Measurement of fat mass using DEXA: a validation study in elderly adults

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1Department of Epidemiology, University of Pittsburgh, Graduate School of Public Health, Pittsburgh, Pennsylvania 15261; 2Department of Radiology, and 5Prevention Sciences Group, University of California, San Francisco 94105; 3Department of Kinesiology, San Francisco State University, San Francisco, California 94132; 2Epidemiology, Demography and Biometry Program, National Institute on Aging, Bethesda, Maryland 20892; 4Department of Preventive Medicine, University of Tennessee, Memphis, Tennessee 38105; and 7Department of Physiology, College of Medicine, University of Arizona, Tucson, Arizona 85721

Received 7 January 1999; accepted in final form 22 February 2000

Salamone, Loram M., Thomas Fuerst, Marjolein Visser, Marialice Kern, Thomas Lang, Maurice Dockrell, Jane A. Cauley, Michael Nevitt, Francis Tylavsky, and Tim G. Lohman. Measurement of fat mass using DEXA: a validation study in elderly adults. J Appl Physiol 89: 345–352, 2000.—The accuracy of total body fat mass and leg fat mass measurements by fan-beam dual-energy X-ray absorptiometry (DEXA) was assessed in 60 healthy elderly subjects (aged 70–79 yr). Total fat and leg fat mass at four leg regions (total leg, thigh, midthigh, and calf) were measured with the QDR 4500A (Hologic, Waltham, MA). The four-compartment model and multislice computed tomography scans were selected as criterion methods for total fat and leg fat mass, respectively. Total fat mass from DEXA was positively associated with fat mass from the four-compartment model with a standard error of the estimate ranging from 1.4 to 1.6 kg. DEXA fan-beam tended to overestimate fat mass for total leg and total thigh fat mass, whereas only marginal differences in fat mass measurements at the midthigh and calf were demonstrated (≤0.08 kg, P < 0.0005). Although there were significant differences between DEXA fan beam and the criterion methods, these differences were of small magnitude, suggesting that DEXA is an accurate method for measurement of fat mass for the elderly.

body composition; dual-energy X-ray absorptiometry; fan beam; computed tomography

Assessment of body composition has become increasingly important in the evaluation of its impact on health and disease. Present methodologies to assess body composition, such as total body water and hydrodensitometry, are limited by assumptions concerning the constancy of biological elements, as well as practical limitations in the ability of the elderly to complete the hydrodensitometry procedure. Other methodologies, such as computed tomography (CT), can be limited by the fact that they assess adipose tissue rather than fat mass (FM); assumptions in the proportion of adipose tissue that is fat tissue may not be accurate, particularly in the elderly.

Although dual-energy X-ray absorptiometry (DEXA) was first developed to measure bone mineral content (BMC), it is now considered a useful tool for the appraisal of gross and regional body composition. The most recent DEXA technology uses a fan-beam X-ray source coupled with multielement solid-state detectors. This has the advantage of increased resolution and scan speed compared with the earlier pencil-beam technology, which utilizes a highly collimated X-ray source with a single detector. Such improvements would be of particular benefit in whole body scanning, which is presently limited by low resolution and scan time as long as 15–20 min. Whether body composition, particularly total body and regional FM, can be measured accurately in the elderly with the DEXA fan-beam technology remains an important research question.

Numerous studies have compared body composition measurements by DEXA with chemical analyses in animals, with in vitro and in vivo assessments under conditions in which the fat content is manipulated, and with reference methods. Marked differences in FM measurements are demonstrated in some (6, 8, 13, 22, 27, 30) but not in all studies (7, 9, 28, 34). From more sophisticated comparisons implementing four-compartment models of body composition, there was reasonable agreement at a population level but substantial error within individuals (7). Of importance, there is limited information on the ability of either fan- or pencil-beam DEXA to accurately measure regional body composition, especially in elderly women and men; indeed, this requires comparisons with tech-
niques such as CT or magnetic resonance imaging. Of these studies, comparisons have been made between adipose tissue volume at the abdomen and DEXA (28, 31), and only crude anthropometric comparisons have been made at the limbs (7).

