Comparison of Estimation Accuracy of Body Density between Different Hydrostatics Weighing Methods without Head Submersion

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Abstract This study compared the accuracy of body density (Db) estimation methods using hydrostatic weighing without complete head submersion ($HW_{withoutHS}$) of Donnelly et al. (1988) and Donnelly and Sintek (1984) as referenced to Goldman and Buskirk's approach (1961). Donnelly et al.'s method estimates Db from a regression equation using $HW_{withoutHS}$, moreover, Donnelly and Sintek's method estimates it from $HW_{withoutHS}$ and head anthropometric variables. Fifteen Japanese males (173.8 ± 4.5 cm, 63.6 ± 5.4 kg, 21.2 ± 2.8 years) and fifteen females (161.4 ± 5.4 cm, 53.8 ± 4.8 kg, 21.0 ± 1.4 years) participated in this study. All the subjects were measured for head length, width and HWs under the two conditions of with and without head submersion. In order to examine the consistency of estimation values of Db, the correlation coefficients between the estimation values and the reference (Goldman and Buskirk, 1961) were calculated. The standard errors of estimation (SEE) were calculated by regression analysis using a reference value as a dependent variable and estimation values as independent variables. In addition, the systematic errors of two estimation methods were investigated by the Bland-Altman technique (Bland and Altman, 1986). In the estimation, Donnelly and Sintek's equation showed a high relationship with the reference ($r=0.960$, $p<0.01$), but had more differences from the reference compared with Donnelly et al.'s equation. Further studies are needed to develop new prediction equations for Japanese considering sex and individual differences in head anthropometry. *J Physiol Anthropol Appl Human Sci 22 (4): 175–179, 2003* http://www.jstage.jst.go.jp/en/

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Introduction

The hydrostatic weighing method (HW) has been used as the gold standard to estimate body composition (Going, 1995; Wagner and Heyward, 1999). Although measurement methods with high accuracy, such as the hydrometry technique, the dual energy X-Ray absorptiometry, imaging technique (magnetic resonance imaging: MRI or computed tomography: CT) and the air displacement system, have been developed, the use of these methods is limited because they need expensive equipment and special testers.

HW is a relatively practical method compared with the above methods except for physical and psychological discomfort when the subject submerges. However, since this method demands the subject to completely submerge with exhaling for a period of time, the practicality of this method is not necessarily good when applied to children, the elderly, physically challenged people and non-swimmers (Gibbons et al., 1985: Demura et al., 1999). Gas volume in the lung after maximal exhaling during HW is the greatest measurement error factor when determining body density (Akers and Buskirk, 1969). Going (1996) demonstrated that an error of 100 ml gas volume corresponded to an error of 0.7% in estimating percent body fat. Especially, in the case of the above-stated subjects, even if he/she exhaled with maximal effort underwater, gas greater than the residual volume (RV) in the lung may remain.

Donnelly et al. (1988) developed a method to estimate body density (Db) using HW without head submersion ($HW_{withoutHS}$). In addition, Donnelly and Sintek (1984) developed a method that estimates the difference (Dp) between HW with head submersion (HW_{withHS}) and $HW_{withoutHS}$ from anthropometry of head parts, and that estimates Db using $HW_{withoutHS}$ corrected by the Dp. Both methods do not demand head submersion for the measurement of Db, and can be used to subjects who find it

hard to tolerate the psychological and physical discomfort of head submersion.

Similarly to HW_{withHS}, $HW_{withoutHS}$ is based on densitometry assuming a 2-component model. Recently, a multi-component model such as 4-component model was also proposed. Although the 4-component model can estimate body composition more accurately than the 2-component model, this method requires measurements of body water and minerals, including the problems of insufficient equipment, time constraints and expense. Therefore, considering practicality, the 4-component approach is not always appropriate and improving the practicality of the 2-component approach is considered to be meaningful. $HW_{withoutHS}$ is an effective approach when you consider the problems associated with head submersion in the traditional HW method.

However, although these methods were reported to be valid (Donnelly et al., 1988; Donnelly and Sintek, 1984), a comparative investigation of the estimation accuracy of these methods revealed that there is no report on when to apply to the same sample. The same sample must be used while comparing the estimation accuracy between the two methods. Furthermore, there is no report that these methods could be applied to Japanese who have different physical characteristics from the subjects in previous studies. It is necessary to examine whether these methods can be applied to Japanese, moreover based on the results, a further study is required to probe the necessity of developing new estimation equations for Japanese. Expanding the application range of $HW_{withoutHS}$ to children, the elderly and the physically challenged throughout the examination of estimation accuracy of the estimation equation of $HW_{withoutHS}$ is expected.

