Comparative Study of Body Composition by Dual-Energy X-ray Absorptiometry

John F. Aloia, Ashok Vaswani, Ruimei Ma and Edith Flaster

Department of Medicine, Winthrop-University Hospital, Mineola, New York and Brookhaven National Laboratory, Upton, New York

Dual-energy x-ray absorptiometry (DEXA) is a readily available technique that has recently been applied to measurement of body composition. In order to validate this technique, results from DEXA were compared with fat-free mass (FFM) and fat mass (FM) measured by total body levels of potassium (TBK), nitrogen (TBN), water (TBW) and carbon (TBC). **Methods:** A healthy population of 127 white women and 38 black women with a body mass index of 18–30 were recruited. **Results:** Compared with each of the other methods, DEXA overestimated FM and underestimated FFM. The slopes of the FM by DEXA versus the FM from each of the four methods were approximately the same, with a s.e.e. ranging from 2.4 to 3.0 units. The slopes of DEXA in comparison to FFM, however, ranged from 0.61 to 0.74 and were significantly less than unity, with a s.e.e. of 1.6 to 2.4 units. **Conclusion:** These findings suggest that at high values of FFM, DEXA is measuring something different from the FFM measured by TBW, TBN and TBK. The program for separating bone and soft tissue and for separating soft tissue into fat and lean at higher values in the DEXA method may need to be adjusted.

Key Words: body composition; dual-energy x-ray absorptiometry

J Nucl Med 1995; 36:1392–1397

Body composition studies have become increasingly important in a society interested in health maintenance, fitness and competitive physical activities. Underwater weighing, long used as a criterion method for measuring body fat has several drawbacks. First, it assumes a constancy of body water with aging. Second, it assumes a constancy of lean and skeletal mass with aging. Both assumptions may be incorrect. Moreover, hydrodensitometry needs to be corrected for sex and ethnicity (*1–3*). Another technique, the measurement of total body water, assumes a constancy of the water to fat-free mass ratio, which probably changes with aging (*4*). The measurement of total body potassium for estimation of fat-free mass requires the availability of an expensive whole-body counter and the assumption that the ratio of total body potassium to fat-free mass is constant between sexes, ages and ethnic groups, which also may be incorrect (*5*).

The development of techniques using neutron activation analysis has permitted a more sophisticated study of body composition and development of a four-component model: mineral ash, water, fat and protein (*6*). In this model, body weight is the sum of these components. We have used a variety of independent techniques to calculate the components of this model, including delayed gamma and prompt gamma neutron activation, inelastic neutron scattering and tritiated water dilution (*7–9*). The expense and lack of general availability of some of these techniques make them unsuitable for the study of large populations, but they may be used to validate other methods.

Dual-energy x-ray absorptiometry (DEXA) has been introduced as a more generally available, precise and relatively inexpensive tool to measure fat and lean tissue mass (*10–13*). DEXA is associated with a low radiation exposure and provides bone mineral as well as fat and lean tissue mass, allowing construction of a three-component model of body composition.

This study is part of a normative study of body composition in women. The purpose of the current study was to compare the use of several of the techniques in body composition measurement to DEXA for the determination of fat-free mass and fat mass. By use of a multicomponent approach to body composition, it was hoped to validate and calibrate the DEXA method with the other methods. It should be noted that there have been several animal carcass validations of the DEXA method and that the use of the more traditional methods as criterion methods is simply because they have been in use for a longer period of time.

METHODS

Subjects

Healthy black and white women were recruited by advertising in the local media and by a direct mail campaign. Exclusion characteristics included any chronic illness, for example, hypertension, diabetes and obesity, and any past history of illness or medication known to affect bone metabolism. The project was approved by the institutional review boards of Winthrop-University Hospital and Brookhaven National Laboratory and written informed consent was obtained from each participant. After initial screening, women were further rejected based on abnormal blood

Received Jun. 3, 1994; revision accepted Oct. 24, 1994.