It is important to provide additional validation of fan-beam DEXA assessments of total and regional body composition as the speed of the machine makes its greater use more likely in the future. The objective of this study was to compare the accuracy of the fan-beam DEXA (QDR 4500A; Hologic, Waltham, MA) technology for the measurement of total FM and leg FM against a four-compartment model and multislice CT, respectively, in elderly women and men. In a separate study, we performed a similar validation study of total body and regional lean mass in this elderly population (31).

METHODS

Study Population

A total of 60 healthy adults, 30 women and 30 men, aged 70–79 yr (mean age 73.7 ± 2.2 yr) was recruited through advertisements in the local media. The majority of the subjects recruited were Caucasian (n = 55) with seven African-Americans. Subjects were free living and had body mass indexes (BMI), by study design, ranging from 17.5 to 39.8 kg/m². All measurements were conducted on the same day.

Measurements

Anthropometry. Body weight was measured on a balance beam scale to the nearest 0.1 kg, and height was measured to the nearest 0.1 cm by using a Harpenden stadiometer (Holtain, Wales, UK). BMI was calculated as weight in kilograms divided by height in meters squared.

DEXA. Measurements of body composition using the DEXA fan-beam technology (Hologic QDR 4500A, Hologic) were made in all subjects. A standardized procedure for patient positioning and utilization of the QDR software was used. The DEXA 4500A scans were analyzed with the most recent software version 8.21.

From DEXA scans, total body FM and four subregions of leg FM were evaluated, including the total leg, thigh, midthigh, and calf. Subregions for the total legs were defined by placing a horizontal line at the lowest point of the ischial tuberosity as the upper cutoff point for the legs and a horizontal line at the ankle joint as the lower cutoff point for the legs. From this, the upper and lower cutoff points were similar to those implemented in the multislice CT technique. A more detailed description of these methods can be found in Visser et al. (31). FM was calculated as follows: leg FM = total mass – (leg lean mass) – (1.82 · leg BMC) (11). FM at the thigh was assessed by using the ischial tuberosity and the knee joint as upper and lower cutoff points, respectively. In addition, midthigh FM (at one-half of the distance between the knee joint and the top of the femur) and calf FM (at two-thirds of the distance between the ankle joint and the knee joint) were assessed by using the smallest DEXA subregion possible, consisting of 3 pixels or 3.96 cm. The coefficients of variation for DEXA were calculated from repeated scans of individuals in the study cohort and were as follows: leg fat 1.6%, thigh fat 2.8%, midthigh fat 7.8%, and calf fat 7.2%.

Four-Compartment Model

The four-compartment model was selected as the reference method with which to validate the DEXA results for the total body FM (18). Measurements of body density, total body water, total bone mineral mass, and body weight are the necessary components of this model. The percentage of body fat was calculated by using the four-compartment model proposed by Lohman et al. (18), including measurements of body density, total body water, and total body bone mineral for each subject.

Body density. Measurements of body density were made with hydrostatic weighing. Residual lung volume, as assessed by helium dilution, was measured by using a Collins spirometry and residual volume device (SRX System, Brain-tree, MA) before submersion. Body volume was adjusted accordingly. The water temperature was set at 32–35°C. With each participant dressed in a bathing suit, 10 submersions at maximal exhalation were performed, and the average of the five most consistent trials (difference 0.02 kg) was used.

Total body water. Total body water was assessed by using deuterium dilution (University of Wisconsin, Madison, WI) (26). An oral dose of deuterium oxide (~4.0 g diluted in 50 ml of water) was measured and administered to each participant. Blood samples were collected before and after 5 h and stored frozen at ~20°C until completion of deuterium analysis by mass spectrophotometry (25). Corrections were made for nonaqueous hydrogen exchange and water density at room temperature. Total body water was calculated as deuterium dilution space (liters) divided by 1.041 (26). The coefficient of variation for the analytic precision of this measurement is <1%.

Total body mineral mass. Total body mineral mass was calculated from total body BMC obtained from the DEXA fan-beam measurement multiplied by 1.25 (18). From the four-compartment model, body composition was estimated by using the formula of Lohman et al. (18), i.e., body fat (%) = [2.747/D – 0.714W + 1.146M – 2.053] · 100, where D is body density from hydrostatic weighing, W is the water fraction of the body (total body water/body wt), and M is the mineral fraction of the body (total body mineral mass/body wt). The mineral was estimated from DEXA BMC and multiplied by 1.25 to account for nonosseous mineral in the body.

