Alterations in growth and body composition during puberty. I. Comparing multicompart ment body composition models

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1Division of Endocrinology, Department of Pediatrics, 2Division of Endocrinology and Metabolism, Department of Medicine, and 4Department of Pharmacology, University of Virginia Health Sciences Center, and 2Department of Human Services, Curry School of Education, University of Virginia, Charlottesville, Virginia 22908

Roemmich, James N., Pamela A. Clark, Arthur Weltman, and Alan D. Rogol. Alterations in growth and body composition during puberty. I. Comparing multicompart ment body composition models. J. Appl. Physiol. 83(3): 927-935, 1997.—A four-compartment (4C) model of body composition was used as a criterion to determine the accuracy of three-compartment (3C) and two-compartment (2C) models to estimate percent body fat (%BF) in prepubertal and pubertal boys (genital I & II, n = 17; genital III & IV, n = 7) and girls (breast I & II, n = 8; breast III & IV, n = 15). The 3C water-density (3C-H$_2$O) and 3C mineral-density models, dual-energy X-ray absorptiometry, the Lohman age-adjusted equations, the Slaughter et al. skinfold equations, and the Houtkooper et al. and Boyle bioelectrical impedance equations were evaluated. Agreement with the 4C model increased with the number of compartments (i.e., body water, bone mineral) measured. Except for the 3C-H$_2$O model, the limits of agreement were large and did not perform well for individuals. The mean %BF by dual-energy X-ray absorptiometry (23.6%) was greater than that of the criterion 4C method (21.7%). For the field methods, the Slaughter et al. skinfold equations performed better than did the Houtkooper et al. and Boyle bioimpedance equations. The hydration of the fat-free mass decreased (genital I & II = 75.7%, genital III & IV = 74.8%, breast I & II = 75.5%, breast III & IV = 74.4%) and the mineral content increased (genital I & II = 4.9%, genital III & IV = 5.0%, breast I & II = 5.1%, breast III & IV = 5.7%) with maturation. The density of the fat-free mass also increased (genital I & II = 1.084 g/ml, genital III & IV = 1.087 g/ml, breast I & II = 1.086 g/ml, breast III & IV = 1.091 g/ml) with maturation. All of the models reduced the %BF overpredicted the Siri 2C model, but only the 4C and 3C-H$_2$O models should be used as criterion methods for body composition validation in children and adolescents.

children; adolescents; body fat; hydrostatic weighing; bioelectrical impedance; skinfolds

ACCURATE ASSESSMENT of body composition in children is necessary to examine the risk of obesity and related health issues as well as to investigate the influence of various interventions on changes in adipose and fat-free tissues. Until recently, most assessments of body composition in children were based on the two-compartment (2C) model of Siri (26), which significantly overestimates percent body fat (%BF). The overprediction in %BF is due to the chemical immaturity of children, who have a lower density of the fat-free mass (FFM) due to a higher proportion of water and lower proportions of mineral and protein in their FFM than in the FFM of the adult cadavers used to derive the 2C model (reviewed in Ref. 4).

The inaccuracy of 2C body composition estimates in children resulted in the development multicompart ment models of body composition measurement (14). In a four-compartment (4C) model, the FFM is divided into its constituent parts: water, mineral, and protein. Two three-compartment (3C) models have also been developed, each of which combines two constituents of the FFM into one compartment. In the 3C water-density (3C-H$_2$O) model, protein and mineral are combined as solids. In the 3C mineral-density (3C-min) model, water and protein are combined to form the lean soft tissue (4). Although the multicompart ment models of body composition should offer improved accuracy, they have not been widely validated in children and adolescents.

