Comparison of body composition methods in overweight and obese children

P. J. Gately, D. Radley, C. B. Cooke, S. Carroll, B. Oldroyd, J. G. Truscott, W. A. Coward, and A. Wright

Comparison of body composition methods in overweight and obese children. J Appl Physiol 95: 2039–2046, 2003; 10.1152/japplphysiol.00377.2003.—The objective of the present study was to investigate the accuracy of percent body fat (%fat) estimates from dual-energy X-ray absorptiometry, air-displacement plethysmography (ADP), and total body water (TBW) against a criterion four-compartment (4C) model in overweight and obese children. A volunteer sample of 30 children (18 male and 12 female), age of (mean ± SD) 14.10 ± 1.83 yr, body mass index of 31.6 ± 5.5 kg/m² and %fat (4C model) of 41.2 ± 8.2%, was assessed. Body density measurements were converted to %fat estimates by using the general equation of Siri (ADPSiri) (Siri WE. Undernutrition in Starvation. In: Proceedings of the 4th International Conference on Nutrition. UNESCO, New York, 1961) of 41.2 ± 8.2%, was assessed. Body density measurements were converted to %fat estimates by using the general equation of Siri (ADPSiri) (Siri WE. Techniques for Measuring Body Composition. 1961) and the age- and gender-specific constants of Lohman (ADPLoh) (Lohman TG. Exercise and Sport Sciences Reviews. 1986). TBW measurements were converted to %fat estimates by assuming that water accounts for 73% of fat-free mass (TBW73) and by utilizing the age- and gender-specific water contents of Lohman (TBWloh). All estimates of %fat were highly correlated with those of the 4C model (r ≥ 0.95, P < 0.001; SE ≤ 2.14). For %fat, the total error and mean difference ± 95% limits of agreement compared with the 4C model were 2.50, 1.8 ± 3.5 (ADPSiri); 1.82, −0.04 ± 3.6 (ADPLoh); 2.86, −2.0 ± 4.1 (TBW73); 1.90, −0.3 ± 3.8 (TBWloh); and 2.74, 1.9 ± 4.0 DXA (dual-energy X-ray absorptiometry), respectively. In conclusion, in overweight and obese children, ADPLoh and TBWloh were the most accurate methods of measuring %fat compared with a 4C model. However, all methods under consideration produced similar limits of agreement.

dual-energy X-ray absorptiometry; air-displacement plethysmography; total body water; four-compartment model

ADULT OBESITY IS RECOGNIZED as a major public health problem for the 21st century, its association with cardiovascular disease and Type 2 diabetes having been well documented. Although it was once believed that the consequences of obesity were only evident in adults, recent findings suggest a range of risk factors is evident in the overweight pediatric population (17). Coupled with the increasing prevalence of pediatric obesity (6, 34, 41, 45), it is now vital that effective intervention strategies are developed. Key to this development is the identification and use of reliable, precise, and accurate methods to assess body composition and determine the efficacy of treatment programs.

In recent years, technological advances have permitted the development of multicompartment models for body composition measurement. Within the four-compartment (4C) model, the fat-free mass (FFM) is divided into its constituent parts, namely water, mineral, and protein. The 4C model incorporates independent measurements of bone mineral content (BMC), total body water (TBW), and body density (Dh) to formulate a body fat measurement. 4C analysis is now considered the “gold standard” for body composition analysis. However, it is not practical for clinical measurements in most settings because the process is costly and time consuming.

Traditionally, two-compartment (2C) models, such as densitometry and hydrometry, have been commonly utilized as reference methods for body composition assessment in children. However, a major weakness in the application of 2C model techniques is the inherent assumptions regarding FFM, namely the stable proportions of its major constituents (water, mineral, and protein) and assumed constant density.

More recently, dual-energy X-ray absorptiometry (DXA) has been introduced and rapidly utilized as a criterion method of body composition assessment (4, 14). To date, only a handful of studies in children have evaluated the accuracy of 2C model analysis and DXA measurements utilizing a criterion 4C model (15, 42, 43, 49, 50). None of these studies have focused specifically on overweight and obese subjects. Bray et al. (4), however, have analyzed 4C model measurements in leaner [body mass index (BMI) 16.42 ± 0.16 kg/m²] and fatter (BMI 22.15 ± 0.45 kg/m²) children separately, against the DXA method.

The aim of the present study was to determine the accuracy of percent body fat (%fat) estimates from
simple and widely used 2C models against %fat derived by a criterion 4C model in overweight and obese children. Second, consideration was given to the agreement between %fat derived by the 4C model and DXA.