CT

CT of the legs was selected as the reference method for the validation of leg fat measurements by DEXA. Because CT measures adipose tissue and DEXA measures fat tissue, the CT values were multiplied by 0.80 to compare similar FM measures from both the CT and DEXA; the assumption that adipose tissue is 80% fat is a potential source of error for this reference method. DEXA divides soft tissue into fat-free mass (FFM) and FM, whereas CT provides muscle tissue mass and adipose tissue mass. Thus a direct comparison between the two methods cannot be made.

Five cross-sectional images at anatomically determined locations of the legs were made by using a GE-9800Q scanner. Each CT image was completed at 120 kVp with a scanning time of 2 s at 70 mA. The anatomic locations are as follows: ankle (at joint), calf (at two-thirds of the distance between ankle joint and knee joint), knee (7 mm above knee
joint), midthigh (at one-half the distance between knee joint and top of femur), and upper thigh (lowest point of the ischial tuberosity). The slice thickness was set at 10 mm for the calf, midthigh, and upper thigh scans and at 5 mm for the ankle and knee scans. A single observer analyzed all CT images. A 40-cm field of view and 512 matrix (pixel size of 0.78 mm) were used for most persons. In heavier persons, a 48-cm field of view (pixel size of 0.93 mm) was used for the upper thigh scan. A standard soft tissue reconstruction algorithm was employed. The external contours of the leg were determined by using a threshold of 224 Hounsfield units, and the external bone contours were derived at 150 Hounsfield units. The resulting contours were examined and adjusted manually if they did not adequately track the tissue boundaries. The CT number intervals of this region were determined by computing the histogram of the soft tissue region, detecting muscle and fat peaks, and setting windows around these peaks. The calculated contours of the fat and muscle distributions were overlaid on the image to ensure accuracy of the results. Intervals were manually adjusted if the fat and muscle areas were not accurately delineated. The fat volume bounded by two adjacent scans 1 and 2 (V1,2) is given by

\[ V_{1,2} = D_{1,2} \times \text{average} (A_{1}, A_{2}), \]

where \( D_{1,2} \) is the distance (in cm) between the scans, and \( A_{1} \) and \( A_{2} \) are the cross-sectional fat areas (in cm\(^2\)) in the two scans (5, 33). All CT images were analyzed by the same technician.

Total leg fat volume is the sum of four areas: ankle/calf, calf/knee, knee/midthigh, and midthigh/upper thigh. Total thigh fat volume is the sum of the two segments: knee/midthigh and midthigh/upper thigh. Fat volumes at the midthigh and at the calf from the 10-mm slice were multiplied by 3.96 to create the same leg area used for the DEXA midthigh and calf subregions. All fat volumes were multiplied by 0.923 to calculate adipose tissue mass, where 0.923 is the assumed constant density (kg/m\(^3\)) of adipose tissue (32).

Lard Study

A specified amount of lard was used to simulate changes in body composition. The mean mass of the two lard packets was 1 and 2 kg. After the total body scan was performed with the use of fan-beam DEXA, a 1-kg lard packet was placed on the ventral side of the trunk and a 1-kg lard packet on the ventral side of the trunk and a 1-kg lard packet on the right leg for a total mass of 4 kg. A second DEXA total body scan was performed on all subjects. Because the lard packets may have partially overlapped the left leg, both legs were analyzed together to analyze changes in leg FM. The lard was chemically analyzed by Covance Laboratories (Madison, WI), and the percent fat was determined to be 98.9%.

Statistical Analyses

Data were analyzed by using the SAS software (SAS Institute, Cary, NC) (24). Data are presented as means ± SD. Pearson product-moment correlations were used to evaluate the strength of the linear associations between the DEXA fan-beam technology and both the four-compartment model and the CT scans. Two subjects had invalid hydrostatic weighing measurements and were excluded from these analyses (n = 58). Paired t-tests were used to assess whether absolute differences existed between the DEXA fan-beam technology and the criterion methods. The Bland-Altman technique was implemented to evaluate the agreement between the two methods of measurement through calculations of mean differences between DEXA fan-beam technology and criterion methods (4). Limits of agreement were calculated as ±2 SD and are displayed in Figs. 1B and 3.

