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Assessment of research-based body composition techniques in healthy elderly men and women using the 4-compartment model as a criterion method

MI Goran[1], MJ Toth[2] and ET Poehlman[2]

[1]*Division of Physiology and Metabolism, Department of Nutrition Sciences, University of Alabama at Birmingham, Birmingham, AL and* [2]*Division of Endocrinology, Metabolism and Nutrition, Department of Medicine, University of Vermont, Burlington, VT, USA*

OBJECTIVE: To examine the accuracy, precision and bias of body fat estimates using traditional research based techniques, relative to those derived from a 4-compartment model in healthy, older men and women.
DESIGN AND SUBJECTS: Cross-sectional comparison of various body composition techniques in 41 healthy women (68.2 ± 6.6 y) and 41 healthy men (70.2 ± 7.0 y) with an age range of 57–90 y.
METHODS: Fat mass (FM) by the 4-compartment (4C) model was compared to that derived by dual energy X-ray absorptiometry (DXA), underwater weight (UWW) and total body water (TBW).
RESULTS: On a group mean basis, FM by the 4C model (24.4 ± 7.4 kg in women, 18.2 ± 7.6 kg in men) was similar to other techniques. The regression between FM by 4C and DXA significantly deviated from the line of identity (FM by 4C = 0.76*FM by DXA + 5.9 kg for women; 0.81*FM by DXA + 3.4 kg for men). FM by UWW was similar to FM by 4C model in men but not women (FM by 4C = 0.87*FM by UWW + 4.3 kg). FM by TBW was similar to FM by 4C model in women, but not men (FM by 4C = 0.80*FM by TBW + 4.7 kg). For DXA, there was no significant bias in estimates of FM in men or women. For UWW, there was significant bias in men with an over-estimate of FM among leaner subjects and under-estimates in fatter subjects. For TBW data, there was a significant bias in men with an under-estimate of FM among leaner subjects and over-estimate in fatter subjects.
CONCLUSIONS: Individual estimates of FM by DXA can be improved by correction factors that calibrate experimental data to standards such as the 4-C model. The assumptions of the Siri 2 compartment model are appropriate in healthy elderly men but not women, where a new equation is suggested. Inaccuracies in FM from TBW data are likely to be explained by age-related changes in the hydration of fat free mass (FFM).

Introduction

Although a variety of methods exist for body composition assessment in humans, there is no direct method for measurement of body fat. The most frequently used techniques are based on a 2-compartment (2C) model of body composition in which body mass is separated into fat and fat-free tissue mass (FM, FFM). Most current methods for estimation of FM and FFM are based on assumptions which do not account for the heterogeneity of the FFM with respect to its chemical composition. This issue is particularly evident in the elderly, where deviations from the assumptions inherent to various body composition methods are likely to occur.[1] For example, the 2C model involving assessment of total body water (TBW) is based on the assumption that the FFM has a constant and fixed hydration of 73.2%,[2] which may in fact be influenced by factors such as gender and ageing.[1] In addition, the classic 2C model approach involving measurement of total body density by underwater weight (UWW) is based on the assumption that body mass is composed of 2 compartments, FM + FFM, and these compartments have fixed densities of 0.9 and 1.1 g/ml, respectively. Age-related bone de-mineralization that tends to occur following menopause[3] may account for an age-related shift in the density of FFM, thus violating the inherent assumptions of the Siri 2C model. These issues however, have not been widely examined in the elderly, other than in the study by Baumgartner *et al.*[1]

Dual energy X-ray absorptiometry (DXA) is a relatively new technique for body composition assessment. It was originally introduced as a technique for assessment of bone mineral density,[4] and subsequent studies have demonstrated its potential as an accurate measure of whole body composition. Validation studies using carcass analysis in pigs as the criteria method suggest that DXA provides accurate and precise estimates of total body composition in the pediatric[5] and adult[6] body weight range. DXA is of particular interest in the elderly because bone mass

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Correspondence: Michael I Goran, PhD, Division of Physiology and Metabolism, Department of Nutrition Sciences, University of Alabama, Birmingham, AL 35294, USA.
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can be separated from the FFM, thereby accounting for potential age-related changes in bone mineral content. A further advantage of DXA is that it is a 3-compartment (3C) system that can separate fat, bone and soft-lean tissue on the basis of tissue density.

