QDR 4500A DXA overestimates fat-free mass compared with criterion methods

FRANCES TYLAVSKY,1 TIMOTHY LOHMAN,2 BARBARA A. BLUNT,3 DALE A. SCHOELLER,4 THOMAS FUERST,5 JANE A. CAULEY,6 MICHAEL C. NEVITT,7 MARJOLEIN VISSER,8 AND TAMARA B. HARRIS9 FOR THE HEALTH ABC STUDY

1Department of Preventive Medicine, University of Tennessee Health Science Center, Memphis, Tennessee 38105; 2Department of Physiology, University of Arizona, Tucson, Arizona 85721; 3PPD Development, Inc., Austin, Texas 78704; 4Department of Nutritional Sciences, University of Wisconsin-Madison, Madison, Wisconsin 53706; 5Synarc, Inc. and 6Department of Epidemiology and Biostatistics, University of California-San Francisco, San Francisco, California 94105; 7University of Pittsburgh, Pittsburgh, Pennsylvania 15261; 8Institute for Research in Extramural Medicine, VU University Medical Center, 1081 BT Amsterdam, The Netherlands; and 9National Institute on Aging, National Institutes of Health, Bethesda, Maryland 20892

Submitted 7 August 2002; accepted in final form 27 October 2002

Tylavsky, Frances, Timothy Lohman, Barbara A. Blunt, Dale A. Schoeller, Thomas Fuerst, Jane A. Cauley, Michael C. Nevitt, Marjolein Visser, and Tamara B. Harris for the Health ABC Study. QDR 4500A DXA overestimates fat-free mass compared with criterion methods. J Appl Physiol 94: 959–965, 2003. First published November 1, 2002; 10.1152/japplphysiol.00732.2002.—This study evaluated the accuracy with which the dual-energy X-ray absorptiometer (Hologic QDR 4500A) measured fat-free mass (FFM), fat mass (FM), and hydration of FFM. In a study of 58 men and women (ages 70–79 yr), the QDR 4500A was found to provide a systematically higher estimate of FFM and lower estimate of FM than a four-component model of body composition. A correction factor from this study was developed and applied to two other samples (n = 13 and 37). We found mean corrected levels of FFM and FM to be equivalent to that obtained by the four-component model or total body water. In addition, the hydration of the corrected FFM was closer to the established hydration level in adult samples and that obtained from the four-component model. These findings suggest that the current calibration of the fan-beam system of the Hologic QDR 4500A provides an overestimate of FFM and underestimate of FM compared with reference methods.

Body composition; hydration of fat-free mass; four-component model of body composition; total body water; dual-energy X-ray absorptiometer

Recent Developments in dual-energy X-ray absorptiometry (DXA) hardware with fan-beam technology have led to new software development for body composition assessment predictive of body composition. The short assessment time of fan-beam technology for body composition analysis allows large samples to be included in clinical, epidemiological, and survey designs. In addition, this technology allows separation of the body mass into bone mass, fat mass (FM), and fat-free mass (FFM) and estimation of regional body composition. However, one of the limitations of fan-beam technology is the magnification of scanned structures as the distance from the X-ray source varies. Recent validation studies have tested the DXA fan-beam (DXAfan) approach with the four-component (4-C) model of body composition analysis (12, 14).

Further investigation of the DXA soft tissue calibration by our group has revealed a systematic bias between the DXA body composition results and several criterion methods, including the 4-C model and total body water (TBW) by deuterium dilution. Work by our group and others suggests that the calibration of the QDR 4500A produces higher total and regional FFM estimates compared with previous generations of Hologic whole body scanners (3) and compared with estimates based on alternative body composition methods (12, 14, 15). These three independent studies confirmed the overestimation of FFM and underestimation of FM and percent fat. Overestimation of FFM varied between 3 and 10%, depending on the validation cohort and criterion method.

Because of the systematic differences between fan-beam and pencil-beam body composition analysis, additional studies are warranted to assess the fan-beam approach. Our study used the 4-C model and DXAfan data to create a correction factor for the DXAfan. We then applied this to two other adult samples of different ages using DXAfan and pencil-beam (DXA pencil) technology with a 4-C model and TBW as criterion methods. The results of the correction for FM (FM_{DXAfan})
and FFM from DXA<sub>fan</sub> (FFM<sub>DXA<sub>fan</sub></sub>) were evaluated against the criterion methods.

