

Body composition techniques and the four-compartment model in children

DAVID A. FIELDS AND MICHAEL I. GORAN

Division of Physiology and Metabolism, Department of Nutrition Sciences, and The Clinical Nutrition Research Unit, University of Alabama at Birmingham, Birmingham, Alabama 35294

Received 2 January 2000; accepted in final form 1 April 2000

Fields, David A., and Michael I. Goran. Body composition techniques and the four-compartment model in children. *J Appl Physiol* 89: 613–620, 2000.—The purpose of this study was to compare the accuracy, precision, and bias of fat mass (FM) as assessed by dual-energy X-ray absorptiometry (DXA), hydrostatic weighing (HW), air-displacement plethysmography (PM) using the BOD POD body composition system and total body water (TBW) against the four-compartment (4C) model in 25 children (11.4 ± 1.4 yr). The regression between FM by the 4C model and by DXA deviated significantly from the line of identity (FM by 4C model = $0.84 \times \text{FM by DXA} + 0.95$ kg; $R^2 = 0.95$), as did the regression between FM by 4C model and by TBW (FM by 4C model = $0.85 \times \text{FM by TBW} - 0.89$ kg; $R^2 = 0.98$). The regression between FM by the 4C model and by HW did not significantly deviate from the line of identity (FM by 4C model = $1.09 \times \text{FM by HW} + 0.94$ kg; $R^2 = 0.95$) and neither did the regression between FM by 4C (using density assessed by PM) and by PM (FM by 4C model = $1.03 \times \text{FM by PM} + 0.88$; $R^2 = 0.97$). DXA, HW, and TBW all showed a bias in the estimate of FM, but there was no bias for PM. In conclusion, PM was the only technique that could accurately, precisely, and without bias estimate FM in 9- to 14-yr-old children.

total body water; hydrostatic weighing; plethysmography

CHILDHOOD OBESITY IS INCREASING at an alarming rate and is predictive of adulthood obesity (9, 12, 26), with deleterious effects on future health status (6, 9, 15, 26). The increasing obesity and strong relation with health risk highlight the importance of identifying accurate techniques for measuring total body fat in children. Accurate techniques are required both for clinical tracking and for monitoring for laboratory-based research studies.

Two-compartment (2C) models, such as total body water (TBW) and densitometry, are commonly used to evaluate body composition in children. This approach, however, may not be the most accurate in children because of potential changes in the various inherent assumptions of 2C techniques during growth and maturation, such as changes in the hydration and the density of the fat-free mass (16). Baumgartner et al. (1) have suggested that the four-compartment model (4C model) be used as the “gold

standard” in adults and the Lohman equation (17), against which other body composition techniques are to be evaluated, in children. This multicompartiment approach involves independent assessment of body density, body water, and bone. This approach can account for deviations in the quality of fat-free mass, in part, because the 4C model measures the individual constituents of the fat-free mass (aqueous and bone) rather than assuming a constant density of 1.100 g/cm^3 and hydration of 73.2%. Although this multicompartiment approach is preferred, it is impractical for most laboratories because of the cost and necessary equipment needed to measure TBW and bone mineralization. Although the advantages of the 4C model are numerous, it has not been widely used or compared with other techniques in a pediatric population.

Therefore, the purpose of this study was to examine the accuracy of body fat estimates from common and traditional body composition techniques including dual-energy X-ray absorptiometry (DXA), hydrodensitometry (hydrostatic weighing; HW), air-displacement plethysmography (PM), and TBW relative to a true criterion of body fat derived from the 4C model in children.

METHODS

Twenty-five healthy children participated in this study, of whom 14 were male (11 Caucasian American and 3 African American) and 11 were female (9 Caucasian American and 2 African American). Subjects were screened by a medical history evaluation and were ineligible if they were taking medications known to affect body composition or physical activity (e.g., prednisone, Ritalin, growth hormone) or had been diagnosed with syndromes known to affect body composition and/or fat distribution (e.g., Cushing’s syndrome, Down’s syndrome, Type I diabetes, hypothyroidism) or had experienced any major illness since birth. The study was approved by the University of Alabama at Birmingham Institutional Review Board for human use, and written informed consent was obtained from each volunteer before testing.

Protocol

The children were admitted to the General Clinical Research Center at the University of Alabama at Birmingham in the late afternoon for an overnight visit. After arrival,

Address for reprint requests and other correspondence: M. I. Goran, Dept. of Preventive Medicine, Inst. for Preventive Research, Univ. of Southern California, 1540 Alcazar St., Los Angeles, CA 90033 (E-mail: goran@hsc.usc.edu).

The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked “advertisement” in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

dinner was served at ~1700, a baseline urine sample was collected, and a dose of deuterium was orally administered. An evening snack was allowed as long as it was consumed before 2000. The following morning, resting energy expenditure was measured, blood was collected for hormone and lipid analysis, and an oral glucose tolerance test was administered (data not reported in this paper). On waking in the morning, two urine samples were collected, and the children were then fed breakfast and allowed to leave. Two weeks later, the children arrived at the Energy Metabolism Research Laboratory at 0700 for the DXA, HW, PM, and TBW tests in the fasted state. Additionally, two urine samples were taken. Total body PM and DXA were randomly administered; however, HW was always performed last to ensure that an elevated body temperature from HW did not affect percent fat estimates while children were in the BOD POD.

