Comparison of the effectiveness of 2 dual-energy X-ray absorptiometers with that of total body water and computed tomography in assessing changes in body composition during weight change^{1–3}

Frances A Tylavsky, Timothy G Lohman, Maurice Dockrell, Thomas Lang, Dale A Schoeller, Jim Y Wan, Thomas Fuerst, Jane A Cauley, Michael Nevitt, and Tamara B Harris

ABSTRACT

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Background: Little information is available on the assessment of changes in body composition as a function of weight change with the use of the fan beam of dual-energy X-ray absorptiometry (DXA).

Objective: The objective was to determine the accuracy of the fan beam of the QDR 4500A densitometer and the pencil beam of the QDR 2000 densitometer in estimating changes in whole-body lean soft tissue mass (LSTM_{DXA}) and fat mass (FM) with weight change.

Design: Thirty-seven subjects who lost 5.7 ± 4.5 kg were measured before and after weight change. Using total body water and computed tomography (CT) of the midthigh, we compared changes in FFM_{TBW} and LSTM_{CT} with changes in LSTM_{DXA}.

Results: Overall, compared with TBW, the fan beam gave a larger estimate of change ($\overline{x} \pm SD$) in LSTM (fan beam – TBW: -0.7 ± 1.6 kg) than did the pencil beam (pencil beam – TBW: -0.1 ± 1.6 kg). When the change in LSTM obtained with the fan beam and pencil beam was regressed against the change in FFM_{TBW}, the slope of the line for the fan beam was 0.97 ($r^{2=}0.61$) and that for the pencil beam was 0.86 ($r^{2=}0.61$). Regression analysis showed that the results between the 2 units were not interchangeable. For the midthigh region, the change in LSTM_{DXA} with the fan beam and pencil beam.

Conclusions: The measurement of change in LSTM with the fan and pencil beams provides the same relation to changes in FFM assessed by TBW, but the 2 systems are not interchangeable. *Am J Clin Nutr* 2003;77:356–63.

KEY WORDS Body composition, dual-energy X-ray absorptiometry, DXA, computed tomography, weight loss, lean body mass, fat mass, total body water

INTRODUCTION

(BMC). Dual-energy X-ray absorptiometry (DXA) has been frequently used by researchers to estimate these measures and to relate the results to health outcomes. Although it is well accepted that DXA provides accurate estimates of BMC, the accuracy of DXA in measuring LSTM and FM is not well established, particularly with the introduction of fan-beam technology. Previous validation studies have compared estimates of LSTM and FM by pencil-beam DXA with estimates by reference methods such as the 4-compartment (4-C) model. These studies found that estimates of LSTM by DXA (LTSM_{DXA}) differ from estimates made with reference methods by -0.7 to 2.9 kg and that estimates of FM by DXA (FM_{DXA}) differ from estimates made with reference methods by -0.4% to -5.3%, depending on the manufacturer of the DXA instrument and the reference method used (1-4). Ellis and Shypailo (5) reported that the pencil beam of the QDR 2000 densitometer (Hologic, Inc, Waltham, MA) estimated LSTM to be 1.0 kg lower and FM to be 0.8 kg higher than the values estimated with the fan-beam system of the QDR 4500A densitometer (Hologic, Inc). In addition, the greater differences in LSTM between the pencil-beam and fan-beam measurements were associated with increasing body mass, whereas differences in FM were inversely related to increases in body mass (5). Thus, the results obtained with a pencil-beam DXA system may not be readily comparable with those of a fan-beam DXA system because of differences in beam geometry and calibration. To address the issue of beam geometry and calibration, Visser et al (6) and Salamone et al (7) used a cross-sectional design to compare fat-free mass (FFM) and FM measured with the fan-beam system of the QDR

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The ability to measure changes in body composition with weight change is important in the study of many weight-related health conditions and overweight itself. Researchers are interested in how weight change affects body composition, including lean soft tissue mass (LSTM), fat mass (FM), and bone mineral content

¹From the University of Tennessee, Memphis (FAT and JYW); the University of Arizona, Tucson (TGL); the University of California, San Francisco (MD, TL, and MN); the University of Wisconsin, Madison (DAS); SYNARC, Inc, San Francisco (TF); the University of Pittsburgh (JAC); and the National Institute on Aging, National Institutes of Health, Bethesda, MD (TBH).

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³Address reprint requests to FA Tylavsky, Department of Preventive Medicine, 66 North Pauline Street, Suite 633, Memphis, TN 38105. E-mail: tylavsky@physio1.utmem.edu.

