Aging in Women—The Four-Compartment Model of Body Composition

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

The four-compartment model of body composition was examined in 155 white women through measurement of total body carbon (TBC), nitrogen (TBN), calcium (TBCa), and water levels. The age (mean ± SD) of the population was 51.4 ± 13.5 years, and values for the four compartments were as follows (in kilograms): protein 8.9 ± 1.0, water 30.9 ± 3.5, mineral 2.6 ± 0.4, and fat 22.6 ± 7.3. There was a linear change with age for protein and water, whereas mineral and fat were curvilinear. These latter two compartments also showed differences in premenopausal and postmenopausal rates of change. Various models were fit to the data to adjust for body size and age. Each of the four compartments (mineral, water, fat, and protein) changed with age, with fat increasing and the other compartments declining. The equation, y = age + age^2 + height + weight, fit the data as well as the other models. Equations are provided to assess body composition in populations with disorders of nutrition, as well as other illnesses, using height, weight, and age as covariates. Since this was a cross-sectional study, longitudinal studies will have to be performed to confirm the accuracy of rates of change with age predicted with each compartment.

FIELD ASSESSMENTS of body fat such as anthropometric measurements, body weight, or body mass index (BMI) are unsatisfactory if quantitative measurement of body composition is desired. Hydrodensitometry is influenced by gender, age, and the density of the musculoskeletal compartment.[1,2] Several two-compartment models using radioactive techniques have been developed.[3,4] Fat mass (FM) is calculated by subtracting estimated fat-free mass, determined using total body water (TBW), total body nitrogen (TBN), or total body potassium, from body weight. Small systematic errors in FFM can lead to greater errors in FM when FM is obtained by subtracting FFM from body weight. Other methods for measurement of body composition are also dependent on physical properties, such as body density (hydrodensitometry), impedance (bioelectric impedance), or attenuation of photons or x-rays (dual-photon and x-ray absorptiometry). The coefficient of variation (CV) of derived FM in most of these methods is larger than the CV of these measured physical properties of the body.[1]

The neutron activation facility at Brookhaven National Laboratory has been expanded to measure the chemical constituents of fat and lean tissue using prompt-gamma neutron activation, in conjunction with measurement of TBW, for measurement of TBN and inelastic neutron scattering for the measurement of total body carbon (TBC).[5-7] In the current study, we measured TBC, TBN, and TBW; total body calcium (TBCa) was estimated by dual-energy x-ray absorptiometry (DEXA). Development of these newer techniques has allowed construction of a more sophisticated four-compartment model of body composition, consisting of mineral ash, fat, protein, and water.[8-11] This report is part of an ongoing project to describe body composition in healthy women using the four-compartment model, and to develop normative values for different ages and body sizes so that deviation from normal body compartments in illness may be detected.

SUBJECTS AND METHODS

Subjects

One hundred fifty-five healthy white women were recruited from advertising in the local media and through a direct-mail campaign. Exclusion characteristics consisted of any chronic illness, including hypertension, diabetes, and obesity, and any past history of illness or medication use 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 chemistries (multichannel chemistries, complete blood cell count, urinalysis, free thyroxine, and thyrotropin) or abnormal physical findings. A BMI of 18 to 33 was considered acceptable for inclusion in the study. The current report includes data on 79 premenopausal and 76 postmenopausal women aged 24 to 79 years. Height was measured using a wall-mounted Harpenden stadiometer (Holtain, Britain) with the participants standing barefoot with the back of their heels pressed against a metal plate to align their feet with the back of the stadiometer. The head plate was lowered onto the head while participants were asked to inhale to achieve maximal height. Participants were weighed while wearing scrubs, using a balanced-beam scale. Some of these data have been previously submitted for publication.[12-14]

TBW

TBW was measured using tritiated-water dilution. The CV of this measurement is less than 1%.

