Annu. Rev. Nutr. 1997. 17:211–35

EVALUATION OF METHODOLOGY FOR NUTRITIONAL ASSESSMENT IN CHILDREN: Anthropometry, Body Composition, and Energy Expenditure

Babette S. Zemel, Elizabeth M. Riley, and Virginia A. Stallings
Division of Gastroenterology and Nutrition, The Children's Hospital of Philadelphia, Department of Pediatrics, The University of Pennsylvania School of Medicine, Philadelphia, Pennsylvania 19104–4399; e-mail: bzemel@wal6000e.udc.upenn.edu

KEY WORDS: reference data, maturation, heredity, catch-up growth, caloric requirements

ABSTRACT

Nutritional status in children is an indicator of health and well-being at both the individual and the population level. Screening for malnutrition should be an integral part of pediatric care universally. Nutritional intervention requires repeated measurement of nutritional status to assess severity and to track progress over time. Methodological issues in the assessment of nutritional status are reviewed with emphasis on anthropometric measurement, body composition, and energy expenditure of children at risk for malnutrition. Use of reference data, measurement error, maturational effects, and hereditary factors are among the issues reviewed and serve as guidelines in the interpretation of measurement of nutritional status.

CONTENTS

0199-9885/97/0715-0211$08.00

INTRODUCTION: THE IMPORTANCE OF NUTRITION ASSESSMENT IN PEDIATRIC CLINICAL CARE AND RESEARCH

Nutritional status affects every aspect of a child's health, including normal growth and development, physical activity, and response to serious illness. The factors influencing nutritional status are very different in industrializing versus industrialized nations. Nevertheless, accurate nutritional assessment should be an integral part of pediatric care universally, and all children should be screened routinely for abnormalities of growth. Children at risk for malnutrition or who are chronically ill should have detailed nutritional assessments. In addition to promoting growth, development, and overall health, nutritional assessment has the added advantage of offering cost-preventive or cost-saving information for clinical care (2), whether through early identification of nutritional stress, through the improvement of clinical outcomes, or through the avoidance of unnecessary nutritional support (75). It is generally accepted that malnutrition negatively affects length of stay, morbidity, and mortality in adult hospitalized patients (19). In the developing world, the relationship between malnutrition, morbidity, mortality, and child development is well recognized, and the effects of intervention are an ongoing area of research (41, 83, 84). In industrialized nations, undernutrition most often occurs in association with organic disorders, chronic disease, or psycho-social disturbance, and overnutrition is becoming an increasing concern (113, 123). In both settings, the interaction between nutrition, disease, and growth, and the long-term consequences of nutritional status, are active areas of pediatric research.

PRINCIPLES OF GROWTH AND BODY-COMPOSITION ASSESSMENT

Growth in infancy, childhood, and adolescence is a consequence of increasing cell size and cell number. This is most commonly assessed by the measurement

Figure 1 From birth to 10 years, growth in the fat-free and fat components of the body occurs, resulting in changes in the relative proportions of these components. Shown here is the body composition of a typical male child. Body fat as percentage of total body weight (percent body fat) reaches a peak during infancy and declines thereafter. Adopted from Fomon et al (31).

of stature and weight. The muscle, fat, and bone compartments also undergo alterations in the absolute amounts and relative proportions of lipid, protein, water, and minerals. Changes in the amount and proportion of the fat- and fat-free mass components in a child are significant, as shown in Figure 1 for males up to age 10 years (31). The measurement of body composition during growth and development provides more detailed information about nutritional status than the measurement of stature and weight alone does because the body compartments are indicative of nutritional stores (68). For example, lean body mass is indicative of the water and protein content of the body, fat indicates energy stores, and bone is the primary site for storage of calcium and other minerals. These body-composition considerations are important in determining the appropriate mode of nutritional assessment, especially among children who may have unusual nutritional needs as a result of disease states or medical treatment.

Most methods of body-composition assessment available for use during growth and development measure whole-tissue compartments using a two-compartment (fat and fat-free mass) or three-compartment (fat, lean body mass, and bone) model. The most commonly used methods are described below.

Technical Considerations in Anthropometric Assessment of Growth and Body Composition

Anthropometric assessment is a rapid, inexpensive, and noninvasive means of determining short- and long-term nutritional status. Although the techniques

and equipment used in anthropometric assessment are relatively simple, they require precision instruments that should be checked regularly for accuracy; they also require carefully trained anthropometrists to ensure accurate, reproducible measurements. Numerous anthropometric measures are used in nutritional assessment, because no single measure can fully characterize nutritional status (28). With carefully obtained measurements and the aid of appropriate reference standards, the nutritional status of samples of subjects in a research or public health setting can be evaluated and periodic checks can be performed for tracking progress over time. In the case of the individual, these tools are used to identify those at risk for malnutrition and its sequelae, and to monitor response to therapeutic intervention (123). Standardized, detailed anthropometric methods have been published (12, 69). Only commonly encountered issues in pediatric anthropometric nutritional assessment are considered below.

WEIGHT, HEAD CIRCUMFERENCE, AND LINEAR GROWTH Weight measurements are easy to obtain and should be made frequently. Infants should be measured without diapers to the nearest 0.01 kg, and older children should be measured to the nearest 0.1 kg, wearing little or no outer clothing and no shoes. When used for research purposes, weight measurements ideally should be taken at the same time of day after the bladder has been emptied, so that children in the same physiological state are compared. When these conditions are met, weight measurements and determination of weight increments can be interpreted with confidence.

Head circumference is another important aspect of nutritional assessment in young children (93). Brain growth is most rapid in the first three years of life, so for children in this age range, head circumference should be monitored routinely. Head circumference reference data are available for children up to 18 years of age (93). Poor growth in head circumference has been observed in severely malnourished children. For children with medical conditions resulting in macrocephaly or microcephaly, head circumference cannot be used as a measure of nutritional status.

Supine length measures are taken for children younger than two to three years, and standing height or stature is measured after two years of age. For older children (older than three years) who are unable to stand erect unsupported, a supine length measurement can be taken. However, when comparing this measurement to a growth chart for stature, the length measurement should be adjusted approximately 1–2 cm (91, 123) before plotting the value on a reference chart for stature.

Proper instrumentation and positioning are key in the measurement of linear growth. For infants, an infantometer or inflexible length board with a fixed head board and moveable footboard is appropriate. Supine length measurements

require an assistant to hold the head in position while the torso and legs are positioned for measurement. For older children, a stadiometer with a head paddle that glides smoothly and is firmly perpendicular to the backboard is ideal for stature measurements. Alternatively, a tape measure permanently fixed to a wall or door frame can be used provided the feet can be placed in alignment with the back and a head paddle that will fit at a 90° angle to the wall is used. Proper positioning for both length and stature involves even placement of the feet; linear alignment of the spine; placement of the heels, buttocks, and back against the stadiometer or length board; and positioning of the head with the Frankfurt plane (an imaginary line extending from the lower margin of the orbit to the upper margin of the auditory meatus) parallel to the footboard or floor. Obese subjects who may not be able to stand with heels, buttocks, and back against the stadiometer should be positioned so that they are standing as upright as possible with their spine in alignment. A stretched height measurement (involving positioning of the spine and head to encourage the child to stand as erect as possible) in children older than five to six years gives more reproducible measurements and is preferred for tracking increments in stature.

Alternative measures of linear growth are available for subjects who are bedridden or for those with spinal curvature, contractures, or musculo-skeletal deformities for whom a length or stature measurement would be inaccurate. A z-score or percentile can be assigned to an upper-arm– or lower-leg–length measurement and used as an indicator of linear growth (126). Upper-arm length and lower-leg length are suitable alternatives to length or stature, with reference charts available for assessing nutritional status in infants and children (125).

Sliding calipers (0–200 mm)—for young infants—or a standard anthropometer (0–57 cm) is used for measuring upper-arm and lower-leg length. For newborns and babies up to 24 months old, the lower-leg–length measure consists of a heel-to-knee measurement, and the upper-arm length is measured from the elbow to the shoulder. A detailed description of the measurement technique is given in Zemel & Stallings (125). Children whose growth in upper-arm or lower-leg length is outside the range for their age and sex may have an unusual growth pattern caused by nutritional deficiency, marked growth, developmental delay, or some other pathology. In nonambulatory children, it is not uncommon for growth abnormalities in the lower-leg length to be more severe than in the upper arm relative to these reference standards (105).