**MATERIALS AND METHODS**

**Subjects**

There were three samples included in these analyses. Sample 1 consisted of 30 men and 28 women, aged 70–79 yr, selected so that 25% had a body mass index (BMI) <25 kg/m<sup>2</sup>, 50% had a BMI of 25–30 kg/m<sup>2</sup>, and 25% had a BMI >30 kg/m<sup>2</sup> (range 17.5–39.8 kg/m<sup>2</sup>), from the study by Visser et al. (15). There were 52 Caucasians and 6 African-Americans. All measurements on a subject were conducted on the same day after an overnight fast. (Two subjects were excluded from the original sample due to technical errors in underwater weighing.)

Sample 2 is a subset of 13 from sample 1 that had an additional measurement of a DXA<sub>pencil</sub> (Hologic QDR 2000) whole body scan. This group consisted of 5 men and 8 women with an age range of 70–75 yr and BMI range of 23.3–35.9 kg/m<sup>2</sup>. There were 11 Caucasians and 2 African-Americans.

In sample 3, 37 adults participating in various weight-loss regimens were recruited (14). The 2 men and 35 women (33 Caucasians and 4 African-Americans) ranged in age from 19 to 71 yr (mean ± SD = 43.2 ± 10.8 yr), with BMI ranging from 23.8 to 38.2 kg/m<sup>2</sup>.

**Body Composition**

FFM, FM, lean soft tissue mass (LSTM), and bone mineral content (BMC) were assessed by using the 4-C model and TBW. The 4-C model was used as the criterion with which to compare FFM obtained from DXA (FFM<sub>DXA</sub>) in samples 1 and 2. TBW was the criterion with which to compare FFM in sample 3. Percent hydration of FFM was calculated as (FFM/TBW) × 100.

**Whole Body DXA**

A Hologic model QDR 4500A fan-beam densitometer (DXA<sub>fan</sub>) and a QDR 2000 densitometer using the pencil-beam mode (DXA<sub>pencil</sub>) were used to measure bone and body composition. LSTM, FM, BMC, and bone mineral density were assessed by using software version 8.21 for the fan beam and enhanced whole body software version 5.71 for the pencil beam. Scan positioning, acquisition, and analysis were standardized. All subjects had fan-beam scans. Pencil-beam scans were done on a subset of sample 2 (n = 13) and all of sample 3 (n = 37).

**4-C Model**

The 4-C model by Lohman and Going (8) was used as the criterion method. This model requires measurements of body density, TBW, total body bone mineral mass, and body weight, and it takes into account interindividual variations in the water content and mineral content of the FFM. Body density was measured by using underwater weighing. Subjects wore a bathing suit. Water temperature was set at 32–35°C. When possible, 10 submersions with maximal exhalation were performed. The average of the five most consistent trials (difference, 0.02 kg) was used. Before submersion, residual lung volume was measured by using a Collins Respirometer (model SVR/PLUS, Braintree, MA). With the mouthpiece in place, subjects were asked to breathe normally until the spirometer equilibrated for collection of data on functional residual capacity. After equilibration, subjects performed a forced inhalation followed by a forced exhalation for collection of inspiratory and expiratory reserve capacity data, respectively. Residual volume was calculated as functional residual capacity minus expiratory capacity. Three separate tests were performed, and the average was used to adjust body volume.

Body composition from the 4-C model was calculated by using the following formula: body fat (% D) = (2.747D – 0.714 + W + 1.146 + M – 2.0503) × 100, where D is body density from underwater weighing, W is the water fraction of the body (TBW/body weight), and M is the mineral fraction of the body [total body mineral mass (TMM)/body weight]. TMM was calculated from measured total body BMC in the skeleton by the DXA<sub>fan</sub> technology. To account for the mineral in nonossseous tissue, total mineral from DXA was multiplied by 1.23. The value was based on data coming from reference man and original work by Brozek et al. (2). FFM was calculated as body weight minus body fat. LSTM was calculated by subtracting BMC from FFM.

