Body Composition of Obese Subjects by Air Displacement Plethysmography: The Influence of Hydration

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Abstract

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Objective: We investigated whether air displacement plethysmography (ADP) could detect small changes in body composition of obese subjects with alterations in hydration.

Research Methods and Procedures: Ten obese subjects (mean BMI, 39.3 ± 2.8 kg/m^2) entered the ADP chamber without and with oil (1, 2, or 4 liters), water (1, 2, or 4 liters), or mixed (1 liter oil + 1 liter water or 2 liters oil + 2 liters water) loads. Real and measured changes in body composition were compared by regression analysis and Bland-Altman procedures.

Results: The ADP-measured changes in volume did not differ from the real values and were strongly correlated with them ($r = 0.98$). In all cases, loads of differing composition and similar volume led to different values of fat, fat-free mass, and percentage fat. Water was detected as increased fat-free mass only with loads of ≥2 liters, most of the water being falsely detected as increased fat mass. The observed changes were correlated with the real ones for fat mass ($r = 0.68$; $p < 0.0001$), fat-free mass ($r = 0.66$; $p < 0.0001$), and percentage fat ($r = 0.61$; $p < 0.0001$), but fat mass changes were overestimated by ~1 kg, and fat-free mass changes were underestimated by ~1 kg. This underestimation increased with the highest water loads, as shown by the Bland-Altman plot ($r = -0.27$; $p < 0.05$). Percentage fat changes were overestimated by 0.8% ($p < 0.001$); the magnitude of the error was correlated with the weight of the water load ($r = 0.62$; $p < 0.0001$).

Discussion: ADP accurately measures changes in body volume, discriminating small changes in body composition. It overestimates changes in adiposity, as most of the increased hydration is detected as an enlarged fat mass.

Key words: adiposity, Bod Pod, weight change, air displacement plethysmograph, body composition

Introduction

Obesity is characterized by enlarged fat mass. Although numerous physical or isotopic methods can be used to measure body composition in obese subjects, only a few, such as body impedance analysis (BIA)[1] (1) or DXA (2), are simple and safe enough to be used in routine clinical practice. Air displacement plethysmography (ADP) is considered a safe, quick, reliable, and valid technique (3), providing accurate measures of body density in obese subjects (4). Das et al. (5) studied the composition of a 45-kg weight loss after gastric bypass surgery in 20 women with massive obesity: the results of ADP alone were in good agreement with the reference three-compartment model.

The ability of ADP to determine the composition of moderate body weight changes in obese subjects remains to be established. The results of ADP alone rely on a two-compartment model that may be flawed if the changes in fat-free mass stem from hydration (6). In contrast to BIA and DXA, ADP offers the unique possibility of verification by weighing and then measuring subjects in the ADP cham-

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[1] Nonstandard abbreviations: BIA, body impedance analysis; ADP, air displacement plethysmography.

Table 1. Characteristics of the oil, water, and mixed loads

	Liquid			Bottle		
Load	Weight (g)	Volume (mL)	Density	Weight (g)	Volume (mL)	Overall density
1 L oil	915	1030	0.8883	32	23	0.8993
2 L oil	1830	2060	0.8883	64	46	0.8993
4 L oil	3663	4107	0.8919	115	84	0.9010
1 L water	1001	1030	0.9718	27	20	0.9790
2 L water	2025	2063	0.9815	39	28	0.9823
4 L water	4050	4126	0.9815	78	56	0.9823
1 L oil + 1 L water	1916	2060	0.9300	59	43	0.9391
2 L oil + 2 L water	3855	4123	0.9349	103	74	0.9430

L, liter(s).

ber with and without loads of known composition. To mimic small changes in adiposity and hydration, we used loads of oil and water.

We compared the results of body composition by ADP in 10 obese subjects without and with loads of differing composition. All of the subjects underwent nine measurements: one without any load, three with oil (1, 2, and 4 liters), three with water (1, 2, and 4 liters), and two with mixed loads (1 liter oil + 1 liter water and 2 liters oil + 2 liters water). The loads were contained in plastic bottles held by the subjects while they were being weighed and when they entered the ADP chamber; they were not ingested by the subjects. The results of the body composition analysis (weight, volume, fat, and fat-free mass) with and without the loads and the real and ADP-measured body composition changes were compared. We also checked that the presence of an empty bottle, or the time interval between the measurements, did not affect the results in 10 normal-weight subjects (control study).

