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 \(D_b\) total body water, and bone mineral content was used as the criterion for evaluating \%BF estimated by the 2- and 3-compartment models. \(D_b\) was measured by HW \([D_{b(HW)}]\) and by use of the AP instrument \([D_{b(AP)}]\) in 30 elderly men and 28 elderly women aged 70–79 y.

Results: \(D_{b(AP)}\) was not significantly different from \(D_{b(HW)}\). 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 \(D_{b(AP)}\) was not significantly different from \(D_{b(HW)}\). Although differences were seen in \%BF between the sexes, we observed no significant differences among the compartment models in each sex for this group of older individuals.


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.

Hydrodensitometry or hydrostatic weighing (HW), also known as underwater weighing, has been the criterion for body-composition measurement since the 1940s (6). HW requires complicated or often custom-made equipment, greater test times than do other methods, and a high degree of subject participation. Unlike HW, the air-displacement plethysmography (AP) instrument we used to measure body composition in the current study places fewer demands on the subject. There remains, however, a need to validate and calibrate this AP method, especially for special populations such as the elderly. Studies by Dempster and Aikens (7) and McCrory et al (8) in which this AP method was used reported that it is a valid and reliable method for assessing the volume of inanimate objects and of men and women aged 20–56 y. However, when examining elderly women, Bergsma-Kadijk et al (9) found that the estimation of %BF was 5% different between the 2-compartment (2C) and the 4-compartment (4C) model that used HW; they concluded that a 2C model was unacceptable compared with a 4C model in an elderly population.

Studies in which this AP instrument was used in an elderly population are lacking, and validity issues arise with the use of a 2C equation for comparison, which does not account for changes in bone mineral content (BMC) or total body water (TBW). The assumptions of the 2C model [that the density of the fat mass and fat-free mass (FFM) is constant] may not be appropriate for an elderly population (9–12). Therefore, this study had 2 purposes: 1) to compare body density \(D_b\) measured by the new AP instrument \([D_{b(AP)}]\) with \(D_b\) measured by HW \([D_{b(HW)}]\) in an elderly population.

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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 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-
BMs = 21–24

Air-displacement plethysmography
The Bod Pod body-composition system (Life Measurement,
Inc, Concord, CA) was also used to measure $D_b$. 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
$^2\text{H}_2\text{O}$/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
$D_b$, measured by HW and by the AP instrument were compared
in the 4C, 3C, and 2C equations. The 2C$_{\text{AP}}$ %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[\frac{4.95}{D_{\text{HW}}} - 4.50\right] \times 100 \\

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

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

3C_{\text{TBWHW}} = \%BF \text{ corrected for TBW and HW with} \\
\text{use of Siri’s TBW formula} \\
= \left[\frac{2.118}{D_{\text{HW}}} - 0.78 \times w \right] - 1.354 \\
\times 100 \\

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

3C_{\text{TBWAP}} = \%BF \text{ corrected for TBW and AP with the} \\
\text{use of Siri’s TBW formula} \\
= \left[\frac{2.118}{D_{\text{AP}}} - 0.78 \times w \right] - 1.354 \\
\times 100
$$
TABLE 1

<table>
<thead>
<tr>
<th>Variable (unit)</th>
<th>All (n = 58)</th>
<th>Men (n = 30)</th>
<th>Women (n = 28)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>73.1 ± 2.24</td>
<td>74.3 ± 2.14</td>
<td>72.8 ± 2.34</td>
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<tr>
<td>Height (cm)</td>
<td>164.6 ± 9.43</td>
<td>173.2 ± 6.03</td>
<td>159.1 ± 5.39</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>75.9 ± 14.87</td>
<td>83.7 ± 12.21</td>
<td>67.5 ± 12.86</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>27.3 ± 4.28</td>
<td>27.8 ± 3.35</td>
<td>26.7 ± 5.09</td>
</tr>
<tr>
<td>TBW (L)</td>
<td>36.9 ± 4.92</td>
<td>43.0 ± 5.16</td>
<td>30.5 ± 4.55</td>
</tr>
<tr>
<td>BMC (g)</td>
<td>2276.2 ± 547.56</td>
<td>2670.6 ± 409.54</td>
<td>1853.5 ± 307.75</td>
</tr>
<tr>
<td>b(AP)</td>
<td>1.0239 ± 0.0192</td>
<td>1.0377 ± 0.0124</td>
<td>1.0091 ± 0.0132</td>
</tr>
<tr>
<td>b(HW)</td>
<td>1.0223 ± 0.0191</td>
<td>1.0351 ± 0.0135</td>
<td>1.0087 ± 0.0140</td>
</tr>
</tbody>
</table>

DISCUSSION

In this group of elderly men and women, no significant differences were found between sawb 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 model was as valid and reliable as the 2CHW model. No significant differences were found between the first and second trials when AP was compared with HW. Dempster and Aitkens (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 r² = 1.00. This however, does not eliminate the possible effect of TBW and BMC on the calculation of %BF in the multicomponent models.

Significant differences were found in the intersection 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 (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 women than in all compartment models (Table 2).

