

ORIGINAL COMMUNICATION

Evaluation of factors determining the precision of body composition measurements by air displacement plethysmography

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Objectives: To investigate methodological precision of air displacement plethysmography for assessment of body composition in a heterogeneous sample of adults.

Design: Accuracy of volume measurements by air displacement plethysmography (ADP) for a range of known volumes was ascertained. Repeated measurements of body volume, lung volume, and derived body composition using the BODPOD measurement system were performed. Influence of surface area estimation on ADP measurement was investigated as a possible source of variation.

Setting: Clinical Nutrition Laboratory, School of Health & Sports Science, University of North London, London, UK.

Subjects: One hundred and two healthy subjects (57 women, 45 men) who ranged in age between 16 and 55 y and in BMI (kg/m²) between 17.8 and 41.9.

Study design: Cross-sectional study of healthy adults for comparison with previous studies. Repeat measurements of raw body volume, lung volume and % body fat (BF) by ADP were all performed on the same day.

Results: From the range of known volumes a marked increase in the CV and a significantly greater measurement error were found at volumes below 40 l ($P=0.04$). Repeat measurements of raw body volume in human subjects resulted in a technical error equivalent to 0.8% BF. There was no significant difference found between measured and predicted lung volume and the 95% confidence interval for difference was only 0.3% BF. Repeat measurements of lung volume in our subset resulted in a technical error equivalent to 0.5% BF. Although body surface area estimation only accounted for variation in % BF of 0.1%, the extent of variation appeared to be governed by leanness ($P<0.001$).

Conclusions: Although ADP retains excellent precision, in practice, repeat measurements of ADP should be performed whenever possible to allow for erroneous volume measurement within one procedure. Protocols for ADP measurement should be created with an awareness of those factors, which may affect measurements.

Sponsorships: This study was supported by the University of North London Diversity & Development Fund.
European Journal of Clinical Nutrition (2003) 57, 770–776. doi:10.1038/sj.ejcn.1601609

Keywords: air displacement plethysmography; body composition; BODPOD; precision

Introduction

A measure of body volume has a number of uses in body composition assessment as it can either be used simply in a two-compartment model (densitometry), or, better still, incorporated into multi-compartment models requiring measured total body water, and/or bone mineral content

(Millard-Stafford *et al*, 2001). However, the measurement of body volume is, in practice, comparatively difficult to perform. Traditionally, the considered 'gold standard' determinant of body volume is hydrostatic weighing (HW), but this is presently being challenged by developments in air displacement plethysmography (ADP), manifested as the BODPOD measurement system. ADP is becoming an increasingly popular method of choice, mainly due to the practical advantages it holds over HW. Indeed, these advantages have led to increased subject acceptability and compliance, and may, therefore provide a very useful tool in the widespread measurement of body composition.

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Received 30 April 2002; revised 10 July 2002; accepted 15 July 2002

To date, ADP-derived body composition has been demonstrated to have good agreement with that derived from HW (McCrorry *et al* 1995; Biaggi *et al*, 2002; Levenhagen *et al*, 1999; Nunez *et al*, 1999; Fields *et al*, 2002). Less good agreement has also been shown using dual X-ray absorptiometry (DXA) as a criterion method of validation (Sardinha *et al*, 1998; Collins *et al*, 1999; Nunez *et al*, 1999; Lockner *et al*, 2000; Weyers *et al*, 2002). Nevertheless, despite overall good agreement in previous studies, there have been some slight discrepancies shown between methodologies, with an observed tendency for ADP to overestimate density, and hence underestimate body fat (BF), compared with HW (Levenhagen *et al*, 1999; Collins *et al*, 1999).

Furthermore, this apparent small bias has suggested to be, in some way, governed by gender and fatness (Levenhagen *et al*, 1999). Differences between methods seen could be due to combined methodological error of the two methods, or inherent errors in the underlying assumptions of one or both methods. ADP has also been investigated in corroboration against or within multi-compartment models, but these studies are limited (Fields *et al*, 2000, 2001; Millard-Stafford *et al*, 2001).

