Body-composition changes with diet and exercise in obese women: a comparison of estimates from clinical methods and a 4-component model

Ellen M Evans, Michael J Saunders, Marie A Spano, Sigurbjorn A Arngrimsson, Richard D Lewis, and Kirk J Caretton

ABSTRACT

Background: Most methods available to clinicians for estimating body-composition changes have been validated against estimates from densitometry, based on a 2-component (fat mass and fat-free mass) model.

Objective: Estimates of changes in percentage body fat (%BF) from dual-energy X-ray absorptiometry (DXA), skinfold thicknesses (SFTs), bioelectrical impedance analysis (BIA), and body mass index (BMI; in kg/m²) were compared with estimates from a 4-component (fat, water, mineral, and protein) model (%BF₄,w,m,p), a more accurate method.

Design: Determinations of body density from hydrostatic weighing, body water from deuterium dilution, bone mineral and %BF from whole-body DXA, resistance from BIA, and anthropometric measures were made in 27 obese women (BMI: 31.1 ± 4.9) assigned to 1 of 3 groups: control (C; n = 9), diet only (DO; n = 9), or diet plus aerobic exercise (DE; n = 9).

Results: After the 16-wk intervention, changes in body mass (BM) averaged 0.5 ± 2.0, −7.2 ± 7.4, and −4.0 ± 3.3 kg and changes in %BF₄,w,m,p averaged 2.1 ± 1.0%, −1.2 ± 1.4%, and −2.4 ± 1.6% in the C, DO, and DE groups, respectively. Compared with changes in %BF₄,w,m,p, the errors (SD of bias) for estimates of changes in %BF by DXA, BIA, SFTs, and BMI were similar (range: ±2.0–2.4% of BM). BIA, SFTs, and BMI provided unbiased estimates of decreases in %BF₄,w,m,p, but DXA overestimated decreases in %BF in the DO and DE groups.

Conclusions: DXA, BIA, SFTs, and BMI are comparably accurate for evaluating body-composition changes induced by diet and exercise interventions; however, small changes in %BF may not be accurately detected by these clinical methods.

ACCOUNT

Bioelectrical impedance analysis, BIA, body mass index, dual-energy X-ray absorptiometry, DXA, anthropometric measures, skinfold thickness, weight loss, body composition, exercise, humans

INTRODUCTION

Measurement of body composition is important in a variety of clinical situations, including weight management. The primary goal of weight-loss programs is to maximize the loss of fat mass (FM) while preserving fat-free mass (FFM) (1). Valid data on body-composition changes is essential to the prescription and evaluation of the efficacy of clinical weight-loss interventions.

Most methods available to clinicians for estimating body-composition changes, including estimates from dual-energy X-ray absorptiometry (DXA), bioelectrical impedance analysis (BIA), skinfold thicknesses (SFTs), and body mass index (BMI; in kg/m²) have been validated against estimates from densitometry, which has been considered the gold standard of indirect laboratory methods (2). Estimation of body fatness from body density (dₒ) assumes that the density of fat is 0.9 kg/L and that the density of FFM (D_NFM) is 1.1 kg/L (3). The assumption that the D_NFM is 1.1 kg/L is, in theory, based on the assumption that the proportions and densities of the constituents of FFM are uniform across individuals. The SD of ±0.01 kg/L for the D_NFM suggests that its assumed constancy leads to an error in estimating body composition of approximately ±4% in the general population (4).

Body-composition estimates from a 4-component model (fat, water, mineral, and protein) account for variation in the water and mineral fractions of FFM, the largest sources of variability in the D_NFM. Therefore, 4-component models provide more accurate estimates of body composition than do other methods and are a better criterion measure for validating other methods used to estimate body composition (4). Few studies have validated clinical methods used to evaluate changes in body composition resulting from weight loss using estimates from a 4-component model as the criterion (5, 6). Because of the inadequate criteria used to validate these clinical methods, it is possible that they may be more or less accurate for assessing body-composition changes than thought previously.

Research suggests that the composition of the weight lost as a result of diet combined with exercise is different from that lost as a result of energy restriction alone: with the former intervention there is a greater loss of FM, and FFM is maintained (7, 8).

