Hydrostatic weighing at residual volume and functional residual capacity

TOM R. THOMAS AND GIL L. ETHERIDGE
Exercise Physiology Laboratory, University of Kansas, Lawrence, Kansas 66045

THOMAS, TOM R., AND GIL L. ETHERIDGE. *Hydrostatic weighing at residual volume and functional residual capacity.* J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 49(1): 157-159, 1980.—Hydrostatic weighing (HW) was performed at both residual volume (RV) and functional residual capacity (FRC) to determine if underwater weighing at different lung volumes affected the measurement of body density. Subjects were 43 males, 18-25 yr. Subjects were submerged in the prone position, and the lung volume was measured by helium dilution at the time of the underwater weighing. Underwater weight was first assessed at FRC followed by assessment at RV. Changes in lung volume were accurately reflected in the underwater weight. Body density (D) was not different with the use of the FRC (mean $D = 1.0778$) or RV (mean $D = 1.0781$) data. Percent fat values for the FRC and RV data were 9.3 ± 5.4 and 9.2 ± 5.1%, respectively, and were not statistically different. The results indicate that the difference between percent fat determinations by HW in the prone position at FRC and RV is negligible. Because measurement of underwater weight at FRC is more comfortable for the subject, this may be the method of choice when the lung volume can be measured during the underwater weighing.

body density; percent body fat; lung volumes

HYDROSTATIC WEIGHING (HW) is one of the most popular techniques and with proper equipment perhaps the most accurate of the indirect methods for determining percent body fat. Assuming that equations derived from limited cadaver studies are correct, the accuracy of the HW method depends on the ability to determine or limit the amount of air in the gastrointestinal tract and to assess the volume of air present in the lungs at the time the subject is weighed underwater (3). These gases act as buoyancy forces and must be accounted for, or the density will be underestimated.

Because residual volume (RV) is easiest to reproduce in and out of water, this volume is most commonly utilized. Measurement of this volume has been performed either out of the water or while the subject is submerged before or after the actual underwater weighing. Recent evidence (6, 7) indicates that submergence affects lung volume and therefore such measurements should be made while the subject is underwater. If the lung volume can be assessed with the subject submerged, the question becomes which lung volume is most appropriate to measure.

Early work by Welch and Crisp (11) indicated that the smallest lung volume, RV, is the most appropriate to measure since it is least affected by hydrostatic pressure, i.e., pressure exerted against the chest cavity by the surrounding water. Measurement of larger lung volumes, such as functional residual capacity (FRC), is more comfortable for the subject but can be utilized for research purposes only if accuracy is not sacrificed.

The purpose of this study was to determine if the use of RV or FRC in HW yields any difference in the body density measurement.

METHODS

Subjects consisted of 43 males; 17 were trained gymnasts and 26 were untrained. The age range was 18–25 yr. Subjects were requested to fast 5 h and avoid flatulent foods 12 h before being tested. Vigorous activity was restricted for the previous 5 h, and, if possible, subjects evacuated the bowel and bladder just before weighing.

Percent fat was assessed by hydrostatic weighing with subjects submerged in a large water tank in the prone position. Each subject was weighed in air on a Toledo platform scale with digital indicator, accurate to 50 g, and weighed in water with a Chatillon autopsy scale, accurate to 25 g. Water temperature was maintained between 33 and 35°C. Lung volumes were measured by helium dilution (4) on a Collins Module Lung Analyzer. A specialized valve attached to the lung analyzer allowed the subject to breathe room air while submerged (Fig. 1). At the end of a normal expiration (FRC), the subject was turned into the spirometer via the valve, and his respiration was monitored during the entire test. Underwater weight was first assessed at FRC for three to five trials. The subject then exhaled maximally and underwater weight was assessed at RV. The mean net weight of three to five trials at each lung volume was used to calculate body density (D) from a standard formula (2). The formula devised by Siri (10) was used to compute percent body fat from body density.

0161-7567/80/0000-0000$01.25

Paired *t* tests and correlation coefficients were used to statistically analyze the data.

Another group of untrained subjects ($n = 40$), aged 18–26 yr, were tested and retested for percent body fat with FRC as the lung volume in order to assess the reproducibility of this method. At least 15 min separated the two determinations.