Research Methods and Procedures

Subjects

Ten obese subjects (five men, five women) participated in the study. Their mean age was 54 ± 13 years (range, 35 to 75 years), mean BMI was 39.3 ± 2.8 kg/m^2 (range, 35.0 to 43.3 kg/m^2), mean body weight was 108.7 ± 15.6 kg (range, 78.8 to 130.0 kg), and mean height was 166 ± 9 cm (range, 150 to 180 cm). Ten normal-weight subjects (six men, four women; mean age, 24 ± 5 years; mean BMI, 23.0 ± 2.1 kg/m^2) also underwent a control study to confirm that the presence of an empty bottle in the chamber, or the time interval between the measurements, did not affect the results. Informed consent was obtained from each subject, and the study was approved by the ethics committee of our institution.

Body Composition

Weight was measured with a high-precision scale as part of the ADP procedure. The ADP (Bod Pod; Life Measurement Instruments, Concord, CA) was calibrated for an empty chamber and a known volume (49.771-liter cylinder) before each measurement. The subjects were weighed, and they then entered the ADP chamber, wearing only underclothes and a swimcap. Duplicate measurements of body volume were performed according to the manufacturer's recommendations; a third measurement was performed when the first two measurements differed by >150 mL. Predicted lung volume was used to calculate body volume, using adult-specific equations (7). Fat and fat-free mass were calculated using the equation of Siri (8), as used by other authors for obese (5) or non-obese subjects (9).

All subjects were studied in the fasting state. Each measurement took 5 to 10 minutes, and the interval between the measurements was <5 minutes: the complete test lasted 90 minutes. The oil (sunflower oil; Eco+, Asnière-sur-Seine, France) and water loads were in open plastic bottles, at room temperature; their volume, weight, and density are listed in Table 1. All of the subjects underwent nine measurements in random order, one basal and one with each of the eight different loads.

The real fat mass changes were +0.915 kg (with 1 liter oil), +1.830 kg (with 2 liters oil), and +3.663 kg (with 4 liters oil). The real fat-free mass changes were +1.001 kg (with 1 liter water), +2.025 kg (with 2 liters water), and +4.050 kg (with 4 liters water). The measured changes were calculated as: Δfat mass = measured fat mass (with the load) − measured fat mass (without the load); and Δfat-free mass = measured fat-free mass (with the load) − measured fat-free mass (without the load).

Table 2. Weight, fat, and fat-free mass during the control study

	T_0				T_{+30} minutes		
	Basal (T_0) (kg)	With empty bottle (kg)	Correlation with T_0 (r)	Absolute difference from T_0 (kg)	T_{+30} minutes (kg)	Correlation with T_0 (r)	Absolute difference from T_0 (kg)
Body weight	68.6 ± 11.1	68.6 ± 11.1			68.6 ± 11.1		
Fat mass	14.4 ± 6.6	14.5 ± 6.8	0.98	0.9 ± 0.6	14.4 ± 6.8	0.99	0.7 ± 0.6
Fat-free mass	54.1 ± 12.5	54.0 ± 12.4	0.99	0.9 ± 0.6	54.1 ± 12.2	0.99	0.7 ± 0.5

T_0, time at baseline measurement; T_{+30}, time after 30-minute interval between measurements.

Statistical Analysis

Basal and modified fat mass, fat-free mass, and percentage fat were compared by ANOVA for repeated measurements. As each of the 10 subjects was analyzed without and with eight different loads (nine testing conditions, and eight different changes of body composition), 80 changes of body composition were induced during the study. These 80 real—and known—changes in body composition were compared with the ADP-measured changes by regression analysis, and a Bland-Altman procedure was performed. SPSS software (version 10.1; SPSS, Inc., Chicago, IL) was used for the calculations. The results are presented as means ± standard deviations, with $p < 0.05$ considered significant.

Results

Control Study

As shown in Table 2, body weight, fat, and fat-free mass were not affected by the presence of the empty bottle or the time between the measurements (all not significant) in the 10 normal subjects (controls). The results for the fat and fat-free mass in the presence of the empty bottle and after a 30-minute delay were well-correlated with the basal results, and the mean absolute differences between the measurements was <1 kg. As expected, the empty bottle (71 g) was not detected during the measurements; its contribution to the real body composition changes was, therefore, disregarded in the calculations.

Measurement of Body Volume and Density

The eight loads in 10 subjects led to a mean real volume change of 2626 ± 1293 mL; the measured change (2592 ± 1268 mL) was comparable to ($p = 0.26$) and well-correlated with the real value ($r = 0.98$), despite the fact that the ADP gave an abnormal result in one measurement (+2213 mL with the 4-liter water load). Because an aberrant value cannot be excluded when a single measurement is made, it was included in the analysis.

