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Original Paper

A Modified Underwater Weighing Method Without Complete Immersion

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Abstract

This study was designed to examine the validity of a modified underwater weighing method for measuring human body volume (BV) that does not require head submersion (MUW). Results were compared with those obtained by the underwater weighing method (UW). The true head volume was calculated from the difference in BV, with and without head submersion. Stepwise regression analysis provided an equation to predict the head volume (HV) from the head girth (HG), the head length (HL), the head breadth (HB), the neck girth (NG), the face length I (FLI), the face length II (FLII), and the cheek girth. The equation for males was HV=0.185*(HG) + 0.122*(FLII) − 8.925, r^2=0.678, SEE=0.216. The equation for females was HV=0.131*(HG) − 0.026*(NG) + 0.112*(FLI) − 6.760, r^2=0.747, SEE=0.154. Cross-validation of predicted HV showed that the correlation coefficients were r=0.759, SEE=0.193 and r=0.749, SEE=0.193, for males and females respectively. Correlation coefficients and SEE between MUW and MW for body volume and % body fat were r=1.000, SEE=0.207 and r=0.983, SEE=1.339 for males and r=1.000, SEE=0.196 and r=0.946, SEE=1.915 for females. It can be concluded that this new method offers promising possibilities for future research with people who are unable to submerge their heads.

Introduction

Improvements in sports performance have resulted from the application of knowledge from many scientific and medical subdisciplines. Appropriate active mass is an essential ingredient for optimizing physical activities. This not only applies to sports involving specific weight categories but to most activities where excess fat is detrimental to performance. However, those outside the sporting population should also be interested in the estimation of body composition, particularly since there is evidence indicating an association between excess fat and a variety of diseases. Quantification of body fat is necessary to study the nature and treatment of obesity, to assess nutritional status, and to determine the responses of patients

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to a wide range of metabolic disorders.

Laboratory methods such as hydrostatic weighing [1, 2], total body water measurement [3-5], whole-body counting of potassium-40 [6], and dual energy x-ray adsorptiometry [7] are established, valid methods for assessing body composition.

Densitometry is the most frequently used laboratory method for measuring percent body fat (% BF). The procedure involves the determination of body density (BD) using Archimedes' principle, and is based on 4 measurements: mass in air, mass when immersed at residual lung volume, water density and residual lung volume (RV). The Siri [8] or Brozek *et al.* [9] equation can then be used to calculate % BF from BD. The measurement of body density by the underwater weighing method (UW) may be considered one of the best of the indirect approaches. However, this technique is time consuming, laborious, and is difficult or impossible for use in many special populations such as the obese, elderly, and disabled.

The development of a new method for measuring body volume was stimulated by the recurring need to determine the gross body composition of subjects for whom underwater weighing is impracticable. This study was designed to examine the validity of a modified underwater weighing method that does not require head submersion for measuring human body volume and compare its accuracy with the underwater weighing method.

Methods

Subjects and subject preparation

Fifty five males and 112 females who volunteered as subjects for this study were randomly divided into two groups: the prediction group and the validation group (Table 1). Informed consent was obtained in accordance with the protocol established in 1997 for human subjects. The subjects reported to the laboratory in the post-absorptive state and were requested to walk around a quadrangle for several minutes in an attempt to eliminate any flatus in the gastrointestinal tract. They were then asked to void as much urine and faeces as possible prior to changing into a bathing suit. The testing order was 1) modified underwater weighing method without head submersion (MUW) followed by 2) underwater weighing method (UW). All experiments were conducted in 1997–1998.

