Preliminary evidence that DEXA provides an accurate assessment of body composition

WENDY M. KOHRT
Division of Geriatrics and Gerontology, Department of Internal Medicine, Washington University School of Medicine, St. Louis, Missouri 63110

Kohrt, Wendy M. Preliminary evidence that DEXA provides an accurate assessment of body composition. J. Appl. Physiol. 84(1): 372–377, 1998.—It was previously found that dual-energy X-ray absorptiometry (DEXA) underestimated central body fat. The purposes of this study were to determine whether an updated version (enhanced version 5.64) of the analysis program corrected this problem (experiment 1) and to compare body composition assessed by DEXA and hydrodensitometry (HD) in women (n = 225) and men (n = 110) across a 21- to 81-yr age range (experiment 2). For experiment 1, 10 subjects underwent DEXA procedures in a control condition and with packets of lard positioned over either the thighs or the truncal region. DEXA accurately quantified the additional mass as ∼96% fat, regardless of position. For experiment 2, DEXA yielded higher (P < 0.001) estimates of fatness than did HD (32.1 ± 12.0 vs. 31.2 ± 10.1%). The mean difference between the two methods was similar in young, middle-aged, and older subjects, but was different in men (HD − DEXA, 1.6 ± 3.4% of body wt) than in women (−2.1 ± 3.8% of body wt). Correcting the density of fat-free mass for variance in the bone mineral fraction of fat-free mass reduced the difference between the methods in men from 1.6 ± 3.4 to −0.7 ± 2.9% but widened it in women from −2.1 ± 3.8 to −3.5 ± 3.4%. A second correction procedure that adjusted for variance in water, protein, and mineral fractions of fat-free mass eliminated the differences in estimates of fat content by DEXA and HD in both men (21.1 ± 9.3 vs. 20.6 ± 8.4%, respectively) and women (37.5 ± 9.3 vs. 36.8 ± 8.0%, respectively). These results provide encouraging, but not definitive, evidence that the assessment of body composition by DEXA is accurate under the specified conditions.

hydrodensitometry; body fat content; fat-free mass

THE TWO-COMPARTMENT MODEL [i.e., fat and fat-free mass (FFM)] for assessing body composition by hydrodensitometry has long been considered the reference method. This is despite the fact that the fundamental underlying assumption, that the fractional composition of the FFM (i.e., water, protein, minerals) is uniform across age and gender, probably makes it less accurate in some subgroups of the population, such as children and the elderly. There is also a practical limitation to using hydrodensitometry to assess body composition in these subgroups because the procedure may be difficult for them to perform. Numerous methodologies have been evaluated as alternatives to hydrodensitometry (9, 10), but the one that has emerged as a likely candidate for a reference method is dual-energy X-ray absorptiometry (DEXA). In addition to being less demanding for the subject, DEXA has the advantage over hydrodensitometry of providing a measure of bone mineral mass in addition to fat mass and FFM (i.e., nonbone), thereby yielding a three-compartment model of body composition. Furthermore, on the basis of theoretical considerations (7, 13) and empirical evidence (2, 3, 5), the measurement of fat mass by DEXA appears to be relatively unaffected by fluctuations in hydration status.

There have been numerous comparisons of body composition assessed by DEXA and hydrodensitometry (4, 6, 11, 14–16, 18, 19), with little congruity among the findings. However, two studies (11, 15) provided clear evidence that DEXA underestimated fat content in central regions of the body. When packets of lard, a material that is similar to endogenous fat in terms of X-ray-attenuation properties, were positioned over peripheral regions of the body, the exogenous mass was correctly measured as ∼96% fat by DEXA. However, when the packets were positioned over central body regions, the exogenous mass was inaccurately quantified as being only ∼55% fat. It is likely that this error was attributable to the method of analyzing the data (i.e., software), not to the data-acquisition process (i.e., hardware). The purpose of this study was, therefore, to reassess the relationships between body composition assessed by DEXA and hydrodensitometry in large groups of women and men across a wide age range, by using an updated version of the analysis software. The accuracy of DEXA was further evaluated in a small group of subjects by adding exogenous fat to either central or peripheral body regions during the imaging process.

