Calibration and validation of an air-displacement plethysmography method for estimating percentage body fat in an elderly population: a comparison among compartmental models1–3

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ABSTRACT

Background: The use of hydrostatic weighing (HW) to measure body composition in the elderly can be difficult and is based on the assumption of constancy of body compartments.

Objective: We calibrated and validated a new air-displacement plethysmography (AP) method for measuring body composition in the elderly.

Design: A 4-compartment equation for calculating percentage body fat (%BF) that used body density (Db), total body water, and bone mineral content was used as the criterion for evaluating %BF estimated by the 2- and 3-compartment models. Db was measured by HW [Db(HW)] and by use of the AP instrument [Db(AP)] in 30 elderly men and 28 elderly women aged 70–79 y.

Results: Db(AP) was not significantly different from Db(HW). However, analysis of variance showed a significant two-way interaction between sex and compartment model (P < 0.02), indicating that the comparisons between the sexes were different across all compartment models. The %BF calculated for the women was significantly higher than that calculated for the men by both HW and AP and for all compartment models.

Conclusion: Our data indicate that Db(AP) was not significantly different from Db(HW). Although differences were seen in %BF between the sexes, we observed no significant differences among the compartment models within each sex for this group of older individuals. Am J Clin Nutr 2001;74:637–42.

KEY WORDS Body composition, elderly, men, women, hydrostatic weighing, air-displacement plethysmography, multicompartment models, body density, percentage body fat

INTRODUCTION

For an aging population, maintenance of skeletal muscle mass is important to retain the ability to perform daily activities (1). Body weight increases from the age of 20 to 50 y but declines after the age of 70 y (2, 3). Along with a gain in body weight, the fat-free body mass declines by 25–30% between the ages of 30 and 70 y (3, 4), while fat mass increases with age (5). Aside from the need to establish guidelines for percentage body fat (%BF) in the elderly, body-composition assessment methods that are quick, easy to use in elderly and other special populations, and provide results similar to those obtained with existing techniques need to be developed, calibrated, and validated.
population, and 2) to compare the 2C model with multicompart-
ment models [3-compartment (3C) and 4C] of body-composition
assessment in an elderly population.

SUBJECTS AND METHODS

Subjects

Thirty men and 30 women aged 70–79 y were recruited by the
University of California, San Francisco, through advertisements
placed in the university and local communities and by contact
with senior citizen organizations in the area. Informed consent
of the subjects was obtained before their participation in the study.
The study was performed in accordance with the Committee for
the Protection of Human Subjects at San Francisco State Uni-
versity. The subjects were required to be healthy 70–79-y-old
adults who could walk up a flight of stairs and submerge them-
selves completely underwater. Subjects were recruited to fill
3 categories of body mass index (BMI; in kg/m2): 1) normal weight
(BMI = 21–24), 2) overweight (BMI = 25–29), and 3) obese
(BMI ≥ 30) (13). The final distribution of subjects across the
BMI categories was ≈25%, 50%, and 25%, respectively. The
study required 1 session per individual. At each session, height,
weight, Db (measured by HW or the AP instrument), residual
volume (RV), TBW, and BMC were measured. BMC and TBW
were measured at the University of California, San Francisco.
All other measurements were done at San Francisco State Uni-
versity. Dry measurements were performed first and HW last.
Each session began in the morning and lasted ≈5–6 h and was
done after the participants fasted overnight (14).

Residual volume

RV was measured by a helium rebreathing technique per-
formed on a Collins SVR/PLUS (Braintree, MA) with a func-
tional residual capacity test. With the mouthpiece in place, the
subject was asked to breathe normally until the spirometer equi-
librated. After equilibration, the subject performed a maximal
inspiration followed by a forced maximal exhalation, which
allowed inspiratory and expiratory reserve capacity to be meas-
ured, respectively. RV was calculated as the functional residual
capacity minus the expiratory reserve capacity (15). For more
consistent results, the subject performed this procedure 3 times
with 5 min of rest between each test. Carbon dioxide absorbant
and dessicant were checked and, if necessary, changed during the
rest periods. The same examiner was used for all subjects. The
average of the 3 tests was used as the calculation of RV.

Hydrostatic weighing

Db was measured while participants wore bathing suits and sat
on a chair suspended in a fiberglass tank. The subjects were
asked to submerge themselves underwater and perform a forced
exhalation. Subjects repeated this task 10 times. Measurements
were taken with an autopsy scale and were recorded to the near-
est 0.01 kg. The average of the 3 highest weights was used for
the calculation of Db.

Body mass index

Height was measured to the nearest 0.1 cm and weight was
measured to the nearest 0.1 kg on a calibrated Detecto weight
scale (Cardinal Scale Manufacturing Company, Webb City, MO).
BMI was calculated in kg/m² (16).

