Cross-calibration of body-composition techniques against dual-energy X-ray absorptiometry in young children

Michael I Goran, Patricia Driscoll, Rachel Johnson, Tim R Nagy, and Gary Hunter

ABSTRACT Using dual-energy X-ray absorptiometry (DXA) as a standard method for determining body composition in children, we evaluated the accuracy of skinfold-thickness measurements (with the Slaughter et al equations, which are based on triceps and calf skinfold-thickness measurements), bioelectrical resistance (BR; with the Kushner et al equations and age-specific hydration constants), and other clinical measurements (individual skinfold thicknesses and body mass index) for the assessment of body fat in children. We studied a heterogeneous group of 49 boys and 49 girls, aged 6.6 ± 1.4 y and weighing 24.1 ± 5.9 kg. Fat mass estimated by DXA was significantly lower than fat mass measured by skinfold thickness, even though fat mass measurements by these two techniques were strongly related to each other. Fat mass estimated by DXA was also significantly lower than fat mass measured by BR, and the model $R^2$ and SEE were not as strong as for the skinfold-thickness technique. Fat mass estimated by DXA also correlated with other clinical indexes such as triceps skinfold thickness, body mass index, body weight, and subscapular skinfold thickness. In forward-regression analysis, subscapular skinfold thickness, body weight, triceps skinfold thickness, sex, and height$^2$/resistance estimated the value for fat mass measured by DXA with a model $R^2$ of 0.91 and an SEE of 0.94 kg fat mass. These studies suggest that existing techniques for assessing body fat in children may be inaccurate. We provide new anthropometric equations based on the use of DXA as a criterion that provide accurate and precise measures of body fat and fat-free mass in white children aged 4–9 y. This approach provides estimates of body fat standardized to a known laboratory standard of chemical analysis of carcasses.

KEY WORDS Skinfold-thickness measurements, dual-energy X-ray absorptiometry, bioelectrical resistance, obesity, body composition, fat mass, fat-free mass, lean mass

INTRODUCTION

Accurate assessment of body composition is important in many areas of nutrition-related research including clinical assessment, obesity-related research, and research into the regulation of growth and development. In addition, accurate measures of body composition such as fat and fat-free mass are often required as scaling factors to normalize physiologic variables (eg, metabolic rate, physical activity, and physical fitness). Despite a recent surge in interest in body-composition techniques, relatively few studies have specifically addressed methodologic aspects in younger children. Age-specific considerations are required because the usual assumptions in multicompartmental models (eg, hydration and density of fat-free mass) are known to be influenced by age and maturation (1, 2). Thus, specific equations for estimating body composition from skinfold-thickness measurements and hydrodensitometry were developed for use in the pediatric population (3, 4). However, practical aspects limit the availability of techniques for use in younger prepubescent children to specialized research-based techniques such as measurements of total body water (5), total-body electrical conductivity (6), and total body potassium (7, 8), and other more convenient and widely available techniques such as bioelectrical resistance (5), skinfold-thickness measurement (1), and other clinical anthropometric evaluations (eg, weight-for-height, ideal body weight, and body mass index). Due to the lack of a standardized criterion by which to compare data, none of the aforementioned techniques has been validated in the pediatric population. Thus, the accuracy and the precision of the aforementioned techniques have not been well documented.

Dual-energy X-ray absorptiometry (DXA) was introduced as an alternative technique for assessment of total as well as regional body composition (9). DXA is based on the exponential attenuation due to 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 advantages of DXA are the relatively quick scan time (20 min), minimal radiation dose (< 1 mSv or less than one-hundredth of the equivalent radiation exposure of one chest X-ray), and the measurement of regional as well as total body composition. Several studies examined the accuracy of the technique through use of carcass analysis in animal models (10–12). In a companion paper (13), we present data that effectively cross-calibrate DXA measures of body fat with a Lunar DPX-L.

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instrument (Lunar Radiation Corporation, Madison, WI) to chemical measures of carcass fat in pigs. The purpose of this study was to examine the accuracy of other widely used body-composition techniques for children (including anthropometric evaluations and bioelectrical resistance) through the use of DXA-adjusted measures in children. Because the aforementioned techniques have not been cross-validated in children, the second objective was to develop simple anthropometric equations for predicting body composition in children with DXA as a criterion.