4500A instrument with estimates obtained with the 4-C model. These studies found that the absolute differences between FFM and FM assessed by DXA and by the 4-C model were comparable with those reported for validation that used the pencil-beam system. However, there is no conclusive evidence regarding the ability of DXA to estimate changes in FFM as a function of weight loss.

The primary objective of this study was to compare estimated changes in LSTM_{DXA} and FM_{DXA} with changes in LSTM and FM estimated by 2 criterion methods for individuals experiencing a change in weight. The fan beam of the QDR 4500A (DXA_{fan}) and the pencil beam of the QDR 2000 (DXA_{pencil}) provided estimates from DXA. Total body water (TBW) from isotope dilution and computed tomography (CT) of the midthigh were the 2 criterion methods. In addition, changes in total weight, bone area, BMC, and bone mineral density (BMD) obtained with the fan-beam and pencil-beam systems were quantified.

SUBJECTS AND METHODS

Participants

Fifty-four adults aged 18-73 y enrolled in different weight-loss regimens were recruited to participate in this study through advertisements in the local media and through various weight-loss programs. Most of the participants were white (n = 45); 9 were African American. Potential subjects were excluded from entering the study if they had a body mass index (BMI; in kg/m^2) > 38, metal implants, a pacemaker, undergone a recent radiographic procedure with contrast material (BaSO₄), severe spinal scoliosis, an extremity amputation, any illness or conditions known to influence hydration status (eg, renal failure, dialysis, and edema), or reported chronic use of medicines known to affect calcium metabolism. Each subject provided written informed consent in accordance with the Human Investigation and Review Boards at the University of Tennessee. Forty-three persons completed the baseline and follow-up measurements. Six persons were excluded from the analysis: 2 had incomplete TBW collections, 1 had a change in FFM from TBW (FFM $_{\text{TBW}}$) that indicated a loss of LSTM and an increase in hydration that were incompatible with weight changes measured by scale and by DXA, and 3 had apparent changes in hydration that were outside the physiologic range. The changes in TBW from baseline were 26%, 35%, and 33%, suggesting an error due to spillage of the dose water or contamination of the blood specimens. The final sample for data analysis consisted of 37 subjects.

Measurements

The participants completed all study measurements before starting their weight-loss programs and again after losing ≥ 6.8 kg or 6 mo after the baseline measurements had been made, whichever occurred first. The participants were enrolled in a variety of weight-loss programs offered commercially or had received gastric bypass surgery. All procedures were conducted on the same day after the subjects had fasted overnight.

Anthropometry

Body weight was measured on a balance-beam scale to the nearest 0.1 kg. Height was measured twice to the nearest 0.1 cm with a Harpenden stadiometer (Holtain, Wales, United Kingdom). If the 2 height measurements differed by > 0.5 cm, a third measurement was performed. The average of the 2 measurements within 0.5 cm was used for these analyses. BMI was calculated as weight in kilograms divided by height squared in meters.

Total body water

TBW was measured by using deuterium dilution with mass spectroscopy (8). An oral dose of deuterium oxide (≈50 g 8.3 atom percent D₂O) was measured to the nearest 0.01 g and administered to each participant after a 6–12-h fast. Plasma samples were collected into EDTA-containing tubes before and 4 h after the isotope administration. Samples were stored frozen at -20 °C and analyzed in batches for deuterium. TBW was calculated as the deuterium dilution space (L) divided by 1.041, yielding kilograms of TBW. The CV was 1.4% based on split sample between batches (9). FFM_{TBW} was calculated as TBW/0.73 (kg), and FM was calculated as scale weight − FFM_{TBW} (kg).

DXA: whole-body, midthigh, and legs

A fan-beam densitometer (model QDR 4500A) and a pencilbeam densitometer (model QDR 2000) were used to measure bone and body-composition components in the entire skeleton. Body composition (LSTM, FM, BMC, and BMD) was assessed by using software version 8.21 (Hologic, Inc) for the fan-beam densitometer and enhanced whole-body software version 5.71 (Hologic, Inc) for the pencil-beam densitometer. The DXA quality-assurance manual for the Health, Aging and Body Composition (Health ABC) study was used to standardize patient positioning and scan analysis. FM and BMC were assessed directly with both DXA systems. LSTM was obtained with the pencil-beam system by subtracting FM and BMC from total body weight measured by DXA for the whole body, legs (measurements of the right and left legs combined), and the midthigh region. A subregion of the midthigh was manually defined at one-half of the distance between the knee joint and the top of the femur. The smallest DXA subregion possible, consisting of 3 pixels or 3.96 cm, was used to approach the size of the CT slice. One subject positioned the thigh subregion on the baseline and follow-up scan.

