmacol.* 1990;68:941–949
83. Kaskoun MC, Johnson R, Goran MI. Comparison of energy intake by food frequency questionnaire with total energy expenditure by doubly labeled water in young children. *Am J Clin Nutr.* 1994;60:43–47
84. Johnson RK, Driscoll P, Goran MI. Cross-calibration of energy intake by 24-hour recall against total energy expenditure by doubly labeled water in young children. *J Am Diet Assoc.* 1996;96:1140–1144
85. Livingstone MBE, Prentice AM, Coward WA, et al. Validation of estimates of energy intake by weighed dietary record and diet history in children and adolescents. *Am J Clin Nutr.* 1992;56:29–35
86. Treiber FA, Leonard SB, Frank G, et al. Dietary assessment instruments for preschool children: reliability of parental responses to the 24-hour recall and food frequency questionnaire. *J Am Diet Assoc.* 1990;90: 814–820
87. Flegal KM, Larkin FA. Partitioning macronutrient intake estimates from a food frequency questionnaire. *Am J Epidemiol.* 1990;131:1046–1058
88. Block G, Thompson FE, Hartman AM, Larkin FA, Guire KE. Comparison of two dietary questionnaires validated against multiple dietary records collected during a 1-year period. *J Am Diet Assoc.* 1992;92: 686–693
89. Nelson M, Black AE, Morris JA, Cole TJ. Between- and within-subject variation in nutrient intake from infancy to old age: estimating the number of days required to rank dietary intakes with desired precision. *Am J Clin Nutr.* 1989;50:155–167
90. World Health Organization. *World Health Organization, Technical Report Series, Number 724. Energy and Protein Requirements.* Geneva, Switzerland: World Health Organization; 1985
91. Elia M, Fuller NJ, Murgatroyd PR. Measurement of bicarbonate turnover in humans: applicability to estimation of energy expenditure. *Am J Physiol.* 1992;263:E676–E687
92. Saccomani MP, Bonadonna RC, Caveggion E, DeFronzo RA, Cobelli C. Bicarbonate kinetics in humans: identification and validation of a three-compartment model. *Am J Physiol.* 1995;269:E183–E192
93. Goran MI. Variation in total energy expenditure in humans. *Obes Res.* 1995;3:59–66
94. Goran MI, Shewchuk R, Nagy TR, Gower BA, Carpenter WH, Johnson R. Longitudinal changes in fatness in Caucasian children of lean and obese parents: no effect of childhood energy expenditure. *Am J Clin Nutr.* In press

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Health Consequences of Obesity in Youth: Childhood Predictors of Adult Disease

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ABSTRACT. Obesity now affects one in five children in the United States. Discrimination against overweight children begins early in childhood and becomes progressively institutionalized. Because obese children tend to be taller than their nonoverweight peers, they are apt to be viewed as more mature. The inappropriate expectations that result may have an adverse effect on their socialization. Many of the cardiovascular consequences that characterize adult-onset obesity are preceded by abnormalities that begin in childhood. Hyperlipidemia, hypertension, and abnormal glucose tolerance occur with increased frequency in obese children and adolescents. The relationship of cardiovascular risk factors to visceral fat independent of total body fat remains unclear. Sleep apnea, pseudotumor cerebri, and Blount's disease represent major sources of morbidity for which rapid and sustained weight reduction is essential. Although several periods of increased risk appear in childhood, it is not clear whether obesity with onset early in childhood carries a greater risk of adult morbidity and mortality. Obesity is now the most prevalent nutritional disease of children and adolescents in the United States. Although obesity-associated morbidities occur more frequently in adults, significant consequences of obesity as well as the antecedents of adult disease occur in obese children and adolescents. In this review, I consider the adverse effects of obesity in children and adolescents and attempt to outline areas for future research. I refer to obesity as a body mass index greater than the 95th percentile for children of the same age and gender.

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ABBREVIATIONS. SES, socioeconomic status; LDL, low-density lipoprotein; NIDDM, noninsulin-dependent diabetes mellitus; BMI, body mass index; PCOD, polycystic ovary disease.

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The most widespread consequences of childhood obesity are psychosocial. Obese children become targets of early and systematic discrimination. As they mature, the effects of discrimination become more culture-bound and insidious. An important sequel of the widespread discrimination and cultural preoccupation with thinness is con-

Measurement Issues Related to Studies of Childhood Obesity: Assessment of Body Composition, Body Fat Distribution, Physical Activity, and Food Intake

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