METHODS

Subjects. Thirty children (18 male and 12 female) participated in the study. Criteria for inclusion were based on subjects being classified as overweight or obese according to international cutoff points for BMI (9). Subjects were recruited from the local community by advertisement in newspapers and general practice surgeries. The main characteristics of the sample are shown in Table 1. The ranges for age, height, and weight were 11.1–17.2 yr, 1.40–1.79 m, and 46.0–111.8 kg, respectively. All measurements were performed on the same day within a 6-h period with subjects in a fasted state. The study protocol was approved by Leeds Teaching Hospital Research Ethics Committee, and both participant written, informed assent and parental/guardian written, informed consent were obtained before testing.

Height and weight. Body mass was measured to the nearest 0.01 kg by using calibrated electronic scales, with participants wearing swimsuits. Stature was measured to the nearest 0.1 cm by using a floor-standing Seca stadiometer (model 220), with subjects standing erect without shoes. BMI was calculated as weight/height$^2$, where weight is expressed in kilograms and height in meters (39).

DXA. DXA measurements of the total body were made by using a Prodigy fan-beam densitometer (GE/Lunar, Madison, WI) (31, 33). The Prodigy utilizes a narrow fan beam (4.5") oriented parallel to the longitudinal axis of the body. A dual-energy X-ray source with peak X-ray energy of 80 kVp and a current of 3 mA with a K-edge filter (cerium 200 mg/cm$^2$) gives effective energies of 38 and 70 keV. The detector consists of an array of energy-sensitive Cadmium Zinc Telluride detectors of length 5 cm (16 elements each 3 mm wide), allowing rapid photon counting. Imaging is typically over a 24-mm length with longitudinal steps of 17 mm. Pixel size for total body standard photon counting. Imaging is typically over a 24-mm length with length 5 cm (16 elements each 3 mm wide), allowing rapid repositioning, on the same day is 2.7% (data not shown).

Measurement of %fat in 10 adult subjects measured twice, with percent of variation for measurement of %fat is 4.0% (data not shown).

Table 1. Subject characteristics

<table>
<thead>
<tr>
<th></th>
<th>All Subjects (n = 30)</th>
<th>Males (n = 18)</th>
<th>Females (n = 12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, yr</td>
<td>14.10 ± 1.83</td>
<td>13.99 ± 1.54</td>
<td>14.27 ± 2.27</td>
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<tr>
<td>Body mass, kg</td>
<td>83.57 ± 17.72</td>
<td>86.79 ± 17.74</td>
<td>78.74 ± 17.30</td>
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<tr>
<td>Height, m</td>
<td>1.63 ± 0.09</td>
<td>1.65 ± 0.09</td>
<td>1.60 ± 0.09</td>
</tr>
<tr>
<td>BMI, kg/m$^2$</td>
<td>31.56 ± 5.01</td>
<td>32.14 ± 6.43</td>
<td>30.68 ± 3.77</td>
</tr>
<tr>
<td>4C body fat, %</td>
<td>41.23 ± 8.15</td>
<td>40.16 ± 9.11</td>
<td>42.84 ± 6.51</td>
</tr>
<tr>
<td>4C FFM, kg</td>
<td>48.64 ± 10.33</td>
<td>51.49 ± 11.26</td>
<td>44.38 ± 7.22</td>
</tr>
<tr>
<td>4C FM, kg</td>
<td>34.93 ± 11.43</td>
<td>35.30 ± 11.53</td>
<td>34.37 ± 11.75</td>
</tr>
<tr>
<td>BMC, kg</td>
<td>2.55 ± 0.53</td>
<td>2.55 ± 0.52</td>
<td>2.56 ± 0.57</td>
</tr>
<tr>
<td>TBW, liters</td>
<td>36.61 ± 7.24</td>
<td>38.41 ± 7.89</td>
<td>33.91 ± 5.15</td>
</tr>
<tr>
<td>TBW/FFM, %</td>
<td>6.48 ± 0.91</td>
<td>6.13 ± 0.85</td>
<td>7.00 ± 0.73</td>
</tr>
<tr>
<td>TBW/FFM, %</td>
<td>75.57 ± 2.86</td>
<td>74.91 ± 2.79</td>
<td>76.57 ± 2.67</td>
</tr>
</tbody>
</table>

Values are means ± SD. BMI, body mass index; FFM, fat-free mass; FM, fat mass; BMC, bone mineral content; TBW, total body water; TBM, total body mineral; D$_{fmm}$, density of the FFM; 4C, 4-compartment model.

