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Review

Comparison of body composition methods: a literature analysis

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Objective: To examine the comparability of different methods to assess percentage body fat (BF%) against underwater weighing (UWW).

Design: A meta-analysis on 54 papers, published in 1985–96, on healthy, adult Caucasians.

Methods: The mean BF% from different studies were treated as single data points. In addition to UWW, the studies included one or more of the following methods: 3- or 4-component model, dual-energy X-ray absorptiometry (DXA), dual-energy photon absorptiometry, isotope dilution, bioimpedance (BIA), skinfolds or near-infrared interactance (NIR). Within each of the methods, the analyses were done separately for different mathematical functions, techniques or instruments.

Main outcome measures: Bias (mean difference) and error (s.d. of difference) between BF% measured by UWW and the other methods.

Results: The 4-component model gave 0.6 (95% confidence interval for the mean, CI: 0.1 to 1.2) BF% higher results than UWW. Also the 3-component model with body density and total body water (+ 1.4 BF%, 95% CI: + 0.3 to + 2.6), deuterium dilution (+ 1.5 BF%, 95% CI: + 0.7 to + 2.3), DXA by Norland (+ 7.2 BF%, 95% CI: 2.6 to 11.8) and BIA by Lukaski *et al.* (+ 2.0 BF%, 95% CI: 0.2 to 3.8) overestimated BF%, whereas BIA by Valhalla Scientific (−2.6 BF%, 95% CI: −4.5 to −0.6) and skinfold equations by Jackson *et al.* (−1.20, 95% CI: −2.3 to −0.1) showed a relative underestimation. The mean bias for the skinfold equation by Durnin & Womersley, against UWW, was 0.0 BF% (95% CI: −1.3 to 1.3). The correlation between the size of measurement and the mean difference was significant for only NIR ($r = -0.77$, $P = 0.003$).

Conclusions: The difference between any method and UWW is dependent on the study. However, some methods have a systematical tendency for relative over- or underestimation of BF%.

Descriptors: anthropometry; body fat; multicomponent models

Introduction

The different models of body composition can be organized into five levels: atomic, molecular, cellular, tissue-system and whole body (Wang *et al*, 1992). In the molecular level, the components of the body can be water, lipids, proteins, minerals and glycogen. The total of all components is the body weight. These body weight models are further named according to the number of components, for example: 2-component model, 3-component model, etc. Models with three or more components are also referred to as multi-component models.

Recently, Wang *et al* (1995) proposed a system of organizing *in vivo* body-composition methods into six classes. The basic idea is that a measurable quantity is connected to body composition by a mathematical function. The quantity used can be a measurable property (property-based methods), such as body impedance or X-ray attenuation, or a component already quantified from a property (component-based methods). Property-based and component-based methods are often combined.

The properties needed for assessment of the molecular composition of human body are measured by numerous techniques (Lukaski *et al*, 1987; Wang *et al*, 1995). Moreover, different instrumentation and mathematical functions multiply the variability of results. It is therefore expected that body composition results obtained by different *in vivo* methods are not identical.

The number of studies comparing results from body composition methods have increased during the past ten years. In most publications, underwater weighing (UWW) has been compared with one or several other methods. Unfortunately, the results have been too divergent to allow any obvious conclusions. Consequently, the purpose of this paper was to analyze studies on body-composition methodology, and to give answers to the following questions: (1) how large is the bias (difference between two mean values) and error (standard deviation of individual differences) of the estimated body fat content (% of body weight, BF%) between UWW and alternative methods? (2) is the magnitude of bias dependent on the size of measurement (BF%), the subjects' gender, or on the instrument or mathematical function used? An analysis of mean values in 54 studies formed the core of the present review. In addition, to get an insight on the comparability of group and individual data, the above questions were also examined by pooling the individual results presented in 10 studies.

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Methods

Selection of studies
This review was restricted to studies published during the years 1985–1996. The 54 studies (see Appendix) selected were identified by Medline computer-search and by scrutiny of the literature. Because only few studies used 3- or 4-component models (in which the body is organized into lipids, water and/or minerals, and the remaining lipid-free mass), UWW (2C model) was chosen as the criterion method for the review. In addition to UWW, the studies included one or more of the following body-composition methods: 3- or 4-component model, dual-energy X-ray absorptiometry (DXA), dual-energy photon absorptiometry (DPA), isotope dilution, bioimpedance (BIA), skinfolds or near-infrared interactance (NIR).

The studies selected had to contain data on BF%, or enough data for calculation of a mean value for BF%, such as body weight and fat or fat-free weight. When body composition was calculated from TBW results by isotope dilution, the ratio FFM = TBW/0.732 was used (Pace & Rathburn 1945). When needed, body density (D_b) was connected to BF% with Siri's (1956) equation (BF% = $(4.95/D_b - 4.50) \times 100$).

In the selected studies, the subjects were healthy Caucasians. Because of potential racial differences in body composition (Ortiz *et al.* 1992), studies with, for example, black or Native American subjects were excluded. In addition, studies with solely young (< 16 y) or aged (> 60 y) subjects were not included in the analysis.

The statistical analyses were done separately for different mathematical functions, techniques and instruments. The following methods were grouped according to mathematical functions: multicomponent methods into 3-component models with body density and total body water TBW (3Cw) or with body density and minerals (3Cm), and the 4-component model (4C) with body density, body minerals and TBW; BIA into the equations of RJL (RJL Systems Inc., Detroit, MI), Lukaski *et al* (1985, 1986); Segal *et al*, (1988), and Valhalla Scientific, San Diego, CA; skinfolds into the equations of Durnin & Womersley (1974); Jackson & Pollock (1978); or Jackson *et al* (1980). The results from isotope analyses were segregated into deuterium (^{2}H) and tritium (^{3}H) dilution, and the results obtained by DXA or DPA by instrumentation: QDR (Hologic Inc., Waltham, MA), DPX (Lunar Radiation Corp., Madison, WI), XR-26 (Norland Corp., Fort Atkinson, WI), and DPA.

Analysis of group results
In the analysis, the mean BF% from different studies were treated as single, unweighed data points. The inter-method difference was calculated by subtracting the UWW result (mean BF%) from the alternative (alt) result. A positive difference indicated a relative overestimation of BF% by the alternative, and vice versa. The data were analyzed by an approach proposed by Altman & Bland (1983), modified to the present analysis with several potential factors affecting the difference between two methods.

Factors associated with the inter-method difference were first studied by a multiple regression analysis (alt = alternative method compared against UWW): alt-UWW =
A + (B × ((alt + UWW)/2) + (C × male) + (D × mixed group). 'Male' and 'mixed group' were used as dummy variables (Kahn & Sempos, 1989): if the subjects were males, male = 1, otherwise male = 0; if the subjects were mixed (males and females) mixed = 1, otherwise mixed = 0. In this approach, the female gender was used as a reference. Letter A refers to the intercept, B to the regression coefficient for the size of measurement, adjusted for the linear effect of gender, and letters C and D to the coefficients for male and mixed gender, respectively, adjusted for the linear effect of the size of measurement and gender.