Table 1 Characteristics of the subjects

	Prediction Group		*Validation Group*	
	Male(n=28)	*Female(n=56)*	*Male(n=27)*	*Female(n=56)*
Age (years)	21.6±4.6	20.0±0.7	21.8±5.1	20.3±1.8
Weight (kg)	64.2±7.6	52.3±6.9	68.8±8.6	52.4±5.1
Height (cm)	172.2±5.6	158.8±4.4	173.4±4.9	158.9±4.8
BMI	21.7±2.5	20.7±2.3	22.9±2.9	20.8±2.2
%BF (%)	10.8±5.2	22.3±6.0	13.6±7.1	20.1±4.6
RV (L)	1.49±0.40	1.20±0.39	1.35±0.20	1.30±0.73

Values are means ± SD. BMI, Body Mass Index; %BF, % Body Fat (Underwater Weighing Method); RV, Residual Volume

Underwater weighing method

The subject's body weight was first determined in air on a balance scale accurate to ± 20g. Underwater weight was measured with the subject submerged in a kneeling position on a swing beneath the surface of the water. The swing was suspended from a Load Cell (Kyouwa Electronic Instruments Co., LTD., LT-50KG) connected to a digital readout. The underwater weight was recorded at the end of a forced exhalation. The water temperature was recorded at every trial and maintained between 34.0 and 38.0℃. The residual volume (RV) was measured by the oxygen rebreathing technique [10] with the subject standing and submerged to the shoulders. Duplicate determinations of RV were made, and the procedure was repeated if more than a 200 ml difference was recorded. The average of the two trials was used for calculations. Abdominal viscera gas and sinus air volume were ignored [11]. Body density (BD) was calculated from the air body weight, underwater weight, water density and RV. Percent body fat (%BF) was calculated according to the formula of Brozek *et al.* [9] from the BD.

Modified underwater weighing method without head submersion

The subject was marked on the neck with red tape. The reference mark was determined, with the aid of a stadiometer, as a horizontal line from the gnathion on the neck below the inferior ear. The subject stood on the swing with head held erect and out of the water and eyes focused straight ahead. The tape marker appeared just above the surface of the water. Furthermore, to assure consistent and proper placement of the head in the water during MUW, the subject flexed the knees to raise or lower the head on the order of the investigator to ensure that the chin just touched the floating bubble wrap. The subject was immersed only to the neck and the underwater weight was taken at the end of an expiration. The true head volume was obtained from the difference between the body volume with total submersion and body volume when immersed only to the neck.

Anthropometry

To estimate the head volume, the following measurements were taken. Head girth (HG) was measured to the nearest 0.1cm in a horizontal plane at the level of the glabella using an anthropometric tape measure (Kyoto Measuring Instruments Corp. Japan). The hair was compressed. Head length was measured to the nearest 0.1 cm between the glabella and opistocranion with a Martin's spreading caliper. Head breadth was measured between the left and right supramental crest with the caliper. Neck girth (NG) was measured just above (inferior to) the Adam's apple with the tape measure. Face length I (FL I) was measured between the gnathion and the vertex with the caliper. Face length II (FL II) was measured in a vertical

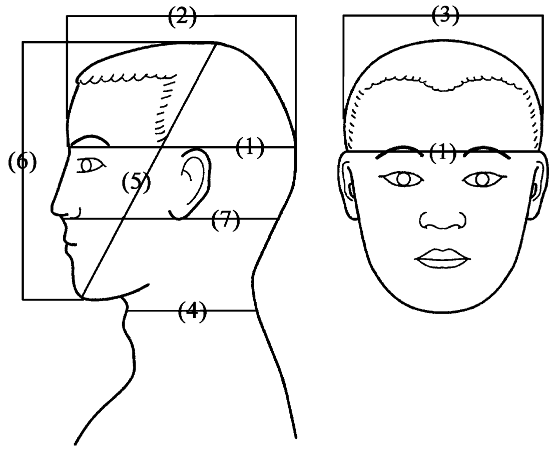

Fig. 1 Anatomical sites for prediction of head volume by multiple regression analysis. (1), Head girth; (2), Head length; (3), Head breadth; (4), Neck girth; (5), Face length I; (6), Face length II; (7), Cheek girth

line between the gnathion and the vertex with the skeletal anthropometer. Cheek girth was measured in a horizontal plane under the nose with the tape measure (Fig. 1).

Statistical analysis

Statistical analyses were performed using a StatView (version J4.02) program. Multiple regression analyses were applied to identify the best predictors of the head volume. The regressions were conducted in a stepwise manner, using the independent variables of head girth, head length, head breadth, neck girth, face length I, face length II, and cheek girth measures. Linear regression analyses were carried out. Correlation coefficients (r) and standard error (SEE) of estimates were calculated. Differences between measured and predicted variables were tested for significance using the paired t test. A five percent significance level was employed.