Despite these previous observations little work has been carried out on the reliability of ADP measurement itself, and there have been limited studies investigating possible source of variation within ADP measurement. Extensive validation of ADP is at an early stage, and this area needs to be fully explored before the BODPOD can ever be considered a suitable alternative to HW. Furthermore, quantifying the precision of ADP has previously only been attempted in relatively small numbers of subjects. In addition to confirming the validity of the BODPOD against other methodologies, this study set out to fully investigate the precision of volume measurement by ADP and the impact this may have on derived body composition. Also, other areas, which may affect precision and accuracy, were also addressed, such as precision of lung volume measurement and its difference to predicted lung volume, and the impact of body surface area. Body surface area estimation is one other possible source of error in body volume measurement by ADP, due to the need to correct for the negative volume effect of isothermal air close to the skin.

Methods

Subjects and protocol

The study population consisted of a heterogeneous sample of men and women (45 males and 57 females). All subjects were healthy adults over the age of 16 y and were recruited from the University staff and student population or via flyer distribution to the local community. The study protocol was approved by the Institutional Ethical Review Board at the University of North London, and all subjects gave written informed consent (obtained from carer for subjects under 18 y).

Air displacement plethysmography

Prior to measurements in human subjects, a series of five repeated measurements was performed on a range of plastic containers filled to a known fixed volume with de-gassed distilled water ranging from 10 to 150 l. The BODPOD system was used to measure the volumes of these containers as that for human measurement outlined below. Known and measured volumes were compared statistically and coefficient of variation calculated.

Body density in human subjects was measured using the BODPOD measurement system as described in detail elsewhere (Dempster & Aitkens, 1995; McCrorry *et al*, 1995). Briefly, subjects were weighed in minimal clothing to the nearest 0.01 kg, and standing height measured to the nearest 0.1 cm using a stadiometer. Still in minimal clothing and wearing a tight fitting acrylic swim cap, measurement of volume was taken using the BODPOD, which consisted of obtaining a mean value from two repeated trials each lasting approximately 40 s. In this study this whole instructed procedure was repeated twice in each subject. In this way each subject provided a repeat of the whole procedure rather than just the two trials. In all cases, percentage body fat (% BF) was calculated from body density by the equation of Siri (1961).

The subjects lung volume (V_{TG}) was measured during normal tidal breathing using a tube connected to the ADP breathing circuit system as described elsewhere (Dempster & Aitkens, 1995; McCrorry *et al*, 1995). A measured value for V_{TG} was obtained for most, but not all of the study population ($n=69$). In a small subset of the population ($n=38$), V_{TG} measurement was repeated to determine variation between measurements. A predicted estimate of V_{TG} based on age, sex and height was also calculated for each individual and compared to measured V_{TG} .

As described elsewhere (Dempster & Aitkens, 1995), the BODPOD measurement system corrects the measured body volume for the effects of adiabatic air by calculating an area artifact. This area artifact varies between individuals solely based on their estimated body surface area. In each subject, area artifact was calculated incorporating three separate formulae for determining body surface area (DuBois & DuBois, 1916; Mosteller, 1987; Shuter & Aslani, 2000). The variation in derived body composition due to variant area artifact was then ascertained.

Statistical analysis

All data are expressed as mean \pm standard deviation. Percentage error was calculated for the range of known volumes as mean measured volume–actual volume/actual volume $\times 100$, as described in the original communication of Dempster and Aitkens (1995). All further statistical analyses were performed using SPSS version 10.0. Pearson's correlations between repeated measured variables were performed followed by paired sample *t*-tests to determine significant differences (a *P* value of <0.05 was taken as

significant). Finally, agreement between repeated measures and precision for measurement was assessed according to Bland and Altman (1986), whereby, precision for a single measurement (technical error) is $\sum d^2/2n$ (where d is the difference between measurements, and n is the number of subjects measured).

Results

Figure 1 shows the resultant coefficient of variation (CV) across the range of known volumes (mean CV=0.102), exhibiting a marked increase in CV at volumes below 40 l. In addition, calculated percentage error was also found to be significantly higher below 40 l ($P=0.04$). The mean percentage error of volume measurement was 0.1% but as with the CV, this percentage error was much higher at volumes below

