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Body fat measurement among Singaporean Chinese, Malays and Indians: a comparative study using a four-compartment model and different two-compartment models

Mabel Deurenberg-Yap[1]*, Gordon Schmidt[2], Wija A. van Staveren[3], Joseph G. A. J. Hautvast[3] and Paul Deurenberg[3]†

[1]*Department of Nutrition, Ministry of Health, Singapore*
[2]*School of Physical Education, Nanyang Technological University, Singapore*
[3]*Department of Human Nutrition and Epidemiology, Wageningen University, The Netherlands*

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This cross-sectional study compared body fat percentage (BF%) obtained from a four-compartment (4C) model with BF% from hydrometry (using ^2H_2O), dual-energy X-ray absorptiometry (DXA) and densitometry among the three main ethnic groups (Chinese, Malays and Indians) in Singapore, and determined the suitability of two-compartment (2C) models as surrogate methods for assessing BF% among different ethnic groups. A total of 291 subjects (108 Chinese, seventy-six Malays, 107 Indians) were selected to ensure an adequate representation of age range (18–75 years) and BMI range (16–40 kg/m^2) of the general adult population, with almost equal numbers from each gender group. Body weight was measured, together with body height, total body water by ^2H_2O dilution, densitometry with Bodpod® and bone mineral content with Hologic® QDR-4500. BF% measurements with a 4C model for the subgroups were: Chinese females 33·5 (SD 7·5), Chinese males 24·4 (SD 6·1), Malay females 37·8 (SD 6·3), Malay males 26·0 (SD 7·6), Indian females 38·2 (SD 7·0), Indian males 28·1 (SD 5·5). Differences between BF% measured by the 4C and 2C models (hydrometry, DXA and densitometry) were found, with underestimation of BF% in all the ethnic-gender groups by DXA of 2·1–4·2 BF% and by densitometry of 0·5–3·2 BF%). On a group level, the differences in BF% between the 4C model and ^2H_2O were the lowest (0·0–1·4 BF% in the different groups), while differences between the 4C model and DXA were the highest. Differences between the 4C model and ^2H_2O and between the 4C model and DXA were positively correlated with the 4C model, water fraction (f_{water}) of fat-free mass (FFM) and the mineral fraction ($f_{mineral}$) of FFM, and negatively correlated with density of the FFM (D_{FFM}), while the difference between 4C model and densitometry correlated with these variables negatively and positively respectively (i.e. the correlations were opposite). The largest contributors to the observed differences were f_{water} and D_{FFM}. When validated against the reference 4C model, 2C models were found to be unsuitable for accurate measurements of BF% at the individual level, owing to the high errors and violation of assumptions of constant hydration of FFM and D_{FFM} among the ethnic groups. On a group level, the best 2C model for measuring BF% among Singaporeans was found to be ^2H_2O.

Fat-free mass: Body fat percentage: Ethnicity: Four-compartment model

Body composition has been studied using different methodologies, each with its own advantages and limitations (Lukaski, 1987; Deurenberg, 1992; Jebb & Elia, 1993). Historically, chemical two-compartment (2C) models based on information from carcass analyses have been used as reference methods, against which other *in vivo* methods have generally been compared. Models have been developed to assess body composition, and one of the oldest models in body composition research is the 2C model of Siri (1961), in which the body is divided into two

Abbreviations: BF%, body fat percentage; BMC, bone mineral content; 2C, two-compartment; 4C, four-compartment; D_b, total body density; DXA, dual-energy X-ray absorptiometry; FFM, fat-free mass; FM, fat mass; $f_{mineral}$, mineral fraction of fat-free mass; $f_{protein}$, protein fraction of fat-free mass; f_{water}, water fraction of fat-free mass; TBW, total body water.

* **Corresponding author:** Dr Mabel Deurenberg-Yap, fax +65 4383605, email Mabel_Yap@moh.gov.sg
† Nutrition Consultant, Singapore.

clearly defined compartments, the fat mass (FM) and the fat free mass (FFM). The determination of body fat percentage (BF%) using whole-body densitometry is based on this model. The assumptions of densitometry are that the densities of the FM and the FFM are constant at 0·9 and 1·1 kg/l respectively. Total body density (D_b) is determined by dividing the mass of the body in air by the volume of the body. The latter can be determined by underwater weighing or by air displacement, and BF% can be calculated using Siri's (1961) formula. In the last decade this assumption of a constant density of FFM has been challenged frequently by researchers, who questioned its validity among different gender, age and ethnic groups and also at different levels of body fatness (Baumgartner *et al.* 1991; Bergsma-Kadijk *et al.* 1996; Visser *et al.* 1997).