Air-displacement plethysmography

The Bod Pod body-composition system (Life Measurement,
Inc, Concord, CA) was also used to measure Db. Body weight,
body volume, and thoracic lung volume were measured for each
subject by using a dual-chambered plethysmograph, an elec-
tronic weigh scale, and BOD POD software, version 1.0 (Life
Measurement, Inc) as described by McCrory et al (8).

Bone mineral content

BMC was measured by using a QDR-4500A bone densitometer
(Hologic Inc, Waltham, MA) with a fan beam array. All scans were
performed and analyzed with the instrument’s proprietary soft-
ware (version 8.21, Hologic Inc) at the University of California,
San Francisco, by the same technician according to the standard
operating procedures recommended by the manufacturer (17).

Total body water

Deuterium dilution was used to measure TBW. A baseline
venipuncture plasma sample was taken at the beginning of test-
ing. A measured amount of deionized water and deuterium (0.1 g
2H2O/estimated kg TBW) was taken orally by each subject. A
final venipuncture plasma sample was taken at the end of the
study ≥4 h after dosing to ensure equilibration of the deuterium
with the body water. Subjects were not allowed to have any food
or beverages during the 4-h equilibration period. The samples
were frozen and shipped to the University of Chicago for analy-
sis of TBW (18).

Percentage body fat equations

Db measured by HW and by the AP instrument were compared
in the 4C, 3C, and 2C equations. The 2CAP %BF and BMC
results were automatically reported by the proprietary software
of these devices, whereas the results for HW required additional
calculations (19). The following %BF equations were used:

Siri’s 2C and 3C models (16, 17) and Selinger’s 4C model (16).

\[
2C_{\text{HW}} = \%BF \text{ from HW with use of Siri’s equation} \\
= \left\lfloor \frac{4.95}{D_{b,\text{HW}}} - 4.50 \right\rfloor \times 100 \tag{1}
\]

\[
2C_{\text{AP}} = \%BF \text{ from AP with use of Siri’s equation} \\
= \left\lfloor \frac{4.95}{D_{b,\text{AP}}} - 4.50 \right\rfloor \times 100 \tag{2}
\]

\[
3C_{\text{BMCHW}} = \%BF \text{ corrected for BMC and HW with} \\
\text{use of Siri’s mineral density formula} \\
= \left\lfloor \frac{6.386}{D_{b,\text{HW}}} + [3.961 \times m] - 6.090 \right\rfloor \times 100 \tag{3}
\]

\[
3C_{\text{TBWAP}} = \%BF \text{ corrected for TBW and HW with} \\
\text{the use of Siri’s TBW formula} \\
= \left\lfloor \frac{2.118}{D_{b,\text{HW}}} - [0.78 \times w] - 1.354 \right\rfloor \times 100 \tag{4}
\]

\[
3C_{\text{BMCAP}} = \%BF \text{ corrected for BMC and AP with the} \\
\text{use of Siri’s mineral density formula} \\
= \left\lfloor \frac{6.386}{D_{b,\text{AP}}} + [3.961 \times m] - 6.090 \right\rfloor \times 100 \tag{5}
\]

\[
3C_{\text{TBWA}} = \%BF \text{ corrected for TBW and AP with the} \\
\text{use of Siri’s TBW formula} \\
= \left\lfloor \frac{2.118}{D_{b,\text{AP}}} - [0.78 \times w] - 1.354 \right\rfloor \times 100 \tag{6}
\]
4CHW = %BF from HW with the use of Selinger’s equation

\[ 4C_{\text{HW}} = \frac{1}{3} \times \left( \frac{2.747}{D_{\text{b(HW)}}} - 0.714 \times w \right) + \frac{1}{3} \times m - 2.0503 \times 100 \]  

(7)

4CAP = %BF from AP with the use of Selinger’s equation

\[ 4C_{\text{AP}} = \frac{1}{3} \times \left( \frac{2.747}{D_{\text{b(AP)}}} - 0.714 \times w \right) + \frac{1}{3} \times m - 2.0503 \times 100 \]  

(8)

where \( w \) is TBW as %BF and \( m \) is BMC as %BF.

Statistics

Pearson’s correlation coefficient was used to determine the relation between \( D_{\text{b(HW)}} \) and \( D_{\text{b(AP)}} \). A three-way analysis of variance was used to determine significant differences in main effects and interactions. Analyses were adjusted for multiple pairwise comparisons by using Bonferroni’s post hoc test. The values are reported as means ± SDs. Line plots were used for graphical purposes to denote linearity and homogeneity of the group. STATISTICA version 5.0 (Stat Soft, Tulsa, OK) was used for statistical analyses. A probability level of <0.05 was used to determine statistical significance.