Results

Stepwise multiple regression analyses of the prediction group resulted in the following equations to predict head volume from anthropometric measurements of the head:

Males : HV=0.185*(HG) + 0.122*(FL II) − 8.925 (r^2 = 0.678, SEE = 0.216)
Females : HV=0.131*(HG) − 0.026*(NG) + 0.112*(FL I) − 6.760 (r^2 =0.747, SEE = 0.154)

A comparison in the validation group between the true HV and the HV predicted from the anthropometric equations is illustrated in the regression plot (Fig. 2). The correlation coefficients were r=0.759 ($p<0.0001$) for males and r=0.749 ($p<0.0001$) for females. The SEE were 0.193 for males and 0.193 for females. Furthermore, no significant differences were found between the true HV and the predicted HV in both males and females. Males had a mean difference of 0.001 ml between the true HV and the predicted HV, while females had a mean difference of 0.012 ml.

Fig. 3 shows the relationship between the body volumes as estimated by UW and MUW. The estimated regression line, the correlation coefficient, and the SEE were Y=0.9995X + 0.0285, 1.000 ($p<0.0001$), 0.207 for males, and Y=1.0118X − 0.5506, 1.000 ($p<0.001$), 0.196 for females.

Fig. 4 shows the relationship between the percent body fat as estimated by UW and MUW. The estimated regression line, the correlation coefficient, and the SEE were Y=1.0353X − 0.4857, 0.983 ($p<0.0001$),

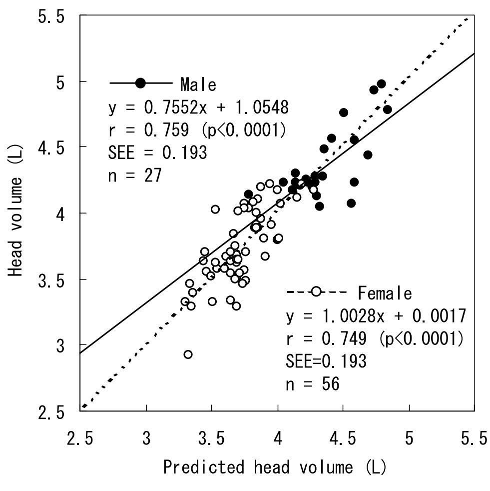

Fig. 2 Relationship between the head volume as measured by (UW volume - MUW volume) and predicted by the stepwise regression equation

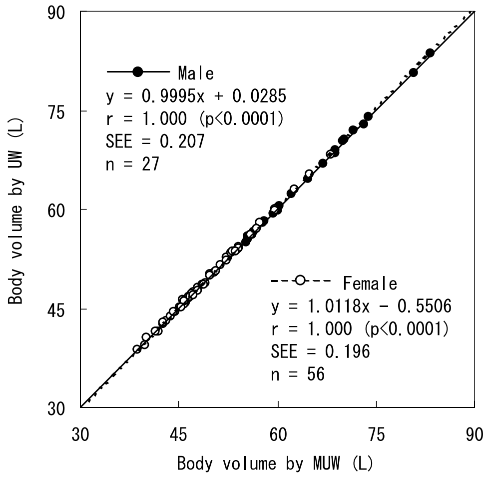

Fig. 3 Relationship between the body volume by underwater weighing and predicted body volume using the stepwise regression equation for head volume and MUW

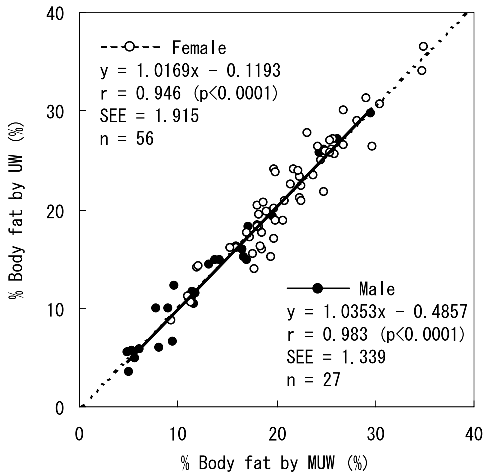

Fig. 4 Relationship between the measurement of percent body fat by underwater weighing and a modified underwater weighing procedure

1.339 for males, and Y=1.0169X − 0.1193, 0.946 ($p<0.001$), 1.915 for females. Furthermore, no significant differences were found between the percent body fat by UW and MUW in both males and females. Males had a mean difference of 0.01% between the percent body fat by UW and MUW, while females had a mean difference of 0.24%.

