Field Methods for Body Composition Assessment Are Valid in Healthy Chinese Adults

Manjiang Yao, Susan B. Roberts, Guansheng Ma,* Hui Pan* and Megan A. McCrory2

Energy Metabolism Laboratory, The Jean Mayer U.S. Department of Agriculture Human Nutrition Research Center on Aging at Tufts University, Boston, MA 02111 and *Department of Student Nutrition, Institute of Nutrition and Food Hygiene, Chinese Academy of Preventive Medicine, Beijing, China 100050

ABSTRACT There is little information on the accuracy of simple body composition methods in non-Western populations. We determined the percentage of body fat (%BF) by isotope dilution [oxygen-18 (H218O) and deuterium oxide (2H2O)] and anthropometry in 71 healthy, urban Chinese adults aged 35–49 y [body mass index (BMI) 18–35 kg/m2]. The accuracy of several prediction equations for assessment of %BF from skinfold measurements was evaluated against %BF determined by H218O dilution. We also assessed the relationship between BMI and %BF, and the fat-free mass (FFM) hydration coefficient for our population. All skinfold measurements yielded means within –2%BF of H218O-derived %BF. However, on the basis of residual plot analysis and the 95% confidence interval (CI) for the mean difference between methods, the equations of Durnin and Womersley (for assessment of body density from skinfolds) coupled with that of Brozek et al. (for assessment of %BF from body density) provided the most valid assessment for individuals. In addition, the FFM hydration coefficient averaged 0.734 ± 0.002 (SEM), indicating that the usually assumed value of 0.732 is appropriate for this population. Finally, although BMI had high specificity (90%) for classifying individuals as having body fat within the normal range (<24%BF for men, and <35%BF for women), it had poor sensitivity (66%) for identifying individuals as having high body fat. We conclude that compared with H218O dilution, skinfold thickness can provide an accurate and reliable assessment of body composition in healthy Chinese adults. Furthermore, using the equation of Brozek et al. may be preferable to using Siri’s equation to predict %BF from body density in populations in which individuals have >30%BF. J. Nutr. 132: 310–317, 2002.

KEY WORDS: • isotope dilution • anthropometry • body mass index • percentage of body fat • fat-free mass hydration coefficient

The prevalence of overweight and obesity is increasing worldwide (1–4). For example, in urban cities of China, ~52% of men and 42% of women are now considered overweight or obese [defined as body mass index (BMI)3 >25 kg/m2] (5). However, there is little information on the body composition of these populations. Because BMI is a relatively poor indicator of adiposity (6–10), and because higher body fatness is generally associated with greater risk for chronic disease (11), more accurate methods are required for quantifying body fatness in non-Western populations.

Isotope dilution [oxygen-18 (H218O) and deuterium oxide (2H2O)] is a well-accepted reference method for measuring body fatness, and has the advantage of being feasible in a wide range of subjects in both clinical and field conditions. However, it requires highly specialized and costly equipment for analysis of isotope enrichment. Moreover, although H218O dilution is preferred over 2H2O dilution due to its smaller isotopic exchange with nonaqueous compounds, it is very expensive for widespread use. An additional concern is whether the standard fat-free mass (FFM) hydration coefficient of 0.732 (12) is valid for different ethnic groups (13,14). For example, the density of FFM differs among different ethnic groups (Caucasian, African-American, Hispanic) (14), and this may be due in part to varying water content of the FFM. Little information on FFM composition exists for Asian groups, but studies have suggested that body water content (15) and total body potassium content (16) of Asians may differ from those of Caucasians.

One alternative field technique that is simple, inexpensive and noninvasive is the measurement of subcutaneous fat thickness, or skinfolds, at selected sites. Several equations for predicting body fatness from skinfolds and other anthropometric measurements have been developed and validated for use in adult Caucasian populations (17) such as those of Durnin and Womersley (18) and Jackson and Pollock (19). However, disagreement remains concerning whether these equations are generalizable to other ethnic groups (14). For example, one study indicated that the equations of Durnin and Womersley

1 Funded by National Institutes of Health grants DK53404 and F32-DK 09747. Contents of this publication do not necessarily reflect the views or policies of the U.S. Department of Agriculture.
2 To whom correspondence should be addressed.
3 Abbreviations used: %BF, percentage of body fat; BMI, body mass index; CI, confidence interval; FFM, fat-free mass; Hb, hemoglobin; H218O, oxygen-18; 2H2O, deuterium oxide; SEE, standard error of the estimate; TBW, total body water.
had low validity for determining body fatness in rural Guatemalan adults with chronic energy deficiency (20), but this may have been because of their general undernourished state rather than their ethnicity per se. There also remains disagreement concerning whether the equations of Durnin and Womersley are applicable to other groups, such as well-nourished Asian populations (21–24).