CIRCUMFERENCES AND SKIN-FOLD MEASUREMENTS Soft tissues generally are more difficult to measure reliably and reproducibly and require a well-trained anthropometrist. Proper techniques are described by Lohman et al (69). Estimates of the measurement error (Table 1) should be considered when interpreting

Table 1 Technical error of measurement[a]

Age range (years)	Intra-observer technical error of measurement	Inter-observer technical error of measurement
Length (cm)		
1–2	0.4	0.5
1–2	0.8	
1.5–2.5		0.5
Height (cm)		
4–11		0.4
		0.2
6–11	0.5	
6–12	0.5	
6–13		0.7
6–14	0.2	0.2
7–9		0.1
8–18	0.5	
9–14	0.5	
12–17	0.3	
5–30	0.3	
20+	0.7	0.15 (males)
		0.3 (females)
Triceps skinfold (mm)		
Newborns	0.1	0.4
1–2	0.6	0.6
		0.8
2–7	0.5	
6–11	0.8	1.9
6–12	0.8	
6–13		1.0
6–14	0.2	0.5
7–9		0.2
8–18	0.7	
9–14	0.5	
12–17	1.6	1.9
5–30	0.4	
20–50		0.7

[a]Adapted from Ulijaszek & Lourie (114).

a single measurement and especially when evaluating changes over time in clinical, research, or public health settings. Indices of fatness and fat distribution, such as skin-fold ratios, have even lower precision than direct measurements do, because measurement errors are compounded by the calculations (77). Stylistic differences, even among well-trained anthropometrists, can develop over time, so periodic checks on intra- and inter-observer reliability are essential for longitudinal data collection.

Mid–upper-arm circumference is a composite measure of muscle, fat, and bone. It has been used as an alternative index of malnutrition in rapid nutritional surveys when weight and stature measurements were not feasible (123). When mid–upper-arm circumference is combined with the triceps skin-fold measurement, upper-arm muscle and fat stores can be estimated (33, 34), and these measures correlate well with total body measures of fat mass and fat-free mass.

The triceps skin-fold thickness is one of the most valuable anthropometric measures of nutritional status, because (*a*) it is a good indicator of energy reserves (35a); (*b*) it correlates well with total body fat stores (99a); and (*c*) excellent reference data for triceps skin-fold thickness from children one year of age through adulthood are available (33). The subscapular skin-fold thickness is a good measure of fat stores on the trunk and is less sensitive to short-term fluctuations in nutritional status (103). Fat stores at this site tend to be preserved under conditions of chronic undernutrition (7, 13, 49, 105). The combination of the triceps and subscapular skin-folds has been used for calculating the sum of skin-folds (34) for nutritional assessment, the percentage of total body fat from prediction equations (9, 26, 27, 101), and the fat patterning using the centripetal fat ratio (8, 103). Other skin-fold thickness measures (e.g. suprailiac, biceps, midaxillary) generally do not contribute significantly more information in terms of nutritional status but are useful in the prediction of total body fat and fat-free mass with anthropometric prediction equations (see Table 3 and text below).

Uses of Anthropometric Measures

USING REFERENCE DATA Reference data based on large samples of healthy children from environments with good living conditions provide an essential tool with which to evaluate nutritional status in both the clinical and the research setting (40, 123). In the clinical setting, growth charts that use the National Center for Health Statistics (NCHS) norms for most anthropometric measures (height, weight, and head circumference) are excellent for assessing nutritional status. These charts are based on data collected for the National Health and Nutrition Examination Survey (NHANES) I (1971–1974) (47). Most commonly, the percentile rank is determined from the growth chart and recorded. However, for some children, it is not possible to assign a percentile rank when their measurements are below the 5th or above the 95th percentile. The percent of the median for age and sex also is used as an indicator of nutritional status, but this measure does not account for variability in the reference population (40, 99, 123). The z-score or standard deviation score avoids these problems. It is calculated as: observed value minus median value for the reference population divided by standard deviation for age and gender. These reference population median and standard deviation values are available in table form for calculating z-scores. In the research setting, z-scores are the preferred method

of representing deviations in growth and nutritional status. The computerized Centers for Disease Control (CDC) Anthropometric Software Program (CDC, Atlanta, GA) can be used to calculate z-scores, exact percentiles, and percentage of median for height and weight for large samples and individuals (18).

Table 2 is a summary of reference data available for assessment of growth and nutritional status. Choice of a reference data set should be considered carefully, with type of measurement, sample characteristics, measurement interval (in the case of incremental growth charts), age range, and ethnicity being the key considerations. Currently, the World Health Organization (WHO) and the CDC use the NCHS growth charts (50) as the internationally accepted reference (123). Revised growth charts are currently being developed by the NCHS for all ages using data from the third National Health and Nutrition Examination Survey. Incremental growth charts for US children have been developed using a number of curve-smoothing techniques. These smoothing techniques may inaccurately estimate the true velocities that occur over smaller measurement intervals (e.g. for infants, a one-month interval for calculating growth velocity may yield different results than the three-month interval used in the development of the incremental growth charts). For this reason, it is imperative that the growth increments be evaluated during intervals of measurement that correspond to the reference data (30).

WEIGHT-FOR-HEIGHT MEASURES As noted above, there is no single anthropometric measure that provides enough information to make a full determination of nutritional status. Weight-for-age is often used to categorize overweight or underweight. However, weight is a composite measure that can reflect altered body composition as in the case of edema, excess muscle or fat, or altered body size, as occurs when stature-for-age is very large or small. Weight-for-height reference charts have been developed as a means of assessing weight while taking into account a child's length or stature. For girls below 138 cm and boys below 146 cm in stature, the NCHS provides a weight-for-height chart (47). The percentage of median weight-for-height is used in the Waterlow classification scheme of malnutrition to assess wasting (119). The body-mass index (weight/height^2) and percentage of ideal body weight are commonly used to categorize obesity. Ideal body weight is defined as the median weight at the age for which a child's height matches the median height (74). Difficulties in the use of weight-for-height ratios arise during the adolescent age range. During puberty, there are pronounced changes in body composition, with males increasing in fat-free mass and females increasing significantly in fatness (32). Consequently, for both males and females the distributions of weight for a given height are very different following the onset of puberty compared with prepubertal age ranges. For early or late-maturing children, these factors should

Table 2 Sources of reference data for growth and body composition of normal children[a]

Type	Reference	Source	Details
Stature/length	47	NCHS-HES II, III, HANES I, and Fels	Weight, stature/length, weight-for-height
Weight	34	NCHS-HANES I and II	Weight, stature/length, weight-for-height, race-specific tables
Head circumference	93	Fels, 0–18 yr	Head circ, 0–18 yr, increments, 0–6 yr
	81	270 English children, 0–7 yr	
	120	Hispanic HANES, HANES II	Whites, blacks, and Mexican Americans
Growth increments	92	Fels, 0–18 yr	Weight, head circ, length, stature Increment curves
	3	Fels, 0–18 yr	Weight, head circ, length, stature Increment tables
	44	Univ. Iowa (1142 whites), Fels (476 whites)	Weight and length
	5	Six cities study, 6532 blacks and whites, 7–18 yr	Height velocity, race-specific
	111	NCHS (see 47), London County Council longitudinal study, 2–18 yr	Height, height velocity curves for early, middle, and late maturers
Body mass index	34	HANES I and II, 1–74 yr	Race-specific
	22	HANES I, 6–50 yr	Race-specific
	48	HANES I, whites, 1–19 yr	
	52	HANES I, 10–24 yr	Weight, stature table for calculating BMI
	78	HANES I, 6–74 yr	Race-specific
	79	HANES I, 6–74 yr	Corrected table for Ref. 78
Circumferences and skin folds	22	HANES I, 6–50.9 yr	Race-specific for triceps and subscap
	57	HANES I	Arm circ, triceps, subscap, race-specific
	33	HANES I, whites, 1–74 yr	Arm circ, triceps, arm muscle area and circ, arm-fat area
	94	Hispanic HANES and HANES II, 6 mo–18 yr	Arm muscle and adipose tissue areas Whites, blacks, and Mexican Americans
Leg length, arm length	102	Mich. Highway Safety Res. Inst., 0–18 yr	Upper-arm length, lower-leg length, and other body dimensions
	125	Mich. Highway Safety Res. Inst., 0–18 yr	Reference charts for upper-arm and lower-leg length

[a]NCHS, National Center for Health Statistics; HES, Health Examination Survey; HANES, Health and Nutrition Examination Survey; Fels, Fels Longitudinal Study; circ, circumference; Subscap, subscapular; BMI, body mass index.

be taken into consideration in using the body-mass index, percent ideal body weight, or other weight-for-height measures for the assessment of nutritional status (123).