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However, this conclusion is based almost entirely on studies that used laboratory and clinical methods based on a 2-component model to assess body composition. Whether or not clinical methods accurately assess alterations in the composition of the weight lost with diet alone compared with diet plus exercise is unknown. Thus, the purpose of this study was to compare estimates of change in percentage body fat (%BF) from DXA, SFTs, BIA, and BMI with estimates from a 4-component (fat, water, mineral, and protein) model (%BF<sub>d,w,m</sub>) after moderate weight loss induced by diet or diet plus aerobic exercise.

**SUBJECTS AND METHODS**

**(Subjects)**

Women meeting the following inclusion criteria were recruited from the community to participate in the study: a BMI > 27, age 20–40 y, premenopausal, not pregnant or attempting to become pregnant, ≥ 3 mo postpartum, not involved in a structured physical activity program in the month previous to the start of the study, nonsmoking, no known medical or nutritional conditions or medication use known to affect body-composition measures, no known cardiopulmonary or metabolic diseases, no signs or symptoms suggestive of possible cardiopulmonary or metabolic disease, and not currently following a weight-reducing diet. Oral contraceptive users (25.9% of the study subjects) were allowed to participate, although they were required to continue their oral contraceptive use throughout the study. Of the study population, 81.5% were white, 11.1% were black, and 7.4% were Hispanic or Asian. The study was approved by the university’s Institutional Review Board, and written consent was obtained from the participants before data collection began.

Seventy-four subjects who met the inclusion criteria were recruited. Subjects were matched for BMI and assigned to 1 of 3 treatment groups: control (C), diet only (DO), or diet plus aerobic exercise (DE). Forty-five subjects dropped out of the study. Twenty-nine subjects successfully completed the interventions and posttest data-collection procedures; however, 2 subjects did not meet the exercise-session-attendance criteria (75%) and were excluded from the sample, resulting in 27 subjects whose data were used in the analysis (C group: n = 9; DO group: n = 9; and DE group: n = 9). Errors with the body-composition methods were evaluated in an independent group of 9 subjects (4 women and 5 men aged 24 ± 3.8 y, 16.6 ± 11.6 %BF<sub>d,w,m</sub>), who were tested on 2 occasions 1 wk apart.

**(Data collection)**

Baseline and postintervention data were collected by using the same protocol. Physical characteristics, physical activity history, body density, total body water, total-body bone mineral and body composition from DXA, body resistance from BIA, and anthropometric measures were determined during a single test session lasting ≈3.5 h. Subjects were asked to arrive at the laboratory well hydrated after 12 h without food and beverages except water, which was consumed based on personal preference and habit. A baseline urine sample, the second void of the morning, was collected to assess hydration status. On average, the subjects were adequately hydrated as evidenced by their ability to give urine samples and a urine specific gravity of 1.019 ± 0.008 kg/L pretest and 1.020 ± 0.006 kg/L posttest (normal range: 1.010–1.025 kg/L) (9). No food or beverages, including water, were consumed during the testing session. For a given subject, baseline and postintervention data were collected during the same phase of the menstrual cycle or oral contraceptive pill sequence to control for changes in body water due to hormonal fluctuations. Menstrual cycle status was determined by self report.

**(Body-composition measures)**

**Anthropometric measures**

Body mass (BM) in air was determined with an electronic scale to the nearest 0.01 kg with subjects wearing the attire to be worn while being weighed underwater. Barefoot standing height was measured to the nearest 0.1 cm with a stadiometer. Maximal chest depth was measured with an anthropometer (Holtain Ltd, Crymych, United Kingdom) after a normal inhalation with the subject in a supine position. SFTs were measured 3 times (to the nearest 0.1 mm) with a Harpenden caliper (British Indicators, Ltd, London) at the triceps, biceps, subscapular, and suprailliac sites as described in the Anthropometric Standardization Reference Manual (10); the mean of 3 trials was used to calculate %BF. The within-subjects SD of replicate measurements of the sum of SFTs on 2 d ≈7 d apart in 9 subjects was 1.0 mm.

**Resistance**

Body resistance was measured according to standard procedures with a standard whole-body tetrapolar bioimpedance analyzer (RJL Systems, Inc, Detroit) on the right side of the body after subjects rested supine for 10–15 min (11, 12). The within-subjects SD of replicate measurements of body resistance on 2 d ≈7 d apart in 9 subjects was 24.4 Ω.