In addition to multicompart ment models, several less-technical and less-expensive techniques for body composition assessment in children have been developed to correct for the maturational changes in the density of the FFM. Lohman (13) has published age-adjusted constants for the Siri equation (27). Once the body density is determined from underwater weighing, it can be used in the age-adjusted Siri equations to calculate the 2C model of body composition. Several investigators have utilized these age-adjusted equations as a criterion method to validate cross-validate skinfold and bioelectrical impedance (BIA) prediction equations (12, 16). However, the validity of the Lohman age-adjusted equations has not been determined. Furthermore, although a limited number of skinfold and BIA equations have been developed based on multicompart ment models (2, 11, 28), these equations have not been adequately cross-validated against multicompart ment models in diverse subject samples. In the present study, we investigated the agreement between 2C, 3C, and 4C models of body composition in children and adolescents.

METHODS

Subjects. Subjects included 24 boys and 23 girls enrolled in a longitudinal study of the endocrine control of growth and maturation at puberty. The study was reviewed and approved by the University of Virginia Human Investigation Committee. Informed consent was obtained from a parent and assent from each child.

All subjects had height, height velocity, and weight within 2 SDs of the mean for chronological age. Height was measured with a Harpenden stadiometer by a trained anthropometrist (J. N. Roemmich). Bone age was determined by the Fels method (21) by an experienced assessor (J. N. Roemmich).
Stage of secondary sex characteristics was assessed by the method of Tanner (29).

Total body water (TBW). Baseline urine samples were collected the morning after an overnight fast at the University of Virginia General Clinical Research Center. The subjects then drank a dose (0.5 g/kg body wt) of 99.9 atom% excess $^2$H$_2$O (Isotec, Miamisburg, OH) diluted with 1.5 g/kg water. The dose bottle was rinsed with 40 ml of tap water. Urine samples were collected at 4 and 5 h postdose and stored in cryogenic vials at $-20^\circ$C until analysis by gas-isotope-ratio mass spectrometry (Metabolic Solutions, Merrimack, NH). The $^2$H$_2$O pool size was calculated from the baseline and equilibrium urine samples as described by Prentice (19). A factor of 1.04 was used to correct for the incorporation of deuterium into nonaqueous tissues (23). The TBW was converted from liters to kilograms by dividing by 0.9937, the density of water at body temperature (10).

Body density. Body density was measured by hydrostatic weighing by using the procedures previously described by Sinning (25). Residual volume (RV) was measured on land by nitrogen washout (32) with the subject seated in the same position as that utilized during the underwater weighing. The RV measurements were repeated until two trials were within $\pm50$ ml.

Bone mineral content (BMC). Soft tissue composition of the total body and measurement of BMC was made by dual-energy X-ray absorptiometry (DEXA) by using a Hologic QDR 2000 bone densitometer (Hologic, Waltham, MA). The subjects removed all metal and clothes containing metal before the scan. The subjects were placed in a supine position and asked to remain still. A series of transverse scans were made with a pencil beam from head to toe of the subject at 1-cm intervals. All scans were then analyzed with Hologic-enhanced whole body software version 5.64 by a single trained technologist. The BMC was divided by 0.88 to correct for fractional lowering of the volume of bone mineral density by absorptiometry compared with the volume of bone ash mineral density (22, 24). The BMC was then converted to total mineral by dividing by 0.824 (14).

4C model. The 4C model equation of Lohman (14) was used as the criterion method to which all other models and equations were compared. The equation is

$$\%BF = \left(\frac{2.747}{D_b} - 0.714W + 1.146B - 2.053\right) \times 100$$

where $D_b$ is body density (g/ml), $W$ is total body water as a fraction of the body weight, and $B$ is osseous mineral as a fraction of the body weight.

3C model. Two 3C model equations were compared. The 3C-$^2$H$_2$O equation proposed by Siri (27) contains the components fat, water, and solids

$$\%BF = \left(\frac{2.118}{D_b} - 0.78W - 1.354\right) \times 100$$

and the 3C-min equation of Lohman (14)contains the components fat, mineral, and other (water and other solids)

$$\%BF = \left(\frac{6.386}{D_b} - 3.96M - 6.090\right) \times 100$$

where $M$ is the mineral (osseous + nonosseous) as a fraction of the body weight.