The second step was undertaken only if the difference was not associated with the size of measurement. The mean difference (bias), 95% confidence interval for the mean (95% CI) and standard deviation (error) was calculated. The bias was considered significant ($P < 0.05$), if the 95% CI did not include zero. Differences between instruments or mathematical functions, within a single method-group, were identified by the analysis of variance (ANOVA) and post hoc *t*-tests.

Analysis of individual data
The analysis of individual data was based on all seven studies showing individual body-composition results (Graves *et al*, 1987; Heymsfield *et al*, 1989a; Brodie *et al*, 1991; McNeill *et al*, 1991; Friedl *et al*, 1992; Withers *et al*, 1992; Sohlström *et al*, 1993) and three studies from our own laboratories (Marken Lichtenbelt *et al*, 1995; Fogelholm *et al*, 1996a,b). The above studies contained data on underwater weighing and one of the following methods: 3Cm, 3Cw, 4C, deuterium dilution, DXA instruments by Lunar (DPX) and Norland (XR-26), BIA equations by RJL Systems and by Lukaski *et al* (1985, 1986), and skinfold equations by Durnin & Womersley (1974) and Jackson *et al* (1980).

Similar to the analysis of group data, the first step was to study associations with the difference between alternative method and UWW. In addition to gender, each study (namely laboratory) may have an effect on the difference. Therefore, the multiple regression was: alt-UWW = A + (B × ((alt + UWW)/2) + (C × male) + (D_1 × study_1) + (D_2 × study_2) etc. Males were coded 1 and females 0. The studies were also dummy coded, using the study with the largest number of subjects as the reference. The second step (calculation of bias and s.d.) was done according to the principles explained for the group analysis. All statistical analyses were done with BMDP statistical software.

Results

In the analysis of group data, out of the 16 methods (instruments or mathematical functions) compared against UWW, only the bias NIR was significantly ($P = 0.003$) associated with the size of measurement (Table 1, Figures 1–6. Consequently, the second step of analysis (ANOVA) was carried out with all remaining methods.

Seven instruments or mathematical functions had a bias significantly ($P < 0.05$) different from zero (Table 2): the 3Cw and 4C models, deuterium dilution, Norland XR-26 (DXA) and BIA by Lukaski *et al* (1985, 1986) equations overestimated BF%, whereas BIA by Valhalla Scientific and skinfold equations by Jackson & Pollock (1978) or Jackson *et al* (1980) significantly underestimated BF%, in relation to UWW. The most significant differences ($P < 0.01$) in bias between techniques or mathematical functions were found among multicomponent models, isotope dilutions, DXA and BIA (Table 2): the bias was more positive for 3Cw than for 3Cm, more positive for deuterium dilution than for tritium dilution, more positive for Norland

Table 1 Analysis of group data: a multiple regression analysis (difference between two methods = A + (B × mean of two methods) + (C × male) + (D × mixed gender)) of factors associated with the difference between alternative methods and underwater weighing

	n^a	r^2	P^b	*Intercept*	*Mean*^{c}	*Male*^{d}	*Mixed*^{e}
Multi-component							
3-comp., mineral	10	0.14	0.58	−1.44	0.04	0.01	
3-comp., water	10	0.29	0.60	−0.54	0.04	1.84	−0.16
4-component	10	0.12	0.83	1.48	−0.04	−0.19	0.92
Isotope dilution							
D_2O	19	0.01	0.99	1.92	−0.00	−0.31	−0.26
T_2O	13	0.22	0.49	−7.02	0.23	2.15	−0.34
DXA, DPA							
Hologic QDR	7	0.56	0.42	11.70	−0.46	−5.04	−1.10
Lunar DPX	19	0.26	0.19	−0.55	0.03	−1.49	2.00
Norland XR-26	4	0.94	0.24	2.67	0.16	−1.95	
DPA	10	0.33	0.25	19.30	−1.59	−6.77	
Bioimpedance							
Lukaski	7	0.60	0.37	−0.72	0.12	−0.53	−1.47
RJL Systems	19	0.21	0.30	5.57	−0.14	−2.94	−3.89
Segal	4	0.47	0.33	−17.60	0.45	5.74	0.24
Valhalla	10	0.24	0.69	−5.17	0.11	0.24	−1.39
Skinfolds							
Durnin	27	0.01	0.99	0.14	−0.01	−0.20	0.47
Jackson	16	0.19	0.44	1.77	−0.12	−1.02	2.20
Near-infrared inter.							
All	15	0.63	0.003	6.21	−0.30^f	−0.95	

[a] Number of data points (studies).
[b] Statistical significance (P-value) for the total regression.
[c] Coefficient for the effect of the size of measurement (mean of underwater weighing and the alternative method).
[d] Coefficient for the effect of male gender, with female gender as the reference.
[e] Coefficient for the effect of mixed groups, with female gender as the reference.
[f] Coefficient different from zero ($P < 0.001$).

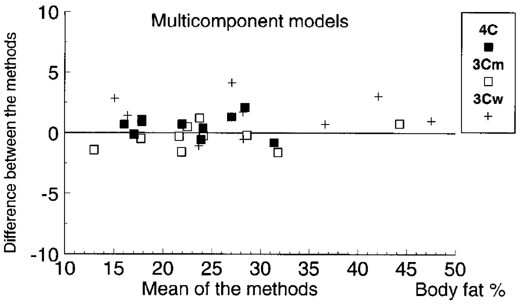

Figure 1 Assessment of percentage body fat by the 4-component model (4C) and 3-component models, with density and body minerals (3Cm), or density and total body water (3Cw), against underwater weighing: the relative bias (multicomponent method minus underwater weighing) plotted against the size of measurement (mean of multicomponent method and underwater weighing). Each data point represents a single, unweighed mean result of one study.

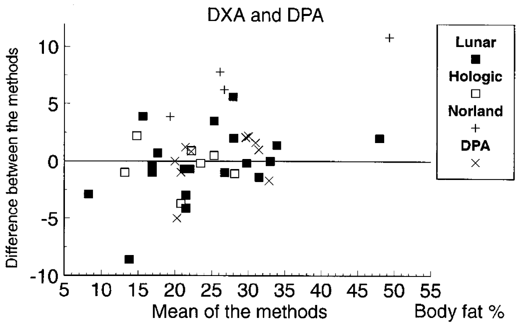

Figure 3 Assessment of percentage body fat by different dual-energy X-ray absorptiometry instruments (Lunar, Hologic or Norland) and dual-energy photon absorptiometry (DPA), against underwater weighing: the relative bias (DXA or DPA minus underwater weighing) plotted against the size of measurement (mean of DXA or DPA and underwater weighing). Each data point represents a single, unweighed mean result of one study.

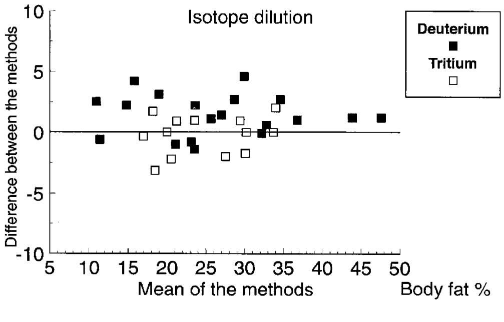

Figure 2 Assessment of percentage body fat by deuterium and tritium dilution against underwater weighing: the relative bias (dilution minus underwater weighing) plotted against the size of measurement (mean of dilution and underwater weighing). Each data point represents a single, unweighed mean result of one study.