Another methodology based on a 2C model is the determination of BF% using ^2H_2O dilution (hydrometry; Forbes, 1987). This method assumes a constant hydration of the FFM (Pace & Rathbun, 1945). It is known that hydration of FFM varies with age (Wang *et al.* 1999*a*,*b*), but it is uncertain whether differences in the hydration of the FFM exist among ethnic groups. The assumption of a constant hydration of the FFM is also adopted by dual-energy X-ray absorptiometry (DXA; Roubenoff *et al.* 1993). Variations in the hydration of FFM can also result in changes in its density, and thus BF% estimation from densitometry. It is obvious that the use of uniform density values or hydration factors when comparing body composition data of different (ethnic) groups may result in biased conclusions (Visser *et al.* 1997; Gurrici *et al.* 1998). For example, when the actual hydration of FFM is higher than the assumed value, there would be an underestimation of BF% using hydrometry and an overestimation of BF% using densitometry.

In recent years many studies have been performed to compare body composition between different ethnic groups (Jiang *et al.* 1991; Ortiz *et al.* 1992; Wang *et al.* 1994, 1996; Gallagher *et al.* 1996; Aloia *et al.* 1997; Gurrici *et al.* 1998; van Loan 1998; Deurenberg-Yap *et al.* 2000). The results of some of these studies may have been biased by violations of assumptions in the body composition techniques used.

With the advent of chemical- and isotope-based methods, it has become possible to subdivide the FFM into its components (water, mineral and protein), and to determine these components with a high level of accuracy (Heymsfield *et al.* 1997; Brodie *et al.* 1998). The use of such multiple-compartment models circumvents the use of non-validated assumptions in 2C models, and enables reliable comparisons to be made between groups where violation of assumptions might be present.

While the use of multiple-compartment models increases the accuracy of body composition measurements and is an important reference method, these models are more costly and require more time and facilities which may not be widely available.

In 1998 a body-composition study was conducted in Singapore as part of the National Health Survey. The study aimed to compare the BF% measured using a chemical four-compartment (4C) model and that obtained from three commonly used 2C models (hydrometry, DXA and densitometry) among the three main ethnic groups (Chinese, Malays and Indians) in Singapore. The other objectives were to examine the validity of assumptions used in the 2C models, and to determine the suitability of 2C models as surrogate methods to measure BF% among these ethnic groups.

Subjects and methods

Participants (300) in the 1998 National Health Survey (Ministry of Health, 1999) were invited to participate in a body-composition study. The subjects were selected in order to cover a wide range of age and (BMI), and to ensure that the three main ethnic groups (Chinese, Malays, Indians) were well represented within each gender group. Based on power calculation, to detect a 2 % point difference in BF% between 4C and other 2C models, twenty-five subjects would be sufficient for each subgroup (ethnic and gender).

In total 108 Chinese, seventy-six Malays and 107 Indians (total *n* 291) were measured. Their ages ranged from 18 to 75 years and their BMI from 16 to 40 kg/m^2. Table 1 gives some characteristics of the subjects. All measurements were performed at the study site situated at the laboratory of the School of Physical Education, Nanyang Technological University, Singapore. Subjects were in the fasting state for at least 6 h and voided before the measurements were taken. All anthropometric measurements were performed by trained observers.

The Singapore National Medical Research Council approved the study protocol and all subjects gave their written informed consent before the measurements were taken.

Body weight was measured to the nearest 0·1 kg in light indoor clothing without shoes, using a digital scale. A correction of 0·5 kg was made for the weight of the clothes. Body height was measured without shoes with Frankfurt plane horizontal (Gordon *et al.* 1988), to the nearest 0·1 cm using a wall-mounted stadiometer. The BMI was calculated.