For correspondence or reprints contact: John F. Aloia, MD, Department of Medicine, Winthrop-University Hospital, 259 First St., Mineola, NY 11501.

chemistries (multichannel chemistries, complete blood count, urinalysis, free T_4, thyroid-stimulating hormone, or abnormal physical findings); 27 women were excluded. A body mass index (BMI) of 18–30 was considered acceptable for inclusion in the study. The current report includes data on 165 women: 38 black and 127 white. Race was self-declared.

Total Body Potassium

Total body potassium is measured by whole-body counting of the radioactive isotope ^{40}K. The Brookhaven whole-body counter was upgraded in 1987 (*14*). It consists of 32 rectangular NaI detectors; 16 are positioned above and 16 below the subject. The precision for the measurement of total body potassium is ±1.4%.

Prompt Gamma Neutron Activation to Measure Total Body Nitrogen

The prompt gamma neutron activation system at Brookhaven National Laboratory has been redesigned with a newly constructed collimator, which incorporates a neutron reflector made of graphite and bismuth, providing a beam of 20 × 45 cm at the level of a bed that is 75 cm above a PuBe source. An aluminum tank containing heavy water is placed on top of the collimator to serve as a premoderator. There are two NaI (Tl) detectors (15.2 × 15.2 cm) which are shielded with bismuth, borated polyethylene, boron, carbide and boric acid. The two detectors are placed symmetrically at a 60° angle from the body axis and a 30° angle from the horizontal plane. The system utilizes a computer-controlled stepping motor to move the subject. Patients are measured in five 20-cm sections, starting from the shoulder position for a total body length of about 100 cm. The total skin dose to a subject is 80 mrem. Three bottle mannequin phantoms of different sizes are used to calibrate the system. The ratio of net hydrogen to nitrogen counts has a small linear dependence on the phantom's volume (*15*). The data acquisition system uses an IBM PC/AT computer equipped with a Nuclear Data multichannel analyzer. The precision for the measurement of nitrogen is ±3% (*15*).

Inelastic Neutron-Scattering System to Measure Total Body Carbon

The inelastic neutron-scattering facility was built in 1987 using a pulsed neutron generator to produce 14 MeV neutrons at a 10-kHz repetition rate (*16,17*). Two 15.2 × 15.2 cm NaI (Tl) shielded detectors are positioned on either side of the subjects. The system was recently upgraded with a new data acquisition system (IBM PC/AT with a Nuclear Data multichannel analyzer) and a new stepping motor. Subjects are measured from shoulder to knee in both the supine and prone positions on a motor-driven platform that scans over the neutron source. The total skin dose is less than 50 mrem (*16*). The number of neutrons produced by the generator is also measured using a plastic scintillator. The system is calibrated daily with an Alderson phantom. The precision for the measurement of carbon is ±3%.

Dual-Energy X-ray Absorptiometry

A whole-body DEXA scanner (DPX-L, Lunar Radiation, Madison, WI) was used to measure mineral, lean and fat mass, as described previously (*11*). The software program was modified by Lunar Radiation (1.3 Y) to correct for differences in patient sizes; this work was done using seven frozen beef phantoms of known fat content (*13,18*). Based on these calibrations, the ratio of soft-tissue attenuation (R_{ST}) at the two energy levels is used to partition soft tissue into fat and lean compartments. The scan was run at medium speed. The precision for total body mass is 1.2%, for soft tissue mass 1.6%, for total fat 5.0% and for total fat-free mass 1.5% (*19*).

Tritiated Water

Total body water was measured by using tritiated water dilution. The precision for the measurement of total body water is less than 1% (*19*).

Calculation of Body Compartments

Fat-free mass was calculated from total body nitrogen, total body water and total body potassium:

$$\text{Fat-free mass} - \text{nitrogen (kg)} = \frac{\text{total body nitrogen (g)}}{33.5}$$

$$\text{Fat-free mass} - \text{water (kg)} = \frac{\text{total body water (L)}}{0.73}$$

$$\text{Fat-free mass} - \text{potassium (kg)} = \frac{\text{total body potassium (g)}}{2.26}$$

$$\text{Total body fat (kg)} = \frac{\text{total body carbon (kg)} - 0.55\ \text{total body protein (kg)}}{0.77}$$

$$\text{Total body protein} = 6.25\ \text{total body nitrogen.}$$

Fat mass was calculated by subtracting fat-free mass from body weight. For DEXA, fat-free mass can be calculated in two ways: as fat mass subtracted from body weight, and as fat mass subtracted from total soft tissue mass. The fat-free mass from DEXA was calculated as the lean soft tissue mass plus total body bone mineral.