Total FM by the DEXA fan beam was compared with total body FM from the four-compartment model by using general linear models. Similarly, leg FM by DEXA was compared with leg FM from CT slices with general linear models. The standard error of the estimate (SEE) reported is the root mean square error. Only 59 subjects (29 men and 30 women) were included in the subregional comparisons because of the exclusion of an outlier whose difference for total leg FM measurements was >3 SD higher than the mean difference between the two measurements.

For the lard study, means and SD are reported. Tests for linear trends were performed by using a linear contrast test. To determine whether the actual differences detected by the fan-beam DEXA were significantly different from the expected differences, 95% confidence intervals were calculated for the actual differences. All P values <0.05 were used to indicate statistical significance.

RESULTS

Characteristics of the Study Population

Table 1 displays the characteristics of the study population. The mean age of the participants was 73.7 ± 2.2 yr. The mean BMI was 27.4 kg/m\(^2\), ranging from 17.5 to 39.8 kg/m\(^2\). Body weight, height, and the percentage of body fat were considerably higher in women than men, with percent fat ranging from 27.2 to 51.2% for the entire population using the four-compartment model. The hydration of the FFM for this population was 72.1 ± 2.0%.

Total Body FM: Fan-Beam DEXA Technology vs. Four-Compartment Model

The mean values for total body FM by the DEXA fan-beam technology and the four-compartment model are shown in Table 2. Small but significant underestimations of total FM (kg) (<1.0 kg, P < 0.0001) by the DEXA fan beam compared with the four-compartment model were found. Nevertheless, the proportion of the variance in total FM from DEXA explained by the four-compartment model is ≥94%, with SEE ranging from 1.4 to 1.6 kg. Figure 1A depicts the strong linear relationship between measurements of total FM (kg) for the fan-beam DEXA and the four-compartment model. The difference between the DEXA fan beam and the four-compartment model is plotted against the

| Table 1. Baseline characteristics of the study population |
|---|---|---|---|---|
|   | Men | Women | Total | Range |
| n  | 30  | 30   | 60   |
| Age, yr | 73.9 ± 2.2 | 73.6 ± 2.3 | 73.7 ± 2.2 | 70.1–79.3 |
| Weight, kg | 83.7 ± 12.2 | 67.9 ± 12.6 | 75.8 ± 14.6 | 38.2–111.0 |
| Height, cm | 173.2 ± 6.1 | 159.1 ± 6.2 | 166.2 ± 9.4 | 147.6–186.5 |
| BMI, kg/m\(^2\) | 27.9 ± 3.7 | 26.9 ± 5.2 | 27.4 ± 4.5 | 17.5–39.8 |
| Body fat, % | 26.1 ± 5.5 | 38.9 ± 6.7 | 32.5 ± 8.8 | 17.1–51.2 |

Values are means ± SD for n subjects. BMI, body mass index. For %body fat on 4-compartment model for n = 30 men and 28 women, P < 0.005.
mean of the two measurements in Fig. 1B. From this, there appears to be a systematic difference between the two measurements beyond a mean total FM of ~30 kg; this bias appears to get larger as total body FM increases, particularly in men (men: $r = -0.40$, $P < 0.05$; women: $r = -0.29$, $P = $ not significant).

Leg FM: Comparison of Fan-Beam DEXA Technology vs. Multislice CT Scans

Table 3 compares the FM measurements at the leg, thigh, midthigh, and calf for the DEXA fan-beam technology and the CT scan. For total leg and total thigh FM, the DEXA fan beam tended to overestimate FM significantly in both women and men, with greater differences observed in women. Similar relative differences (difference as a percentage of the CT estimated mass) in midthigh and calf FM between the two measurements were demonstrated. Absolute mean differences for the total leg FM were 1.1 kg ($P < 0.0001$), whereas at the midthigh and calf differences were ≤0.08 kg ($P < 0.0005$). A large proportion of the variance in DEXA fan-beam leg FM measures was explained by FM from CT, with $R^2$ ranging from 0.95 to 0.98 and SEE ranging from 0.03 to 0.43 kg. At the calf, only ~82% of the variance in calf FM from DEXA could be accounted for by FM from CT; these results were similar in women and men.