The measured weight changes (2416 ± 1208 g) were also well-correlated ($r = 0.99$) with the real values (2468 ± 1223 g), although the 52-g difference was significant ($p < 0.001$).

The initial density of the 10 subjects was 1.01388 ± 0.019022. With the loads, the measured value (1.01201 ± 0.01724) did not differ from the real density (1.01223 ± 0.01784), and these values were well-correlated ($r = 0.99$).

Detection and Discrimination of Changes in Body Composition

The findings on fat, fat-free mass, and percentage fat for each type of load are summarized in Table 3. Percentage fat increased only with oil-containing loads. Fat mass increased with all of the loads, even with water; however, oil loads always led to higher fat mass than water loads of similar volume. Fat-free mass increased with water loads, reaching significantly higher than basal values with ≥2-liter loads. It did not change significantly with oil loads, although it tended to decrease ($p = 0.08$). Water loads always led to higher fat-free mass than oil loads of similar volume. The changes in body composition, therefore, correctly differed according to the loads: more fat mass with oil than with water and more fat-free mass with water than with oil (one exception: fat mass did not significantly differ between 2 liters oil and 1 liter oil/1 liter water; $p = 0.059$). However, most of the water loads were falsely detected as increased fat mass.

Comparison between Real and Measured Changes in Body Composition

Over the 80 experiments, the observed changes in adiposity (percentage fat) were correlated with the real changes (Figure 1A) but were overestimated by 0.8% ($p < 0.001$), as shown by the Bland-Altman plot in Figure 1D. The magnitude of the error was correlated with the weight of the water load ($r = 0.62$; $p < 0.0001$). The observed changes in fat mass were correlated with the real changes (Figure 1B),

Table 3. Body weight and composition in the nine testing conditions

	Body weight (kg)	Fat-free mass (kg)	Fat mass (kg)	Percentage fat
Basal	108.7 ± 15.6	55.4 ± 14.9	53.2 ± 10.1	49.4 ± 8.8
1 L water	109.7 ± 15.6***	55.7 ± 14.4	54.0 ± 10.5*	49.5 ± 8.6
2 L water	110.7 ± 15.6***	56.0 ± 14.6*	54.7 ± 10.5***	49.8 ± 8.6
4 L water	112.8 ± 15.6***	57.0 ± 14.6**	55.7 ± 10.6***	49.8 ± 8.5
1 L oil	109.6 ± 15.6***	54.8 ± 14.5†††	54.8 ± 10.3***†††	50.3 ± 8.6**†††
2 L oil	110.5 ± 15.6***	55.0 ± 14.4†††	55.5 ± 10.5***††	50.6 ± 8.5**†††
4 L oil	112.4 ± 15.6***	54.7 ± 14.3†††	57.6 ± 10.3***†††	51.6 ± 8.4***†††
1 L water + 1 L oil	110.6 ± 15.6***	55.5 ± 14.6††‡	55.1 ± 10.3***†	50.2 ± 8.5**††‡
2 L water + 2 L oil	112.6 ± 15.6***	56.1 ± 14.4††‡‡‡	56.4 ± 10.6***††‡‡‡	50.4 ± 8.4**††‡‡‡

*, **, *** indicate $p < 0.05$, $p < 0.01$, $p < 0.001$ vs. basal values (no load), respectively.
†, ††, ††† indicate $p < 0.05$, $p < 0.01$, $p < 0.001$ vs. water loads of similar volume.
‡, ‡‡, ‡‡‡ indicate $p < 0.05$, $p < 0.01$, $p < 0.001$ vs. oil loads of similar volume.

although they were overestimated by ~1 kg ($p < 0.001$), as shown by the Bland-Altman plot in Figure 1E. The observed changes in fat-free mass were also correlated with the real changes (Figure 1C), but they were underestimated by ~1 kg ($p < 0.001$), as shown by the Bland-Altman plot in Figure 1F; this also demonstrates a significant bias, as the underestimation increased with increasing water loads.

The observed changes in fat and fat-free mass with the different loads are plotted against the real changes in Figure 2; in every case, the ADP found more fat and less fat-free change than reality, and the error was magnified with increasing water loads. This resulted in an overestimation of adiposity, which was especially pronounced with the highest water loads, as shown in Figure 3.