Prompt-Gamma Neutron Activation

The prompt-gamma neutron activation system at Brookhaven National Laboratory has been redesigned with a newly constructed collimator that incorporates a neutron reflector made of graphite and bismuth, providing a beam at the level of a bed that is 75 cm above a PuBe source.[8,15] An aluminum tank containing heavy water is placed on top of the collimator to serve as a premoderator. There are two NaI (T1) detectors (15.2 × 15.2 cm) that 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 uses 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 approximately 100 cm. The total skin dose to a subject is 80 mrem.[16] Three bottle phantoms of

---

From the Department of Medicine, Winthrop-University Hospital, Mineola; and Brookhaven National Laboratories, Upton, NY.
Submitted December 16, 1994; accepted April 26, 1995.
Supported by National Institutes of Health Grants No. RO1-AR37520-05 and PO1-DK42618.
Address reprint requests to John F. Aloia, MD, Winthrop-University Hospital, 259 First St, Mineola, NY 11501.

0026-0495/96/4501-0007$03.00/0

different size are used to calibrate the system. The ratio of net hydrogen to nitrogen counts has a small linear dependence on phantom volume. The CV is 2.5%.

Inelastic Neutron Scattering System

The inelastic neutron scattering system facility was built in 1987. A pulsed-neutron generator is used to produce 14-MeV neutrons at a 10-kHz repetition rate. Two 15.2 × 15.2-cm NaI (T1) detectors are positioned on either side of the subject. The system was recently upgraded with a new data-acquisition system (IBM-PC with Nuclear Data multichannel analyzers; Brookhaven National Lab, Upton, NY) and a new stepping motor.[15] 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.[15] The number of neutrons produced by the generator is also measured using a NE102 plastic scintillator. The system is calibrated daily with an Alderson anthropomorphic phantom (The Phantom Laboratory, Cambridge, NY). The CV is 3%.

DEXA

A whole-body DEXA scanner (DPX-L; Lunar Radiation, Madison, WI) with software program 1.3Y was used to measure mineral mass.[16,17] The CV is less than 1%.

Calculation of Body Compartments

Total body fat (TBF) was calculated from TBC and total body protein (TBPr) as TBF (kg) = [TBC (kg) − 0.55TBPr (kg)]/0.77, and TBPr = 6.25(N/H) × TBH, where H is hydrogen. Mineral ash was calculated as 2.94TBCa. TBCa was obtained from DEXA.

In this model, body weight = TBW + TBPr + TBF + 2.94TBCa.[18,19]

Statistical Analysis

The following models were fit to each of the four compartments to adjust the data for age and body size (height and weight):

1. $y = a + b\,(\text{height}) + c\,(\text{weight}) + d\,(\text{age}) + e\,(\text{age}^2)$

2. $\ln y = a + b\,(\text{height}) + c\,(\text{weight}) + d\,(\text{age}) + e\,(\text{age}^2)$

3. $y = a\,(\text{height}^b)(\text{weight}^c)(\text{age}^d)$,

where y is protein, water, mineral, or fat.

These models were used to estimate the effects of the covariates of height, weight, and age on body compartments. To minimize colinearity between age and age squared, age was entered into both terms in the equation as age minus its mean. We then fit the model for age and age squared, and followed by fitting the residuals from that model to a linear model of weight and height. This has the effect of including the natural changes of weight and height with age in the age model, and then fitting the effects of weight and height that were independent of age. For compartments in which the age-squared term was not statistically significant, the linear effect of age was used in the first model, before fitting weight and height. In addition, linear regressions were performed for each compartment versus age for premenopausal and postmenopausal women and the slopes were tested for statistically significant differences.

RESULTS

Clinical characteristics of the women are listed in Table 1. The age at menopause is similar to that observed in other studies. All women designated as postmenopausal had appropriately elevated follicle-stimulating hormone and luteinizing hormone levels and decreased estradiol levels. Table 2 presents the values by decade of age and the overall means for each compartment.