**TBW**

TBW was assessed by deuterium dilution measured with mass spectroscopy (13). An oral dose of deuterium oxide (~50 g, 8.3 atom percent D<sub>2</sub>O) was measured to the nearest 0.01 g and administered to each participant after a 6- to 12-h fast. Plasma samples using a dry EDTA tube were collected before and 4 h after the isotope administration. Samples were stored frozen at −20°C and analyzed in batches for deuterium. The deuterium dilution space was calculated from the enrichment of deuterium in plasma water in the 4-h sample compared with the predose sample. Subjects were allowed a small amount of fluid at 1 h after the dose, and corrections were made in those in whom intake exceeded 200 ml. TBW was calculated as deuterium dilution space (liters) divided by 1.042, yielding kilograms of TBW. (13) FFM obtained from TBW (FFM<sub>TBW</sub>) was calculated as TBW/0.73 (kg), and FM was calculated as scale weight minus FFM<sub>TBW</sub> (kg).

**Statistical Analysis**

Means and standard deviations were calculated for all measures of body composition, as well as for physical characteristics of the participants. Paired t-tests were used to determine absolute differences between two methods, with a P value of < 0.05 considered statistically significant. Linear regression analysis was used to compare the FFM obtained from the 4-C model (FFM<sub>4-C</sub>) or FFM<sub>TBW</sub> to FFM<sub>DXA</sub> by pencil beam (FFM<sub>DXA<sub>pencil</sub></sub>) and FFM<sub>DXA<sub>fan</sub></sub>. The standard error of the estimate reported is the root mean square error. The method of Bland and Altman (1) was used to compare DXA with the criterion methods.

**RESULTS**

**Characteristics of the Study Population**

The characteristics of three samples assessed for body composition are shown in Table 1. In sample 1, 58 persons provided information from the 4-C model and fan-beam system to evaluate the relationship between FFM<sub>4-C</sub> and FFM<sub>DXA<sub>fan</sub></sub>. This sample reflects individuals between the ages of 70 and 80 yr and with a BMI ranging between normal weight to obese. Sample 2 was a subset of sample 1 and provided information from 13 individuals to compare FFM obtained from pencil-beam and fan-beam systems. Sample 3 provided information for 37 participants for both the fan and pencil-
Comparison of FFMDXAfan with FFMDXAfan,k

Sample 1. The mean FFMDXAfan was 50.7 kg (Table 1), and FFMDXAn,k was 53.5 kg. The FFMDXAn,k was 5.5% higher than FFMDXAfan (P < 0.0001). The results of the FFMDXAn,k regressed on FFMDXAfan are presented in Fig. 1A (n = 58). The intercept was not significantly different from zero, so the slope was determined with a zero intercept. The slope of the regression suggests that the DXAfan consistently overestimated FFM by 3.6% and indicates that the absolute error in FFMDXAfan compared with FFMDXAfan,k increased progressively as FFM increased. When the differences between the uncorrected FFMDXAn,k (FFMDXAn,k,uncorrected) and FFMDXAfan,k were plotted against the mean of the two measurements, there was no association with an increase in FFM (r = 0.16; P = 0.21) (Fig. 1B). The slope of the regression line between FFMDXAn,k and FFMDXAfan,k was then applied as a correction factor to FFMDXAn,k to yield a corrected FFMDXAn,k (FFMDXAn,k,corrected). When the differences between FFMDXAn,k,corrected and FFMDXAn,k were plotted against the mean of the two measurements, there was no association with increase in FFM (r = -0.16; P = 0.22) (Fig. 1C). To evaluate if this correction factor was appropriate for FFMDXAn,k, we examined the relationship between FFMDXAn,k,corrected and FFMDXAfan,k in sample 2 and FFMDXAn,k,corrected and FFMTBW in sample 3. These same analyses were performed on the corrected FFMDXAn,k. To obtain the corrected FFMDXAn,k, the total weight from DXA was subtracted from the corrected FFM. BMC was held constant in the correction process.