Statistical Methods

Regressions were run using the values obtained by DEXA for fat or fat-free mass as the dependent variable against each corresponding value determined by the single method and by the multicomponent model. Errors in determining fat-free mass and fat mass were calculated by the standard error of estimate or the variation about the regression line. Because age, body size, ethnicity and menstrual status could influence the results, multiple regressions were carried out for the entire population and each subgroup of race and menstrual status with covariates of BMI and age. Black/white comparisons were done by Student's t-test. We also used the methods of Bland and Altman (*20*) to see if there were any unusual trends in the measures with respect to residuals dependent on the mean or any other anomalies in the relationships.

RESULTS

In this study, 91 of the participants were premenopausal and 74 were postmenopausal. The clinical characteristics of the groups are given in Table 1. There were more white than black women in our sample. The black women were significantly younger, heavier and had a greater BMI. There were no significant differences between the groups in height.

Fat and lean mass measurements were examined for a relationship with age. In the white postmenopausal group, fat-free mass as measured by potassium showed a signifi-

TABLE 1
Clinical Characteristics: Mean (s.e.)

			Significance	
	Black	White	B/W	Combined
No.	38	127		165
Age	42.9 (1.65)	51.3 (1.21)	0.0001	49.4 (1.04)
Weight (kg)	66.3 (1.21)	63.1 (0.68)	0.02	63.8 (0.60)
Height (cm)	162.2 (0.85)	162.4 (0.59)	ns	162.4 (0.49)
BMI	25.2 (0.47)	23.9 (0.24)	0.01	24.2 (0.22)

B/W = black/white; BMI = body mass index; ns = not significant.

cant decline with age. Separate analyses were carried out for subgroups defined by ethnicity and menopausal status. The DEXA lean mass measurements were adjusted by adding the bone mineral content to the lean tissue mass measurement as given by DEXA, providing a closer estimate of fat-free mass which includes skeletal tissue. The slopes for total body fat were close to 1, indicating a one-to-one correspondence between the DEXA and the other fat measures. All of the slopes were significantly different from one for the fat-free mass regressions.

When we analyzed the data for the postmenopausal women, we found similar findings for the relationships between DEXA fat mass and the other fat measures and DEXA fat-free mass and the other fat-free mass measures. Thus, there was a slope of approximately unity with the fat measures and a slope of about 0.75 for the fat-free measures. No matter which subgroup we investigated (premenopausal, postmenopausal, whites only) we found similar slopes that were not close to unity.

When the combined data are considered, all the fat-free mass measurements were significantly different from each other (Table 2). The fat mass derived from DEXA and total body potassium were indistinguishable, as were the fat from total body nitrogen and fat from total body carbon (which includes total body nitrogen in the calculation). The rest of the estimates of fat mass were statistically different from each other.

TABLE 2
Measurements of Fat Mass and Fat-Free Mass by the Various Methods: Mean (s.e.)

Method	Fat mass	Fat-free mass
DEXA	22.2 (0.49)	40.0 (0.31)
TBK	21.9 (0.48)	41.9 (0.45)
TBC	20.8 (0.48)	
TBN	20.8 (0.51)	43.0 (0.35)
TBW	19.1 (0.45)	44.7 (0.38)

DEXA = dual-energy x-ray absorptiometry; TB = total body; K = potassium; C = carbon; N = nitrogen; W = water.