Assessment of bone mineral content by DXA. Total bone mineral content, fat, and soft-lean tissue were measured by use of a Lunar DPX-L densitometer (Lunar Radiation, Madison, WI). All body scans were analyzed by using Pediatric Version 1.5 extended-analysis program for total body composition

Assessment of total body density by HW. Total body density was measured by underwater weighing, with simultaneous measurement of residual lung volume by using the closed-circuit oxygen dilution technique (27). Underwater weight was measured to the nearest 50 g in a stainless steel tank in which the subject, wearing a one-piece swimsuit, was suspended from an LCL 20 shear beam load cell calibrated from 0 to 10,000 g (Omega, Stamford, CT). After one practice trial, underwater weight and residual lung volume were measured simultaneously five times. The average of multiple trial densities within 0.001 g/cm³ were used from the underwater weight. Fat mass was calculated from whole body density (g/cm³) with the Lohman equation (17), which is similar to the Siri equation (23) but uses age-dependent constants for changes in the density of the fat-free mass and hydration status (see Table 1).

Assessment of total body density by PM. Total body density was also evaluated with the BOD POD body composition system (version 1.69, Life Measurement Instruments, Concord, CA) as previously described (4). Briefly, the testing procedure involves several steps. First, calibration was conducted before subject entry into the BOD POD. Calibration involves the computation of the ratio of the pressure amplitudes (reference chamber and testing chamber) for an empty chamber and a known volume (49.860 liters) (3). After the calibration was completed and the testing procedures were fully explained, the subject then entered the BOD POD in a tight-fitting swimsuit for two trials of ~45 s each. During this stage, the subject's raw body volume (Vb_{raw}) was determined. The last step involved measurement of the thoracic gas volume (Vtg). This stage requires the subject to sit quietly in the BOD POD and breathe through a disposable tube and

filter connected to the reference chamber in the rear of the BOD POD. After four or five normal breaths, the airway was occluded during midexhalation, and the subject was instructed to make two quick, light pants.

Body density (Db) from the BOD POD was calculated as follows

$$Db = M/(Vb_{raw} + 0.40 Vtg - SAA)$$

where surface area artifact (SAA) is automatically computed by the computer software and is used to account for isothermic air due to the subject's body surface area and M is the mass of the subject. Fat mass was then calculated from whole body density (g/cm³) with the Lohman equation, as described in *Assessment of body density by HW* (17).

Assessment of TBW by isotope dilution. Total body water was determined using deuterated water (²H₂O). The dosing procedure followed the technique developed by Schoeller and colleagues (21, 22). Briefly, the isotope-loading dose was ~0.12 g ²H/kg body mass. Two urine samples were taken the morning after dosing (at the General Clinical Research Center), and two additional urine samples were taken ~10 days after dosing (at the Physiology and Metabolism Lab). ²H₂O dilution space was calculated from the enrichment of ²H₂O in the body at zero time by extrapolation of the log enrichment vs. time plots back to zero time (2) using the following equation (8, 22)

$$\text{Dilution space (liters)} = d/20.02 \times 18.02 1/R \times E$$

where d is grams of ²H₂O given, R is the standard ratio of ²H to ¹H (0.00015576), and E is enrichment of ²H₂O at the extrapolated zero time (the % above background). All samples were done in triplicate on an Optima mass spectrometer (Micromass, Beverly, MA). Total body water was determined by taking the mean of the zero-time isotope dilution space for ²H₂O and dividing by 1.04 to correct for the exchange with nonaqueous tissues (22). Total body water was divided by 0.9937 (this is the density of water at body temperature) to convert from liters to kilograms. Fat mass was estimated from TBW by correcting for the hydration status of the child by using the Lohman equation, and fat mass was calculated as the difference between body weight and fat-free mass (17).

Calculation of fat mass using the 4C model. The 4C model from Lohman (17) was used as the criterion method against which all the other body composition techniques (DXA, HW, PM, and TBW) were evaluated. The 4C equation is as follows

$$\%Fat = (2.747/Db - 0.714 W + 1.146 B - 2.053) \times 100$$

where Db is body density (g/cm³), W is water content of the body in liters expressed as a fraction of body mass, and B is bone mineral content in kilograms expressed as a fraction of body mass.

Statistics

Accuracy, precision, and bias were examined in each of the individual body composition techniques. Fat mass by the 4C model was selected as the criterion method because this model involves the fewest assumptions. Statistical significance was set at $P < 0.05$.

Regression analysis was employed to determine the accuracy of the individual body composition techniques. The technique being examined was considered accurate if the regression between fat mass by the 4C model and the technique in question had a slope not significantly different from 1 and an intercept not significantly different from 0. This analysis tests the hypothesis that the regression of fat mass by the 4C

Table 1. Equations for estimating %fat from body density

Age, yr	Boys		Girls	
	C ₁	C ₂	C ₁	C ₂
9–10	5.30	4.80	5.35	4.95
11–12	5.23	4.81	5.25	4.84
13–14	5.07	4.64	5.12	4.69

C₁ and C₂ are to be substituted into the Siri (23) equation, where %fat = (C₁/Db - C₂) × 100. Values were taken from Lohman (17).

model and by the other techniques do not significantly deviate from the line of identity.