Total body water (TBW) was determined using ^2H_2O dilution. The subject drank a precisely weighed amount of ^2H_2O (amount given varied between 10 and 11 g). At 3 h after dosing, a 10 ml venous blood sample was taken and plasma was separated and stored at −20°C until analyses were performed. Plasma was sublimated and the sublimate was analysed for ^2H concentration using i.r. spectroscopy (Lukaski & Johnson, 1985). From the given dose and the ^2H concentration in the sublimate, TBW was calculated, assuming a 5 % ^2H exchange with non-aqueous compartments in the body (Forbes, 1987). The within-individual CV of this methodology to measure TBW was found to be 1·5 % by the authors (M Deurenberg-Yap, G Schmidt, WA van Staveren, JGAJ Hautvast and P Deurenberg, unpublished results). The CV is increased by about 0·5 % when hydrometry is used to estimate FFM, owing the hydration factor of 0·735 used (Schoeller, 1996). BF% was then calculated using the following equations:

$$\mathrm{FFM} = \mathrm{TBW}/0{\cdot}735,$$

$$\mathrm{BF\%} = (\mathrm{BW} - \mathrm{FFM}) \times 100/\mathrm{BW},$$

where BW is body weight.

Table 1. Characteristics of Singaporean study subjects (Mean values and standard deviations)

	Chinese		Malays		Indians		Total	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Females								
n	61		33		53		147	
Age (years)	36·5	12·9	35·6	13·9	36·3	9·6	36·2	12·0
Body weight (kg)	54·9[a]	11·1	58·1	11·5	61·1[b]	14·1	57·8	12·6
Body height (m)	1·58[a]	0·06	1·54[b]	0·06	1·57	0·06	1·57	0·06
BMI (kg/m^2)	22·1[a]	4·8	24·5	4·9	24·9[b]	5·3	23·6	5·2
Body density (kg/l)	1·0309[a]	0·0185	1·0190[b]	0·0160	1·0199[b]	0·0182	1·0243	0·0186
TBW (kg)	26·0	3·4	26·3	4·0	27·0	5·1	26·4	4·2
BMC (g)	2281	315	2223	272	2309	319	2278	307
BF% 4C	33·5[a]	7·5	37·8[b]	6·3	38·2[b]	7·0	36·2	7·4
Males								
n	47		43		54		144	
Age (years)	40·7	13·6	41·4	12·3	43·4	12·9	41·9	12·9
Body weight (kg)	65·0	10·8	69·0	12·4	69·8	11·9	68·0	11·8
Body height (m)	1·69	0·05	1·66[a]	0·06	1·70[b]	0·07	1·68	0·06
BMI (kg/m^2)	22·8[a]	3·5	25·0[b]	3·8	24·3	3·7	24·0	3·7
Body density (kg/l)	1·0448	0·0148	1·0431	0·0198	1·0410	0·0155	1·0428	0·0167
TBW (kg)	36·0	4·4	37·1	4·6	36·0	5·2	36·3	4·8
BMC (g)	2709	379	2896	371	2844	419	2816	397
BF% 4C	24·4[a]	6·1	26·0	7·6	28·1[b]	5·5	26·2	6·5

[a,b] Mean values within rows with unlike superscript letters were significantly different ($P < 0.05$); TBW, total body water; BMC, bone mineral content; BF% 4C, percentage body fat measured by the four-compartment model.

Body density was determined using air plethysmography (Bodpod®, Body Composition System; Life Measurements Instruments, Concord, CA, USA) according to the instructions of the manufacturer. The method is described in detail by Dempster & Aitkens (1995), who also reported a mean test-retest CV of 1·7 % for body fat measurements. BF% was calculated using Siri's (1961) formula:

$$BF\% = 495/D_b - 450.$$

Bone mineral content (BMC) was measured using a Hologic® DXA whole-body X-ray densitometer (QDR-4500; Hologic® Waltham, MA, USA; software version V8.23a:5). As Hologic® measurements generally result in systematically lower BMC measurements compared with Lunar® measurements (Lunar Radiation Corps, Madison, WI, USA; Tothill *et al.* 1994), BMC data were corrected to Lunar® values. This was found to be necessary as the Lunar® machine was used for development of the equation of the 4C model of Baumgartner *et al.* (1991). A correction factor based on phantom measurements (Lunar aluminium 'spine' phantom) using a Lunar DPXL absorptiometer (software version 1.35) was determined. The established correction factor of 1·167 for the phantom was confirmed by three sets of measurements performed on two subjects over a period of 1 year. For each set these two subjects were measured twice within 1 week with both systems. The CV of BMC measurement by DXA is 1·5 %, while that for BF% measurement is 3·8–6·9 %, depending on the level of body fat (Lohman, 1996). Total body mineral was calculated as 1·235×BMC (Baumgartner *et al.* 1991; Wang *et al.* 1998).

