Body composition by air-displacement plethysmography by using predicted and measured thoracic gas volumes

MEGAN A. MCCRARY, PAUL A. MOLÉ, TERRI D. GOMEZ, KATHRYN G. DEWEY, AND EDMUND M. BERNAUER
Departments of Nutrition and Exercise Science, University of California, Davis, California 95616-8669

McCrory, Megan A., Paul A. Molé, Terri D. Gomez, Kathryn G. Dewey, and Edmund M. Bernauer. Body composition by air-displacement plethysmography by using predicted and measured thoracic gas volumes. J. Appl. Physiol. 84(4): 1475–1479, 1998.—The BOD POD, a new air-displacement plethysmograph for measuring human body composition, utilizes the inverse relationship between pressure and volume (Boyle's law) to measure body volume directly. The quantity of air in the lungs during tidal breathing, the average thoracic gas volume (Vtg), is also measured by the BOD POD by using a standard plethysmographic technique. Alternatively, the BOD POD provides the use of a predicted Vtg (Vtg pred). The validity of using Vtg pred in place of measured Vtg (Vtg meas) to determine the percentage of body fat (%BF) was evaluated in 50 subjects (36 women, 14 men; ages 18–56 yr). There was no significant difference between Vtg meas and Vtg pred (mean difference ± 5E, 53.5 ± 63.3 ml) nor in %BF by using Vtg meas vs. Vtg pred (0.2 ± 0.2 %BF). On an individual basis, %BF measured by using Vtg meas vs. Vtg pred differed within ±2.0% BF for 82% of the subjects; maximum differences were −2.9 to +3.0% BF. For comparison, data from 24 subjects who had undergone hydrostatic weighing were evaluated for the validity of using predicted vs. measured residual lung volume (VR pred vs. VR meas, respectively). Differences between VR meas and VR pred and in %BF calculated by using VR meas vs. VR pred were significant (187 ± 46 ml and 1.4 ± 0.3% BF, respectively; P < 0.001). On an individual basis, %BF determined by using VR meas vs. VR pred differed within ± 2.0% BF for 46% of the subjects; maximum differences were −2.9 to +3.8% BF. With respect to %BF measured by air displacement, our findings support the use of Vtg pred for group mean comparisons and for purposes such as screening in young to middle-aged individuals. This contrasts with the use of VR pred in hydrostatic weighing, which leads to significant errors in the estimation of %BF. Furthermore, although the use of Vtg pred has some application, determining Vtg meas is relatively simple in most cases. Therefore, we recommend that the use of Vtg meas remain as standard experimental and clinical practice.

fractional lung volumes; hydrostatic weighing; validity; densitometry; body volume

A NEW AIR-DISPLACEMENT plethysmograph (BOD POD body composition system; Life Measurement Instruments, Concord, CA) for measurement of body composition has recently been described (6). This system utilizes the inverse relationship between pressure (P) and volume (V) (Boyle’s law: P1V1 = P2V2) to determine body volume (Vb). Once Vb is determined, the principles of densitometry are used to determine body composition from body density (Db = mass/volume) (2, 4). A previous study in our laboratory indicated that body composition estimates by the BOD POD are not significantly different from those determined by hydrostatic weighing (HW) (16). Thus a chief advantage of the BOD POD is that it represents a densitometric method that is based on air displacement rather than on water immersion; therefore, it is simpler and more rapid than HW and potentially has wider clinical application.

Measurement of Db by HW typically requires determination of residual lung volume (VR) to correct for air remaining in the lungs after maximal exhalation (13). Any air remaining in the body (e.g., in the lungs or gastrointestinal tract) will have the effect of increasing buoyancy, leading to an overestimate of Vb, an underestimate of Db, and thus an overestimate of the percentage of body fat (%BF). Although VR can be measured accurately by numerous techniques, such as O2 dilution, N2 washout, and Hedilution, several investigators have examined whether VR can be predicted without compromising the accuracy of body composition measurements by HW (8, 11, 14, 17, 22). Whereas group means can sometimes be predicted with accuracy (17, 22), VR is usually systematically over- or underestimated, and resulting errors have been observed of up to ~4.0% BF in normal, healthy subjects (8, 11, 14, 17). In addition, individual errors in the calculation of %BF resulting from the use of predicted VR (VR pred) can be unacceptably high (22).

