Air Displacement Plethysmography for Estimating Body Composition Changes with Weight Loss in Middle-Aged Japanese Men

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Keywords

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Dual energy X-ray absorptiometry ·
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Summary

Aim: To examine the degree to which air displacement plethysmography (ADP) can track body composition changes in response to weight loss in obese Japanese men. **Method:** 50 men, aged 30–65 years with a mean BMI of 30 kg/m², were included in a 3-month weight loss program. Percentage of fat mass (%FM) was determined by dual energy X-ray absorptiometry (DXA) and ADP at baseline and month 3. **Results:** With 6.2 ± 4.3 kg of weight loss, %FM, as determined by DXA and ADP, significantly decreased by 3.9 ± 2.9% and 3.9 ± 3.3%, respectively. There was no mean difference for change (Δ) in %FM between the two methods. DXA-derived Δ %FM significantly correlated with Δ %FM determined by ADP ($R^2 = 0.48$, $p < 0.01$). Furthermore, the Bland-Altman plots demonstrated no systematic bias for Δ %FM ($r = -0.20$, $p = 0.17$). However, %FM by ADP ($r = 0.42$) at baseline and Δ %FM by ADP ($r = -0.54$) were significantly correlated to the differences between Δ %FM by DXA and ADP. **Conclusion:** These results suggest that ADP is comparably accurate for evaluating Δ %FM when compared with DXA, although there were proportional biases.

Introduction

The obesity epidemic has become one of the biggest public health concerns worldwide, including Asian countries [1, 2], because of its close relationship to chronic diseases such as hypertension, dyslipidemia, diabetes and cardiovascular disease [3, 4]. Since obesity is characterized and defined as the excess accumulation of body fat, accurate measurements of body composition are of utmost importance for public health and clinical perspectives. The ability of health professionals to accurately estimate body composition changes in obese individuals is also critical for determining the effectiveness of weight loss or management strategies.

Several body composition methods are available, which differ in terms of their theoretical bases and scientific assumptions as well as in terms of their cost, complexity and subject acceptability. For example, hydrostatic weighting (HW) has long been considered the gold standard for measuring body composition [5]. However, it requires many methodological assumptions and inconveniences that limit its usefulness and widespread application. Consequently, dual energy X-ray absorptiometry (DXA) has emerged as one of the most accurate techniques to assess body composition. DXA uses a three-compartment model to provide an estimate of bone mineral content, fat and lean soft tissue. DXA is easier to administer than HW and correlates well with other measures of body composition such as HW, total body water and multicompartiment approaches [6, 7]. DXA can also detect body composition changes due to weight loss [8].

Air displacement plethysmography (ADP) has emerged as a fairly novel technique that provides a body composition estimate from body density using a two-compartment model, as does HW [9]. The biggest difference between ADP and HW is that ADP does not require participants to exhale maximally while submerged under water. Therefore, ADP seems much more feasible and comfortable than HW. Cross-sectional studies showed that percentages of fat mass (%FM) estimated by ADP highly correlate with those from DXA [10, 11].

Only few studies have demonstrated that ADP was sensitive enough to detect, similarly to DXA, moderate body composition changes over various time periods (from 2 to 16 months) and percent weight loss (from 4.7 to 7.0%), primarily among Caucasian adults [11–13]. Asians, including Japanese, have greater %FM than Caucasians for the same BMI and age [14]. Therefore, it is important to determine whether ADP is a valid method of tracking body composition changes in Japanese men.

The purpose of this study was to examine whether ADP could accurately track body composition changes in response to weight loss in obese Japanese men, using DXA as a reference method. Better understanding of this issue will be useful for designing longitudinal studies regarding body composition as well as in providing clinically relevant information for health professionals.