The linear association between the two methods (DEXA fan beam and CT) is depicted in Fig. 2. Correlations were $r = 0.99$ for the total leg, thigh, and midthigh but slightly lower for the calf ($r = 0.91$, $P < 0.0001$ for all). Figure 3 demonstrates the degree of agreement between DEXA fan beam and CT for measuring leg FM and regional leg FM. Given the moderate-to-strong positive correlations at the total leg and each of its subregions, it appears that the overestimation of FM by DEXA fan beam may be associated with the level of FM. As the amount of FM in the legs increases, greater differences between the measurements are demonstrated. These findings were consistent for men and women at the leg and each of its subregions, except at the midthigh in which no association was demonstrated in men (men: $r = 0.01$, $P = $ not significant; women: $r = 0.33$, $P < 0.10$).

Lard Experiment

Because the lard packets consisted of ~98.9% FM, the expected differences detectable for FM after 1- and 2-kg additions were 0.989 and 1.978 kg, respectively. Only 62.7 and 60.6% of exogenous fat were identified as fat in the trunk region after 1- and 2-kg additions, respectively (Tables 4 and 5) compared with 80% when the lard was positioned over the legs. The test for linear trends after sequential additions of lard was significant at $P = 0.004$ for FM at both legs but was not significant for either trunk FM or total FM. Similar
analyses were performed for lean mass for which we would expect no differences from the addition of lard packets, and this was true. Results for total mass were similar to those observed for FM.

**DISCUSSION**

In this population of 60 healthy elderly women and men of varying BMI, total FM measurements from the DEXA 4500A fan beam, the most recent generation of DEXA scanners, compare favorably with those from the criterion method, the four-compartment model. On average, absolute differences between DEXA and the four-compartment model were small (1 kg and SEEs of 1.4–1.6 kg) but statistically significant for the total population. From the validation study of FM at four different regions of the leg in which multislice CT scans were selected as the criterion method, moderate-to-strong agreement between the two methods was demonstrated. Of interest, in a previous publication based on this study population, DEXA fan-beam technology also appeared to offer considerable promise for the assessment of fat-free body mass and leg muscle mass (31). Specifically, FFM by DEXA was positively correlated with FFM by the four-compartment model ($R^2 = 0.98$, $SEE = 1.6$ kg) and with CT at all four sites, with $R^2$ ranging from 0.96 (total leg and total thigh) and 0.94 (midthigh) to 0.86 (calf).

Numerous in vivo studies have compared DEXA measures of body composition (Hologic 2000) with similar reference methods. Johansson et al. (13) compared DEXA with hydrodensitometry, skinfold thickness, and bioelectrical impedance and reported DEXA measures for FM as being consistently lower than the other measures. Similarly, the percent body fat from DEXA (Lunar DPX) was 7.5 and 4.5% less than that from a four-compartment model for men and women, respectively (34). In contrast, others have shown that the percentage of fat measured by DEXA was higher than that measured by total body potassium or from a multicomponent model (1, 8).

![Fig. 2. Relationship between fat mass by DEXA fan beam and by multislice computed tomography (CT) in elderly men (●) and women (○) at 4 leg regions with line of identity shown. A: total leg. B: thigh. C: midthigh. D: midcalf.](image)

Table 3. Comparison of DEXA fan beam for measuring leg fat mass vs. computed tomography