The precision of the body composition techniques was assessed by the R^2 and the standard error of the estimate (SEE).

Potential bias between the techniques and the criterion method (i.e., the 4C model) was examined by using residual plots. This particular test examines the difference in fat mass between a technique and the criterion method as a function of fat mass by the criterion method. A nonsignificant correlation indicates no bias in the technique across the range of fatness.

RESULTS

The physical characteristics of the subjects are presented in (Table 2). A summary of fat mass estimates from all of the body composition techniques is presented in Fig. 1, and their respective P values are given in Table 3. Accuracy of fat mass was examined by the regression of fat mass by the 4C model against fat mass by each of the independent body composition techniques. The relationships between fat mass by the 4C model and by the independent techniques in question are shown in the top panels of Figs. 2–5, and a summary of the regression analyses is shown in Table 4.

The regressions for fat mass by DXA and fat mass by TBW vs. fat mass by the 4C model significantly deviated from the line of identity because of slopes that were significantly different from 1.0 (Table 4). However, the regression relationships for fat mass by HW and fat mass by PM vs. fat mass by the 4C model did not deviate significantly from the line of identity (Table 4).

Precision of the individual body composition techniques was determined from the R^2 and the SEE from the regression analysis; a summary of these results is listed in Table 4. TBW provided the most precise estimate of body fat levels, with fat mass by TBW explaining 98% of the variance in fat mass by the 4C model and SEE of 1.5 kg. Fat mass by PM explained 97% of the variance in fat mass by the 4C model with a SEE of 1.7 kg, fat mass by DXA explained 95% of the variance in fat mass by the 4C model with a SEE of 2.0 kg, and, lastly, fat mass by HW explained 95% of the variance in fat mass by the 4C model with a SEE of 2.1 kg.

Residual plots were performed for each technique to determine whether bias existed between the technique being studied and the criterion method (4C model). This approach examines the discrepancy between the

Table 2. *Physical characteristics*

Age, yr	11.4 ± 1.4
Body weight, kg	52.5 ± 16.7
Height, cm	153.0 ± 11.4
Bone mineral, kg	1.9 ± 0.51
Body density from PM, g/cm ³	1.0332 ± 0.0204
Body density from HW, g/cm ³	1.0384 ± 0.0187*
TBW kg	25.9 ± 6.9

Values are means ± SD. TBW, total body water. *Hydrostatic weighing (HW) density statistically higher than air-displacement plethysmography (PM) density ($P < 0.001$).

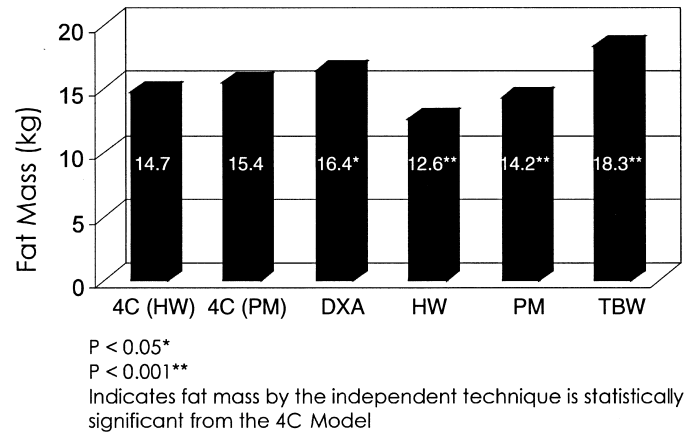


Fig. 1. Fat mass by various body composition techniques. 4C HW, 4-compartment model using density from hydrostatic weighing (HW); 4C PM, 4C model using density from plethysmography (PM); DXA, dual-energy X-ray absorptiometry; TBW, total body water.

technique in question and the 4C model as a function of fat mass as determined by the 4C model. The plots are shown in the bottom panels of Figs. 2–5 and in Table 5. For DXA, there was a significant correlation for the discrepancy with fat mass by the 4C model ($r = 0.47$). For HW, there was a significantly negative correlation with fat mass by the 4C model ($r = -0.53$). For TBW, there was a significant correlation for the discrepancy with fat mass by the 4C model ($r = 0.61$). PM was the only technique examined that did not exhibit any bias across the range of body fatness ($r = -0.34$).

DISCUSSION

This study examined the accuracy, precision, and bias of fat mass as assessed by DXA, HW, PM, and TBW relative to the 4C model in children. This is significant because to date only a paucity of literature exists examining common laboratory techniques with the 4C model in children. Our major finding is that, of the four laboratory techniques studied, it appeared that PM was a valid technique for the assessment of body fat in children. However, DXA can be used if a “correction factor” is used.