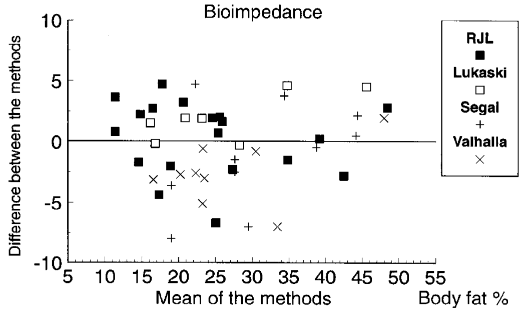

Figure 4 Assessment of percentage body fat by different bioimpedance equations (RJL Systems, Lukaski *et al* (1985, 1986), Segal *et al* (1988), Valhalla Inc.) against underwater weighing: the relative bias (bioimpedance minus underwater weighing) plotted against the size of measurement (mean of bioimpedance and underwater weighing). Each data point represents a single, unweighed mean result of one study.

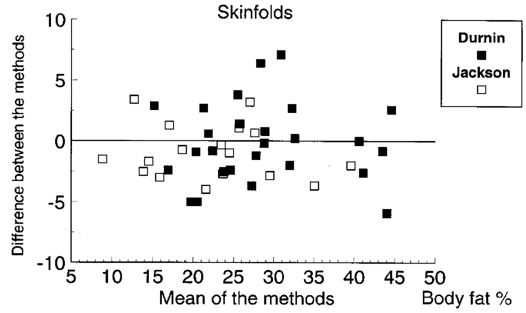

Figure 5 Assessment of percentage body fat by skinfold equations of Durnin & Womersley (1974), or by the Jackson group (Jackson & Pollock, 1978; Jackson *et al*, 1980), against underwater weighing: the relative bias (skinfold minus underwater weighing) plotted against the size of measurement (mean of skinfolds and underwater weighing). Each data point represents a single, unweighed mean result of one study.

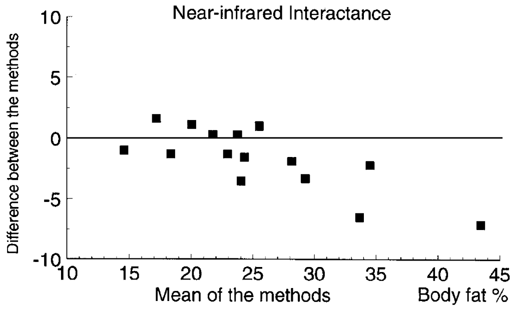

Figure 6 Assessment of percentage body fat by near-infrared interactance (NIR) against underwater weighing: the relative bias (NIR minus underwater weighing) plotted against the size of measurement (mean of NIR and underwater weighing). Each data point represents a single, unweighed mean result of one study.

Table 2 Analysis of group data: comparison of underwater weighing against other methods for body fat (BF%, percent of body weight) assessment

	Bias	*95% CI*[a]	*s.d.*	*ANOVA*[b]
Multicomponent				0.01
3-comp., mineral	−0.3	−1.0 to 0.4	1.0	Aa
3-comp., water	1.4	0.3 to 2.6	1.6	A
4-component	0.6	0.1 to 1.2	0.9	a
Isotope dilution				0.006
D_2O	1.5	0.7 to 2.3	1.6	A
T_2O	−0.2	−1.2 to 0.8	1.6	A
DXA, DPA				<0.001
Hologic QDR	−0.3	−2.1 to 1.4	1.9	A
Lunar DPX	−0.3	−1.8 to 1.3	3.2	B
Norland XR-26	7.2	2.6 to 11.8	2.9	ABC
DPA	0.6	−0.3 to 1.6	1.3	C
Bioimpedance				0.03
Lukaski	2.0	0.2 to 3.8	2.0	A
RJL Systems	0.3	−1.2 to 1.7	3.0	a
Segal	−1.2	−4.2 to 1.8	4.2	
Valhalla	−2.6	−4.5 to −0.6	2.6	Aa
Skinfolds				0.20
Durnin	−0.0	−1.3 to 1.3	3.3	
Jackson	−1.2	−2.3 to −0.1	2.0	

[a] 95% confidence interval for the bias.

[b] Differences in bias within one method group: *P*-value for the analysis of variance. Identical letters indicate statistical significance between techniques or mathematical functions: A, B, C: $P < 0.01$; a: $0.01 < P < 0.05$.

XR-26 than for any other DXA techniques, and more negative for BIA by Valhalla Scientific, compared against the BIA equation by Lukaski *et al* (1985, 1986) and RJL Systems.

The standard deviation of bias appeared to be smallest (0.9–1.6 BF%) for multicomponent methods, dilution techniques and DPA (Table 2). The corresponding results for the remaining methods were between 1.9 and 4.2 BF%.

Using the individual data, the difference of 3Cm, Norland XR-26, BIA equations by Lukaski *et al* (1985, 1986) and RJL Systems, and skinfold equations by Durnin & Womersley (1974), against UWW, was significantly associated ($P < 0.001$) with the size of measurement (Table 3). Moreover, the study (laboratory) had a significant ($P < 0.05$) impact on the error of 3Cm, BIA equation by RJL and skinfold equation by Durnin & Womersley (1974).

The s.d. of difference was smallest for the multicomponent methods and Lunar DPX (2.0–2.7 BF%), corresponding to a 95% agreement range (±2 s.d.) of 4–5 BF% below and above the bias (Table 4). The analysis of individual data was, however, limited by the small number of studies with individual data and by the very limited data without an association between the size of measurement and difference.

Discussion

Multicomponent models and isotope dilution

The theoretical problems of UWW (2C model) are associated with the assumption of fixed density of FFM (Lohman, 1992). This assumption implies mainly that the proportions of minerals, water and proteins in FFM are constant and not affected by, for instance, sex, age, body weight and body composition. Because these assumptions are not always met, multicomponent methods are now regarded as superior to the 2C model (Martin & Drinkwater, 1991; Lohman, 1992).

The assumptions needed in the 2C model of body composition may be less suitable when applied to children, aged people, subjects with illnesses affecting water balance and/or bone density or non-Caucasian populations (Martin & Drinkwater, 1991; Ortiz *et al*, 1992; Cote *et al*, 1993).