**Densitometry**

Body density was measured by underwater weighing and by using the Archimedes’ principle to determine body volume. Underwater body weight was determined with a Chatillon (Greensboro, NC) autopsy scale to the nearest 0.25 kg, with residual lung volume measured simultaneously with a closed-circuit, oxygen-rebreathing, nitrogen-dilution technique that was a modified version of Goldman and Buskirk’s method (13). The volume of gas in the gastrointestinal tract was assumed to be 0.1 L. The within-subjects SD of replicate measurements of body density on 2 d ≈7 d apart in 9 subjects was 0.0013 kg/L.

**Body water**

Total body water was measured by using deuterium oxide dilution according to the technique of Davis et al (14). After a baseline blood sample was taken, subjects ingested a known quantity of <sup>2</sup>H<sub>2</sub>O (0.3 g <sup>2</sup>H<sub>2</sub>O/kg BM) in 100 mL distilled water. Another 100 mL distilled water was used as a rinse and then consumed to ensure complete ingestion of the tracer. After a 3-h equilibrium period during which all urine was collected, another 100 mL distilled water was used as a rinse and then consumed to ensure complete ingestion of the tracer. After a 3-h equilibrium period during which all urine was collected, another blood sample was taken. Blood samples were centrifuged at 1670 × g and 0°C for 20 min and plasma was stored at −70°C. Plasma samples were purified by diffusion by incubating equal volumes of plasma and deionized water at 37°C for 48 h in incubation dishes (Bel-Air Products, Pequannock, NJ) (15). Isotope abundance in the purified plasma sample was determined in duplicate with an isotope ratio mass spectrometer (MAT 251; Finnigan, Bremen, Germany). Total body water was corrected for <sup>2</sup>H<sub>2</sub>O loss in urine and decreased 4% to account for hydrogen.
exchange with protein and carbohydrate during the 3-h equilib- 
rium period (16).

The within-subjects SD of replicate measurements of body 
water on 2 d = 7 d apart in 9 subjects was 0.50 L. The within-
subjects SD of 2 measurements of body water from the same 
blood sample on a given day was 0.25 L, which was consid-
ered to be the technical error associated with the measure- 
ment of total body water.

Bone mineral

Bone mineral ash and %BF were determined with whole-body 
scans by DXA (QDR-1000W, enhanced whole-body analysis soft-
ware version 5.71; Hologic, Inc, Waltham, MA). Bone mineral 
ash was multiplied by 1.2741 to estimate the total-body bone 
mineral ash. The constant 1.2741 assumes that 4.18% of the 
ash was multiplied by 1.2741 to estimate the total-body bone 
mineral ash expressed relative to BM. The within-subjects SD of 
replicate measurements of bone mineral content and %BF on 
2 d = 7 d apart were 11.6 g and 0.5% of BM, respectively.

Body-composition calculations

In addition to the estimates of %BF, 5 estimates of %BF 
from different methods were calculated. %BF was estimated 
from $d_p$, (%BF$D$) by using the Siri equation (18) based on a 
2-component (FM and FFm) model:

$$\text{%BF}_D = (495/d_p) - 450$$

where it is assumed that the density of fat is 0.9 kg/L and that the 
$D_{FM}$ is 1.1 kg/L. The within-subjects SD of replicate measure-
ments of %BF on 2 d = 1 wk apart in 9 subjects was 0.6% of BM.

%BF was estimated from $d_p$, total body water, and total 
body mineral by using the following equation from Lohman 
(4), which is based on a 4-component model (fat, water, min-
eral, and protein):

$$\text{%BF}_{d,m} = [(2.747/d_p) - (0.714w) + (1.146m) - 2.0503] \times 100$$

where w is total body water measured by $\text{H}_2\text{O}$ dilution expressed 
relative to BM and m is total body mineral estimated from bone 
mineral ash expressed relative to BM. The within-subjects SD of 
replicate measurements of %BF on 2 d = 1 wk apart in 9 sub-
jects was 0.6% of BM.

FFM was calculated from %BF and BM. The protein con-
tent of FFM was calculated as follows: protein mass = FFM – 
water mass – mineral mass. The $D_{FFM}$ was estimated from the 
water, mineral, and protein fractions of FFM (estimated from the 
4-component model) and their respective densities by using the 
following equation:

$$D_{FFM} = 1/[(w/d_p) + (m/d_m) + (p/d_p)]$$

where $p$ is protein. The within-subjects SD of replicate mea-
surements of $D_{FFM}$ on 2 d = 1 wk apart in 9 subjects was 
0.0015 kg/L.