DXA Findings

The regression between fat mass by the 4C model and fat mass by DXA significantly deviated from the line of identity (actual fat mass = $0.84 \times$ fat mass by DXA + 0.95). Additionally, DXA showed bias across the range of fatness, whereby DXA underpredicted fat mass in leaner subjects and overpredicted fat mass in heavier subjects. This may be attributed to heavier children not fitting exactly within the scan area. Thus some of the upper limb fat mass may have been left out in the calculation of fat mass by the computer software. To our knowledge, this is the first study to cross-validate the DXA against the 4C model in children using the Lunar DPX-L. Roemmich et al. (20) found similar results using a Hologic DXA. That study found percent fat estimates by DXA to be systematically

Table 3. Comparison table between fat mass by the independent techniques and their respective P values

	DXA (16.4)	HW (12.6)	PM (14.2)	TBW (18.3)	4C (HW) (14.7)	4C (PM) (15.4)
DXA (16.4)		$P < 0.000$	$P < 0.000$	$P < 0.009$	$P < 0.003$	$P = 0.084$
HW (12.6)			$P < 0.002$	$P < 0.000$	$P < 0.000$	$P < 0.000$
PM (14.2)				$P < 0.000$	$P = 0.176$	$P < 0.001$
TBW (18.3)					$P < 0.000$	$P < 0.000$
4C (HW) (14.7)						$P < 0.002$
4C (PM) (15.4)						

Values in parentheses are fat mass in kilograms. DXA, dual-energy X-ray absorptiometry; 4C, four-compartment model.

higher in both males and females and across the range of maturation (9–15 yr) compared with the 4C model. They conclude that the Hologic DXA overestimates percent fat because the computer software assumes a hydration status of 73.2%.

DXA is commonly used in the assessment of body composition in children. This is primarily because of the ease with which the test can be administered and because until recently it was the only alternative to HW. DXA has advantages over other laboratory techniques in that it can give whole body estimates of body composition as well as of regional composition of fat, lean mass, and bone. Pintauro et al. (19) validated

DXA measures of fat mass against carcass analysis using a pig model as the criterion method. They found that the relationship between DXA fat and carcass fat significantly deviated from the line of identity. However, Pintauro et al. used multivariate analysis to help explain the discrepancy in DXA and the carcass data, and they derived a correction factor that would improve the accuracy in DXA measures of body composition. The correction factor is

$$\text{Fat mass} = (0.78 \times \text{DXA lean}) + (0.16 \times \text{body wt}) + 0.34 \text{ kg}$$

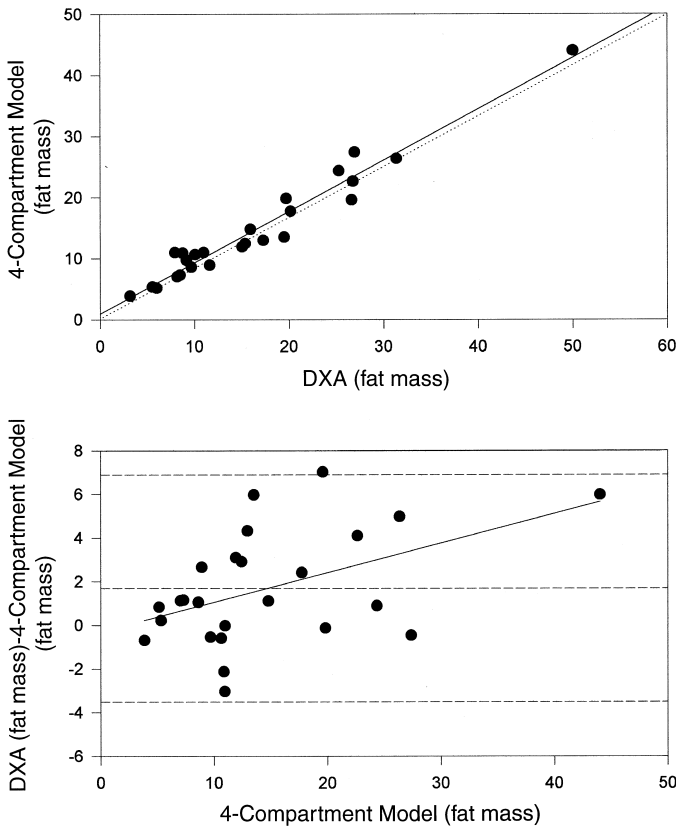


Fig. 2. Top: regression of fat mass by 4C model against fat mass by DXA. Dotted line is line of identity (regression slope = 1; regression intercept = 0). Regression line significantly deviated from line of identity ($P < 0.05$). Bottom: residual plot. Middle dashed line represents mean difference of fat mass from DXA minus fat mass from 4C model; upper and lower dashed lines represent ± 2 SD from the mean. Solid line is regression line. Bias between the techniques was observed, as indicated by a significant P value ($P < 0.05$).