Participants and Methods

Participants

We recruited participants from communities around the University of Tsukuba for 3-month weight loss programs through local newspaper advertisements and study flyers. Eligibility criteria included the following: i) men, ii) aged 30–65 years, iii) a BMI >25 kg/m² according to the domestic obesity guideline [15] and iv) no history of cardiovascular disease. In Japan, despite the fact that only 2–3% has been characterized as having a BMI ≥ 30 kg/m², the prevalence of metabolic disorders is relatively high [16, 17]. Thus, the cutoff value for the definition of obesity for Asian populations was used [15]. After an orientation session, 54 men participated in the weight loss programs in 2007. The men were non-randomly assigned to receive either a dietary program (n = 30) or an exercise program (n = 24). These two weight loss methods were employed to achieve a wide range of %FM changes. We excluded four men with incomplete assessments after the programs. Thus, data from the remaining 50 men (dietary program: n = 26; exercise program: n = 24) were analyzed. We fully explained the purpose and design of the study to each participant before they gave written informed consent. The research protocol was approved by the institutional review board at the University of Tsukuba and thus meets the standards of the Declaration of Helsinki.

Weight Loss Programs

The dietary program consisted of weekly group-based 90-min instructional sessions for 3 months and of individual counseling by trained staff. In each session, the participants received lectures on low-calorie diets and eating behaviors. We instructed them to consume a well-balanced 1,680-kcal diet per day. The exercise program consisted of 90-min sessions of aerobic exercise three times per week for 3 months. Each exercise session began with 15–30 min of warm-up activities such as stretching. The session was followed by 30–60 min of brisk walking performed

outdoors in the campus of the University of Tsukuba and finished with 15–30 min of cool-down activities.

Energy Intake and Expenditure

Energy intake in kilocalorie of both weight loss programs was assessed before and during a 2-week period (weeks 9 and 10) by 3-day weighed dietary records, and dietary recall interviews for each participant were performed by skilled dietitians. The dietary data for each participant were analyzed by using commercially available computer software (Excel Eiiyo-kun, Kenpakusha, Tokyo, Japan). Total energy expenditure was also assessed by a validated uniaxial accelerometer (Lifecorder-EX; Suzuken, Nagoya, Japan). The accelerometer was firmly attached to the participant's clothing (belt or waistband) during all waking hours (except while bathing and sleeping) 2 weeks before starting the 3-month programs, for baseline examination, and throughout the programs. 42 men (23 in the dietary group and 19 in the exercise group) successfully completed the measurements described above.

Measurement Procedures

We instructed the participants not to participate in vigorous physical activity or alcohol consumption within 24 h prior to body composition measurement and to refrain from eating or drinking for 2 h prior to the measurements. The participants removed all metal objects and jewelry during the measurements. We assessed height to the nearest 0.1 cm using a wall-mounted stadiometer. Body weight was measured to the nearest 0.01 kg using DXA equipment. We then calculated BMI as body weight in kilograms divided by squared height in meters. Waist circumference was measured to the nearest 0.1 cm at the level of the umbilicus using a flexible retractable fiberglass tape measure. We always implemented DXA measurement first and then ADP within 30 min. All measurements were conducted in the same order at baseline and at month 3.

Dual Energy X-Ray Absorptiometry

We measured %FM by DXA (%FM_{DXA}) using a Lunar DPX-NT densitometer (Lunar, Madison, WI, USA). We calibrated the densitometer every day according to manufacturer's recommendations. The densitometer calculated soft tissue mass, including fat and lean tissue mass, from the ratio of mass attenuation coefficients (R value) at 40–50 keV and 80–100 keV. We defined fat-free mass as lean tissue mass plus bone mineral content. During each measurement, the participants remained motionless in the supine position while the scanning arm passed over his body in parallel 1-cm strips. To minimize technical error, the same examiner operated the densitometer and positioned the participant at baseline and month 3. The coefficients of variations (CVs) in %FM with repeated examinations were less than 2% in our laboratory (n = 33).