Similarly, measurement of Db by air displacement requires determination of the quantity of air in the lungs during normal tidal breathing, or the average thoracic gas volume (Vtg). As described by Dempster and Aitkens (6), Vb determined by Boyle’s law is underestimated by 40% of the Vtg because the air in the lungs, because of its isothermal nature, is 40% more compressible than the surrounding air (adiabatic conditions). Failure to correct for this phenomenon will result in an overestimate of Db and, consequently, an underestimate of %BF. Thus an ancillary measurement of Vtg by the BOD POD is incorporated into the testing
procedure (15). Alternatively, the BOD POD also offers the use of a predicted Vtg (Vtgpred). In certain situations, such as when screening a large number of subjects or repeatedly testing the same subject to evaluate changes in body composition, the use of Vtgpred would be time saving if it offered a reasonable estimate of Vtg.

Therefore, the purpose of this analysis was threefold. We sought to 1) compare measured Vtg (Vtgmeas) and Vtgpred (Vtgmeas vs. Vtgpred); 2) determine the effect of using Vtgpred on the estimation of %BF; and 3) compare and contrast the use of Vtgpred with air displacement with the use of VRpred in conjunction with HW.

MATERIALS AND METHODS

Air-displacement plethysmography. Body composition data were studied from the 50 subjects who had most recently been tested in our laboratory by air displacement with Vtgmeas. Subjects were healthy and not on medication known to affect lung volumes. One subject smoked cigarettes but had lung volume measurements that were well within the range of those for the remaining subjects. The methods used are described in detail elsewhere (6, 16). Briefly, after voiding the bladder, each subject was weighed to the nearest gram while wearing a swimsuit. Height was measured to the nearest centimeter. The BOD POD was calibrated according to the manufacturer’s instructions, and raw body volume (Vbraw) was determined. Finally, Vtg was measured in the BOD POD by using a technique, common to standard pulmonary plethysmography, called the “panting maneuver” (7). While wearing a noseclip, the subject breathed through a tube; after two to three normal breaths, the airway was occluded for 3 s at midexhalation. During this time, the subject was instructed to gently puff against the occlusion by alternately contracting and relaxing the diaphragm. This technique is analogous to the gentle repeated exhalations one might use to fog one’s glasses before cleaning them.

The airway pressure was measured, and Boyle’s law was utilized to determine Vtg. Vb was calculated by using the formula

\[ V_b = V_{braw} + 0.40 \times Vtg - SAA \]  

where SAA is the surface area artifact, a term used to correct for the underestimation of Vb by Boyle’s law because of the isothermal air conditions at the skin’s surface (6). Db was then calculated as mass/Vb. Substituting for Vb, the equation for Db determined by the BOD POD (DbBP) becomes

\[ Db_{BP} = \frac{M}{(V_{braw} + 0.40 \times Vtg - SAA)} \]  

where M is body mass. %BF was then derived from DbBP by using the Siri formula (20). All measurements conducted with the BOD POD used software versions 1.50 and 1.53. These two versions did not differ with respect to the measurement or prediction of Vtg.

HW. Twenty-four of the subjects who had been tested by air displacement had also undergone HW on the same day. The subjects were weighed underwater, according to standard procedures described in detail by McCrory et al. (16). Vt was measured on land by using the O2-dilution technique (21). Db from HW (DbHW) was calculated as

\[ Db_{HW} = \frac{M_s}{(M_s - M_w) / D_w} - V_R \]  

where \( M_s \) is body mass in air, \( M_w \) is body mass in water, and \( D_w \) is the temperature-corrected water density (4). %BF was calculated from DbHW by using the Siri formula (20).

Lung volume prediction. Because Vtg is measured at the midpoint of exhalation, Vtgpred was calculated as

\[ Vtg_{pred} = FRC + 0.5 \times V_T \]  

where FRC is functional residual capacity, and VR is the tidal volume estimated during normal breathing. FRC and VR were predicted from age and height according to the following formulas as developed by Crapo et al. (5).