%fat is calculated using a cylinder of known volume (50.146 liters) and manual calibration of the scales, using two 10-kg weights, was performed. After the calibration, subjects were weighed, then entered the Bod Pod chamber wearing only a tight-fitting swimsuit and swim cap. To calculate raw $V_b$, two 50-s measurements were performed. If these measurements were within 150 ml they were accepted and the mean volume used for further calculations. If, however, they differed by >150 ml, a third test was administered. If two of the three measurements fell within 150 ml, their mean was used for calculations, if not, the whole process including calibration was repeated.

Actual $V_b$ was computed by the computer software and corrected for a surface area artifact (a term used to correct for the effects of isothermal air near the subject’s body surface) and thoracic gas volume ($V_{tg}$) (12). $V_{tg}$ was calculated by the supplied software using the functional residual capacity equations of Crapo et al. (11) and assumed tidal volume falling within 150 ml; their mean was used for further calculations. If, however, they differed by >150 ml, a third test was administered. If two of the three measurements fell within 150 ml, their mean was used for calculations, if not, the whole process including calibration was repeated.

To obtain %fat estimates, $V_b$ was first converted to $D_b$ (body mass/$V_b$). %Fat was then calculated by using the general equation of Siri (47) (ADPSiri), and the age- and gender-specific equations of Lohman (27) (ADP_Loh). All equations are of the form

%fat = \left( \frac{X}{D_b} - Y \right) \times 100

where $X$ and $Y$ are constants derived from the equation

%fat = \left( \frac{1}{D_b} \left( \frac{d_2}{d_1} - \frac{d_2}{d_1} \right) \right) \times 100

where $d_2$ represents the constant density of fat (0.9 g/cm$^3$) and $d_1$ represents the assumed density of the FFM ($D_{fmm}$) compartment as given by Siri (47) and Lohman (27).

In our laboratory, the between-trial coefficient of variation for measurement of %fat in 44 overweight and obese adolescents (BMI, 30.52 ± 5.61 kg/m$^2$) measured twice on the same day is 4.0% (data not shown).

TBW. TBW was determined by $^2$H$_2$O dilution using saliva samples. A baseline saliva sample was collected, and then a dose of 0.35 mol $^2$H$_2$O in 100 ml water was orally administered. The exact amount of dose given was determined by weighing the dosing bottle before and after administration. Further saliva samples were then collected at 4, 5, and 6 h postdose.

$^2$H enrichment in the saliva samples was measured by using isotope ratio mass spectrometry after equilibration.
with H₂ gas, as described elsewhere (22). The precision of the isotope ratio measurements for the predose samples was 0.3 parts/million (ppm) SD at an average value of 151.6 ppm. Corresponding values for the postdose samples were 0.32 ppm SD at 322.1 ppm.

TBW was determined by a plateau method, which assumes equilibration of the administered dose of H₂O throughout the TBW space within the 4- to 6-h period after dosing. The H₂O dilution space was calculated by using previously published equations (38) and reduced by 4% to account for the exchange of deuterium with nonaqueous hydrogen (10, 46). FFM was then estimated by assuming that water accounts for 73% of FFM (35) (TBW₇₃) and utilizing the age- and gender-specific water contents given by Lohman (TBW₉₀) and Altman (2). Potential bias between %fat estimates by each method and 4C analysis was examined by using paired sample t-tests. For all analyses, the alpha level adopted for statistical significance was P < 0.05.

\[
\text{FFM} = \frac{\text{TBW}}{h} \times 100
\]

where h represents the assumed water content of FFM. FM was then calculated as the difference between body mass and FFM. %Fat was then calculated as

\[
\%\text{Fat} = \frac{\text{FM}}{\text{BM}} \times 100
\]

**4C model.** Measurements of body mass, Dᵢ, TBM, and TBW were combined to yield a criterion 4C model estimation of %fat (27)

\[
\%\text{fat} = \left( \frac{2.7474}{D_i} - 0.7145w + 1.1474m - 2.0503 \right) \times 100
\]

where w is TBW (in liters) expressed relative to body mass and m is TBM (in kg) expressed relative to body mass.

The hydration, bone mineral, and TBM fractions of FFM were calculated as TBW/FFM, BMC/FFM, and TBM/FFM, respectively, where FFM was derived from the 4C model. Additionally, the Dᵢₚᵣᵦ was calculated as

\[
D_{\text{frm}} = 1/(w/d_w) + (m/d_m) + (p/d_p)
\]

where w, m, and p represent the water, TBM, and protein fractions of FFM, respectively, and dₙ, d_m, and d_p represent their respective densities of 0.9937, 3.038, and 1.34 g/cm³.