Discussion

Hydrodensitometry and hydrometry are two of the standard methods often used in evaluating body composition. Hydrodensitometry is viewed by many experts as the best method. But UW is time-consuming, laborious, and is difficult or impossible for use in many special populations such as the obese, elderly, and disabled. Several previous researchers have attempted to accurately measure body volume using methods which do not require underwater weighing.

There are two methods for estimating body volume without underwater weighing. In one, with the subject in an airtight chamber, Boyle's law is used to determine body volume by altering the volume of the chamber a known amount by means of a piston mechanism, and reading the change in pressure. The method [12-14] is called the air displacement, pneumatic method, or plethysmometric method. The other is the gas dilution technique [15-18]. With the subject in a closed chamber, a known volume of helium or SF6 is introduced. The gas is distributed quickly throughout the chamber and the subject's lungs. By determining the concentration of the gas in the chamber, it is possible to calculate the subject's volume. Both of these methods have the important advantage that it is not necessary to measure RV and is suitable for use with children, elderly people, and patients. Both methods have thermodynamic difficulties. Both the temperature effect and the influence of respiratory gas exchange in the chamber must be adequately compensated for. Also, the apparatus required are very expensive.

Garrow *et al.* [19] investigated a new apparatus in which the subject stood in water up to neck level, with the head covered by a clear-Perspex lid. As usual, the body volume of the subject, without the head volume, was determined by using Archimedes' principle. The head volume of the subject was determined by using plethysmography, which eliminates the need for measuring residual volume. The results showed that the correlation coefficient of fat mass between estimates by the new method and total body potassium was 0.949, between the new method and total body water was 0.971, and between total body potassium and total body water was 0.978. However, the %body fat calculated from his data showed that the correlation coefficient between estimates by the new method and total body potassium was 0.641, between the new method and total body water was 0.789, and between total body potassium and total body water was 0.830. It was concluded that the new method can't be used to provide an accurate estimate of the composition after a small weight loss in an individual since deviations of up to 4 kg of fat occur between fat losses based on change in density and those based on the more reliable energy balance method.

Donnelly *et al.* [20] have described an underwater weighing method without head submersion in which subject position and head placement are standardized using a horizontal line from the angle of the mandible to a site on the neck inferior to the ear lobe as a reference level. A winch attached to an autopsy scale is used to raise or lower the subject to the desired depth and the subject flexes or extends the neck, following the investigator's instructions, so that the water just touches the inferior surface of the chin and the horizontal reference mark. The test-retest reliability of body density at total lung capacity (TLC) using this technique was good (r=0.98) with a mean difference of 0.0008g/ml. Nevertheless, body density at TLC with the head above the water was only moderately correlated with body density measured at RV while the subject was fully submerged (r=0.88, SEE=0.0067 in males and r=0.85, SEE=0.0061 in females). In the cross-validation groups, the correlations were r=0.95, SEE=0.0043 in males and r=0.82, SEE=0.0084 in females. He suggested that predicted density was better in males than females, but no explanation for this apparent difference was given.

On the other hand, the results of this study showed that the correlations of the density were r=0.964, SEE=0.0032 in males and r=0.973, SEE=0.0030 in females. The differences in the correlations between our method and Donnelly's method may be explained by the fact that head volume is accounted for in our method while it was not in Donnelly's. In fact, the mean true head volumes measured in our experiment were 4.31 L (range: 3.79–4.97) in males and 3.74L (range: 2.92–4.22) in females. It is important to estimate head volume accurately when using MUW.

This observation suggests that MUW may provide meaningful estimates of body composition in people who are unable to submerge their heads. We also think that further research is required to more accurately predict head volume.

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