Table 3 Analysis of individual data: a multiple regression analysis (Difference between two methods = A + (B × mean of two methods) + (C × male) + (D_1 × $study_1$) + (D_2 × $study_2$)) of factors associated with the difference between alternative methods and underwater weighing

	n[a]	r^2	*P*[b]	*Intercept*	*Mean*[c]	*Male*[d]	*Study*[e]	*References*[f]
Multi-component								
3-comp., mineral	143	0.33	< 0.001	−4.22	0.11*		[h]	3, 4, 7
3-comp., water	34	0.05	0.69	1.48	0.03	−0.02		5, 7
4-component	34	0.02	0.87	0.34	0.06	−0.30		5, 7
Isotope dilution								
D_2O	64	0.12	0.16	0.06	0.14	0.94		5, 7, 9, 10
DXA, DPA								
Lunar DPX	46	0.25	0.02	0.01	0.05	−3.24		7, 10
Norland XR-26	119	0.18	< 0.001	−0.56	0.23[g]			3, 4
Bioimpedance								
Lukaski	61	0.13	0.02	−6.01	0.34[g]			1, 3
RJL Systems	101	0.19	< 0.001	7.65	−0.24[g]		[h]	2, 4
Skinfolds								
Durnin	157	0.56	< 0.001	25.70	−0.61[g]		[h]	3, 4, 7, 8
Jackson	57	0.01	0.66	−2.57	−0.10			3, 7

[a] Number of data points (individuals).
[b] Statistical significance (*P*-value) for the total regression.
[c] Coefficient for the effect of the size of measurement (mean of underwater weighing and the alternative method).
[d] Coefficient for the effect of male gender, with female gender as the reference.
[e] Association between individual studies and the error.
[f] References: (1) Graves *et al*, 1987; (2) Brodie *et al*, 1991; (3) Fogelholm *et al*, 1996a; (4) Fogelholm *et al*, 1996b; (5) Friedl *et al*, 1992; (6) Heymsfield *et al*, 1989a; (7) Marken Lichtenbelt *et al*, 1995; (8) McNeill *et al*, 1991; (9) Sohlström *et al*, 1993; (10) Withers *et al*, 1992.
[g] Coefficient different from zero ($P < 0.001$).
[h] The effect (coefficient) of at least one study was significantly ($P < 0.05$) different from zero.

Table 4 Analysis of individual data: comparison of underwater weighing against other methods for body fat (BF%, percent of body weight) assessment

	Bias	*95% CI*[a]	*s.d.*
Multicomponent			
3-comp., water	1.7	1.0 to 2.4	2.1
4-component	1.0	0.2 to 1.7	2.0
Isotope dilution			
D_2O	2.8	1.9 to 3.8	3.7
DXA, DPA			
Lunar DPX	−1.1	−1.2 to −0.3	2.7
Skinfolds			
Jackson	−4.6	−5.4 to −3.8	3.0

[a] 95% confidence interval for the bias.

Studies on the above subjects were, however, not included in the present analysis. For the above reason, and even more because the number of studies using multicomponent models was very limited, UWW was chosen as the criterion variable for the present analysis. Nevertheless, this does not imply that the results from UWW would be considered correct.

The body composition models using deuterium dilution to measure TBW (3Cw, 4C and deuterium dilution) gave, on average, higher BF% estimations than UWW. To control for different hydration constants, the constant (0.732) by Pace & Rathburn (1945) was used in this review, even in the two studies with an originally different (0.72) constant (Fuller *et al*, 1992, 1994).

In addition to the hydration constant, the equilibration time between deuterium administration and collection of urine, saliva or blood specimen varied from 2–3 h (Bunt *et al*, 1989; Friedl *et al*, 1992; Withers *et al*, 1992; Cote *et al*, 1993; Pritchard *et al*, 1993; Wellens *et al*, 1994; Bergsma-Kadijk *et al*, 1996) to 4–6 h (Fuller *et al*, 1992; Kooy *et al*, 1992; Marken Lichtenbelt *et al*, 1995), and to extrapolation to zero-time during a two-week ${}^{2}H_2{}^{18}O$ experiment (Sohlström *et al*, 1993; Goran *et al*, 1994). All the above times might have been too short, because it seems that the equilibration of the marker in body fluids is not complete until approximately 10 h after dose administration (Marken Lichtenbelt *et al*, 1994, 1996). If a complete isotope enrichment is not reached, TBW and FFM are underestimated and BF% is overestimated. Because the present analysis clearly indicate an upward shift in BF% estimation with all equations using deuterium-measured TBW, the assumptions for equilibration time warrant further studies. Another possibility is that the typical hydration constant (0.732) should be smaller (for example 0.72).

It has been conjectured that the water and bone mineral content of the female body are more variable, compared with males, and that the 2C model would be less valid for females (Bunt *et al*, 1989; Vogel & Friedl, 1992; Cote *et al*, 1993). This hypothesis was not really supported by the present literature analysis, because gender had no effect on the bias between UWW and 4C or 3Cw models. Further, the possible effect of gender on the bias between UWW and 3Cm should be interpreted with great caution, because the statistical analysis was based on only two studies with male and five with female subjects.

The individual data showed a positive association between the size of measurement and the difference between 3Cm and UWW. This implies that the fraction of bone mineral mass in body weight, or in FFM, increased with increasing obesity (Martin & Drinkwater, 1991; Lohman, 1992). A high bone mineral fraction would increase the density of FFM and lead to lower BF% estimations with the 2C model (UUW), and vice versa. The apparent increase in bone mineral fraction could be a result of a known positive association between bone mineral and total body mass (Wardlaw, 1996). However, the increasing positive bias of the 3Cm model could also be an artefact, caused by an artificial relation between bone mineral density and the thickness of body fat layer in some DXA software versions (Mazess *et al*, 1992).

Dual-energy X-ray and dual-photon absorptiometry

Some investigators have proposed that the body-composition data from DXA could replace UWW as the reference method for body-composition assessment (Pritchard *et al*, 1993). According to the present analysis, the instruments of Norland Inc. gave very much overestimated BF% estimations. The results from Pierson *et al* (1995) support the above conclusion. However, the most recent software versions by Norland (version 2.5.2) appear to yield BF% estimations that are much closer to UWW (Fogelholm M, Sievänen H, unpublished observations).

DXA by Hologic and Lunar, and DPA, gave results that were, on average, close to UWW. Nevertheless, despite no significant relative bias, some differences between the Lunar DPX and UWW were > 5 BF% (Johansson *et al*, 1993; Pritchard *et al*, 1993). It is known that changes of the software may affect the outcome. Two studies reporting large bias (≥ 1 s.d., namely, 3.0 BF%) used newer software versions (3.4 or 3.6) (Pritchard *et al*, 1993; Tothill *et al*, 1994), while studies with smaller bias used both new (Hansen *et al*, 1993; Wellens *et al*, 1994) and older (1.3, 1.3z) versions (Bergsma-Kadijk *et al*, 1996; Fuller *et al*, 1992; Marken Lichtenbelt *et al*, 1995; Tataranni & Ravussin, 1995). Unfortunately, several papers, including two out of the three used in the individual data analysis, did not give any information on the software version. Nevertheless, it appears that software version is unable to fully explain the variation of Lunar DPX results against UWW.

Recently, Paton *et al* (1995) reported large (5.8 BF%) and Tataranni *et al* (1996) smaller (1.7 BF%) differences between two DPX machines using the same software. The inter-machine variability is likely to contribute to the variation of DPX (or any DXA instrument) against UWW in meta-analytical evaluations. DXA is certainly a promising approach on analysis of body composition, but the comparability of different instruments and software versions need to be improved.

Bioimpedance, skinfolds and near-infrared interactance

The comparison of four common BIA equations revealed rather large dissimilarities, especially between the extremes (equations by Lukaski (1985, 1986) and Valhalla Scientific). The noticeably wide distribution of bias (s.d.) in studies using the body-composition specific BIA-equation by Segal *et al* (1988) might have been caused by difficulties in choosing between equations for lean or obese subjects. Because single-frequency BIA measures mostly extracellular water (Foster & Lukaski, 1996), not fat directly, some of the discrepancies between BIA and UWW might have been caused by variations in fluid distribution.