We applied a correction factor for FFM and FM derived from the comparison of the QDR 4500A with a 4-C model (6). LSTM was obtained with the fan-beam system by multiplying FFM by 0.964 and subtracting BMC estimated from the whole body, legs (measurements of the right and left legs combined), and midthigh region. FM was obtained by subtracting the adjusted LSTM and BMC from the total weight of the whole body, legs, and midthigh region.

CT of the midthigh

Total volume, total lean tissue, and total fat of the midthigh were estimated from CT of the left leg. A 10-mm cross-sectional image at one-half the distance between the knee joint and the top of the femur was made with a Somaton Plus Scanner (Siemens Corp, Iselin, NJ). Each CT image was completed at 120 kVp with a scanning time of 2 s at 70 mA. A single observer analyzed all cross-sectional images. The external contours of the leg were determined by using a threshold of -224 Hounsfield units (HU), and the external bone contours were derived at 150 HU. The resulting contours were viewed and manually adjusted if they did not adequately track the boundaries. The CT number intervals of this region were determined as follows. First, the histogram of the soft tissue region was computed and then adipose tissue and muscle peaks were determined and windows were set around the peaks. To ensure the quality of the results, the calculated contours of the adipose tissue and muscle distribution were overlaid on the image. Intervals were adjusted manually if the areas were not accurately depicted. Thirty participants had complete CT scans at baseline and follow-up and technically acceptable measurements

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Variable	White women $(n = 37)$			White	White men $(n = 2)$			African American women $(n = 4)$		
	$\overline{x} \pm SD$	Min	Max	$\overline{x} \pm SD$	Min	Max	$\overline{x} \pm SD$	Min	Max	
Age (y)	43.3 ± 10.6	22.9	70.7	28.9 ± 14.7	18.6	39.3	45.2 ± 8.8	27.2	53.8	
Weight (kg)	82.4 ± 10.5	64.5	99.7	118.2 ± 1.9	116.8	119.6	86.5 ± 13.4	68.8	102.5	
Height (cm)	163.1 ± 5.0	150.0	170.0	180.5 ± 0.1	180.5	180.6	168.4 ± 8.0	158.0	177.2	
BMI (kg/m ²)	30.9 ± 3.6	23.8	38.3	36.3 ± 0.6	35.8	36.7	29.3 ± 4.3	24.1	33.1	
Weight change (kg)	-5.7 ± 4.4	4.1	-14.5	-9.1 ± 0.2	-8.9	-9.2	-3.7 ± 5.3	3.2	-9.5	

TABLE 1

 Selected characteristics of the study population¹

¹Min, minimum; Max, maximum.

from the fan-beam and pencil-beam DXA systems. Two subjects had a change in muscle volume that was > 3 SD from the mean difference; they were determined to be outliers with regard to the DXA measurements and, thus, were excluded from the analysis.

Comparison of CT and DXA

DXA divides body tissue into FFM and FM, whereas CT provides muscle and adipose tissue volumes. These methodologic differences were taken into account when $LSTM_{DXA}$ and FM_{DXA} were compared with lean mass measured by CT (LSTM_{CT}) and FM measured by CT (FM_{CT}). Lean tissue volumes determined from CT were multiplied by 1.04 to calculate lean mass by using 1.04 as the constant density (kg/m³) of lean tissue (10). All fat volumes were multiplied by 0.923 to calculate adipose tissue mass. The assumed constant density (kg/m3) of adipose tissue was 0.923 (10). Adipose tissue measured by CT consists of 80% fat and a lean compartment of 20% water, proteins, and minerals. This lean tissue compartment within adipose tissue is measured as lean tissue by DXA. Therefore, we subtracted the lean compartment in adipose tissue from adipose tissue and added the lean compartment to the muscle tissue and skin measurements by CT before we compared the measurements with those made by DXA. Lean mass determined by CT and FM_{CT} were multiplied by 3.96 to create the same area used for the DXA midthigh subregion.