Another difficulty in the use of weight-for-height ratios is that they do not accurately distinguish between adiposity and muscularity. Children with high lean-body mass can easily be misclassified as overweight or obese. The use of a triceps skin-fold measurement in combination with body-mass index is likely to give a more accurate categorization of adiposity and has been proposed for determining the overweight among children 10 years of age and older (52).

PREDICTION EQUATIONS Whole-body measures of fat-free mass, fat mass, and percent body fat can be estimated from prediction equations that use skin-fold thickness measurements (9, 26, 27, 101). Table 3 summarizes some of these prediction equations used for children and adolescents. These prediction equations yield results that are highly correlated with results from other methods for body-composition determination. It is important that these prediction equations be used on children within the appropriate age range. Race, obesity, and

Table 3 Equations for predicting body composition from anthropometry

Two–skin-fold method for prediction of percent body fat (101)[a]	
Prepubescent white males	% body fat $= 1.21\,(T + S) - 0.008\,(T + S)^2 - 1.7$
Prepubescent black males	% body fat $= 1.21\,(T + S) - 0.008\,(T + S)^2 - 3.2$
Pubescent white males	% body fat $= 1.21\,(T + S) - 0.008\,(T + S)^2 - 3.4$
Pubescent black males	% body fat $= 1.21\,(T + S) - 0.008\,(T + S)^2 - 5.2$
Postpubescent white males	% body fat $= 1.21\,(T + S) - 0.008\,(T + S)^2 - 5.5$
Postpubescent black males	% body fat $= 1.21\,(T + S) - 0.008\,(T + S)^2 - 6.8$
All females	% body fat $= 1.33\,(T + S) - 0.013\,(T + S)^2 - 2.5$
When sum of triceps and subscapular is greater than 35 mm, use	
All males	% body fat $= 0.783\,(T + S) + 1.6$
All females	% body fat $= 0.546\,(T + S) + 9.7$
Four–skin-fold method for prediction of percent body fat[b]	
Prepubertal children (9)	
Males	Body density $= 1.1690 - 0.0788$ log sum of 4 skin folds
Females	Body density $= 1.2063 - 0.0999$ log sum of 4 skin folds
	Percent body fat $= ([4.95/\text{body density}] - 4.5)\,100$
Adolescents (26)	
Males	Body density $= 1.1533 - 0.0643$ log sum of 4 skin folds
Females	Body density $= 1.1369 - 0.0598$ log sum of 4 skin folds
	Percent body fat $= ([4.95/\text{body density}] - 4.5)\,100$

[a]T, Triceps; S, subscapular.

[b]Sum of four skin folds equals triceps plus biceps plus subscapular plus suprailiac.

puberty status are factors that have been included in some prediction equations. The standard error of the estimate reported for some of these prediction equations (26, 101) for percentage of body fat is approximately 3.5%. Therefore, the predicted values for total body fat and fat-free mass are more applicable for evaluating groups of children than individuals. Adequate reference data for fat-free mass, fat mass, and percent body fat are not available for children.

Other Methods of Body-Composition Assessment

Other methods for determining total body water (TBW), fat-free mass, lean body mass, bone mass, and fat mass are available for the research and, in some cases, the clinical setting. These include isotope dilution methods, bioelectrical methods, and bone densitometry.

ISOTOPE DILUTION METHODS Stable isotopes use the classic dilution principle to estimate the size of various compartments of the body. Deuterium oxide (^2H_2O) or oxygen-18 (^{18}O) are naturally occurring stable isotopes used in the research setting to safely and effectively measure the size of the TBW in infants and children (97). Following determination of baseline levels of ^2H_2O or ^{18}O, a concentrated dose of isotope is administered orally. After an equilibration period of several hours, the concentration of the isotope is determined in a body fluid such as urine, blood, or saliva. The ideal time for sampling to determine TBW depends on the physiologic fluid being analyzed (95a). The size of the TBW is extrapolated according to the dilution principle, using the size of the dose and the isotopic concentrations of the physiologic fluid at baseline and at equilibrium. The stable isotopes of ^2H_2O and ^{18}O will overestimate TBW unless corrected by 4% and 1%, respectively, as a result of the mixing of these isotopes with nonaqueous fractions of the body. TBW measurements can be used to estimate fat-free mass using age-appropriate hydration factors (31), which estimate the fraction of the TBW in fat-free mass. Fat mass and percent body fat can be calculated once the fat-free mass is determined. Sodium bromide can be used in a similar manner to estimate the extracellular water compartment (114a) so that the distribution of TBW in the intra- and extracellular water compartments can be determined.

BIOELECTRICAL METHODS The water and electrolytes in the body have electrical properties that can be measured for estimation of TBW or fat-free mass. Pediatric and adult devices that measure total body electrical conductivity (TOBEC, EM-Scan, Springfield, IL) are available and provide accurate, rapid, non-invasive estimates of fat-free mass, fat mass, and percentage body fat. The subject passes through a low-energy electromagnetic coil, causing alterations in the conductance in the coil. The measured change in the electrical signal is proportional to the total body electrolyte content, a large component of the

highly conductive fat-free mass and a minimal component of the poorly conductive fat mass. This measurement then is converted to body composition estimates by computerized prediction equations developed for this methodology (29, 115, 116). Several reference methods of body composition determination were used to derive these prediction equations, including hydrodensitometry, isotope dilution, and potassium-40 and chemical analysis of infant miniature pigs (8a).

Bioelectrical impedance analyzers are another class of devices now available from several manufacturers. They measure the impedance of a low-energy electrical signal as it passes through the body, which is proportional to the length of the conductor (a function of height) and inversely proportional to the cross-sectional area (volume). As with the TOBEC device, this method uses a calibration equation to convert the resistance signal to estimates of body composition. Prediction equations based on hydrodensitometry and isotope dilution reference methods have been devised and tested for children and adolescents (39, 56, 64).

ABSORPTIOMETRY METHODS Dual photon absorptiometry (DPA) and dual-energy X-ray absorptiometry (DXA) are techniques that measure three compartments of the body: bone mass, lean body mass, and fat mass. Because of their varying densities, bone, lean tissue, and fat attenuate the energy beams differentially. By using dual energy beams, it is possible to solve for three tissue compartments (85). DXA is becoming increasingly available for clinical and research use and provides more accurate measurements than DPA does. The radiation exposure of DXA is extremely low (0.3 mrad), and whole-body estimates of body composition for infants, children, and adolescents can be obtained in fewer than five minutes. In addition, since bone-mineral density is one of the sources of variability that contributes to errors in estimating the density of fat-free mass, measurement of bone mineral improves the accuracy in estimating fat-free mass in a two-compartment model (38, 45, 117). Compared with the bioelectrical and anthropometric methods of body-composition assessment described above, DXA has the added advantage of being independent of sample-based prediction equations.

CONSIDERATIONS IN THE USE OF GROWTH AND BODY-COMPOSITION MEASUREMENTS TO ASSESS NUTRITIONAL STATUS

The Population Versus the Individual

The interpretation of growth and body-composition data for assessment of nutritional status depends, in part, on whether an individual child or a group of

children is being evaluated. Childhood growth is an excellent indicator of the overall health status of a community, because the pediatric and geriatric age ranges are more sensitive to fluctuations in infectious disease and nutritional deprivation (40). In addition, health surveys that use growth data provide an estimate of the prevalence of malnutrition by applying a criterion such as minus two standard deviations below the median height-for-age. However, in a population with a high prevalence of growth failure or malnutrition, it is likely that all children, including those with anthropometric values above the cut-off for malnutrition, are affected and are not attaining the growth status they would have attained under more ideal circumstances (61, 123).