This study aimed at comparing the accuracy of the estimation methods developed by Donnelly et al. (1988) and Donnelly and Sintek (1984) when applied to healthy Japanese young people.

Methods

Subjects

Fifteen Japanese males and fifteen females aged from 17 to 26 years participated in this study (males: 173.8±4.5 cm, 63.6±5.4 kg, 21.2±2.8 years; females: 161.4±5.4 cm, 53.8± 4.8 kg, 21.0±1.4 years). The subjects' mean height and body weight did not differ significantly from standard values for Japanese people of the same age (Laboratory of Physical Education, Tokyo Metropolitan University, 2000). Before testing, the aim and procedure of the study were explained in detail and a written informed consent was obtained from each subject.

HW With or Without Head Submersion

This study measured hydrostatic weight under the two conditions: one condition is with head submersion (HW_{withHS}) in which the subjects submerged their heads completely, the other one is without head submersion ($HW_{withoutHS}$) in which

the subject was not required to submerge the head. Subjects sat on a chair attached to a weighing scale (AD-6204, A&D). After exhaling, the subjects submerged and the hydrostatic weight was measured. The subject's position in the water at $HW_{withoutHS}$ is referred to that in the procedure of Donnelly et al. (1988). Thus, the subject did not submerge until the water just touched the inferior surface of the chin and the horizontal reference line. The head was rotated up or down following the investigator's instruction. The RV was measured in the water without head submersion with a nitrogen washout technique (system 9, Minato Medical Corp.) based on the open-circuit method. Hydrostatic weight was measured 5 times for each method of HW_{withHS} and $HW_{withoutHS}$. The mean value of the middle measurements was used for HW_{withHS} measurement (Weltman and Katch, 1981; Marks and Katch, 1986). The mean value of the middle three measurements was used for $HW_{withoutHS}$, because the placement of the subject in the HW tank was either too high or low in relation to the neck reference line, and this influenced the measurement error (Donnelly et al., 1988). Water temperature was maintained from 35 to 37°C and gas in the viscera was assumed at 150 ml. Before the measurement, all subjects were asked to fast for two hours, to avoid exercise and to excrete. They were allowed to wear only swimming suits during measurements.

Anthropometry of Head

Five head parameters (head circumference, head length, head breadth, neck girth, and head thickness) were selected by referring to the previous studies (Kondo et al., 1999; Larsen 1979). Head girth was the length through the glabella and opistocranion. Neck girth was measured on the inferior horn of thyroid cartilage. Head length was measured between the vertex and gnathion in an orbitomeatal plane while keeping a horizontal level between the tragion and orbitale. Head breadth was measured between the left and right euryon. Head thickness was measured between the glabella and opistocranion. A cloth tape or slide caliper was used, as appropriate, for the measurements.

Prediction Equation of Body Density

This study estimated body density by the three equations of Goldman and Buskirk (1961), Donnelly et al. (1988), and Donnelly and Sintek (1984). The estimation accuracy of the methods of Donnelly et al. (1988) and Donnelly and Sintek (1984) was compared using Goldman and Buskirk (1961) as the reference (1).

$$Db1 = W/\{((W - HW_{withHS})/0.9937) - RV - VGI\} \qquad (1)$$

Where, W: body weight, HW_{withHS}: HW measured by submerging head completely, RV: residual volume, VGI: gas in the viscera assumed at 150 ml.

Donnelly et al. (1988) developed prediction equations (2-2 and 2-3) that estimate the body density (Db2) from the body density ($Db_{withoutHS}$) calculated by substituting $HW_{withoutHS}$ for

Table 1   Agreement of reference (Db1) and predictors (Db2 and Db3) in body density

	Db1 Mean	SD	Db2 Mean	SD	t-test	r	SEE	Mean Difference	Limits of Agreement
Total	1.064	0.013	1.070	0.014	**	0.936	0.047	−0.006	0.020
Male	1.074	0.008	1.082	0.007	**	0.798	0.005	−0.008	0.020
Female	1.054	0.009	1.058	0.007	**	0.908	0.004	−0.004	0.016
	Db3 Mean	SD			t-test	r	SEE	Mean Difference	Limits of Agreement
Total	1.078	0.014			**	0.960	0.004	−0.014	0.016
Male	1.089	0.009			**	0.870	0.004	−0.015	0.017
Female	1.067	0.009			**	0.934	0.004	−0.013	0.014