Statistical analysis

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Data were analyzed by using SAS software (11). Means and SDs were calculated for all continuous measures of bone and body composition and for the physical characteristics of the participants. Paired *t* tests were used to determine absolute differences between 2 methods and between changes from baseline. A *P* value <0.05 was considered statistically significant. A Bonferroni adjustment

was made for multiple comparisons. Pearson's product-moment correlation analysis was used to compare changes in body composition between 2 methods. Linear regression was used to compare the changes in FFM_{TBW} with the changes in LSTM_{DXA} by pencil beam and fan beam. The SEE reported is the root mean square error. The method of Bland and Altman (12) was used to compare DXA with the criterion methods. To establish the interchangeability between the fan-beam and pencil-beam systems, a regression between the 2 measurements was done to test simultaneously whether the regression line had a slope of 1 and an intercept of 0.

RESULTS

The characteristics of the study population by race and sex are shown in **Table 1**. The mean (\pm SD) age of the participants was 43.2 \pm 10.7 y (range: 18.6 \pm 70.7 y). On average, the BMIs indicated that most of the participants were obese; however, normal-weight and overweight subjects were also part of the sample. Although the group lost weight overall, some subjects gained up to 4.1 kg over the study period (3.4 \pm 2.3 mo).

The absolute changes in weight and body composition obtained by TBW and the fan-beam and pencil-beam systems are shown in **Table 2**. The fan-beam and pencil-beam estimates of weight change were not significantly different from those obtained by scale. The correlation coefficients between the change in scale weight and the change in weight assessed by the fan-beam system were 0.96 (P < 0.0001) and 0.97 (P < 0.0001) for the pencil-beam scanner. The fan-beam system (DXA – TBW) provided higher estimates of change in LSTM and lower estimates of change in FM than did the TBW method. The correlation between FM_{DXApencil}, FM_{DXAfan}, and FM_{TBW} ranged from 0.87 to 0.95 (P < 0.0001). No significant differences in changes in FM_{DXApencil} and FM_{TBW} were observed.

TABLE 2

Comparison of changes (Δ) in body composition assessed by fan-beam and pencil-beam dual-energy X-ray absorptiometry (DXA) and total body water (TBW)^{*i*}

Variable	Δ Body weight		Δ LSTM		Δ Fat mass			Δ Bone mineral content				
	$\overline{x} \pm SD$	Min	Max	$\overline{x} \pm SD$	Min	Max	$\overline{x} \pm SD$	Min	Max	$\overline{x} \pm SD$	Min	Max
Total body water (kg)	$-5.7 \pm 4.5^{2,3}$	-14.5	4.1	-0.8 ± 2.5	-4.9	2.4	-4.9 ± 3.8^{3}	-11.3	4.2	_	_	_
Whole-body DXA (kg)												
Fan beam	-5.1 ± 4.1^4	-13.0	4.1	-1.5 ± 2.1^{3}	-5.9	3.6	-3.6 ± 2.9^{3}	-9.4	2.1	-0.013 ± 0.05	-0.201	0.071
Pencil beam	-5.2 ± 4.4^{3}	-12.9	4.4	-0.7 ± 2.2^{3}	-5.5	3.3	-4.5 ± 3.7^{3}	-11.9	2.9	-0.021 ± 0.05	-0.164	0.094
Differences												
Fan – TBW (kg)	0.6 ± 1.5^{4}	-3.8	3.0	-0.7 ± 1.6^4	-5.2	2.2	1.3 ± 1.9^{4}	-5.1	5.1			
Pencil – TBW (kg)	0.6 ± 1.1^4	-1.6	2.9	-0.1 ± 1.6	-3.6	3.1	0.4 ± 1.9	-2.8	5.4	—	_	_

 $^{1}n = 37$. Min, minimum; Max, maximum; LSTM, lean soft tissue mass.

²Measured by scale.

 $^{3.4}$ Change from baseline compared with 0 (paired t test with a Bonferroni adjustment for multiple comparisons): $^{3}P < 0.0001$, $^{4}P < 0.03$.

CHANGE IN SOFT TISSUE MASS WITH WEIGHT CHANGE



FIGURE 1. Relation between change (Δ) in lean soft tissue mass (LSTM) assessed by dual-energy X-ray absorptiometry (DXA) with a fan-beam (LSTM_{DXAfan}) or pencil-beam (LSTM_{DXAfan}) system and change in fat-free mass (FFM) assessed by total body water (TBW). A, C, and E: unity (.....), best fit (—), and 95% CI (---); B, D, and E: mean difference (.....) and reference line (—).