Air Displacement Plethysmography

We measured %FM by ADP (%FM_{ADP}) using a Bod Pod (Life Measurement Inc., Concord, CA, USA) according to manufacturer's instructions. The physical concepts and operational principles of ADP were described elsewhere [10]. Before each measurement, an examiner calibrated the Bod Pod six consecutive times to estimate the mean volume of the chamber with the 49.490 l cylinder. The participant wore trunks and a swim cap to minimize clothing and compress air, thereby estimating volume variations. Then, the participant was weighed on an electronic scale which was calibrated in advance with two standard 10-kg weights. The participant sat quietly in the chamber while their raw body volume (Vb) was measured consecutively until two values within 150 ml were obtained. We estimated thoracic gas volume (Vtg) by having participants perform the panting maneuver according to manufacturer's instructions until a successful measurement (the *merit* and *airway* value was less than 1 or 35 cm H₂O) was obtained. Briefly, the participant wore a nose clip and breathed normally for three breathing cycles through a tube connected to the internal system. At the midpoint of an exhalation, the airway tube was momentarily occluded. And, the exam-

Table 1. Comparison of body composition results obtained using DXA and ADP at baseline and month 3 among middle-aged obese Japanese men*

	Dietary program (n = 26)			Exercise program (n = 24)			Combined (n = 50)		
	Baseline	Month 3	Change	Baseline	Month 3	Change	Baseline	Month 3	Change
Age, years	47.1 ± 7.9			48.5 ± 9.4			47.8 ± 8.6		
Height, cm	170.1 ± 5.1			170.0 ± 6.3			170.1 ± 5.6		
Body weight, kg	87.6 ± 11.2	78.7 ± 11.2	−8.8 ± 3.6 ^e	87.8 ± 10.1	84.4 ± 9.2	−3.4 ± 2.9 ^e	87.7 ± 10.6	81.5 ± 10.6	−6.2 ± 4.3 ^e
BMI, kg/m ²	30.2 ± 3.2	27.1 ± 3.1	−3.1 ± 1.3 ^e	30.4 ± 3.4	29.2 ± 3.0	−1.2 ± 1.0 ^e	30.3 ± 3.2	28.1 ± 3.2	−2.2 ± 1.5 ^e
Overweight ^a , %	46.2	53.8		58.3	62.5		52.0	58.0	
Obese ^b , %	53.8	15.4		41.7	33.3		48.0	24.0	
Waist circumference, cm	102.1 ± 7.8	92.9 ± 8.8	−9.2 ± 4.5 ^e	102.4 ± 7.8	97.9 ± 6.9	−4.5 ± 2.8 ^e	102.3 ± 7.7	95.3 ± 8.3	−7.0 ± 4.4 ^e
Fat-free mass ^c , kg	57.1 ± 6.4	55.4 ± 5.7	−1.7 ± 1.6 ^e	58.8 ± 5.5	58.5 ± 5.1	−0.3 ± 1.5	57.9 ± 5.9	56.9 ± 5.6	−1.0 ± 1.7 ^e
Bone mass ^c , g	3046 ± 475	3065 ± 466	19 ± 126	3074 ± 363	3113 ± 394	39 ± 113	3060 ± 421	3088 ± 429	29 ± 119
Body volume ^d , l	85.5 ± 11.6	75.8 ± 11.7	−9.7 ± 4.1 ^e	85.1 ± 10.7	81.1 ± 9.6	−4.1 ± 3.2 ^e	85.3 ± 11.0	78.3 ± 10.9	−7.0 ± 4.6 ^e
Body density ^d , kg/l	1.02 ± 0.01	1.03 ± 0.01	0.01 ± 0.01 ^e	1.03 ± 0.01	1.03 ± 0.01	0.01 ± 0.01 ^e	1.02 ± 0.01	1.03 ± 0.01	0.01 ± 0.01 ^e
%FM									
DXA	34.5 ± 4.4	29.1 ± 6.0	−5.4 ± 3.0 ^e	32.8 ± 4.1	30.4 ± 4.9	−2.4 ± 1.8 ^e	33.7 ± 4.3	29.7 ± 5.4	−3.9 ± 2.9 ^e
ADP	34.9 ± 4.6	29.7 ± 5.4	−5.2 ± 3.3 ^e	31.8 ± 4.6	29.2 ± 4.8	−2.6 ± 2.8 ^e	33.4 ± 4.8	29.5 ± 5.1	−3.9 ± 3.3 ^e
Δ between DXA and ADP	−0.4 ± 2.8	−0.6 ± 2.6	−0.2 ± 2.2	1.0 ± 3.0	1.2 ± 3.0	0.2 ± 2.8	0.3 ± 2.9	0.2 ± 2.9	0.0 ± 2.5

Δ = Differences.