It has been suggested that BIA underestimates BF% in obese people (Hodgdon & Fitzgerald, 1987; Heitman, 1994), perhaps because of insensitivity of BIA to detect variations in body composition of the trunk region (Gray *et al*, 1989). The present analysis with individual data supported the above conclusion, but only when the equation by RJL Systems was used. In contrast, the equations of Lukaski *et al* (1985, 1986) showed a tendency for increased relative overestimation by BIA in the more obese study population.

The classical skinfold equations of Durnin & Womersley (1974) agreed, on average, very well with UWW. However, in relation to UWW, the equations by the Jackson group (1978, 1980) underestimated BF%. It has been proposed that the Jackson & Pollock (1978) and Jackson *et al* (1980) equations would be more suitable than Durnin & Womersley (1974) equations for assessment of physically active, lean people (Wilmore, 1992). Because all studies with the Durnin & Womersley (1974) equation were done with subjects with > 15 BF%, the above suggestion could not be examined. In contrast to lean subjects, taking skinfolds from very obese people may be technically difficult which could affect the validity (Gray *et al*, 1990). However, the present group analysis did not show any associations between the bias of skinfolds and the size of measurement (BF%).

The negative bias of NIR was caused by an underestimation of BF% in all studies on subjects with > 25 BF%. The relative underestimation was remarkable in obese subjects. Perhaps the near-infrared beam does not penetrate deep enough to identify thick fat layers in the forearm. However, NIR uses a multiple regression equation with age, sex, weight and height as other independent variables (Brooke-Wavell *et al*, 1995). Consequently, other factors, besides the penetration of the near-infrared beam, may contribute to the underestimated BF% in obese subjects.

General discussion

The present literature review included 54 studies, in which one or several body-composition of methods were compared against UWW. The division for analysis was made by model (multicomponent methods), instrument (DXA), tracer (dilution techniques) or regression equation (BIA, skinfolds). One could argue that the division should be more accurate, for instance, results from DXA analyzed by instrument and software, dilution techniques by tracer and assumed exchange of tracer with non-aqueous components, etc. However, it was felt that the clarity of presentation and interpretation of the results would have suffered from an increasing number of analytical units with only a few data points.

The 4C model gave 0.6 BF% higher results than UWW. Also the 3Cw model, deuterium dilution, DXA by Norland (XR-26) and BIA by Lukaski *et al* (1985, 1986) equations overestimated BF%, whereas BIA by Valhalla Scientific and skinfold equations by Jackson & Pollock (1978) or Jackson *et al* (1980) showed a relative underestimation. The bias for Lunar DPX and skinfold equation by Durnin & Womersley (1974), against UWW, was zero. The correlation between the size of measurement and the bias was significant for only NIR (negative).

Although the difference on any alternative method against UWW is dependent on the study, the present analysis indicates that some methods have a systematical tendency for relative over- or underestimation of BF%. The studies selected for this review presented results for healthy, Caucasian subjects with a wide range of BF% (8–50). Hence, the above results on comparability of body-composition methods might be different in children, elderly subjects, non-Caucasians or diseased people.

Especially subjects with BF% between 15 and 35 were well represented in numerous studies. Therefore, additional body-composition method-comparisons in the above range of BF% do not add very much to the existing knowledge. Nevertheless, more studies using multicomponent methods are warranted. Also different DXA instruments need more validation in the obese range, preferably against multicomponent models. Finally, only a few studies have compared the composition of weight loss by different methods (Deurenberg *et al*, 1989; Ross *et al*, 1989; Albu *et al*, 1992; Kooy *et al*, 1992). More work on the assessment of changes in body composition need to be done.

Appendix 1

Studies on body-composition methodology selected for the present review

Reference	*Gender*[1]	*Weight (kg)*	*Body fat (%)*[2]	*Methods used*[3]
Bergsma-Kadijk *et al*, 1996	F	63.7	27.3	UWW, 3Cw, 4C, D_2O, DXA1
Brodie *et al*, 1991	M	84.2	15.4	UWW, BIAr
Brodie *et al*, 1992	F	63.5, 79.3, 68.7, 86.8	24.6, 35.6, 19.5, 39.1	UWW, BIAr, NIR
Brooke-Wavell *et al*,, 1995	M	78.9	29.1	UWW, SFd, NIR
Bunt *et al*, 1989	M	74.3	11.7	UWW, D_2O
Clark *et al*, 1993	M	81.0	17.4	UWW, DXAn, SFj
Cote *et al*, 1993	F	62.1	24.2	UWW, 3Cm, 3Cw, RC, D_2O
Eaton *et al*, 1993	F	59.5	25.0	UWW, BIAr, SFj, NIR
Eckerson *et al*, 1992	M	72.6	9.6	UWW, BIAr, SFj
Elia *et al*, 1990	M,F	67.1	25.8	UWW, BIAv, SFd, NIR
Fogelholm *et al*, 1996a	F	55.8	22.2	UWW, 3Cm, DXAn, BIAl, SFd
Fogelholm *et al*, 1996b	F	92.1	43.9	UWW, 3Cm, DXAn, BIAr, SFd
Forslund *et al*, 1996	M	79.6	18.0	UWW, 3Cm
Friedl *et al*, 1992	M	75.2	17.3	UWW, 4C, D_2O, DXA1
Fuller & Elia, 1989	M,F	67.5	25.0	UWW, BIAv, SFd
Fuller *et al*, 1992	F	66.5	21.6	UWW, 4C, D_2O, DXA1, BIAv, SFd, NIR
Fuller *et al*, 1994	F	112.2	47.0	UWW, D_2O, BIAr, BIAv, BIAo, SFd, NIR
Goran *et al*, 1994	M	115.0, 71.0	36.3, 13.7	UWW, 3Cw, D_2O
Graves *et al*, 1987	F	48.2	15.4	UWW, BIAl, BIAr, SFj
Gray *et al*, 1989	M,F	91.0	39.0	UWW, RJLs
Gray *et al*, 1990	M,F	100.7, 93.9	25.0, 40.6	UWW, SFd, SFj
Hansen *et al*, 1993	F	61.0	29.9	UWW, DXA1
Heymsfield *et al*, 1989a	M,F	65.0, 59.4	20.0, 33.7	UWW, T_2O, DPA
Heymsfield *et al*, 1989b	M,F	65.0, 59.7	20.0, 30.2	UWW, DPA
Heymsfield *et al*, 1990	M,F	71.7, 60.8	21.6, 30.9	UWW, T_2O, DPA
Heyward *et al*, 1992	F	58.3, 68.8	23.6, 36.9	UWW, BIAo, SFj, NIR
Horswill *et al*, 1990	M	76.4	15.7	UWW, 3Cw, 4C
Hortobagyi *et al*, 1992	M	107.2	19.0	UWW, BIAr, SFj, NIR
Johansson *et al*, 1993	M	79.3	18.1	UWW, DXA1, BIAv, SFd
Kaminsky *et al*, 1993	M	?	11.0	UWW, BIAr, SFj
Kooy *et al*, 1992	M,F	97.1, 85.5	32.5, 43.3	UWW, D_2O, BIAl, BIAs, SFd
Lukaski *et al*, 1990	M,F	75.3	16.9	UWW, BIAl
Marken Lichtenbelt *et al*, 1995	F	52.4	17.4	UWW, 4C, D_2O, DXA1
McLean *et al*, 1992	M,F	79.7, 61.1	16.4, 25.1	UWW, SFj, NIR
McNeill *et al*, 1991	F	57.3, 81.8	24.4, 42.4	UWW, BIAo, SFd
Penn *et al*, 1994	M	73.0	17.1	UWW, 4C, T_2O, DXA1
Pierson *et al*, 1991	M,F	75.0, 61.1	20.8, 28.9	UWW, T_2O, DPA, BIAs, SFd
Pritchard *et al*, 1993	M,F	67.6, 65.1	13.7, 25.1	UWW, D_2O, DXAh, DXA1, BIAr, SFd
Ross *et al*, 1992	M	88.3, 82.1	28.4, 19.9	UWW, BIAl, BIAr, BIAs, SFd
Scherf *et al*, 1986	M,F	75.4	27.3	UWW, SFd, SFj
Segal *et al*, 1985	M,F	83.7	28.5	UWW, 3Cw, T_2O, BIAs, SFd
Siconolfi *et al*, 1995	M,F	69.2	26.3	UWW, 3Cw, 4C, D_2O
Snead *et al*, 1993	M	75.0, 81.5	13.7, 22.7	UWW, 3Cm, DXAh
	F	58.3, 63.0	21.8, 28.7	
Sohlström *et al*, 1993	F	60.3	27.6	UWW, D_2O
Stout *et al*, 1994	M	77.0	15.1	UWW, BIAr, SFj, NIR
Tataranni & Ravussin, 1995	M,F	75.0, 128.8	27.0, 47.0	UWW, DXA1
Tothill *et al*, 1994	M,F	59.0	23.6	UWW, DXAh, DXA1, DXAn, BIAr
Van Loan *et al*, 1992	M,F	78.1, 64.0	23.5, 32.3	UWW, 3Cm, 4C, D_2O, DXA1
Verlooy *et al*, 1991	M,F	68.9	22.8	UWW, DPA, SFd
Wang *et al*, 1989	M,F	77.5, 51.2	21.3, 28.6	UWW, DPA
Wang *et al*, 1993	M,F	72.0, 64.0	23.0, 33.0	UWW, T_2O, DXA1, BIAs, SFd
Wellens *et al*, 1994	M,F	78.5, 63.9	22.5, 33.2	UWW, D_2O, DXA1
Wilmore *et al*, 1994	M,F	88.6, 68.0	23.6, 30.9	UWW, BIAv, SFd, SFj, NIR
Withers *et al*, 1992	M	64.2	9.7	UWW, D_2O, DXA1