METHODS

All DEXA assessments were performed on the sameologic QDR-1000/W instrument (Hologic, Waltham, MA) as in the previous study from this laboratory (15). Data were analyzed by using version 5.64 of the enhanced whole body software package. When 12 women, aged 60–74 yr underwent total body DEXA procedures three times at weekly intervals, the coefficients of variation for total mass, fat mass, bone mineral mass, and nonbone FFM were 0.9 ± 0.4, 1.6 ± 1.0, 0.8 ± 0.3, and 1.8 ± 0.9%, respectively. Body density was measured by hydrodensitometry as described previously (8), and relative body fat content was estimated from body density by using the equation of Brožek et al. (1).
All volunteers provided their written consent to participate after being fully informed of the nature of the study. The studies were approved by the Human Subjects Committee at Washington University School of Medicine.

Experiment 1: Assessment of Exogenous Fat in Central and Peripheral Body Regions

It was found previously, by using the same DEXA instrument and version 5.50 of the enhanced whole body software package, that exogenous fat mass in central regions of the body was underestimated by DEXA (15). To determine whether this problem persisted in the updated version of the analysis program, this experiment was repeated in 10 subjects (5 women, 5 men), aged 28 ± 4 yr. Packets of lard (total mass = 1.51 kg) of uniform thickness (~2.5 cm) were positioned over the body during the DEXA procedure. Scans were performed with exogenous fat over the central body region proximal to the superior anterior iliac spine, with exogenous fat over the thighs, and with no exogenous fat. Each participant underwent all three procedures on the same day.

Experiment 2: Comparison of Body Composition by DEXA and Hydrodensitometry

It was previously reported that differences in relative body fat content estimated by DEXA and hydrodensitometry were ±1.5% of body weight in young women and men (15). However, with advancing age there was a widening discrepancy between the methods, with DEXA yielding estimates of fat mass that were 3.7 and 5.3% of body weight lower than hydrodensitometry values in >60-yr-old women and men, respectively. This was believed to be related to the underestimation of fat in central regions of the body by DEXA. The purpose of experiment 2 was to determine whether these patterns of differences were still apparent with the use of the new version of the body composition analysis software. Body composition was assessed by DEXA and hydrodensitometry in 110 men, ranging in age from 21 to 81 yr, and 225 women, ranging in age from 21 to 80 yr. The subjects were divided into young (<40 yr), middle-aged (40–59 yr), and older (>60 yr) groups. The previous report (15) included data on 185 of these 335 volunteers.

Bone mineral content (BMC) correction of density of FFM (DFFM). To determine whether differences between estimates of body fat content by DEXA and hydrodensitometry were related to variability in the BMC of the FFM, estimates of DFFM for each individual were used to derive a BMC-corrected estimate of body composition from body density. \( D_{FFM} \) was estimated in individuals by the following equation

\[
1/D_{FFM} = f_W/d_W + f_P/d_P + f_{OM}/d_{OM} + f_{NM}/d_{NM}
\]

where \( f \) and \( d \) are the fractions and densities, respectively, of the water (W), protein (P), osseous mineral (OM), and nonosseous mineral (NM) constituents of the FFM. Assumed values for densities were 0.99371, 1.34, 2.982, and 3.317 g/ml for W, P, OM, and NM, respectively (1). The water fraction of the FFM (W/FFM) was assumed to be 0.732 (1), and the osseous mineral fraction was calculated from DEXA measurements as BMC divided by FFM (BMC/FFM). The nonosseous mineral fraction was assumed to be 22.5% of the osseous mineral fraction (1). Finally, protein was assumed to be the remaining fraction after accounting for the other constituents (\( f_P = 1 - f_W - f_{OM} - f_{NM} \)). Using these assumed values, the simplified form of the equation above is

\[
1/D_{FFM} = 0.93663 - (0.511 * \text{BMC}/\text{FFM})
\]

The corrected body fat content was then calculated by using the following equation

\[
1/D_B = f_f/D_F - f_{FFM}/D_{FFM}
\]

where \( D_b \) is body density measured by hydrodensitometry, \( D_F \) is the density of fat (value assumed to be 0.88876 g/ml) (1), \( f_f \) is fractional fat content of the body, and \( f_{FFM} \) is fractional fat-free content of the body (\( f_{FFM} = 1 - f_f \)).