*Values are means ± SD.

^aBMI of 25–30 kg/m².^bBMI of greater than 30 kg/m².^cMeasured by DXA.^dMeasured by ADP.^eSignificantly different from baseline.

iner signaled him to perform three small puffs of air into the tube while maintaining a tight seal around the end of the tube. We used the measured V_{tg} to calculate a corrected V_b (raw V_b minus V_{tg}) and computed body density as body weight divided by the corrected V_b. We calculated %FM_{ADP} using Siri's equation [18]. The CVs in %FM with repeated examinations were less than 5% in our laboratory (n = 8).

Statistical Analysis

We chose DXA, which is not a recognized gold standard, as the reference method as it has been considered a reasonable alternative to a multicompartiment approach [8]. After stratifying by program, we applied a paired Student's t-test to compare the mean %FM from DXA and ADP at each time point and to assess the difference between measurements at baseline and month 3. A simple linear regression analysis examined the proportion of %FM_{DXA} and %FM_{ADP} at each time point. Bland-Altman plots [19] assessed the potential bias between DXA and ADP at each time point in wide ranges of body composition and body composition changes (Δ). We tested the null hypothesis that the slope was equal to zero in the models to consider the presence of bias. In addition, Pearson's correlation coefficients were calculated to explain the variance of the difference between Δ%FM by DXA and ADP. A p value less than 0.05 was regarded as statistically significant. We performed all statistical analyses using SAS, version 9.1 (SAS Institute, Inc., Cary, NC, USA).

Results

Table 1 describes baseline characteristics and compares body composition results obtained using DXA and ADP at base-

Table 2. Summary of simple regression analysis and Bland-Altman approach for %FM by ADP at baseline and month 3 compared to DXA

	Baseline	Month 3
Simple regression analysis		
Slope	0.71	0.91
Intercept	9.97	2.94
r	0.79	0.85
R ²	0.63	0.72
SEE	2.62	2.92
P	<0.01	<0.01
Bland-Altman approach		
Bias ^a	0.25	0.25
95% LoA ^b	−5.52, 6.02	−5.48, 5.98
r	−0.18	0.13
p	0.20	0.37

SEE = Standard error of estimate; LoA = limits of agreement. ^aMean difference between DXA and ADP (i.e., DXA minus ADP).^bUpper and lower 95% LoA.

line and month 3. Attendance rates were 77.5% for dietary sessions and 86.8% for exercise sessions. The weight loss programs significantly reduced body weight, waist circumference, body volume and %FM, and significantly increased body density in both programs and in the combined data. Fat-free mass

Fig. 1. Simple regression analysis for changes (Δ) in %FM determined by DXA and ADP. The bold solid line indicates the regression line between $\Delta\%FM$ from DXA and ADP. The dashed lines represent 95% prediction intervals. ●: participants engaged in dietary program, ○: participants engaged in exercise program, SEE: standard error of estimate.

Fig. 2. Bland-Altman plots for the systematic bias in the estimation of changes (Δ) in %FM between DXA and ADP. The middle solid line indicates the mean difference between $\Delta\%FM$ from DXA and ADP. The upper and lower dashed lines represent limits of agreement (± 2 SD from the mean). ●: participants engaged in dietary program, ○: participants engaged in exercise program.

Fig. 3. Relation of changes (Δ) in %FM determined with DXA minus the $\Delta\%FM$ estimated by ADP to baseline %FM determined by ADP (left) and the $\Delta\%FM$ determined by ADP (right). The middle solid line indicates the mean difference between $\Delta\%FM$ estimated from DXA and ADP. The upper and lower dashed lines represent limits of agreement (± 2 SD from the mean). ●: participants engaged in dietary program, ○: participants engaged in exercise program.

measured by DXA was significantly decreased in dietary program and combined data. In contrast, bone mass remained unchanged for all groups. There were no significant differences between the two methods in %FM at both time points or in $\Delta\%FM$ in response to weight loss.