In this study, we assessed the body composition of healthy, well-nourished, urban Chinese adults by isotope dilution and anthropometry (skinfolds and BMI). Estimates of the percentage of body fat (%BF) from skinfold measurements using different equation approaches were compared with %BF determined by the Durnin and Womersley method of H218O dilution. We also assessed the relationship between %BF and BMI, and tested the validity of the standard FFM hydration coefficient (0.732) for this population.

SUBJECTS AND METHODS

Subjects. The subjects were adult men and women (n = 71) aged 35–49 y who were living in urban areas of Beijing, China. All reported stable economic circumstances and living conditions during at least the past 5 y, and had a wide range of physical activity patterns based on a brief interview-administered screening questionnaire (25). Subjects were in good health as judged by a normal physical examination and blood hemoglobin (Hb) concentration (standard Hb based on a brief interview-administered screening questionnaire (25) –35 g/L for women (26)], and were free from any known medical conditions that might cause edema or disturbances in fluid or electrolyte balance, or prevent them from being physically active. Additional exclusion criteria included postmenopausal status in women, smoking >20 cigarettes per day, drinking >2 alcoholic drinks per day, and weight change of >3 kg or a self-reported change in habitual physical activity level during the past year. Details of the subjects are given in Table 1. The studies were conducted at the Institute of Nutrition and Food Hygiene, Beijing, with ethical approval obtained from the Human Investigations Review Committee at the Chinese Academy of Preventive Medicine and New England Medical Center/Tufts University. Written informed consent was obtained from all subjects before the start of the study.

Study design. The study was conducted over a 9-d period; during that time, %BF was determined from isotope dilution and anthropometric measurements on two occasions. Throughout the study, all subjects lived at home and continued their usual activities and eating patterns. Measurements were conducted at the research unit of the Institute of Nutrition and Food Hygiene, and subjects usually traveled there by leisurely walking or bicycling (<8.05 km).

Isotope dilution measurements. On study d 1, a mixed H218O dose containing 0.10 g/kg body mass of H218O and 0.08 g/kg body mass of H216O was given orally to each subject early in the morning at the research unit after an overnight fast and collection of a baseline urine specimen. The dose was followed by two 25-mL water rinses of the dose container. A standard breakfast of two slices of white bread and a 500 mL bag of 2% fat milk was given 1 h after dosing (28), with no >25 g additional optional food items (such as sugar or pickles). Subjects were then required to remain sedentary and not to consume any food or water while urine samples were collected from complete voids made at 3, 4, and 5 h after dose administration (the first two samples were taken for equilibration purposes). In a subset of subjects (n = 12) in whom a possible failure to obtain a subsequent urine sample was anticipated, an additional 50 mL of water was orally administered. After completion of urine collections, subjects were discharged from the unit and carried out their usual daily activities during the following 2–8 d. On the morning of d 9, subjects returned to the research unit after an overnight fast. Each subject was given an oral dose of 0.05 g/kg body weight of H216O after collection of a baseline urine specimen (second void of the day). Postdose urine specimen collection and other procedures were identical to those on study d 1. Aliquots of all samples were placed into airtight storage tubes (Cryos cryogenic vials, Vargard International, Neptune, NJ) immediately after collection, and stored at −20°C before shipment on dry ice to Tufts University for isotope analysis.

Abundances of H18O and H216O in dilutions of the isotope doses and in urine specimens (baseline and 5 h postdose on d 1 and 9) were analyzed using a Hydra gas isotope ratio mass spectrometer (PDZ Europa, Crewe, UK). Urine and dilute dose samples were prepared for 16O/18O and 1H/2H analysis using the equilibration technique of Prosser and Scrimgeour (29). Briefly, 0.5 mL of urine sample was pipetted into an Exetainer tube (Labco, High Wycombe, UK). For 16O/18O analysis, the vial was sealed with a rubber septum and then CO2 was added by a needle pierced through the septum. For 1H/2H determination, a small (5 × 30 mm) glass vial (Chromacol, Trumbull, CT) partially filled with 5% platinum on alumina catalyst (Aldrich Chemical, Milwaukee, WI) was added to the Exetainer tube, and then H2 was added after the vial was capped. The only major modification made in our laboratory to the procedure of Prosser and Scrimgeour was to use a gas autosampler with a flushing needle (PDZ Europa, Cheshire, UK) to introduce the equilibration gas instead of introducing it manually through a vacuum line. After the tubes were filled, they were equilibrated at 20 ± 1°C overnight (for 18O) or for 3 d (for 2H). The tubes were introduced sequentially into a helium flow that was dried by magnesium perchlorate and then analyzed by the mass spectrometer set to detect either 16O/18O or 1H/2H. The enrichments of the equilibrated samples were compared with the enrichments of equilibrated local water standards (themselves calibrated against SMOW and SLAP). Triplicate isotope analyses of each urine and dose sample were performed. The CV for day-to-day repeated measures of H18O and H216O abundances in standards averaged 0.03 and 0.08%, respectively.