**Statistical analysis.** The relationship between DXA, ADP, Siri, ADP₉₀, TBW₇₃, and TBW₉₀, and 4C analysis %fat estimates were examined by using paired sample t-tests, the correlation coefficient (r) and least squares linear regression. The accuracy of the precision of body fatness by the regression analysis was evaluated by using the coefficient of determination (r²) and the standard error of estimate (SEE). Agreement between body composition estimates was examined by two methods: 1) total error (TE) \( \text{TE} \) = \( \sum \text{y} \cdot \text{y}^\prime/N \), as described by Lohman (26), where Y is % fat method I, Y is % fat method 2, and N is number of subjects; and 2) calculation of the 95% limits of agreement, as described by Bland and Altman (2). Potential bias between %fat estimates by each method and 4C analysis was examined by using residual plots and stepwise regression analysis. This analysis reveals whether differences between %fat estimates were related to variability in the TBW and BMC of FFM. Differences in mean values for the measured and assumed TBW/FFM, TBM/FFM, and Dᵢₚᵦ were examined by paired sample t-tests. For all analyses, the alpha level adopted for statistical significance was P < 0.05.

**RESULTS**

A summary of the results relating to the accuracy of and bias in measurement of %fat as assessed by DXA, ADP₉₀, ADP₉₀, TBW₇₃, and TBW₉₀ relative to the 4C model are presented in Table 2. All %fat estimates using DXA, air-displacement plethysmography (ADP), and TBW were significantly correlated with 4C %fat (males: all r ≥ 0.98, P < 0.001; females: all r ≥ 0.95, P < 0.001). Furthermore, the variation around the regression line was similar for all methods (males: 1.61–2.06%; females: 1.68–2.14%).

Comparing all subjects, mean ± SD %fat determined by ADP₉₀ (41.2 ± 8.5%) and TBW₇₃ (40.9 ± 8.0%) produced a nonsignificant difference compared with 4C %fat (41.2 ± 8.3%). In contrast, DXA and ADP₉₀ significantly underestimated mean %fat (43.1 ± 7.5%, P < 0.001; 43.0 ± 8.5%, P < 0.001, respectively) as measured by the 4C method, whereas TBW₇₃ significantly underestimated %fat (39.2 ± 8.1%, P < 0.001). Separate analysis of male and female children showed similar findings.

TE, the mean difference between %fat estimates, ranged from 1.59 to 3.27%. In all cases, TBW₇₃ revealed the highest TE (2.55–3.27%) followed by DXA (2.52–3.05%) and ADP₉₀ (2.33–2.74%). In addition, for all methods, female subjects revealed higher TE than male subjects (Table 2).

Summarized in Table 3 and displayed in Fig. 1, the 95% limits of agreement were relatively similar for

<table>
<thead>
<tr>
<th>Method</th>
<th>Means ± SD</th>
<th>r²</th>
<th>Intercept</th>
<th>Slope</th>
<th>SEE</th>
<th>TE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DXA</td>
<td>43.1 ± 7.5</td>
<td>0.94</td>
<td>-4.387</td>
<td>1.058</td>
<td>2.02</td>
<td>2.74</td>
</tr>
<tr>
<td>ADP₉₀</td>
<td>43.0 ± 8.5</td>
<td>0.96</td>
<td>1.021</td>
<td>0.935</td>
<td>1.74</td>
<td>2.50</td>
</tr>
<tr>
<td>ADP₉₀</td>
<td>42.2 ± 8.5</td>
<td>0.95</td>
<td>2.451</td>
<td>0.941</td>
<td>1.81</td>
<td>1.82</td>
</tr>
<tr>
<td>TBW₇₃</td>
<td>39.2 ± 8.1</td>
<td>0.93</td>
<td>3.059</td>
<td>0.973</td>
<td>2.12</td>
<td>2.86</td>
</tr>
<tr>
<td>TBW₇₃</td>
<td>40.9 ± 8.0</td>
<td>0.95</td>
<td>0.653</td>
<td>0.991</td>
<td>1.95</td>
<td>1.90</td>
</tr>
<tr>
<td>TBW₉₀</td>
<td>38.6 ± 9.5</td>
<td>0.95</td>
<td>3.991</td>
<td>0.937</td>
<td>2.06</td>
<td>2.55</td>
</tr>
<tr>
<td>TBW₉₀</td>
<td>40.1 ± 9.4</td>
<td>0.96</td>
<td>1.978</td>
<td>0.953</td>
<td>1.89</td>
<td>1.84</td>
</tr>
</tbody>
</table>