BF% was calculated using the 4C model (including FM, TBW, total body mineral and a remaining compartment, consisting of protein and carbohydrate) as described by Baumgartner *et al.* (1991):

$$BF\% = 205 \times (1{\cdot}34/D_b - 0{\cdot}35 \times A + 0{\cdot}56 \times M - 1),$$

where A is water fraction of body weight and M is mineral fraction of body weight.

FFM (kg) was calculated as body weight minus FM. The water fraction of the FFM (f_{water}) was calculated as TBW/FFM, the mineral fraction ($f_{mineral}$) as M/FFM and the protein fraction ($f_{protein}$) as $1 - f_{water} - f_{mineral}$. As $f_{protein}$ is a derived value, the difference between $f_{protein}$ and the assumed value of 0·196 needs to be interpreted by taking into account the problem of correlation of $f_{protein}$ with f_{water} and $f_{mineral}$. The density (kg/l) of the FFM was calculated as:

$$D_{FFM} = 1/(f_{water}/0{\cdot}993 + f_{mineral}/3{\cdot}038 + f_{protein}/1{\cdot}340),$$

where 0·993 is the density of water, 3·038 the density of minerals and 1·340 the density of protein at 37°C (Deurenberg *et al.* 1989*a*).

Data were analysed using the SPSS version 8.01 for Windows program (SPSS, Chicago, IL, USA). Correlations are Pearson's correlation coefficients, or partial correlation with correction for possible confounders. Differences in variables within groups were tested with the paired *t* test. One sample *t* test was used to test the composition and density of the FFM from assumed values. Differences between the ethnic groups were tested using ANOVA analyses of covariance with Bonferroni *post hoc* tests for multiple comparisons. Bland & Altman (1986) procedures were used for testing agreement between methods. The level of significance was set at $P < 0.05$. Values are presented as means and standard deviations, unless otherwise stated.

Results

Table 1 gives the characteristics of the study subjects. Overall the men were slightly older than the women. As expected, the men were taller and heavier than the women.

Table 2. Composition of fat-free mass (FFM) by gender and ethnic group for Singaporean Chinese, Malay and Indian participants in the body-composition study†

(Mean values and standard deviations)

	Chinese		Malays		Indians		Total	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Females								
Water fraction	0·725*	0·026	0·737	0·028	0·727*	0·026	0·728*	0·026
Mineral fraction	0·079*	0·010	0·078*	0·008	0·078*	0·009	0·078*	0·009
Protein fraction	0·196	0·031	0·186*	0·028	0·195	0·027	0·193	0·029
Density of FFM (kg/l)	1·1082*	0·0073	1·1038*	0·0098	1·1070*	0·0098	1·1068*	0·0090
Males								
Water fraction	0·738[a]	0·019	0·735[a]	0·026	0·721[b]*	0·026	0·731	0·025
Mineral fraction	0·069	0·005	0·071	0·008	0·071	0·008	0·070*	0·007
Protein fraction	0·193[a]	0·020	0·193[a]	0·026	0·208[b]*	0·029	0·199	0·026
Density of FFM (kg/l)	1·0987[a]	0·0066	1·1011	0·0100	1·1052[b]*	0·0086	1·1019*	0·0088

[a,b] Mean values within rows with unlike superscript letters were significantly different (ANOVA, Bonferroni testing; $P < 0{\cdot}05$).
Mean values were significantly different from assumed values (density of FFM 1·100, water fraction 0·735, mineral fraction 0·069, protein fraction 0·196): *$P < 0{\cdot}05$.
† For details of subjects and procedures, see Table 1 and p. 492.

There was no age difference among the ethnic groups for both men and women. Among the women, Chinese women were the lightest and tallest with lowest BMI, highest D_b and lowest BF%. No significant difference was noted for TBW and BMC between the ethnic groups. For the men, Indians were the tallest, and had the highest BF%. Malay men were the shortest and had the highest BMI. Chinese men had the lowest BMI and BF%. There were no significant differences in weight, TBW, BMC and D_b among men of different ethnic origins.