Table 1. Clinical Characteristics of Subjects

Characteristic	Mean ± SD
Height (cm)	162.3 ± 6.5
Weight (kg)	65.7 ± 9.7
BMI (kg/m²)	24.0 ± 3.4
Age (yr)	51.4 ± 13.5
Age at menopause (yr)	50.8 ± 2.8
Smokers	14%
Median income	$50,000-$74,999
Median education	4 years' college
Ca intake (mg)	744 ± 24

The analyses were consistent for the three models that adjust for age and body size, with no substantial differences between them. The intercept reported in Table 3 is the sum of intercepts from the two separate portions of model 1. Since there were no substantial differences in the three models, model 1 is presented here in Figs 1 to 4 and regression equations are presented in Table 3. When the data were fit with two linear regressions, one for premenopausal women and one for postmenopausal women, there were significant differences only between the slopes for mineral ($P < .0001$) and fat ($P < .0001$) compartments. This confirms the curvilinear trends detected by the age + age² model.

All covariates (height, weight, and age) were significant for model 1 for all compartments, as shown by the regression coefficients in Table 3. For the same height and weight, TBF increases while the other compartments decrease with age. With the same weight and age, TBF decreases while the other compartments increase with height. With similar height and age, all compartments increase with weight.

DISCUSSION

In the current study, we measured body fat through the measurement of body carbon as first introduced by Kyere et al[20] and later by a miniature neutron source developed by Sandia and Brookhaven National Laboratories.[6,21] There are two main sources of TBC: fat and protein. The contributions of glycogen and bone mineral ash to TBC are low (<3%). Measurement of TBC can be a most direct assessment of body fat if the value is adjusted for the

Table 2. Body Composition by Decade of Age (kg, mean ± SD)

Age	No. of Subjects	Protein	Water	Mineral	Fat
20-30	8	9.9 ± 0.8	33.2 ± 2.0	2.9 ± 0.3	14.6 ± 5.5
31-40	29	9.2 ± 0.8	31.5 ± 2.8	2.8 ± 0.3	19.7 ± 6.7
41-50	44	9.1 ± 0.8	31.4 ± 3.6	2.8 ± 0.3	24.2 ± 7.1
51-60	25	8.8 ± 1.0	30.4 ± 3.8	2.6 ± 0.4	23.4 ± 7.2
61-70	35	8.4 ± 1.0	30.0 ± 3.9	2.4 ± 0.3	24.8 ± 7.3
71-80	14	8.4 ± 0.9	29.3 ± 3.8	2.2 ± 0.3	21.5 ± 6.8
Overall	155	8.9 ± 1.0	30.9 ± 3.5	2.6 ± 0.4	22.6 ± 7.3

Table 3. Regression Coefficients (mean ± SE) for Each Compartment Using a Multivariate Linear Model

Parameter	Protein	Water	Mineral	Fat
Intercept	−.32 ± 1.41	−12.04 ± 4.20	−1.29 ± .51	31.08 ± 7.41
Age (yr)	−.03 ± .005	−.08 ± .021	−.02 ± .002	.15 ± .042
Age^2 (yr)	—	—	−.0004 ± .001	−.01 ± .003
Height (cm)	.04 ± .009	.17 ± .026	.02 ± .003	−.29 ± .047
Weight (kg)	.04 ± .006	.24 ± .017	.01 ± .002	.62 ± .030
% variation explained	51	69	66	81

contribution of carbon due to protein. Nitrogen represents protein well, since 99% of the body's nitrogen is in protein.

Svendsen et al[22] compared body fat measurement in 46 elderly subjects using DEXA, bioelectrical impedance analysis, and anthropometry. Correlation coefficients between observed values and those predicted from published equations were high ($r = .9$). However, predictive power was not good. Pierson et al,[21] in a study of eight methods in 389 normal participants, also found that although correlations were high between methods, values for body fat varied from 26% to 35%.