| DXA    | 40.2 ± 9.1 | 0.96 | -3.902    | 1.054 | 1.97 | 2.52 |
| ADP₉₀  | 41.9 ± 9.2 | 0.97 | 0.769     | 0.976 | 1.61 | 2.33 |
| ADP₉₀  | 40.4 ± 9.0 | 0.97 | 0.001     | 0.994 | 1.67 | 1.59 |
| TBW₇₃  | 38.6 ± 9.5 | 0.95 | 3.991     | 0.937 | 2.06 | 2.55 |
| TBW₉₀  | 40.1 ± 9.4 | 0.96 | 1.978     | 0.953 | 1.89 | 1.84 |

| DXA    | 42.8 ± 6.5 | 0.90 | -8.038    | 1.129 | 2.14 | 3.05 |
| ADP₉₀  | 45.1 ± 5.5 | 0.93 | 5.560     | 0.835 | 1.86 | 2.74 |
| ADP₉₀  | 42.4 ± 7.8 | 0.94 | 8.334     | 0.914 | 1.68 | 2.11 |
| TBW₇₃  | 40.2 ± 5.7 | 0.91 | -0.974    | 1.090 | 2.03 | 3.27 |
| TBW₉₀  | 42.2 ± 5.5 | 0.92 | -5.261    | 1.139 | 1.93 | 2.00 |

DXA, dual-energy X-ray absorptiometry; ADP₉₀, air-displacement plethysmography according to Siri with equation (47); ADP₉₀, air-displacement plethysmography according to Lohman with equation (27); TBW₇₃, total body water (TBW) assuming water is 73% of total body weight. *P < 0.05. †P < 0.01. ‡P < 0.001.
Residual plot comparisons considered whether differences between methods and criterion 4C %fat estimates were related to the hydration and bone mineral fractions of the FFM. In all cases, the relationship with the hydration fraction was greater than with the bone mineral fraction. Consequently, stepwise multiple regression analysis was used to assess the additional variance explained by the bone mineral fraction beyond that explained by the hydration fraction (Table 4).

DISCUSSION

Until relatively recently, 2C analysis of body composition was considered the gold standard against which simpler techniques such as skinfold calipers, circum-

<table>
<thead>
<tr>
<th></th>
<th>All Subjects (n = 30)</th>
<th>Males (n = 18)</th>
<th>Females (n = 12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DXA</td>
<td>1.9 ± 4.0</td>
<td>1.7 ± 3.8</td>
<td>2.2 ± 4.4</td>
</tr>
<tr>
<td>ADP&lt;sub&gt;Siri&lt;/sub&gt;</td>
<td>1.8 ± 3.5</td>
<td>1.8 ± 3.1</td>
<td>1.8 ± 4.2</td>
</tr>
<tr>
<td>ADP&lt;sub&gt;Loh&lt;/sub&gt;</td>
<td>−0.04 ± 3.6</td>
<td>0.2 ± 3.2</td>
<td>−0.4 ± 4.2</td>
</tr>
<tr>
<td>TBW&lt;sub&gt;73&lt;/sub&gt;</td>
<td>−2.0 ± 4.1</td>
<td>−1.6 ± 4.0</td>
<td>−2.7 ± 3.9</td>
</tr>
<tr>
<td>TBW&lt;sub&gt;Loh&lt;/sub&gt;</td>
<td>−0.3 ± 3.8</td>
<td>−0.1 ± 3.7</td>
<td>−0.6 ± 3.9</td>
</tr>
</tbody>
</table>

Table 3. Mean difference (method minus 4C model) ± 95% limits of agreement between each method and 4C model %fat estimates

Fig. 1. Bland and Altman plots comparing percent body fat (%fat) determined by the 4-compartment (4C) model and dual-energy X-ray absorptiometry (DXA; A), Siri (47) air-displacement plethysmography (ADP<sub>Siri</sub>; B), Lohman (27) air-displacement plethysmography (ADP<sub>Loh</sub>; C), total body water measurements assuming that water accounts for 73% of total body weight (TBW<sub>73</sub>; D), and Lohman (27) total body water (TBW<sub>Loh</sub>; E) in all overweight/obese subjects. ■, Male subjects; △, female subjects.
ference measurements, and bioelectrical impedance analysis were validated (23, 51). However, 2C analysis may itself not be valid, especially in overweight and obese children. The present study was designed to investigate the ability of two commonly utilized 2C techniques, namely densitometry and hydrometry, to accurately assess %fat in overweight and obese children compared with a 4C criterion measure. In addition, consideration was given to DXA, a technique becoming more frequently used as a criterion measure (4, 14).