In addition to DXA, multi-compartment models have been proposed to overcome the aforementioned limitations of the 2C models. Multi-compartment models combine independent measurements of body compartments to estimate body composition with minimal assumptions. The chemical model of body composition, presented by Heymsfield *et al*,[7] is based on the actual chemical composition of the body, that is, water, mineral, protein, and fat (with negligible contribution from glycogen). Several of these components can be measured directly without assumptions (that is, body water using isotope dilution and bone mineral by DXA). The 4-compartment (4C) model combines these direct measures with a direct measure of total body density (by hydrodensitometry) in a model that can estimate body fat mass with minimal assumption. Since the 4C model represents a comprehensive analysis of the chemical components of the body with minimal assumptions, it has been suggested as a 'gold standard' technique. Comparison of body composition techniques against data derived from the 4C model has been recommended as a calibration (or 'cross-validation') approach which can account for individual variation in the chemical composition of the FFM.[1]

The specific aim of this study was to compare and cross-calibrate body fat estimates using traditional research based techniques (that is, hydrodensitometry, DXA, total body water (TBW)), against body fat data derived from the 4C model in healthy, older men and women. By cross-calibrating widely used techniques against the 4C model, our objectives were to: a) examine the assumptions of hydrodensitometry and TBW methodologies for body fat estimates in the elderly and, b) develop 'correction' equations that calibrate currently used techniques to the 4C model in an effort to improve standardization of body composition techniques in the elderly.

Methods

Subjects

Eighty-two healthy, Caucasian, men ($n = 41$) and women ($n = 41$) were recruited for this study from Burlington, Vermont and surrounding areas. Subjects were aged 57–90 y and were weight-stable (± 2 kg) within the past year as indicated by medical history. In addition, subjects were characterized by the following: no clinical symptoms of heart disease, no exercise limiting non-cardiac disease (arthritis, peripheral vascular disease, cerebral vascular disease), no history of oophorectomy, resting blood pressure less than 160/90 mm Hg, normal resting electrocardiogram (ECG), normal ECG response to an exercise stress test, absence of any medication that could affect cardiovascular function or metabolic rate and no family history of diabetes. None of the women was receiving hormone replacement therapy. The experimental procedures used in this study were approved by the Committee on Human Research for the Medical Sciences (University of Vermont) and written informed consent was obtained from each volunteer prior to investigation.

Protocol

Subjects were asked to refrain from exercising for at least 36 h before testing. Volunteers were admitted to the Clinical Research Center between 14:00–16:00 h on the afternoon prior to metabolic testing and fed a standardized meal (4184 kJ, 15% protein, 30% fat and 55% carbohydrate) at approximately 17:30 h. Volunteers were not required to eat the entire meal and were given extra food if they requested it. The volunteers were then fasted until completion of testing the following morning. Subjects were dosed with doubly labeled water the evening prior to testing, and in the morning the following tests were conducted in the fasted state: UWW for assessment of total body density, DXA for assessment of total bone mineral density and total body composition, collection of urine samples for TBW and anthropometric evaluation (see below for further details on these methods).

Body composition measures

4-compartment model. The body composition criterion method that we used, determined body fat by the 4C model, as described by Baumgartner *et al*.[1] This model assumes densities of 0.9 g/cc for fat, 0.99 g/cc for water, 3.042 g/cc for bone mineral and 1.34 g/cc for the unmeasured fraction of the body composed of protein and glycogen. The model calculates percent body fat from the independent measures of total body density (by UWW, as described below), the fraction of body weight that is water (by isotope dilution, as described below) and the fraction of body weight that is mineral (by DXA, as described below).