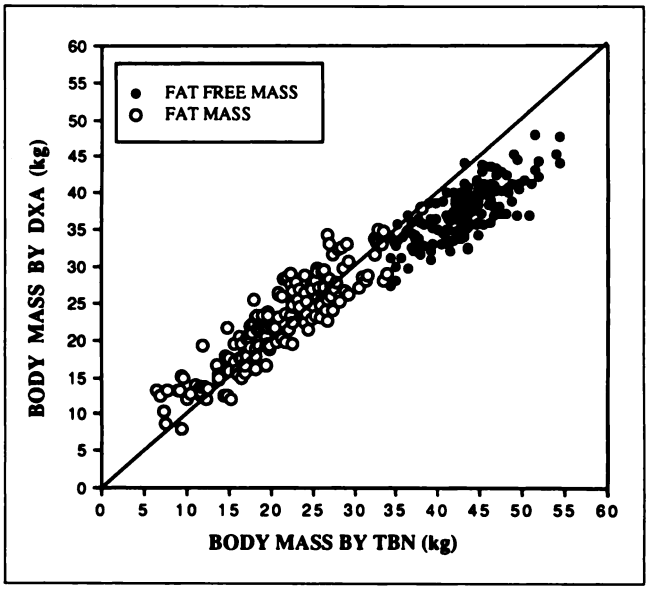

FIGURE 1. Fat mass and fat-free mass as measured by DEXA is plotted against fat mass and fat-free mass from total body nitrogen with the line of unity. DEXA overestimates fat and underestimates fat-free mass as measured by total body nitrogen.

The regressions of fat-free mass and fat mass are depicted in Figures 1–3. The average of all the methods (excluding DEXA) are regressed against the DEXA values for fat and fat-free mass (Fig. 4)

It may be seen that the predictive power of DEXA is relatively better for the fat measurement than for the fat-free measurement. The best agreement for fat mass measurements was between DEXA and fat mass measured from water. DEXA (fat) = 3.1 + fat mass (water). For this

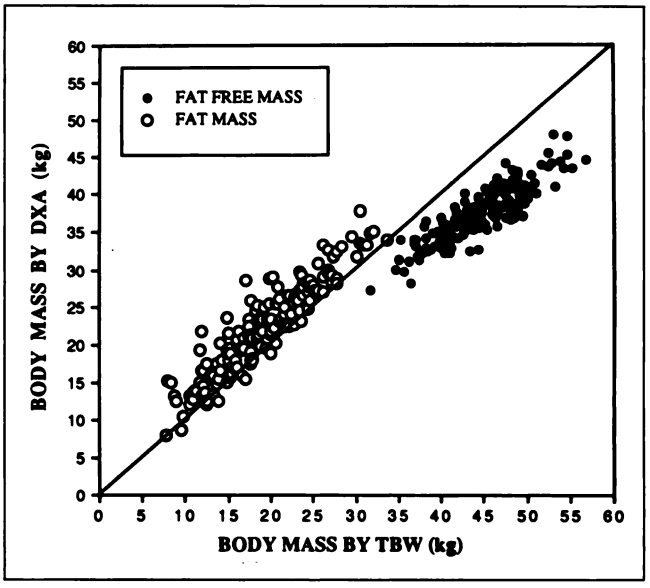

FIGURE 2. Fat mass and fat-free mass (DEXA) is plotted against fat mass and fat-free mass measured by total body water with the line of unity. DEXA overestimates fat and underestimates fat-free mass as measured by total body water.

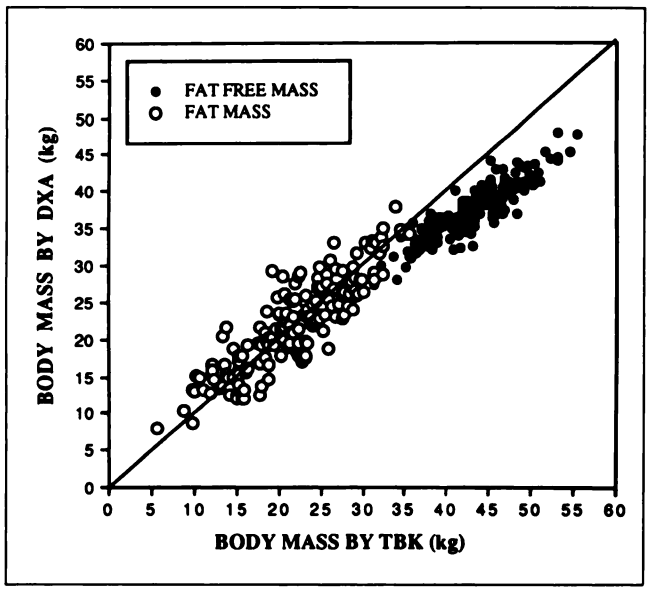

FIGURE 3. Fat mass and fat-free mass (DEXA) is plotted against fat mass and fat-free mass measured by total body potassium with the line of unity. DEXA overestimates fat and underestimates fat-free mass as measured by total body potassium.