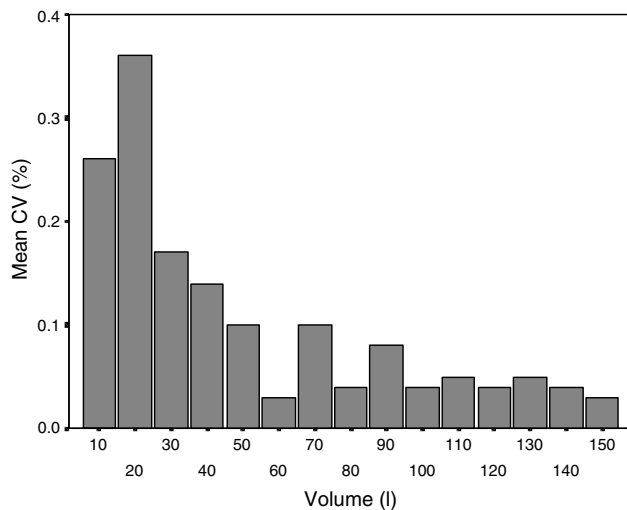


Figure 1 Resultant coefficient of variation in ADP volume measurement across a range of known volumes.

20 l. The mean percentage error observed corresponds to a measurement error of approximately 50 ml for an introduced volume of 50 l.

The descriptive statistics for the study population and summary data obtained by ADP from the BODPOD are shown in Table 1. A significant gender difference was observed for mean measured and predicted lung volumes, whole body volume, mean % BF, as well as absolute weight of FM and FFM. A strong positive correlation was observed between repeated measurements of body volume ($r^2=0.999$, $P<0.001$) and lung volume ($r^2=0.949$, $P<0.001$), although this was slightly lower for predicted and measured lung volume ($r^2=0.794$, $P<0.001$). Following a paired sample t -test, there was no significant difference between repeated measures for both body volume ($P=0.61$) and lung volume ($P=0.84$) and between measured and predicted lung volume ($P=0.44$).

Figure 2 shows the residual plot for repeated measures of body volume. The limits of agreement between repeated measurements of volume in terms of derived BF were $\pm 2.3\%$. However, the 95% confidence interval for the mean difference was $\pm 0.3\%$ BF. From this, the calculated precision for a single measurement was equivalent to 0.8% BF.

Figure 3a shows the residual plot for differences between measured and predicted lung volume. The limits of agreement between measured and predicted lung volume in terms of derived body fat were -3.1 to 3.3% . However, the 95% confidence interval for the difference is $\pm 0.3\%$ BF.

Figure 3b shows the residual plot for repeated measures of lung volume. The limits of agreement between two repeated measures of lung volume in terms of derived body fat were -1.3 to 1.4% . However, the 95% confidence interval for the difference was $\pm 0.2\%$ BF. The calculated precision for a single lung volume measurement (technical error) was equivalent to 0.5% BF.

The influence of predicted body surface area on ADP measurement demonstrated a significant difference

Table 1 Subject characteristics

	Females (n=57)		Males (n=45)	
	Mean (\pm s.d.)	Range	Mean (\pm s.d.)	Range
Age (y)	30.2 \pm 9.6	19–55	31.2 \pm 10.6	16–52
Weight (kg)	65.8 \pm 13.9	46.7–114.6	78.6 \pm 10.0*	62.1–107.2
Height (cm)	166.8 \pm 5.9	155.1–177.3	177.5 \pm 6.1*	160.0–189.6
BMI (kg/m ²)	23.7 \pm 5.1	17.8–41.9	24.9 \pm 2.7	20.7–32.1
Body surface area (m ²) _{DuBois and DuBois}	1.73 \pm 0.16	1.46–2.19	1.96 \pm 0.14*	1.67–2.32
Raw body volume (l)	61.822 \pm 14.51	42.181–112.405	71.581 \pm 10.10*	55.968–101.559
Lung volume _{measured} (l) (n=69) [†]	3.22 \pm 0.59	2.08–4.73	4.27 \pm 0.82*	1.90–5.49
Lung volume _{predicted} (l)	3.32 \pm 0.24	2.87–3.93	3.94 \pm 0.39*	2.22–4.61
% BF	30.3 \pm 9.0	15.7–50.1	16.2 \pm 7.4*	4.4–38.3
FM (kg)	20.8 \pm 10.6	7.3–52.7	13.1 \pm 7.6*	3.2–34.9
FFM (kg)	44.9 \pm 5.7	34.7–61.9	65.5 \pm 7.4*	49.8–80.6

BMI=body mass index, FM=fat mass, FFM=fat-free mass.,
*Significant gender difference ($P<0.001$).