Isotope dilution spaces were calculated by using the computer program DLW (30). The peak isotopic abundances 5 h after dosing were used to calculate the dilution space, assuming no loss of isotope between dosing and 5 h. To correct for the known isotopic exchange with nonaqueous organic compounds, TBW was calculated as the H218O dilution space at 5 h postdose divided by 1.01, and as the H216O dilution space at 5 h postdose divided by 1.04 (31). FFM was

### Table 1

<table>
<thead>
<tr>
<th>Subject characteristics</th>
<th>Men</th>
<th>Women</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>33</td>
<td>38</td>
</tr>
<tr>
<td>Age, y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>43.1 ± 0.7</td>
<td>42.8 ± 0.6</td>
<td></td>
</tr>
<tr>
<td>Body mass, kg</td>
<td>73.4 ± 2.2</td>
<td>64.7 ± 2.0*</td>
</tr>
<tr>
<td>Weight change, g/d</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(averaged over 9 d)</td>
<td>4</td>
<td>± 20</td>
</tr>
<tr>
<td>Height, cm</td>
<td>172.0 ± 1.1</td>
<td>160.3 ± 1.0**</td>
</tr>
<tr>
<td>Body mass index, kg/m²</td>
<td>24.7 ± 0.6</td>
<td>25.1 ± 0.7</td>
</tr>
<tr>
<td>Skinfold thickness, mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biceps</td>
<td>7.6 ± 0.6</td>
<td>13.6 ± 0.9**</td>
</tr>
<tr>
<td>Triceps</td>
<td>13.3 ± 0.9</td>
<td>25.7 ± 1.2**</td>
</tr>
<tr>
<td>Subscapular</td>
<td>22.7 ± 1.4</td>
<td>29.2 ± 1.5*</td>
</tr>
<tr>
<td>Abdominal</td>
<td>24.4 ± 1.8</td>
<td>32.3 ± 1.4**</td>
</tr>
<tr>
<td>Suprailiac</td>
<td>13.7 ± 1.3</td>
<td>24.8 ± 1.6**</td>
</tr>
<tr>
<td>Thigh</td>
<td>16.8 ± 1.2</td>
<td>35.1 ± 1.6**</td>
</tr>
</tbody>
</table>

1 Values are means ± SEM and are based on the average of measurements conducted on study d 1 and 9.

2 Significantly different from men: * P ≤ 0.01; ** P ≤ 0.001 (independent sample t test).

3 Not significantly different from 0 for either men or women (one-sample t test).
Anthropometry. Anthropometric measurements were obtained in the fasting state on the mornings of d 1 and 9. Body mass and height measurements were made in triplicate. Body mass was measured to ± 0.23 kg (0.5 lb) using a digital electronic scale (model 68977, Country Technology, Gays Mills, WI), with subjects wearing minimum clothing (i.e., underwear), and height was measured to ± 0.1 cm using a steel strip stadiometer. Skinfold thickness was measured to the nearest 1.0 mm using Harpenden calipers (model 32). Skinfold measurements were taken at each site and if a difference of >1.0 mm was observed, a third measure was taken. The mean of the two measurements within 1.0 mm was used in further analysis. In addition, for the biceps, triceps and thigh sites, the mean thickness of the left and right sides was used in the calculations.

%BF was calculated from anthropometric measurements using two sets of prediction equations, i.e., those developed in an Asian population (97% born in China) (33) and generalized equations (18). The equations of Wang et al. (33) were used to calculate the FFM hydration coefficient (TBW/FFM) as the reference standard, and utilize BMI and age in addition to skinfolds. The equations are as follows: %BF (men) = 0.471 · BMI + 0.082 · age + 0.327 · triceps + 0.132 · abdominal + 0.289 · thigh − 4.40, adjusted R² = 0.39, standard error of the estimate (SEE) = 4.9%; and %BF (women) = 0.899 · BMI + 0.029 · age + 0.279 · triceps + 0.117 · subscapular + 0.172 · suprailiac + 0.188 · thigh − 0.57, adjusted R² = 0.54, SEE = 4.4%. Units are as follows: BMI, kg/m²; age, y; and skinfolds, mm. The equations of Durnin and Womersley (18) predict body density (kg/L) as follows: %BF (Siri) = [(body mass/(2.118/body density)) − 450, and %BF (Bland–Altman) = (457/body density) − 414.2. The regression coefficients (r) were calculated to assess associations between variables. The within-subject CV between skinfolds measured on d 1 and 9 was calculated for each site to assess measurement consistency. To determine whether skinfold measurement variability was a function of skinfold thickness, regression analysis was used to test for an association between the absolute difference between measurements on d 1 and 9 and their means at each site.