Body Composition and Hydration Status of FFM: Corrected and Uncorrected

Sample 2. Total weight, FFM, LSTM, FM, TMM, percent TMM of FFM, and percent hydration of FFM for those in sample 2 (n = 13) are presented in Table 2. Values for the components of body composition are presented as obtained from the 4-C model, the pencil-beam system, and the fan-beam system before (uncorrected) and after correction (corrected) using the correction factor derived from the 4-C model. There were no differences in total weight between that obtained from the scale and from the fan and pencil-beam systems. FFMTBW was higher than FFMDXAPH, lower than FFMDXAPen, lower than FFMDXAn,k,uncorrected, and not different than FFMDXAn,k,corrected. There were no differences in TMM obtained with the fan or pencil beam. The percent hydration of FFMDXAPen was higher than expected, and the FFMDXAn,k,uncorrected was lower than the percent hydration obtained by the FFMDXAfan,k. The hydration of FFMDXAn,k,corrected (71.5 ± 2.1%) was the same as FFMDXAw, corrected (P > 0.05). On the contrary, compared with the 4-C model, FM was estimated to be higher by the pencil beam, lower by the uncorrected fan beam, and no different for the corrected fan beam. TMM was 6.4% higher as assessed by the pencil-beam compared with the fan-beam system (P < 0.0002). Compared with the percentage of TMM to FFMDXAfan,k, the pencil beam yielded higher values and the uncorrected fan-beam values were the same. Compared with the percent hydration for FFMDXAw, corrected, the FFMDXAn,k,corrected was higher and the FFMDXAn,k,uncorrected was lower than would be expected. There were no differences in the percent hydration of FFMDXAw, corrected compared with that obtained from the FFMDXAn,k,corrected. Sample 3. Total weight, FFM, LSTM, FM, TMM, percent TMM of FFM, and percent hydration of FFM for those in sample 3 are presented in Table 3. Values are presented for body composition obtained by using TBW, the pencil-beam system, and the fan-beam system before (uncorrected) and after the correction (corrected). Data are provided for the sample at baseline and after 3.4 ± 2.3 mo of follow-up. Subjects lost an average of 5.7 ± 4.5 kg over the 3-mo period. There were no differences in total weight between that obtained from the scale and from the fan and pencil-beam systems. At baseline, FFMTBW as the criterion method was higher than FFMDXAw, corrected and lower than FFMDXAn,k,uncorrected. In contrast, compared with the FM TBW, FM was estimated to be higher by the pencil beam and lower by the uncorrected fan beam. TMM was higher when assessed by the pencil than by the fan beam. The percentage of TMM to FFM was lower for uncorrected fan beam, and the pencil beam was lower than that for FFMDXAw, corrected. The percent hydration of FFMDXApencil was higher than that for FFMDXAn,k,uncorrected. When the uncorrected DXAfan,k measurements were corrected to the 4-C model, no difference was found between the criterion FFMTBW and FFMDXAn,k,corrected (Fig. 2). When the correlation analysis was repeated, excluding the one outlier, the results were r = -0.04, P = 0.8. Similar findings for FFM, FM, TMM, percent TMM of FFM, and percent hydration were obtained at the follow-up visit (Table 3).

Table 1. Characteristics of study populations

<table>
<thead>
<tr>
<th></th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>58</td>
<td>13</td>
<td>37</td>
</tr>
<tr>
<td>Age, yr</td>
<td>73.7 ± 2.2</td>
<td>72.5 ± 1.2</td>
<td>43.2 ± 10.8</td>
</tr>
<tr>
<td>Gender (M/F)</td>
<td>30/28</td>
<td>5/8</td>
<td>2/35</td>
</tr>
<tr>
<td>Ethnicity (B/W)</td>
<td>6/52</td>
<td>2/11</td>
<td>4/33</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>75.9 ± 14.9</td>
<td>81.1 ± 13.1</td>
<td>84.4 ± 13.5</td>
</tr>
<tr>
<td>Height, cm</td>
<td>168.6 ± 9.2</td>
<td>165.2 ± 9.3</td>
<td>164.6 ± 6.6</td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>27.2 ± 4.5</td>
<td>29.9 ± 4.3</td>
<td>31.1 ± 3.8</td>
</tr>
<tr>
<td>FFM, kg</td>
<td>50.7 ± 11.7a</td>
<td>51.1 ± 12.4a</td>
<td>48.8 ± 6.6a</td>
</tr>
<tr>
<td>FFMDXAn,k, kg</td>
<td>53.5 ± 12.0</td>
<td>53.7 ± 12.9</td>
<td>51.3 ± 7.4</td>
</tr>
</tbody>
</table>