RESULTS

The body composition of the untrained and trained groups were very different (12.2 vs. 4.9% fat). However, values for body density were similar regardless of the lung volume utilized; i.e., for the trained group mean D at RV was 1.0880 and mean D at FRC was 1.0882, and for the untrained group mean D at RV was 1.0714 and mean D at FRC was 1.0709. Because comparison between RV and FRC data was not affected by the degree of leanness, the data were combined (Table 1). Differences in lung volumes (mean FRC, 2.260 liters; mean RV, 1.706 liters) were accurately reflected in the respective underwater weights (mean difference between lung volumes was 0.554 liters and mean difference between underwater weights was 0.540 kg). Percent body fat values for FRC and RV data were 9.3 ± 5.2% and 9.2 ± 5.1%, respectively, and were not statistically different. Body density measures were nearly identical regardless of the lung volume used. The correlation coefficient between the two density determinations was 0.99, and the mean absolute difference (Ā diff) was 0.0016 ± 0.0013 g/ml.

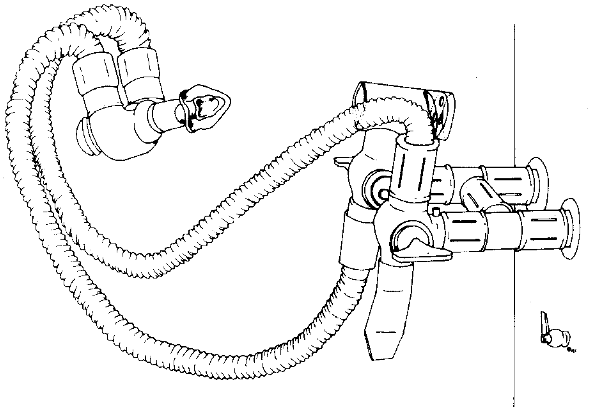

FIG. 1. Breathing valve. This apparatus attached to lung analyzer allows subject to breath either room air or helium mixture from analyzer while submerged. The valve consists of plastic H adaptor, which connects to analyzer, two three-way valves, one-way flutter valve, and Daniels' breathing valve modified for one-way flow only.

Test-retest reliability for body density of the HW-FRC method was 0.99; *mean test 1*, 1.0651; and *mean test 2*, 1.0649. These densities corresponded to percent body fat values of 14.8 and 14.9, respectively (Table 2).

DISCUSSION

The results of this study indicate that the difference between percent body fat determinations by HW at FRC and RV is negligible. Data collected by Welch and Crisp in 1958 (11) indicated that HW at 50% VC (mean, 3.87 liters) elicited a consistently higher body density than did HW at RV (mean, 1.66 liters) (1.0576 vs. 1.0559 g/ml, respectively). They interpreted these findings as indicating that hydrostatic pressure during immersion has a greater compressing effect on a larger lung volume. This compression is not reflected in the spirometer and thus presumably caused an overestimation of the lung volume at 50% VC. Largely because of these data, most HW methodologies have been developed with RV as the preferred lung volume.

Recent evidence (5, 9) suggests that measurement of RV may be inaccurate when assessed by dilution techniques during immersion. Robertson and others (9) compared dilution and plethysmographic techniques and observed that the dilution method underestimated RV or FRC by about 200 ml when the subject was submerged. This underestimation was caused by trapped air behind closed airways where it is not detected by dilution techniques. This 200-ml difference was masked at total lung capacity (TLC) by differences in immersed vital capacity (VC). Thus, TLC in immersed subjects was similar in dilution or plethysmographic techniques. In light of these data, the density at 50% VC, which was interpreted as erroneous by Welch and Crisp, may be more accurate than the density associated with RV, a volume more subject to gas-trapping error.

The data of Robertson and others (9) suggest that RV measured out of the water may be a more accurate reflection of actual RV during immersion. However, individual variation as high as 360 ml between dilution measures out of the water and plethysmographic measures in the water indicate that lung volume measurement during the time of HW may be important. In addition, Girandola and others (7) found RV measured by N_2 washout to be increased as a result of immersion. Thus, the effect of gas trapping due to hydrostatic pressure may not be a constant factor. If gas trapping can be eliminated, then FRC measured simultaneous with un-

TABLE 1. *Hydrostatic weighing at FRC and RV*

	FRC				RV			
	Fat, %	Density, g/ml	Lung Vol, liters BTPS	Underwater Wt, kg	Fat, %	Density, g/ml	Lung Vol, liters BTPS	Underwater Wt, kg
Mean	9.3	1.0778	2.260	3.016	9.2	1.0781	1.706	3.556
±SD	±5.2	±0.0124	±0.516	±0.778	±5.1	±0.0120	±0.710	±0.710
Mean diff*	0.1	−0.0003	0.554	−0.540				
Ā diff	0.6	0.0016						
r*	0.99	0.99						

Number of subjects was 43. FRC, functional residual capacity; RV, residual volume; Ā diff, mean absolute difference. * FRC vs. RV data.