relationship, the slope was 1.00 (see Table 3), so a simple addition of 3.1 kg (the intercept) to the fat mass as calculated from water will give an unbiased estimate of the fat measurement by DEXA. Conversely, DEXA − 3.1 will give an unbiased estimate of fat mass:water. It is interesting that the total body water is believed to overestimate fat mass by as much as 5%, which is similar to the 4.9% observed in the current study (*21*).

The other measurements of fat mass had slopes that were significantly (but not greatly) different from unity. The intercepts were also significantly different from zero. Examination of the plots reveal no evidence of nonlinearity and a test for curvilinearity suggests that a straight line may be used to fit the relationships. To adjust the DEXA measurements, they have to be multiplied by a constant and adjusted for the intercepts. The other fat measurements can be estimated by:

$$\text{Fat mass} - \text{carbon} = (\text{DEXA} - 2.9)/.93$$

$$\text{Fat mass} - \text{potassium} = (\text{DEXA} - 2.9)/.88$$

$$\text{Fat mass} - \text{nitrogen} = (\text{DEXA} - 4.3)/.86.$$

Similarly, the fat-free measurements can be estimated by:

$$\text{Fat-free mass} - \text{potassium} = (\text{DEXA} - 14.3)/.61$$

$$\text{Fat-free mass} - \text{nitrogen} = (\text{DEXA} - 9.3)/.71$$

$$\text{Fat-free mass} - \text{water} = (\text{DEXA} - 6.9)/.74.$$

In the case of the fat-free mass measurements, the slopes were consistently less than unity, indicating disagreement in the methods with DEXA. Fat-free mass was calculated from both actual body weight and from lean tissue mass added to total body bone mineral content. Since the best agreement was obtained from the latter computation, it is used in the tables and figures, that is, fat-free $\text{mass}_{\text{DEXA}}$ = lean tissue $\text{mass}_{\text{DEXA}}$ + mineral $\text{mass}_{\text{DEXA}}$. The regression of DEXA values against values obtained from the average of the other methods is displayed in Figure 5. It is evident that compared to the other methods DEXA consistently overestimates fat mass and underestimates fat-free mass. Examination of the data by the method of Bland and Altman (*20*) was carried out. The differences between the fat-free mass methods were plotted against the average of the two methods. There was a significant trend away from zero (perfect agreement), as the average fat-free mass values increased. There was no significant trend with the fat measures.

When we examined the DEXA values in women as BMI increased, the difference between fat mass comparing DEXA and the other methods was constant. Yet, the fat-free mass differences between the methods increased with higher BMIs. The fat-free mass from the other methods increased more than the values from DEXA. Moreover, as BMI increased, the DEXA measurement of soft tissue mass agreed less with actual body weight (the DEXA measurements were less).

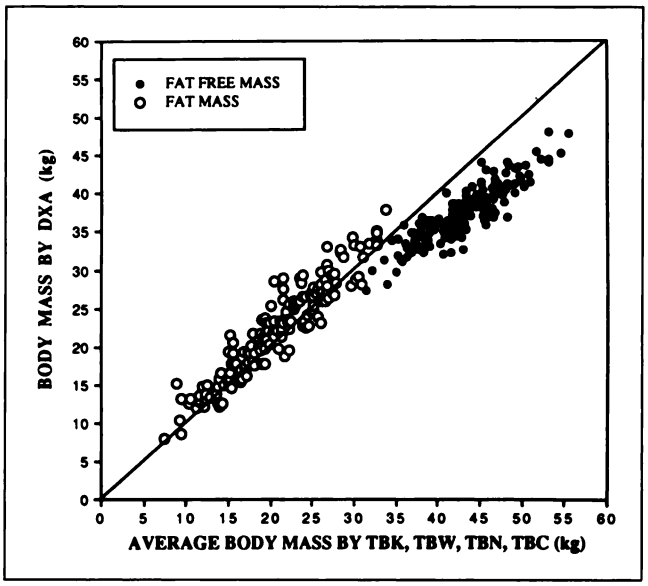

FIGURE 4. Fat mass and fat-free mass (DEXA) is plotted against fat mass and fat-free mass calculated from the average of all fat mass and fat-free mass measurements (carbon, nitrogen, potassium, water) with the line of unity. Underestimation of fat-free mass and the overestimation of fat mass by DEXA is apparent.