For individual children, any underlying medical condition and other circumstances often need to be considered in interpreting the clinical significance of growth and body-composition measurements. For children with serious medical conditions and a high risk of malnutrition due to the primary disease, treatment, oral-motor problems, or altered dietary intake and physical activity, the criteria for malnutrition screening at the population level, such as the Waterlow (119) criteria, may be too low for use in clinical practice. In the chronic disease setting, there may be a far more significant health risk to postponing nutritional intervention until that criterion is reached. In addition, there are numerous reasons, some of which are described below, why an individual's growth is at a particular percentile on the reference charts. A primary consideration is that there is variability in growth and body composition in children from all populations. For example, 5% of healthy children are below the NCHS 5th percentile for stature, so a single measurement of an individual's stature is not sufficient to determine whether this represents failure-to-thrive or normal growth and nutritional status in a healthy short child (123). Incremental growth, supplemental health information, and mid–parental- or sibling-height status are necessary for clinical interpretations of growth for determining nutritional status.

Another consideration in interpreting growth and body composition in individuals is the error of measurement of a single measurement or of growth velocities involving two measurements, or in the case of anthropometric prediction equations the prediction error. In large-sample studies, the certainty of a mean value increases as the sample size increases, thereby reducing the effect of measurement error on the estimate. For an individual, the measurement error of a single measurement may be as large as the difference between percentile ranks. For example, the intra-individual technical error of measurement for children 6–11 years old for a triceps skin-fold measurement is 0.8 mm, and the inter-individual measurement error is 1.9 mm (see Table 1). The difference between the 5th, 10th, and 25th percentiles in this age range is usually 1 mm for both males and females (33).

Normal Versus Optimal Growth

Among the primary applications of assessment of nutritional status is the use of this information to assure that the genetic potential for growth is attained and to minimize health risks associated with malnutrition, both overnutrition and undernutrition. However, both concepts, genetic potential for growth and minimization of health risk, are poorly defined theoretical constructs and are difficult to implement at the current stage of scientific knowledge. Given the multigenic control of growth in height and body composition, there is no operational definition of "the genetic potential for growth." The use of mid-parental height for adjustment of height measurements (see below) is only an approximation of the genetic potential for growth because it assumes that children will grow like their parents. Optimal growth cannot be defined on the basis of the current WHO/CDC reference data, because they are based on large numbers of children measured cross sectionally. Therefore, these reference data cannot be used to evaluate an individual's longitudinal growth pattern as optimal or suboptimal, nor can they be used to distinguish between normal variability and a mild pathological problem. An additional problem is that maximal growth is not necessarily equivalent to optimal growth, especially given the increasing problem of obesity in both developing and developed countries. In increasing numbers, research efforts are focusing on the long-term health consequences of growth and body composition on disease severity and progression during childhood and on health and longevity in adulthood, particularly with respect to obesity, osteoporosis, and cardiovascular disease. These efforts will help refine our understanding of normal versus optimal growth.

Short- Versus Long-Term Growth

Infancy and adolescence are periods of extremely rapid growth. Careful examination of growth in these age ranges indicates that the growth occurs in spurts or short bursts of rapid growth followed by periods of stasis (65). Even during periods of slower growth, such as mid-childhood, growth spurts occur (110). Small growth spurts can be difficult to detect because of the measurement error issues discussed above. Detection requires short measurement intervals (days or weeks depending on the age of the subjects and goals of measurement), precision instruments, and careful, consistent measurement techniques. Seasonal fluctuations in growth velocity also occur (66, 71), with growth velocity being greatest in the spring and lowest in the winter. The interval between measurements, such as 3, 6, or 12 months, should be comparable to that used in the development of the reference percentiles. Differences in the time interval can lead to over- or underestimation of the true growth rate relative to the reference percentiles (30).

For research purposes, several tools are available for assessment of short-term growth. These include the knee-height measuring device and the kneemometer, both of which measure short-term growth in the length of the lower leg (23, 51). A similar device has been developed for ulnar length measures (16). The technical errors of measurement for these devices are very small, so that small increases in length can be attributed to growth rather than to measurement error. The measurement error for height is sufficiently large (approximately 0.5 cm) that an interval of at least six months is recommended to be assured of measurable growth in children and adolescents.

Heredity Versus Environment

The goal of growth and body-composition evaluation for the purposes of nutritional assessment is to identify the child at risk of morbidity and mortality due to inadequate nutrition. In theory, this requires partitioning the factors that influence growth and body composition into those that are environmental—due to dietary intake, physical activity, disease state, or social factors—and those that are heritable and resistant to nutritional intervention. Twin studies and parent-child correlation analyses show that the heritability of stature is greater during adolescence than in childhood (35, 50, 58, 72).

Unfortunately, the tools available for adjusting for the heritable component of growth are limited. Among children under five years of age, those who are well-off from different ethnic groups are more similar in growth than are those from the same ethnic group of different socioeconomic backgrounds (46). Accordingly, both the CDC and the WHO promote the use of a single growth-reference set (47, 123) that applies to all ethnic groups. In the United States, charts have been developed for adjustment for mid-parental height up to age 18 to account, in part, for the heritability of length and stature (53). However, these charts are based on parents and children enrolled in the Fels Longitudinal Study, consisting of predominantly white, middle-class families from Ohio. Whether or not these adjustments are appropriate for children of other ethnic groups remains to be determined.

Ethnic differences in body composition have been noted and appear to have a heritable component. For example, people of African ancestry have greater bone density than do those of European ancestry (4, 67), and people of Asian ancestry have lower bone density than do both groups (124). Differences in body density among black versus white people have been reported (100), although these may be due to the known differences in bone density. Minor ethnic differences in body-mass index and skin-fold thicknesses also have been noted for Americans of white races versus those of black races, and race-specific reference tables have been published (22, 34, 100).

Table 4 Equations for predicting basal metabolic rate[a] in children

Age range (yr)	Males	Females
From weight (kg)[b]		
<3	60.9W − 54	61.0W − 51
3–10	22.7W + 495	22.5W + 499
10–18	17.5W + 651	12.2W + 746
From weight (kg) and height (cm)[c]		
<3	0.167W + 15.174H − 617.6	16.252W + 1.0232H − 413.5
3–10	19.59W + 1.303H + 414.9	16.969W + 1.618H + 371.2
10–18	16.25W + 1.372H + 515.5	8.365W + 4.65H + 200.0

[a]In kilocalories.
[b]From Reference 122.
[c]From Reference 98.

Compensatory (Catch-up) Growth

Children who experience impaired growth as a result of illness or deficiency states, including hormone deficiencies and nutritional deprivation, have been known to undergo a period of increased growth velocity known as catch-up or compensatory growth once the source of impairment has been corrected (109). For example, apparently well children with mild impairment of growth responded to zinc supplementation with increased rates of growth (37). However, the understanding of compensatory growth is limited. Impairments that occur for long periods or in older children are less likely to be fully compensated following treatment than if they were to occur in children younger than two years of age (40, 123). One possible explanation comes from a study of undernourished Guatemalan children showing that degree of stunting was greater than the degree of retardation in skeletal development was (73), which suggests that nutritional stunting is only partly reversible. Thus, for children older than five years, small stature can be more a reflection of previous nutritional deprivation than of current nutritional status (123).

Sexual and Skeletal Maturation

The hormonal changes of puberty have a significant effect on growth, body composition, and skeletal maturation. Altered pubertal development may be due to an underlying medical condition or to nutritional factors. Malnutrition, both overnutrition and undernutrition, affects sexual and skeletal maturation. Particularly during the years approaching and including the adolescent age range, skeletal and pubertal maturation should be assessed. Obese children are more likely to be early maturers, experiencing an earlier onset of pubertal development and more rapid skeletal maturation than normal weight children do

(36), whereas chronic undernutrition can delay skeletal maturation and the onset and duration of puberty (14, 15). Therefore, determination of puberty status is a vital component of the assessment of nutritional status. Determination of sexual maturity is based on the Tanner system for growth of pubic hair in both sexes, breast development in females, and genital development in males (108). Age at menarche is also noted for females. Age at entry into Tanner stages is used to classify children as early or late maturers for purposes of assessing growth velocities during adolescence (111). For large-sample research studies, a self-assessment instrument has been devised using pictographs of Tanner's puberty stages (76). Interpretation of other measures of growth and body composition should be sensitive to maturity status during the adolescent years.