The composition of the FFM (calculated using the 4C model) by gender and ethnic group is presented in Table 2. No significant difference was detected for the density of FFM, f_{water}, $f_{mineral}$ and $f_{protein}$ between the women of different ethnic groups. For men, the Chinese had the lowest density of FFM and highest f_{water}, while Indians had the highest $f_{protein}$. When tested against the assumed density of FFM of 1·100 (Siri, 1961), women of all three ethnic groups and Indian men had significantly higher density of FFM ($P < 0{\cdot}05$). Chinese women, Indian women and Indian men also had significantly lower ($P < 0{\cdot}05$) f_{water} than the assumed 0·735 (Wang *et al.* 1999b). All women had significantly higher ($P < 0{\cdot}05$) $f_{mineral}$ than the assumed 0·069, while Malay women and Indian men had significantly different ($P < 0{\cdot}05$) $f_{protein}$ compared with the assumed 0·196. There was no difference in the composition of FFM between the different age-groups in the present study (data not shown).

The differences in BF% between the 4C model and various 2C models for the three ethnic groups are shown in Table 3. DXA and densitometry both underestimated BF% in all groups, while there was a slight overestimation of BF% with hydrometry among Chinese and Indian women, and Indian men. Generally, for both men and women in all ethnic groups, the difference in BF% between the 4C model and ^2H_2O was smallest, ranging from 0·1 (SD 2·5) % in Malay women to −1·4 (SD 2·7) % in Indian men. On the other hand, the difference in BF% between the 4C model and DXA was the greatest (from 2·1 (SD 2·6) % in Chinese women to 4·2 (SD 2·4) % in Chinese men). For women the differences in BF% between the 4C model and all the other 2C models among ethnic groups were not significant. Among men, the difference in BF% between the 4C model and ^2H_2O was significantly higher for Indian men compared with the other two groups ($P < 0{\cdot}05$), with hydrometry overestimating BF% in Indians. The difference in BF% between the 4C model and densitometry in Indian men was significantly greater than that for Chinese men ($P < 0{\cdot}05$). These mean differences in BF% between the 4C model and the 2C models were not statistically significant between ethnic groups (for men) after correction for age, f_{water} and $f_{mineral}$ differences among groups, using analysis of covariance with Bonferroni testing for multiple comparisons. Fig. 1 presents the 95 % CI for the differences in BF% between the 4C model and 2C models. For most groups, these differences in BF% were significantly different from zero ($P < 0{\cdot}05$), except among Malay men and women (hydrometry) and Chinese men (hydrometry and densitometry).

Table 4 shows the partial correlations between the

Table 3. Comparison of differences between percentage body fat derived from the four-compartment model (4C) and those derived from the two-compartment models, by ethnic and gender groups for Singaporean Chinese, Malay and Indian participants in the body-composition study*

(Mean values and standard deviations)

	Chinese		Malays		Indians	
	Mean	SD	Mean	SD	Mean	SD
Females						
4C minus:						
Hydrometry	−1·0	2·3	0·1	2·5	−0·8	2·4
DXA	2·1	2·6	2·5	2·5	2·3	2·4
Densitometry	3·2	2·1	1·9	2·6	2·7	2·6
Males						
4C minus:						
Hydrometry	0·3	2·0	0·0	2·6	−1·4	2·7
DXA	4·2	2·4	3·9	2·4	3·2	3·0
Densitometry	0·5	2·0	1·2	3·0	2·5	2·6

No significant statistical difference between ethnic groups using analysis of covariance (with Bonferroni test for multiple comparisons), with correction for differences in age, water fraction and mineral fraction between groups (for details, see pp. 492–493).
DXA, dual-energy X-ray absorptiometry.
* For details of subjects and procedures, see Table 1 and pp. 492–493.