2C model. The original Siri 2C model (26) was included in the analysis to demonstrate the ability of the multicompart-model to correct for the overestimation of %BF of the Siri model. The Siri equation is

$$\%BF = \left(\frac{4.95}{D_b} - 4.50\right) \times 100$$

The age- and gender-specific equations of Lohman (13), which account for maturation-related changes in the density of the FFM, were also used to predict the %BF.

Anthropometry. All measurements were made by one experienced anthropometrist (J. N. Roemmich). The recommendations of Harrison et al. (7) were followed relative to landmarks and methods. Measurements of triceps, subscapular, and calf skinfolds were taken on the right side of the body with a Harpenden caliper and recorded to the nearest 0.1 mm. The equations used to predict %BF were those of Slaughter et al. (28), which were derived by using a multicompart-model as the criterion method and adjusted for gender and maturation. The equations that utilize the triceps and subscapular skinfolds are referred to as Slaughter T + S, and the Slaughter et al. equations that utilize the triceps and calf skinfolds are referred to as Slaughter T + C. The within-day reliability of the skinfold measures was assessed by computing the technical error of measurement and coefficient of variation (CV; Table 1) as previously described (17).

BIA. BIA was measured with a Valhalla 1990B impedance analyzer (Valhalla, San Diego, CA). The subject removed shoes, socks, and any metal (jewelry and clothing) and was then placed in a supine position on a dry, nonconductive surface for 5 min before the measurement. The subject remained motionless, with the arms and legs slightly abducted and not touching other body parts. A 500-µA, 50-kHz electrical signal was induced, and resistance was measured via a four-electrode arrangement. Bioelectric resistance was measured from the right hand to the right foot. Source electrodes were placed on the anterior surface of the foot at the distal end of the second metatarsal and the posterior surface of the hand at the distal end of the third metacarpal. The receiving electrodes were placed between medial and lateral malleoli of the ankle and the styloid processes of the radius and ulna. The source electrodes were at least 5 cm distal to the receiving electrodes.

Two body composition prediction equations that were developed by using multicompart-models as the criterion were cross-validated. The equation of Houtkooper et al. (11) that predicts FFM is

$$FFM = 0.61 (height^2/resistance) + 0.25 (weight) + 1.31$$

and the equation of Boileau (3), derived specifically for use

Table 1. Technical error of measurement and coefficient of variation of the skinfold thickness measures for all subjects

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Technical Error of Measurement, mm</th>
<th>Coefficient of Variation</th>
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<tbody>
<tr>
<td>Subscapular</td>
<td>0.43</td>
<td>3.91</td>
</tr>
<tr>
<td>Triceps</td>
<td>1.05</td>
<td>7.24</td>
</tr>
<tr>
<td>Medial calf</td>
<td>0.53</td>
<td>3.48</td>
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</table>

Values are for 47 subjects.
Table 2. Subject characteristics, including maturational stage (distribution of stages are shown), and four-compartment estimates of body composition grouped by gender and pubertal stage

<table>
<thead>
<tr>
<th></th>
<th>Males (n = 24)</th>
<th>Females (n = 23)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Genital I &amp; II (n = 17)</td>
<td>Genital III &amp; IV (n = 7)</td>
</tr>
<tr>
<td>Age,† yr</td>
<td>10.9 ± 0.3</td>
<td>13.4 ± 0.5</td>
</tr>
<tr>
<td>Height,† cm</td>
<td>144.7 ± 2.1</td>
<td>165.8 ± 3.7</td>
</tr>
<tr>
<td>Bone age,† yr</td>
<td>11.2 ± 0.4</td>
<td>14.5 ± 0.6</td>
</tr>
<tr>
<td>Pubertal stage</td>
<td>Genital I (n = 15)</td>
<td>Genital III (n = 3)</td>
</tr>
<tr>
<td>Weight,† kg</td>
<td>37.42 ± 2.28</td>
<td>53.53 ± 3.84</td>
</tr>
<tr>
<td>Body density,* g/ml</td>
<td>2.48 ± 1.24</td>
<td>34.65 ± 2.09</td>
</tr>
<tr>
<td>Total body water,† kg</td>
<td>19.88 ± 1.43</td>
<td>13.68 ± 2.40</td>
</tr>
<tr>
<td>%Body fat,†</td>
<td>29.67 ± 1.58</td>
<td>46.24 ± 2.66</td>
</tr>
<tr>
<td>Fat mass,† kg</td>
<td>7.80 ± 1.01</td>
<td>7.30 ± 1.70</td>
</tr>
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</table>