Values are means ± SD; n, no. of subjects. Sample 1 participants are from Visser et al. (15). Sample 2 participants are from Visser et al. (15) with QDR 4500A and QDR 2000 scans. Sample 3 participants are from Tylavsky et al. (14) at baseline. M, male; F, female; B, black; W, white; BMI, body mass index; FFM, fat-free mass; FFMDXAn,k, FFM obtained from dual-energy X-ray absorptiometer (DXA) fan beam. *From four-component (4-C) model. †From total body water (TBW).
Fig. 1. A: sample 1; n = 58. Relationship between corrected fat-free mass (FFM) from the QDR 4500A [fan-beam dual-energy X-ray absorptiometer (FFM_{DXAfan})] and FFM from the four-component (4-C) model (FFM_{4C}). SEE, standard error of the estimate; r, Pearson product moment correlation. B: sample 1, n = 58. Difference between uncorrected FFM_{DXAfan} and FFM_{4C} vs. average uncorrected FFM_{DXAfan} and FFM_{4C}. C: sample 1, n = 58. Difference between corrected FFM_{DXAfan} and FFM_{4C} vs. average corrected FFM_{DXAfan} and FFM_{4C}. 

\[ r = 0.99 \]
\[ \text{SEE} = 1.6 \text{ kg} \]

\[ FFM_{4C} = 0.964 \text{ FFM}_{DXAfan} \]
The present study found higher FFM (5.5%) as estimated from DXA fan beam than that estimated from the 4-C model (n = 58) in a sample of men and women between 70 and 80 yr of age. The proposed equation, FFM = 0.964 FFM\textsubscript{DXA\textsubscript{fan}} (kg), corrects DXA\textsubscript{fan} measurement to the 4-C model. By using a proportional correction, i.e., 2.5 kg for 70-kg FFM vs. 1.1 kg for 30-kg FFM, the equation corrects for the observed correlation between the difference between methods and the mean FFM (r = 0.16, P < 0.22). Applying this correction to two other samples, we found the mean levels of FFM to be equivalent to that obtained by the 4-C model or TBW. In addition, the hydration of corrected FFM is the same as obtained from the 4-C model. These findings suggest that the current calibration of the fan-beam system of the QDR 4500A provides an overestimate of FFM and underestimate of FM and our correction factor eliminates these biases.

Calibration of DXA units can be modified by the manufacturer to provide differing amounts of lean and fat tissue. New generations of DXA scanners (software and hardware changes) are often compared with results from the previous generation to judge the ability to transition from older to newer technology. Our results from two independent samples confirm that the calibration of the QDR 4500A produces higher total FFM and lower FM estimates compared with the Holosoft whole body pencil-beam scanners. Although our correction factor decreases the estimates of FFM and, consequently, increases the FM to match the 4-C model, the corrected FFM is still substantially less than estimated by the QDR 2000.

The TMM of the fat free body using the QDR 2000 is higher than that using DXA4500A in both samples 2 and 3. The mineral expressed as a percentage of the corrected FFM in \textit{sample 3} before and after weight loss (61.2% and 6.2%, respectively) is comparable to that found in a young adult population by Evans et al. (4) at 6.1% using DXA\textsubscript{pencil} (Hologic QDR 1000W) and somewhat lower than that found in reference human (6.8%) (2). The differences in mineral calibration between the two scanners used in this study reflect differences between specific scanners rather than calibration differences between models.