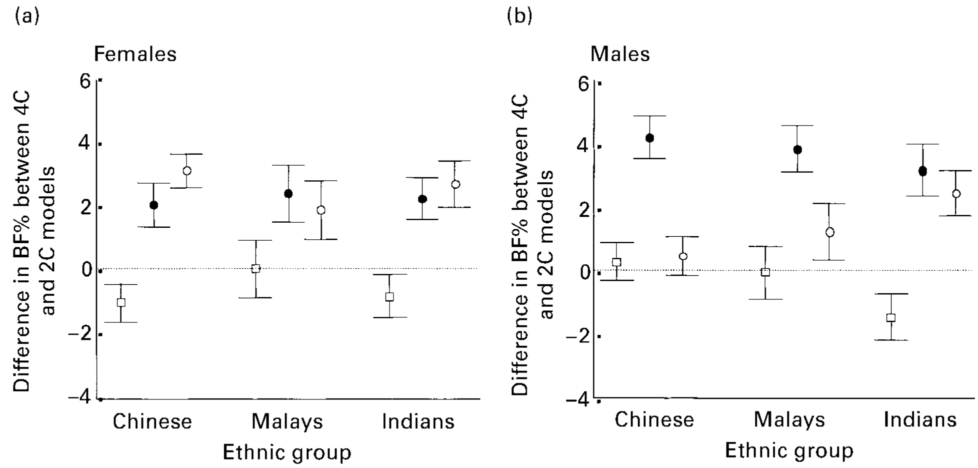

Fig. 1. Comparison of differences in body fat percentage (BF%) obtained from the four-compartment (4C) model and from two-compartment (2C) models (hydrometry, □; dual-energy X-ray absorptiometry, ●; densitometry, ○). (a) female and (b) male Singaporean Chinese, Malay and Indian participants in the body-composition study. Points are means with 95 % CI represented by vertical bars. For details of subjects and procedures, see Table 1 and p. 492.

differences in BF% from the 4C model and the 2C models and BF% from the 4C model (Fig. 2), f_{water}, $f_{mineral}$ and the density of FFM, with correction for age and ethnicity. The differences between BF% from the 4C model and BF% from both ^2H_2O and densitometry were strongly correlated with the f_{water}. However, the difference in BF% between the 4C model and ^2H_2O was positively correlated (r 0·99 for both men and women), while the difference in BF% between the 4C model and densitometry was negatively correlated (females r −0·86, males r −0·89; $P < 0·05$).