DISCUSSION

DEXA studies of body composition use the measurement of a physical property. Testing is safe and inexpensive and simultaneously measures fat mass, lean mass, and mineral mass. DEXA data provide a three-component model. Because DEXA is readily available, we compared each of these other methods with DEXA. The agreement

TABLE 3
A Comparison of Fat-Free Mass and Fat Mass Determined by DEXA Versus Other Methods

Variable	Slope	s.e.	INTERC	s.e.	s.e.e.	ADJR^2	Significance
			Fat Mass (DEXA)				
FM-C	0.93	0.032	2.9	0.69	2.53	0.84	0.0001
FM-K	0.88	0.038	2.9	0.87	3.04	0.76	0.0001
FM-N	0.86	0.031	4.3	0.67	2.61	0.83	0.0001
FM-W	1.00	0.032	3.1	0.63	2.35	0.86	0.0001
Avg. FM	0.99	0.027	1.7	0.59	2.08	0.89	0.0001
			Fat-Free Mass (DEXA)				
FFM-K	0.61	.025	14.3	1.06	1.86	0.79	0.0001
FFM-N	0.71	.042	9.3	1.83	2.43	0.63	0.0001
FFM-W	0.74	.030	6.9	1.33	1.83	0.79	0.0001
Avg. FFM	0.77	.027	6.6	1.16	1.63	0.84	0.0001

FM = fat mass; FFM = fat-free mass; C = carbon; K = potassium; N = nitrogen; W = water.

of the fat mass DEXA measurements with the other measurements was greater than the agreement of fat-free mass DEXA with the other measurements. The value for soft tissue mass from DEXA does not include mineral mass, which is included in the other measurements. Thus, to make the measurements of fat-free mass compatible, mineral mass must be added to the DEXA measurement to adjust "lean tissue mass" to "fat-free mass." Even with this modification, however, the DEXA value underestimates fat-free mass and may overestimate fat mass.

In the DEXA method, body thickness, variation in fat distribution and the fat content of the marrow are the major sources of biologic variation in estimation of fat content from soft tissue and hence also the determination of lean tissue mass. The mass of soft tissue used in the estimation of fat/lean comprises only about 55% to 60% of total body soft tissue. It is assumed that the composition of the body over areas of bone is the same as over areas where there is no bone. Such an assumption may be incorrect, introducing a large error in estimating fat-free mass and fat mass. Moreover, soft tissue is not identical to fat tissue, so that another correction must be made to increase comparability among methods. DEXA assumes that the absorptometric characteristics of lean content of soft tissue do not vary from individual to individual, so that the variation in the ratio of soft tissue (RST) reflects variations in fat and not lean composition.

The newer versions of Lunar software attempt to compensate for tissue thickness by: (a) determining RST regionally on a pixel to pixel basis and (b) the use of a digital filter to minimize the effect of statistical noise at thicknesses above 22 cm (*22*). In the current study, it appears that there needs to be further adjustment in the Lunar software. As tissue thickness increases (increasing BMI) the whole-body soft tissue counted becomes less than actual body weight. Furthermore, although the fat measurement is not substantially affected, the fat-free mass measurement is lowered.