RESULTS

Two women were eliminated from the data set because of their inability to properly perform the forced exhalation underwater and the adequate number of submergences. As expected, \( D_{\text{b}} \) was significantly different between the men and women (Table 1), but \( D_{\text{b(HW)}} \) was not significantly different from \( D_{\text{b(AP)}} \). As also shown in Table 1, age and BMI were not significantly different between the sexes; all other variables were significantly different between the men and women.

The mean TBW for all subjects combined was 36.9 ± 7.92 L for TBW. The ratio of TBW to FFM (TBW/FFM) was 71.5%, slightly below the accepted standard of ≈73% (20). The average TBW for men was 43.0 ± 5.16 L and TBW/FFM was 70.4%. In women, TBW averaged 30.50 ± 4.55 L and TBW/FFM was 76.1%. The BMC for men and women combined was 2276.2 ± 547.56 g, giving a ratio of BMC to FFM (BMC/FFM) of 4.5%. The reference norm for BMC/FFM is 6.8% ± 0.9% (16). BMC was higher in the men than in the women (2670.6 ± 409.54 compared with 1835.5 ± 307.75 g), resulting in a lower BMC/FFM in the men (4.4% compared with 4.6% of the reference norm of 6.8% in men and women, respectively).

No significant differences were observed in %BF for the main effects of sex, method, or compartment model. However, a significant interaction was observed for sex by compartment models. %BF was significantly higher for the men than the women in all compartment models (Table 2).

Pearson’s correlation coefficients (Table 3) were used to examine the association between %BF from HW and AP, as well to compare the 2C equations with the multicompartiment equations. The correlation coefficient for \( D_{\text{b(HW)}} \) compared with \( D_{\text{b(AP)}} \) was \( r = 0.91 \) for both sexes combined, 0.74 for men, and 0.89 for women. Not surprisingly, the combination of the sexes yielded higher correlations because of the larger sample size and the heterogeneity of the group, which consequently created a greater range in the data (Figures 1–3 and Table 3).

DISCUSSION

In this group of elderly men and women, no significant differences were found between \( D_{\text{b}} \) measured by either HW or the AP instrument. This agrees with the results of the study conducted by McCrory et al (8) in which the 2C\textsubscript{AP} model was as valid and reliable as the 2C\textsubscript{HW} model. No significant differences were found between the first and second trials when AP was compared with HW. Dempster and Aitken (7) showed in their study, which used inanimate objects, excellent reliability with repeated measures. A between-day analysis that was done by using 1 cylinder and 20 trials yielded a %BF error of 0.1%. When 5 sequential measures were performed with the use of different volumes (25, 50, 75, 100, 125, and 150 mL), a linear plot was drawn with \( r^2 = 1.00 \). This however, does not eliminate the possible effect of TBW and BMC on the calculation of %BF in the multicompartiment models.

Significant differences were found in the interaction of the compartment models (2C, 3C, and 4C equations) and sex (men and women). Within a sex group, the compartment models did not differ in the estimation of %BF; however, between the sexes the estimates of %BF for all compartment models were different: the women had higher %BF than the did the men. These findings differ from the results reported by Bergsma-Kadijk et al (9) in which the 2C and 3C compartment models were significantly

### TABLE 1

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<tr>
<th>Variable</th>
<th>All (n = 58)</th>
<th>Men (n = 30)</th>
<th>Women (n = 28)</th>
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<tr>
<td>Age (y)</td>
<td>73.1 ± 2.24</td>
<td>73.4 ± 2.14</td>
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<td>Height (cm)</td>
<td>166.4 ± 9.43</td>
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<td>159.1 ± 6.39</td>
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<td>Weight (kg)</td>
<td>75.9 ± 14.87</td>
<td>83.7 ± 12.21</td>
<td>67.5 ± 12.86</td>
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<td>BMI (kg/m²)</td>
<td>27.3 ± 4.28</td>
<td>27.8 ± 3.35</td>
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<td>TBW (L)</td>
<td>36.9 ± 7.92</td>
<td>43.0 ± 5.16</td>
<td>30.5 ± 4.55</td>
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<tr>
<td>BMC (g)</td>
<td>2276.2 ± 547.56</td>
<td>2670.6 ± 409.54</td>
<td>1835.5 ± 307.75</td>
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<tr>
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### TABLE 2

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<th>Men (n = 30)</th>
<th>Women (n = 28)</th>
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<td>4CHW</td>
<td>31.8 ± 8.98</td>
<td>26.5 ± 6.12</td>
<td>37.5 ± 8.03</td>
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<td>32.2 ± 9.03</td>
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<td>19.2 ± 6.69</td>
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<td>2CHW</td>
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<td>2CAP</td>
<td>34.4 ± 8.99</td>
<td>28.3 ± 6.22</td>
<td>40.9 ± 6.62</td>
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1 ± SD. 4C, 4 compartment; 3C, 3 compartment; 2C, 2 compartment, HW, hydrostatic weighing; AP, air-displacement plethysmography; BMC, bone mineral content; TBW, total body water.