Among the differences between the DXA\textsubscript{fan} and DXA\textsubscript{pencil}, the magnification effect has been shown to affect the measurements of bone area, hip geometry (11), and FFM and FM (3) for the Hologic technology. Mazess and Barden (9) also compared fan beam (Expert and Prodigy from GE/Lunar) with pencil beam (DPX from GE/Lunar) for lean tissue mass and percent fat, finding less systematic variation between modes but large prediction errors for the Expert but not for the Prodigy. Our studies performed on the QDR 4500A used software version 8.21. This version corrects for differential magnification at each pixel. If beam magnification were an underlying factor contributing to differences in the assessment of FFM from the fan beam, then the Bland-Altman plots should show an increasing difference between the two methods as FFM increases. In \textit{sample 1}, the error in measurement between the fan beam and the 4-C model appears to increase with increasing levels of FFM, but this increase was not significant; thus fan beam appears to be an unbiased estimator of FFM with increasing levels of hydration status from sample 2

<table>
<thead>
<tr>
<th></th>
<th>4-C Model</th>
<th>QDR 2000\textsubscript{pencil} Uncorrected\textsuperscript{a}</th>
<th>QDR 4500A Uncorrected\textsuperscript{c}</th>
<th>QDR 4500A Corrected\textsuperscript{a}</th>
<th>TBW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total weight, kg</td>
<td>86.7 ± 12.9</td>
<td>81.2 ± 13.0</td>
<td>82.7 ± 13.0</td>
<td>82.7 ± 13.0</td>
<td>76.7 ± 3.3</td>
</tr>
<tr>
<td>FFM, kg</td>
<td>51.1 ± 12.4</td>
<td>48.4 ± 12.2</td>
<td>53.7 ± 12.9</td>
<td>51.8 ± 12.4</td>
<td>49.4 ± 11.9</td>
</tr>
<tr>
<td>LSTM, kg</td>
<td>45.8 ± 11.2</td>
<td>45.9 ± 11.5</td>
<td>51.4 ± 12.3</td>
<td>49.4 ± 11.9</td>
<td>30.9 ± 5.3</td>
</tr>
<tr>
<td>TMM, kg</td>
<td>2.8 ± 0.7</td>
<td>3.1 ± 0.9</td>
<td>2.9 ± 0.8</td>
<td>2.9 ± 0.8</td>
<td>5.3 ± 1.1</td>
</tr>
<tr>
<td>%TMM of FFM</td>
<td>5.8 ± 0.5</td>
<td>6.4 ± 0.5</td>
<td>5.4 ± 0.4</td>
<td>5.6 ± 0.4</td>
<td>7.7 ± 2.5</td>
</tr>
<tr>
<td>%Hydration of FFM</td>
<td>72.6 ± 3.3</td>
<td>76.7 ± 3.0</td>
<td>69.0 ± 2.0</td>
<td>71.5 ± 2.1</td>
<td>61.2 ± 1.7</td>
</tr>
</tbody>
</table>

Values are means ± SD for n = 37 subjects. LSTM, lean soft tissue mass; FFM, fat mass; TMM, total body mineral mass; QDR 2000\textsubscript{pencil}, QDR 2000 densitometer using the pencil-beam mode. \textsuperscript{a}Values measured directly from the QDR 2000 or QDR 4500A. \textsuperscript{c}Corrected values with the use of equation derived from regressing FFM\textsubscript{DXA\textsubscript{fan}} on 4-C FFM (0.964 × FFM\textsubscript{DXA\textsubscript{fan}}). \(P < 0.00001\) compared with corrected QDR 4500A using a paired t-test.

DISCUSSION

Table 3. Body composition estimates and hydration from sample 3

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Follow-up</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>QDR 2000\textsubscript{pencil} Uncorrected\textsuperscript{a}</td>
<td>QDR 4500A Uncorrected\textsuperscript{c}</td>
</tr>
<tr>
<td>Total weight, kg</td>
<td>85.7 ± 13.6</td>
<td>84.6 ± 13.4</td>
</tr>
<tr>
<td>FFM, kg</td>
<td>45.0 ± 6.1</td>
<td>51.3 ± 7.4</td>
</tr>
<tr>
<td>LSTM, kg</td>
<td>42.0 ± 5.8</td>
<td>48.4 ± 7.1</td>
</tr>
<tr>
<td>FM, kg</td>
<td>38.3 ± 9.6</td>
<td>33.3 ± 7.7</td>
</tr>
<tr>
<td>TMM, kg</td>
<td>3.016 ± 0.632</td>
<td>2.978 ± 0.395</td>
</tr>
<tr>
<td>%TMM of FFM</td>
<td>6.72 ± 0.63</td>
<td>5.84 ± 0.60</td>
</tr>
<tr>
<td>%Hydration of FFM</td>
<td>80.0 ± 2.5</td>
<td>70.2 ± 2.0</td>
</tr>
</tbody>
</table>