ESTIMATING CALORIC REQUIREMENTS IN PEDIATRIC RESEARCH AND CLINICAL PRACTICE

Energy imbalance results in the clinical pathologies of undernutrition and overnutrition. The assessment of true energy intake is difficult to determine accurately, especially in children with poor oral-motor function or gastrointestinal problems. In the research setting, total and resting energy expenditure can be estimated by using combinations of the following methods: doubly labeled water (96), indirect calorimetry (106), whole-body calorimetry, thermic effect of food assessment, and heart-rate monitoring (104). Clinically, the measurement of resting energy expenditure (REE) can be used in conjunction with estimates of physical activity to predict total caloric needs. This method is more accurate than estimated energy expenditure from prediction equations (59). The measurement of REE is also a useful research tool for the determination of caloric needs in special groups of infants, children, and adolescents (106).

In the clinical setting, population standards for energy recommendations, such as the Recommended Dietary Allowance from the United States, should not be used for individual children who may have atypical body sizes, body composition, and/or physical activity associated with disease. Rather, more useful estimates may be derived from the formulas developed by the WHO (122). These formulas allow for more individualized prediction of REE because they are based on gender, age, and body weight. One caveat to the use of standard prediction equations is that they were developed to reflect the energy requirements of healthy children in usual environmental and physical activity conditions, and they may not be applicable for some children with disease-associated changes in energy expenditure (59, 106), such as those described for cystic fibrosis, sickle cell disease, inflammatory bowel disease, and liver disease, to name a few. Additionally, there is variability in REE among individuals (75). Therefore, for children with special needs, the measurement of

REE may be preferable to estimations based on prediction equations, resulting in a reduction of complications associated with overfeeding and cost savings through the avoidance of unnecessary nutritional support.

Total energy expenditure (TEE) can be estimated from the adjustment of REE values by an activity factor appropriate for the individual considered. For example, in normally active healthy children, the activity factors range between 1.50 and 1.89 times the REE, whereas in children with spastic quadriplegic cerebral palsy, the physical activity factor is much lower (approximately 1.3 times the REE). Additional methods for estimating caloric requirements have been published, such as one that accounts for level of motor function in mentally retarded children (24), and a factorial method that accounts for REE needs, muscle-tone alterations, and catch-up growth or nutritional repletion in malnourished children with cerebral palsy (63).

For research purposes, the ideal method of assessing TEE in infants and children is estimated by the doubly labeled water method (95, 96). The stable isotopes of $^{2}H_2O$ or ^{18}O, used in the determination of TBW, are used to determine carbon dioxide production over a 7- to 10-day period under free-living conditions. The method is easily tolerated by infants and children. When used in conjunction with a REE measurement, physical activity can be estimated as the net difference between TEE and REE, or as a physical activity ratio, TEE/REE. Also, when weight is stable, TEE reflects total daily energy intake.

These measures of energy expenditure are valuable for identifying the etiology of malnutrition in groups of children known to be at risk. Malnutrition can result from altered energy intake in the form of abnormal energy consumption, absorption, or unusual energy losses, or from altered energy expenditure resulting from abnormal REE, thermic effect of food, physical activity, or growth. REE and TEE measurements assist in characterizing the source of energy imbalance as either altered energy intake or expenditure. For example, children with spastic quadriplegic cerebral palsy have lower REE and lower TEE compared to controls, whereas children with cystic fibrosis have higher REE and similar TEE to controls (106). In addition to understanding the causes of malnutrition, quantification of REE and TEE are important research goals for the development of sound recommendations for nutritional therapy in children at risk for malnutrition.

APPLICATION OF NUTRITIONAL ASSESSMENT TECHNIQUES WITH ATTENTION TO THE CHILD WITH SPECIAL NEEDS

In hospitalized children, and in children with chronic disease or certain congenital syndromes, growth faltering and poor nutritional status are common. Research efforts focus on the identification of nutritional problems and their

Table 5 Disease-specific reference data guide[a]

Disease	Reference
Preterm/LBW infants	17
Achondroplasia	55
Cerebral palsy	62
Down's syndrome	21
	90
	20
Duchenne muscular dystrophy	43
Fragile X syndrome	10
Marfan syndrome	118
	86
	42
Noonan syndrome	121
	88
Prader-Willi syndrome	54
	11
Silver-Russell syndrome	112
	1
	25
Turner's syndrome	89
	70
	60
	80
	107
	6
Williams syndrome	82

[a]Partially adapted from Ranke (87). LBW, Low birth weight.

causes or correlates, the effects of intervention, and the long-term consequences on disease progression. For all children, the goal is to achieve normal growth and development, so for many patient groups, acceptance of a disease-specific reference for growth may minimize the severity of nutritional disorders. For some congenital syndromes (such as Down's syndrome) and other health conditions (such as the low-birth-weight infant) associated with growth abnormalities, disease-specific growth references are appropriate for more accurately assessing nutritional status and understanding the limitations of a treatment regimen. A selection of disease-specific growth charts are described in Table 5.

SUMMARY

Nutritional assessment is an important component in providing optimal health care to children. It is used in the clinical setting, as well as in nutritional surveillance and research. Assessment of growth and body composition is the primary

means of nutritional assessment. Measurement of REE and TEE are additional important tools in determining energy needs. Proper instrumentation, carefully obtained measurements, and suitable reference data are essential for meaningful assessment of nutritional status. The availability of alternative measures of assessing nutritional status, such as upper-arm and lower-leg length, and growth reference data for special groups of children have expanded the applications of nutritional assessment to meet the needs of more diverse groups of children. Special considerations, including the effects of pubertal maturation on indices of nutritional status and the genetic potential for growth, are reviewed and reflect the current shortcomings and future areas of research in nutritional assessment of children.

ACKNOWLEDGMENTS

Special thanks to Dr. Ellen Fung for assistance in the preparation of this manuscript.

Literature Cited

1. Angherm V, Zachmann M, Prader A. 1979. Silver-Russell syndrome. Obervations in 20 patients. *Helv. Paediatr. Acta.* 34:297–308
2. Barrocas A, Belcher D, Champagne C, Jastram C. 1995. Nutrition assessment practical approaches. *Clin. Geriatr. Med.* 11(4):675–713
3. Baumgartner R, Roche AF, Himes JH. 1986. Incremental growth tables: supplementary to previously published charts. *Am. J. Clin. Nutr.* 43:711–22
4. Bell NJ, Shary J, Stevens J. 1991. Demonstration that bone mass is greater in black than in white children. *J. Bone Miner. Res.* 6:719–23
5. Berkey CS, Dockery DW, Wang X, Wypij D, Ferris B Jr. 1993. Longitudinal height and velocity standards for U.S. adolescents. *Stat. Med.* 12:403–14
6. Bernasconi S, Larizza D, Benzo L, Volta C, Vannelli S, et al. 1994. Turner syndrome in Italy: familial characteristics, neonatal data, standards for birth weight and weight from infancy to adulthood. *Acta Paediatr.* 83:292–98
7. Bogin B, MacVean RB. 1981. Nutritional and biological determinants of body fat patterning in urban Guatemalan children. *Hum. Biol.* 53:259–68
8. Bogin B, Sullivan T. 1986. Socioeconomic status, sex, age, and ethnicity as determinants of body fat distribution for Guatemalan children. *Am. J. Phys. Anthropol.* 69:527–35

8a. Boileau RA. 1988. Utilization of total body electrical conductivity in determining body composition. In *Designing Foods*, pp. 251–327. Washington, DC: Natl. Acad. Sci.