SUBJECTS AND METHODS
Subjects
The data set consisted of 98 observations in 50 prepubescent children aged 4–10 y and included repeat measures in 24 children. Because the repeat measures were performed after a period of 1 y and we observed significant changes (by paired *t* test) in body weight (3.2 kg), fat mass by DXA (2.1 kg), height (0.085 m), triceps skinfold thickness (4.5 mm), subscapular skinfold thickness (1.2 mm), sum of eight skinfold thicknesses (16 mm), and height^2/resistance (2.4 cm^2/I), we included these measurements in the analysis as independent observations. One-half of the observations were in girls and one-half in boys. The children were recruited by newspaper advertisements, word of mouth, and from announcements sent home with children from school. The children were all white except for four girls who were of Native American descent. The physical characteristics of this heterogenous group are shown in Table 1. The studies were approved by the Committee on Human Research for the Medical Sciences at the University of Vermont.

Measurement of body composition by DXA
The criterion for assessment of body composition was DXA with a Lunar DPX-L densitometer (Lunar Radiation Corporation) and the pediatric medium scan mode (software version 1.5d). In the companion paper (13), we report that the regression between pig carcass fat and DXA-measured fat with the pediatric medium scan mode has a model R^2 equal to 0.98, a regression coefficient of 0.87, and an intercept that was not significantly different from zero (0.19 kg). Thus, to calibrate DXA measures of fat mass to pig carcass fat, fat mass by DXA was adjusted according to the derived regression equation [actual fat mass = (fat mass measured by DXA × 0.87) + 0.19 kg]. Use of DXA-adjusted data therefore allows comparison of all data back to actual chemical measures of body fat.

Anthropometric and body-composition measurements
Subjects were weighed wearing light clothing (usually a T-shirt and shorts or underwear) and without shoes on a beam scale to the nearest 0.01 kg. Height was measured to the nearest 0.5 cm via a fixed wall-mounted metric ruler. In 135 DXA measures in children, the correlation between DXA weight (x ± SD, 25.3 ± 0.64 kg) and weight measured on the scale (25.91 ± 0.60 kg) was highly significant (r = 0.94, *P* < 0.001). Body mass index was determined by dividing weight by height squared. Anthropometric measurements included eight skinfold-thickness measurements (axilla, chest, abdomen, subscapular, suprailiac, triceps, calf, and thigh) and waist and hip circumferences. Skinfold thickness was measured according to the procedures of Lohman et al (14); three measurements were averaged for each site. All skinfold-thickness measurements were performed with the same pair of skinfold calipers by one of two research assistants who were trained by the same person. Body fat was estimated from skinfold-thickness measurements at the triceps and calf with the sex-specific pediatric equations of Slaughter et al (15).

Fat and fat-free mass were also estimated from total body resistance. Whole-body resistance was measured with a tetrapolar bioelectrical-impedance analyzer (RJL 101A, Detroit) as described previously (5). Total body water was estimated from height/resistance and body weight with the equations of Kushner et al (16). Fat-free mass was estimated from total body water by applying age- and sex-specific hydration factors for fat-free mass as described previously (5), and fat mass was derived by subtracting fat-free mass from body weight. We previously cross-validated the Kushner et al equations in similarly aged young children and showed that the test-retest intraclass reliability of body composition by bioelectrical resistance in children in the laboratory in Vermont was > 0.99 (5).