DXA. Total body bone mineral content, fat, and soft-lean tissue mass were measured using a Lunar DPX-L densitometer (Lunar Radiation Corporation, Madison, WI) in the morning following an overnight fast. All scans were analyzed using the Lunar Version 1.3 DPX-L extended analysis program for total body composition (the algorithms in this older software are essentially similar to those in the most recent version 1.3z). Total body mineral was estimated as 1.279 times larger than bone mineral as measured by DXA.[1]

UWW. Total body density was measured by underwater weighing, with simultaneous measurement of residual lung volume by the helium dilution method, the morning after an overnight fast. Our underwater weighing facility is an elevated tank measuring $39.5 \times 45.8 \times 45$ inches. Subjects sit on a metal chair which is externally connected to a platform scale with a digital readout. Subjects are asked to lean forward on the chair until full body submergence and UWW is recorded on a digital scale. UWW is averaged from a total of six observations. Body fat was calculated from whole body density (g/ml) with the Siri equation,[8] which assumes constant densities for fat and fat free tissue of 0.9 g/cc and 1.1 g/cc, respectively. The test-retest reliability of FM in the elderly with our underwater weighing system has an intraclass correlation coefficient of > 0.98 and a coefficient of variation (CV) $< 5\%$.[9,10]

TBW. This was determined by isotope dilution techniques using both deuterium and oxygen-18 labeled water as previously described.[11] Briefly, a mixed dose of doubly labeled water was orally administered the evening prior to testing and after collection of a baseline urine sample (10 ml). The isotope loading dose was approximately 0.15 g and 0.12 g of oxygen-18 and deuterium, per kg body mass. Two samples were collected the morning after dosing and an additional two samples were collected in the morning 10 days later. All samples were analyzed in triplicate for deuterium and oxygen-18 using the off-line zinc reduction method[12] and equilibration technique,[13] respectively, as previously described.[14] Zero time enrichments of deuterium and oxygen-18 were calculated from the intercepts of the semi-logarithmic plot of isotope enrichment in urine *vs* time after dosing. Isotope dilution spaces were calculated using the equation of Coward.[15] TBW was taken as the average of the oxygen-18 dilution space divided by 1.01 and the deuterium dilution space divided by 1.04. FFM was estimated from TBW by assuming that fat free tissue has a hydration constancy of 73.2%,[2,16,17] and FM was estimated from the difference between body mass and FFM.

Statistics

Various statistical tests were performed to examine accuracy, precision and bias of the various techniques relative to the 4C model. FM by the 4C model was used as the criteria method because this model involves the least assumptions.[1,7] The statistical tests (using a significance level of $P < 0.05$) were as follows:

Group mean accuracy of the various techniques in men and women was examined by performing a two-way analysis of variance using gender and measurement method as the main grouping variables. The gender by method interaction term was used to examine whether the differences between techniques were specific to a particular gender.

Table 1 Physical characteristics

Variable	*Combined* [a] *(n = 82)*	*Women*[a] *(n = 41)*	*Men*[a] *(n = 41)*
Age (y)	69.2	68.2	70.2
	(6.8)	(6.6)	(7.0)
Body weight (kg)	69.5	64.1	74.9
	(11.9)		
(10.2)	(11.0)		
Bone mineral (kg)	2.5	2.1	2.9
	(0.57)	(0.30)	(0.41)
Body density (g/ml)	1.0301	1.0183	1.0419
	(0.0189)	(0.0159)	(0.0137)
Total body water (kg)	35.6	28.8	42.4
	(8.5)	(4.3)	(5.6)
Fat mass (kg)	21.3	24.4	18.2
	(8.1)	(7.3)	(7.6)

[a] Values are means ± standard deviation in parentheses; Fat

Individual accuracy of the techniques was examined by a regression procedure. The other techniques examined were considered accurate if the regression between FM by the 4C model and the individual techniques under examination had a slope not significantly different from 1.0 and an intercept not significantly different from zero. This analysis therefore examines the hypothesis that the regression line between FM by the 4C model and other techniques examined is not significantly different from the line of identity (that is, FM by technique $y =$ FM by technique x).