Abbreviations: [1] M = male, F = female; [2] Body fat (% of body weight) by underwater weighing; [3] UWW = underwater weighing, 3C = 3-component model (m = with bone or body minerals, w = with total body water); 4C = 4-component model; D_2O = deuterium dilution, T_2O = tritium dilution; DXA = dual-energy X-ray absorptiometry (h = Hologic QDR, 1 = Lunar DPX, n = Norland XR-26), DPA = dual-photon absorptiometry; BIA = bioimpedance (1 = equation by Lukaski *et al* (1985, 1986), r = manufacturer's equation by RJL Systems, s = equation by Segal *et al* (1988), v = manufacturer's equation by Valhalla Scientific, o = other equations); SF = skinfolds (d = equation by Durnin & Womersley (1974), j = equation by Jackson & Pollock (1978) or by Jackson *et al* (1980); NIR = Near-infrared interactance.

References

Albu J, Smolowitz J, Lichtman S, Heymsfield SB, Wang J, Pierson RN & Pi-Sunyer FX (1992): Composition of weight loss in severely obese women: a new look at old methods. *Metabolism* **41**, 1068–1074.

Altman DG & Bland JM (1983): Measurement in medicine: the analysis of method comparison studies. *Statistician* **32**, 307–317.

Bergsma-Kadijk JA, Baumeister B & Deurenberg P (1996): Measurement of body fat in young and elderly women: comparison between a four-compartment model and widely used reference methods. *Br. J. Nutr.* **75**, 649–675.

Brodie DA, Eston RG, Coxon AY, Kreitzman SN, Stockdale HR & Howard AN (1991): Effect of changes of water and electrolytes on the validity of conventional methods for measuring fat-free mass. *Ann. Nutr. Metab.* **35**, 89–97.

Brodie DA & Eston RG (1992): Body fat estimations by electrical impedance and infra-red interactance. *Int. J. Sports Med.* **13**, 319–325.

Brooke-Wavell K, Jones PRM, Norgan NG & Hardman AE. (1995): Evaluation of near infra-red interactance for assessment of subcutaneous and total body fat. *Eur. J. Clin. Nutr.* **49**, 57–65.

Bunt JC, Lohman TG & Boileau RA (1989): Impact of total body water fluctuations on estimation of body fat from body density. *Med. Sci. Sports Exerc.* **21**, 96–100.

Clark RR, Kuta JM & Sullivan JC (1993): Prediction of percent body fat in adult males using dual energy x-ray absorptiometry, skinfolds, and hydrostatic weighing. *Med. Sci. Sports Exerc.* **25**, 528–535.

Cote KD & Adams WC (1993): Effect of bone density on body composition estimates in young adult black and white women. *Med. Sci. Sports Exerc.* **25**, 290–296.

Deurenberg P, Weststrate JA & Hautvast JGAJ (1989): Changes in fat-free mass during weight loss measured by bioelectrical impedance and by densitometry. *Am. J. Clin. Nutr.* **49**, 33–36.

Durnin JVGA & Womersley J (1974): Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. *Br. J. Nutr.* **32**, 77–97.

Eaton AW, Israel RG, O'Brien KF, Hortobagyi T & McGammon MR (1993): Comparison of four methods to assess body composition in women. *Eur. J. Clin. Nutr.* **47**, 353–360.

Eckerson JM, Housh TJ & Johnson GO (1992): The validity of visual estimations of percent body fat in lean males. *Med. Sci. Sports Exerc.* **24**, 615–618.

Elia M, Parkinson SA & Diaz E (1990): Evaluation of near infra-red interactance as a method for predicting body composition. *Eur. J. Clin. Nutr.* **44**, 113–121.

Fogelholm M, Kukkonen-Harjula K, Sievänen H, Oja P & Vuori I (1996a): Body composition assessment in lean and normal-weight young women. *Br. J. Nutr.* **75**, 793–802.

Fogelholm M, Sievänen H & Vuori I (1996b): Assessment of fat mass before and during weight loss in obese women. *Med. Sci. Sports Exerc.* **28**, S150.

Forslund AH, Johansson AG, Sjödin A, Bryding G, Ljunghall S & Hambraeus L (1996): Evaluation of modified multicompartment models to calculate body composition in healthy males. *Am. J. Clin. Nutr.* **63**, 856–862.

Foster KR & Lukaski HC (1996): Whole-body impedance—what does it measure? *Am. J. Clin. Nutr.* **64**, 388S–396S.

Friedl KE, DeLuca JP, Marchitelli LJ & Vogel JA (1992): Reliability of body-fat estimations from a four-compartment model by using density, body water, and bone mineral measurements. *Am. J. Clin. Nutr.* **55**, 764–770.