Statistics
Pearson correlation coefficients were used to examine the relation between fat mass measured by DXA and fat mass measured by other techniques and other anthropometric measures. In comparing the different techniques, we used fat mass measured by DXA as the criterion because this technique has been standardized against the laboratory standard of carcass analysis (13). Body fat mass estimated from by skinfold-thickness measurements and by bioelectrical resistance was compared with that estimated by DXA through use of paired *t* tests. The procedures of Lohman et al (14) were followed for the development and cross-validation of a new equation for estimating fat mass. The data set was randomly split into validation and cross-validation groups in the ratio of 2:1. Independent *t* tests were used to establish similarity between the validation and cross-validation groups. Forward-regression analysis was used to derive the predictors of fat mass, as measured by DXA, in the validation group. The independent variables considered in the model were as follows: height^2/resistance, body weight, sex, individual skinfold-thickness measurements, and age. The regression equation developed in the validation group was used to predict fat mass in the cross-
validation groups. The criteria for determination of successful cross-validation were as follows: no significant differences between measured and estimated means of fat-free mass in the cross-validation group, as assessed by an independent t test; a correlation coefficient \((r)\) between the measured and estimated fat-free mass in the cross-validation groups comparable to the multiple \(R^2\) value of the regression in the validation groups; and minimal shrinkage in predictive power (SEE). These cross-validation procedures were used to establish whether the equation was stable to sample-specific variations. Thereafter, the data of the validation and cross-validation groups were pooled to generate an equation with the largest sample size possible.

All statistics were computed using SAS FOR WINDOWS (version 6.08; SAS Institute Inc, Carey, NC). The level of statistical significance was set at \(P \leq 0.05\) for all tests. Data are cited as means ± SDs unless stated otherwise.

RESULTS

The simple correlations between fat mass and percentage body fat measured by DXA and other measures of body fat and anthropometric measures are shown in Table 2. Fat mass measured by DXA was strongly correlated with fat mass measured by skinfold thickness \((r^2 = 0.87)\), fat mass measured by bioelectrical resistance \((r^2 = 0.76)\), and other anthropometric and skinfold-thickness measures \((r^2 = 0.64–0.83)\). Table 2 also shows that the correlations between techniques are higher when fat mass measured by DXA is expressed as absolute kilograms rather than as a percentage of body weight.

Table 3 and Table 4 summarize the cross-validation data from the comparison of fat mass measured by DXA versus fat mass measured by skinfold thickness and by bioelectrical resistance. The skinfold-thickness technique accurately estimated fat mass in girls but overestimated fat mass by 0.5 kg in boys (Table 3), although, as shown in Table 4, the regression between fat mass measured by DXA and fat mass measured by skinfold thicknesses had a high \(R^2\) and a low SEE. The relation between fat mass measured by DXA and fat mass measured by skinfold thicknesses was best explained by a linear fit compared with an exponential-curve fit, power function, or logarithmic (base 10) fit \((R^2 = 0.67, 0.75, \text{and} 0.77, \text{respectively})\). Bioelectrical resistance significantly overestimated fat mass measured by DXA in boys and girls. The relation between fat mass measured by DXA and fat mass measured by bioelectrical resistance was best explained by a linear fit compared with an exponential-curve fit, power function, or logarithmic (base 10) fit \((R^2 = 0.55, 0.55, \text{and} 0.59, \text{respectively})\). The relation between fat mass measured by DXA and fat mass measured by skinfold thicknesses and by bioelectrical resistance is shown in Figure 1.

The relations between fat mass measured by DXA and three simple clinical indexes of body composition (triceps skinfold thickness, subscapular skinfold thickness, and body mass index) are shown in Figure 2. The comparisons in Figure 2 show that subscapular skinfold thickness provides a reasonable index of overall body fat mass. Interestingly, the three indexes examined were more weakly related to percentage body fat \((R^2 = 0.44–0.58)\). The regression equations provided in Figure 2 are for the purposes of converting these clinical indexes into more meaningful measures of total body composition.

We next developed an equation to estimate fat mass from the simpler anthropometric measures. The sample was randomly split into two groups in the ratio of 2:1. There was no significant difference by \(t\) test between subject characteristics (age, weight, height, sex ratio, skinfold-thickness measurements, height/\(r^2\)/resistance, and fat mass measured by DXA) in the validation and cross-validation groups. A preliminary equation

<table>
<thead>
<tr>
<th>Table 2</th>
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| Simple correlations \((r^2)\) between fat mass or percentage body fat measured by dual-energy X-ray absorptiometry (DXA) and fat mass measured by other techniques, and simple anthropometric and obesity indexes