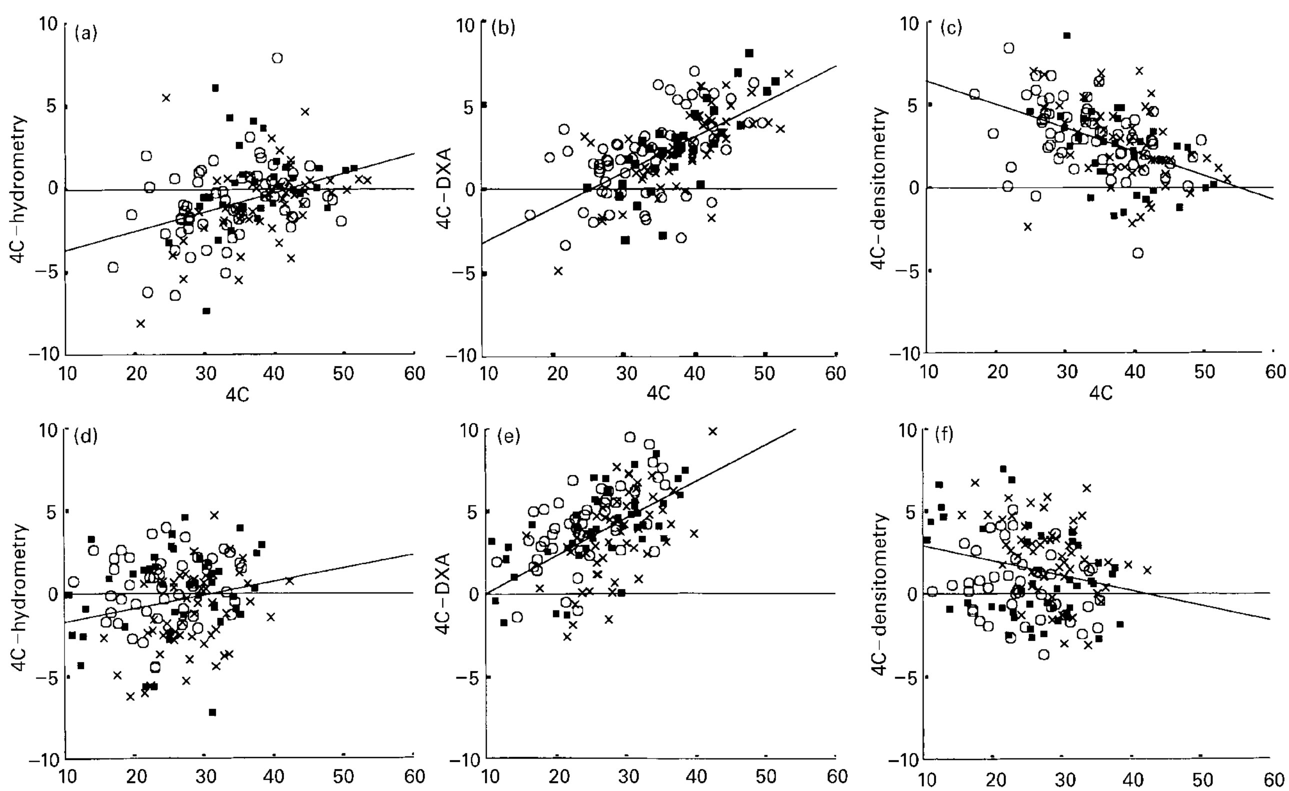

Fig. 2. Regression lines showing differences in body fat percentage (BF%) between the four-compartment (4C) model and two-compartment models (hydrometry, dual-energy X-ray absorptiometry (DXA) and densitometry) *v.* BF% from the 4C model in different Singaporean ethnic groups (Chinese, ○; Malays, ■; Indians, ×) for (a-c) female and male (d-f) participants in the body-composition study. For details of subjects and procedures, see Table 1 and p. 492.

Table 4. Correlations (r)† between the differences in percentage body fat BF% from the four-compartment model (4C) and the two-compartment models and BF% 4C water fraction (f_{water}) mineral fraction ($f_{mineral}$) and density (D_{FFM}) of fat-free mass (FFM) for Singaporean Chinese, Malay and Indian participants in the body-composition study‡

	BF% 4C	f_{water}	$f_{mineral}$	D_{FFM}
Females				
4C minus:				
Hydrometry	0·35*	0·99*	0·19*	−0·85*
DXA	0·62*	0·57*	0·15	−0·47*
Densitometry	−0·39*	−0·86*	0·31*	0·99*
Males				
4C minus:				
Hydrometry	0·33*	0·99*	0·02	−0·90*
DXA	0·56*	0·51*	0·18*	−0·38*
Densitometry	−0·33*	−0·89*	0·41*	0·99*

DXA, dual-energy X-ray absorptiometry.
* $P < 0·05$.
† Pearson partial correlation coefficients with correction for age and ethnicity.
‡ For details of subjects and procedures, see Table 1 and p. 492.

The difference in BF% between the 4C model and DXA was also significantly correlated with f_{water} (females r 0·57, males 0·51, $P < 0·05$). The differences in BF% between the 4C model and ^2H_2O, densitometry and DXA were also strongly correlated with the density of FFM, but they were the opposite of those of f_{water}. The $f_{mineral}$ was correlated positively with the differences in BF% between the 4C model and ^2H_2O and densitometry in women, and DXA and densitometry in men, but to a lesser extent than for f_{water}.

Discussion

The present study shows that the use of 2C models to determine BF% in adult Singaporeans instead of 4C models leads to large individual errors in the BF% measurement. On a group level, the best 2C model for BF% measurement was found to be hydrometry.

The study samples were selected from the population sample of the National Health Survey conducted in 1998 (Ministry of Health, 1999), to ensure that there was adequate representation from each of the three ethnic groups (Chinese, Malays and Indians) for each gender group. As the purpose of the present study was to compare BF% measurement using different methodologies, it was vital that there were enough subjects in the entire age and BMI range of the main sample of the survey rather than to have a truly random sample of the population. Nonetheless, the conclusions of this study are relevant for adult Chinese, Malays and Indians in Singapore.

All measurements were performed using the same instrumentation and by the same team of investigators using standardised protocols in order to avoid any systematic technical bias. A correction factor of 1·167 was applied to BMC measurements in this study using the Hologic® absorptiometer to correct for measurements obtained using the Lunar® absorptiometer. This correction was necessary as the Baumgartner *et al.* (1991) formula used in the present study was developed using a Lunar® absorptiometer. The correction factor was obtained by making twenty repeated phantom measurements using each absorptiometer and also by making repeated sets of measurements for two subjects scanned using both types of absorptiometer over a period of 1 year. This factor is close to the factor of 1·154 found by Tothill *et al.* (1994). Body volume as measured by air displacement using the Bodpod® and hydro-densitometry gave comparable results, as reported in the literature for young adults (Dempster & Aitkens, 1995; McCrory *et al.* 1995; Nuñez *et al.* 1999). However, small differences have also been reported between air displacement and hydro-densitometry, with values from air displacement being both higher (Yee & Kern, 1998) and lower (Collius *et al.* 1998; Millard-Stanford *et al.* 1998).