The added values of the three compartments determined by DEXA (fat, lean, bone mineral), where lean and bone mineral represent fat-free mass was 62.2 kg, while body weight was 63.8 kg. We are not certain as to the reason for this discrepancy. Lohman (*23*) states that DEXA measures only osseous bone mineral, and to obtain total body bone mineral the value from DEXA must be adjusted. Such an adjustment would result in the sum of fat-free mass and fat mass approximating body weight. This correction, however, is not generally applied, and our lean tissue mass from DEXA is lower than some other population studies. The recent demonstration (*24*) that changes in hydration can change lean tissue mass may provide an explanation. Radiographically water is recognized as 91.4% lean tissue and 8.6% fat tissue. DEXA assumes that body water accounts for 73.2% of lean mass. Our participants were all studied under standardized conditions: fasting overnight, after emptying their bladder. It is likely that most population studies did not control the state of hydration.

Using body density as a criterion variable for determining fat-free mass, Lohman (*23*) concluded that a prediction error of 1.8 kg for women was excellent. The values we obtained comparing DEXA with the other measures of fat-free mass would be considered very good to excellent. It may be argued that no method is so completely validated that it may be used as a criterion method. Accepting this criticism, we have compared DEXA with multiple other methods that are not interdependent, and find that DEXA values must be adjusted to be consistent with fat-free mass calculated from total body water, potassium or nitrogen.

Comparison of the elemental partition model with the values for fat obtained from DEXA is of interest. This model, along with the other two-compartment measurements of fat mass suggest that DEXA overestimates fat mass. Haarbo et al. (*13*) noted that the percentage of fat measured by DEXA was higher than that measured by total body potassium, and that fat-free mass by DEXA was lower, which is consistent with our findings.

On the other hand, Johansson et al. (*25*) compared DEXA with underwater weighing, skinfold thickness and bioimpedance analysis and found that DEXA measurements for fat were consistently lower than the other mea-

sures. This, of course, has not been found in all studies, including the current study. Since DEXA accurately measures body weight, it is believed to provide an accurate assessment of soft tissue mass. This accuracy may diminish with increasing body thickness. Johansson et al. (*25*) conjecture that there may need to be an adjustment of the way soft tissue is partitioned into fat-free mass and fat mass. This conclusion is consistent with the current study in which fat mass is overestimated and fat-free mass is underestimated by DEXA compared with other methods.

CONCLUSION

In a multicomponent approach to body composition, several models for the measurement of fat-free mass and fat mass were compared with each other and with DEXA. Although the agreement of DEXA with the other methods was very good, DEXA tended to underestimate fat-free mass and overestimate fat mass.

The slope of DEXA compared to each of the measures of fat mass approximated unity, indicating similar agreement over the whole scale. The slope of DEXA compared to each of the fat-free mass measures was consistently less than unity. The non-DEXA fat-free mass measurements are independent of each other, and slopes of less than unity was a consistent finding. The agreement of DEXA with the other fat-free mass measurements was closer at lower values of fat-free mass. Thus, there is something in the DEXA measurement that produces less agreement with other measures of fat-free mass at higher values. Further studies should be performed to examine the reasons for this discrepancy.

ACKNOWLEDGMENTS

This study was supported from the National Institutes of Health grants PO1-DK42618 and RO1-AR37520-05 and grant DEAC02 76CH00016 from the U.S. Department of Energy.