9. Brook CGD. 1971. Determination of body composition of children from skinfold measurements. *Arch. Dis. Child.* 46:182–84
10. Butler MG, Brunschwig A, Miller LK, Hagerman RJ. 1992. Standards for selected anthropometric measurements in males with the Fragile X syndrome. *Pediatrics* 89:1059– 62
11. Butler MG, Meaney FJ. 1991. Standards for selected anthropometric measurements in Prader-Willi syndrome. *Pediatrics* 88:853 (Abstr.)
12. Cameron N. 1986. The methods of auxological anthropology. In *Human Growth: a Comprehensive Treatise*, ed. F Falkner, JM Tanner, 3:3–46. New York: Plenum. 2nd ed.

13. Cameron N, Johnston FE, Kgamphe JS, Lunz JS. 1992. Body fat patterning in rural South African black children. *Am. J. Hum. Biol.* 4:353–64
14. Cameron N, Jones PR, Moodie A, Mitchell J. 1986. Timing and magnitude of adolescent growth in height in Cape Coloured children after kwashiorkor. *J. Pediatr.* 108(3):548–55
15. Cameron N, Mitchell J, Meyer O, Moodie A, Bowie MD, et al. 1988. Secondary sexual development of 'Cape Coloured' girls following kwashiorkor. *Ann. Hum. Biol.* 15(1):65–76
16. Caruso-Nicoletti M, Cassorla F, Skerda M, Ross JL, Loriaux DL, Cutler GB. 1985. Short term, low dose estradiol accelerates ulnar growth in boys. *J. Clin. Endocrinol. Metab.* 61:896–98
17. Casey PH, Kraemer HC, Bernbaum J, Yogman MW, Sells JC. 1991. Growth status and growth rates of a varied sample of low birth weight, preterm infants: a longitudinal cohort from birth to three years of age. *J. Pediatr.* 119(4):599–605
18. Centers for Disease Control. 1996. CDC standard deviation-derived growth reference curves derived from NCHS/CDC reference population. NCHS growth curves for children, birth to 18 years. *US Ser. 11-No. 165, DHEW Publ. No. (PHS) 78–1650.* Atlanta, GA: CDC Anthropometric Software Package
19. Charney P. 1995. Nutrition assessment in the 1990s: where are we now? *Nutr. Clin. Pract.* 10(4):131–39
20. Cronk CE. 1978. Growth of children with Down's syndrome: birth to age 3 years. *Pediatrics* 61:564–68
21. Cronk CE, Crocker AC, Pueschel SM, Shea AM, Zackai E, et al. 1988. Growth charts for children with Down's syndrome: 1 month to 18 years of age. *Pediatrics* 81:102–10
22. Cronk CE, Roche AF. 1982. Race- and sex-specific reference data for triceps and subscapular skinfolds and weight/stature.[2] *Am. J. Clin. Nutr.* 35: 347–54
23. Cronk CE, Stallings VA, Spender Q, Ross JL, Widdoes HD. 1989. Measurement of short term growth with a new knee height measuring device. *Am. J. Hum. Biol.* 1:421–28
24. Culley WJ, Middleton TO. 1969. Caloric requirements of mentally retarded children with and without motor dysfunction. *J. Pediatr.* 75:380–84
25. Davies PSW, Valley R, Preece MA. 1988. Adolescent growth and pubertal progression in the Silver-Russell syndrome. *Arch. Dis. Child.* 63:130–35
26. Durnin JVGA, Rahaman MM. 1967. The assessment of the amount of fat in the human body from measurements of skinfold thickness. *Br. J. Nutr.* 21:681–89
27. Durnin JVGA, Womersley J. 1974. Body fat assessment from total body density and its estimation from skinfold thickness measurements on 481 men and women aged 16 to 72 years. *Br. J. Nutr.* 32:77–97
28. Dwyer JT. 1991. Concept of nutritional status and its measurement. In *Anthropometric Assessment of Nutritional Status*, ed. JH Himes, pp. 5–28. New York: Wiley-Liss
29. Fiorotto ML, de Bruin NC, Brans YW, Degenhart HJ, Visser HKA. 1995. Total body electrical conductivity measurements: an evaluation of current instrumentation for infants. *Pediatr. Res.* 37(1):94–100
30. Fomon SJ. 1991. Reference data for assessing growth of infants. *J. Pediatr.* 119:415–16
31. Fomon SJ, Haschke F, Ziegler EE, Nelson SE. 1982. Body composition of reference children from birth to age 10 years. *Am. J. Clin. Nutr.* 35:1169–75
32. Forbes GB. 1986. Body composition in adolescence. In *Human Growth: a Comprehensive Treatise*, ed. F Falkner, JM Tanner, 2:119–145. New York: Plenum. 2nd ed.
33. Frisancho A. 1981. New norms of upper limb fat and muscle areas for assessment of nutritional status. *Am. J. Clin. Nutr.* 34:2540–45
34. Frisancho A. 1990. *Anthropometric Standards for the Assessment of Growth and Nutritional Status.* Ann Arbor, MI: Univ. Mich. Press
35. Frisancho AR, Guire K, Babler W, Borkan G, Way A. 1980. Nutritional influences on child development and genetic control of adolescent growth of Quechuas and Mestizos from the Peruvian lowlands. *Am. J. Phys. Anthropol.* 52:367–76
35a. Garn SM. 1991. Implications and applications of subcutaneous fat measurement to nutritional assessment and health risk evaluation. In *Anthropometric Assessment of Nutritional Status*, ed. J Hines. New York: Wiley-Liss
36. Garn SM, Clark DC, Guire KE. 1974. Level of fatness and size attainment. *Am. J. Phys. Anthropol.* 40:447–50
37. Gibson RS, Vanderkooy PTD, Macdonal

AC, Goldman AM, Ryan BA, Berry M. 1989. A growth-limiting mild zinc-deficiency syndrome in some Southern Ontario boys with low height percentiles. *Am. J. Clin. Nutr.* 49:1266–73
38. Goran MI, Driscoll P, Johnson R, Nagy TR, Hunter G. 1996. Cross-calibration of body composition techniques against dual-energy X-ray absorptiometry in young children. *Am. J. Clin. Nutr.* 63:299–305
39. Goran MI, Kaskoun MC, Carpenter WH, Poehlman ET, Ravussin E, Fontvieille A. 1993. Estimating body composition of young children by using bioelectrical resistance. *J. Appl. Physiol.* 75(4):1776–80
40. Gorstein J, Sullivan K, Yip R, de Onis M, Trowbridge F, et al. 1994. Issues in the assessment of nutritional status using anthropometry. *Bull. WHO* 72(2):273–83
41. Grantham-McGregor S. 1990. Morbidity, nutritional deficiencies and child development in developing countries. In *Diet and Disease in Traditional and Developing Societies*, ed. GA Harrison, JC Waterlow, pp. 62–75. Cambridge: Cambridge Univ. Press
42. Gray JR, Bridges AB, Mole PA, Pringle T, Boxer M, Paterson CR. 1993. Osteoporosis and the Marfan syndrome. *Postgrad. Med. J.* 69:373–75
43. Griffiths RD, Edwards RHT. 1988. A new chart for weight control in Duchenne muscular dystrophy. *Arch. Dis. Child.* 63:1256–58
44. Guo S, Roche AF, Fomon SJ, Nelson SE, Chumlea WC, et al. 1991. Reference data on gains in weight and length during the first two years of life. *J. Pediatr.* 119:355–62
45. Gutin B, Litaker M, Islam S, Manos T, Smith C, Treiber F. 1996. Body-composition measurement in 9–11-y-old children by dual-energy X-ray absorptiometry, skinfold-thickness measurements, and bioimpedance analysis. *Am. J. Clin. Nutr.* 63:287–92
46. Habicht JP, Yarbrough C, Martorell RM, Klein RM. 1974. Height and weight standards for preschool children. *Lancet* 1:611–14
47. Hamill PVV, Dridz TA, Johnson CL, Reed RB, Roche AF, Moore W. 1979. Physical growth: National Center for Health Statistics percentiles. *Am. J. Clin. Nutr.* 32:607–29
48. Hammer LD, Kraemer HC, Wilson DM, Ritter PL, Dornbusch SM. 1991. Standardized percentile curves of body-mass-index for children and adolescents. *Am. J. Dis. Child.* 145:259–63
49. Hammond MI, Lewis MN, Johnson EW. 1966. A nutritional study of cerebral palsied children. *J. Am. Diet. Assoc.* 49:196–201
50. Harrison GA, Schmitt LH. 1989. Variability in stature growth. *Ann. Hum. Biol.* 16(1):45–51
51. Hermanussen M, Geiger-Benoit K, Burmesiter J, Sippell WG. 1988. Knemometry in childhood: accuracy and standardization of a new technique of lower leg length measurement. *Ann. Hum. Biol.* 15:1–16
52. Himes JH, Dietz WH. 1994. Guidelines for overweight in adolescent preventive services: recommendations from an expert committee. *Am. J. Clin. Nutr.* 59(2):307–16
53. Himes JH, Roche AF, Thissen D, Moore WM. 1985. Parent-specific adjustments for evaluation of recumbent length and stature of children. *Pediatrics* 75:304–13
54. Holm VA, Nuggent JK. 1992. Growth in the Prader-Willi syndrome. *Birth Defects Orig. Artic. Ser.* 18(3B):93–100
55. Horton WA, Rotter JI, Rimoln DL, Scott CI, Hall JG. 1978. Standard growth curves for achondroplasia. *Pediatrics* 93:435–38
56. Houtkooper LB, Going SB, Lohman TG, Roche AF, Van Loan M. 1992. Bioelectrical impedance estimation of fat-free body mass in children and youth: a cross-validation study. *J. Appl. Physiol.* 72(1):366–73
57. Johnson CL, Fulwood R, Abraham S, Bryner JD. 1981. Basic data on anthropometric measurements and angular measurements of the hip and knee joints for selected age groups 1–74 years of age: United States, 1971–75 *DHHS Publ. No. (HRA) 81–1669, Vital & Health Stat. Ser. 11, No. 219.* Hyattsville, MD: Natl. Cent. Health Stat.
58. Johnston FE, Wainer H, Thissen D, MacVean R. 1976. Hereditary and environmental determinants of growth in height in a longitudinal sample of children and youth of Guatemalan and European ancestry. *Am. J. Phys. Anthropol.* 44(3):469–76
59. Kaplan AS, Zemel BS, Neiswender KM, Stallings VA. 1995. Resting energy expenditure in clinical pediatrics: measured versus prediction equations. *J. Pediatr.* 127(2):200–5
60. Karlberg J, Albertsson-Wikland K, Naeraa RW, Rongen-Westerlaken C, Wit J-M, et al. 1993. Reference values for