<table>
<thead>
<tr>
<th></th>
<th>CT</th>
<th>Fan Beam</th>
<th>Difference</th>
<th>$R^2$</th>
<th>SEE</th>
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<tr>
<td>Total leg, kg</td>
<td></td>
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<tr>
<td>Men</td>
<td>4.5 ± 1.6</td>
<td>5.2 ± 2.1</td>
<td>0.7 ± 0.5*</td>
<td>0.97</td>
<td>0.37</td>
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<tr>
<td>Women</td>
<td>6.4 ± 2.1</td>
<td>7.9 ± 2.6</td>
<td>1.5 ± 0.6*</td>
<td>0.97</td>
<td>0.42</td>
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<tr>
<td>Total</td>
<td>5.5 ± 2.1</td>
<td>6.6 ± 2.6</td>
<td>1.1 ± 0.7*</td>
<td>0.97</td>
<td>0.43</td>
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<tr>
<td>Thigh, kg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Men</td>
<td>3.4 ± 1.2</td>
<td>3.8 ± 1.4</td>
<td>0.4 ± 0.2*</td>
<td>0.97</td>
<td>0.23</td>
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<tr>
<td>Women</td>
<td>5.0 ± 1.6</td>
<td>5.7 ± 1.8</td>
<td>0.7 ± 0.4*</td>
<td>0.97</td>
<td>0.32</td>
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<tr>
<td>Total</td>
<td>4.2 ± 1.6</td>
<td>4.7 ± 1.9</td>
<td>0.5 ± 0.3*</td>
<td>0.98</td>
<td>0.28</td>
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<td>Midthigh, kg</td>
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<tr>
<td>Men</td>
<td>0.3 ± 0.1</td>
<td>0.3 ± 0.1</td>
<td>0.04 ± 0.03*</td>
<td>0.95</td>
<td>0.03</td>
</tr>
<tr>
<td>Women</td>
<td>0.6 ± 0.2</td>
<td>0.6 ± 0.2</td>
<td>0.05 ± 0.05*</td>
<td>0.96</td>
<td>0.05</td>
</tr>
<tr>
<td>Total</td>
<td>0.4 ± 0.2</td>
<td>0.5 ± 0.2</td>
<td>0.04 ± 0.04*</td>
<td>0.97</td>
<td>0.04</td>
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<tr>
<td>Calf, kg</td>
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<tr>
<td>Men</td>
<td>0.1 ± 0.1</td>
<td>0.2 ± 0.1</td>
<td>0.03 ± 0.03†</td>
<td>0.78</td>
<td>0.03</td>
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<tr>
<td>Women</td>
<td>0.2 ± 0.1</td>
<td>0.3 ± 0.1</td>
<td>0.07 ± 0.05*</td>
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<td>Total</td>
<td>0.2 ± 0.1</td>
<td>0.2 ± 0.1</td>
<td>0.05 ± 0.05*</td>
<td>0.82</td>
<td>0.04</td>
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</table>

Values are means ± SD for n = 29 men and 30 women (total 59). CT, computed tomography. Significant differences at *$P < 0.0001$ and †$P < 0.0005$. 

![Fig. 2. Relationship between fat mass by DEXA fan beam and by multislice computed tomography (CT) in elderly men (●) and women (○) at 4 leg regions with line of identity shown. A: total leg. B: thigh. C: midthigh. D: midcalf.](image)
Most recently, Clasey et al. (6) demonstrated a prediction error of ±5% when comparing fan-beam and pencil-beam DEXAs (Hologic 2000) with the four-compartment model. This study, however, is limited by the large variation reported in the hydration of the FFM [78.7 ± 5.8 (SD)%], which is considerably higher than the 2.0% variability in our study and the range of 1.1–2.4% reported by others (10, 17, 18). This variability challenges the accuracy of the body water data of Clasey et al. and, therefore, the validity of their four-compartment model.

This is the first study to validate subregional FM measurements at the leg, thigh, midthigh, and calf by the DEXA fan beam with multislice CT scans. Although generally good agreement for regional FM measurements was found between the two methods, DEXA appeared to overestimate FM at the leg and to a lesser extent at the thigh compared with CT measurements. This overestimation appeared to be associated with the level of FM; i.e., as leg FM increased, differences between the two measurements increased. It is also possible that this validation was limited by the number of axial slices made across the length of the leg, and perhaps a more accurate validation of DEXA leg FM with CT necessitates more than five axial slices. Another study validated DEXA measures of abdominal fat by using CT as a reference method and demonstrated that DEXA measures accounted for 80% of the variance in intra-abdominal fat by CT (28). Only one study has compared anthropometric estimates of limb composition and volume with DEXA, and moderate correlations were reported (7). For this study, adipose tissue as measured by CT was presumed to consist of 80% fat and 20% water, proteins, and minerals (32). This assumption was based on the chemical analyses of fat biopsies in 16 men and women (32) and is reasonable given the similar estimates of the nonfat fraction within adipose tissue, ranging from 14 to 32%, reported in the literature (2, 19); the degree to which this value varies with increasing age is presently unknown.