Values are means ± SE with range for age given in parentheses; n, no. of subjects. *Significant gender effect, P = 0.05. †Significant maturation effect, P ≤ 0.05.

with the Valhalia bioimpedance analyzer, also predicts FFM is

\[
\text{FFM (Valhalla)} = \frac{4.138 + 0.657 \text{ (height}^2/\text{resistance})}{0.16 \text{ (weight)} - 0.131 \text{ (gender)}}
\]

where gender is a categorical variable (+1 = male, -1 = female).

Proportional composition of FFM. The proportional contribution of water, mineral, and protein to the FFM was calculated by dividing the TBW, osseous mineral (OM), nonosseous mineral (NOM), and protein by the FFM. The NOM was obtained by multiplying M by 0.176 (14). The protein/FFM was calculated as protein/FFM = 1 - (TBW/FFM + OM/FFM + NOM/FFM). The density of the FFM (DFFM) was calculated by assuming a density of 0.9937 for water, 2.982 for OM, 3.317 for NOM, and 1.34 g/ml for protein. The carbohydrate (assumed to be 0.6% of the FFM) was added to the protein fraction (8).

Statistical analyses. Each model and prediction equation was compared for agreement to the 4C model with Bland–Altman (bias) between two models was plotted against the value obtained from the 4C model. According to Bland and Altman, (2) gender × (2) maturation was used to compare physical characteristics and differences in bias. When the groups were combined, a one-way analysis of variance was used to compare the mean estimates of %BF for the 2C, 3C, and 4C models. Pearson-product moment correlations were computed between the criterion 4C and other models. The constant error (CE) and total error (TE) were computed as described by Thorland et al. (30).

RESULTS

The physical characteristics of the subjects are shown in Table 2. There were no gender-by-maturation interactions. There were several gender differences: the boys had a greater D₀ and lower amounts of %BF and fat mass than did the girls. The gender differences in TBW (P = 0.08) and FFM (P = 0.07) approached significance. As expected, there were also several differences due to pubertal maturation. The more pubertally advanced boys and girls were older, taller, more skeletally mature, heavier, and had greater amounts of body water, %BF, and FFM than did the prepubertal boys and girls. The maturational differences in body density (P = 0.08) approached significance.

Table 3 shows the proportional contribution of water, mineral and protein to the FFM. The pubertal subjects tended to have a smaller (P = 0.09) water fraction of the FFM (TBW/FFM) and a greater (P = 0.05) total min-
The TE of the 3C-H2O equation was 2.36-fold lower than that of the 3C-min model, which had the next smallest limits of agreement. All but nine of the %BF difference scores for the 3C-H2O model were within ±1 SD. The bias tended to be larger in the prepubertal subjects (P = 0.08, Table 5). The DEXA model (Fig. 2C) produced a mean overprediction bias of −1.88 %BF and, except for the skinfold and BIA models, the limits of agreement (2SD = ±8.30 %BF) were larger than any of the other models tested. When the estimates of %BF for all subjects were combined into one group (data not shown), the %BF by DEXA was significantly greater than that of the 4C model.