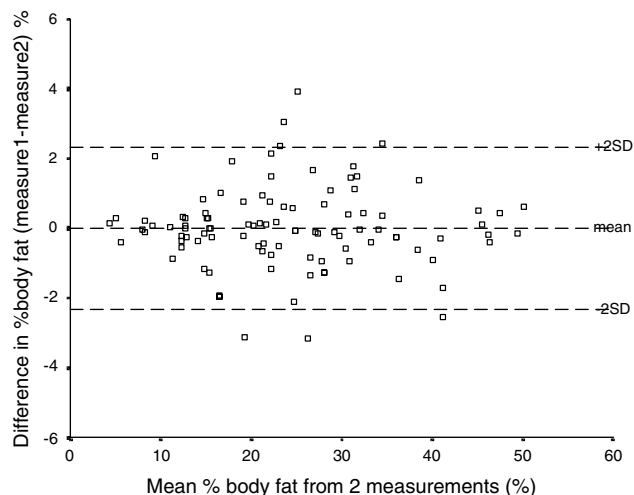


Figure 2 Analysis of the individual residual % BF scores due to repeat measures of body volume by ADP.

($P=0.03$) in derived % BF between the formula of DuBois and DuBois (1916) and that of Shuter and Aslani (2000). However, this difference was only of the magnitude of 0.1% body fat. Furthermore, there was a significantly negative relationship between this difference and fatness (% BF) ($r^2 = -0.4093$, $P < 0.001$) as shown in Figure 4. In addition, a significantly positive relationship was found between the predicted surface area and FFM ($r^2 = 0.710$, $P < 0.001$), even after correcting for height ($r^2 = 0.5976$, $P < 0.001$), (Figure 5a and b).

Discussion

In this study the repeat measurements on known volumes showed both high re-reproducibility and accuracy, thus supporting the original communication of the BODPOD methodology (Dempster & Aitkens, 1995). However, there was an apparent discrepancy in volume measurement at volumes below 40l. This was probably due to a minor calibration problem of the instrument at a high chamber to body volume ratio (ie the volume introduced is small compared to that of the chamber). Low volumes, (below 40l), would be associated predominantly with children, and would highlight a need for caution when measuring this population group. Indeed, previous studies on ADP measurement in children have demonstrated a measurement bias compared with HW and DXA (Dewit *et al*, 2000; Nunez *et al*, 1999; Lockner *et al*, 2000). Nevertheless, ADP may still be a more practical and equally precise method of body composition measurement in children compared with HW, especially in multi-compartment models (Wells & Fuller, 2001).

The test-retest variability in measured raw body volume, equivalent to 0.8% BF was less than (Demerath *et al*, 2002) or comparable with that found in some studies (Miyatake *et al*,