Baumgartner et al[23] also studied body composition in elderly volunteers. They observed that densitometry assumes a constant density of the FFM of 1.10 g/mL across age, gender, and ethnic groups. Using a four-compartment model based on hydrodensitometry, tritiated-water dilution, and dual-photon absorptiometry, they measured body composition in 98 elderly men and women. They found that their estimates were significantly different from values obtained using Siri's two-compartment model. The differences were primarily associated with variations in hydration of the FFM. They also noted that although TBW may decrease with age, the percent of weight that is water remains constant. The relative constancy of TBW as percent body weight may be seen in Fig 5 from our data. Heymsfield et al[1] reviewed the use of the newer techniques such as DEXA and neutron inelastic scattering to partition body compartments in a more sophisticated model than has been possible with simply considering the body to consist of FM and FFM. TBW, when used to calculate FFM, assumes a constant (72% to 74%) hydration of fat-free tissue. Use of total body K by whole-body counting of ^{40}K assumes gender and ethnic constants for the concentration of potassium in fat free tissue.

Our data also establish the loss of body protein with aging. The decline in mineral mass with age has been known for some time, and indeed contributes to the errors in body composition methods such as hydrodensitometry, which include mineral mass as part of the FFM.

In the current study, there were linear declines in water and protein and curvilinear changes in fat and mineral with aging. Other investigators have been concerned about the application of data from younger individuals to the elderly, and our data show that body composition data must be corrected for age and body size. The 40- to 60-year-old age group has a lower percentage of body water and protein and a higher percentage of body fat than the 20- to 40-year-old group, with less dramatic changes in the 60- to 80-year-old age group (Fig 5).

Using in vivo neutron activation for measurement of TBCa and whole-body counting for measurement of ^{40}K, an isotope that allows assessment of total body potassium, we previously predicted from cross-sectional studies that there is acceleration of loss of FFM and skeletal mass at menopause.[24,25] We later noted that this is demonstrable with repeated measures in a study with a prospective design.[26] Most recently, in a prospective study of prevention of bone

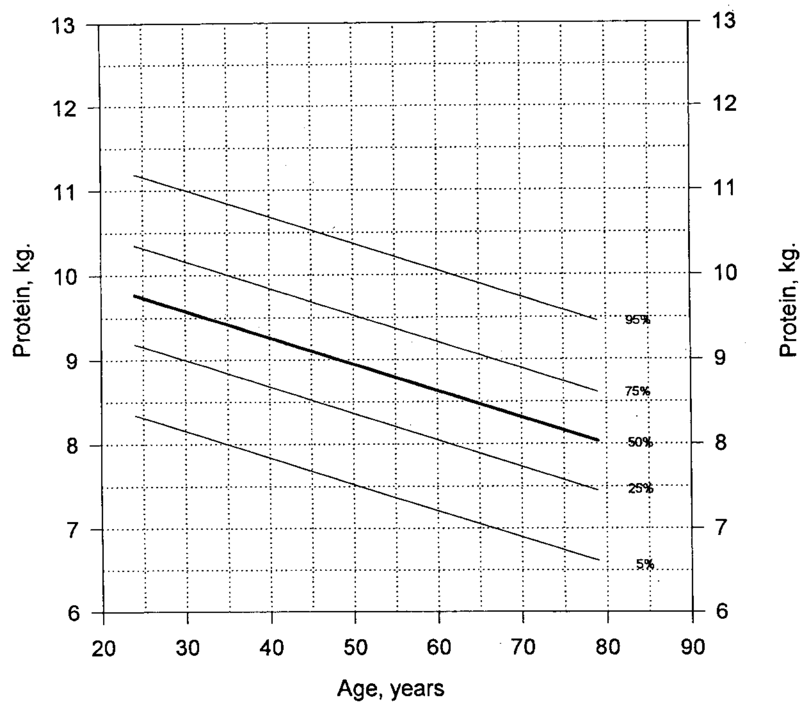

Fig 1. TBPr at different ages, depicted in percentiles. Data not adjusted for body size.