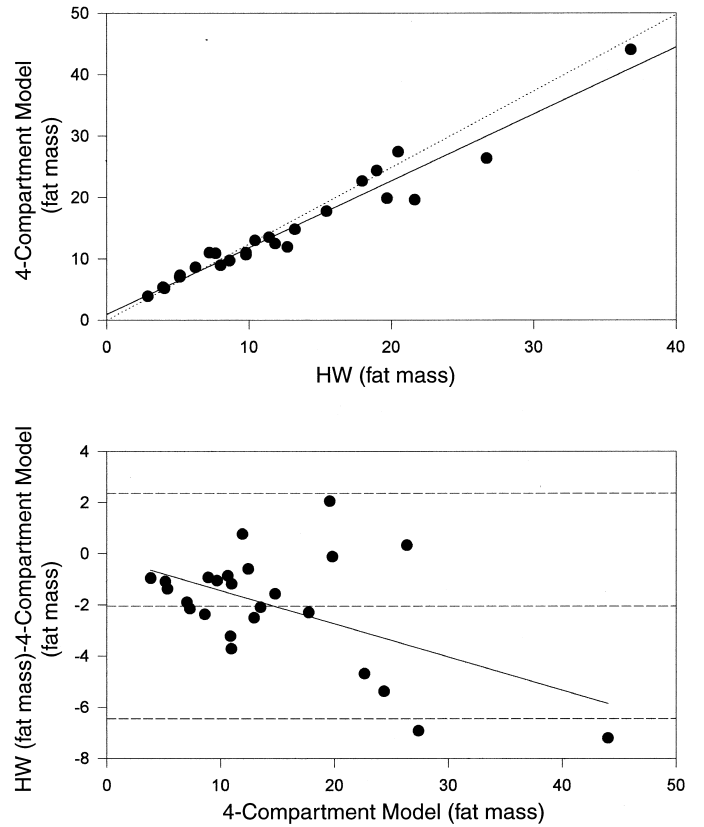


Fig. 3. Top: regression of fat mass by 4C model against fat mass by HW. Dotted line is line of identity (regression slope = 0). Slope and intercept were not significantly different from 1 and 0, respectively. Bottom: residual plot. Middle dashed line represents mean difference of fat mass from HW minus fat mass from 4C model; upper and lower dashed lines represent ± 2 SD from the mean. Solid line is regression line. Bias between the techniques was observed, as indicated by a significant P value ($P < 0.01$).

This correction factor improves on the measurement of fat mass because the regression equation has been standardized with a known laboratory standard (direct carcass analysis of the pigs) (19).

When the correction factor was applied to the DXA data in the current study, the regression between fat mass by the 4C model and fat mass by DXA did not significantly deviate from the line of identity (4C fat mass = $0.92 \times$ fat mass by DXA - 0.75 kg). Additionally, no bias was observed between the two techniques. Thus it appears that DXA can be used in evaluation of body composition in children as long as the Pintauro correction factor is used with the benefit of regional bone, lean, and fat estimates. Therefore, our current analysis reiterates the importance of the previously described DXA correction factor.

Hydrostatic Weighing Findings

The regression between fat mass by HW and by the 4C model did not significantly deviate from the line of identity (actual fat mass = $1.09 \times$ fat mass by HW + 0.94 kg). The residual plot analysis indicated that fat mass was underestimated in the fatter children and overestimated in the leaner children (Table 3, Fig. 3, bottom).

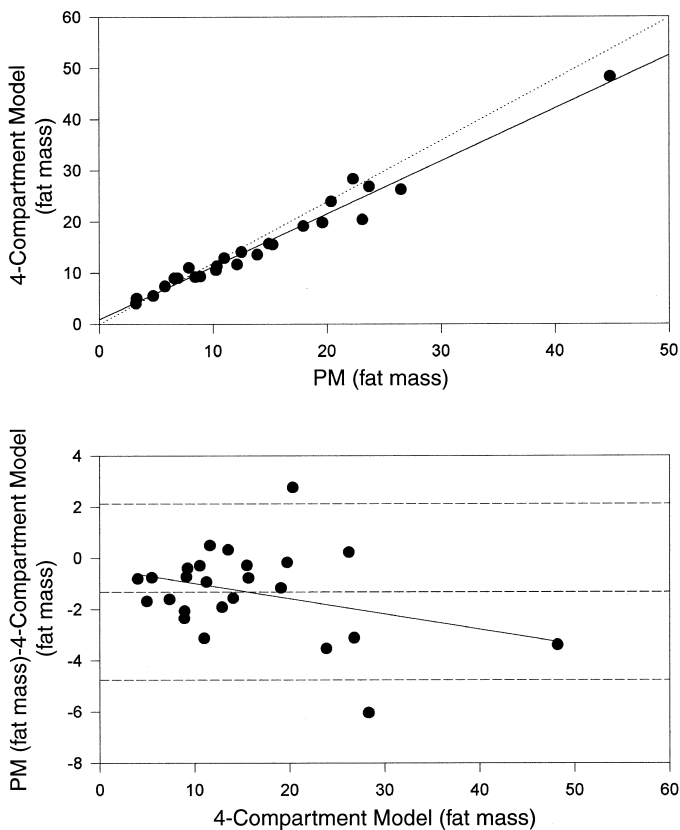


Fig. 4. Top: regression of fat mass by 4C model against fat mass by PM. Dotted line is line of identity (regression slope = 1; regression intercept = 0). Slope and intercept were not significantly different from 1 and 0, respectively. Bottom: residual plot. Middle dashed line represents mean difference of fat mass from PM minus fat mass from 4C model; upper and lower dashed lines represent ± 2 SD from the mean. No bias between the techniques was observed.