The skinfold equations also reduced the bias relative to the 2C Siri model. The Slaughter T+C and Slaughter

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### Table 4. Correlation statistics used for cross-validation of prediction equations against four-compartment criterion

<table>
<thead>
<tr>
<th>Model</th>
<th>$r^2$</th>
<th>CE, %BF</th>
<th>TE, %BF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siri 2C</td>
<td>0.783</td>
<td>5.15</td>
<td>5.929</td>
</tr>
<tr>
<td>Lohman age-adjusted</td>
<td>0.778</td>
<td>1.14</td>
<td>3.387</td>
</tr>
<tr>
<td>3C-min</td>
<td>0.812</td>
<td>0.40</td>
<td>2.956</td>
</tr>
<tr>
<td>3C-H2O</td>
<td>0.990</td>
<td>0.75</td>
<td>0.880</td>
</tr>
<tr>
<td>DEXA</td>
<td>0.713</td>
<td>1.88</td>
<td>4.421</td>
</tr>
<tr>
<td>Slaughter T+C</td>
<td>0.610</td>
<td>0.31</td>
<td>4.898</td>
</tr>
<tr>
<td>Slaughter T+S</td>
<td>0.621</td>
<td>0.10</td>
<td>4.788</td>
</tr>
<tr>
<td>Houtkooper et al. BIA</td>
<td>0.434</td>
<td>0.68</td>
<td>5.340</td>
</tr>
<tr>
<td>Boileau BIA</td>
<td>0.402</td>
<td>−2.18</td>
<td>6.065</td>
</tr>
</tbody>
</table>

Values are for 47 subjects. CE, constant error; TE, total error; BF, body fat; 2C, 2-compartment model; 3C, 3-compartment model; 3C-min, 3C mineral-density model; 3C-H2O, 3C water-density model; DEXA, dual-energy X-ray absorptiometry; Slaughter T+C and T+S, Slaughter et al. equations that utilize the triceps and subscapular skinfolds, respectively; BIA, bioelectrical impedance.

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The $r^2$, CE, and TE for %BF for each of the body composition models compared with the 4C model are shown in Table 4. The $r^2$ ranged from 0.990 (3C-H2O) to 0.402 (Boileau BIA). As shown by the CE, the Houtkooper et al. and the Boileau BIA equations underpredicted the %BF by a mean of 0.68 and 2.18 %BF, respectively. All of the other models and equations overpredicted the %BF by varying amounts. As expected, the CE of the Siri 2C model was significantly greater than all other models. The CE of the Boileau BIA equation was significantly different from all other equations except the Houtkooper et al. BIA equation. The TE reflects the difference between the actual (criterion 4C) and predicted %BF values (i.e., reflects dispersion around the line of identity) (30). The TE ranged from 0.88 %BF (3C-H2O) to 6.07 %BF (Boileau BIA). The TE of the 3C-H2O equation was 2.36- to 5.89-fold lower than the TE values derived from the other models and equations.

The Siri 2C model overpredicted the %BF by 5.15% and had a large amount of variation around the mean bias (Fig. 1A). The error of some predictions was beyond the large ±2 SD limits of agreement. The overprediction of %BF by the Siri 2C model was dependent on the %BF ($r^2 = 0.15, P = 0.007$) and produced larger overpredictions at lower %BF. Furthermore, the bias was greater in the male than in the female subjects (Table 5). Use of the age-adjusted constants of Lohman in the Siri 2C model (Fig. 1B) reduced the bias to a mean overprediction of 1.14 %BF. The limits of agreement (Fig. 1B) were still large, ranging from a 5% underestimation to an 8% overestimation of %BF. Several data points were near or beyond the large ±2 SD limits of agreement. Similar to the Siri 2C model, the bias was greater in the male than in the female subjects, and the overprediction of %BF was dependent on the %BF ($r^2 = 0.08, P = 0.06$). At the upper end of the range for %BF, only one estimate was above the mean difference. The maturational difference in bias approached (P = 0.09) significance (Table 5). Correction for the proportional mineral composition (3C-min, Fig. 2A) also reduced the mean overprediction bias (0.40 %BF) but did not improve the agreement beyond that of the age-adjusted equations of Lohman. The Siri 3C-H2O model (Fig. 2B) had a mean overprediction of 0.75 %BF and the narrowest limits of agreement (2SD = ±0.99 %BF). The limits of agreement of the 3C-H2O equation were 5.16-fold lower than that of the 3C-min model, which had the next smallest limits of agreement. All but nine of the %BF difference scores for the 3C-H2O model were within ±1 SD. The bias tended to be larger in the prepubertal subjects (P = 0.08, Table 5). The DEXA model (Fig. 2C) produced a mean overprediction bias of −1.88 %BF and, except for the skinfold and BIA models, the limits of agreement (2SD = ±8.30 %BF) were larger than any of the other models tested. When the estimates of %BF for all subjects were combined into one group (data not shown), the %BF by DEXA was significantly greater than by the 4C model.