Repeated-measures ANOVA, with isotope dilution method as a within-subject factor and gender as a between-subject factor, was performed to detect significant differences in %BF by method. If the interaction term of gender by isotope dilution method was not significant, Tukey’s honestly significant difference multiple comparison procedure was used to compare differences among the %BF values determined by isotope dilution with genders combined. If the interaction term was significant, differences were compared for each gender separately. To assess the agreement among the isotope dilution determinations, linear regression analyses and Bland–Altman analyses were carried out (40). To determine how well %BF estimated from skinfold equations reflected H218O-derived %BF, %BF from H218O was regressed onto predicted %BF, and the residuals were plotted against the predicted variables. These plots were then examined for curvilinearity (by adding a square term of predicted %BF to the original model and testing for its significance) and heteroskedasticity (by dividing the sample by a median split of predicted %BF and testing for homogeneity of variances on the residuals). The 95% confidence intervals (CI) around the mean difference between methods were also calculated to assess the range of agreement for individuals (similar to calculation of 95% limits of agreement in Bland–Altman analysis). Regression analysis was also used to determine the relationships between BMI and both %BF and FFM, and whether these relationships differed by gender. Finally, the sensitivity and specificity of BMI were calculated as previously described (41). For all tests, statistical significance was accepted at P < 0.05.

RESULTS

Body mass was very stable during the study period (Table 1). Skinfold measurements did not differ significantly between d 1 and 9 at any site. The between-day average CV within subjects were 5.6% (biceps), 4.5% (triceps), 3.1% (subscapular), 4.3% (abdominal), 4.5% (suprailiac) and 3.0% (thigh). The within-subject absolute difference in skinfold thickness measured on d 1 and 9 was not significantly related to the mean measurement between d 1 and 9 at any site (data not shown), indicating that the variability of skinfold measurements was independent of the magnitude of the thickness. When skinfold variability was examined by BMI category, the CV were 2.7–6.4% for subjects with BMI < 25 kg/m² (n = 41), and 3.2–5.3% for BMI ≥ 25 kg/m² (n = 30).

The H218O dilution space was similar on d 1 and 9 as expected, it was consistently larger than the H218O dilution space (1972.7 ± 45.0 and 1976.5 ± 45.0 mol for H218O on d 1 and 9, and 1925.13 ± 43.27 mol for H218O on d 1, P < 0.001). Mean values for TBW calculated from the dilution spaces of H218O (d 1), H216O (d 1), and H216O (d 9) were 34.35 ± 0.77, 34.18 ± 0.77, and 34.25 ± 0.78 kg, respectively. There was a significant association between the d 9 and d 1 differences in body mass and TBW from H216O (r = 0.45, P < 0.001), but not between differences in body mass and %BF. %BF determined by the three isotope dilutions is shown in Table 2. There were significant main effects of isotope dilution (P = 0.029) and gender (P < 0.001) on %BF, but their interaction was not significant. As shown, %BF measured on d 1 by H216O was slightly higher than that measured by H218O (Δ%BF = 0.35, 0.06, P = 0.19). Linear regression and Bland–Altman analyses (Fig. 1) of %BF determined by H218O and H216O dilutions on the same day, and H218O dilution on different days, indicated a high degree of agreement. The regression lines (panels A and C) did not differ significantly from the line of identity (y = x), and the regression equations

Downloaded from https://academic.oup.com/jn/article-abstract/132/2/310/4687107 by guest on 01 March 2019
TABLE 2

The percentage of body fat (%BF) determined from isotope dilution and anthropometric methods in healthy Chinese adults.

<table>
<thead>
<tr>
<th></th>
<th>Men</th>
<th>Women</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>33</td>
<td>38</td>
</tr>
<tr>
<td>%BF by isotope dilutions(^{2,3})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H(_{2})(^{18})O (d 1)</td>
<td>25.4 ± 1.1(^a)</td>
<td>36.2 ± 0.8(^a)</td>
</tr>
<tr>
<td>H(_{2})O (d 1)</td>
<td>25.5 ± 1.1(^b)</td>
<td>36.7 ± 0.8(^b)</td>
</tr>
<tr>
<td>H(_{2})(^{18})O (d 9)</td>
<td>25.6 ± 1.1ab</td>
<td>36.3 ± 0.8ab</td>
</tr>
<tr>
<td>%BF by anthropometric measurements(^{4})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wang et al. (33)</td>
<td>23.2 ± 1.1*</td>
<td>37.9 ± 1.3*</td>
</tr>
<tr>
<td>Durnin and Womersley (18)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Siri equation (34)</td>
<td>25.4 ± 1.0</td>
<td>38.1 ± 0.7*</td>
</tr>
<tr>
<td>Brozek et al. equation (35)</td>
<td>24.7 ± 0.9</td>
<td>36.5 ± 0.7</td>
</tr>
</tbody>
</table>

\(^{1}\) Values are means ± SEM.