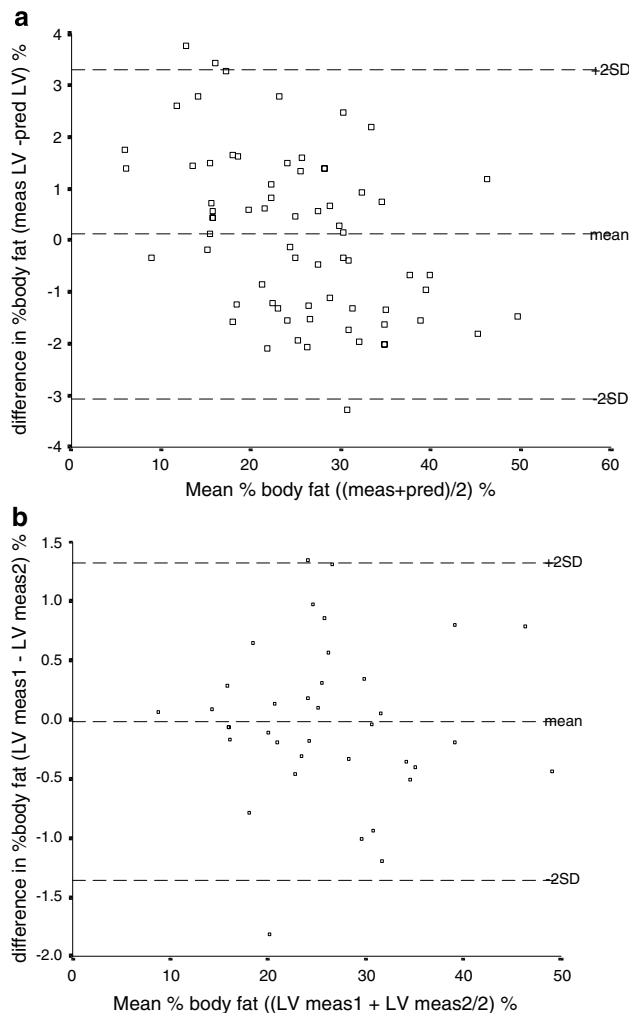


Figure 3 Analysis of the individual residual % BF scores due to lung volume measurement or prediction. (a) Residuals of measured lung volume against predicted ($n = 69$). (b) Residuals for repeat measurement of lung volume ($n = 38$).

1999; Vescovi *et al*, 2001; Wells & Fuller, 2001), but greater than that found by others (McCrory *et al*, 1995; Collins *et al*, 1999). However, unlike some of these studies, the variation in measured body volume was assessed in repeats of the whole test procedure (which consisted of the mean of two serial measures of raw volume), and so better highlighted precision of one complete procedure. Furthermore, the test-retest variation in body volume in this study was performed on a substantially greater number of subjects than in previous studies (McCrory *et al*, 1995; Collins *et al*, 1999; Miyatake *et al*, 1999).

It may well be the case that in one whole procedure both serial measures of raw body volume are in acceptable agreement with each other, but may both be erroneous (ie the measurements are precise but inaccurate). For almost all subjects the whole first procedure is an unknown experience,

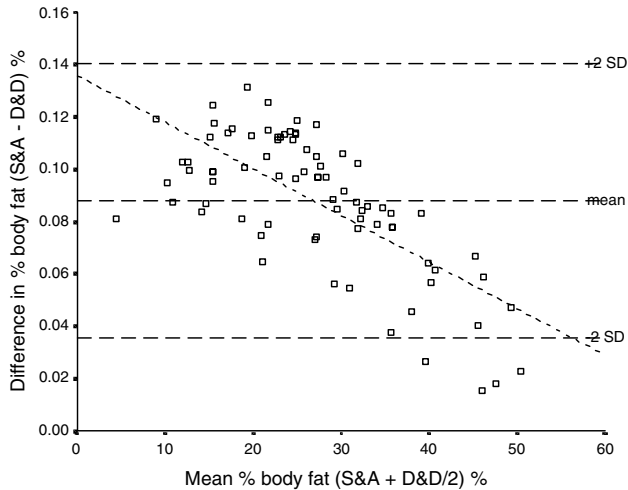


Figure 4 Analysis of the individual residual % BF scores due to calculated surface area (DuBois & DuBois vs. Shuter & Aslani) ($r^2=0.409$). S&A=surface area artifact calculated using the BSA formula of Shuter & Aslani (2000). D&D=surface area artifact calculated using the BSA formula of DuBois & DuBois (1916).

despite the explanation by the investigator, and as such, the subject is generally more at ease with the second procedure and therefore more compliant and comfortable inside the BODPOD. In addition, factors such as slight changes in temperature and air pressure can affect measurement of volume, as well as subject movement, clothing (Fields *et al*, 2000a), body hair, and even how the swim cap is enclosing the hair (Higgins *et al*, 2001).

Due to the observed variation in measured raw body volume, in this and other studies, one suggestion is that for measurements in individuals it may be prudent to perform repeat tests in order to be confident that the measurement of volume is not erroneous. This may be particularly appropriate considering that during a single measurement cycle, three volume measurements are sometimes taken if there is discrepancy between the first two. One proposal would be to perform at least two complete tests, if these two tests show a difference in % BF greater than 0.5%; then a third test may be appropriate. Indeed, the methodology of HW involves repeat measures of weight in water; therefore so as a comparable method of densitometry, the volume measurement in the BODPOD should also be repeated. Nevertheless, the technical error for ADP measurement observed in this study (0.8% BF) is still comparatively lower than that of HW (0.99% BF, Wells & Fuller, 2001), providing further evidence for the BODPOD's good precision.

