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The four-compartment model of body composition in obese Chilean schoolchildren, by pubertal stage: Comparison with simpler models

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ABSTRACT

Objectives: We assessed the agreement of body fat and fat-free mass measured by simpler methods against the four-compartment model (4C).
Methods: In 60 obese schoolchildren (body mass index ≥95th percentile) between the ages of 8 and 13 y who were recruited from one school in Chile, multicompartmental body composition was estimated with the use of isotopic dilution, plethysmography (BodPod), radiographic absorptiometry (DEXA), and anthropometric equations. These results were compared to those of the 4C model, which is considered the gold standard.
Results: For body fat, the 4C model showed the best agreement with DEXA for boys in Tanner stages I and II ($r = 0.971$) and with isotopic dilution for boys in Tanner stages III and IV ($r = 0.984$). The best agreement in girls occurred with isotopic dilution, regardless of pubertal stage ($r = 0.948$ for Tanner stages I and II; $r = 0.978$ for Tanner stages III and IV). Both isotopic dilution and the Huang, Ellis, and Deurenberg anthropometric equations underestimated body fat in boys; by contrast, DEXA, BodPod, and the Slaughter equation overestimated body fat in boys. All of the equations underestimated body fat in girls. For fat-free mass in both boys and girls, the 4C model showed the best agreement with isotopic dilution, regardless of pubertal stage. The Huang equation showed the best agreement for boys ($r = 0.730$ for Tanner stages I and II; $r = 0.695$ for Tanner stages III and IV) and for girls in Tanner stages I and II ($r = 0.884$). The Ellis equation had the best agreement for girls in Tanner stages III and IV ($r = 0.917$).
Conclusions: For obese Chilean children of both sexes, isotopic dilution and DEXA were the two-compartment methods that had the best agreement with the gold-standard 4C model for both body fat and fat-free mass; these were followed by the Huang and Ellis anthropometric equations.

Introduction

In Chile, the prevalence of childhood obesity has climbed to 23.1%, and metabolic syndrome affects 25% to 35% of obese Chilean schoolchildren (body mass index ≥ 95th percentile) [1, 2]. Scientific evidence suggests that increased body fat (BF)—especially if it is distributed in the abdominal area—is an early risk factor for cardiovascular disease. Increased BF also correlates directly with disorders related to heart disease, including the magnitude and prevalence of insulin resistance, dyslipidemia, systemic inflammation, type 2 diabetes mellitus, high blood pressure, heart attack, and premature death [3–7]. Therefore, improving pediatric BF assessment in terms of both improving the accuracy of the measurement and having a better understanding of its relationship with cardiometabolic disorders is an important objective for both scientific research and clinical practice [8–10].

Nutritional status assessment is usually based on a global indicator that obscures the underlying body composition, such as

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the BF and fat-free mass (FFM) percentages. Childhood obesity is defined with the use of the body mass index formula, which measures weight in relation to height [11,12]. This indicator is the most widely applied formula for using weight to predict health risk, but it has significant limitations, including the failure to distinguish between BF and FFM [13]. Because obesity-related health risks are attributable to BF rather than FFM, various alternative methods have been proposed to quantify risk [3], such as the following: waist circumference and waist-to-hip ratio [14]; upper arm length and sitting height [15] or knee height [16] in relation to weight; waist-to-height ratio [17]; a body adiposity index [18]; an index of central obesity [19]; maternal body size [20]; bioimpedance spectroscopy [21]; and estimates of the percentage of body fat (%BF) [22]. This last measure, %BF, seems to provide the most accurate and predictive measure of BF and its associated health risks; however, the methods used to measure %BF are costly, sophisticated, or invasive, thereby making the measure difficult to apply to large population samples [13,23,24]. One alternative is to estimate body composition with the use of anthropometric techniques, in which body measurements are used as inputs for equations that predict BF and FFM. This method is simple, inexpensive, and easy to apply in a pediatric population. Therefore, it would be useful to determine how well these equations approximate the gold standard [25]. Most evaluations of pediatric body composition are based on Siri's two-compartment (2C) model [26], which has been shown to overestimate %BF. This discrepancy is attributable to the chemical immaturity of children. Because children have a higher proportion of water and a lower proportion of minerals and proteins, they have a lower density of FFM as compared with adults [27]. To improve the accuracy of such estimates, more precise methods have been developed, such as multiple-compartment models to estimate BF and FFM in children and adolescents [28]. The 4C model divides the body into constituent fractions of fat, water, minerals, and protein. This 4C model is considered the gold standard for determining body composition in adults [29], but it has not been widely validated in children and adolescents [27]. Therefore, the aim of this study was to assess the agreement of BF and FFM measures obtained by simpler models (e.g., the 2C model, anthropometric equations) with those obtained by the four-compartment (4C) model in obese schoolchildren.