Precision was assessed by the model R^2 and standard error of the estimate from the regression procedures described above.

Individual bias was examined using the procedures of Bland and Altman.[18]This analysis examines the difference in FM between a technique and the criteria method as a function of FM by the criteria method. The Bland and Altman plot[18] tests the hypothesis that methodological error is randomly distributed across the spectrum of body fat content, as indicated by a non-significant correlation between technique error and body fat level.

Results

The physical characteristics of the 82 healthy men and women are described in Table 1. Group mean accuracy of the independent techniques in men and women was examined by comparison of FM by the 4C model with the other independent techniques by a two-way analysis of variance (Table 2). The gender term was highly significant ($P < 0.001$), but there was no significant effect of method ($P > 0.9$) and no significant method by gender interaction ($P > 0.5$). These results indicate that the women in the sample were fatter than

Table 2 Body fat mass (kg) by different methods in healthy elderly men and women

Technique	*Combined*	*Women*	*Men*
4-compartment model	21.3 ± 8.1	24.4 ± 7.4	18.2 ± 7.6
DXA	21.0 ± 8.6	23.9 ± 8.4	18.2 ± 8.0
Underwater weight	21.2 ± 7.8	23.3 ± 7.9	19.2 ± 7.2
Total body water	21.0 ± 9.2	24.8 ± 4.3	17.1 ± 9.1

Group mean comparison of body fat mass by different techniques against fat mass by the 4-compartment model. Data were examined using a 2-way (gender and method) analysis of variance; there was a significant main effect of gender, but no significant effect of method and no significant gender by method interaction.
DXA = dual energy x-ray absorptiometry.

the men, but the group mean estimates of body fat were not influenced by measurement method.

Accuracy of the body fat estimates on an individual basis was examined by the regression of FM by the 4C model against FM by the other techniques. The relationships between FM by the 4C model and the independent techniques examined are shown in Figure 1. A summary of the regression analysis of independent techniques against the 4C model is shown in Table 3. The relationship between FM by DXA and FM by the 4C model significantly deviated from the line of identity in both men and women. The relationship between FM by the 4C model and by DXA was explained by the following 'correction' equations:

$$\text{Actual FM} = 0.81 * \text{FM by DXA} + 3.4\,\text{kg for men}$$

$$\text{Actual FM} = 0.76 * \text{FM by DXA} + 5.9\,\text{kg for women}$$

FM estimated by UWW was equivalent to FM by the 4C model in men, but not women, where the relationship was described by the equation:

$$\text{Actual FM} = 0.87 * \text{FM by UWW} + 4.3\,\text{kg for women}$$

FM by TBW was equivalent to FM by the 4C model in women, but not men where the relationship was explained by the following equation:

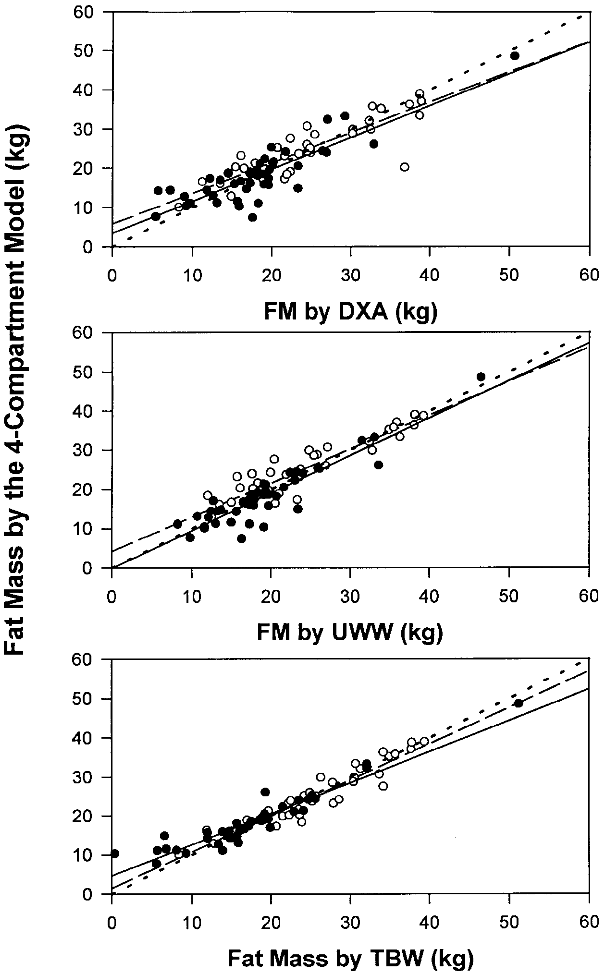

Figure 1 Comparison of fat mass (FM) by the 4-compartment (4C) model *vs* the other techniques examined. Top panel is for FM by dual energy X-ray absorptiometry (DXA). Middle panel is for FM by underwater weight (UWW). Bottom panel is for FM by total body water (TBW). Data are shown separately for men (solid circles and solid line) and women (open circles, long dashed line). The dotted line is the line of identity (regression slope = 1.0, regression intercept = 0).

$$\text{Actual FM} = 0.80 * \text{FM by TBW} + 4.7\,\text{kg for men}$$

Precision of the individual techniques was determined from the Model R^2 and standard error of the estimate

Table 3 Summary of regression of fat mass by the 4-compartment model against other independent techniques

Independent technique	R^2	*Intercept (kg)*	*Slope*	*SEE (kg)*
DXA				
Combined	0.78	4.0 ± 1.1*	0.83 ± 0.05*	3.8
Men	0.73	3.4 ± 1.6*	0.81 ± 0.08*	4.0
Women	0.77	5.9 ± 1.7*	0.76 ± 0.07*	3.6
Underwater Weight				
Combined	0.84	1.2 ± 1.0	0.95 ± 0.05	3.2
Men	0.82	−0.1 ± 1.4	0.96 ± 0.07	3.2
Women	0.85	4.3 ± 1.4*	0.87 ± 0.06*	2.8
Total Body Water				
Combined	0.91	3.8 ± 0.7*	0.84 ± 0.03*	2.4
Men	0.90	4.7 ± 0.8*	0.80 ± 0.04*	2.4
Women	0.90	1.5 ± 1.3	0.92 ± 0.05	2.4

*Intercept significantly different from zero, or slope significantly different from 1.0. SEE is the standard error of the estimate; DXA = dual energy x-ray absorptiometry.