In the present study, conversion of D∞ using the age- and gender-specific equations of Lohman (27) resulted in mean %fat estimates that showed better agreement with the 4C model compared with the general equation of Siri (47) (Table 2). Roemmich et al. (43) reported similar findings in 47 children, aged 8.5–15.4 yr, compared with a 4C model that used hydrostatic weighing (4C-HW) as the measure for D∞. In their studies, for all subjects, the Siri (47) and Lohman (28) equations overestimated mean %fat by 5.15 and 1.14%, respectively. These findings are to be expected, because the Siri conversion equation is derived from the analysis of three adult male cadavers and assumes a D∞min of 1.100 g/cm³ on the basis of water, protein, osseous mineral, and nonosseous mineral FFM fractions of 73.8, 19.4, 5.6, and 1.2%, respectively (5, 47). However, in children, variation in the hydration (3) and mineral fractions (30) of FFM is high, resulting in an unstable D∞min throughout growth. The Lohman (27) equations, based on age and gender, allow for changes in the FFM constituents and were, therefore, likely to give more accurate %fat estimates.

Furthermore, the Lohman (27) equations also resulted in lower TE in both male and female subjects (Table 2). The TE represents the mean sample error between techniques and has been suggested as the best single measure for evaluating differences between a new and criterion measure (7). Consistent with our findings, Roemmich et al. (43) showed a TE of 5.9% between Siri (47) and 4C %fat was reduced to 3.4% when the Lohman (28) equations were utilized. It is important to note, however, that TE makes no allowance for a constant measurement bias. Accordingly, the standard error and 95% limits of agreement were similar for ADPSiri and ADPcoh, compared with the 4C model, ranging from 1.61 to 1.86% and ±3.1 to ±4.2, respectively. Roemmich et al. also reported similar limits of agreement for the Siri and Lohman equations, ranging from ±5.77 to ±6.77, compared with a 4C-HW model.

To further assess 2C ADP %fat estimates, consideration was given to the relationship between differences in ADP and 4C %fat and the hydration and bone mineral fractions of FFM. In both male and female subjects, the relationship with TBW/FFM was positive and statistically significant (r ≥ 0.68, P < 0.01). In contrast, the association between mean differences and BMC/FFM was not significant for both ADP equations. However, stepwise multiple regression analysis revealed that BMC/FFM explained significant additional variance for differences between ADPSiri and 4C %fat in both male and female subjects, whereas differences between ADPcoh and 4C %fat explained significant additional variance in male subjects only (Table 4). These results are in accordance with previous findings in adults, which suggest that variation in the hydration fraction of the FFM is the key element in the %fat error between a 2C densitometric model compared with 4C analysis (8, 48). It should be considered, however, that in the determination of the hydration and mineral fractions of the FFM, TBW and BMC measurements are used both in the numerator and denominator. As such, any differences between 2C and 4C %fat estimates are partly due to the weighting of the water and bone mineral constituents within the 4C model equation (29).

To our knowledge, the present study is the first to compare 2C and 4C %fat estimates in overweight and obese children. Furthermore, there are limited data available on the proportional fractions of FFM in obese children. Battistini et al. (1), in obese children aged 8–13 yr, found a relative expansion in ECW. However, in our sample of obese children, the mean hydration fraction of the FFM was nonsignificantly higher in male (0.1%) and female subjects (1%) compared with the values assumed for “normal” weight subjects (Table 5). Consistent with the proposal of Fuller and Elia (18), Goulding et al. (19) reported a higher BMC fraction of the lean tissue mass in obese children compared with normal weight controls in both male and female subjects. However, in the present study, the mean bone mineral and thus TBM fraction of the FFM in our sample (males 6.1%; females 7.0%) was greater than that assumed by the Lohman (27) equations in female subjects only (males 6.1%; females 5.9%). It should be noted that the numbers in our sample were relatively small, and thus our findings may not be universally applicable. Further investigation is required.
The final method to be evaluated in the present study was DXA. In both male and female subjects, DXA significantly overestimated mean %fat (41.8 ± 8.4 and 45.1 ± 5.5%, respectively; both P < 0.01) compared with 4C analysis (40.2 ± 9.1 and 42.8 ± 6.5%, respectively). These findings are consistent with those previously found in children where DXA was compared with 4C-HW models. Roemmich et al. (43) reported that DXA overestimated mean %fat by between 1.13 and 3.43%, with the magnitude of error differing for gender and maturational stage groups, but not in a consistent pattern. Bray et al. (4) reported a DXA overestimation of 1.06% fat in leaner subjects and 3.22% in fatter subjects compared with the 4C model proposed by Wells et al. (49). Wong et al. (50) reported that DXA overestimated mean %fat by 3.9% in a group of 141 young female subjects (9–17 yr). In addition, Roche et al. (42) reported that DXA FFM values were significantly less in subjects age 8–25 yr (1.67 kg; P < 0.01) compared with estimates based on a 4C-HW model. In only one study in children has DXA been compared with both a 4C-HW model and a second that utilized ADP to measure D<sub>b</sub> (15) (4C-ADP). In this study, Fields and Goran (15) reported that DXA measured a mean 1.7 kg greater FM than the 4C-HW and 1 kg greater FM than the 4C-ADP model.