%BF was estimated from the sum of 4 SFT measurements 
by using the equation of Durnin and Womersley (19):

$$d_p = 1.1267 - [0.0626 \times (\log \Sigma S)]$$

where $\Sigma S$ is the sum of the triceps, biceps, subscapular, and suprailiac 
SFTs. The within-subjects SD of replicate measurements of 
%BF on 2 d = 1 wk apart in 9 subjects was 0.5% of BM.

%BF was estimated from BIA by using the equation of Segal 
et al (20) for obese individuals:

$$\text{FFM} = 9.3794 + (0.0009 \times Ht^2)$$

$$- (0.015 \times R) + (0.3 \times BM)$$

$$- (0.07 \times \text{age})$$

where Ht is height in centimeters and R is resistance in ohms. 
The within-subjects SD of replicate measurements of %BF on 2 d 
= 1 wk apart in 9 subjects was 0.5% of BM. %BF was also esti-
mated from BMI by using the equation of Deurenberg et al (21):

$$\text{%BF}_{BMI} = (1.2 \times \text{BMI})$$

$$+ (0.23 \times \text{age}) - 5.4$$

The within-subjects SD of replicate measurements of %BF on 
2 d = 1 wk apart in 9 subjects was 0.1% of BM.

Diet and exercise regimens

Dietary protocol

Resting energy expenditure was estimated from FFM (22), 
increased 10% to account for the thermic effect of food, and then 
corrected by a factor of 1.5 for daily activity (23) to obtain an 
estimate of 24-h energy expenditure. FFM was estimated by 
using the DXA estimates of body composition that were avail-
able immediately on completion of the baseline testing. For the 
16-wk intervention period, subjects in the DO and DE groups 
were prescribed a diet that reduced their estimated daily energy 
requirements by 4.19 MJ/d (1000 kcal/d). The prescribed diet 
followed the American Diabetic Association exchange system. 
No subject was prescribed a diet providing <5.02 MJ/d (1200 
kcal/d). Subjects were requested to limit their fat intake to ≤30% 
of total energy. The foods consumed were self-selected and no 
supplements were prescribed. At baseline, 5 and 10 wk of the 
intervention, and posttesting, 3-d dietary food records (2 week-
days and 1 weekend day) were completed at home. In addition, 
24-h dietary recalls were completed through an interview and by 
using food models to represent portion sizes to assess compli-
ance with the diet. Because there was no significant difference in 
reported energy intakes between the average of the 3-d diet 
records and the 24-h interview, the average of the 4 d (3-d diet 
record and 1 24-h recall) was used in the data analysis. Total 
energy and macronutrient contents were calculated by analyzing 
the food records with THE FOOD PROCESSOR software 
(ESHA, Salem, OR). All subjects were strongly encouraged to 
attend weekly group meetings for dietary education and assis-
tance with individual success strategies. All subjects consuming 
the energy-restricted diet were requested to maintain the pre-
scribed diet until the posttest was conducted.

Aerobic exercise protocol

In addition to the energy-restricted diet described above, 
women in the DE group participated in walking-jogging classes 
on an indoor track 4 times/wk. Subjects were prescribed a walk-
ing-jogging protocol in which ~1.47 MJ (350 kcal) was 
expended per session on the basis of walking-jogging speed and 
BM (24, 25) for an approximate weekly energy expenditure of 
~5.86 MJ (1400 kcal). Subjects progressed to the prescribed 
energy expenditure according to individual capabilities over the 
initial 3 wk. Exercise sessions were supervised by the investiga-
tor. Exercisers maintained the prescribed exercise program until 
the posttest was conducted.
Physical activity assessment

Daily physical activity, excluding the prescribed exercise, was assessed by using the 7-d Physical Activity Recall Interview (26). Physical activity was assessed at baseline, 5 and 10 wk of the intervention, and posttest. All subjects were requested to maintain normal daily physical activity. Subjects assigned to the C and DO groups were specifically requested to abstain from any structured exercise.