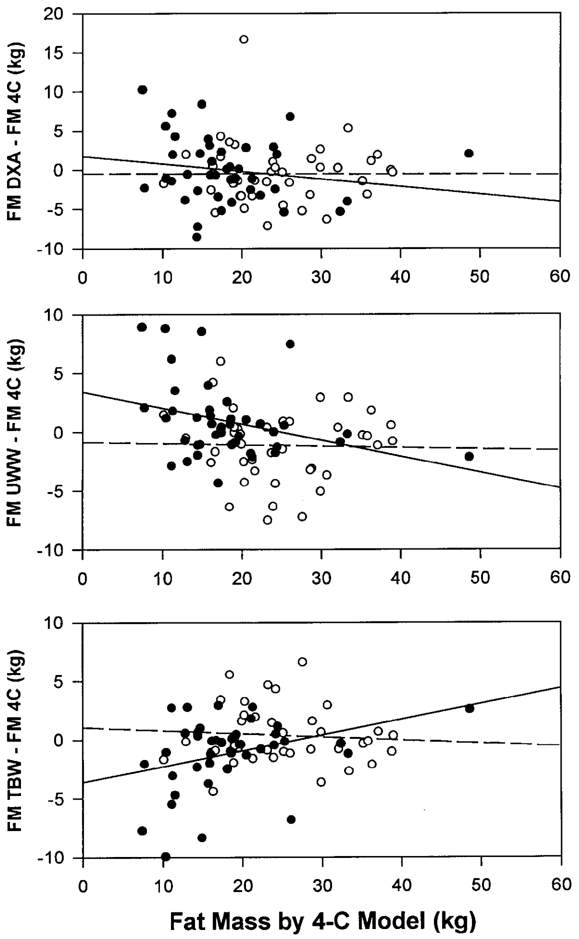

Figure 2 Bland and Altman[18] analysis of the discrepancy in body fat content between various techniques and the 4-compartment (4C) model as a function of actual body fat content (as derived by the 4C model). Top panel is the discrepancy for FM by dual energy X-ray absorptiometry (DXA). Middle panel is the discrepancy for FM by underwater weight (UWW). Bottom panel is the discrepancy for FM by total body water (TBW). Data are shown separately for men (solid circles and solid line) and women (open circles, long dashed line). See Table 4 for summary of the significant correlations.

from the regression procedures described above and listed in Table 3. The TBW technique provided the most precise estimates of body fat levels. Body fat estimated by the TBW technique explained 90% of the variance in body fat by the 4C model and the estimates had a standard error of 2.4 kg. Body fat from UWW explained 82–85% of the variance in body fat by the 4C model and the estimates had a standard error of 3.2 kg in men and 2.8 kg in women. Body fat from DXA had a lower level of precision, explaining 73–77% of the variance in body fat by the 4C model and the estimates had a standard error of 4.0 kg in men and 3.6 kg in women.

We performed a Bland and Altman[18] analysis in order to examine bias in the discrepancy between techniques. This approach examines the discrepancy between techniques as a function of FM, as determined by the 4C model (Figure 2, Table 4). For DXA, there was no significant bias in body fat estimates in men or women. For UWW, the overestimation of FM was significantly and inversely related to FM in males ($r = -0.28$) and there was no such bias in women. For TBW, there was a significant correlation for the discrepancy with FM by the 4C model in males ($r = 0.24$) and there was no such bias in women. Thus, the DXA technique was the only technique examined which was free of bias originating from body fat content.

Table 4 Bland and Altmann[18] analysis: Summary of the correlations between the discrepancy between techniques and fat mass by the 4 compartment model

Technique examined	*r combined*	*r women*	*r men*
DXA	NS	NS	NS
Underwater weight	−0.28	NS	−0.33
Total Body Water	0.24	NS	0.33

Lack of correlation indicates that error in body fat estimates from the technique under examination are not biased by body fat content (as determined by the 4-compartment model); positive correlation indicates that the technique examined underestimates body fat in leaner subjects and over-estimates body fat in fatter subjects; negative correlation indicates that the technique examined over-estimates body fat in leaner subjects and under-estimates body fat in fatter subjects (see Figure 4). DXA = dual energy X-ray absorptiometry; NS = not statistically significant.

A summary of the findings with respect to accuracy, precision, and bias for the techniques examined is provided in Table 5.

Discussion

We examined the accuracy, precision, and bias of body fat estimates derived by DXA, underwater weighing and TBW in elderly men and women, relative to those obtained by the 4C model (Table 5). Our analysis provides 'correction' equations and factors that cross-calibrate body composition techniques to the 4C model, thus improving method standardization. In addition, we examined several assumptions in the 2C models of underwater weighing and TBW techniques that are frequently used to estimate FM. In the following discussion, we consider our findings as they relate to the three techniques examined.

DXA

The regression between FM by the 4C model and DXA differed significantly from the line of identity in both men and women indicating inaccuracy in the estimation of individual estimates of body fat (Table 3). The individual inaccuracy however, was not biased by differences in body fat content. DXA was the only technique examined which was free of bias originating from body fat content. Thus, DXA provides precise estimates of total body fat in older men and women and accuracy of body fat estimates on an individual basis (relative to the 4C model) can be improved by application of the correction factors indicated in Table 3. It is important to note that

Table 5 Summary of the performance of body composition techniques relative to the 4-compartment model

Technique	*Group accuracy*		*Individual accuracy*		*Precision (R^2; SEE, kg)*		*Bias from body fat*	
	Men	*Women*	*Men*	*Women*	*Men*	*Women*	*Men*	*Women*
DXA	Yes	Yes	No	No	73% (4.0)	77% (3.6)	No	No
Underwater weight	Yes	Yes	Yes	No	82% (3.2)	85% (2.8)	Yes	No
Total body water	Yes	Yes	No	Yes	90% (2.4)	90% (2.4)	Yes	No

DXA = dual energy x-ray absorptiometry.

application of these correction factors are specific to Lunar derived DXA data in the elderly and standardize the methodology relative to the 4C model.