As with the study of McCrory *et al* (1998), there was no significant difference found between the predicted and the measured residual lung volume in our subjects, nor was there any significant difference in estimated body composition between the two forms of lung volume measurement. Nevertheless, other studies have failed to agree on the accuracy of predicted residual lung volume as discrepancies

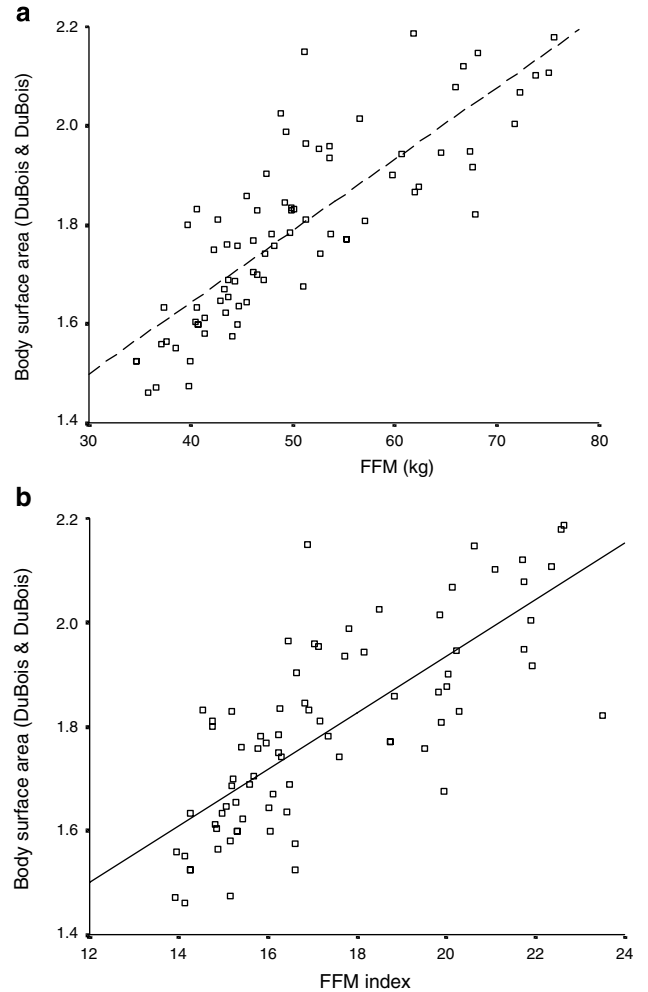


Figure 5 Relationship between body surface area and absolute leanness. (a) Relationship between FFM and calculated body surface area ($r^2=0.712$). (b) Relationship between FFM index and calculated body surface area ($r^2=0.598$).

between the predicted and the measured can give rise to erroneous estimates of % BF (Wilmore, 1969; Hackney & Deutsch, 1985). However, these studies cannot be compared directly with the prediction equations (Crapo *et al*, 1982) used by the BODPOD. However, it is likely that differences in lung volume will have less impact in ADP compared to HW as raw body volume is corrected by calculated 40% of residual lung volume ($0.4 \times$ residual lung volume).

Nevertheless, the recent study by Demerath *et al* (2002) demonstrated a significant difference in % BF by ADP between measured and predicted lung volume in children but not in adults. Although our findings are limited to adults, the observed differences in this study show that on an individual basis, % BF can deviate by as much as 3% BF between the predicted and the measured lung volume, but that systematic under or overprediction of lung volume, or even gender differences do not explain this discrepancy. In

addition, the observed range of measured lung volume values were far greater than predicted values, suggesting that predictive formulae are more unsuitable at extremes of lung volume. These findings add to the lack of congruence with regard to accuracy of lung volume prediction (Forsyth *et al*, 1988), at the same time highlighting inter-subject variability as the main cause of observed difference.

While using predicted lung volume might be considered acceptable in group comparison, the difference between measured and predicted lung volume may have an impact on derived % BF at an individual level. It would be prudent to measure lung volume whenever possible; however, for certain individuals this may not be practical (eg the elderly, children, and those with pulmonary dysfunction). Additionally, even in healthy subjects, the procedure of lung volume measurement in the BODPOD cannot always be completed successfully. In our subset the resultant difference between repeat measures of lung volume using the BODPOD corresponded to a difference of as much as 1.4% BF for an individual. However, the precision for a single lung volume measurement (technical error) was only equivalent to 0.5% BF, which is in accordance with the unpublished observations disclosed in McCrory *et al* (1998). The observed variation between lung volume test and retest, for individuals suggests that the variability in this aspect of the BODPOD measurement system can impact upon derived BF for an individual. While it may be impractical to include repeat lung volume measurement within a study protocol, a better suggestion would be, if measuring lung volume, to use the practice option available to familiarize the subject with the procedure (as described in the BODPOD instruction manual).