Statistical analysis

Data were analyzed with SPSS for Windows version 7.0 (SPSS Inc, Chicago). One-way analysis of variance was used to assess the significance of differences among groups on variables of interest pretest. A two-way (group-by-time) mixed-model analysis of variance and follow-up tests for simple effects were used to determine the significance of differences in daily physical activity, dietary energy intake, and dietary composition. Analysis of variance on change scores was used to assess the significance of differences among groups on body-composition measures (4-component model); Tukey’s post hoc analysis was performed if there was a significant finding. Analysis of variance and Tukey’s post hoc analysis (among groups within method) and planned comparisons (all clinical estimates compared with %BFd,na) were used to determine the significance of differences in %BF pretest and changes in %BF. Individual agreement between clinical estimates of change in %BF and changes in %BFd,na was assessed by using the Bland-Altman approach (27). Relations between variables were described by using simple linear regression analysis. An experiment-wise α level of 0.05 was used. Bonferroni correction was used to control the family-wise error rate (Pfa) when multiple comparisons were conducted.

RESULTS

Analysis of food records indicated no significant difference in total energy intake among groups at baseline (grand mean: 8.3 ± 2.5 MJ; P > 0.05). Energy intake was significantly lower in the DE than in the C group at the 5-wk (5.6 ± 1.3 and 7.5 ± 2.1 MJ) and posttest (5.7 ± 1.7 and 7.2 ± 1.8 MJ; P < 0.05) time points; however, there was no significant difference at the 10-wk time point (5.8 ± 1.5 and 6.6 ± 1.4 MJ, respectively). Energy intake was not significantly different between the DE and DO groups or between the DO and C groups at any time point (P > 0.05). The control group decreased its reported estimated daily energy intake by ≈2.1 MJ (500 kcal) from baseline values at each time point. Because self report was used to assess dietary compliance, the validity of the data was questionable. In addition, because dietary compliance was sampled monthly, sensitivity to more frequent changes in energy intake was lacking. The decrease in reported energy intake in the absence of weight change in the control group supports this contention.

For the DE group, attendance at the exercise sessions averaged 86 ± 5%. Total energy expenditure for the intervention averaged 86.1 ± 10.9 MJ (20562 ± 2603 kcal) with an average energy expenditure per exercise session of 1.4 ± 0.1 MJ (329 ± 26 kcal). Total walking distance averaged 352 ± 45 km (219 ± 28 miles), with an average distance per exercise session of 5.6 ± 0.5 km (3.5 ± 0.3 miles). Daily physical activity (in kJ·kg⁻¹·min⁻¹), excluding the prescribed exercise, assessed by using the 7-d Physical Activity Recall Interview (26) was not significantly different among groups or across time points (baseline: 150.7 ± 16.3; 5 wk: 148.6 ± 10.0; 10 wk: 145.3 ± 7.5; posttest: 145.3 ± 11.3). This nonsignificant finding suggested that the DE group did not change their spontaneous, nonexercise daily physical activity when initiating the walking program. In addition, it suggests that because daily physical activity did not differ significantly among groups and remained constant in all groups throughout the intervention, it did not significantly affect differences in body-composition changes during the intervention period.

Physical characteristics of the subjects at baseline are presented in Table 1. There were no significant differences between groups in age, height, mass, BMI, or %BFd,na, before the intervention. Changes in BM and body composition based on a 4-component model are presented in Table 2. There were no significant differences between groups in any component pretest. BM changed 0.5%, −7.9%, and −4.8% in the C, DO, and DE groups, respectively. There was a significant difference in the change between the C and DE groups. When data for the one individual who lost ≈25 kg was removed from the analysis, the difference in BM change between the C and DO groups remained significant (DO: −4.9 ± 3.4 kg). There was a significant difference in BM change between the C and DE groups; however, no significant difference in BM change existed between the DO and DE groups. FM decreased 11% in the DO group and 10% in the DE group. These decreases were significantly greater than those in the C group, but were not significantly different from each other. The composition of the BM loss differed markedly, with ≈60% and ≈90% of the loss being FM in the DO and DE groups, respectively. There were no significant differences among the groups in changes in FFM, water, mineral, and protein mass.

A comparison of %BF estimates from a 4-component model with those from DXA, BIA, SFT, and BMI are presented in Table 3. No significant differences existed pretest between the groups with a given method. All estimates of %BF loss in the DO group were significantly greater than those in the C group. All estimates of %BF loss in the DE group were significantly greater than those in the C group, except %BFd,na. No significant differences in estimates of %BF change were found between the DO and DE groups. In the C group pretest, only %BFdxa was significantly greater than %BFd,na (Pf < 0.013). All clinical estimates of changes in %BF were significantly smaller than changes in %BFd,na in the C group (Pf < 0.013). In the DO group, no significant differences were found between the clinical estimates of %BFdxa and %BFd,na.