REFERENCES

1. Heymsfield SB, Wang J, Lichtman S, Kamen Y, Kehayias J, Pierson RN. Body composition in elderly subjects: a critical appraisal of clinical methodology. *Am J Clin Nutr* 1989;50:1167–1175.
2. Baumgartner RN, Heymsfield SB, Lichtman S, Wang J, Pierson RN. Body composition in elderly people: effect of criterion estimates on predictive equations. *Am J Clin Nutr* 1991;53:1345–1353.
3. Johansson AG, Forslund A, Sjodin A, Mallmin H, Hambraeus Ljunghall S. Determination of body composition—a comparison of dual-energy x-ray absorptiometry and hydrodensitometry. *Am J Clin Nutr* 1993;57:323–326.
4. Cohn SH, Abesamis C, Yasumura S, Aloia JF, Zanzi I, Ellis KJ. Comparative skeletal mass and radial bone mineral content in black and white women. *Metabolism* 1977;26:No. 2.
5. Wang J, Russell M, Mazariego M, et al. Body fat by dual-photon absorptiometry: comparisons with traditional methods in Asians, blacks and whites. *Am J Hum Biol* 1992;4:501–510.
6. Heymsfield SB, Lichtman S, Baumgartner RN, et al. Body composition of humans: comparison of two improved four-compartment models that differ in expense, technical complexity and radiation exposure. *Am J Clin Nutr* 1990;52:52–58.
7. Vartsky D, Ellis KJ, Vaswani AN, Yasumura S, Cohn SH. An improved calibration for the in vivo determination of body nitrogen, hydrogen and fat. *Phys Med Biol* 1094;39:209–218.
8. Burkinshaw L, Hedge AP, King RF, Cohn SH. Models of the distribution of protein, water and electrolytes in the human body. *Infusions Ther* 1990; 17(suppl 3):21–25.
9. Ellis KJ, Yasumura S, Vartsky D, Vaswani AN, Cohn SH. Total body nitrogen in health and disease: effects of age, weight, height and sex. *J Lab Clin Med* 1982;917–926.
10. Mazess RB, Peppler WW, Gibbons M. Total body composition by dual-photon (^{153}Gd) absorptiometry. *Am J Clin Nutr* 1984;40:834–839.
11. Mazess RB, Barden HS, Bisek JP, Hanson J. Dual-energy x-ray absorptiometry for total-body and regional bone-mineral and soft-tissue composition. *Am J Clin Nutr* 1990;51:1106–1112.
12. Hassager C, Christiansen C. Influence of soft tissue body composition on bone mass and metabolism. *Bone* 1989;10:415–419.
13. Haarbo J, Gotfredsen J, Hassager C, Christiansen C. Validation of body composition by dual energy x-ray absorptiometry (DEXA). *Clin Physiol* 1991;11:331–341.
14. Dilmanian FA, Weber DA, Yasumura S, et al. Performance of delayed- and prompt-gamma neutron activation systems at Brookhaven National Laboratory. In: Yasumura S, Kamen Y, Lidotsky L, et al., eds. *Advances in in vivo body composition studies*. Plenum Press, New York, 1990.
15. Stamatelatos IE, Dilmanian FA, Mat R, et al. Calibration for measuring total body nitrogen with a newly upgraded prompt gamma neutron activation facility. *Phys Med Biol* 1993;38:615–626.
16. Cohn SH, Ellis KJ, Vartsky D, et al. Comparison of methods of estimating body fat in normal subjects and cancer patients. *Am J Clin Nutr* 1981;34: 2839–2847.
17. Kehayias JJ, Heymsfield SBN, LoMonte AF, et al. In vivo determination of body fat by measuring total body carbon. *Am J Clin Nutr* 1991;53:1339–1344.
18. Heymsfield SB, Wang J, Heshka S, et al. Dual-photon absorptiometry: comparison of bone mineral and soft tissue mass measurements in vivo with established methods. *Am J Clin Nutr* 1989;49:1283–1289.
19. Formica C, Atkinson MG, Nyulasi I, et al. Body composition following hemodialysis: studies using dual-energy x-ray absorptiometry and bioelectrical impedance analysis. *Osteoporosis Int* 1993;3:192–197.
20. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1986;1:307–310.
21. Culebras JM, Fitzpatrick GF, Brennan MF, et al. Total body water and the exchangeable hydrogen. II. A review of comparative data from animals based on isotope dilution and desiccation, with a report of new data from the rat. *AJP* 1977;232:R60–65.
22. Mazess RB, Bisek J, Trempe J, Pourchot S. Effects of tissue thickness on body composition measurement using dual-energy x-ray absorptiometry [Abstract]. *Bone* 1992;13:280.
23. Lohman TG. Skinfolds and body density and their relationship to body fatness: a review. *Hum Biol* 1981;53:181–2235.
24. Horber FF, Thomi F, Casez JP, et al. Impact of hydration status on body composition as a measured by dual energy x-ray absorptiometry in normal volunteers and patients on hemodialysis. *Br J Radio* 1992;65:895–900.
25. Johansson AG, Forslund A, Sjodin A, et al. Determination of body composition: a comparison of dual-energy x-ray absorptiometry and hydrodensitometry. *Am J Clin Nutr* 1993;57:323–326.