Change in whole-body LSTM: TBW compared with DXA

The relation between LSTM_{DXA} and FFM_{TBW} is depicted in **Figure 1**. When LSTM_{DXAfan} was regressed against the change in FFM_{TBW}; the β coefficient included 1 (95% CI: 0.68, 1.19), and the intercept was not significantly different from 0 (-0.01, 0.95; Figure 1A). When LSTM_{DXApencil} was regressed on FFM_{TBW}, the β coefficient included 1 (0.63, 1.11), and the intercept was not significantly different from 0 (-0.70, 0.41; Figure 1C). When the differences

between LSTM_{DXAfan} and FFM_{TBW} were plotted against the mean of the 2 measurements, the fan-beam system provided higher estimates of change in LSTM with losses in LSTM and lower estimates with gains in LSTM than did the TBW method (Figure 1B). No systematic differences between LSTM_{DXApencil} and FFM_{TBW} were apparent (Figure 1D). When these same analyses were performed comparing FFM_{DXA} with FFM_{TBW}, we obtained the identical results (data not shown). The percentage change in hydration of FFM_{DXA} with weight

TABLE 3

Changes in body weight, lean soft tissue mass (LSTM), and fat mass as assessed with computed tomography (CT) of the thigh and dual-energy X-ray absorptiometry (DXA) of the thigh and legs¹

<u> </u>	, 0	0	
	$\overline{x} \pm SD$	Min	Max
Δ Body weight (kg)	-5.2 ± 4.3^{2}	-11.1	4.1
Δ Thigh, by CT			
Total volume (cm ³)	-68.7 ± 81.4^{2}	-117.1	207.7
LSTM (g)	-44.7 ± 50.1^2	-108.6	118.2
Fat mass (g)	-45.7 ± 52.6^{2}	-122.4	136.6
Δ Thigh, by DXA			
Total mass (g)			
Pencil beam	-59.9 ± 66.6^{2}	-225.2	56.3
Fan beam	-85.1 ± 68.4^{2}	-224.4	45.6
LSTM, by DXA (g)			
Pencil beam	-11.8 ± 38.0	-114.9	52.3
Fan beam	-24.9 ± 34.3^{2}	-107.5	48.5
Total fat (g)			
Pencil beam	-48.5 ± 47.1^{2}	-156.4	57.3
Fan beam	-112.1 ± 51.5^{2}	224.4	3.60
Δ Legs, by DXA			
Total mass (kg)			
Pencil beam	-1.71 ± 1.6^{2}	-5.4	1.5
Fan beam	-1.75 ± 1.7^{2}	-5	2.8
LSTM (kg)			
Pencil beam	-0.34 ± 0.99	-3.1	1.4
Fan beam	-0.67 ± 1.17^{3}	-3.9	5
Total fat mass (kg)			
Pencil beam	-1.38 ± 1.2^{2}	-3.5	0.9
Fan beam	-1.27 ± 1.0^{2}	-3.3	0.86

 $^{1}n = 28$. Min, minimum; Max, maximum.

^{2,3}Significant change from baseline compared with 0 (paired *t* test with a Bonferroni adjustment for multiple comparisons): ${}^{2}P < 0.001$, ${}^{3}P < 0.05$.

change was 0.99 ± 4.4 (P = 0.03) with the fan-beam system and was 0.45 ± 4.4 (P = 0.53) with the pencil-beam system.

Change in whole-body FM: TBW compared with DXA

When FM_{DXAfan} was regressed against the change in FM_{TBW}, the β coefficient included 1 (1.11; 95% CI: 0.89, 1.33) and the intercept included 0 (-0.93; -1.94, 0.09). The same results were obtained when $FM_{DXApencil}$ was regressed against the change in FM_{TBW}. The β coefficient for FM_{DXApencil} included 1 (0.89; 0.72, 1.06), and the intercept was not significantly different from 0 (-0.93; -1.94, 0.09). FM_{DXAfan} explained 75% of the variability in the change in $\text{FM}_{\text{TBW}}\text{,}$ and $\text{FM}_{\text{DXApencil}}$ explained 76% of the variability in the change in FM_{TBW} (data not shown).

