A new gas dilution method for measuring body volume

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This study was designed to examine the validity of a new gas dilution method (GD) for measuring human body volume and to compare its accuracy with the results obtained by the underwater weighing method (UW). We measured the volume of plastic bottles and 16 subjects (including two females), aged 18–42 years with each method. For the bottles, the volume measured by hydrostatic weighing was correlated highly ($r = 1.000$) with that measured by the new gas dilution method. For the subjects, the body volume determined by the two methods was significantly correlated ($r = 0.998$). However, the subject's volume measured by the gas dilution method was significantly larger than that by underwater weighing method. There was significant correlation ($r = 0.806$) between GD volume – UW volume and the body mass index (BMI), so that UW volume could be predicted from GD volume and BMI. It can be concluded that the new gas dilution method offers promising possibilities for future research in the population who cannot submerge underwater.

Keywords: gas dilution method, underwater weighing method, body volume, body density, percent body fat

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 given the correlative evidence indicating an association between obesity and a variety of diseases. Quantification of body fat is needed to study the nature and treatment of obesity, to assess nutritional status and to determine the response of patients to a wide range of metabolic disorders.

Laboratory methods such as hydrostatic weighing^{1,2}, total body water measurement^{3–5}, and whole-body counting⁶ of potassium-40 are established and valid methods of assessing body composition.

Densitometry is the most frequently used laboratory method for measuring percent body fat (% BF). This involves the determination of body density (BD) using Archimedes' principle, and is based on four measurements: mass in air, mass when immersed at residual lung volume, water density and residual lung volume (RV). The Siri⁷ or Brožek⁸ equation can then be used to calculate % BF from BD. The measurement of BD by the underwater weighing method (UW) may be considered one of the best of the indirect approaches. However, this procedure is time consuming, and requires expensive equipment and considerable tester expertise.

The development of the gas dilution method (GD) for measuring body volume was stimulated by the recurring need to determine the gross body composition of subjects for whom underwater weighing was impracticable. While these methods are capable of estimating the volume of an inanimate object, investigators have previously had little success with live subjects.

New gas dilution method

This study was designed to examine the validity of a new gas dilution method (Shimadzu, BSF-100, Japan) for measuring human body volume and compare its accuracy with the UW method.

In this application the solvent was air at atmospheric pressure in a rigid, closed chamber, whose inner volume was approximately 385 l. In the chamber two fans were installed at the bottom corner with flow pass to stir the solute. When the chamber was occupied by a subject, the total volume of air, including air in the respiratory spaces, was $V_0 - V$, where V_0 was the chamber volume and V the tissue volume of the subject. V_1 volume of sulfur hexafluoride (SF_6) was transferred into the chamber through the SF_6 supply line (from SF_6 tank to measuring tube). After equilibration, opening the vent valve attached to the chamber kept the pressure balanced with the atmosphere, and then the concentration of SF_6 , $X(\text{ppm})$, was measured continuously by a non-dispersive infrared gas analyser. During this time, the sampling air was cooled down by the refrigerator to keep the measuring cell temperature and rate of humidity constant (Figure 1). The time during which the subject breathes ordinarily in the

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Figure 1. Schematic diagram of apparatus for determining body volume by the gas dilution method

chamber was almost 4 min, enough to replace residual air in the lungs with air containing SF₆. We obtained the formula $X/10^6 = V_1/(V_0 - V + V_1)$. Thus, the body volume is obtained from the equation, $V = V_0 + V_1 - (V_1/X)10^6$. Percent BF is calculated from the BD and Brožek⁸ equation. The same plastic bottles whose volume was determined by the UW method were also measured by the new GD method. Five trials were performed on each plastic bottle. The average of the five measurements was used for the volume of the plastic bottles.

The results given by the two methods were compared by linear regression, with UW volume as the dependent variable against GD volume as the independent variable. The paired *t* test was used to compare the subject's UW volume and the GD volume. The linear regression analysis with the difference between GD volume and UW volume as the dependent variable was made against the BMI as the independent variable. Furthermore, simple regression analysis was done between the UW volume as the dependent variable and GD volume minus the fitted volume, which was determined by the third regression model (GD volume – UW volume vs BMI). Lastly, the dependent variable of % BF was calculated by UW volume. The independent variable was % BF calculated by the modified GD volume.