BMC, water, and protein correction of DFFM. Because the BMC correction of DFFM had differential effects in men and women (see RESULTS), a second correction procedure, based on the findings of Modlesky and colleagues (12), was evaluated. Briefly, in comparisons of men with either an average i.e., control) or a high degree of muscularity (i.e., weight lifters), these investigators found that increased muscularity was associated with an increased W/FFM and a decreased protein fraction (P/FFM) of FFM. In weight lifters, FFM averaged 77.1 kg, and the W/FFM and P/FFM were 74.8 and 19.9%, respectively. In controls, FFM averaged 59.4 kg, and the W/FFM and P/FFM were 72.6 and 21.5%, respectively. Because of the difference in muscularity between men and women, it seems plausible that there are gender differences in the W/FFM and P/FFM and that such differences would result in an erroneous assessment of body composition by hydrodensitometry. Whether such differences could account for the lack of agreement in the assessment of body composition by hydrodensitometry and DEXA was therefore explored.

For this correction procedure, it was assumed that the W/FFM and P/FFM were linearly related to FFM and that the mean data in the two groups of men studied by Modlesky et al. (12) defined the relationships. These relationships were used to estimate the average \( f_W \) and \( f_P \) of FFM for men and women from the DEXA-derived measurements of FFM. BMC/FFM was assumed to be the value measured by DEXA, and the nonosseous mineral fraction was assumed to be the remainder \( (1 - f_W - f_P - f_{OM}) \).

Statistical Analyses

Body composition measurements from experiment 1 were analyzed by using a one-way analysis of variance for repeated measures. In the event of a significant F ratio, the Tukey post hoc test was used to identify significant differences among the experimental conditions. Differences in estimates of body composition by DEXA and hydrodensitometry were compared by using a two-way analysis of variance (age group, gender) to determine whether the differences between the methods varied by age group or gender. All data are presented as means ± SD unless otherwise specified. Statistical significance was accepted as \( P < 0.05 \).

RESULTS

Experiment 1

The placement of 1.51 kg of exogenous fat over central or peripheral regions of the body had no effect on estimates of either bone-free FFM (P = 0.93) or bone mineral mass (P = 0.21) (Table 1). The additional mass was correctly estimated to be fat, and this was not affected by the region of placement.

Experiment 2

In the 335 participants in experiment 2, the estimates of relative body fat content by the two methods were highly correlated (\( r = 0.95 \); \( P < 0.01 \)), but DEXA
Table 1. Fat, fat-free, and bone mineral mass measured in 10 subjects by DEXA in a control condition and with exogenous fat positioned over either central or peripheral regions of the body

<table>
<thead>
<tr>
<th>Condition</th>
<th>Total</th>
<th>Fat</th>
<th>Nonbone</th>
<th>Bone mineral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>68.07 ± 10.20</td>
<td>12.69 ± 6.12</td>
<td>52.70 ± 12.03</td>
<td>2.68 ± 0.49</td>
</tr>
<tr>
<td>Trunk</td>
<td>69.53 ± 10.27</td>
<td>14.10 ± 6.41</td>
<td>52.76 ± 11.90</td>
<td>2.71 ± 0.48</td>
</tr>
<tr>
<td>Thighs</td>
<td>69.67 ± 10.18</td>
<td>14.23 ± 5.64</td>
<td>52.72 ± 12.05</td>
<td>2.69 ± 0.47</td>
</tr>
</tbody>
</table>

Values are means ± SD. DEXA, dual-energy X-ray absorptiometry.

*Different from control, P < 0.001.

yielded significantly (P < 0.001) higher values than did hydrodensitometry (32.1 ± 12.0 vs. 31.2 ± 10.1% of body wt). The mean difference in the estimates of body fat content by using the two methods was similar in all three age groups but was different in men and women (Fig. 1, Table 2). In men, the estimated relative of body fat content was significantly lower by DEXA than by hydrodensitometry (21.1 ± 9.3 vs. 22.7 ± 8.2% of body wt, respectively), whereas in women the estimate by DEXA was higher (37.5 ± 9.3 vs. 35.3 ± 8.1% of body wt, respectively). Similarly, there were gender-related differences in the estimates of fat mass and FFM (Table 2).