DXA is one of the few body composition techniques to be validated using carcass analysis (usually in pigs) as a criteria method. The Lunar densitometer used in this study has previously been shown to provide accurate estimates of body fat, as compared to carcass analysis, in the pediatric[5] and adult[6] body weight range. However, in the adult and pediatric weight range, the relationship between carcass fat and DXA fat is also significantly different from the line of identity. Thus, our studies comparing DXA to the 4C model support the previously performed carcass studies, suggesting that DXA provides accurate group mean estimates of body fat but there are small errors in individual estimates, which can be corrected for by adjusting data as described above.

Underwater weighing

The regression between FM by UWW and the 4C model was not significantly different from the line of identity in men, but there was a significant deviation in women (Table 3). The magnitude of the underestimation of body fat in women was not influenced by body fat content, whereas the Bland and Altman[18] analysis indicated a tendency to overestimate body fat among leaner men (Table 4).

The regression of FM by UWW using the Siri equation against the 4C model in men suggests that the assumed values of 1.1 g/ml and 0.9 g/ml for the densities of fat (that is essential plus non-essential lipids) and FFM (that is lipid free mass) are appropriate in healthy elderly men. In women, however, the lack of equivalence of FM by UWW and the 4C model suggests deviations from the Siri assumptions. We examined the assumptions of the underwater weighing 2C model in two ways. First, the density of FFM was calculated from the relative contributions of the aqueous and mineral fractions of the FFM (from the 4C model), as previously described by Baumgartner *et al.*[1] In agreement with previous studies,[1,19] our calculations verified the assumed value of 1.10 g/ml for the density of FFM in both men and women, and therefore does not support the suggestion that the discrepancy in women between UWW and the 4C model is explained by a difference in the density of FFM. One limitation of the calculation of density of FFM is the inclusion of an assumption that the density of protein plus glycogen mass is constant. In a second approach, we therefore derived estimates for the density of FM and FFM that were not dependent on *a priori* assumptions for the densities of the individual components. Equations similar in type to the Siri equation (%Fat = 4.95/Density − 4.5) were obtained by regression percent body at (from the 4C model) against the inverse of body density. We then tested the regression parameters against the Siri constants of 4.95 (for the slope) and −4.5 (for the intercept). In men the slope (4.16 ± 0.52) and intercept (-3.76 ± 0.50) were not statistically significant from the assumed values. In women, the slope (3.62 ± 0.38) and intercept (-3.18 ± 0.38) were both statistically significant from the assumed values, yielding the following equation for women:

$$\%\text{Fat} = 3.62/\text{Density} - 3.18.$$

The discrepancy between the Siri equation and the new equation proposed for healthy elderly women varies as a function of relative body fat content. For example, if the Siri equation estimates percent body fat to be 20% in a woman, the value derived according to the equations described above would be 26% and the error from the Siri estimate would be −6% body fat.

The suggested equation for women was used to derive values for the density of fat and fat-free tissue mass by solving the new equation for density at a percent fat of 0% and 100%. Using this approach we obtained values of 0.87 and 1.14 g/ml for the density of fat and FFM in these healthy elderly women. We were surprised by the value derived for density of FFM, as values lower than 1.10 g/ml would be hypothesized in elderly women as a result of bone de-mineralization. In addition, the value of 0.87 g/ml for the density of lipids in the body is difficult to explain. The density of body fat has been previously measured men and women and is 0.9 g/ml at 37°C for subcutaneous and internal body fat, with inter-individual variation of 1%. In fact, samples from two of the five subjects in the studies of Fidanza *et al*,[20] which established the value of 0.9 g/ml were obtained from elderly women. Unfortunately, the current study cannot explain the reasons for the altered values for the density of fat and FFM in our sample, and further studies are need. Nevertheless, use of the new equation described above is recommended for healthy elderly women and this approach standardizes the data relative to the 4C model.