**Table 1. Physical characteristics of subjects**

<table>
<thead>
<tr>
<th></th>
<th>Women (n = 36)</th>
<th></th>
<th>Men (n = 14)</th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Range</td>
<td>Mean ± SD</td>
<td>Range</td>
</tr>
<tr>
<td>Age, yr</td>
<td>30 ± 7</td>
<td>18–42</td>
<td>32 ± 11</td>
<td>21–56</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>63.8 ± 8.8</td>
<td>50.0–94.1</td>
<td>78.1 ± 14.2†</td>
<td>58.2–118.3</td>
</tr>
<tr>
<td>Height, cm</td>
<td>165.2 ± 6.8</td>
<td>152.4–182.2</td>
<td>176.3 ± 7.1†</td>
<td>165.1–188.0</td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>23.4 ± 3.0</td>
<td>18.7–32.3</td>
<td>25.0 ± 3.4</td>
<td>21.2–35.4</td>
</tr>
<tr>
<td>Vtgmeas, liters</td>
<td>3.337 ± 0.590</td>
<td>2.066–4.834</td>
<td>4.242 ± 0.631†</td>
<td>3.116–5.000</td>
</tr>
<tr>
<td>Vtgpred, liters</td>
<td>3.312 ± 0.250</td>
<td>2.829–4.007</td>
<td>4.116 ± 0.437†</td>
<td>3.492–4.692</td>
</tr>
<tr>
<td>VRmeas, liters*</td>
<td>1.190 ± 0.225</td>
<td>0.840–1.676</td>
<td>1.610 ± 0.261†</td>
<td>1.215–1.980</td>
</tr>
<tr>
<td>VRpred, liters*</td>
<td>1.468 ± 0.264</td>
<td>1.165–1.956</td>
<td>1.691 ± 0.330</td>
<td>1.182–2.269</td>
</tr>
</tbody>
</table>

|                  |          |          |                  |          |
| BMI, body mass index; Vtgmeas, measured thoracic gas volume; Vtgpred, predicted thoracic gas volume; VRmeas, measured residual lung volume; VRpred, predicted residual lung volume; n, no. of subjects. *Subsample: women, n = 13; men, n = 11. †Significantly different from women, P < 0.01; ‡significantly different from women, P < 0.03.
RESULTS

Physical characteristics of the subjects are shown in Table 1. On average, the men weighed more and were taller than the women (P < 0.01). Because of the height difference, the men had a larger Vtg meas, Vtgpred, and VRmeas than did the women (P < 0.01). The gender difference in VRpred approached but did not reach statistical significance (P = 0.06). Vtg pred was not significantly different from Vtg meas for either gender; VRpred was significantly higher than VRmeas in the women but not in the men (P < 0.03).

Mean values for the predicted and measured lung volumes and for %BF calculated by using predicted and measured lung volumes are shown in Table 2. There was no significant difference between Vtg pred and Vtg meas, nor in %BF measured by air displacement calculated by using Vtg pred vs. Vtg meas. In contrast, VR was overpredicted by 187 ml or 14% (P = 0.0004). This had the effect of significantly underestimating %BF by HW when calculated by using VRpred (P = 0.0004). Results from the linear regression analyses of measured on predicted variables are also shown in Table 2. R² values for Vtg and VR were 0.63 and 0.52, indicating moderate agreement between predicted and measured lung volumes. Whereas the standard error of the estimate (SEE) for VR was less than one-half that for Vtg (0.22 vs. 0.44 liters), they are similar when expressed as a percentage of the mean corresponding predicted lung volume (±0.14 and ±0.12%, respectively). R² values for regressions of %BF calculated by using the measured lung volume vs. that calculated using the predicted lung volume were high for both methods (0.98 and 0.96 for air displacement and HW, respectively), and corresponding SEEs were ±1.36 and ±1.67% BF, respectively.