Change in whole-body LSTM and FM by DXA: fan beam compared with pencil beam

Compared with the pencil-beam system, the fan-beam system overestimated the change in LSTM_{DXAfan} by -0.8 ± 1.4 kg (P < 0.029). Conversely, the fan-beam system underestimated the change in FM_{DXAfan} by 0.9 ± 1.3 kg (P < 0.0001) compared with the pencil-beam system. When the change in LSTM_{DXAfan} and FM_{DXAfan} was regressed on the complementary measurement from the pencil-beam system, the slope of the line relating the change in $\mathrm{LSTM}_{\mathrm{DXA}}$ between the pencil-beam and fan-beam systems was 0.86 (P < 0.0001), with an intercept of 0.53 (P = 0.06): R^2 of 0.60, and SEE of 1.4 kg (Figure 1E). The correlation for the difference between $\ensuremath{\mathsf{LSTM}}_{\ensuremath{\mathsf{DXAfan}}}$ and LSTM_{DXApencil} and the mean of the 2 measurements showed no bias with the change in LSTM (Figure 1F). A test of the intercept = 0 and the slope = 1 for the regression of $LSTM_{DXAfan}$ on LSTM_{DXApencil} simultaneously showed that the changes in LSTM estimated with the fan-beam and pencil-beam systems were not equivalent (P < 0.006).

The slope of the line relating FM_{DXAfan} to $FM_{DXApencil}$ was 1.20 (95% CI: 1.06, 1.34; P < 0.0001), with an intercept of -0.21 $(-0.56, 0.74; P = 0.54), R^2$ of 0.89, and SEE of 1.2 kg. When the difference between $\mathrm{FM}_{\mathrm{DXAfan}}$ and $\mathrm{FM}_{\mathrm{DXApencil}}$ was plotted against the mean of the 2 measurements (data not shown), there was a moderate negative correlation between the change in FM_{DXA} with decreasing weight loss and increasing weight gain (r = -0.61, P < 0.0001).

A significant decrease in bone area with weight change was not seen with the fan-beam system $(0.61 \pm 1.84 \%; P = 0.06)$ but was observed with the pencil-beam system (-0.89 ± 2.35 %; P < 0.02). No significant differences in BMC with weight change were observed between the fan-beam $(-0.59 \pm 2.3\%; P = 0.11)$ and the pencil-beam $(0.99 \pm 2.19\%)$ systems (P = 0.009). No significant changes in BMD were observed between the fan-beam $(0.15 \pm 1.55\%; P = 0.97)$ and pencil-beam $(-0.02 \pm 1.75\%;$ P = 0.93) systems. There were no significant differences (P > 0.93) 0.05) between the estimates of change in bone area, BMC, and BMD between the fan-beam and pencil-beam systems.

Change in LSTM and FM of the thigh: CT compared with DXA

CT scans of the thigh (n = 28) showed a decrease in total volume, LSTM, and FM with weight change (Table 3). The decrease in LSTM_{CT} at the thigh was positively correlated with the change in LSTM at the midthigh as assessed by the fan-beam and pencilbeam systems (Table 4). Positive correlations were also obtained

TABLE 4

Correlation (r) between estimates of change (Δ) in lean soft tissue mass (LSTM) and fat mass of the midthigh by dual-energy X-ray absorptiometry (fan and pencil beams) and computed tomography (CT)¹

	Δ Body weight	Fan b	eam	Pencil beam		
		ΔLSTM	ΔFM	ΔLSTM	ΔFM	
Δ Body weight (kg)		0.37 (0.0561)	0.48 (0.010)	0.68 (0.0001)	0.47 (0.012)	
Δ Midthigh, by CT						
Total volume (cm ³)	0.83 (0.001)	0.49 (0.009)	0.69 (0.0001)	0.32 (0.094)	0.64 (0.0002)	
LSTM (g)	0.80 (0.0001)	0.55 (0.003)	0.68 (0.0001)	0.60 (0.001)	0.59 (0.001)	
Fat mass (g)	0.80 (0.0001)	0.54 (0.003)	0.67 (0.001)	0.37 (0.06)	0.66 (0.001)	

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TABLE 5

Correlation (r) between estimates of change (Δ) in lean soft tissue mass (LSTM) and fat mass (FM) of the leg and of the midthigh by dual-energy X-ray absorptiometry (fan and pencil beams)¹