Note   Db1: Db predicted from Goldman and Buskirk's equation (1961)
  Db2: Db predicted from Donnelly et al.'s equation (1988)
  Db3: Db predicted from Donnelly and Sintek's equation (1984)
  Limits of agreement indicates the range of mean difference±2SD
  **: p<0.01, ns: not significant

equation (2-1).

$$Db_{withoutHS} = W/\{((W - HW_{withoutHS})/0.9937) - RV - VGI\}$$
$$(2\text{-}1)$$

$$Db2 = 0.5829*(Db_{withoutHS}) + 0.4059 \text{ (male)} \quad (2\text{-}2)$$

$$Db2 = 0.4745*(Db_{withoutHS}) + 0.5173 \text{ (female)} \quad (2\text{-}3)$$

Where, $HW_{withoutHS}$: HW measured by submerging without head, $Db_{withoutHS}$: body density estimated from $HW_{withoutHS}$.

Donnelly and Sintek (1984) developed prediction equations (3-1 and 3-2) to firstly estimate the difference (D) between $HW_{withoutHS}$ and HW_{withHS} from head width and head length (3-1), then to estimate body density (Db3) by substituting D and $HW_{withoutHS}$ for equation (3-2). In this method, sex differences in head anthropology characteristics were not considered.

$$D = 4605.94 - 247.56X_1 - 182.93X_2 \quad (3\text{-}1)$$

$$Db3 = W/\{((W - (HW_{withoutHS} + D))/0.9937) - RV - VGI\} \quad (3\text{-}2)$$

Where, X_1: head width, X_2: head length.

Statistical Analyses

The body densities were calculated by the correlation coefficients between estimation values and the reference. The standard errors of estimation (SEE) were calculated by regression analysis using Db1 as dependent variables and the other estimation values as independent variables. In addition, the agreement and systematic error of each estimation method were investigated by the Bland-Altman technique (Bland and Altman, 1986). The means and the standard deviations of the differences between the reference and each predictor were calculated and a plot of the difference vs. average value

between the reference and each predictor was created. The limit of agreement, as determined by mean differences (2SD, was also calculated. In fact, it is not possible to statistically define an acceptable agreement (Bland and Altman, 1986), however, these plots may assist in the determination of agreement and systematic errors. The significant level in this study was set at p<0.05.

Results

Table 1 shows the results of the consistency of body density estimation values.

The significant differences were found between the references (Db1), calculated from HW_{withHS}, and the estimation values (Db2 and Db3), respectively. The mean differences between Db1 and Db2 were −0.0062 g/ml (total), −0.0083 g/ml (males) and −0.0041 g/ml (females). Similarly, the mean differences between Db1 and Db3 were −0.0142 g/ml (total), −0.0154 g/ml (males) and −0.0130 g/ml (females). The differences from D1 were greater in Db3 than in Db2.

On the other hand, regarding the relationships between the reference and estimation values, the relationship with Db3 was higher and SEE of Db3 was lower than those of Db2 (Db2: r=0.936 SEE=0.0469 (total), r=0.798 SEE=0.0051 (male), r=0.908 SEE=0.0040 (female); Db3: r=0.960 SEE=0.0037 (total), r=0.870 SEE=0.0041 (male), r=0.934 SEE=0.0035 (female).

In the results of the Bland-Altman technique (Figure 1), Db3 tended to overestimate Db1 as compared with Db2. The limits of agreement between Db1 and Db2 tended to be greater in males (0.020) than in females (0.016). In relation to the limits of agreement calculated for the total sample, those between Db1 and Db3 tended to be smaller than those between Db1 and Db2.
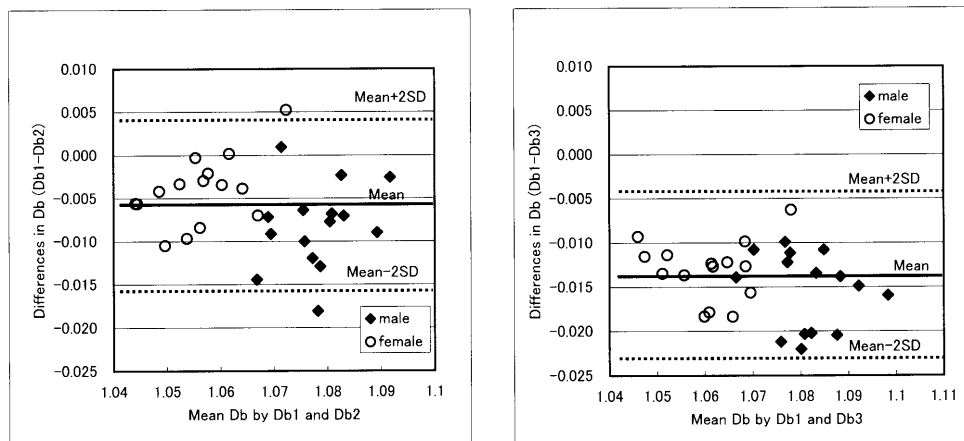
Fig. 1   Agreement of references and predictors assessed by Bland-Altman technique.