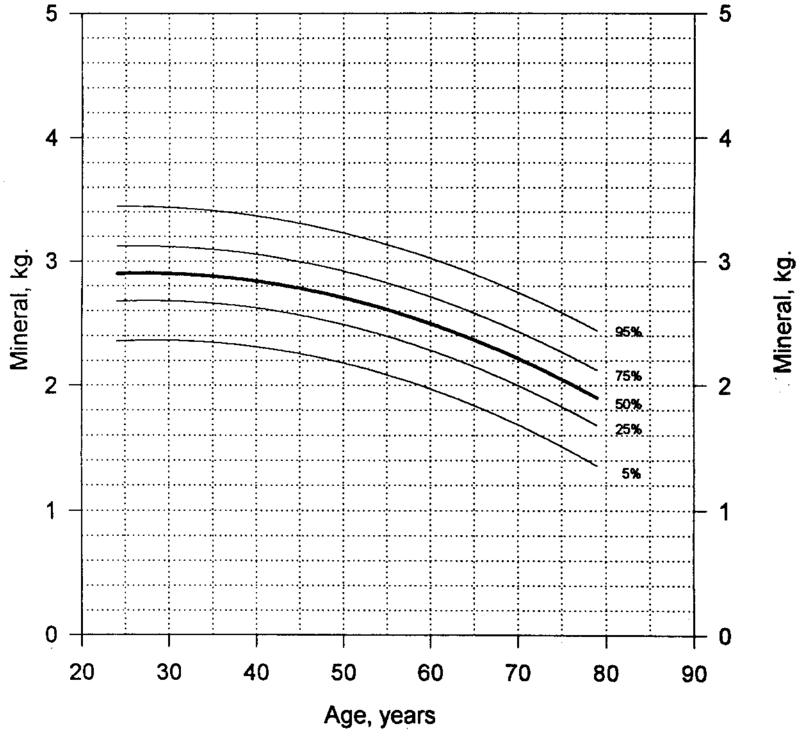

Fig 2. Total body mineral at different ages, depicted in percentiles. Data not adjusted for body size.

loss using dual-photon absorptiometry, we observed that women at menopause experience a gain of FM and a loss of lean mass.[27] Using neutron-activation techniques and DEXA in the current study, we also observed significant differences in the gain in FM and the loss of mineral mass when premenopausal and postmenopausal rates were compared.

One of the problems with expression of the data as percent body weight is the magnitude of correlation between the various compartments and body size. Thus, water and fat are correlated most with weight, whereas protein and mineral are not closely correlated with weight, but age is more important. On the other hand, the curvilinear trend of fat, with a decline in our older participants who weigh less, may be seen as an actual increase in the percent of body weight consisting of fat (Fig 5).