\(^{2}\) H\(_{2}\)\(^{18}\)O, oxygen-18; H\(_{2}\)O, deuterium oxide.

\(^{3}\) Significant main effects of isotope-dilution determination (P = 0.029) and gender (P < 0.001), but no significant gender by isotope-dilution determination interaction effect on %BF (repeated-measures two-way ANOVA). Variables with different superscript letters are significantly different (P < 0.05) (Tukey’s honestly significant difference multiple comparison procedure).

\(^{4}\) Significantly different from %BF determined by H\(_{2}\)\(^{18}\)O dilution (P < 0.05) (multiple paired-sample t tests with Bonferroni’s adjustment).

FIGURE 1 Comparison of the percentage of body fat (%BF) determined from isotope dilutions of oxygen-18 (H\(_{2}\)\(^{18}\)O) and deuterium oxide (H\(_{2}\)O) in healthy Chinese adults. Linear regressions (panels A and C) of %BF by H\(_{2}\)\(^{18}\)O and H\(_{2}\)O dilutions on d 1 (y = 0.985x + 0.121, adjusted R\(^2\) = 0.996, SEE = 0.510, P < 0.001), and by H\(_{2}\)O dilution on d 1 and 9 (y = 1.002x + 0.105, adjusted R\(^2\) = 0.975, SEE = 1.268, P < 0.001), and their corresponding Bland-Altman plots (panels B and D). In the Bland-Altman plots, solid lines indicate mean difference between methods, and dotted lines indicate upper and lower 95% limits of agreement.

FIGURE 2 Relationship between the fat-free mass (FFM) hydration coefficient and the percentage of body fat (%BF) determined from oxygen-18 (H\(_{2}\)\(^{18}\)O) dilution in healthy Chinese adults. The dotted reference line indicates the mean value for FFM hydration coefficient.

gave very low SEE and very high R\(^2\). Furthermore, the 95% limits of agreement from Bland-Altman analyses (panels B and D) were relatively narrow and were smaller for H\(_{2}\)\(^{18}\)O and H\(_{2}\)O dilutions on the same day (2SD = -0.69, 1.39%BF) than from H\(_{2}\)O dilution on separate days (2SD = -2.68, 2.36%BF). As can be seen, none of the individual differences was a function of body fatness.

The calculated FFM hydration coefficient averaged 0.734 ± 0.002 and did not differ significantly between men and women (Figure 2). Although the FFM hydration coefficient varied between 0.690 and 0.770 among individuals, it did not vary systematically across the range of body fatness for the study population.

%BF predicted anthropometrically is also shown in Table 2. %BF predicted by the equations of Wang et al. (33) was significantly different from %BF determined by H\(_{2}\)\(^{18}\)O dilution in both men (Δ%BF = -2.2 ± 0.5, P < 0.001) and women (Δ%BF = 1.7 ± 0.7, P = 0.013). The %BF predicted from the equations of Durnin and Womersley (18) differed somewhat depending on whether Siri’s equation (34) or that of Brozek et al. (35) was used to convert predictions of body density into %BF. When Siri’s equation (34) was used, the predicted %BF was significantly different from H\(_{2}\)\(^{18}\)O-derived %BF for women (Δ%BF = 2.0 ± 0.5, P < 0.001), but not for men (Δ%BF = 0.1 ± 0.4). However, when the equation of Brozek et al. (35) was used, there was no difference between predicted and H\(_{2}\)\(^{18}\)O-derived %BF for either men (Δ%BF = -0.6 ± 0.4) or women (Δ%BF = 0.3 ± 0.5). Although several of the mean differences were statistically significant, they were generally small (less than ~2.0%BF).