Materials and methods

Subjects

The subjects were 60 obese schoolchildren between the ages of 8 and 13 y (13 boys and 27 girls) who were recruited from an elementary school in the commune of Macul in Santiago, Chile. The study group was a convenience sample that was chosen based on the school's proximity to the measurement center. The inclusion criteria were a body mass index at the 95th percentile or greater according to the Centers for Disease Control and Prevention National Center for Health Statistics reference standards [30], full-day school enrollment, the consent of the parents, and the assent of the children. The exclusion criteria were diagnosis with a psychomotor disorder or the use of medications that affect body composition, physical activity, dietary intake, or biochemical parameters. The study was approved by the Ethics Committee of the University of Chile.

Biological age

Pubertal development was classified by Tanner stage in accordance with female breast development and male genital development [31]. Tanner stage was evaluated by visual inspection during the physical examination, which was performed by the study's pediatrician.

Anthropometry

Fasting weight and height were measured in the early morning. The children wore underwear only and stood on the scale with their feet near the center, their arms at their sides, and their heads in a neutral position so that the line from the corner of the eye to the origin of the ear was parallel with the floor. Weight was measured using an electronic precision scale (SECA® Model 767) with a sensitivity of 10 grams. Height was measured using a Holtain stadiometer (SECA) with a sensitivity of 0.1 cm. Both values were imported via a Precision Hispana touch screen. Four skinfold measurements were obtained in triplicate (i.e., biceps, triceps, subscapular, and suprailiac) with the use of a Lange caliper with millimetric precision (1 mm) using the technique described by Lohman and colleagues [32].

Anthropometric equations

The following anthropometric equations were performed:

a) *Slaughter* [33]. %BF is estimated on the basis of the triceps and subscapular skinfolds and by sex, pubertal stage, and race.

Girls:
$\%BF = 1.33 \times (\text{Triceps} + \text{Subscapular}) - 0.013 \times (\text{Triceps} + \text{Subscapular})^2 - 2.5$
Prepubescent boys:
$\%BF = 1.2 \times (\text{Triceps} + \text{Subscapular}) - 0.008 \times (\text{Triceps} + \text{Subscapular})^2 - 1.7$
Pubescent boys:
$\%BF = 1.2 \times (\text{Triceps} + \text{Subscapular}) - 0.008 \times (\text{Triceps} + \text{Subscapular})^2 - 3.4$
Postpubescent boys:
$\%BF = 1.2 \times (\text{Triceps} + \text{Subscapular}) - 0.008 \times (\text{Triceps} + \text{Subscapular})^2 - 5.5$

If the sum of the measures of the triceps and subscapular folds is greater than 35 mm, then the following equations are used:

Girls:
$\%BF = 0.546 \times (\text{Triceps} + \text{Subscapular}) + 9.7$
Boys:
$\%BF = 0.783 \times (\text{Triceps} + \text{Subscapular}) + 1.6$

b) *Ellis* [34,35]. BF in kg is estimated on the basis of height and weight and by race and sex.

Hispanic girls:
$\text{BF (kg)} = 0.677 \times \text{Weight (kg)} - 0.217 \times \text{Height (cm)} + 15.5$
Hispanic boys:
$\text{BF (kg)} = 0.591 \times \text{Weight (kg)} - 1.82 \times \text{Age (y)} + 3.36$

c) *Deurenberg* [36]. %BF is estimated on the basis of body density (BD), which in turn is estimated on the basis of four skinfold measures (i.e., biceps, triceps, subscapular, and suprailiac) and by pubertal stage.

$\%BF = (562 - 4.2) \times (\text{Age [y]} - 2) - (525 - 4.7) \times (\text{Age [y]} - 2)/\text{BC (kg/L)}$

BD is calculated on the basis of the following equations:

Prepubescent girls:
$\text{BD (kg/L)} = 1.1187 - 0.0630 \times \log(\sum 4 \text{ Skinfolds}) + 1.9 \times (\text{Age [y]} \times 10^{-3})$
Pubescent girls:
$\text{BD (kg/L)} = 1.1074 - 0.0504 \times \log(\sum 4 \text{ Skinfolds}) + 1.6 \times (\text{Age [y]} \times 10^{-3})$
Postpubescent girls:
$\text{BD (kg/L)} = 1.1830 - 0.0813 \times \log(\sum 4 \text{ Skinfolds})$
Prepubescent boys:
$\text{BD (kg/L)} = 1.1133 - 0.0561 \times \log(\sum 4 \text{ Skinfolds}) + 1.7 \times (\text{Age [y]} \times 10^{-3})$
Pubescent boys:
$\text{BD (kg/L)} = 1.0555 - 0.0352 \times \log(\sum 4 \text{ Skinfolds}) + 3.8 \times (\text{Age [y]} \times 10^{-3})$
Postpubescent boys:
$\text{BD (kg/L)} = 1.1324 - 0.0429 \times \log(\sum 4 \text{ Skinfolds})$

d) *Huang* [37]. BF in kg is estimated on the basis of weight, age, and sex (girls = 0, boys = 1).

$\text{BF (kg)} = 0.632 \times \text{Weight (kg)} - 1.606 \times \text{Age (y)} - 1.882 \times \text{Sex} + 3.330$

Isotopic dilution

Total body water was measured via deuterium dilution. The isotope was administered orally at a dose of 4 grams of deuterium oxide (99.8%) in accordance with the subject's body weight. Body water values were derived from deuterium oxide concentrations according to the plateau method. Subjects fasted for a 3-h equilibration period to minimize changes in total body water content [38]. A baseline saliva sample of approximately 2 mL was taken, and then the dose of deuterium was given along with 20 mL of water. The post-dose saliva sample was

Table 1
Physical characteristics and body composition of the sample by sex and pubertal stage

Variable	Boys		Girls	
	Genital stages I and II (n = 19) Stage I (n = 8) Stage II (n = 11)	Genital stages III and IV (n = 14) Stage III (n = 8) Stage IV (n = 6)	Breast stages I and II (n = 5) Stage I (n = 4) Stage II (n = 1)	Breast stages III and IV (n = 22) Stage III (n = 15) Stage IV (n = 7)
Age (y)[*,†]	11.5 ± 1.1	13.6 ± 1.0	8.4 ± 0.8	11.5 ± 1.7
Weight (kg)[*,†]	60.9 ± 13.5	76.3 ± 11.7	38.5 ± 5.1	58.2 ± 14.3
Height (cm)[*,†]	149.4 ± 12.0	161.4 ± 4.8	131.1 ± 3.7	147.8 ± 8.0
Total body water (L)[*,†]	26.9 ± 5.5	35.6 ± 5.0	17.8 ± 2.1	25.6 ± 5.2
Bone mineral density (kg)[*,†]	1.8 ± 0.5	2.4 ± 0.3	1.2 ± 0.1	1.7 ± 0.4
Four-component model				
BF (kg)[*,†]	25.3 ± 7.9	28.6 ± 9.3	14.4 ± 3.1	24.1 ± 8.5
BF (%)	41.2 ± 6.0	36.9 ± 7.9	37.2 ± 4.3	40.4 ± 6.2
FFM (kg)[*,†]	35.6 ± 7.7	47.7 ± 6.4	24.1 ± 2.6	34.1 ± 6.9
Two-component model				
Isotopic dilution BF (kg)[*,†]	24.8 ± 7.8	28.4 ± 8.2	15.4 ± 2.9	24.4 ± 7.8
Isotopic dilution BF (%)	40.3 ± 5.7	36.8 ± 6.7	39.9 ± 3.6	41.3 ± 4.3
Isotopic dilution FFM (kg)[*,†]	36.1 ± 7.3	47.9 ± 6.8	23.1 ± 2.7	33.8 ± 7.1
DEXA BF (kg)[*,†]	25.6 ± 8.2	30.1 ± 8.8	14.8 ± 2.8	24.6 ± 8.0
DEXA BF (%)	41.5 ± 5.6	39.0 ± 7.0	38.3 ± 3.0	41.6 ± 4.7
DEXA FFM (kg)[*,†]	35.3 ± 6.7	46.2 ± 6.5	23.7 ± 2.6	33.6 ± 6.9
Plethysmography BF (kg)[*,†]	27.2 ± 8.3	30.6 ± 10.5	15.2 ± 3.6	25.5 ± 9.5
Plethysmography BF (%)	44.4 ± 6.7	39.2 ± 9.0	39.1 ± 6.1	42.6 ± 7.9
Plethysmography FFM (kg)[*,†]	33.7 ± 8.0	45.7 ± 5.9	23.3 ± 7.3	32.7 ± 7.0
Anthropometric equations				
Slaughter BF (kg)[*,†]	26.2 ± 9.3	30.7 ± 11.3	11.6 ± 3.3	20.7 ± 8.0
Slaughter BF (%)[*]	42.3 ± 7.6	39.5 ± 9.9	29.5 ± 5.3	34.5 ± 6.6
Slaughter FFM (kg)[†]	34.7 ± 7.2	45.6 ± 6.5	26.9 ± 1.9	37.5 ± 7.6
Huang BF (kg)[*,†]	21.4 ± 8.1	27.9 ± 7.1	14.2 ± 2.5	21.7 ± 7.1
Huang BF (%)	34.1 ± 6.0	36.1 ± 4.0	36.7 ± 2.6	36.6 ± 4.1
Huang FFM (kg)[*,†]	39.5 ± 5.8	48.4 ± 5.0	24.3 ± 2.9	36.5 ± 7.6
Ellis BF (kg)[†]	18.4 ± 7.5	23.7 ± 6.7	13.1 ± 2.8	22.8 ± 8.2
Ellis BF (%)[*]	29.1 ± 6.2	30.6 ± 4.3	33.7 ± 3.0	38.2 ± 4.6
Ellis FFM (kg)[*,†]	42.5 ± 6.2	52.6 ± 6.2	25.4 ± 2.5	35.4 ± 6.3
Deurenberg BF (kg)[*,†]	18.0 ± 4.8	19.3 ± 3.7	11.9 ± 3.2	17.5 ± 6.1
Deurenberg BF (%)[*,†]	29.4 ± 3.2	25.2 ± 2.2	30.3 ± 4.7	29.4 ± 3.7
Deurenberg FFM (kg)[*,†]	42.9 ± 9.4	57.0 ± 8.5	26.6 ± 2.0	40.7 ± 8.5