Total body BMC was lower in women than in men (2,017 ± 338 vs. 2,950 ± 390 g; P < 0.01) and was lower in the >60-yr-old subjects (2,172 ± 516 g) than in the middle-aged (2,568 ± 484 g) or young (2,744 ± 516 g) women and men (Table 2). There was a significant age-by-gender interaction effect for BMC/FFM such that it was lower in older women than in young or middle-aged women, and lower in young and middle-aged men than in age-matched women (Table 2).

BMC correction of DFFM. The differences in the estimates of body fat content by the two methods were significantly and inversely (r = −0.57, P < 0.01) related to variance in BMC/FFM in all subjects. When regres-

DISCUSSION

In a previous study, we reported that DEXA (Hologic QDR-1000/W instrument; enhanced software version 5.50) underestimated fat in central regions of the body (15). This was demonstrated unequivocally by positioning packets of lard, a substance that is nearly identical to endogenous fat in terms of X-ray-attenuation characteristics, over central or peripheral regions of the body.
during the DEXA procedure. Whereas the exogenous material was correctly identified as ~96% fat when it was positioned peripherally, it was estimated to be only ~55% fat when it was placed on central regions of the body. Similar regional errors were reported by Milliken et al. (11) when body composition was assessed on the Lunar DEXA instrument by using version 1.3y of the analysis software. In the present study, the original experiment (15) was repeated and data were analyzed by using an updated version of the Hologic enhanced whole body analysis application (version 5.64). The updated program accurately assessed the exogenous material as being ~96% fat, regardless of whether it was positioned over central or peripheral regions of the body. Although this finding does not provide definitive evidence that the assessment of body composition by DEXA is valid, it does ensure that a known problem has been rectified and that DEXA accurately assesses changes in fat mass of ~1.5 kg.

In our previous study (15), we also compared estimates of body fat content measured by hydrodensitometry and DEXA and found good agreement between the methods in young women and men, but a widening discrepancy in those in middle-aged to older people. Estimates of body fat were significantly lower by DEXA than by hydrodensitometry by 3.7 and 5.3% of body mass for younger women and men, respectively.

Table 2. Comparisons of body composition by DEXA and HD in women and men grouped by age