The skinfold equations also reduced the bias relative to the 2C Siri model. The Slaughter T+C and Slaughter
Table 5. Mean bias and \( \pm 2 \) SD limits of agreement for %BF by gender and pubertal stage

<table>
<thead>
<tr>
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<th>Males (n = 24)</th>
<th>Females (n = 23)</th>
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<tbody>
<tr>
<td></td>
<td>Genital I &amp; II</td>
<td>Genital III &amp; IV</td>
</tr>
<tr>
<td>Siri 2C*</td>
<td>-6.28 ± 6.10</td>
<td>-6.86 ± 6.61</td>
</tr>
<tr>
<td>Lohman age adjusted*</td>
<td>-1.53 ± 6.28</td>
<td>-3.91 ± 6.77</td>
</tr>
<tr>
<td>3C-Min</td>
<td>-0.82 ± 6.06</td>
<td>-1.47 ± 6.56</td>
</tr>
<tr>
<td>3C-H2O</td>
<td>-0.87 ± 0.96</td>
<td>-0.77 ± 1.04</td>
</tr>
<tr>
<td>DEPA</td>
<td>-1.13 ± 8.41</td>
<td>-3.43 ± 9.09</td>
</tr>
<tr>
<td>Slaughter T + C*</td>
<td>-0.70 ± 9.81</td>
<td>-4.06 ± 10.58</td>
</tr>
<tr>
<td>Slaughter T + S</td>
<td>-0.52 ± 9.81</td>
<td>-2.83 ± 10.58</td>
</tr>
<tr>
<td>Houtkooper et al BIA</td>
<td>0.87 ± 10.96</td>
<td>-2.61 ± 12.94</td>
</tr>
<tr>
<td>Boileau BIA*†</td>
<td>2.46 ± 11.21</td>
<td>-3.39 ± 14.82</td>
</tr>
</tbody>
</table>

Values are means ±2SD. n. No. of subjects. For each comparison, bias is %BF from criterion 4-compartment method minus %BF from alternative method. *Significant gender effect, P ≤ 0.05. †Significant maturation effect, P ≤ 0.05.

DISCUSSION

The ability of existing body composition equations to predict %BF was tested in children and adolescents. All were validated against a 4C model of body composition that reduces error by accounting for individual and maturational differences in the proportions of water and mineral to the FFM. Except for the Siri 2C equation, all of the equations tested were based directly on, or originally validated against, a multicompart- ment model of body composition. Our results indicate that the mean estimates of %BF from the Siri 2C model and DEXA were significantly greater than the criterion 4C model. Comparison of the limits of agreement (±2SD of the mean bias, Figs. 1–4) demonstrated that the 3C-H2O model agreed with the 4C model at least 5.16-fold better than the other models and equations. Except for the 3C-H2O model, the limits of agreement with the 4C model were large and the models did not perform well for the individual.

The proportional composition of the FFM and DFFM data presented here (Table 3) compare favorably with previous investigations of children and adolescents and support the validity of our 4C model and the results presented herein. The TBW/FFM of prepubertal boys and girls has been reported to range from 73.1 to 76.2% and from 72.2 to 77.0%, respectively, while the TBW/FFM of pubertal boys and girls ranges from 74.2 to 75.0% and from 74.0 to 75.5%, respectively (3, 8, 10, 13, 15, 31). The M/FFM has also been previously reported to be greater in girls (5.0%) than in boys (4.9%) at age 10.5 yr and to not increase substantially in boys between ages 10.5 and 13.5 yr (8, 9, 31). The M/FFM of prepubertal girls increases from 5.3% at 12.5 yr to as much as 7.0% by 14.5 yr (31).