Methods

Subjects and subject preparation

Fourteen men and two women, aged 18–41 years, volunteered as subjects for this study (Table 1). Informed consent was obtained in accordance with the established protocol 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 followed was: (1) UW method; and (2) the new GD method.

Underwater weighing method

The subjects' body weight was first determined in air on a balance scale accurate to ± 20 g. Underwater weight was measured with the subject submerged in a kneeling position on a chair beneath the surface of the water. It was suspended from a Load Cell (Shinko Densi, MFG-250, Japan) connected to a digital readout. The underwater weight was measured at the end of a forced exhalation. The water temperature was recorded at every trial and maintained at about 38.0°C.

The residual volume (RV) was measured by the nitrogen washout technique with autspirometer (Minato, System 9, Japan) prior to UW. Abdominal viscera gas and sinus air volume were ignored⁹.

BD was calculated from air body weight, underwater weight, water density and RV. %BF was calculated according to the formula of Brožek⁸ from BD.

The volume of the plastic bottles, filled with the weights and water, was determined by the UW

Table 1. Physical characteristics of subjects

Subject	Sex	Age (yr)	Height (cm)	Weight (kg)	BMI (kg/m ²)
1	M	20	178.5	67.60	21.22
2	M	21	170.1	71.05	24.56
3	M	21	176.0	67.90	21.92
4	M	20	167.3	66.30	23.69
5	M	21	166.0	63.35	22.99
6	M	21	170.0	74.60	25.81
7	M	21	164.6	55.65	20.54
8	M	22	178.9	82.80	25.87
9	M	25	171.8	68.50	23.21
10	M	30	174.6	61.15	20.06
11	M	33	170.0	64.30	22.25
12	M	34	171.0	78.35	26.79
13	M	40	170.2	76.80	26.51
14	M	42	175.3	71.95	23.41
15	F	20	161.5	54.10	20.74
16	F	20	156.4	55.50	22.69

M: male, F: female; BMI: body mass index

method. The water temperature was maintained at about 25.0°C.

Results

The relationship between volume as measured by UW and volume as measured by the GD method in five plastic bottles is illustrated in the regression plot (Figure 2). The correlation coefficient (*r*) between the two methods was 1.0 (*P* < 0.0001). The estimated regression line was $y = 0.983x + 1.101$; 90% confidence intervals for the slope were 0.990 and 0.989; those for the midpoint $x = 64.446$ were 64.274 and 64.63. The estimated standard error of the gas dilution technique was 0.171.

Measurements were performed on 16 volunteers aged 18–42 years. The results are presented in Figure 3. The observed correlation coefficient (*r*) was 0.998 (*P* < 0.0001); the regression line was $y = 0.924x + 2.252$; 90% confidence levels for the slope were 0.969 and 1.031, and those for the midpoint $x = 66.614$ were 63.594 and 64.072. The estimated standard error of the GD technique was 0.542 l. The reproducibility of body volume of a subject measured by the dilution method was examined by repeating the measurement ten times. The estimated mean, standard deviation and coefficient of variation (CV) were 70.58 l, 0.349 l and 0.494 respectively.

The mean BV measured by UW and by the GD technique were 63.83 l and 66.61 l, respectively (Table 2). The mean BV measured by the GD technique was significantly (*P* < 0.0001) higher than that measured by UW. The mean difference between the two was 2.78 l.

The relationship between (GD volume – UW volume) and BMI is shown in Figure 4. The correlation between (GD volume – UW volume) and

Table 2. The volumes of 16 subjects as measured by the underwater method and the gas dilution method

Subject	UW volume (l)	GD volume (l)
1	63.23	65.47
2	65.99	69.55
3	63.46	65.40
4	61.70	64.00
5	59.07	62.06
6	69.69	73.68
7	52.74	55.52
8	79.45	83.38
9	64.88	67.50
10	58.38	60.05
11	61.78	64.79
12	74.87	78.88
13	72.88	76.34
14	68.25	70.61
15	51.69	53.02
16	53.27	55.58
Mean(s.d.)	63.83(7.96)	66.61(8.59)

BMI was *r* (SEE): 0.845(0.461). The estimated regression line was $y = 0.327x - 4.841$.