<table>
<thead>
<tr>
<th>Index</th>
<th>(r^2) with fat mass by DXA</th>
<th>(r^2) with percentage body fat by DXA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fat mass by ST</td>
<td>0.87</td>
<td>0.55</td>
</tr>
<tr>
<td>Body fat (%) by ST</td>
<td>0.71</td>
<td>0.61</td>
</tr>
<tr>
<td>Fat mass by BR</td>
<td>0.76</td>
<td>0.48</td>
</tr>
<tr>
<td>Body fat (%) by BR</td>
<td>0.48</td>
<td>0.48</td>
</tr>
<tr>
<td>Body weight</td>
<td>0.72</td>
<td>0.34</td>
</tr>
<tr>
<td>Body mass index</td>
<td>0.71</td>
<td>0.45</td>
</tr>
<tr>
<td>Triceps ST</td>
<td>0.64</td>
<td>0.59</td>
</tr>
<tr>
<td>Subscapular ST</td>
<td>0.79</td>
<td>0.52</td>
</tr>
<tr>
<td>Other STs</td>
<td>0.61–0.76</td>
<td>0.42–0.55</td>
</tr>
<tr>
<td>Triceps + subscapular ST</td>
<td>0.83</td>
<td>0.64</td>
</tr>
<tr>
<td>Triceps + calf ST</td>
<td>0.71</td>
<td>0.58</td>
</tr>
<tr>
<td>Sum of eight STs</td>
<td>0.81</td>
<td>0.61</td>
</tr>
</tbody>
</table>

\(^1\) Fat mass by ST (skinfold thickness) is based on the equations by Slaughter et al (15); fat mass by BR (bioelectrical resistance) is based on the equations by Kushner et al (16); other skinfold thicknesses assessed are described in the text. All correlations are significant at \(P < 0.001\), except for height/\(r^2\)/resistance, which is significant at \(P < 0.05\).

<table>
<thead>
<tr>
<th>Table 3</th>
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</table>
| Fat mass measured by dual-energy X-ray absorptiometry (DXA), skinfold thickness (ST), and bioelectrical resistance (BR) in children

<table>
<thead>
<tr>
<th>Method</th>
<th>Girls ((n = 49))</th>
<th>Boys ((n = 49))</th>
<th>Girls and boys ((n = 98))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(kg)</td>
<td>(kg)</td>
<td>(kg)</td>
</tr>
<tr>
<td>DXA</td>
<td>5.5 ± 3.3</td>
<td>4.0 ± 2.5</td>
<td>4.8 ± 3.0</td>
</tr>
<tr>
<td>(1.6–20.0)</td>
<td>(1.2–12.1)</td>
<td>(1.3–20.0)</td>
<td></td>
</tr>
<tr>
<td>ST and equation by Slaughter</td>
<td>5.5 ± 3.3</td>
<td>4.5 ± 2.8(^2)</td>
<td>5.0 ± 3.1(^2)</td>
</tr>
<tr>
<td>et al (15)</td>
<td>(2.5–19.6)</td>
<td>(2.1–14.9)</td>
<td>(2.1–19.6)</td>
</tr>
<tr>
<td>BR and equation by Kushner</td>
<td>6.7 ± 3.6(^2)</td>
<td>4.6 ± 3.0(^2)</td>
<td>5.7 ± 3.4(^2)</td>
</tr>
<tr>
<td>et al (16)</td>
<td>(3.3–21.7)</td>
<td>(1.2–16.3)</td>
<td>(1.2–21.7)</td>
</tr>
</tbody>
</table>

\(^1\) \(\bar{x} \pm SD\).

\(^2\) Significantly different from fat mass measured by DXA (paired \(t\) test), \(P < 0.05\).
with subscapular skinfold thickness, triceps skinfold thickness, body weight, and sex was developed for estimating fat mass by DXA (model $R^2 = 0.92$). This equation was used to predict fat mass in the cross-validation group. There was no significant difference between fat mass measured by DXA in the cross-validation group and that estimated from the preliminary equation ($R^2$ for measured versus estimated fat mass = 0.88).