Some caution in the application of this model must be

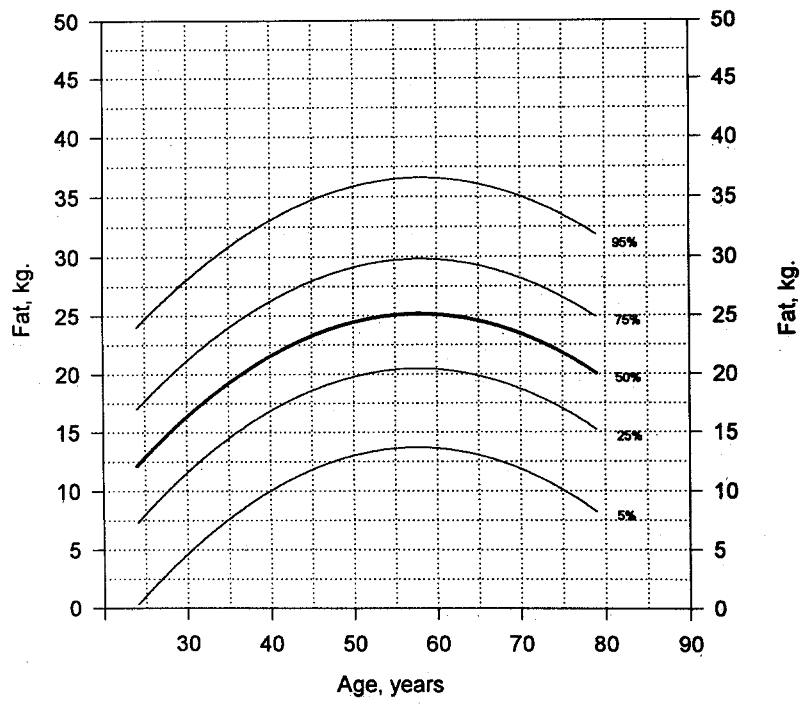

Fig 3. TBF at different ages, depicted in percentiles. Data not adjusted for body size.

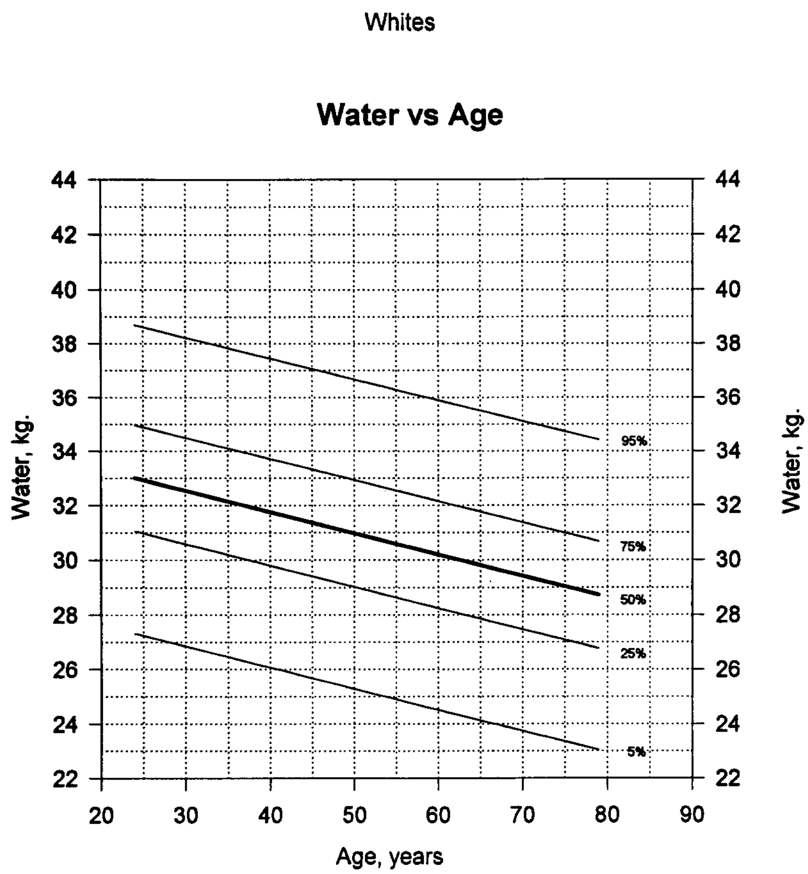

Fig 4. TBW at different ages, depicted in percentiles. Data not adjusted for body size.

advised. Our population was composed of middle-class white women, and of course the data cannot be extrapolated to men or other ethnic groups. Socioeconomic factors may also need to be considered. Finally, models developed from cross-sectional studies have well-known hazards and must be confirmed by prospective studies. Mean values for the four compartments are presented in Table 2 by decade of age. Regressions of each of the compartments against age were highly significant ($P < .0001$), with TBF increasing with age and the other compartments declining. Mineral ash and fat showed different premenopausal and postmenopausal slopes. The Brookhaven group and others