Discussion

Our first objective was to check the accuracy of ADP for the measurement of body volume changes in obese subjects. The ADP measurement of density has been validated against an underwater weighing technique in obese subjects (4), but this did not demonstrate that moderate (1- to 4-liter) volume changes, commonly observed in clinical practice, would be measured accurately by ADP. Our results show that this is the case, as the measured values did not differ from the real changes in volume, and there was a high correlation coefficient. One of the 80 volume measurements was abnormal; Wells and Fuller (9) also found outlying results in 2 of 57 repeated measurements. Despite this rare occurrence of error, we showed that ADP provided a reliable estimate of moderate changes in body volume, with a similar accuracy to the measurement of weight changes using high-precision scales.

Our second objective was to determine whether the ADP could distinguish the moderate changes of body composition we induced. Indeed, loads of similar weight but differing in the proportion of oil and water consistently led to different results for body composition analysis, as shown in Table 3. The presence of water was detected as a significantly increased fat-free mass, but only with water loads of ≥2 liters. ADP seemed to be more sensitive for the detection of oil loads as fat mass.

Our third objective was to compare the calculated changes in fat mass, fat-free mass, and percentage fat, based on ADP measurements, to the real changes. Although the measured changes were correlated to the real values, they were biased, with an underestimation of fat-free mass and an overestimation of fat mass, as shown in Figure 2; most of the water loads were detected as an enlargement of fat mass. This was not unexpected: although the water loads are fat-free, their density (0.98) was far below the density of fat-free mass as postulated for the Siri equation (1.1), and they ranged between the initial density of the subjects (1.01) and the density of fat (0.9). Our results, therefore, reflect the extent of the error of the two-compartment model on a change in hydration of the fat-free mass. As shown in Figure 3, each liter of water was associated with an ~0.5% overestimation of adiposity.

In practice, such changes in fat-free mass hydration do occur during moderate weight changes. For example, Packianathan et al. (6), using deuterium dilution to measure total body water, reported a 1.3% increase in fat-free mass hydration 6 months after the onset of insulin therapy in type 2 diabetic patients. The over-hydration in obese subjects may, therefore, explain why ADP usually finds higher percentage fat than other methods in such patients (10–13). Although the results of DXA do not seem to be significantly affected by hydration status, it may not be a simple alternative for routine assessment of body composition: apart