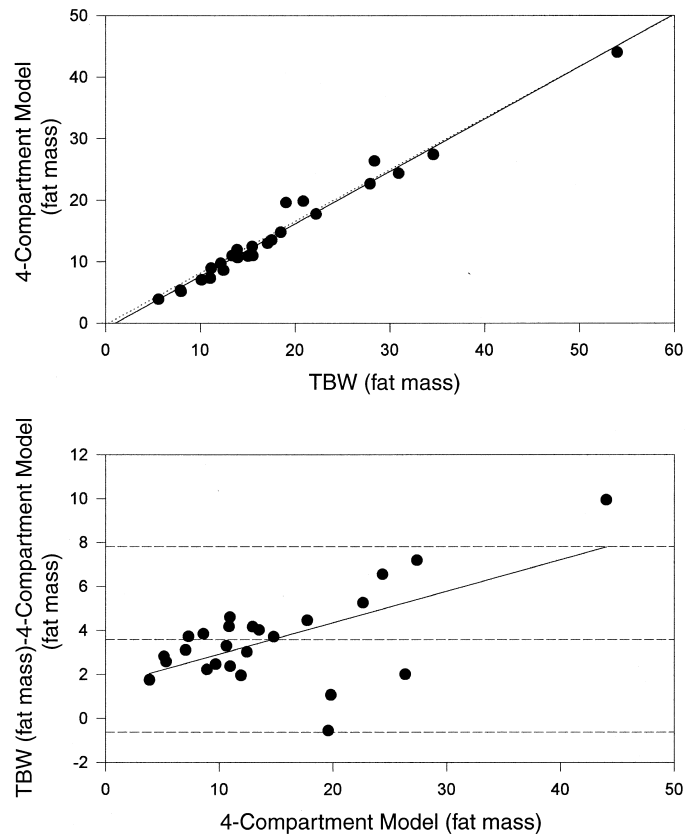


Fig. 5. Top: regression of fat mass by 4C model against fat mass by TBW. Dotted line is line of identity (regression slope = 1; regression intercept = 0). Regression line significantly deviated from the line of identity ($P < 0.05$). Bottom: residual plot. Middle dashed line represents mean difference of fat mass from TBW minus fat mass from 4C model; upper and lower dashed lines represent ± 2 SD from the mean. Solid line is regression line. Bias between the techniques was observed, as indicated by a significant P value ($P < 0.01$).

The regression of fat mass by HW using the Lohman age- and gender-adjusted equations (17) against the 4C model in children suggests that the assumed densities for the fat-free mass are appropriate. The use of HW as a measurement tool to evaluate body composition in children is difficult, partly because subject compliance is difficult. It is difficult for many children of 12 yr of age or younger to submerge their heads under the water while exhaling all the air in their lungs and remaining still. Thus HW is not commonly used as a technique to evaluate body composition in pediatric populations and is generally not recommended for practical reasons, especially with younger children.

Table 4. Summary of regression of fat mass by the 4C model vs. the other independent techniques

	R^2	Intercept, kg	Slope	SEE, kg
DXA	0.95	0.95 ± 0.76	$0.84 \pm 0.04^*$	2.0
HW	0.95	0.94 ± 0.80	1.09 ± 0.05	2.1
PM	0.97	0.88 ± 0.64	1.03 ± 0.38	1.7
TBW	0.98	-0.89 ± 0.60	$0.85 \pm 0.03^*$	1.5

*Slope significantly different from 1 ($P < 0.05$). SEE, standard error of the estimate.

Table 5. *Residual plot analysis: summary of the discrepancy between techniques between the independent techniques and the 4C model*

	<i>r</i> Value
DXA	0.47* ($P < 0.018$)
HW	-0.53* ($P < 0.006$)
PM	-0.34 ($P = 0.100$; NS)
TBW	0.61* ($P < 0.001$)

A nonsignificant (NS) correlation demonstrates that no significant bias in fat mass exists between the technique under examination and the 4C model. A positive correlation indicates that the technique being studied underestimated fat mass in leaner subjects and overestimated fat mass in heavier subjects. A negative correlation indicates that the technique being studied underestimated fat mass in heavier subjects and overestimated fat mass in leaner subjects.

PM Findings

The regression between fat mass by PM and the 4C model did not significantly deviate from the line of identity (actual fat mass = $1.03 \times$ fat mass by PM + 0.88 kg), indicating that PM is a valid technique for the evaluation of body composition in children. In addition, the residual plot analysis showed no bias across the range of fatness.

To date, only one study has looked at the feasibility of PM in children (18). PM has several advantages over the more traditional 2C-based model, HW. Subject compliance is high because head submersion under water is unnecessary, the subject appears to tolerate the test more easily, and the chamber is less intimidating than the hydrostatic tank.

However, PM is not without limitations. First, the greatest sources of error when using PM are temperature, pressure, and relative humidity (5, 7, 10, 11, 24, 25). This was the major reason that PM was not used until recently, although the basic principle had been around for ~ 100 yr. Our study attempted to minimize this source of error by having all subjects be evaluated in the plethysmograph before exercise testing. Second, Taylor et al. (25) demonstrated a large degree of variation in body volume measurements when there is movement within the chamber during testing. We found that it took approximately twice as long to measure a child (30 min) vs. an adult (17 min). This was primarily a result of the children not remaining still for the test. When we encouraged all the children to remain still, we encountered moderate success. Third, the ratio of chamber volume to subject volume has been recommended to be below 6 (7). This study yielded a ratio close to 9. Currently, nothing can be done to resolve the chamber volume-to-subject volume ratio given the current specifications of the BOD POD instrument. However, the first two issues can be alleviated by performing all tests before exercise testing and encouraging the children to remain still during the measurement.

In summary, PM is a valid technique in the determination of body composition in children as indicated by regression analysis (regression of 4C model fat mass

and PM fat mass not significantly different from the line of identity) and residual plots (no bias was observed, as indicated by a nonsignificant correlation in the residual plot; Fig. 3).