Figure 1A and B, illustrates the residuals from the linear regressions of Vtgmeas on Vtgpred and of VRmeas on VRpred, respectively, plotted against the corresponding predicted lung volume. For both Vtg and VR, there appear to be an approximately equal number of positive and negative residuals, indicating that the prediction errors are fairly evenly distributed around zero; i.e., there is little skewness. Tests for curvilinearity and heteroskedasticity were not significant.

Residuals from the linear regressions of %BF calculated by using measured lung volume vs. that calculated using the predicted lung volume were high for both methods (0.98 and 0.96 for air displacement and HW, respectively), and corresponding SEEs were ±1.36 and ±1.67% BF, respectively.

For individual subjects, calculating differences in %BF by using measured and predicted lung volumes yielded the following results. For air displacement, estimates of %BF by using Vtgpred were within ±1% BF calculated by using Vtgmeas for 58% of subjects and ±2%
BF calculated by using $V_{tg_{\text{meas}}}$ for 82% of subjects. However, for HW, estimates of %BF by using $V_{R_{\text{pred}}}$ were within $\pm 1\%$ BF calculated by using $V_{R_{\text{meas}}}$ for 25% of subjects and $\pm 2\%$ BF by using $V_{R_{\text{meas}}}$ for 46% of subjects.

The error in estimation of %BF by using predicted lung volume in relation to the difference between predicted and measured lung volumes is illustrated in Fig. 3. When $V_{tg}$ is underpredicted, %BF is underestimated; when $V_{tg}$ is overpredicted, %BF is overestimated. In contrast, when $V_R$ is underpredicted, %BF is overestimated; when $V_R$ is overpredicted, %BF is underestimated. Thus a given error in lung volume prediction by air displacement and HW affects the calculation of %BF in opposite directions, a function of Eqs. 2 and 3 (see MATERIALS AND METHODS). In addition, it can be seen from Fig. 3 that a given error in the prediction of $V_{tg}$ will have less than one-half the effect on measurement of %BF by air displacement than will the same error in the prediction of $V_R$ on measurement of %BF by HW; this is also a function of Eqs. 2 and 3.

**DISCUSSION**

The principal findings of this study show that, on average, $V_{tg_{\text{pred}}}$ did not differ significantly from $V_{tg_{\text{meas}}}$, and there was no difference in body composition estimates measured by air displacement by using $V_{tg_{\text{pred}}}$ rather than $V_{tg_{\text{meas}}}$. In contrast, $V_R$ was systematically overpredicted, leading to a group mean underestimate of 1.4% BF from HW. Further analysis revealed that, although the outer ranges of individual estimates of %BF by using the predicted vs. measured lung volume for air displacement and HW were similar ($\pm 3-4\%$ BF), for air displacement the majority of subjects (82%) fell within $\pm 2\%$ BF of that when using $V_{tg_{\text{meas}}}$ but for HW, only about one-half of the subjects (46%) fell within $\pm 2\%$ BF of that when using $V_{R_{\text{meas}}}$.

Finally, it is notable that a given absolute error in $V_{tg_{\text{pred}}}$ will lead to an error in the estimation of %BF that is less than one-half that of using $V_{R_{\text{pred}}}$. This is attributable to the fact that only 40% of the $V_{tg}$ enters into the calculation of $V_b$ by air displacement (Eq. 2), whereas 100% of the $V_R$ enters into the calculation of %BF by HW (Eq. 3).