spontaneous growth in Turner girls and its use in estimating treatment effects. In *Basic and Clinical Approach to Turner Syndrome*, ed. I Hibi, K Takano, pp. 83–92. Amsterdam: Excerpta Med.
61. Keller W. 1991. Stature and weight as indicators of nutritional status. In *Anthropometric Assessment of Nutritional Status*, ed. JH Himes, pp. 113–22. New York: Wiley-Liss
62. Krick J, Murphy-Miller P, Zeger S, Wright E. 1996. Pattern of growth in children with cerebral palsy. *J. Am. Diet. Assoc.* 96(7):680–85
63. Krick J, Murphy PE, Markham JFB, Shapiro BK. 1992. A proposed formula for calculating energy needs of children with cerebral palsy. *Devel. Med. Child Neurol.* 34:481–87
64. Kushner RF, Schoeller DA, Fjeld CR, Danford L. 1992. Is the impedance index (ht^2/R) significant in predicting total body water? *Am. J. Clin. Nutr.* 56:835–39
65. Lampl M, Veldhuis JD, Johnsons ML. 1995. Saltation and stasis: a model of human growth. *Science* 268:442–47
66. Lee PA. 1980. Independence of seasonal variation of growth from temperature change. *Growth* 44:54–57
67. Li J-Y, Specker BL, Ho ML, Tsang RC. 1989. Bone mineral content in black and white children 1 to 6 years of age. Early appearance of race and sex differences. *Am. J. Dis. Child.* 143:1346–49
68. Lohman TG. 1986. Applicability of body composition techniques and constants for children and youths. *Exerc. Sport Sci. Rev.* 14:325–57
69. Lohman TG, Roche AR, Martorell R. 1988. *Anthropometric Standardization Reference Manual*. Champaign, IL: Hum. Kinet.
70. Lyon AJ, Preece MA, Grant DB. 1985. Growth curve for girls with Turner syndrome. *Arch. Dis. Child.* 60:932–35
71. Marshall WA, Swan AVN. 1971. Seasonal variation in growth rates of normal and blind children. *Hum. Biol.* 43:502–16
72. Martorell R, Mendoa FS, Castill RO, Pawson IG, Budge CC. 1987. Short and plump physique of Mexican-American children. *Am. J. Phys. Anthropol.* 73(4):475–88
73. Martorell RM, Yarbrough C, Klein RE, Lechtig A. 1979. Malnutrition, body size, and skeletal maturation: interrelationships and implications for catch-up growth. *Hum. Biol.* 51(3):371–89
74. Mascarenhas MR, Zemel BS, Stallings VA. 1996. Nutritional assessment in pediatrics: Nutrition. *Int. J. Appl. Basic Nutr. Sci.* In press
75. McClave SA, Snider HL. 1992. Use of indirect calorimetry in clinical nutrition. *Nutr. Clin. Pract.* 7(5):207–23
76. Morris NN, Udry JR. 1980. Validation of a self-administered instrument to assess stage of adolescent development. *J. Youth Adolesc.* 9:271–80
77. Mueller WH, Kaplowitz HJ. 1994. The precision of anthropometric assessment of body fat distribution in children. *Ann. Hum. Biol.* 21(3):267–74
78. Must A, Dallal GE, Dietz WH. 1991. Reference data for obesity: 85th and 95th percentiles of body mass index (wt/ht^2). *Am. J. Clin. Nutr.* 53(4):839–46
79. Must A, Dallal GE, Dietz WH. 1991. Reference data for obesity: 85th and 95th percentiles of body mass index (wt/ht^2)—a correction. *Am. J. Clin. Nutr.* 54:773
80. Naeraa RW, Nielsen J. 1990. Standards for growth and final height in Turner's syndrome. *Acta Paediatr. Scand.* 79:182–90
81. Ounsted M, Moar VA, Scott A. 1985. Head circumference charts updated. *Arch. Dis. Child.* 60:936–39
82. Pankau R, Partsch CJ, Gosch A, Oppermann HC, Wessel A. 1992. Statural growth of Williams-Beuren syndrome. *Eur. J. Pediatr.* 151:751–55
83. Pelletier DL. 1994. The potentiating effects of malnutrition on child mortality: epidemiologic evidence and policy implications. *Nutr. Rev.* 52(1):409–15
84. Powell CA, Walker SP, Himes JH, Fletcher PD, Grantham-McGregor SM. 1995. Relationships between physical growth, mental development and nutritional supplementation in stunted children: the Jamaican study. *Acta Paediatr.* 84:22–29
85. Prentice A. 1995. Application of dual-energy X-ray absorptiometry and related techniques to the assessment of bone and body composition. In *Body Composition Techniques in Health and Disease*, ed. PSW Davies, TJ Cole, pp. 1–13. Cambridge: Cambridge Univ. Press
86. Pyeritz RE, Murphy EA, Lin SJ, Rosell EM. 1985. Growth and anthropometrics in the Marfan syndrome. In *Endocrine Genetics and the Genetics of Growth*, ed. CJ Papadatos, CS Bartsocas, pp. 135–40. New York: Liss