Having shown cross-validation of the preliminary equation, we combined the sample to provide a data set with a larger sample size. Forward-regression analysis was repeated and the results are shown in Table 5. Subscapular skinfold thickness, weight, triceps skinfold thickness, height^2/resistance, and sex explained 91% of the variation in total fat mass as measured by DXA. To try to maximize the $R^2$ and lower the SEE we included polynomials and sums of skinfold-thickness measurements [including the sum of eight skinfold-thickness measurements and the sum of triceps and calf and triceps plus subscapular skinfold-thickness measurements, as used in the equations by Slaughter et al (15)]. However, these alternative approaches did not improve the model $R^2$ or the SEE.

With a similar approach, the multiple-regression model for estimating fat-free mass is as follows:

\[
\text{FFM} = (0.16 \times (H^2/R)) + (0.67 \times \text{weight}) - (0.11 \times \text{triceps}) - (0.16 \times \text{subscapular}) + (0.43 \times \text{sex}) + 2.41 \, \text{kg} \quad (J)
\]

where $H^2/R$ is height^2/resistance in cm^2/Ω, weight is body weight in kg, triceps and subscapular are skinfold thicknesses in mm, and sex is 0 for girls and 1 for boys. Model $R^2$ equals 0.91; SEE equals 0.94 kg (19% of mean fat-free mass).

**DISCUSSION**

The main purpose of this study was to reevaluate existing techniques for clinical- and research-based measures of body composition. It was timely to address this issue because of recent work from our laboratory in establishing the accuracy of DXA in the pediatric population, and in developing equations for cross-calibrating DXA measures with chemical measures in pig carcasses (13). Our analysis failed to cross-validate existing techniques against DXA measures. However, we developed new anthropometric equations that provide accurate estimates of body fat. The advantage of the approach proposed is that all...
measures and estimates are relative to a known laboratory standard, namely chemical measures in whole carcasses of pigs.

One of the most comprehensive studies of body-composition techniques in children was by Slaughter et al (1), who studied 310 subjects (aged 8–29 y), including 66 prepubescent children (50 boys and 16 girls). A multicompartmental model of body composition was used as a criterion 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 the development of sex-, race-, and maturation-specific equations for estimating body fat based on measurement of either triceps plus calf (two sex-specific equations) or triceps plus subscapular skinfold thickness (nine equations recommended depending on sex, race, maturation state, and sum of skinfold-thickness measurements). Our study shows a strong relation between fat mass calculated by the Slaughter et al equations and fat mass measured by DXA, although on a group-mean basis there was a systematic difference between the two techniques that was more pronounced in boys (0.5-kg overestimate by the Slaughter et al equations). Using Lohman’s age-adjusted hydrodensitometry equations, Janz et al (17) also failed to cross-validate the Slaughter et al equations on the basis of triceps and calf skinfold-thickness measurements in girls. A possible explanation for the differences between equations for predicting fat mass may be the low sample size of girls (n = 16) in the study of Slaught et al (1).

Bioelectrical resistance is another commonly used technique in children because it is simple, and quick to apply. The technique has been cross-validated in children against measurements of total body water (5) and total body potassium (8). Several issues remain unresolved, including whether age-specific equations should be used (18). In young children we showed previously that the relation between measured total body water (by oxygen-18 and deuterium dilution) and estimated total body water (from height2/resistance and the Kushner et al equations) was strong (R2 = 0.88, SEE = 0.63 kg) (5). However, because bioelectrical resistance is based on an estimation of total body water, a further concern in children relates to uncertainty of the hydration level of fat-free mass in children at different stages of maturation. To avoid this uncertainty, Schaefer et al (8) estimated fat-free mass from measurements of total body potassium in a sample of 112 healthy children (4–19 y) and showed that fat-free mass could be estimated from bioelectrical resistance and age with an R2 of 0.98 and a root-mean-square error of 1.98 kg.