2 For all values, there was a significant sex by compartment model interaction, \( P < 0.05 \).
TABLE 3

Pearson’s correlation coefficients for the relations between methods used to calculate percentage body fat

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<th>2C_HW</th>
<th>3C_BMC_HW</th>
<th>3C_TBWHW</th>
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\(^1\)2C, 2 compartment; 3C, 3 compartment; 4C, 4 compartment; HW, hydrostatic weighing; BMC, bone mineral content; TBW, total body water; AP, air-displacement plethysmography.
\(^2\)P < 0.05.

Different from the 4C model when tested on elderly women. A review by Heymsfield et al (21) analyzed measured compared with calculated densities of the 4 compartments of the body: fat, water, protein, and minerals. They concluded that the 4C model accounted for >97% of the total body weight whether the densities were calculated or measured. By contrast, a 2C model was not able to yield such a high percentage because of the assumptions of a 2C model and a steady decline in total body calcium, potassium (minerals), and protein for both elderly men and women after the age of 25 years (21).

As shown in Table 2, the older individuals had a greater %BF than the younger ones, which was compounded by the loss of FFM or sarcopenia in the older individuals (9, 13). The mean %BF in this population in the use of the 4C model was 26.75 ± 6.31% for the men and 37.6 ± 8.11% for the women. The men had a %BF >44% greater than that of the reference man, which is normally considered to be 15%BF. The women had a %BF >33% greater than that of the reference woman, which is normally 25%BF (13). These elevated amounts of %BF are similar to those previously reported in the literature (13).

Declining BMC (21, 22) and fluctuations of TBW (23, 24) are not uncommon in the elderly (25). First, other studies showed that BMC was 6.8 ± 0.9% of FFM (16). This would yield a predicted BMC of 3410 ± 450 g given the FFM of this elderly population. In this study, the BMC was 2276 ± 547 g. This is 2.5 SDs below the reference value of 6.8% of FFM. The lower BMC in our study population may have been due to the calibration of the QDR-4500A bone densitometer or may represent the actual bone mineral status of this elderly population.

Age-related bone loss likely led to a lower BMC in the elderly men and women studied here. Consequently, the fraction of total FFM that is represented by BMC will be lower than that seen in a younger population.

The bone mineral calibration of the QDR-4500A bone densitometer has been compared with previous models (17). In general, close agreement (mean differences of <1–2%) was seen.

FIGURE 1. Scatter plot of the relation between percentage body fat measured by the 2-compartment (2C) models and that measured by the 4-compartment (4C) equation. HW, hydrostatic weighing; AP, air-displacement plethysmography instrument. 2C_HW = 0.9225x + 0.0428, R = 0.91. The equations used to calculate percentage body fat are given in the text.
when the bone mineral density results of the spine, femur, or forearm from the QDR-4500A bone densitometer were compared with those from earlier Hologic models. However, 2 studies showed that the total body BMC measured by the QDR-4500A bone densitometer is 5–6% lower than that observed with the QDR-2000 (26) and QDR-1000 bone densitometers (27).

Second, TBW varies with age and FFM (24). It is commonly believed that the older the individual the less body water he or she has because of higher body fat or reduced hydration (13). However, Schoeller and Jones (24) noted that with advancing age overall hydration remains constant and may become even slightly higher, suggesting that the hydration status of the elderly was not a factor that affected body composition.

The human body, if normally hydrated, consists of 73% of FFM as water (24, 26). Consequently, if this elderly group were normally hydrated, the TBW should be $\approx 37$ L; in fact, the average measured TBW for this sample was 36.94 ± 7.92 L. Changes in hydration amounts with advancing age are currently unknown. Some researchers have reported dehydration among elderly individuals (13, 16), whereas others have not (24). Our results suggest that this particular group of individuals was not dehydrated, which allows us to conclude that the 2C water estimations are valid.

Addition of the BMC to the 3C model (Figure 2) resulted in no significant difference in the estimate of %BF compared with the 2C (Figure 1), 3C TBW, and 4C (Figure 3) models. Thus, the addition of TBW (Figure 2) did not result in a significant difference in the estimation of %BF in either the 3C or 4C models. Furthermore, the combination of BMC and TBW in the 4C model did not result in an estimate of %BF significantly different from that of any of the other models.

In conclusion, HW has drawbacks when used in an elderly population. The tests are time consuming and the subjects must be in good physical condition to perform the procedure. The new AP instrument was faster, less physically challenging for the participants, and provided results that were not significantly different from those obtained with traditional HW. Finally, the use of multicompartiment models did not provide estimates of %BF significantly different from those obtained by the 2C model in this particular group of older individuals.

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REFERENCES