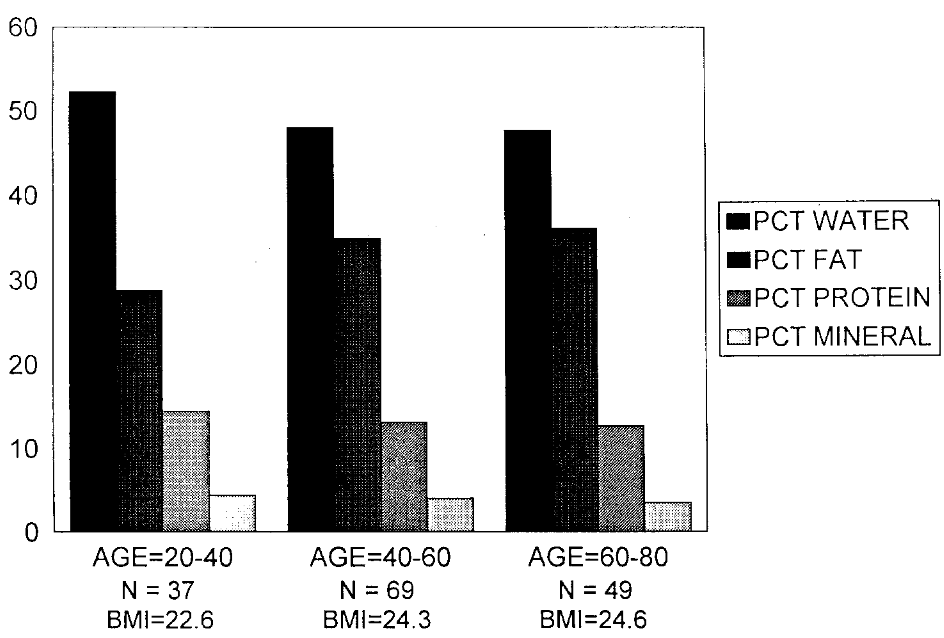

Fig 5. Each compartment depicted as a percentage (PCT) of body weight for different age groups.

have shown that TBCa declines slightly before menopause, with a more rapid decline following menopause.[23] Our population showed an increase of body fat with aging, with a subsequent decline after age 60 years.

In summary, we have used the four-compartment model of body composition to develop normative values for changes in body composition with age. The equations we provide should be applicable to the determination of deficits and excesses in any of these compartments resulting from illness.

REFERENCES

1. Heymsfield SB, Wang J, Lichtman S, et al: Body composition in elderly subjects: A critical appraisal of clinical methodology. Am J Clin Nutr 50:1167-1175, 1989

2. Van Itallie TN, Segal KR, Yang MU: Clinical assessment of body fat content in adults: Potential role of electrical impedance methods, in Roche AF (ed): Body Composition Assessments in Youth and Adults. Report of the Sixth Ross Conference on Medical Research. Columbus, OH, Ross Laboratories, 1985, pp 5-8

3. Cohn SH, Parr RM: Nuclear-based techniques for the in vivo study of human body composition. Report of an Advisory Group of the International Atomic Energy Agency. Clin Phys Physiol Meas 6:275-301, 1985

4. Burkinshaw L, Hill GL, Morgan DB: Assessment of the distribution of protein in the human body by in vivo neutron activation analysis. Nuclear Activation Techniques in the Life Sciences. Proc Symp Vienna. Vienna, Italy, IAEA 1978, pp 787-798

5. Kehayias JJ: Aging and body composition: Possibilities for future studies. Am Inst Nutr 123:454-458, 1993

6. Kehayias JJ, Heymsfield SB, LoMonte AF, et al: In vivo determination of body fat by measuring total body carbon. Am J Clin Nutr 53:1339-1344, 1991

7. Vartsky D, Ellis KJ, Cohn SH: In vivo quantification of body nitrogen by neutron capture prompt gamma-ray analysis. J Nucl Med 20:1158-1165, 1979