TBW Findings

The main findings for the TBW data revealed an overestimation in fat mass in the heavier children relative to the other techniques with the regression between fat mass by the 4C model and fat mass by TBW significantly deviated from the line of identity (actual fat mass = $0.85 \times$ fat mass by TBW - 0.89 kg). Additionally, TBW showed bias across the range of fat mass, with leaner children having an underprediction in fat mass and more obese children having an overprediction in fat mass.

The TBW technique potentially has the greatest source of error because it relies on the assumption of a constant hydration status for the fat-free mass. We attempted to alleviate varying hydration status due to maturation by using age and gender constants developed by Lohman (16, 17). Even when this adjustment was used, it would appear that TBW was not a valid technique for the assessment of body composition in children.

With the use of the measured value for TBW and the estimates of fat-free mass derived from the 4C model using the density from PM (because PM was found to be a valid technique), our data suggest a hydration status of 70%. This hydration status should be viewed with caution because fat-free mass was derived from techniques that were not independent from each other (TBW appearing in both the numerator and denominator). This hydration status is similar to that reported by Hewitt et al. (72.7%; Ref. 13) but is lower than that reported by Roemmich et al. (75.6%; Ref. 20) and Lohman (17). There are three possible explanations for our lower hydration status. 1) To correct for isotope exchange with nonaqueous hydrogen atoms, we used a correction of 1.04, whereas others used a smaller correction (0.95–0.97), thus reducing our estimates of TBW by $\sim 6\%$ (1, 13, 14). 2) Children in our group were substantially heavier and more obese than those in the studies of Hewitt et al. and Roemmich et al. (13, 20). This could potentially lead to more variation in the estimates of TBW. 3) The standard deviation for our TBW was 6.9 kg, which is substantially larger than what has been reported ($\sim 2\%$) (13, 20). We are currently exploring other explanations for our seemingly lower hydration status.

Recommendations

This study investigated the feasibility in using DXA, HW, PM, and TBW in the evaluation of body composition in children. DXA and TBW were shown not to be valid, as indicated by slopes that deviated significantly from the line of identity. DXA, HW, and TBW showed bias across the range of fatness; thus only PM was shown to be valid with no bias.

We performed the same analysis with fat-free mass as was performed with fat mass (i.e., regression of 4C model fat-free mass vs. fat-free mass of independent techniques and residual plots). The same relationships that are reported for fat mass were seen for fat-free mass.

Recently, DXA has become the primary accepted research tool for evaluation of body composition in children, partly because of the ease of the test but also because no real viable alternatives existed until now. In 1995, Life Measurement Instruments developed an instrument based on plethysmographic principles called the BOD POD. It has advantages over HW in that it does not involve water displacement and it does not require radiation exposure as DXA does. To our knowledge, only one other study, by Nunez et al. (18), has investigated the efficacy of the BOD POD in children. They found that the regression of total body density by PM vs. total body density by HW significantly deviated from the line of identity. One possible explanation for this discordance could be the apparel of the children. The study by Nunez had the children wear a minimal amount of clothing, whereas we supplied standardized clothing for both boys (Speedo swimsuit) and girls (a tight-fitting swimsuit top and bottom). A prior finding from this lab found the type of clothing to affect measurement in the BOD POD (4).

The 4C model has obvious advantages over 2C models because the reliance on a constant for the proportions and densities of the fat mass is eliminated. The 4C model ameliorates the effect of maturation, hydration status of the fat-free mass, and bone mineralization in the estimation of body fatness. This is an important issue in children because it has been shown that hydration status decreases and bone mineralization increases with age (16). However, the cost of the 4C model does not allow wide implementation of the 4C model for most labs. Thus a more practical measurement tool is needed. We feel that our data support the use of PM as an accurate, precise, and nonbiased tool in the evaluation of body composition in children.

Conclusions

This study investigated the accuracy, precision, and bias in four research-based techniques (DXA, HW, PM, and TBW) using the 4C model as the criterion method. These data support the use of PM as a valid body composition tool that can accurately, precisely, and without bias estimate fat mass in 9- to 14-yr-old children. However, the need exists for more research to be done in groups of minority children. Additionally, DXA can be used to accurately assess body composition provided that the correction factor by Pintauro et al. is used. DXA may also be useful in evaluation of regional bone mass, lean mass, and fat mass.

This research was supported by the US Department of Agriculture (grant 95-37200-1643), by the National Institute of Child Health and Human Development (grants RO1 HD/HL-33064 and RO1 DK-

49779-03), and in part by a General Clinical Research Center grant (MO1-RR-00032).