The mean DFFM of the present study also agrees with previously reported ranges. The DFFM of boys and girls aged 9–10.5 yr ranges from 1.084 to 1.089 g/ml and from 1.082 to 1.087 g/ml, respectively. The DFFM of boys and girls aged 13–14 yr ranges from 1.078 to 1.074 g/ml and from 1.072 to 1.073, respectively (2, 3, 8, 9, 14).

The overestimation of %BF in prepubertal and pubertal boys and girls by the Siri 2C equation is due to an assumed constant TBW/FFM of 73.2% and M/FFM of 6.8%, resulting in a constant DFFM of 1.11 g/ml (4). For instance, the Siri 2C model overpredicted the %BF more for boys than for girls but comparison of the DFFM data (Table 3) shows the girls had DFFM closer to the assumed 1.1 g/ml. Several 3C models of body composition have been developed to correct for individual and maturational differences in the TBW/FFM and M/FFM. However, these models require cross-validation in diverse subject populations (2). Correction for M (3C-min model, Fig. 2) reduced the bias to 0.40 %BF compared with 5.15 %BF for the Siri 2C model. However, the TE of the 3C-min model was 2.36-fold higher than the 3C-H2O equation and, in toto, the 3C-H2O model performed much more accurately than did the 3C-min model (Fig. 2). The 3C-min model (Fig. 2) did not appreciably improve the agreement (2SD = + 6.06 %BF) beyond that of the Lohman age-adjusted equations (Fig. 1, discussed below). Thus the 3C-min model, which requires a radiation exposure (albeit small), does not perform well at the individual level and does not improve the prediction accuracy of body composition in children beyond the less-invasive age-adjusted equations of Lohman.
Correction for the TBW may more accurately assess %BF than correction for M because water accounts for 74–79% and mineral a relatively small 4–7% of the FFM (26). Viewed from another perspective, the SD of the CE between the 4C and 3C-H2O models was 0.49 %BF, which is the reduction in error variability by including a mineral component in the 4C model (24). The SD of the CE between the 4C and 3C-min model was 3.02 %BF.

Despite the high agreement between the 3C-H2O and criterion 4C models (Fig. 2), the bias was dependent (P = 0.08) on the maturation of the subjects (Table 5). This may be due to the 3C-H2O model not correcting for the M/FFM. The M/FFM of the prepubertal subjects was farther from the assumed constant than in the pubertal subjects. However, the mean bias was small in all subject groups, and the ±2SD limits of agreement were <1 %BF. Thus our data support the conclusions of Siconolfi et al. (24) and Lohman (14) that the 3C-H2O model is a valid predictor of %BF. The data do not support use of the 3C-min model as a criterion method in children and adolescents.

Although the multicompartment models offer advantages in accuracy, many investigators cannot utilize them because of cost and technical constraints. Thus Lohman (13) published age-adjusted constants for the Siri 2C equation. These equations have been described as a criterion method (4, 13) and have been used to validate (12, 16) other methods. The Lohman age-adjusted equations reduced the overprediction by the Siri 2C model (Fig. 1). However, the limits of agreement were large and very similar to the Siri 2C equation (Fig. 1). The Lohman equations assume a greater DFFM.
than found in the boys in the present study, which resulted in the overestimation of the %BF (Table 5). In addition, the bias of the Lohman equations tended (r = 0.28, P = 0.06) to be dependent on the %BF and generally overestimated the %BF of males with <12 %BF.

Thus the Lohman age-adjusted equations should not be used to validate new or preexisting equations because, as shown in Fig. 1, if the TBW/FFM or M/FFM of a child differs from the average for that age and gender, a large prediction error can occur (13). As suggested by Lohman (13), to further refine these equations, future investigations should continue to report the water and mineral fractions of the FFM. Refined equations will be needed for use with children, and new skinfold equations should be developed and validated by using either the 3C-H2O or 4C models of body composition.