87. Ranke MB. 1996. Disease-specific standards in congenital syndromes. *Horm. Res.* 45(Suppl. 2):35–41
88. Ranke MB, Heidemann P, Knupfer C, Enders H, Schmaltz AA, Bierich JR. 1988. Noonan syndrome: growth and clinical manifestations in 144 cases. *Eur. J. Pediatr.* 148:220–27
89. Ranke MB, Pfluger H, Rosendahl W, Stubbe P, Enders H, et al. 1983. Turner's syndrome: spontaneous growth in 150 cases and review of the literature. *Eur. J. Pediatr.* 141:81–88
90. Rarick GL, Seefeldt V. 1974. Observations from longitudinal data on growth in stature and sitting height of children with Down's syndrome. *J. Ment. Defic. Res.* 18:63–78
91. Roche AF, Davila GH. 1974. Differences between recumbent length and stature within individuals. *Growth* 38:313–20
92. Roche AF, Himes JH. 1980. Incremental growth charts. *Am. J. Clin. Nutr.* 33:2041–52
93. Roche AF, Mukherjee D, Guo S, Moore WM. 1987. Head circumference reference data: birth to 18 years. *Pediatrics* 79(5):706–12
94. Ryan AS, Wellens R, Roche AF, Kuczmarski RJ. 1996. Reference data for arm muscle and arm adipose tissue areas in Mexican Americans from the Hispanic Health and Nutrition Examination Survey (HHanes 1982–1984): comparisons with Whites and Blacks from NHanes II (1976–1980). *Am. J. Hum. Biol.* 8:389–403
95. Schoeller DA. 1988. Measurement of energy expenditure in free-living humans by using doubly labeled water. *J. Nutr.* 118:1278–89
95a. Schoeller DA, Kushner RF, Taylor P, Dietz WH, Bandini L. 1985. Measurement of total body water: isotope dilution techniques. In *Body Composition Assessments in Youth and Adults, Rep. 6th Ross Conf. Med. Res.*, pp. 24–29. Columbus, OH: Ross Labs
96. Schoeller DA, Ravussin E, Schutz Y, Acheson KJ, Baertschi P, Jequier E. 1986. Energy expenditure by doubly labeled water: validation in humans and proposed calculation. *Am. J. Physiol.* 250:R823–30
97. Schoeller DA, van Santen E, Peterson DW, Dietz W, Jaspan J, Klein PD. 1980. Total body water measurement in humans with ^{18}O and ^{2}H labeled water. *Am. J. Clin. Nutr.* 33:2686–93
98. Schofield WN. 1985. Predicting basal metabolic rate: new standards and review of previous work. *Hum. Nutr. Clin. Nutr.* 39C(1S):5–42
99. Shann R. 1993. Nutritional indices: Z, centile, or percent? *Lancet* 341:526–27
99a. Siervogel RM, Roche AF, Himes JH, Chumlea WC, McCammon R. 1982. Subcutaneous fat distribution in males and females from 1 to 39 years of age. *Am. J. Clin. Nutr.* 36:162–71
100. Slaughter MH, Lohman TG, Boileau RA, Christ CB, Stillman RJ. 1990. Differences in the subcomponents of fat-free body in relation to height between black and white children. *Am. J. Hum. Biol.* 2:209–17
101. Slaughter MH, Lohman TG, Boileau RA, Horswill CA, Stillman RJ, et al. 1988. Skinfold equations for estimation of body fatness in children and youth. *Hum. Biol.* 60(5):709–23
102. Snyder RG, Schneider LW, Owings CL, Reynolds HM, Golomb DH, Schork MA. 1977. Anthropometry of infants, children and youths to age 18 for product safety design. *Highw. Saf. Res. Inst. Rep. No. UM-HSRI–77–17.* Ann Arbor, MI: Highw. Saf. Res. Inst., Univ. Mich.
103. Spender QW, Cronk CE, Stallings VA. 1988. Fat distribution in children with cerebral palsy. *Ann. Hum. Biol.* 15(3):191–96
104. Spurr GB, Prentice AM, Murgatroyd PR, Goldberg GR, Reina JC, Christman NT. 1988. Energy expenditure from minute-to-minute heart-rate recording: comparison with indirect calorimetry. *Am. J. Clin. Nutr.* 48:552–59
105. Stallings VA, Cronk CE, Zemel BS, Charney EB. 1995. Body composition in children with spastic quadriplegic cerebral palsy. *J. Pediatr.* 126:833–39
106. Stallings VA, Zemel BS. 1996. Role of disease in energy balance in children. *Am. J. Hum. Biol.* 8(2):189–98
107. Suwa S. 1992. Standards for growth and growth velocity in Turner's syndrome. *Acta Paediatr. Jpn.* 34:206–21
108. Tanner JM. 1962. *Growth at Adolescence.* Oxford: Blackwell
109. Tanner JM. 1986. Growth as a target-seeking function: catch-up growth and catch-down growth in man. In *Human Growth: a Comprehensive Treatise*, ed. F Falkner, JM Tanner, 1:167–79. New York: Plenum. 2nd ed.
110. Tanner JM, Cameron N. 1980. Investigation of the mid-growth spurt in height, weight and limb circumference in single-year velocity data from the

London 1966–67 growth survey. *Ann. Hum. Biol.* 7:565–77
111. Tanner JM, Davies PSW. 1985. Clinical longitudinal standards for height and height velocity for North American children. *J. Pediatr.* 107(3):317–29
112. Tanner JM, Lejarraga H, Cameron N. 1975. The natural history of the Silver-Russell syndrome: a longitudinal study of thirty-nine cases. *Pediatr. Res.* 9:611–23
113. Troiano RP, Flegal KM, Kucsmarski RJ, Cambell SM, Johnson CL. 1995. Overweight prevalence and trends for children and adolescents. The National Health and Nutrition Examination Surveys, 1963 to 1991. *Arch. Pediatr. Adolesc. Med.* 149:1085–91
114. Ulijaszek SJ, Lourie JA. 1994. Intra- and inter-observer error in anthropometric measurement. In *Anthropometry: the Individual and the Population*, ed. SJ Ulijaszek, CGN Mascie-Tayor, pp. 30–55. Cambridge: Cambridge Univ. Press
114a. Vaisman N, Pencharz P, Koren G, Johnson JK. 1987. Comparison of oral and intravenous administration of sodium bromide for extracellular water measurements. *Am. J. Clin. Nutr.* 48:552–59
115. Van Loan MD. 1990. Assessment of fat-free mass in teen-agers: use of TOBEC methodology. *Am. J. Clin. Nutr.* 52(4):586–90
116. Van Loan MD, Keim NL, Belko AZ. 1990. Body composition assessment of a general population using total body electrical conductivity TOBEC. In *Sports, Medicine and Health*, ed. GPH Hermans, pp. 665–70. Geneva: Elsevier Sci.
117. Van Loan MD, Mayclin PL. 1992. Body composition assessment: dual-energy X-ray absorptiometry (DEXA) compared to reference methods. *Eur. J. Clin. Nutr.* 46:125–30
118. Vetter U, Meyerhofer R, Lang D, von Bernuth G, Ranke MB, Schmaltz AA. 1990. The Marfan syndrome—analysis of growth and cardiovascular manifestation. *Eur. J. Pediatr.* 149:452–56
119. Waterlow JC. 1972. Classification and definition of protein-calorie malnutrition. *Br. Med. J.* 3:566–69
120. Wellens R, Roche AR, Ryan AS, Guo S, Kuczmarski RJ. 1995. Head circumference for Mexican American infants and young children from the Hispanic Health and Nutrition Examination Survey (HHanes 1982–1984): comparisons with Whites and Blacks from NHanes II (1976–1980). *Am. J. Hum. Biol.* 7:255–63
121. Witt DR, Keena BA, Hall JG, Allanson JE. 1986. Growth curves for height in Noonan syndrome. *Clin. Genet.* 30:150–53
122. World Health Organization. 1985. Energy and protein requirements. *Tech. Rep. Ser. 724.* Geneva: WHO
123. World Health Organization. 1995. Physical status: the use and interpretation of anthropometry. *Tech. Rep. Ser. 854.* Geneva: WHO
124. Yano K, Heilbrun LK, Wasnich RD, Hankin JH, Vogel JM. 1985. The relationship between diet and bone mineral content of multiple skeletal sites in elderly Japanese-American men and women living in Hawaii. *Am. J. Clin. Nutr.* 42:877–88
125. Zemel BS, Stallings VA. 1996. Energy requirements and nutritional assessment of the disabled child. In *Nutrition in Pediatrics, Basic Science and Clinical Applications*, ed. Walker WA, Watkins JB, pp. 169–77. Charleston, SC: Neville
126. Zemel BS, Stallings VA. 1997. Alternative measure for assessing linear growth. In *Cambridge Encyclopedia of Human Growth and Development*, ed. SJ Ulijasgek, FE Johnston, MA Preece, In press. Cambridge: Cambridge Univ. Press