Fuller NJ & Elia M (1989): Potential use of bioelectric impedance of the 'whole body' and of body segments for the assessment of body composition: comparison with densitometry and anthropometry. *Eur. J. Clin. Nutr.* **43**, 779–791.

Fuller NJ, Jebb SA, Laskey MA, Coward WA & Elia M, (1992): Four-component model for the assessment of body composition in humans: comparison with alternative methods, and evaluation of the density and hydration of fat-free mass. *Clin. Sci.* **82**, 687–693.

Fuller NJ, Sawyer MB & Elia M (1994): Comparative evaluation of body composition methods and predictions, and calculation of density and hydration fraction of fat-free mass, in obese women. *Int. J. Obes.* **18**, 503–512.

Goran MI, Poehlman ET, Danforth E & Nair KS (1994): Comparison of body fat estimates derived from underwater weight and total body water. *Int. J. Obes.* **18**, 622–626.

Graves JE, Pollock ML & Sparling PB (1987): Body composition of elite female distance runners. *Int. J. Sports Med.* **8**, 96–102.

Gray DS, Bray GA, Gemayel N & Kaplan K (1990): Skinfold thickness measurements in obese subjects. *Am. J. Clin. Nutr.* **51**, 571–577.

Gray DS, Bray GA, Bauers M, Kaplan K, Gemayel N, Wood R, Greenway F & Kirk S (1989): Effect of obesity on bioelectrical impedance. *Am. J. Clin. Nutr.* **50**, 255–260.

Hansen NJ, Lohman TG, Going SB, Hall MC, Pamenter RW, Bare LA, Boyden TW & Houtkooper LB (1993): Prediction of body composition in premenopausal females from dual-energy X-ray absorptiometry. *J. Appl. Physiol.* **75**, 1637–1641.

Heitman BL (1994): Impedance: a valid method in assessment of body composition?. *Eur. J. Clin. Nutr.* **48**, 228–240.

Heymsfield SB, Wang J, Kehayias J, Heska S, Lichtman S & Pierson RN (1989a): Chemical determination of human body density *in vivo*: relevance to hydrodensitometry. *Am. J. Clin. Nutr.* **50**, 1282–1289.

Heymsfield SB, Wang J, Heshka S, Kehayias JJ & Pierson RN (1989b): Dual-photon absorptiometry: comparison of bone mineral and soft tissue mass measurements in vivo with established methods. *Am. J. Clin. Nutr.* **49**, 1283–1289.

Heymsfield SB, Lichtman S, Baumgartner RN, Wang J, Kamen Y, Aliprantis A & Pierson RN (1990): Body composition of humans: comparison of two improved four-compartment model that differ in expense, technical complexity, and radiation exposure. *Am. J. Clin. Nutr.* **52**, 52–58.

Heyward VH, Cook KL, Hicks VL, Jenkins KA, Quatrochi JA & Wilson WL (1992): Predictive accuracy of three field methods for estimating relative body fatness of nonobese and obese women. *Int. J. Sport. Nutr.* **2**, 75–86.

Hodgdon JA & Fitzgerald PI (1987): Validity of impedance predictions at various levels of fatness. *Hum. Biol.* **59**, 281–298.

Horswill CA, Lohman TG, Slaughter MH, Boileau RA & Wilmore JH (1990): Estimation of minimal weight of adolescent males using multicomponent models. *Med. Sci. Sports Exerc.* **22**, 528–532.

Hortobagyi T, Israel RG, Houmard JA, O'Brien KF, Johns RA & Wells JM (1992): Comparison of four methods to assess body composition in black and white athletes. *Int. J. Sport Nutr.* **2**, 60–74.

Jackson AS & Pollock ML (1978): Generalized equations for predicting body density of men. *Br. J. Nutr.* **40**, 497–504.

Jackson AS, Pollock ML & Ward A (1980): Generalized equations for predicting body density of women. *Med. Sci. Sports Exerc.* **12**, 175–182.

Johansson AG, Forslund A, Sjödin A, Mallmin H, Hambraeus L & Ljunghall S (1993): Determination of body composition—a comparison of dual-energy x-ray absorptiometry and hydrodensitometry. *Am. J. Clin. Nutr.* **57**, 323–326.

Kahn HA & Sempos CT (1989): *Statistical Methods in Epidemiology*. New York: Oxford University Press.

Kaminsky LA & Whaley MH (1993): Differences in estimates of percent body fat using bioelectrical impedance. *J. Sports Med. Phys. Fitness* **33**, 172–177.

Kooy van der K, Leenen R, Deurenberg P, Seidell JC, Westerterp KR & JGAJ Hautvast (1992): Changes in fat-free mass in obese subjects after weight loss: a comparison of body composition measures. *Int. J. Obes.* **16**, 675–683.

Lohman TG (1992): *Advances in Body Composition Assessment*. Champaign: Human Kinetics.

Lukaski HC, Johnston PE, Bolonchuk WW & Lykken GI (1985): Assessment of fat-free mass using bioelectrical impedance measurements of the human body. *Am. J. Clin. Nutr.* **41**, 810–817.

Lukaski HC, Bolonchuk WW, Hall CB & Siders WA (1986): Validation of tetrapolar bioelectrical impedance method to assess human body composition. *J. Appl. Physiol.* **60**, 1327–1332.

Lukaski HC (1987): Methods for the assessment of human body composition: traditional and new. *Am. J. Clin. Nutr.* **46**, 537–556.

Lukaski HC, Bolonchuk WW, Siders WA & Hall CB (1990): Body composition assessment of athletes using bioelectrical impedance measurements. *J. Sports Med. Phys. Fitness* **30**, 434–440.

Marken Lichtenbelt van WD, Westerterp KR & Wouters L (1994): Deuterium dilution as a method for determining total body water: effect of test protocol and sampling time. *Br. J. Nutr.* **72**, 491–497.

Marken Lichtenbelt van WD, Fogelholm M, Ottenheijm R & Westerterp KR (1995): Physical activity, body composition and bone density in ballet dancers. *Br. J. Nutr.* **74**, 439–451.

Marken Lichtenbelt van WD, Kester A, Baarends EM & Westerterp KR (1996): Bromide dilution in adults: optimal equilibration time after oral administration. *J. Appl. Physiol.* **81**, 653–656.

Martin AD & Drinkwater DT (1991): Variability in the measures of body fat. Assumptions or technique?. *Sports Med.* **11**, 277–288.

Mazess RB, Bisek J, Trempe J & Pourchot S (1992): Effects of tissue thickness on body composition measurement using dual-energy x-ray absorptiometry. *Bone* **13**, 280 (Abstract).

McLean KP & Skinner JS (1992): Validity of Futrex-5000 for body composition determination. *Med. Sci. Sports Exerc.* **24**, 253–258.

McNeill G, Fowler PA, Maughan RJ, McGaw BA, Fuller MF, Gvozdanovic D & Gvozdanovic S (1991): Body fat in lean and overweight women estimated by six methods. *Br. J. Nutr.* **65**, 95–103.