Previous data from our laboratory showed excellent test-retest reliability of the bioelectrical-resistance technique in children; the intraclass correlation coefficient was > 0.99 for duplicate estimates spread 2 wk apart in 26 children (5). In addition, our previous finding showing cross-validation of bioelectrical resistance against total body water in two independent laboratories suggested that the technique was robust to interlaboratory and interuser variation (5). However, in the present study we noted significant differences between bioelectrical-resistance data and DXA data. Moreover, the R2 and SEE for the comparison of bioelectrical resistance with DXA were less impressive than the values observed when comparing the skinfold-thickness technique with DXA.

Many previous studies that derived predictive models of body composition used percentage body fat as the major dependent variable. One alternative approach that we used in this study was to use fat mass rather than percentage body fat as the dependent variable. Our data suggest that this approach may increase the predictive power of body-composition models in general. As shown in Table 2, the relations between body-composition techniques and between simple anthropometric indexes and measurement of body fat by the reference technique are higher when body fat is expressed in absolute terms (kg) as opposed to as a percentage of body weight. The correlations between percentage body fat and anthropometric indexes did increase when percentage fat was transformed by an arc sine square root function. However, the correlation coefficients for the transformed percentage fat data remained lower than the correlations for fat mass. When repeating the main multiple-regression analysis with percentage body fat by DXA as the dependent variable, the maximum R2 that we could achieve was ∼0.7 (compared with an R2 of 0.91 when fat mass was the dependent variable and body weight was included as a predictor variable; Table 5). These data indicate that skinfold-thickness measurements are more strongly related to fat mass than to percentage body fat. Moreover, the accuracy of prediction equations for body composition may be improved when absolute body fat mass, rather than percentage body fat, is used as a dependent variable.

The main multiple-regression analysis presented includes nontransformed individual skinfold-thickness measures. Previous studies included the sum of two or more skinfold thicknesses, and in some cases skinfold-thickness data were trans-
formed with logarithm or power functions (1). In other data analysis we included the sum of skinfold-thickness measurements used in other studies in children (ie, triceps + subscapular and triceps + calf) as well as the sum of all eight skinfold-thickness measurements. However, inclusion of these terms, including logarithm and squared transformations, in a multiple-regression analysis did not improve the model $R^2$ or the SEE. Thus, our analysis does not justify the inclusion of sums of individual skinfold thicknesses or the inclusion of transformations because they do not improve the predictive power of the model.

We were surprised by the strong correlation between individual skinfold-thickness measurements and fat mass measured by DXA because skinfold thickness is simply a measure of subcutaneous fat thickness in a discrete anatomic location, whereas DXA estimates whole-body fat mass through a subtraction of fat-free mass from total body mass. In adults, previous reports comparing the skinfold-thickness technique with DXA suggested similar correlations between relative body fat content measured by the two techniques. Pierson et al (19) reported correlations of $r$ equal to 0.83 for females and $r$ equal to 0.76 for males for percentage body fat measured by DXA versus percentage body fat measured by skinfold thickness; these correlations are similar to the value of 0.78 reported for children in Table 2. In addition, unpublished data from 206 adult women studied in our laboratory in Birmingham also suggest a strong relation between fat mass measured by DXA and body weight ($r^2 = 0.81$), body mass index ($r^2 = 0.81$), triceps skinfold thickness ($r^2 = 0.66$), and subscapular skinfold thickness ($r^2 = 0.71$).

One additional application of our analysis is the derivation of equations for translating clinical anthropometric indexes into whole-body composition data (Figure 2). The equations in Figure 2 are not meant to serve as prediction equations nor to replace the prediction equation developed in Table 5, which should provide the most accurate estimate of body composition. The univariate equations in Figure 2 have limited use because of the lower $R^2$ and poor SEE compared with the multiple-regression model described in Table 5. However, because bioelectrical resistance is not always available, the combined equation with subscapular skinfold thickness, body weight, and triceps skinfold thickness may be useful, especially because the addition of height$^2$/resistance only leads to a small improvement in the model $R^2$ and SEE.