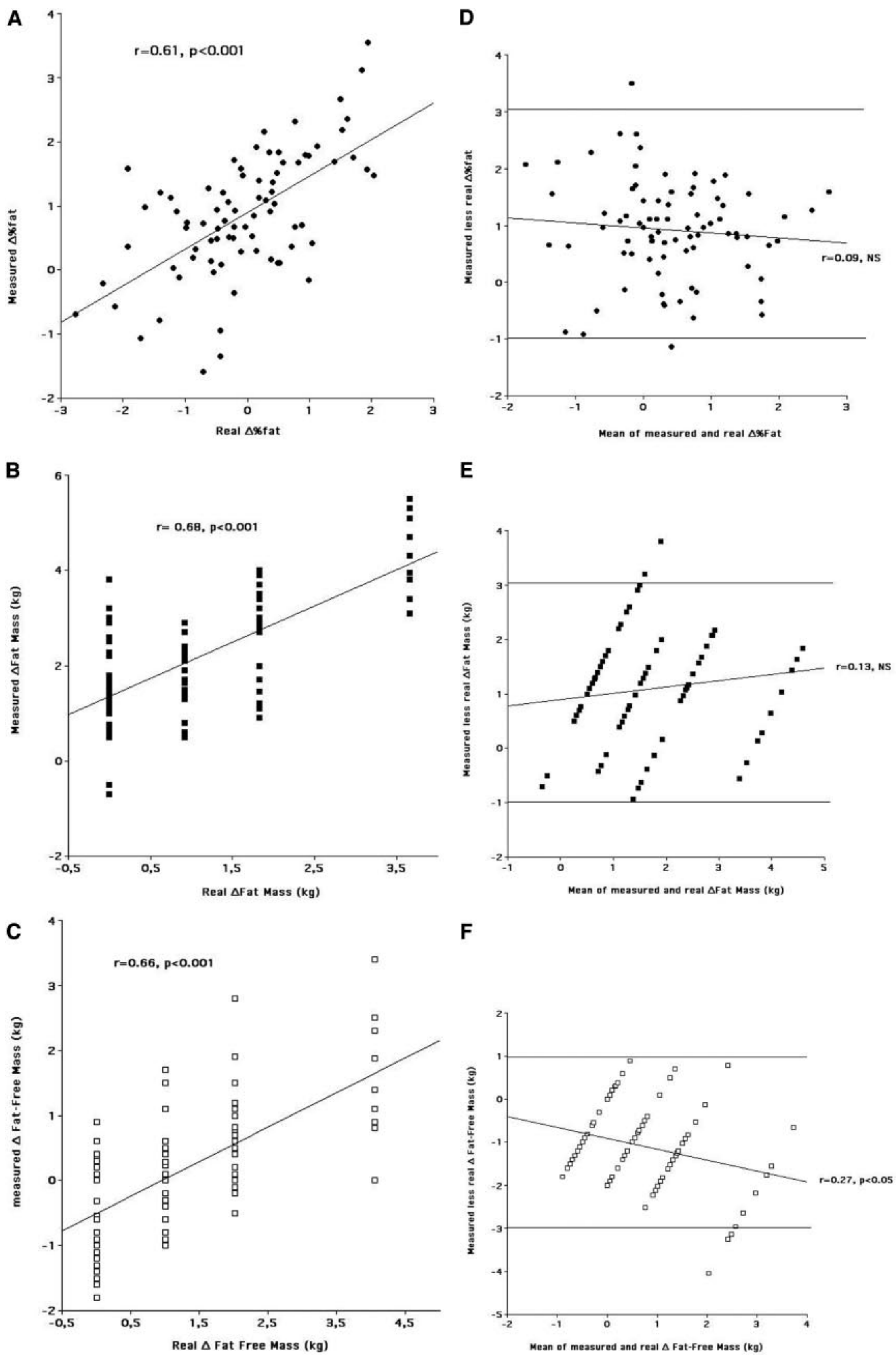

Figure 1: Regression analysis of the measured changes (y axis) of percentage fat (A), fat mass (B), and fat-free mass (C) against their real changes (x axis). The respective Bland-Altman plots are also shown (D, E, and F).

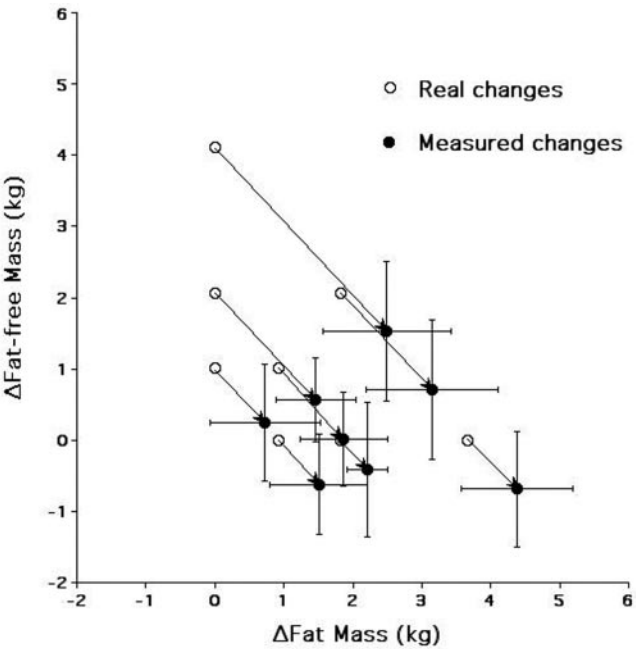

Figure 2: Real (open circles) and measured (closed circles) changes in fat (kg, x axis) and fat-free mass (kg, y axis) with the eight different loads. Each circle represents the mean (± standard deviation) value for the 10 subjects. The ADP-measured changes are ranked similarly to the real changes but systematically underestimated for fat-free mass changes and overestimated for fat mass changes.