Ortiz O, Russel M, Daley TL, Baumgartner RN, Waki M, Lichtman S, Wang J, Pierson RN & Heymsfield SB (1992): Differences in skeletal muscle and bone mineral mass between black and white females and their relevance to estimates of body composition. *Am. J. Clin. Nutr.* **55**, 8–13.

Pace N & Rathburn EN (1945): Studies on body composition III: The body water and chemically combined nitrogen content in relation to fat content. *J. Biol. Chem.* **158**, 685–691.

Paton NIJ, Macallan DC, Jebb SA, Pazianas M & Griffin GE (1995): Dual-energy X-ray absorptiometry results differ between machines. *Lancet* **346**, 899–900.

Penn I-W, Wang Z-M, Buhl KM, Allison DB, Burastero SE & Heymsfield SB (1994): Body composition and two-compartment model assumptions in male long distance runners. *Med. Sci. Sports Exerc.* **26**, 392–397.

Pierson RN, Wang J, Thornton JC, Kotler DP, Heymsfield SB, Weber DA & Ma RM (1995): Bone mineral and body fat measurements by two absorptiometry systems: comparisons with neutron activation analysis. *Calcif. Tissue Int.* **56**, 93–98.

Pierson RN, Wang J, Heymsfield SB, Russel-Aulet M, Mazariegos M, Tierney M, Smith R, Thornton JC, Kehayias J, Weber DA & Dilmanian FA (1991): Measuring body fat: calibrating the rulers. Intermethod comparisons in 389 normal Caucasian subjects. *Am. J. Physiol.* **261**, E103–E108.

Pritchard JE, Nowson CA, Strauss BJ, Carlson BJ, Kaymakci B & Wark JD (1993): Evaluation of dual energy X-ray absorptiometry as a method of measurement of body fat. *Eur. J. Clin. Nutr.* **47**, 216–228.

Ross R, Leger L, Martin P & Roy R (1989): Sensitivity of bioelectrical impedance to detect changes in human body composition. *J. Appl. Physiol.* **67**, 1643–1648.

Ross R, Leger L, Morris D, De Guise J & Guardo R (1992): Quantification of adipose tissue by MRI: relationship with anthropometric variables. *J. Appl. Physiol.* **72**, 787–795.

Scherf J, Franklin BA, Lucas CP, Stevenson D & Rubenfire M (1986): Validity of skinfold thickness measures of formerly obese adults. *Am. J. Clin. Nutr.* **43**, 128–135.

Segal KR, Gutin B, Presta E, Wang J, Van Itallie TB (1985): Estimation of human body composition by electrical impedance methods: a comparative study. *J. Appl. Physiol.* **58**, 1565–1571.

Segal KR, Van Loan M, Fitzgerald PI, Hodgdon JA & Van Itallie TB (1988): Lean body mass estimation by bioelectrical impedance analysis: a four-site cross-validation study. *Am. J. Clin. Nutr.* **47**, 7–14.

Siconolfi SF, Gretebeck RJ & Wong WW (1995): Assessing total body protein, mineral, and bone mineral content from total body water and bone density. *J. Appl. Physiol.* **79**, 1837–1843.

Siri WE (1956): The gross composition of the body. In *Advances in Biological and Medical Physics*, eds. CA Tobias, JH Lawrence. New York: Academic Press, pp 239–280.

Siri WE (1961): Body composition from fluid spaces and density: Analysis of methods. In *Techniques for Measuring Body Composition*, eds. J Brozek, A Henschel. Washington DC: National Academy of Sciences, pp 223–224.

Snead DB, Birge SJ & Kohrt W (1993): Age-related differences in body composition by hydrodensitometry and dual-energy X-ray absorptiometry. *J. Appl. Physiol.* **74**, 770–775.

Sohlström A, Wahlund L-O & Forsum E (1993): Adipose tissue distribution as assessed by magnetic resonance imaging and total body water by magnetic resonance imaging, underwater weighing, and body-water dilution in healthy women. *Am. J. Clin. Nutr.* **58**, 830–838.

Stout JR, Eckerson JM, Housh TJ, Johnston GO & Betts NM (1994): Validity of percent body fat estimations in males. *Med. Sci. Sports Exerc.* **26**, 632–636.

Tataranni PA & Ravussin E (1995): Use of dual-energy X-ray absorptiometry in obese individuals. *Am. J. Clin. Nutr.* **62**, 730–734.

Tataranni PA, Pettitt DJ & Ravussin E (1996): Dual energy X-ray absorptiometry: inter-machine variability. *Int. J. Obes.* **20**, 1048–1050.

Tothill P, Avenell A, Love J & Reid DM (1994): Comparisons between Hologic, Lunar and Norland dual-energy X-ray absorptiometers and other techniques used for whole-body soft-tissue measurements. *Eur. J. Clin. Nutr.* **48**, 781–794.

Van Loan MD & Mayclin PL (1992): Body composition assessment: dual-energy X-ray absorptiometry (DEXA) compared to reference methods. *Eur. J. Clin. Nutr.* **46**, 125–130.

Verlooy H, Dequeker J, Geusens P, Nijs & Goris M (1991): Body composition by intercomparison of underwater weighing, skinfold measurements and dual-photon absorptiometry. *Br. J. Radiol.* **64**, 765–767.

Vogel JA & Friedl KE (1992): Body fat assessment in women. *Sports Med.* **13**, 245–269.

Wang J, Heymsfield SB, Aulet M, Thornton JC & Pierson RN (1989): Body fat from body density: underwater weighing vs. dual-photon absorptiometry. *Am. J. Physiol.* **256**, E829–E834.

Wang J, Dilmanian FA, Thornton J, Russel M, Burastero S, Mazariegos M, Heymsfield SB & Pierson RN (1993): *In vivo* neutron activation analysis for body fat: comparisons by seven methods. In *Human Body Composition*, eds. KJ Ellis, JD Eastman. New York: Plenum Press, pp 31–34.

Wang Z-M, Pierson PN & Heymsfield SB (1992): The five-level model: a new approach to organizing body-composition research. *Am. J. Clin. Nutr.* **56**, 19–28.

Wang Z-M, Heshka S, Pierson RN, & Heymsfield SB (1995): Systematic organization of body-composition methodology: an overview with emphasis on component-based methods. *Am. J. Clin. Nutr.* **61**, 457–465.

Wardlaw GM (1996): Putting body weight and osteoporosis into perspective. *Am. J. Clin. Nutr.* **63**, 433S–436S.

Wellens R, Chumlea WC, Guo S, Roche AF, Reo NV & Siervogel RM (1994): Body composition in white adults by dual-energy x-ray absorptiometry, densitometry, and total body water. *Am. J. Clin. Nutr.* **59**, 547–555.

Wilmore J (1992): Body weight and body composition. In *Weight and Performance in Athletes*, eds. KD Brownell, J Rodin, JH Wilmore. Philadelphia: Lea & Febinger, pp 77–93.

Wilmore KM, McBride PJ & Wilmore JH (1994): Comparison of bioelectric impedance and near-infrared interactance for body composition assessment in a population of self-perceived overweight adults. *Int. J. Obes.* **18**, 375–381.

Withers RT, Smith DA, Chatterton BE, Schultz CG & Gaffney RD (1992): A comparison of four methods of estimating the body composition of male endurance athletes. *Eur. J. Clin. Nutr.* **46**, 773–784.