Pearson’s correlation coefficients (Table 3) were used to examine the association between %BF (HW and AP, as well as to compare the 2C equations with the multicompartent equations. The correlation coefficient for D_bw compared with D_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).

TABLE 2

Percentage body fat as calculated with use of the different body-composition models

<table>
<thead>
<tr>
<th>Models</th>
<th>All (n = 58)</th>
<th>Men (n = 30)</th>
<th>Women (n = 28)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4CHW</td>
<td>31.8 ± 8.98</td>
<td>26.5 ± 6.12</td>
<td>37.5 ± 8.03</td>
</tr>
<tr>
<td>4CAP</td>
<td>32.2 ± 9.03</td>
<td>27.1 ± 6.51</td>
<td>37.7 ± 8.20</td>
</tr>
<tr>
<td>3CBMCHW</td>
<td>26.8 ± 10.54</td>
<td>19.2 ± 6.69</td>
<td>35.0 ± 7.26</td>
</tr>
<tr>
<td>3CTBW</td>
<td>33.3 ± 8.71</td>
<td>28.4 ± 6.00</td>
<td>38.6 ± 8.10</td>
</tr>
<tr>
<td>3CBMCAP</td>
<td>27.8 ± 10.30</td>
<td>20.8 ± 7.10</td>
<td>35.3 ± 7.53</td>
</tr>
<tr>
<td>3CTBAP</td>
<td>33.6 ± 8.77</td>
<td>28.9 ± 6.33</td>
<td>38.7 ± 8.24</td>
</tr>
<tr>
<td>2CHW</td>
<td>33.6 ± 9.07</td>
<td>27.1 ± 5.70</td>
<td>40.6 ± 6.39</td>
</tr>
<tr>
<td>2CAP</td>
<td>34.4 ± 8.99</td>
<td>28.3 ± 6.22</td>
<td>40.9 ± 6.62</td>
</tr>
</tbody>
</table>

Notes:
1 ± SD. 4C, 4 compartment; 3C, 3 compartment; 2C, 2 compartment.
2 HW, hydrostatic weighing; AP, air-displacement plethysmography;
3 BMC, bone mineral content; TBW, total body water.
than the younger ones, which was compounded by the loss of women after the age of 25 y (21).

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.

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 between the equations. The correlations between the BMC obtained with the different densitometers are given in Table 3.

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 with the use of the 4C model was $26.75 \pm 6.31\%$ for the men and $37.6 \pm 8.11\%$ 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 $\approx 6.8 \pm 0.9\%$ of FFM (16). This would yield a predicted BMC of $3410 \pm 450$ g given the FFM of this elderly population. In this study, the BMC was $2276 \pm 547$ 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.

<table>
<thead>
<tr>
<th></th>
<th>2C_HW</th>
<th>3C_BMCCHW</th>
<th>3C_TBWHW</th>
<th>2C_AP</th>
<th>3C_BMCAP</th>
<th>3C_TBWHW</th>
<th>4C_AP</th>
<th>4C_HW</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>All</strong></td>
<td>1.00</td>
<td>0.99*</td>
<td>0.89*</td>
<td>0.91*</td>
<td>0.91*</td>
<td>0.84*</td>
<td>0.86*</td>
<td>0.91*</td>
</tr>
<tr>
<td>2C_HW</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.88*</td>
<td>0.88*</td>
<td>0.89*</td>
<td>0.82*</td>
<td>0.84*</td>
</tr>
<tr>
<td>3C_BMCCHW</td>
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<td>1.00</td>
<td>1.00</td>
<td>0.87*</td>
<td>0.87*</td>
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<td>0.98*</td>
<td>0.98*</td>
</tr>
<tr>
<td>3C_TBWHW</td>
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<td>1.00</td>
<td>1.00</td>
<td>0.99*</td>
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<td>0.90*</td>
<td>0.92*</td>
</tr>
<tr>
<td>2C_AP</td>
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<td>1.00</td>
<td>1.00</td>
<td>0.90*</td>
<td>0.90*</td>
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<tr>
<td>3C_BMCAP</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.92*</td>
<td>0.92*</td>
<td>0.92*</td>
<td>0.92*</td>
<td>0.92*</td>
</tr>
<tr>
<td>3C_TBWHW</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.97*</td>
<td>1.00</td>
<td>1.00</td>
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<tr>
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<td>1.00</td>
<td>1.00</td>
<td>0.97*</td>
<td>1.00</td>
<td>1.00</td>
<td>0.97*</td>
<td>1.00</td>
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<tr>
<td>4C_HW</td>
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<td>1.00</td>
<td>1.00</td>
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<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

12C, 2 compartment; 3C, 3 compartment; 4C, 4 compartment; HW, hydrostatic weighing; BMC, bone mineral content; TBW, total body water; AP, air-displacement plethysmography.

*P < 0.05.

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.
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 \( \pm 7.92 \) 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 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), 3CTBW, and 4C (Figure 3) models. Thus, the combination of BMC and TBW in the 4C model did not result in an estimate of %BF significantly different from 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 multicompartment 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