In summary, our data suggests that: 1) The 2-compartment density model of Siri is accurate in healthy elderly men but not women and, 2) The new equation described above is suggested as a more accurate equation for converting density to body fat in healthy elderly women. Use of this equation should theoretically improve the accuracy of the underwater weighing technique in healthy elderly women, and provide estimates that are cross-calibrated against the 4C model.

TBW

The regression between FM by UWW and the 4C model was not significantly different from the line of identity in women, but there was a significant deviation in men (Table 3). The magnitude of the underestimation of body fat in men indicated a tendency to underestimate body fat among leaner men (Table 4).

The main source of error with the TBW technique is use of the assumption of a constant 73.2% hydration of the FFM. We estimated the hydration of FFM by dividing TBW by FFM (using body weight minus FM from the 4C model), and found a significant effect of gender (72.4 ± 4.6% in women *vs* 74.7 ± 3.8% in men; $P = 0.02$). The hydration value reported in women is similar to that observed by Mazariegos *et al*[19] (72.5%) using similar techniques in 19 elderly women, but slightly lower than the value reported by Baumgartner *et al*,[1] also using similar techniques in 63 women (74.4 ± 3.9%). The hydration factor for FFM reported in men is similar to that observed by Baumgartner *et al*[1] using similar techniques in 35 men (74.3 ± 4.5%). Thus, the previous study by Baumgartner *et al*[1] did not observe a gender difference in the hydration of FFM. The slightly higher value for the hydration of FFM in men observed in the current study accounts for the discrepancy between FM from TBW and the 4C model. The increased hydration of FFM in men (74.7%) explains the 1.2 kg under-estimate of body fat mass by the TBW technique when using an assumption of 73.2%. Thus, our data suggest that use of the hydration constants of 72.4% and 74.7% for men and women, respectively, should improve the accuracy of body fat estimates from the TBW method in healthy elderly subjects.

Error propagation

The major advantage of the 4C model is the minimal reliance on assumptions, thus increasing the accuracy of the model irrespective of biological variability in the composition of FFM.[8] As originally demonstrated by Siri,[8] and more recently by Heymsfield *et al*,[21] error propagation is improved when using the 4C model. For example, a 1% measurement error in total body density leads to a 15% error in body fat when estimated from the conventional 2C model, and this is reduced to a 9% error propagation in the 4C model. Similarly, a 1% error in measurement of TBW causes an error of 1.9% in body fat estimates when using the 2C model compared to an error propagation of 1.2% in the 4C model. Thus, a further advantage of the 4C model is that it is robust to measurement error in the individual components.

Summary and recommendations

In summary, we examined the performance of a number of research-based body composition techniques in healthy elderly men and women in terms of accuracy, precision and bias using data derived from the 4C model as a criterion method. We concur with Baumgartner *et al*,[1] that age-specific corrections are needed for body composition techniques in the elderly. In Table 5 we have summarized our analysis of the various methods. Although our paper focuses on estimating body FM, the statements regarding accuracy, precision and bias are similar for FFM (except where FM is over-estimated, FFM will be under-estimated etc). Our findings are summarized as follows: 1) The individual accuracy of DXA in the elderly can be improved by application of correction factors that calibrate experimental data to known standards such as the 4C model and carcass analysis; 2) The Siri 2C model and associated assumptions regarding density of FM and FFM are appropriate in healthy elderly men but not women. Using the 4C model as a criteria method we suggest a new equation for estimating body fat in women from body density. The Siri equation and the proposed new equation therefore provide accurate estimates of total body FM and 3) Inaccuracies in body fat estimated from TBW are likely explained by age-related changes in the hydration of FFM.

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