Energy intake was significantly decreased from $2,062 \pm 236$ to $1,567 \pm 285$ kcal/day in the dietary program. Total energy expenditure significantly increased from $2,422 \pm 242$ to $2,662 \pm 284$ kcal/day during the exercise program. In the combined data, there were significant reductions in energy intake (from $2,172 \pm 351$ to $1,841 \pm 496$ kcal/day) and significant increases in total energy expenditure (from $2,462 \pm 230$ to $2,585 \pm 263$ kcal/day) through the weight loss programs.

Table 2 summarizes the simple regression analyses and the Bland-Altman plots for %FM at baseline and month 3 using DXA as the reference method. Coefficients of determination (R^2) were moderate to high (≥ 0.6) for %FM at baseline. After weight loss, the R^2 for %FM slightly increased (≥ 0.7). The

Bland-Altman plots demonstrated no significant bias in %FM at both time points.

Figure 1 displays the results of simple regression analyses for $\Delta\%FM$ by DXA and ADP. The R^2 coefficients for $\Delta\%FM$ were moderate (≥ 0.4). Almost all plots for $\Delta\%FM$ were within the 95% prediction intervals.

Figure 2 depicts the results of the Bland-Altman plots for assessing bias in the estimation of $\Delta\%FM$ between the two methods. The plots demonstrated no significant bias in $\Delta\%FM$. In addition, almost all individual plots for $\Delta\%FM$ in both programs were within the 95% limits of agreement.

Figure 3 shows relation of $\Delta\%FM$ determined with DXA minus $\Delta\%FM$ estimated from ADP to baseline %FM determined by ADP and the $\Delta\%FM$ determined by ADP. ADP-derived %FM at baseline proved to be positively related to the differences between $\Delta\%FM$ by DXA and ADP ($r = 0.42$, $p < 0.01$). Similarly, ADP-derived $\Delta\%FM$ was inversely associated with the difference ($r = -0.54$, $p < 0.01$).

Discussion

The present study examined whether ADP could track body composition changes with weight loss in middle-aged Japanese men using DXA as the reference method. We found that ADP, using Siri's equations, tracked $\Delta\%FM$ in a manner similar to that derived by DXA. We also demonstrated a uniform distribution of measurement errors (DXA minus ADP) in $\Delta\%FM$ across the range of $\Delta\%FM$ in the Bland-Altman analysis. However, we also showed that $\%FM$ from individuals with larger $\%FM$ by ADP and/or with greater $\Delta\%FM$ is overestimated as compared to the DXA method.

To date, few studies have examined the ability of ADP to accurately estimate body composition change over a period of weight loss [11–13]. In 22 obese men and women with a mean BMI of 30 kg/m², Weyers et al. [11] reported no significant mean differences in $\Delta\%FM$ between DXA and ADP using Siri's equation after an 8-week moderately energy-restricted diet. The R^2 between DXA and ADP in their study was 0.44 for $\Delta\%FM$ ($p < 0.05$). Frisard et al. [12] also reported that R^2 between DXA and ADP exhibited 0.24–0.28 for $\Delta\%FM$ (Brozek's and Siri's equations) in 56 obese men and women. Elberg et al. [20] revealed good agreement of $\Delta\%FM$ between DXA and ADP using Siri's equation in natural changes over 1 year in 86 boys and girls ($R^2 = 0.59$). Moreover, a recent study of Minderico et al. [13] demonstrated no significant differences in $\Delta\%FM$ between DXA and ADP in 93 obese women. They described an R^2 of 0.76 for $\Delta\%FM$ between DXA and ADP. The current study also demonstrated no significant differences in $\Delta\%FM$. R^2 between DXA and ADP was 0.48 for $\Delta\%FM$ ($p < 0.01$). Our results are consistent with these prior studies.