Table 1

<table>
<thead>
<tr>
<th>Measure</th>
<th>Control (n = 9)</th>
<th>Diet only (n = 9)</th>
<th>Diet + exercise (n = 9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>34.7 ± 5.8</td>
<td>32.0 ± 6.9</td>
<td>29.2 ± 6.6</td>
</tr>
<tr>
<td>(24–40)</td>
<td>(22–40)</td>
<td>(21–39)</td>
<td></td>
</tr>
<tr>
<td>Height (cm)</td>
<td>166.4 ± 2.5</td>
<td>168.7 ± 8.8</td>
<td>66.2 ± 5.8</td>
</tr>
<tr>
<td>(163.1–169.8)</td>
<td>(153.4–179.4)</td>
<td>(157.5–175.1)</td>
<td></td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>88.5 ± 10.4</td>
<td>91.1 ± 23.1</td>
<td>81.7 ± 7.2</td>
</tr>
<tr>
<td>(75.4–103.5)</td>
<td>(58.2–131.8)</td>
<td>(67.1–93.0)</td>
<td></td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>32.0 ± 4.0</td>
<td>31.9 ± 7.2</td>
<td>29.6 ± 2.3</td>
</tr>
<tr>
<td>(26.8–38.1)</td>
<td>(26.6–43.7)</td>
<td>(27.1–33.6)</td>
<td></td>
</tr>
<tr>
<td>%BFd,na</td>
<td>43.1 ± 4.1</td>
<td>41.1 ± 4.5</td>
<td>43.2 ± 3.4</td>
</tr>
<tr>
<td>(35.7–50.6)</td>
<td>(35.3–48.4)</td>
<td>(38.9–49.4)</td>
<td></td>
</tr>
</tbody>
</table>

1 x ± SD; range in parentheses. %BFd,na, percentage body fat with a 4-component (fat, water, mineral, and protein) model; d, density. There were no significant differences between groups, P > 0.05.
The agreement between changes in %BF<sub>dec</sub> and %BF<sub>BMI</sub> was similar to the other clinical estimates of change in %BF (Figure 2D; −4.1% to 8.4% of BM; 0.7 ± 2.4% of BM). In the subject in the DO group who lost the most BM (25 kg), ≈50% of the loss was FM (on the basis of the 4-component model); therefore, BMI greatly overestimated the change in %BF. Reanalysis of the data without this subject’s data improved the agreement between changes in %BF<sub>dec</sub> and %BF<sub>BMI</sub> (−4.1% to 3.0% of BM; 0.3 ± 1.9% of BM) and resulted in changes in %BF<sub>BMI</sub> that agreed the closest with changes in %BF<sub>dec</sub> when there was moderate weight loss.

**DISCUSSION**

We used estimates of body composition from a 4-component model as a criterion measure to assess the accuracy of clinical

<table>
<thead>
<tr>
<th>Component</th>
<th>Control (n = 9)</th>
<th>Diet only (n = 9)</th>
<th>Diet + exercise (n = 9)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pretest</td>
<td>Posttest</td>
<td>Change</td>
</tr>
<tr>
<td>Body mass</td>
<td>88.5 ± 10.4</td>
<td>88.9 ± 9.3</td>
<td>0.5 ± 2.0</td>
</tr>
<tr>
<td>Fat mass</td>
<td>38.3 ± 7.3</td>
<td>40.4 ± 7.1</td>
<td>2.1 ± 1.2</td>
</tr>
<tr>
<td>Fat-free mass</td>
<td>50.1 ± 4.8</td>
<td>48.5 ± 3.9</td>
<td>−1.6 ± 1.5</td>
</tr>
<tr>
<td>Water mass</td>
<td>36.6 ± 4.1</td>
<td>35.1 ± 2.9</td>
<td>−1.4 ± 1.6</td>
</tr>
<tr>
<td>Mineral mass</td>
<td>3.0 ± 0.3</td>
<td>3.0 ± 0.3</td>
<td>0.012 ± 0.04</td>
</tr>
<tr>
<td>Protein mass</td>
<td>10.6 ± 1.2</td>
<td>10.4 ± 0.9</td>
<td>−0.2 ± 0.9</td>
</tr>
</tbody>
</table>