<table>
<thead>
<tr>
<th>Variable</th>
<th>Women</th>
<th></th>
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<th>Men</th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>DEXA</td>
<td>HD</td>
<td>Difference</td>
<td>DEXA</td>
<td>HD</td>
<td>Difference</td>
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<tr>
<td></td>
<td>Fat, %</td>
<td></td>
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<tr>
<td>20–39 yr</td>
<td>24.2± 6.6</td>
<td>21.4± 5.1</td>
<td>−2.8± 2.9</td>
<td>12.9± 6.5</td>
<td>14.5± 5.6</td>
<td>1.7± 2.8</td>
</tr>
<tr>
<td>40–59 yr</td>
<td>31.1± 7.0</td>
<td>28.4± 6.3</td>
<td>−2.7± 2.0</td>
<td>21.2± 7.4</td>
<td>22.2± 5.9</td>
<td>1.0± 3.2</td>
</tr>
<tr>
<td>&gt;60 yr</td>
<td>40.5± 7.3</td>
<td>38.5± 5.2</td>
<td>−2.0± 4.0</td>
<td>25.9± 7.5</td>
<td>27.5± 5.7</td>
<td>1.6± 3.8</td>
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<td></td>
<td>FM, kg</td>
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<tr>
<td>20–39 yr</td>
<td>14.4± 5.7</td>
<td>12.7± 4.6</td>
<td>−1.7± 1.9</td>
<td>10.2± 6.0</td>
<td>11.4± 5.3</td>
<td>1.2± 2.1</td>
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<tr>
<td>40–59 yr</td>
<td>19.9± 6.6</td>
<td>18.1± 5.8</td>
<td>−1.8± 1.5</td>
<td>17.8± 7.7</td>
<td>18.4± 6.2</td>
<td>0.6± 2.6</td>
</tr>
<tr>
<td>&gt;60 yr</td>
<td>27.9± 9.2</td>
<td>26.2± 7.3</td>
<td>−1.7± 3.0</td>
<td>21.6± 8.8</td>
<td>22.5± 7.0</td>
<td>0.9± 3.0</td>
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<td></td>
<td>FFM, kg</td>
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<tr>
<td>20–39 yr</td>
<td>43.6± 4.3</td>
<td>45.3± 4.4</td>
<td>1.7± 1.8</td>
<td>67.0± 5.8</td>
<td>65.7± 6.0</td>
<td>−1.3± 2.3</td>
</tr>
<tr>
<td>40–59 yr</td>
<td>43.0± 4.3</td>
<td>44.7± 4.5</td>
<td>1.7± 1.3</td>
<td>64.0± 5.7</td>
<td>63.1± 6.4</td>
<td>−0.9± 2.4</td>
</tr>
<tr>
<td>&gt;60 yr</td>
<td>39.3± 4.6</td>
<td>40.7± 5.4</td>
<td>1.4± 2.7</td>
<td>59.3± 5.4</td>
<td>58.0± 6.6</td>
<td>−1.3± 2.9</td>
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<td></td>
<td>BMC, kg</td>
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<tr>
<td>20–39 yr</td>
<td>2.3± 0.3</td>
<td>2.1± 0.2</td>
<td>−0.2± 0.1</td>
<td>3.1± 0.4</td>
<td>3.0± 0.5</td>
<td>0.1± 0.5</td>
</tr>
<tr>
<td>40–59 yr</td>
<td>2.3± 0.2</td>
<td>2.0± 0.2</td>
<td>−0.3± 0.1</td>
<td>2.9± 0.4</td>
<td>2.8± 0.4</td>
<td>0.1± 0.5</td>
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<tr>
<td>&gt;60 yr</td>
<td>1.9± 0.3</td>
<td>2.0± 0.3</td>
<td>−0.1± 0.1</td>
<td>2.7± 0.4</td>
<td>2.6± 0.4</td>
<td>0.1± 0.5</td>
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<td></td>
<td>BMC/FFM, %</td>
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<tr>
<td>20–39 yr</td>
<td>3.1± 0.4</td>
<td>2.9± 0.4</td>
<td>−0.2± 0.1</td>
<td>4.8± 0.5</td>
<td>4.5± 0.5</td>
<td>0.3± 0.5</td>
</tr>
<tr>
<td>40–59 yr</td>
<td>3.1± 0.4</td>
<td>2.9± 0.4</td>
<td>−0.2± 0.1</td>
<td>4.8± 0.5</td>
<td>4.5± 0.5</td>
<td>0.3± 0.5</td>
</tr>
<tr>
<td>&gt;60 yr</td>
<td>4.0± 0.5</td>
<td>3.8± 0.5</td>
<td>−0.2± 0.1</td>
<td>4.8± 0.5</td>
<td>4.5± 0.5</td>
<td>0.3± 0.5</td>
</tr>
</tbody>
</table>

Values are means ± SD; n = 10 subjects. HD, hydrodensitometry; FM, fat mass; FFM, fat-free mass; BMC, bone mineral content. aSignificant main effect for gender, P < 0.05. bSignificant main effect for age group, >60-yr old subjects different from younger age groups, P < 0.05. cSignificant age × gender interaction effect; d different from younger women; e different from age-matched women; all P < 0.05.

Fig. 2. Relationships of differences between estimates of body fat content by HD and DEXA (Body Fat_HD - DEXA) to bone mineral content fraction of fat-free mass (BMC/FFM) in men (○; solid line; r = −0.58) and women (●; dashed line; r = −0.51).

Fig. 3. Estimates of body fat content in young, middle-aged, and older women and men determined by HD by using an assumed constant (1) for density of fat-free mass (D_{FFM}; hatched bars), values for D_{FFM} that were corrected for individual variance in BMC/FFM (BMC corrected; cross-hatched bars), and values for D_{FFM} that were corrected for individual variance in BMC/FFM and for suspected gender-related differences in water and protein fractions of FFM (open bars). Values are compared with estimates of body fat content measured by DEXA (solid bars). Different from DEXA, *P < 0.01, †P < 0.05.
weight in >60-yr-old women and men, respectively. The differences were not attributable to the lower BMC/FFM in the older participants because corrections for BMC/FFM accounted for differences in body fat of 1% of body weight. Rather, given the results of the exogenous fat experiments, we interpreted the discrepancy between the methods as an underestimation of fat by DEXA in central regions of the body because older men and women tend to preferentially accumulate fat in the abdominal region (8). In the present study, the discrepancy between hydrodensitometry and DEXA in the measurement of body fat content was similar in all age groups, suggesting that DEXA no longer underestimated fat mass in these subgroups of subjects with central fat accumulation.