Regression and residual analyses for the agreement between %BF predicted anthropometrically and %BF measured by H\(_{2}\)\(^{18}\)O dilution are shown in Figure 3. Although SEE and R\(^2\) values indicated relatively good agreement between %BF predicted by the equations of Wang et al. (33) and H\(_{2}\)\(^{18}\)O-derived %BF, the slope of the regression line differed significantly from 1.0, and the intercept differed from 0 (panel A). Furthermore, residuals from this analysis plotted against %BF predicted from the equations of Wang et al. (33) (panel B) showed that the differences in %BF were significantly related to the predicted values (r = 0.70, P < 0.001). This indicated that the equations of Wang et al. (33) underestimated H\(_{2}\)\(^{18}\)O-derived %BF at lower body fatness and overestimated %BF at higher body fatness. In addition, the 95% CI around the mean difference was ~8.1 to 7.9%BF, indicating substantially wide variation in the agreement between the skinfold equations of Wang et al. (33) and the reference H\(_{2}\)\(^{18}\)O dilution method among indi-
significant curvilinearity ($P = 0.049$) and a marginally significant relationship between the residuals and predicted %BF ($r = 0.23, P = 0.06$) when Siri’s (34) but not that of Brozek et al. (35) was used. This indicated a nonrandom distribution of the residuals when Siri’s equation (34) was used. Moreover, direct comparison of the application of Siri’s equation (34) vs. that of Brozek et al. (35) showed that although the results agreed within ±1%BF for individual subjects having $<28%$BF, Siri’s equation (34) yielded values 1–2%BF higher for subjects having 28–42%BF, and values >2%BF higher for subjects having >42%BF.

Relationships between BMI and %BF determined by $H_2^{18}$O dilution are shown in Figure 4, left panel. As shown, this relationship differed significantly between genders such that women had a higher %BF than men at any given BMI. In addition, the regression line for men had a steeper slope. There was also a significant relationship between BMI and FFM (adjusted $R^2 = 0.78$, $P < 0.001$; data not shown). In addition, like the BMI-%BF relationship, the BMI-FFM relationship also differed significantly by gender ($P < 0.001$), with a steeper slope for women. The association between FFM and BMI (partial $r = 0.56, P < 0.001$) was further found to be independent of fat mass (partial $r = 0.93, P < 0.001$).

The ability of BMI to detect fatness was determined by plotting individual variations in %BF within each of the three BMI categories (Fig. 4, right panel). %BF ranged from 11 to 39, 18 to 44 and 33 to 45%BF in the BMI categories of $<25$, 25–29, and ≥30 kg/m², respectively. Further calculations demonstrated that >30% of the subjects who had high body fat based on the healthy %BF cut-off values (shown by horizontal lines on graph) were classified as normal weight by BMI, but only three subjects who had body fat within the normal range by the healthy %BF cut-off values were categorized as overweight by BMI. Therefore, BMI had poor sensitivity (65.9%), but high specificity (90.0%) for detecting body fatness.

**DISCUSSION**

The principal findings of this study were that group mean values for %BF can be estimated accurately from skinfold thickness in a Chinese population, but that there are different results for men and women. The regression analysis showed that the BMI-%BF relationship differed significantly between genders such that women had a higher %BF than men at any given BMI. In addition, the regression line for men had a steeper slope. There was also a significant relationship between BMI and FFM (adjusted $R^2 = 0.78$, $P < 0.001$; data not shown). In addition, like the BMI-%BF relationship, the BMI-FFM relationship also differed significantly by gender ($P < 0.001$), with a steeper slope for women. The association between FFM and BMI (partial $r = 0.56, P < 0.001$) was further found to be independent of fat mass (partial $r = 0.93, P < 0.001$).

The ability of BMI to detect fatness was determined by plotting individual variations in %BF within each of the three BMI categories (Fig. 4, right panel). %BF ranged from 11 to 39, 18 to 44 and 33 to 45%BF in the BMI categories of $<25$, 25–29 and ≥30 kg/m², respectively. Further calculations demonstrated that >30% of the subjects who had high body fat based on the healthy %BF cut-off values (shown by horizontal lines on graph) were classified as normal weight by BMI, but only three subjects who had body fat within the normal range by the healthy %BF cut-off values were categorized as overweight by BMI. Therefore, BMI had poor sensitivity (65.9%), but high specificity (90.0%) for detecting body fatness.
experiences in the accuracy of individual estimates of %BF among different skinfold equations. Using H\textsubscript{2}\textsuperscript{18}O dilution as the reference technique, the most valid anthropometric assessment of %BF for individuals was obtained by coupling the equations of Durnin and Womersley (16) to estimate body density with the equation of Brozek et al. (35) to estimate %BF from body density. We additionally showed that the standard FFM hydration coefficient of 0.732 was appropriate for this population, and that BMI had a low sensitivity for identifying individuals as having high body fat.