1% ± SD. 
2Significantly different from control group, P < 0.05.
methods (DXA, BIA, SFT, and BMI) to estimate body-composition changes induced by diet or diet plus aerobic exercise. We found that the errors (SD of bias) in estimates of change in %BF by DXA, BIA, SFT, and BMI were similar when compared with the criterion method. BIA, SFT, and BMI estimates of change in %BF were unbiased, whereas DXA overestimated the loss in %BF in the intervention groups. The associations between changes in %BF estimated with the clinical methods and changes in %BF measured with DXA were stronger than the associations between changes in %BF estimated by densitometry, suggesting that the accuracy of these clinical methods was better than thought previously on the basis of studies using estimates made with densitometry as the criterion.

Estimates of change in %BF by DXA overestimated the loss in %BF and underestimated the gain in %BF. Compared with changes estimated with the 4-component model, the magnitude of error was similar to that of less-sophisticated clinical methods. The biased estimation of change in %BF compared with a 4-component model was contradictory to the findings of Albu et al (6) and Fogelholm et al (5), who found that dual-photon absorptiometry and DXA, respectively, provided an accurate estimation of the mean change in %BF. Data from the present study agree with Fogelholm et al’s finding that errors with DXA were comparable with errors with BIA, SFT, and BMI estimates of the change in %BF.

Errors in %BF estimated with the assumption of a constant hydration of the soft lean tissue mass may have contributed to the discrepancy of estimates of change in %BF compared with the 4-component model. Whole-body composition estimates with DXA assume a constant hydration of lean soft tissue with any deviation causing a systematic error in the estimation of %BF (28). Research has shown that BM lost during hemodialysis or 0.8–2.4 L water ingestion did not greatly affect estimates of fat or lean tissue measured by DXA (29). Dehydration was correctly identified by DXA as lean tissue with no change in fat or bone loss (30). Theoretical calculations (31) and other data (32) indicate that a 5% change in the water fraction of FFM would result in an error in FMDXA of ~0.4–0.5 kg, which corresponded to a difference between %BF measured and %BF estimated of ~2.7% of BM (32).

In the present study, the relation between the water fraction of FFM and the discrepancy between estimates of change in %BF with the 4-component model and with DXA were evaluated by using FFM measured with the 4-component model because the FFM estimate with the 4-component model is heavily influenced by the error estimate, thereby affecting both the numerator and denominator, possibly resulting in a spurious association. Indeed, a significant relation existed between the difference between changes in %BF measured and changes in %BF measured with DXA estimated with the 4-component model ($r = -0.43$, $P < 0.05$), whereas this relation did not exist when FFM was used as the dependent measure ($r = 0.15$, $P > 0.05$). A change in hydration of FFM was significantly related to the difference between change in %BF estimated with DXA and change in %BF measured with DXA. Regression analysis determined that a 5% change in the water fraction of FFM ($\approx 3.6\%$) resulted in a difference in BM of 2.2% between changes in %BF measured and changes in %BF measured with DXA. Although our findings should be interpreted cautiously because of the use of FFM measured with DXA to calculate the change in the water fraction of FFM, it suggests that changes in lean tissue mass hydration may have accounted for some of the difference between estimates of change in %BF measured with DXA and the criterion method.

Another error in %BF estimated results from changes in body tissue thickness. An increase in object thickness causes preferential loss of lower-energy photons relative to high-energy photons, termed “beam hardening,” resulting in altered attenuation constants for the various tissues, which may lead to error in body-composition estimates (33). In the present study, changes in BMI or body depth were not related to the difference between estimates of change in %BF by the 4-component model and DXA. These findings may be related to the homogeneous subject pool used and the restricted range of change in BMI and body depth.
It is important to note that the conclusions regarding DXA’s ability to correctly assess \( %\text{BF}_{\text{d,w,m}} \), apply to the equipment used (Hologic QDR 1000W with enhanced software version 5.71) and that significant differences exist between manufacturers and software that could result in different findings (34–36).