REFERENCES

1. Baumgartner RN, Heymsfield SB, and Lichtman S. Body composition in elderly people: effect of criterion estimates on predictive equations. *Am J Clin Nutr* 53: 1345–1353, 1991.
2. Coward WA, Prentice AM, Murgatroyd PR, Davies HL, Cole TJ, Sawyer M, Goldberg GR, Halliday D, and Mac-Namara PJ. Measurement of CO₂ and water production rates in man using ²H,¹⁸O-labeled H₂O: comparisons between calorimeter and isotope values. In: *Human Energy Metabolism: Physical Activity and Energy Expenditure Measurements in Epidemiological Research Based Upon Direct and Indirect Calorimetry*. Vageningen, The Netherlands: Euro-Nutr, 1984, p. 126–128. (Euro-Nutr Publ. Ser. 5)
3. Dempster P and Aitkens S. A new air displacement method for the determination of human body composition. *Med Sci Sports Exerc* 27: 1692–1697, 1995.
4. Fields DA, Hunter GR, and Goran MI. Validation of the BOD POD with hydrostatic weighing: influence of body clothing. *Int J Obes* 24: 200–205, 2000.
5. Fomon SJ, Jensen RL, and Owen GM. Determination of body volume of infants by a method of helium displacement. *Ann NY Acad Sci* 110: 80–90, 1963.
6. Freedman DS, Srinivasan SR, Valdez RA, Williamson DF, and Berenson GS. Secular increases in relative weight and adiposity among children over two decades: the Bogalusa heart study. *Pediatrics* 99: 420–426, 1997.
7. Gnaedinger RH, Reineke EP, Pearson AM, Van Huss WD, Wessel JA, and Montoye HJ. Determination of body density by air displacement, helium dilution, and underwater weighing. *Ann NY Acad Sci* 110: 96–108, 1963.
8. Goran MI, Peters EJ, Herndon DN, and Wolfe RR. Total energy expenditure in burned children using the doubly labeled water technique. *Am J Physiol Endocrinol Metab* 259: E576–E585, 1990.
9. Gortmaker SL, Dietz WH, Sobol AM, and Wehler CA. Increasing pediatric obesity in the United States. *Am J Dis Child* 141: 535–540, 1987.
10. Gundlach BL, Nijkrake HGM, and Hautvast JGAJ. A rapid and simplified plethysmometric method for measuring body volume. *Hum Biol* 52: 23–33, 1980.
11. Gundlach BL and Visscher GJW. The plethysmometric measurement of total body volume. *Hum Biol* 58: 783–799, 1986.
12. Guo SS and Chumlea WC. Tracking of body mass index in children in relation to overweight in adulthood. *Am J Clin Nutr* 70: 145S–148S, 1999.
13. Hewitt MJ, Going SB, Williams DP, and Lohman TG. Hydration of the fat-free body mass in children and adults: implications for body composition assessment. *Am J Physiol Endocrinol Metab* 265: E88–E95, 1993.
14. Heymsfield SB, Wang J, Lichtman S, Kamen Y, Kehayias J, and Pierson N. Body composition in elderly subjects: a critical appraisal of clinical methodology. *Am J Clin Nutr* 50: 1167–1175, 1989.
15. Lauer RM and Clarke WR. Childhood risk factors for high adult blood pressure: the Muscatine study. *Pediatrics* 84: 633–641, 1989.
16. Lohman TG. Applicability of body composition techniques and constants for children and youths. *Exerc Sport Sci Rev* 14: 325–357, 1986.
17. Lohman TG. Assessment of body composition in children. *Pediatr Exerc Sci* 1: 19–30, 1989.
18. Nunez C, Kovera AJ, Pietrobello A, Heshka S, Horlick M, Kehayias JJ, Wang Z, and Heymsfield SB. Body composition in children and adults by air displacement plethysmography. *Eur J Clin Nutr* 53: 382–387, 1999.
19. Pintauro SJ, Nagy TR, Duthie CM, and Goran MI. Cross-calibration of fat and lean measurements by dual energy X-ray absorptiometry to pig carcass analysis in the pediatric body weight range. *Am J Clin Nutr* 63: 293–298, 1996.

20. **Roemmich JN, Clark PA, Weltman A, and Rogol AD.** Alterations in growth and body composition during puberty. I. Comparing multicompartment body composition models. *J Appl Physiol* 83: 927–935, 1997.
21. **Schoeller DA.** Hydrometry. In: *Human Body Composition*, edited by Roche AF, Heymsfield SB, and Lohman TG. Champaign, IL: Human Kinetics, 1996, p. 25–43.
22. **Schoeller DA, van Santen E, Peterson W, Dietz W, Jaspan J, and Klein PD.** Total body water measurement in humans with ^{18}O and ^2H labeled water. *Am J Clin Nutr* 33: 2686–2693, 1980.
23. **Siri WE.** Body composition from fluid spaces and density: analysis of methods. In: *Techniques for Measuring Body Composition*, edited by Brozek J and Henschel A. Washington, DC: Natl. Acad. Sciences/Natl. Res. Council, 1961, p. 223–224.
24. **Sly PD, Lanteri C, and Bates JHT.** Effect of the thermodynamics of an infant plethysmograph on the measurement of thoracic gas volume. *Pediatr Pulmonol* 8: 203–208, 1990.
25. **Taylor A, Scopes JW, du Mont G, and Taylor BA.** Development of an air displacement method for whole body volume measurement of infants. *J Biomed Eng* 7: 9–17, 1985.
26. **Troiano RP, Flegal KM, Kuczmarski RJ, Campbell SM, and Johnson CL.** Overweight prevalence and trends for children and adolescents. *Arch Pediatr Adolesc Med* 149: 1085–1091, 1995.
27. **Wilmore JH.** A simplified method for the determination of residual lung volume. *J Appl Physiol* 27: 96–100, 1969.
28. **Zumdahl SS.** Gases. In: *Chemistry*. Lexington, MA: Heath, 1989, p. 178–180.