When all subjects were considered together, there was only a small, but significant, difference in the estimates of body fat content by DEXA (32.1 ± 12.0%) and hydrodensitometry (31.2 ± 10.1%). However, pooling all subjects masked the larger differences that were apparent when men and women were considered separately. In men, the estimate of body fat content was 1.6 ± 3.4% of body weight lower by DEXA than by hydrodensitometry, whereas in women it was 2.1 ± 3.8% higher by DEXA. In both men and women, the discrepancy between the methods was significantly and inversely related to BMC/FFM. Estimates of body fat were higher by hydrodensitometry in subjects with a low BMC/FFM, and higher by DEXA in subjects with a high BMC/FFM. Correction of DFFM for individual variance in BMC/FFM reduced the difference in estimates of body fat content between the methods in men (BMC-corrected hydrodensitometry, 20.4 ± 8.6% vs. DEXA, 21.1 ± 9.3%), but widened the gap between the methods in women (BMC-corrected hydrodensitometry, 33.9 ± 8.2% vs. DEXA, 37.5 ± 9.3%).

The relatively good agreement between BMC-corrected estimates of body fat from hydrodensitometry and DEXA in men provides encouraging indirect evidence that DEXA is an accurate method of assessing body composition. However, if this is true, then the discrepancy between the methods in women implies that assumptions underlying the estimation of DFFM are gender specific; that is, that the W/FFM, P/FFM, and/or BMC/FFM are not the same in women and men. In support of this, Modlesky and colleagues (12) found that men with a high degree of muscularity (i.e., weight lifters) had a larger W/FFM and smaller P/FFM and BMC/FFM than men with average muscularity. These findings suggest that skeletal muscle hypertrophy is not accompanied by proportional increases in other tissues of the lean compartment, thereby resulting in variance in W/FFM, P/FFM, and BMC/FFM. It seems plausible that if men with average muscularity have a smaller W/FFM and larger P/FFM and BMC/FFM than men with a high degree of muscularity, then similar differences may exist between women and men with average muscularity. The finding in the present study and by others (17, 18) that BMC/FFM was larger in young and middle-aged women than in men supports this hypothesis. Furthermore, when DFFM was corrected for individual variance in BMC/FFM and for gender-specific estimates of W/FFM and P/FFM based on the data of Modlesky et al. (12), there were no longer any age- or gender-related differences in the estimates of body fat content by hydrodensitometry and DEXA (Fig. 3). If the assumptions underlying the gender-specific corrections of DFFM are reasonable, these results suggest that DEXA is superior to hydrodensitometry for the assessment of body composition.

In summary, both the exogenous fat experiment (i.e., experiment 1) and the comparisons of DEXA and hydrodensitometry (i.e., experiment 2) provided encouraging, but not definitive, evidence that the assessment of body composition by DEXA is accurate when data are acquired on the Hologic QDR-1000/W instrument and analyzed with version 5.64 of the enhanced whole body analysis program. Further studies must be conducted to confirm and extend our findings before DEXA can be endorsed as a reference method for the assessment of body composition. In experiment 1, it was demonstrated that DEXA accurately assessed a 1.5-kg exogenous fat mass positioned on the body during the scanning procedure, but additional studies should be performed to determine whether this accuracy extends to manipulations of both fat and FFM in amounts in excess of 1.5 kg. With regard to experiment 2, assumptions regarding gender-related differences in W/FFM and P/FFM were based on evidence that such differences exist between men of average muscularity and those with a high degree of muscularity (12). Studies must be carried out to verify whether such gender-related differences in W/FFM and P/FFM do, in fact, exist, and to more precisely quantify these parameters.

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Address for reprint requests: W. M. Kohrt, Washington Univ. School of Medicine, 660 S. Euclid, Campus Box 8113, St. Louis, MO 63110 (E-mail: wkohrt@mgate.wustl.edu).

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