TABLE 2. *Test-retest reliability for body density using FRC as the lung volume in hydrostatic weighing*

	Test 1	Test 2	A Diff
Mean	1.0651	1.0649	0.0023
± SD	±0.0177	±0.0183	±0.0016
$r = 0.99$			

Values are means ± SD of 40 subjects. FRC, functional residual capacity; A diff, absolute difference.

derwater weighing should be accurate. Other authors (1, 5) have indicated that deep breathing during the lung volume measurement could eliminate the gas trapping during immersion. In the present study, subjects were required to breathhold three to five times. This procedure caused increased breathing (rate and depth) to recover each time. Thus, gas trapping may have been reduced.

The use of TLC as the volume measured during HW awaits further investigation. The use of this lung volume would eliminate gas trapping (5, 9). However, preliminary experiments in our laboratory indicate that scale fluctuations caused by maximal inspiration may be a problem.

The utilization of FRC and the specialized breathing valve (Fig. 1) offer distinct advantages over the widely used HW methods (2, 8). Weighing at FRC allows the subject more air in the lungs while breathholding. This is more comfortable for the subject and usually causes less scale oscillation than total expiration and breath-holding underwater at RV. Previously reported methods (2, 8) have stressed the importance of observing at least 10 underwater weights at RV to achieve acceptable results. In the present study, the mean weight of three to five trials was used in the calculations. This number of trials yields accurate and reliable measures of underwater weight and lung volume because the subject is simultaneously monitored on a spirometer during the weighing. In this way each subject can be weighed exactly at FRC, or the repeatability of the maximal expiration for RV can be monitored. Such a system makes it no longer necessary to reproduce the lung volume in and out of the water. The underwater weight and the lung volume can be measured simultaneously.

The results indicate that HW in the prone position at FRC and RV produce similar body density and percent body fat results. Because measurement of the underwater weight at FRC is more comfortable for the subject and causes less scale fluctuation, this may be the method of choice when the lung volume can be assessed during the underwater weighing.

We thank Dr. James Orr for his review of the manuscript and helpful suggestions, Mary Ann Klotz for her assistance in the data collection and illustration of the breathing valve, and Dianne Lingle for her help in preparing the manuscript.

This study was supported by the University of Kansas General Research Fund and Biomedical Sciences Support Grant RR-07037.

Received 4 September 1979; accepted in final form 27 February 1980.

REFERENCES

1. Arborelius, M., Jr., U. I. Balldin, B. Lilja, and C. E. G. Lungren. Regional lung function in man during immersion with the head above water. *Aerospace Med.* 43: 701-707, 1972.
2. Behnke, A. R., and J. H. Wilmore. *Evaluation and Regulation of Body Build and Composition.* Englewood Cliffs, NJ: Prentice-Hall, 1974, p. 22-24.
3. Buskirk, E. R. Underwater weighing and body density: a review of procedures. In: *Techniques for Measuring Body Composition*, edited by J. Brozek and A. Henschel. Washington, DC: Natl. Acad. Sci.-Natl. Res. Council, 1961, p. 90-107.
4. *Clinical Spirometry.* Braintree, MA: Warren E. Collins, 1967.
5. Dahlback, G. O., and C. E. G. Lungren. Pulmonary air-trapping induced by water immersion. *Aerospace Med.* 43: 768-774, 1972.
6. Etheridge, G. L., and T. R. Thomas. The effect of body position and water immersion on lung volumes of women (Abstract). *Med. Sci. Sports* 10: 61, 1978.
7. Girandola, R. N., R. A. Wiswell, J. G. Mohler, G. T. Romero, and W. S. Barnes. Effects of water immersion on lung volumes: implications for body composition analysis. *J. Appl. Physiol.: Respirat. Environ. Exercise Physiol.* 43: 276-279, 1977.
8. Katch, F., E. D. Michael, and S. M. Horvath. Estimation of body volume by underwater weighing: description of a simple method. *J. Appl. Physiol.: Respirat. Environ. Exercise Physiol.* 44: 679-682, 1978.
9. Robertson, C. H., Jr., C. M. Engle, and M. E. Bradley. Lung volumes in man immersed to the neck: dilution and plethysmographic techniques. *J. Appl. Physiol.: Respirat. Environ. Exercise Physiol.* 44: 679-682, 1978.
10. Siri, W. E. *Body Composition from Fluid Spaces and Density.* Berkeley, CA: Donner Lab Med. Physics, Univ. Cal. Rep., 19 March, 1956.
11. Welch, B. D., and C. E. Crisp. Effect of level of expiration on body density measurement. *J. Appl. Physiol.: Respirat. Environ. Exercise Physiol.* 12: 399-402, 1958.