Of the four previous studies, two examined the presence of systematic bias in the estimation of $\Delta\%FM$ by using a Bland-Altman approach. Minderico et al. [13] indicated no significant bias, suggesting the ability of ADP to assess $\Delta\%FM$ against the widespread variations ($p = 0.67$; r value not shown). In contrast, Elberg et al. [20] reported that ADP underestimated $\Delta\%FM$ as the $\%FM$ gain was increased in children ($r = 0.35$, $p < 0.01$). In the current study, we found no significant bias in $\Delta\%FM$ in the Bland-Altman approach, suggesting the ability of ADP to track $\%FM$ ($r = 0.20$, $p = 0.17$). These mixed results might be accounted for by the amount of $\Delta\%FM$ during follow-up periods. Along with Minderico et al. [13], we conducted weight loss intervention studies that produced large $\Delta\%FM$ (mean changes of greater than 3%) while Elberg et al. [20] detected less than 1% of $\Delta\%FM$. Similar results were also found when comparing DXA to bioelectrical impedance, potassium counting and deuterium dilution [12, 21]. However, our data also suggest that $\%FM$ from individuals with larger $\%FM$ by ADP and/or with greater $\Delta\%FM$ by ADP are overestimated as compared to the DXA method. Thus, results of similar interventions might be interpreted with caution. To our knowledge,

this is the first study assessing the ability of ADP to detect $\Delta\%FM$ in Asian populations using DXA as the reference method. Asians have a generally greater $\%FM$ than Caucasians for the same BMI and age [14]. Therefore, it is important to examine the validity of ADP for body composition change in Asian populations.

It is worth addressing the advantages of ADP in research, clinical and public health settings. ADP can measure a large number of participants and a wide range of participant types. It also has the advantages of lower initial investment and no radiation exposure, even though the radiation exposure of DXA is extremely low. Since the current study revealed that ADP can track $\Delta\%FM$ with no significant bias, ADP can be applied to longitudinal intervention studies around body composition to estimate $\Delta\%FM$ as well as weight management strategies in clinical or public health settings. However, researchers and practitioners should consider the possibility of a $\pm 2\%$ standard error of estimate in the estimation of $\Delta\%FM$ when the participants experienced approximately 7% of weight loss.

This study has several strengths to address. First, the study population was Asian men. Previous studies with similar designs all included mainly Caucasians men and women [11–13], whereas our study enrolled a Japanese population. Our results were mostly consistent with previous studies; thus the ethnic difference may not contribute to, or hinder, the ability of ADP to track body composition changes. Second, this study elicited enough weight loss to investigate the study purpose. Previous studies with similar designs produced 4.7–7.0% weight loss [11–13]. Our study also obtained 7.0% weight loss (approximately 10% weight loss in the dietary program), enabling us to utilize one of the widest ranges of weight loss of all published studies.

However, there were also several limitations. First, we did not validate ADP compared to the multicompartiment models. Obviously, DXA is not a gold standard and seems to include certain limitations such as an ability to detect lean tissue mass changes in regions with large areas of bone pixels. In addition to this, according to the previous studies [22, 23] weight loss resulted in slight (1–2%) reduction in hydration fraction of fat-free mass. This would potentially increase $\%FM$ determined by DXA. However, Nord and Payne [24] reported that DXA was relatively insensitive to tissue hydration status compared to other clinical methods using the classical two-compartment model. Taken together, it is difficult to dismiss the possibility that DXA itself could be the cause of the observed bias. To correct the bias, further investigations using multicompartiment models would be necessary. Second, we were unable to consider any gender-specific or age-related differences since our study recruited only middle-aged men. Therefore, it remains unclear whether our results can be extrapolated to women and older adults. In addition, we acknowledge our relatively small sample size as a limitation.

In summary, the current study indicated that the mean changes in %FM were similar with the two methods investigated. After an approximately 7% weight loss in obese Japanese men, DXA- and ADP-derived $\Delta\%$ FMs were highly correlated. In the Bland-Altman approach, measurement errors (DXA minus ADP) in $\Delta\%$ FM were uniformly distributed across the ranges of body composition changes. However, %FM from individuals with larger %FM by ADP and/or with greater $\Delta\%$ FM might be overestimated as compared to DXA method.

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Disclosure

None of the authors had a conflict of interest regarding any aspect of this work.

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