Isotope dilution is generally considered an accurate method for estimation of FFM from TBW (42). In the present study, H\textsubscript{2}\textsuperscript{18}O and H\textsubscript{2}O administered simultaneously and H\textsubscript{2}O administered on different days gave virtually identical mean results and very close individual results. Greater individual variations in %BF derived from the H\textsubscript{2}O administered on separate days may be explained by normal day-to-day biological variation in TBW (34). Our between-day within-subject SD over 9 d for TBW was ±0.38 kg, which was smaller than the ±1.0 L (0.99 kg) within a similar time frame (7 d) reported by Friedl et al. (43). This difference is probably related to the analytical method used to measure isotopic abundance because isotope ratio mass spectrometry is known to have greater technical precision than the infrared spectrophotometry method used by Friedl and co-workers (43).

One concern with the use of H\textsubscript{2}\textsuperscript{18}O dilution as the reference method is whether the standard FFM hydration coefficient of 0.732 is accurate for the population in question. The hydration coefficient of 0.732 for FFM used in most TBW-based assessments of body fatness was originally derived from limited data on chemical analyses of mammalian cadavers (12,44). Although this assumed value may be accurate for many individuals and populations, deviations from this constant are recognized and it remains unclear whether biological factors such as ethnicity and adiposity significantly influence the stability of FFM hydration. We therefore assessed the hydration of FFM (TBW/FFM\textsubscript{d}) in our subjects, using independent measurements of TBW and FFM. Using this method, the mean FFM hydration coefficient for our study population averaged 0.734, which is very close to the standard hydration coefficient of 0.732. This implies that the standard value is accurate for an urban Chinese population and corroborates other work in this area (13). However, among individuals, we found that FFM hydration varied (0.69–0.77%). This range is exactly the same as that derived from a cellular level FFM hydration model developed by Wang et al. (45) and similar to results from in vitro human cadaver studies (0.68–0.81) (12). Individual variations in FFM hydration reflect normal physiologic variability, and in part methodological errors in measuring TBW and FFM. With respect to the physiologic variations, the FFM hydration model by Wang et al. (45) indicates that individual variations in four cellular level determinants, including hydration of body cell mass, hydration of extracellular fluid, the ratio of extracellular solids to TBW and the ratio of extracellular water to intracellular water, may all contribute directly to the observed variability in FFM hydration.

We used Siri's three-compartment model as the basis for calculating the FFM hydration coefficient for our population according to standard methodology [see, for example, (13,36,37)]. A three-compartment model (incorporating TBW and body density) is thought to be superior to two-compartment models (incorporating either body density alone or TBW alone) because it takes into account individual variations in hydration, and thus physiologic deviations from an assumed average hydration level (46). One potential drawback to our method for calculating the FFM hydration coefficient for our population is that there was no direct measurement of body density (e.g., by hydrodensitometry or air displacement plethysmography). Instead, body density was calculated from the skinfold equation of Durnin and Womersley. However, we felt comfortable with this substitution because on average this equation provided results that agreed closely with %BF determined by the reference method (H\textsubscript{2}\textsuperscript{18}O dilution). Nevertheless, because of this potential methodological limitation, additional studies involving a more direct measurement of body density are warranted to confirm our findings.

Concerning the prediction of %BF from skinfold thickness, two early studies suggested that equations derived in Europeans may be applicable to Asians. Regression equations of the sum of 10 skinfolds against body density determined by hydrostatic weighing derived in Czechoslovakian adults (47) did not differ significantly from those derived in Taiwanese adults (48). However, previous studies are in disagreement over the accuracy of the widely used generalized prediction equations of Durnin and Womersley (18) for estimating %BF in adults of Chinese racial origin. Both Wang and Deurenberg (22) and de Waart et al. (23) compared predicted %BF with a reference technique (underwater weighing or H\textsubscript{2}O dilution) and concluded that the equations are valid for Chinese adults. In contrast, others have reported that the equations overestimated (24) and underestimated (21) %BF compared with %BF determined from those same reference methods in adult Chinese subjects. The studies that evaluated the Durnin and Womersley equations (18) in Chinese adults used Siri's equation (34) to convert body density to %BF, as did Durnin and Womersley originally. In the present study, the equations of Durnin and Womersley (18) combined with Siri's equation (34) gave relatively accurate mean values for %BF (within ~2%BF of H\textsubscript{2}\textsuperscript{18}O-derived %BF) but there was a tendency for the equations to overestimate body fatness at high levels of body fat. Similarly, the equations of Wang et al. (33) overestimated %BF at high levels of fatness, and also underestimated %BF in lean individuals.