Discussion

In light of Donnelly et al's method (1988), $Db_{withoutHS}$ was calculated by substituting $HW_{withoutHS}$ for the prediction equation of Db developed by Goldman and Buskirk (1961), and then body density (Db2) was estimated from the prediction equation using $Db_{withoutHS}$ as an independent variable. Moreover, in accordance with Donnelly and Sintek's method (1984), the difference (D) between $HW_{withoutHS}$ and HW_{withHS}, which was almost equal to head weight, was estimated from a multiple regression equation using head width and head length as independent variables, and then body density (Db3) was estimated from the value by adding the D value to $HW_{withoutHS}$. Both methods are practical, especially for subjects who find it hard to completely submerge with exhaling for a period of time since neither requires head submersion by the subjects. This study compared the estimation accuracy when applying these methods to the same sample.

Compared to Db1, both of Db2 and Db3 were significantly greater. In the correlations and SEE values calculated for the total sample, the correlations tended to be higher and SEE was smaller in the relationship between Db1 and Db3 as compared with those in the relationship between Db1 and Db2. The limit of agreement was also lower in Db3 than in that of Db2. These results indicate that Donnelly and Sintek's method tends to underestimate Db, and overestimate %BF, but this method shows a higher relationship with the reference and a smaller estimation error as compared with Donnelly et al.'s method.

Donnelly et al. (1988) reported that the mean of error between Db1 and Db2 was 0.0014 g/ml in females, corresponding to an error of 0.7% in %BF, and 0.0001 g/ml in males and the error of %BF was almost nil (0.03%). Although the mean difference between Db3 and Db1 was not reported by Donnelly and Sintek (1984), the difference between Db3 and Db1 obtained in this study corresponded to over 5% in %BF, and this estimation error is considered to be large in the estimation of %BF. Donnelly and others (1988) reported that the correlation and SEE between Db2 and the reference were

$r=0.95$ and SEE$=0.0043$ in males, and $r=0.82$ and SEE$=0.0084$ in females. Donnelly and Sintek (1984) also reported that the correlations between Db3 and the reference were 0.92 in males and 0.98 in females.

As compared with the results in the previous studies, in this study the mean differences from the reference and standard errors of estimation tended to be greater, and the correlation with the reference tended to be lower. In general, when applying a prediction equation to another sample, the estimation errors are expected to be greater as compared with the reference. Furthermore, the results in this study were influenced by the differences in physical characteristics and race (Najjar and Kuczmarski, 1989; Malina and Bouchard, 1991). The subjects in this study were significantly smaller in weight compared with those of Donnelly et al. (1988). Differences in physical characteristics, especially fatness, influence the estimation errors in the assessment of body density (Israel et al., 1990). Especially, since Donnelly et al.'s equation directly predicts Db from the $Db_{withoutHS}$ using the regression equation, the estimation accuracy of the equation was influenced by the differences in these factors. The Donnelly and Sintek's equation defines head width and head length as independent variables to estimate body density, and these anthropometry variables are influenced by the differences in physical characteristics and race.

In addition, in comparing the estimation accuracy between the two methods, Donnelly and Sintek's equation, using head anthropometric variables as independent variables, showed a high relationship and small estimation errors with the reference. However, this method showed more mean differences from the reference as compared with those of Donnelly et al.'s equation. One of the reasons for this result is considered that Donnelly and Sintek's equation did not consider the sex difference in head anthropometric variables. Head anthropometric variables, such as head length, width, volume and weight, were different between males and females, and the prediction equations to estimate these variables were developed for each sex in previous studies (Larsen, 1979;

Kondo et al., 1999). This may influence the results in this study. So, further studies are needed to compare estimation accuracy between equations considering and not considering sex differences, and to develop a new prediction equation for Japanese.

In summary, this study indicates that it showed a higher relationship with the reference and a smaller SEE compared with the Donnelly et al.'s equation although the Donnelly and Sintek's equation underestimates Db and overestimates %BF compared with the Donnelly et al.'s equation. Further studies are needed to develop a new prediction equation for Japanese considering sex differences and individual differences in head anthropometric and physique characteristics.

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