The magnitude of error for the estimation of change in \( %\text{BF}_{\text{d,w,m}} \) was nearly identical for BIA, SFT, and BMI, and there were no systematic differences between methods. These findings do not agree with those of Fogelholm et al (5), who found that BIA and SFT measurements underestimated the change in FM compared with the estimates made with a 4-component model. Regarding BIA, the authors speculated that their refeeding, weight-stabilization period after weight loss may have resulted in an expansion of intracellular water caused by glycogen resynthesis. Single-frequency BIA at a frequency of 50-kHz is more dependent on extracellular water than on total body water (37).

Therefore, the change in total body water may not have been detected accurately by BIA. The findings of the present study also may have been influenced by the small change in \( %\text{BF}_{\text{d,w,m}} \) induced as a result of the weight-loss protocol.

Although BMI provided the least accurate assessment of \( %\text{BF}_{\text{d,w,m}} \) before the intervention, on average, BMI estimated the change in \( %\text{BF}_{\text{d,w,m}} \) as well as or better than did DXA, BIA, and SFT. This finding is important considering the relatively low cost of the method and the minimal skill needed to use it. These findings agree with those of Fogelholm et al (5). The accuracy of BMI in predicting the change in \( %\text{BF}_{\text{d,w,m}} \) is largely dependent on the composition of the weight lost. Deviations from a typical weight-loss composition of 15–25% FFM and 75–85% FM result in greater errors in prediction of the change in \( %\text{BF}_{\text{d,w,m}} \). Our findings suggest that BMI is comparable with DXA, BIA, and SFT measurement in predicting changes in \( %\text{BF}_{\text{d,w,m}} \).

Although the above findings are based on the assumption that differences between clinical estimates of \( %\text{BF} \) and \( %\text{BF}_{\text{d,w,m}} \) resulted from error in the clinical estimate of \( %\text{BF} \), estimates of \( %\text{BF} \) with a 4-component model are not without error. It has been suggested that increased error associated with the greater number of measurements contributing to \( %\text{BF}_{\text{d,w,m}} \) may negate its greater theoretic accuracy (38). We and others (39) found, however, that the within-subjects SD for replicate measurements of \( %\text{BF}_{\text{d,w,m}} \) is low (=0.6% of BM) and similar to that derived with other indirect methods based on fewer measurements (eg, within-subjects SD for replicate measurements of \( %\text{BF}_f \) of ≈0.6% of BM), indicating that propagation of measurement error is not a significant problem. Furthermore, it must be recognized that measurements of \( %\text{BF}_{\text{d,w,m}} \) are not completely independent of \( %\text{BF}_{\text{DXA}} \) or \( %\text{BF}_f \) because density and bone mineral are used in the calculation of \( %\text{BF}_{\text{d,w,m}} \). The effect of this lack of independence is not known.

Data from this study highlight the difficulty in accurately assessing small changes in body composition with clinical methods. For example, the SEEs for predicting changes in \( %\text{BF}_{\text{d,w,m}} \) from changes in \( %\text{BF}_{\text{DXA}} \), \( %\text{BF}_{\text{BIA}} \), \( %\text{BF}_{\text{SFT}} \), and \( %\text{BF}_{\text{BMI}} \) were 1.9%, 2.1%, 2.0%, and 2.1% of BM, respectively, for an average SEE of ≈2.0% of BM for the clinical methods. With the use of the law of propagation of errors and assuming that the criterion measure is not error free (within-subjects SD of \( %\text{BF}_{\text{d,w,m}} \): 0.6% of BM), the portion of the SEE attributable to the clinical method is reduced to
To detect a true change in %BF from a weight loss in 95% of individuals, %BF would have to change by ≥3.8%.

In conclusion, the results suggest that errors in estimation of the change in %BF by DXA, BIA, SFT measurement, and BMI are similar when compared with a 4-component model. The associations between estimates of change in %BF with the clinical methods and changes in %BF measured were stronger than the associations between changes in the clinical methods and changes in %BF estimated by densitometry. Furthermore, the magnitude of error in the clinical assessment methods was not affected by type of weight-loss intervention (diet or diet plus aerobic exercise). Although BIA, SFT, and BMI estimates of mean changes in %BF were unbiased, DXA overestimated the loss in %BF in the intervention groups. Because the average error of prediction with the clinical methods used in this study was ~2% of BM, small physiologic changes in %BF with weight loss may not be quantified accurately with these clinical assessment methods.

REFERENCES