To try and elucidate possible sources of methodological error, this study chose to investigate the impact that body surface area estimation (BSA) had on ADP measurement. The BODPOD takes a correction for the negative volume effect of isothermal air close to the skin by use of a derived surface area artifact (SAA), highly dependent on estimated body surface area as described below. As body surface area estimation is a main determinant of this SAA it may be a possible source of inaccuracy within this method (Vescovi *et al*, 2001).

$$\text{Body density} = \text{Weight}/(\text{raw body volume-surface area artifact} + (0.4 \times \text{lung volume}))$$

However, despite the significant difference in % BF observed using two prediction formulae for BSA, the magnitude of this difference was only 0.1% BF. Nevertheless, differences between BSA formulae increased at decreasing fatness (increased leanness), and on further analysis, the strong relationship between BSA and FFM seen in both men and women indicated that BSA increased proportionally with FFM. This suggests that at extremes of body composition, BSA estimation may be more unreliable. BSA may be under-predicted in lean individuals (hence under-predicted SAA), which can lead to an overestimation of body density (hence underestimated % BF). Conversely, BSA may be overesti-

mated in individuals of greater fatness (hence over-predicted SAA), leading to underestimated body density (overestimated % BF). However, it would be difficult to propose this as an explanation of differences between ADP and HW in other studies, as the magnitude of difference shown in this study is very small. Furthermore, there are currently no reliable and accurate methods to measure BSA directly. In addition, current predictive equations take no account of gender, whereby both body density and the more superficial distribution of BF in women could impact upon BSA. Nevertheless, this study does point towards possible gender differences in BSA, which may have wider significance.

In general, our study confirms the methodological error associated with ADP appears to be comparable, and perhaps favorable to that of HW. In addition, our findings on reliability in body volume and derived % BF by ADP are in agreement with that of others (McCrory *et al*, 1995; Collins *et al*, 1999; Demerath *et al*, 2002). In addition, the impact of differences between measured and predicted lung volumes in this study is also comparable with other investigators (McCrory *et al*, 1995; Demerath *et al*, 2002). Nevertheless, despite good reliability shown in ADP by this and other studies there still remains certain methodological issues which may affect accuracy and precision, which need to be addressed. For example: the impact of body hair, gender differences, compressibility of subcutaneous fat, environmental influences such as ambient temperature and pressure and inter-laboratory differences between BODPOD machines and laboratory environment.

In addition, it is important to note that, to date, accuracy of body composition by ADP compared with other methods has yet to be confirmed. The differences seen between HW, ADP and DXA were recently reviewed by Fields *et al* (2002) and demonstrated limits of agreement between ADP and DXA or HW of approximately $\pm 4\%$ BF. This potentially large difference could be due to the combined imprecision of the two methodologies, but also due to true methodological differences. It is difficult to state better accuracy in one method over another as differences between methods could be due to errors in the underlying assumptions they rely on, such as the assumed constancy of fat-free in densitometry, or tissue hydration assumptions made in DXA. To fully elucidate this issue more comparative studies of ADP with multi-compartment models need to be undertaken, or alternatively studies comparing ADP with other methods of body composition measurement such as MRI which may not rely as heavily on physiological/chemical assumptions.

Conclusion

In conclusion, this study has shown that measurement of body composition by ADP should be undertaken with some awareness of those factors, which may bring about variation in the result. As with HW, it may be most appropriate to perform repeat procedures, and also to ensure consistency in lung volume measurement or prediction when comparing

results. Although on the surface ADP is a simple procedure to perform, there lies behind a complex interplay of environmental, physiological and anatomical factors on which the final outcome is dependent. If these are not fully understood and/or ignored, misinterpretation of results is likely to occur. Nevertheless, ADP may still provide a more practical and more precise method of densitometry than HW.

Acknowledgements

The authors would like to thank Dr Dympna Gallagher, Dr Jack Wang and Chris Nunez from the Obesity Research Centre, Columbia University, St Luke's Hospital, New York, NY, USA for help with the development of the TBW method. They would also like to acknowledge the intellectual input of Dr Nigel Fuller, and the technical support of Karlene Marsh. This study was funded by the University of North London Diversity and Development Fund.

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