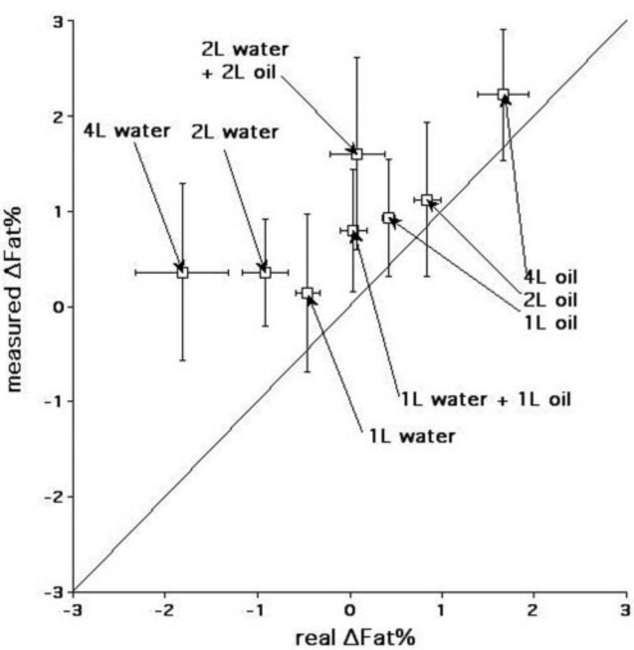

Figure 3: Measured changes of percentage fat as a function of the real changes. Each square represents the mean (± standard deviation) value for the 10 subjects. Increased hydration is associated with overestimated adiposity.

from the exposure to X-rays, the results have been reported to be highly dependent on the actual device used and its associated software (14). Three-compartment models based on ADP-density and BIA-total body water measurements (15) need to be further developed for valid measurement of body composition in routine clinical practice.

In summary, ADP is a reliable technique that gives a precise measurement of body volume changes in obese subjects. Moderate (~1- to 2-kg) changes of fat and fat-free mass can, therefore, be distinguished in a small ($n = 10$) number of subjects. But the results are biased according to the hydration status: most added water is detected as fat, owing to its low density.

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References

1. **Boulier A, Fricker J, Thomasset AL, Apfelbaum M.** Fat-free mass estimation by the two-electrode impedance method. *Am J Clin Nutr.* 1990;52:581–5.
2. **Heymsfield SB, Wang J, Heshka S, et al.** Dual-photon absorptiometry: comparison of bone mineral and soft tissue mass measurements in vivo with established methods. *Am J Clin Nutr.* 1989;49:1283–9.
3. **Fields DA, Goran MI, McCrory MA.** Body-composition assessment via air-displacement plethysmography in adults and children: a review. *Am J Clin Nutr.* 2002;75:453–67.
4. **Ginde SR, Geliebter A, Rubiano F, et al.** Air displacement plethysmography: validation in overweight and obese subjects. *Obes Res.* 2005;13:1232–7.
5. **Das SK, Roberts SB, Kehayias JJ, et al.** Body composition assessment in extreme obesity and after massive weight loss induced by gastric by-pass surgery. *Am J Physiol Endocrinol Metab.* 2003;284:E1080–8.
6. **Packianathan IC, Fuller NJ, Peterson DB, et al.** Use of a reference four-component model to define the effects of insulin treatment on body composition in type 2 diabetes: the "Darwin study." *Diabetologia.* 2005;48:222–9.
7. **Crapo RO, Morris AH, Clayton PD, et al.** Lung volumes in healthy non-smoking adults. *Bull Eur Physiopathol Resp.* 1982;18:419–25.
8. **Siri WE.** Body composition from fluid spaces and density: analysis of methods. In: Brozek J, Henschel A (eds). *Techniques for Measuring Body Composition.* Washington DC: National Academy of Sciences; 1961, pp. 223–44.
9. **Wells JC, Fuller NJ.** Precision of measurement and body size in whole-body air-displacement plethysmography. *Int J Obes Relat Metab Disord.* 2001;25:1161–7.
10. **Frisard MI, Greenway FL, DeLany JP.** Comparison of methods to assess body composition changes during a period of weight loss. *Obes Res.* 2005;13:845–54.

11. **Vescovi JD, Zimmerman SL, Miller WC, et al.** Evaluation of the BOD POD for estimating percentage body fat in a heterogeneous group of adult humans. *Eur J Appl Physiol.* 2001;85:326–32.
12. **Fields DA, Wilson GD, Gladden LB, et al.** Comparison of the BOD POD with the four-compartment model in adult females. *Med Sci Sports Exerc.* 2001;33:1605–10.
13. **Wagner DR, Heyward VH, Gibson AL.** Validation of air displacement plethysmography for assessing body composition. *Med Sci Sports Exerc.* 2000;32:1339–44.
14. **Genton L, Karsegard VL, Zawadynski S, et al.** Comparison of body weight and composition measured by two different dual energy X-ray absorptiometry devices and three acquisition modes in obese women. *Clin Nutr.* 2005;25:428–37.
15. **Salle A, Ryan M, Guilloteau G, et al.** "Glucose control-related" and "non-glucose control-related" effects of insulin on weight gain in newly insulin-treated type 2 diabetic patients. *Br J Nutr.* 2005;94:931–7.