Although we focused the major data analysis on methods to determine fat mass, our findings have similar implications for estimation of fat-free mass. Thus, relative to DXA, fat-free mass from skinfold thicknesses was underestimated by the same magnitude that fat mass was overestimated. Because fat-free mass can easily be estimated by subtracting fat mass from body mass, we did not develop additional equations for fat-free mass. Nevertheless, to demonstrate the relations among fat-free mass, height$^2$/resistance, skinfold thicknesses, and sex we presented the results from a forward-regression model with fat-free mass measured by DXA as the dependent variable. Equation 1 highlights several important points. First, height$^2$/resistance is more strongly related to fat-free mass than to fat mass. Second, skinfold thickness and sex influence the relation between fat-free mass and height$^2$/resistance. We previously found similar results in adults and showed that obesity and sex influence the relation between fat-free mass and height$^2$/resistance when hydrodensitometry is used as a criterion (20). Thus, we proposed an alternative equation for estimating fat-free mass from height$^2$/resistance that incorporates body weight, sex, and, in this case, suprailiac skinfold thickness (model $R^2 = 0.92$, SEE = 3.58 kg). Collectively, our data provide further support for the utility of height$^2$/resistance in improving the accuracy of anthropometric estimates of body composition in children.

Several limitations of this study should be considered. First, the reported SEEs appear low in absolute magnitude (on the order of 1–2 kg fat mass), although it should be noted that this error is actually quite high when considered relative to a group mean value for body fat of 4.8 kg. Thus, the equations provided are for estimating body fat mass and are not intended to replace measurement of body fat by DXA. Second, this study was limited to a narrow age range of prepubescent children (4–9 y of age) and the data do not support the need for an age term in the prediction equations. However, the results should not be extrapolated to other stages of maturation or age ranges, especially because other studies support a significant effect of maturation state on the relation between skinfold thickness and body composition (1). Third, we cannot extrapolate our findings to other ethnic groups of children because our sample was predominantly white. Although we included four Mohawk girls in the current study, we do not see any reason to exclude them from the analysis. We reanalyzed our data excluding them from the sample and found no significant change in any parameter or statistical test. Also, when ethnic background was included as an independent variable in developing the regression model it was never selected as a significant variable. However, studies in larger samples of other ethnic groups seem warranted because previous studies suggested an influence of ethnic background on the relation between skinfold thicknesses and body fat. Finally, we modified the DXA data by applying correction factors derived from a validation study with carcass analysis in pigs as the standard technique, thus assuming that pig and human fat are similar in amount, composition, and distribution (13). Clearly, there are likely to be differences in body composition between children and pigs although they were similar for body weight (24.1 ± 5.9 kg in children compared with 25.5 ± 7.0 kg in pigs) and fat mass (5.0 ± 3.3 kg in children compared with 4.8 ± 3.0 kg in pigs). Given these limitations, the major advantage of our proposed approach is that estimates of body fat in children are standardized relative to a known and defined laboratory standard (ie, carcass analysis in pigs).

We did not consider the use of hydrodensitometry in this study for several reasons, even though age-specific constants for the density of fat-free mass were developed in previous studies (3, 4). In our experience, measuring underwater weight in young prepubescent children is impractical, mainly because of the difficulty of obtaining a reliable recording of underwater weight during full-body submergence with maximal exhalation. Moreover, hydrodensitometry is a less appealing technique because it is more time-consuming and labor-intensive and places more demands on subject’s cooperation compared with DXA. The practical limitations of underwater weighing in young children excludes the potential for using several of the available multicompartiment models that rely on knowledge of total body density.

In summary, we compared several body-composition techniques with DXA in young prepubescent children. In our
companion study, we cross-validated DXA against carcass analysis in pigs, showing that DXA is an accurate and precise method provided that calibration equations are applied (13). We showed that skinfold-thickness measurements (Slaughter et al. equations) and bioelectrical resistance (Kushner et al. equations) provide reasonable estimates of fat mass in children, although a systematic error exists for both techniques, and the precision is less for bioelectrical resistance. We propose a new equation combining anthropometric measures, including two skinfold-thickness measures, with height\(^2\)/resistance, that provides accurate and precise measures of body fat and fat-free mass in white children aged 4–9 y. This approach provides estimates of body fat standardized to the known laboratory standard of chemical analysis of carcasses.

REFERENCES