The relationship in 16 subjects between volume as measured by UW and (GD volume – fitted difference volume of BMI) is illustrated in the regression plot (Figure 5). The correlation coefficient (*r*) between the two was 0.998 (*P* < 0.0001). The estimated regression line was $y = 0.994x - 0.366$; 90% confidence intervals for the slope were 0.968 and 1.020; those for the midpoint $x = 63.833$ were 63.631 and 64.035. The estimated standard error was 0.458 l.

Figure 6 shows the relationship between %BF as estimated by the UW volume and %BF as estimated by (GD volume – fitted difference volume of BMI).

Figure 2. Relationship between the volume of five plastic bottles as measured by underwater weighing and the gas dilution method

Figure 3. Relationship between the body volume of 16 subjects as measured by underwater weighing and the gas dilution method. The line shown is the fitted regression line

Figure 4. Relationship between (GD volume - UW volume) and BMI (kg/m^2)

Figure 5. Relationship between volume as measured by underwater weighing and (GD volume - fitted difference volume of BMI)

The correlation coefficient (r) was 0.845 ($P < 0.0001$). The estimated regression line was $y = 0.722x + 5.047$; 90% confidence intervals for the slope were 0.507 and 0.937; those for the midpoint $x = 18.068$ were 16.793 and 19.343. The estimated standard error of the predicted %BF was 2.895.

Discussion

There are two methods for estimating BV without UW. In one, with the subject in an airtight chamber, BV can theoretically be determined by altering the

Figure 6. Relationship between percent body fat as estimated by underwater weighing volume and (GD volume - fitted difference volume of BMI)

volume of the chamber a known amount by means of a piston mechanism, and reading the change in pressure, according to Boyle's law. This method¹⁰⁻¹² is called air displacement, pneumatic method or plethysmometric method. The other is the helium dilution technique¹³⁻¹⁵. With the subject in a closed chamber, a known volume of helium is introduced. The helium is distributed quickly throughout the chamber and throughout the gas in the subject's lungs. Determining the concentration of the helium in the chamber calculates the subject's volume.

Both of these methods have important advantages, for example, the unnecessary of measuring RV and their suitability for children, aged people and patients.

However, the two methods have thermodynamic difficulties. Both the temperature effect and the influence of respiratory gas exchange in the chamber must be adequately taken care of. The thermal conductivity bridge used to measure the helium concentration in the chamber also responds to the accumulation of CO_2 and water vapour provided by the subjects¹⁶. In reality, these methods are not used in universities, institutes or hospitals that study body composition because of the complicated operation.

However, using the new GD method, after equilibration of SF_6 , opening the vent valve to the ambient atmosphere can prevent the pressure from increasing, because the pressure in the chamber increases owing to the human body temperature. The non-dispersive infrared gas analyser can measure exactly the SF_6 concentration, because the sampling air is cooled down by the refrigerator to keep the measuring cell temperature and density of humidity constant. SF_6 is used to estimate the functional distribution of pulmonary ventilation - perfusion ($\dot{V}_A/\dot{Q}$) ratio¹⁷⁻¹⁹. SF_6 is suitable for the GD method

because it is inactive physiologically and absorbed into the human body less than nitrogen gas²⁰.

In plastic bottles a high correlation ($r = 1.000$) was found between the volume as determined by UW and that by GD. Furthermore, there were no differences between the volumes as measured by UW and GD. For the subjects, the BV determined by UW were correlated highly ($r = 0.998$) with the volume determined by GD. However, the subjects' volume measured by GD were significantly larger than that by UW. No investigator has reported previously on this point. It follows, therefore, that the water pressure against a submerged body, the sitting posture underwater and the forced maximal exhalation influence BV. Also, there was a significant correlation ($r = 0.845$) between (GD volume – UW volume) and BMI, such that UW volume could be predicted from GD volume and BMI. This observation suggests that the GD method may provide meaningful estimates of BV in those subjects who cannot submerge underwater. We also think that further research is required to clarify between the true human body volume and density.

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