On a group level, the mean differences in BF% between the 4C model and ^2H_2O and densitometry were small, at 2·5 % or less, while the mean difference in BF% between the 4C model and DXA was higher, between 2·1 % and 4·2 %. Generally, the BF% obtained from hydrometry agreed most closely with that from the 4C model, with the smallest mean difference (Table 3 and Fig. 1). However, individual errors were much higher, owing partly to biological variation in the composition of the FFM (mainly in f_{water} and to a lesser extent $f_{mineral}$) and partly to measurement errors inherent for each method. The maximum individual error was about 10 % for all three methods.

The correlations of differences in BF% between the 4C model and ^2H_2O and densitometry with BF% from the 4C model (Fig. 2) are partly contributed by the differences in f_{water} and density of FFM between lean and obese subjects observed in this study. Leaner subjects tended to have lower f_{water} and higher density of FFM than the assumed values of 0·735 and 1·100 kg/l (data not shown) respectively, leading to overestimation of BF% by hydrometry and underestimation of BF% by densitometry. This increase in f_{water} and decrease in density of FFM with increasing BF% confirmed the theory discussed in the literature (Deurenberg *et al.* 1989*b*; Waki *et al.* 1991). No age influence on f_{water} and density of FFM was observed in the subjects of the present study, even though this effect was reported in other studies (Deurenberg *et al.* 1989*a*; Bergsma-Kadijk *et al.* 1996) most probably owing likely due to the lack of sufficient subjects in the extreme age-groups (<20 years and >65 years) in the present study sample. Some researchers have conjectured that the water and BMC of the female body are more variable than those in males, and that 2C models would be less valid with higher individual error in females (Bunt *et al.* 1989; Vogel & Friedl, 1992; Côté & Adams, 1993). However, the present study does not support this hypothesis, as it can be seen from Tables 2 and 3 that in both males and females similar variability exists in the composition of FFM and biases in BF% measurement for different 2C models.

The differences in BF% from the 4C model and the three 2C models were mainly related to f_{water}, density of FFM and, to a lesser extent, the $f_{mineral}$, as can be seen in Table 4. An f_{water} smaller than the assumed 0·735 causes an overestimation of BF% by hydrometry (Pullicino *et al.* 1990), while a higher density of FFM than the assumed 1·100 kg/l would lead to underestimation of BF% by densitometry (Fogelholm & van Marken Lichtenbelt, 1997). In the present study, the f_{water} values for the subgroups were very close to the assumed value, leading to small mean bias and error when estimating BF% using hydrometry. On the other hand, the higher density of FFM in most groups resulted in systematic underestimation of BF% by densitometry at the group level. DXA also systematically underestimated BF% in all groups in the present study. The positive correlation of the bias from BF% estimation by DXA with f_{water} and $f_{mineral}$ and negative correlation with density of FFM showed that DXA has its limitations (Laskey *et al.* 1992; van Loan & Mayclin, 1992) and is not entirely free of assumption of constant hydration (Roubenoff *et al.* 1993).

Conclusion

From the present study, it was found that in almost all groups there were significant differences between BF% measured by the 4C model and that measured using hydrometry, DXA and densitometry. On a group level, there was systematic underestimation of BF% by DXA and densitometry due mainly to violation of assumptions of constant hydration and density of FFM used in these 2C models. The difference in BF% between the 4C model and ^2H_2O approached zero for all groups. The differences in BF% from the 4C model and ^2H_2O, densitometry and DXA between ethnic groups were mostly attributed to the differences in composition of FFM, mainly f_{water} and partly to $f_{mineral}$. Similarly, the relationship between the differences in BF% from the 4C model and ^2H_2O, and densitometry and DXA and the degree of body fatness could be partly explained by the increasing f_{water} and decreasing density of FFM as BF% increases. There was no observed age influence on the differences between BF% measured by the 4C model and different 2C models.

There were considerable errors for all the 2C models due to individual differences in the f_{water} and density of FFM from the assumptions made in these models. Thus, on an individual level, to obtain an accurate measure of BF%, a 4C model would be advisable. Certainly, if the hydration and density of FFM in specific population groups are known and used, hydrometry and densitometry could be used as measurements of BF%. However, as this approach is not always feasible for population studies, the choice of method would need to take into account the precision of the methodology and the agreement of the method with the reference 4C model. In these conditions, BF% measurement using hydrometry is the method of choice when compared with densitometry and DXA. Additional advantages of hydrometry that make it suitable for use in field conditions are low respondent burden and no requirement for cumbersome instrumentation.

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