In this study, $V_R$ was overpredicted by 187 ml on average, and the overprediction of $V_R$ occurred to a greater extent in women compared with men. In a variety of studies conducted in healthy subjects, $V_{R_{\text{pred}}}$ has been reported to be, on average, 1.23 liters less than $V_{R_{\text{meas}}}$ (11), 495 ml greater than $V_{R_{\text{meas}}}$ (8), and approximately equal to $V_{R_{\text{meas}}}$ (8, 11, 17, 22). There appears to be no consistency as to whether $V_R$ is over- or underpredicted in women vs. men. The lack of congruence among these studies with regard to the accuracy of $V_{R_{\text{pred}}}$ may be related to intersubject variability but also to the particular equation used to predict $V_R$. There are several prediction equations for $V_R$ (e.g., Refs. 1, 3, 5, 9, 10, 12, 18, 22), each developed by using different reference techniques (e.g., $O_2$ dilution and He dilution). The agreement of $V_{R_{\text{pred}}}$ and $V_{R_{\text{meas}}}$ likely depends on the method used to measure $V_R$. Forsyth et
al. (8) reported that average $V_{R_{\text{meas}}}$ range in women was from 1.130 to 1.437 liters and in men was from 1.236 to 1.759 liters, depending on the method used to measure $V_R$. The equations by Crapo et al. (5) were used in the present study to predict $V_R$ (Eqs. 6 and 7) because the manufacturer of the BOD POD incorporates the estimate of FRC by those authors in their prediction of $V_{tg}$ (Eq. 5). To our knowledge, there are no published studies on the prediction of $V_R$ by using the Crapo et al. (5) equations in conjunction with HW, so a direct comparison with other studies is not possible. In the present study, $V_R$ was predicted by equations developed by using He dilution, yet $V_R$ was measured by O₂ dilution. These differing methods may be responsible to some degree for the differences between $V_{R_{\text{pred}}}$ and $V_{R_{\text{meas}}}$.

Despite the lack of agreement among studies on the accuracy of $V_R$ prediction, most investigators have found that erroneous estimates of %BF for individual subjects can arise when using $V_{R_{\text{pred}}}$. Wilmore (22) reported that using $V_{R_{\text{pred}}}$ had no effect on the estimation of %BF for the group, but individual estimates deviated quite substantially from that calculated by using $V_{R_{\text{meas}}}$ in some cases deviating by >4% BF. Similarly, Hackney and Deutsch (11) calculated that, on average, with a standardized man of 70 kg and 15% BF as the subject, calculating %BF by using the $V_{R_{\text{pred}}}$ values obtained in their study resulted in average overestimates of 16.0% BF by using the Wilmore equation (22) and of 11.6% BF by using the Boren equation (3).

Keys and Brozek (13) have calculated that an error of ±100 ml in $V_R$ results in an error of ±0.8% BF by HW for a person weighing 70 kg with 20% BF. Because only 40% of the $V_{tg}$ is used in the calculation of $V_b$ measured by air displacement, an error of ±100 ml in $V_{tg}$ would result in an error of only ±0.3% BF (assuming $V_{b_{\text{raw}}} = 64.0 l$, $V_{tg} = 40.0 l$, and SAA = −0.9 l). It would take an error of ~10% in $V_{tg}$ determination for a $V_{tg}$ of 4.0 liters (±400 ml) to produce an error of ±0.8% BF by air displacement in the same 70-kg, 20% BF person. We have observed that, on average, the between-day coefficient of variation of $V_{R_{\text{meas}}}$ is ±3.5% ($n = 22$; unpublished observations). For a $V_{tg}$ of 4.0 liters, this represents an error of ±140 ml and a resulting error of about ±0.4% BF.

Conclusion. Our findings support the use of $V_{R_{\text{pred}}}$ in conjunction with air-displacement plethysmography for group mean comparisons and for purposes such as screening in young to middle-aged individuals. This contrasts with the use of $V_{R_{\text{pred}}}$ in conjunction with HW, which leads to significant errors in the estimation of %BF. Furthermore, although the use of $V_{tg_{\text{pred}}}$ may be valuable in some circumstances, obtaining $V_{tg_{\text{meas}}}$ is relatively simple in most cases. Therefore we recommend that the use of $V_{tg_{\text{meas}}}$ remain a part of standard experimental and clinical practice. The results of this study do not necessarily apply to other groups, such as pediatric or elderly subjects, or to those with pulmonary dysfunction. Additional research is needed to determine the validity of $V_{tg_{\text{pred}}}$ in these groups.

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Address for reprint requests: M. A. McCrory, Energy Metabolism Laboratory, Jean Mayer USDA Human Nutrition Research Center on Aging at Tufts Univ., 711 Washington St., Boston, MA 02111-1524 (E-mail: mccrory_em@mhnrc.tufts.edu).

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