Unfortunately, there are few, if any, appropriate skinfold equations for use with children, and new skinfold equations should be developed and validated by using either the 3C-H2O or 4C models of body composition. The lack of agreement for %BF between the Houtkooper et al. (11) and Boileau (2) BIA equations and the 4C model (Fig. 4) is surprising because they were validated against a 4C model. In addition to large limits of agreement, the bias of both BIA equations was dependent on the %BF. Both equations overestimated the %BF of lean subjects (males) and underestimated the %BF of fatter individuals. When originally validated, the Houtkooper et al. BIA equation predicted the FFM with an \( r^2 \) of 0.95, SE of estimate (SEE) of 2.1 kg, and a CV of 5.1%. With use of FFM as the prediction variable in the present study, the \( r^2 \) was 0.91, SEE was 2.8 kg, and the TE was 2.43 kg FFM. The Houtkooper et al. BIA equation overpredicted the FFM by a mean of 0.36 kg with a ±2SD limit of agreement of 5.06 kg. Some of the interstudy differences could be due to the use of the Valhalla BIA analyzer in the present study while Houtkooper et al. used an RJL analyzer. The importance of choosing the same analyzer that was used to develop the prediction equations has been previously discussed (6), Boileau (2) reported separate equations for Valhalla and RJL instruments. For the Boileau Valhalla equation, the SEE was 1.75 kg FFM. In the present study, the \( r^2 \), SEE, and TE were 0.88, 2.3 kg FFM, and 2.62 kg FFM, respectively. The Boileau equation produced a mean overestimation of 0.58 kg FFM and the ±2 SD limits of agreement were significantly different from zero.

An important element of body composition research is to develop field methods such as anthropometry and BIA that permit accurate body composition assessments in clinical, educational, and health club settings. Slaughter et al. (28) published skinfold equations that were validated against a 4C model. However, they have not been adequately cross-validated by using a multicompartiment model of body composition. In the present study, the skinfold equations did not perform well for the individual. Reilley et al. (20) cross-validated the Slaughter \( T+S \) equation against a modification of the Siri 2C model and also found large limits of agreement. For male subjects, the Slaughter \( T+S \) equation overestimated %BF by ~3.5% with ±2SD limits of agreement of ~7% BF. For female subjects, Slaughter \( T+S \) underestimated %BF by ~2.5% with limits of agreement of 12% BF. Thus the Slaughter et al. (28) skinfold equations, which were thought to be the most accurate for children and adolescents, require further refinement.
5.64 kg. The Boileau equation produced more bias in girls, especially prepubertal girls.

In conclusion, all of the models and equations tested reduced the bias of the Siri 2C model for the determination of %BF in children and adolescents. However, except for the 3C-H$_2$O model, on a child by child basis there is generally low agreement between the 4C model estimates of %BF and estimates that (1) correct for the M/FFM (3C-min model), (2) correct for average amounts of TBW/FFM and M/FFM (Lohman age-adjusted equations, 3) are based on the DEXA method and, 4) are based on skinfolds and BIA. Investigators can have high confidence when using the 3C-H$_2$O model, and it can be used as the criterion method in validation studies. The same conclusion cannot be made for the 3C-min model. The Lohman age-adjusted equations predict as well as DEXA and the 3C-min model, so the expense and radiation of the necessary DEXA scan can be avoided. Because of general lack of agreement, investigators and clinicians must be careful when estimating %BF in children. New equations must be developed and validated against a criterion 4C model. Because of the inability of the current models to predict %BF of children on an individual basis, the practice of making %BF predictions must be addressed. Until more accurate equations are developed, investigators and health care professionals who do not have access to the 3C-H$_2$O model may want to consider using a sum of skinfolds in conjunction with the height and weight rather than reporting an errant %BF.

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