		Fan	beam	Pencil beam		
	Δ Body weight	ΔLSTM	ΔFM	ΔLSTM	ΔFM	
Δ Body weight (kg)		0.37 (0.0561)	0.48 (0.010)	0.68 (0.0001)	0.47 (0.012)	
ΔLeg, by DXA						
LSTM (kg)						
Fan beam	0.58 (0.001)	0.54 (0.003)	0.23 (0.24)	0.48 (0.0105)	0.28 (0.14)	
Pencil beam	0.34 (0.07)	0.53 (0.004)	0.80 (0.0001)	0.68 (0.0001)	0.77 (0.0001)	
Fat mass (g)						
Fan beam	0.82 (0.0001)	0.39 (0.04)	0.79 (0.0001)	0.01 (0.98)	0.77 (0.0001)	
Pencil beam	0.89 (0.0001)	0.45 (0.01)	0.80 (0.0001)	0.77 (0.0001)	0.87 (0.00001)	

 $^{1}n = 28$; P values in parentheses.

when FM_{CT} of the midthigh was compared the FM_{DXAfan} and $FM_{DXApencil}.$

DXA of the legs compared with DXA of the thigh

The regional assessment of the legs (n = 28) by DXA showed a loss of total mass with weight change with both the fan-beam and pencil-beam systems (Table 3). The decrease in LSTM was significant as assessed with the fan-beam system but not with the pencil-beam system. The change in $\mathrm{LSTM}_{\mathrm{DXA}}$ of the legs was positively correlated with the change in body weight by DXA_{fan} and DXA_{pencil}. Moderate correlations were obtained when the change in LSTM_{fan} of the legs was compared with the change in $LSTM_{DXA}$ of the midthigh as assessed with the fan-beam and pencil-beam systems (Table 5). Stronger correlations were obtained when change in FM of the legs was compared with the change in FM of the midthigh as assessed with the fan-beam and pencil-beam systems. We found positive correlations between $LSTM_{CT}$ of the midthigh region compared with $LSTM_{DXAfan}$ (r = 0.46, P < 0.02) and LSTM_{DXApencil} (r = 0.35, P < 0.08) of the legs (data not shown). Positive correlations between FM_{CT} of the midthigh region compared with FM_{DXAfan} of the legs (r = 0.80, P < 0.0001) and FM_{DXAfan} (r = 0.77, P < 0.0001) were also observed (data not shown).

DISCUSSION

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The more rapid whole-body scan time of the fan-beam systems compared with that of the pencil-beam systems makes fan-beam systems a better choice for large-scale epidemiologic studies. On the basis of regression analysis, we found that the fan-beam system of the QDR 4500A and the pencil-beam system of the QDR 2000 provide the same relation between change in LSTM_{DXA} and FFM_{TBW}. In addition, there were positive correlations between the change in LSTM_{DXA} and FM_{DXA} of the midthigh and the change in the complementary measure of the midthigh as assessed by CT and of the legs as assessed by DXA.

Magnification of a fan beam has been shown to affect measurements of bone area and hip geometry (13) and could also affect measurements of soft tissue mass. Our study used the most recent software release (version 8.21) for the QDR 4500A, which adjusts for differential magnification at each pixel. We found that, with weight change, the 2 systems provide small but similar estimates of change in BMD despite the differences in beam geometry. Although the percentage change in bone area and BMC was significant with the pencil-beam system, the clinical significance is questionable. This result agrees with the results of Patel et al (14), ie, BMD is not affected by weight change, whereas other studies have proposed that differences in BMD with weight loss are artifacts of DXA methodology (15–17).

Differences in the calibration of DXA scanners have led to absolute differences in estimates of LSTM_{DXA} and FM_{DXA} between manufacturers (18, 19), which makes it difficult to compare study results. Work by our group and others suggests that the calibration of the QDR 4500A model produces higher total and regional FFM estimates than do previous generations of Hologic whole-body scanners (5) and alternative methods for assessing body composition (6, 7, 20). Our study extends these differences to the estimation of change in LSTM and FM for the whole body, midthigh, and leg regions. Using the TBW method as a comparison, we found that both the pencil-beam and fan-beam systems provided the same relation between change in LSTM_{DXA} and change in FFM_{TBW}. However, a simultaneous comparison of the slope and intercept of the regression of LSTM_{DXAfan} on LSTM_{DXApencil} suggested that the fan-beam system is not interchangeable with the pencil-beam system for estimating LSTM.

Technical measurement error, differences in BMC, and concentration of water can contribute to variability in the estimation of FFM_{TBW} by deuterium dilution (21). In the current study, BMC was not included in the estimates of LSTM_{DXA}, thus introducing a potential error due to variation in change in BMC. The change in BMC in this study was <1%, which is within the range of precision error of DXA instruments. When we repeated all the analyses that compared FFM_{DXA} with FFM_{TBW}, our results were equivalent to those obtained with LSTM_{DXA}.