8. Dilmanian FA, Weber DA, Yasumura S, et al: Performance of the delayed- and prompt-gamma neutron activation systems at Brookhaven National Laboratory, in Yusumura S, Kamen Y, Lidofsky L: Advances in In Vivo Body Composition Studies. New York, NY, Plenum, 1990, pp 309-315

9. Rico H, Revilla M, Villa LF, et al: The four-compartment models in body composition: Data from a study with dual-energy x-ray absorptiometry and near-infrared interactance on 815 normal subjects. Metabolism 43:417-422, 1994

10. Snead DB, Birge SJ, Kohrt WM: Age-related differences in body composition by hydrodensitometry and dual-energy x-ray absorptiometry. J Appl Physiol 74:770-775, 1993

11. Wellens R, Chumlea WC, Guo S: Body composition in white adults by dual-energy x-ray absorptiometry, densitometry, and total body water. Am J Clin Nutr 59:547-555, 1994

12. Aloia JF, Vaswani A, Ma R, et al: Comparison of body composition in black and white premenopausal women. J Lab Clin Med (submitted)

13. Aloia JF, Vaswani A, Ma R, et al: Comparative study of body composition by dual energy x-ray absorptiometry. J Nucl Med 36:1392-1397, 1995

14. Aloia JF, Vaswani A, Ma R, et al: To what extent is bone mass determined by fat-free or fat mass? Am J Clin Nutr 61:1110-1114, 1995

15. Stamatelatos IE, Dilmanian FA, Ma R, et al: Calibration for measuring total body nitrogen with a newly upgraded prompt gamma neutron activation facility. Phys Med Biol 38:615-626, 1993

16. Mazess RB, Barden HS, Bisek JP, et al: Dual-energy x-ray absorptiometry for total-body and regional bone-mineral and soft-tissue composition. Am J Clin Nutr 51:1106-1112, 1990

17. Mazess RB, Peppler WW, Gibbons M: Total body composition by dual-photon (^{153}Gd) absorptiometry. Am J Clin Nutr 40:834-839, 1984

18. Hassager C, Sorenson SS, Nielsen B, et al: Body composition measurement by dual photon absorptiometry: Comparison with body density and total body potassium measurements. Clin Physiol 9:353-360, 1989

19. International Commission on Radiologic Protection: Report of the Task Group on Reference Man. ICRP Publication No. 23. Oxford, UK, Pergamon, 1975, p 289

20. Kyere K, Oldroyd B, Osby CB, et al: The feasibility of measuring total body carbon by counting neutron inelastic scatter gamma rays. Phys Med Biol 37:805-819, 1982

21. Pierson RN Jr, Wang J, Heymsfield SB, et al: Measuring body fat: Calibrating the rulers. Intermethod comparisons in 389 normal caucasian subjects. Am J Physiol 261:E103-E108, 1991

22. Svendsen OL, Haarbo J, Heitmann BL, et al: Measurement of body fat in elderly subjects by dual-energy x-ray absorptiometry, bioelectrical impedance, and anthropometry. Am J Clin Nutr 53:1117-1123, 1991

23. Baumgartner RN, Heymsfield SB, Lichtman S, et al: Body composition in elderly people: Effect of criterion estimates on predictive equations. Am J Clin Nutr 53:1345-1353, 1991

24. Cohn SH, Abesamis C, Yasumura S, et al: Comparative skeletal mass and radial bone mineral content in black and white women. Metabolism 26:171-178, 1977

25. Cohn SH, Abesamis S, Zanzi, et al: I. Body elemental composition: Comparison between black and white adults. Am J Physiol 232:E419-E422, 1977

26. Aloia JF, Vaswani A, Ellis K, et al: A model for involutional bone loss. J Lab Clin Med 106:630-637, 1985

27. Aloia JF, Vaswani A, Russo L, et al: The influence of menopause and hormonal replacement therapy on body cell mass and body fat mass. Am J Obstet Gynecol 172:896-900, 1995