Many studies have simulated changes in FM to assess the ability of DEXA to accurately detect changes in FM (12, 21, 27, 28). We demonstrated that artificial changes in FM, at quantities chosen to mimic physiological changes, were measured accurately at the legs and total body but were underestimated at the trunk by ~40%. Tests for linearity were only significant for the legs and total body and not for the trunk, suggesting an inability of the DEXA fan beam to detect small, sequential changes in trunk FM. In a study by Milliken et al. (21), only 50% of fat added to the trunk was detected, compared with 92% at the thigh (Lunar DPX). Similarly, the addition of 2-kg strips of fat to the thigh was almost completely detected by DEXA (96%; Hologic 1000), whereas strips of fat added to the trunk were only partially measured (55%) (27), suggesting that DEXA may not accurately detect changes in trunk FM. The limitation of DEXA in detecting changes in FM might be attributed to the following. 1) Soft tissue analysis is possible only in those pixels that do not contain bone mineral. Because the trunk region has

Fig. 3. Difference in fat mass between DEXA fan beam and multislice CT against the mean at 4 leg regions. A: total leg. B: thigh. C: midthigh. D: midcalf. Solid lines, mean difference; dotted lines, limits of agreement (±2 SD). ○, Elderly women; ●, elderly men.
large soft tissue regions interspersed with multiple bony regions, particularly at the ribs, this extrapolation process is more complex and subject to greater error. 2) Also, lard packets on the trunk are occluded by the spine, pelvis, ribs, and sternum, leaving only the unoccluded portion to be measured (20). However, in a more recent study by Kohrt (16), DEXA (Hologic QDR 1000/W; version 5.64, enhanced whole body program software) accurately quantified the addition of 1.5 kg of exogenous FM positioned over either the thighs or truncal region as ~96% fat, irrespective of position.

Corrections in analytic software (version 8.21) have been made by Hologic to properly integrate mass measured by a fan-beam scanner. The fan-beam scanner samples the entire subject with no overlap between adjacent pixels across the entire extent of the fan beam. Implementing known fan-beam geometry, high-energy attenuation, and the fact that the body is uniquely sampled by the fan beam, mass was integrated along each ray of the beam (14). The close agreement between DEXA fan-beam values and criterion methods, even at small subregions of the leg, indicates that these adjustments in the analysis algorithm are effective.

Potential sources of error in in vivo FM measurements from DEXA include differences in body thickness, variations in fat distribution and the fat content of bone marrow, difficulties in evaluating FM under- or overlying bone, and unknown variance in the hydration status of FFM (15, 18, 23). An important assumption made by DEXA is that the hydration of FFM is uniform and fixed at 0.73 ml/g, when indeed this value among older adults has been shown to range from 68 to 78% (29). Altered hydration status with aging can result in an error in the amount of lean tissue attributed to each pixel and, ultimately, to greater error in the fat compartment. However, based on data from Baumgartner et al. (3) that compare a hydration value of 68% to one of 78%, only 0.34 kg of FM or ~0.5% fat is demonstrated; this difference is well within the measurement error of DEXA. Another limitation of this study is its cross-sectional design; clearly, information on the measurement of individual changes in body composition is of great interest.

Based on this cross-sectional validation study, the DEXA fan-beam measurements of total body fat and leg FM in elderly adults compares favorably with criterion methods, including the four-compartment model and multislice CT, respectively. Our results were similar in women and men. These findings suggest that the DEXA fan beam offers substantial promise for the cross-sectional assessment of total body fat and leg FM in elderly women and men. Further improvement in methods for measuring body composition remains important in better defining normal changes in health, with aging, and in evaluating the effects of disease.

We thank the technicians at the Department of Radiology, University of California at San Francisco; Alice Yee for performing hydrostatic weighing measurements; Dr. Dale Schoeller for conducting the total body water measurements; and Dr. Thomas Lang for reading computed tomography scans. The Health ABC DEXA and Body Composition Working Group is part of the Health, Aging, and Body Composition Study and consists of Tamara Harris, Marjolein Visser, Jean Langlois, Jane Cauley, Loran Salamone, Thomas Fuerst, Michael Nevitt, Maurice Dockrell, Francis Tylavsky, and consultants Tom Kelly and Timothy Lohman.
This work was supported by National Institute on Aging Grants NO1-AG-6–2101, NO1-AG-6–2103, and NO1-AG-6–2106 and a grant from Hologic.

REFERENCES

17. Lesser GT and Marholsky J. Body water compartments with human aging using fat-free mass as the reference standard.