We therefore also evaluated the equations of Durnin and Womersley (18) combined with those of Brozek et al. (35) to assess whether the accuracy of the skinfold equations could be improved over using Siri's equation (34). The results from our regression and residual analyses of predicted %BF against H\textsubscript{2}\textsuperscript{18}O-derived %BF indicate that use of the equation of Brozek et al. (35) with those of Durnin and Womersley (18), instead of Siri's equation (34), is more accurate in populations with lower BMI and %BF (34,35). However, he also showed that as body fatness increases, Siri's equation (34) results in increasingly higher %BF estimates compared with the equation of Brozek et al. (35), which was in agreement with our finding. In view of the rising worldwide prevalence of overweight and obesity, our results suggest that the routine use of the equations of Durnin and Womersley (18) combined with that of Brozek et al. (35) rather than Siri's equation (34) may now be preferable.

In this study, the agreement between %BF estimated by H\textsubscript{2}\textsuperscript{18}O dilution and anthropometry was generally good (within ~2%BF), suggesting that the biological and technical sources of error in these methods were minimal for the group as a whole, or the errors were of opposite directions and tended to cancel. In some individuals, however, relatively large variations between methods were observed, which depended on the skinfold equation used. These individual differences can be
attributed to the biological and technical sources of error in both methods. In our population, the most likely source of biological variation with respect to isotope dilution involved individual differences in FFM hydration (shown in Fig. 2). For prediction of %BF by skinfolds, the primary biological sources of variation in our population may have been individual inconsistencies in the distribution of subcutaneous and internal fat, and deviations from the assumed FFM density of 1.1 kg/L (the latter applicable when Siri’s equation was used to convert body density to %BF). Technical errors in isotope analysis were extremely small due to the high measurement precision of the mass spectrometer used in this study, whereas those in skinfold measurement were minimized by having the same, highly trained tester measure all subjects, and by using the average measurements between 2 d in the calculations. It should also be noted that in our study, estimation of %BF from the equations of Wang et al. (33) yielded the least robust residual plot and the widest 95% CI compared with the equations of Durnin and Womersley (18), indicating that the body composition measurement method against which the skinfold equation was originally validated also may be important [dual photon absorptiometry for Wang et al. (33) vs. hydrodensitometry for Durnin and Womersley (18)].

A further finding in our study was that BMI had poor sensitivity for identifying individuals with high body fat. This was also reported by others (8,21). BMI is a commonly used index of adiposity, particularly in epidemiologic studies. In the present study, high correlations between BMI and %BF (r = 0.86 for men and 0.85 for women) and low SEE from the regression equations (see = 3.33 for men and 2.76 for women) were comparable to those of previous studies in which correlations coefficients between BMI with %BF ranged from 0.58 to 0.78 for men and 0.53 to 0.77 for women, and see varied from 3.6 to 4.7 for men and 3.0 to 5.4 for women (6,9,49–55). However, only 41% of the variance in %BF was explained by the variance in BMI. Our data indicate that the reason BMI is such a poor indicator of fatness is that BMI reflects not only the fat mass, but also, and independently, the FFM.

Although BMI had high specificity (90%) for correctly classifying individuals as having normal body fat, it had poor sensitivity (63%) for correctly identifying individuals as having high body fat. Currently, there is no consensus as to what %BF correspond to “healthy” and “unhealthy.” Recently, however, provisional cut-off values for healthy %BF levels based on the standard BMI classifications (38) were published (39) and were used in our analysis. Although the exact sensitivity and specificity estimates for BMI will change depending on the cut-off values chosen, the principle remains the same, i.e., BMI is a relatively poor indicator of adiposity in individuals of Chinese racial origin.

In summary, the standard hydration coefficient for FFM appears to be accurate for use in urban Chinese adults. In addition, simple measurements of skinfold thickness, carried out by a single trained anthropometrist, can provide accurate and reliable estimates of body fatness in Chinese adults provided that appropriate prediction equations are used. Our results also suggest that the combination of the equations of Durnin and Womersley (18) with that of Brozek et al. (35) are the most accurate for estimation of %BF in populations varying widely in body fatness, and that skinfold measurement by a single highly-trained anthropometrist may be preferable to using BMI to determine adiposity in field studies. Further studies are required to confirm our findings and examine in more detail the relationship between BMI and body fatness in different ethnic groups.

ACKNOWLEDGMENTS

We thank B. M. Popkin at the University of North Carolina at Chapel Hill, K. Y. Guo at the Institute of Nutrition and Food Hygiene and F. Zheng at the Institute of Parasitic Diseases, Chinese Academy of Preventive Medicine, for discussions about the protocol; Y. P. Li, S.H.J. Gao and J. Song for their technical assistance; G. G. Dolni-kowski and I. Ellis for isotopic analyses; G. E. Dallal for statistical advice; P. Fuss for editorial assistance with the manuscript; and the subjects and their families for participating in the study.

LITERATURE CITED