Analysis of the individual agreement revealed that DXA had the second highest TE for both male and female subjects (Table 2). In addition, the limits of agreement were slightly higher than all the other methods except TBW<sub>73</sub>. Wells et al. (49) and Roemmich et al. (43) also found that DXA produced larger limits of agreement than other 2C age-adjusted models, compared with a 4C-HW model. In their studies, however, the magnitude of difference between DXA and other 2C models compared with the 4C-HW model were greater than in the present study as were the limits of agreement for all methods under consideration in the present study.

To further assess DXA %fat estimates, consideration was given to the relationship between differences in DXA and 4C %fat and the hydration and bone mineral fractions of FFM. In all cases, the relationship with TBW/FFM (males, r = −0.59, P < 0.05; females, r = −0.84, P < 0.001) was significantly higher than BMC/FFM (males, r = −0.19, P = 0.46; females, r = 0.31, P < 0.33). Stepwise multiple regression analysis revealed that BMC/FFM explained no significant additional variance beyond that explained by TBW/FFM (Table 4). It has been reported that a theoretical variation of 5% in the TBW/FFM would result in a FM error of <0.5 kg (24). However, in a sample of 172 young adults, Prior et al. (37) used regression analysis to show that a 5% variation in TBW/FFM is associated with a 2.7% change in %fat between methods. Regression analysis in the present study indicated a similar effect: a 5% variation in TBW/FFM resulting in a 2.1 and 3.2% change in the difference between methods in male and female subjects, respectively. Thus it would appear that differences between %fat estimates by DXA and 4C analysis are, in part, due to variation in

It is noteworthy that, although in the present study obese female subjects had significantly larger mean TBM/FFM than assumed by the Lohman (27) equations, this did not result in a significantly higher mean D<sub>fm</sub> (Table 5). These findings suggest that even if BMC/FFM is increased in obese subjects, the increase has no significant effect on D<sub>fm</sub> if there is a concomitant increase in the TBW/FFM. Such findings are hardly surprising because the correlation between D<sub>fm</sub> and TBW/FFM was −0.96 and between D<sub>fm</sub> and TBM/FFM was 0.10 (data not shown). Again, as noted previously, caution is warranted when interpreting results that rely on measurements that are not wholly independent.

The large proportion of TBW in the body, the present study also evaluated the use of hydrometry to estimate FFM and thus calculation of %fat. In the present study, conversion of TBW with the use of the age- and gender-specific hydration values of Lohman (27) resulted in mean %fat estimates that agreed better with those determined by the 4C model, compared with the assumed 73% adult hydration fraction proposed by Pace and Rathbun (35) (Table 2). The 73% hydration fraction is lower than would be expected in normal-weight children and was lower than the mean hydration fraction found in the present sample of obese children. Accordingly, TBW<sub>73</sub> overestimated mean FFM and thus underestimated mean %fat. The underestimation was less in male subjects because their TBW/FFM was closer to 73% than female subjects. In addition to mean %fat estimates that agreed better with mean 4C %fat, TBW<sub>Loh</sub> produced lower SEE and TE than TBW<sub>73</sub> in both male and female subjects (Table 2). Again, however, it is important to note that the 95% limits of agreement were similar, ranging from ±3.7 to ±4.1. Stepwise multiple regression analysis revealed that nearly all the variance between TBW and 4C %fat estimates was explained by TBW/FFM (85–97%, all P < 0.001). Only for TBW<sub>Loh</sub> in female subjects did BMC/FFM explain additional significant variance (6%, P < 0.05).