Values are means ± SD for n = 37 subjects. \textsuperscript{a}Values were measured directly from the QDR 2000 or QDR 4500A. \textsuperscript{b}Corrected values with the use of the equation derived from regressing FFM\textsubscript{DXA\textsubscript{fan}} on FFM\textsubscript{4-C} (0.964 × FFM\textsubscript{DXA\textsubscript{fan}}). \textsuperscript{c}Scale weight. \(P < 0.0001\) compared with TBW using a paired t-test. \(P < 0.015\) compared with TBW using a paired t-test. \(P < 0.00005\) compared with corrected QDR 4500A using a paired t-test.
FFM (Fig. 1B). However, previous work by Salamone et al. (12) shows an increased error in assessment of FM > 30 kg of total body fat compared with the 4-C model. Whether this increased error is due to magnification or the difficulty in assessing body composition, which overlies the skeleton, remains to be determined. Theoretically, estimation of soft tissue by DXA can be affected by small differences in hydration (10). Experimental data support that DXA readily measures increases in fluid retention from dialysis or the loss of fluids with dehydration (5, 6) through estimates of FFM. Thus different levels of fluid retention can affect the percent hydration of FFM, depending on when the measurements of TBW and FFM were obtained. In all of our samples, FFM_{TBW} and FFM_{DXA} were measured at the same visit after an overnight fast; thus the disparity in the percent hydration of FFM between the fan and pencil beam evidenced in this study cannot be attributed to differences in tissue hydration. Differences in X-ray attenuation of soft tissue determine whether tissue is considered to be FFM and FM by DXA. The mineral content of the TBW is largely responsible for these differences in X-ray absorption. Thus, whereas DXA cannot be used to measure true hydration of FFM, any difference between the apparent hydration from DXA and that of the 4-C analysis suggests a calibration offset. When FFM from the fan beam is corrected for the systematic differences with the 4-C model, the hydration of FFM moves closer to the established physiological value of 72–73% (16) and to that found in several studies with body water and DXA (7).

Limitations of estimating body composition are inherent in the methods available for use by researchers. Whereas the definitive method to assess body composition is carcass analysis, this option is limited for most validation studies. Technical measurement error, day-to-day variation in BMC, and the concentration of water can contribute to variability in the estimation of FM and FFM by scale weight, hydrodensitometry, TBW, and DXA (7). By incorporating each of these methods, the 4-C model takes advantage of minimizing the error associated with estimating body fat, water, mineral, and protein from one- or two-component models (7).

In summary, we found systematic differences in the assessment of FFM and FM between the fan system and pencil-beam systems from Hologic. In addition, we found that the systematic differences in body composition estimates between the fan-beam system and 4-C model or TBW could be alleviated by applying a correction factor of 0.964. After the correction was applied in two samples, the average FFM and FM were the same as those obtained from the 4-C model and TBW, and the hydration of FFM was closer to the established hydration level in adult samples. Consistent results in populations that included men, women, African-Americans, as well as Caucasians, over a large age and weight range suggest that a correction made to FFM and FM obtained by the QDR 4500A should be considered when evaluating body composition studies. Further validation studies are needed that include children through young adults with a broad range of BMI before this correction factor can be applied to these populations.

The research of M. Visser has been made possible by a fellowship of the Royal Netherlands Academy of Arts and Sciences. This study
was supported by National Institute on Aging contract nos. N01-AG-6–2106, N01-AG-6–2102, and N01-AG-6–2103. Support was obtained from Hologic, Inc.

REFERENCES