Hydration of FFM has been reported to range between 65% and 81%, with lower values in the obese, as assessed by DXA instruments from various manufacturers (3, 4, 22-24); these results agree with those from cadaver studies (25-28). With weight loss, the relative quantities of water, protein, and fat in the adipose tissue may differ depending on the timing of the assessment (15), thereby theoretically affecting the estimation of FM and FFM by DXA and TBW (29). Weight-loss studies have reported that the hydration of FFM increases by 1.9-2.8% with loss of body weight determined by FFM_{DXA} (22, 24). In the current study we found that, with weight change, there was a 1% increase in hydration of FFM_{DXA} with the fan-beam system and no increase with the pencil-beam system; however, there was considerable variation among the participants. Our estimates of change in lean mass by TBW fall within the physiologic range reported by other researchers (22, 30, 31), who used TBW to quantify changes in FFM with weight loss (mean loss: -0.1-2.2 kg: SEE: 0.8-1.3 kg). This suggests that our values are an equally valid estimate of change in lean tissue.

The ability of the fan-beam DXA to estimate losses of lean mass and FM in specific regions of the body has been evaluated primarily though the addition of fat at the thigh and trunk region (7). The current study compared changes in $LSTM_{DXA}$ and FM_{DXA} of the midthigh region with changes in $LSTM_{CT}$ and FM_{CT} that accompanied changes in weight. The anatomical landmarks of the femur and the minor quantities of bone, cartilage, or tendons make the midthigh an ideal location to estimate changes in lean mass by CT and DXA. We found that DXA underestimated changes in LSTM and overestimated changes in FM compared with CT. The differences may have been due to the underlying assumptions used to estimate LSTM_{DXA} and FM_{DXA} and LSTM_{CT} and $\text{FM}_{\text{CT}}.$ We assumed that 20% of adipose tissue assessed by CT consisted of nonfat components, including water, protein, and mineral. Thus, this quantity was added to the lean component as assessed by CT. Studies report that the nonfat fractions within adipose tissue range from 32% to 14%; however, whether the value changes with weight change is not known.

The studies by Visser et al (6) and Salamone et al (7) show that estimates of muscle and FM derived from CT of the leg and midthigh are highly correlated with estimates of lean mass and FM derived by fan-beam DXA for the same region in a crosssectional study. The lower correlation coefficients between CT and fan-beam and pencil-beam DXA for the midthigh and legs found in the current study may reflect the current study's emphasis on changes in LSTM and FM resulting from changes in weight. Estimating change usually results in lower correlation coefficients than those obtained in cross-sectional studies because of the compounding of random errors when the difference in measurements is compared.

The factor most likely to affect the ability of DXA to estimate change in soft tissue is the difficulty in evaluating fat and lean mass under or over bone. Salamone et al (7) showed that fan-beam DXA estimated 80% of the change in FM when lard was placed on the thigh region. The physiologic changes in soft tissue due to weight change in our study were unable to be directly quantified but were most likely within the realm of the simulated changes by Salamone et al (7).

The effect of beam hardening on assessment of soft tissue is a concern when an X-ray source is used to measure persons who are overweight. Because the loss of weight in our subjects was moderate, the effects of beam hardening that were present at baseline were also present at follow-up. Consequently, the effect of beam hardening in a longitudinal study would be less than the effect on a single measurement.

During weight change, FM and LSTM usually change in the same direction; the change is generally greater in FM than in LSTM. Changes in FM and LSTM in our population reflect this concordance of change with fan-beam DXA, pencil-beam DXA, TBW, and CT of the thigh. The positive association between change in LSTM and FM between the fan-beam DXA and site-specific LSTM_{CT} suggests that the fan-beam DXA may provide a reasonable assessment of changes in lean and fat stores in the whole body and in the midthigh region and legs. This is pertinent information for the design of large-scale epidemiologic studies for assessing changes in LSTM or FM of the whole body and legs with minimal radiation exposure.

In conclusion, although small absolute differences in the loss of LSTM and FM were found between the fan-beam and pencilbeam DXA systems, both units showed the same relation between changes in LSTM and changes in TBW. However, regression analysis suggests that the results with the fan-beam and pencilbeam systems are not interchangeable. Because of the known differences in calibration and beam geometry, other studies are needed to determine the relations between the fan-beam and pencil-beam systems of other manufacturers.

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