Table 5. Mean constituent fractions and density of the FFM in comparison with the values assumed by the Siri and Lohman equations

<table>
<thead>
<tr>
<th></th>
<th>All Subjects (n = 30)</th>
<th>Males (n = 18)</th>
<th>Females (n = 12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBW/FFM, %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td>75.6</td>
<td>74.9</td>
<td>76.6</td>
</tr>
<tr>
<td>Assumed Lohman</td>
<td>75.1</td>
<td>74.8</td>
<td>75.6</td>
</tr>
<tr>
<td>Assumed Siri</td>
<td>73.8†</td>
<td>73.8</td>
<td>73.8‡</td>
</tr>
<tr>
<td>TBW/FFM, %†</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td>6.5</td>
<td>6.1</td>
<td>7.0</td>
</tr>
<tr>
<td>Assumed Lohman</td>
<td>6.0</td>
<td>6.1</td>
<td>5.9‡</td>
</tr>
<tr>
<td>Assumed Siri</td>
<td>6.8</td>
<td>6.8‡</td>
<td>6.8</td>
</tr>
<tr>
<td>D&lt;sub&gt;fm&lt;/sub&gt;, g/cm&lt;sup&gt;3&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td>1.092</td>
<td>1.092</td>
<td>1.092</td>
</tr>
<tr>
<td>Assumed Lohman</td>
<td>1.092</td>
<td>1.093</td>
<td>1.091</td>
</tr>
<tr>
<td>Assumed Siri</td>
<td>1.100‡</td>
<td>1.100‡</td>
<td>1.100‡</td>
</tr>
</tbody>
</table>

Values are means. Significantly different from measured: *P < 0.05; †P < 0.01; ‡P < 0.001.
the TBW/FFM. Again it must be noted that our sample is small and, as such, results may not be universally applicable. Further investigation is required.

Several other areas have also been identified as potential sources of error when DXA measurements are performed (44). Although it has been reported that some of the sources of potential error have been rectified by the introduction of improved software (25), concern is still warranted regarding the estimation of soft tissue in bone-containing pixels (36). DXA estimates of fat/lean tissue are assumed to be in the same proportion in pixels containing bone as they are in the adjacent non-bone-containing pixels. Furthermore, investigation needs to be initiated to study the effects of increasing tissue thickness on the Prodigy fan-beam densitometer.

In the present study, we have assumed that 4C analysis provides the most accurate estimates of %fat. It is important to remember that there is no true gold standard of body composition analysis. As such, all studies in humans are essentially a comparison between methods, each of which are based on certain assumption and approximations. For a detailed review of the assumptions of the 4C model, see Heymsfield and colleagues (20, 21). In addition to the well-recognized assumptions of the 4C model, two variables that may be construed as limiting factors in the present study are the use of ADP to measure Db and the use of software-predicted estimates of Vtg. The present study is one of the first to use ADP for Db measurement in a 4C model, and to date findings regarding the accuracy of ADP Db measurements are equivocal (16). However, the only study that has considered the accuracy of ADP Db in a 4C model concluded that the use of ADP-derived Db was an acceptable alternative to Db derived by hydrostatic weighing when %fat in a 4C model was estimated (32). In addition, Fields and Goran (15) reported no significant mean difference in FM measurements in children by a 4C-ADP model compared with that derived by 4C-HW. Regarding the second limiting factor of the use of software-predicted Vtg, the literature is equivocal on the importance of this variable as a limiting factor (40). Furthermore, it should be noted that because only 40% of Vtg enters the Bod Pod formula used to calculate Vb, the impact on %fat values is small. An overprediction of 0.5 liters of Vtg for a 70-kg adolescent would result in a 1.4% overestimation in %fat.

Conclusion. In the present study, use of ADP and TBW with the age- and gender-specific values given by Lohman resulted in the most accurate mean %fat estimates in both male and female overweight and obese children compared with the criterion 4C model. However, based on the 95% limits of agreement, all methods evaluated demonstrate similar levels of variability.

As levels of childhood obesity increase, so does the need for practical and accurate methods of body composition analysis. When the accuracy of methods is similar, consideration must also be given to the following areas: precision, information provided, expense, speed, ease of use, invasiveness, and subject compliance. Although 4C analysis may be the preferred method of choice in research institutions, its cost, speed, and reliance on several different techniques make it unsuitable for wide-scale implementation. It is beyond the scope of this study to discuss in detail the practical application of each method, but in a clinical context we believe ADP and DXA to be the most promising methods; both are quick, easy to administer, and require minimal subject compliance. As noted, however, further investigation is required to overcome bias in DXA %fat measurement. TBW does, however, have obvious advantages for body composition assessment in a nonlaboratory setting.

Finally, it is important to realize that although the present study provides information on the accuracy of several body composition measurement methods, further research is required because the true worth of any method will undoubtedly be in its ability to accurately assess longitudinal changes in body composition.

DISCLOSURES

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