BF, Body fat; DEXA, dual-energy x-ray absorptiometry; FFM, fat-free mass
[*] Significant difference by gender; $P < 0.05$.
[†] Significant different by pubertal stage; $P < 0.05$.

taken after a 3-h waiting period, during which the subjects did not urinate or ingest other liquids or foods. The sample was frozen at a temperature of –20°C. To analyze the deuterium content in the saliva, the sample was thawed and equilibrated with hydrogen gas with the addition of 5% platinum-on-alumina powder for 3 d. The deuterium/hydrogen ratio in the resultant gas was analyzed with the use of mass spectrometry (Hydra, Europa Scientific, Crewe and Cheshire, UK).

Plethysmography

Body volume and BD were measured using air-displacement plethysmography (BodPod, model 2000, Life Measurement, Inc, Concord, MA, USA). The children were evaluated while they were wearing underwear only, with no metal objects on their person and a swim cap over their hair. The children were then weighed on a scale calibrated to a precision of 5 g. The system first measured the pressure in the empty chamber and then measured the difference with the person inside using a 50-L calibration cylinder; the measurements were repeated two or three times. The total body volume calculated with this method was used as an input in the 4C equation.

Dual-energy x-ray absorptiometry

Bone mineral density was estimated with the use of dual-energy x-ray absorptiometry (DEXA) via the latest-generation Ghc Lunar Prodigy DPX-NT (Lunar Radiology, Madison, WI, USA). The system evaluates the entire body in a 5-min cycle. The children were positioned in a supine position on an examination table; they were wearing underwear and covered with a sheet.

The two-compartment model

The 2C model divides the body into BF and FFM. Isotopic dilution, plethysmography, and DEXA were used to produce three estimates of body composition according to the 2C model.

The four-compartment model [39–41]

The 4C model divides the body into fat, water, protein, and minerals. Because the 4C model adjusts for mineral content, estimates of FFM hydration fraction and density are more precise as compared with the 3C model. The 4C model is considered the gold standard because it accounts for more of the sources of variability of its components. This equation has been validated previously in children of the same age group [42].

The 4C model makes use of the following equation:

BF (kg) = [(2.747 × Body volume [L; plethysmography])–(0.710 × Total body water [L; isotopic dilution])] + [(1.460 × Bone mineral content [kg; DEXA]) – (2.050 × Body weight [kg])]

Statistical analysis

Descriptive statistics including minimum, maximum, and frequency distribution were derived for all variables. The Shapiro–Wilk goodness-of-fit test and the homogeneity of variance test were performed for continuous variables. For variables that fulfilled the assumption of normality, averages and standard deviations were calculated; for variables that were not normally distributed, median and interquartile ranges were calculated. Two-way analyses of variance were performed for [(2) Sex × (2) Pubertal stage] to compare physical characteristics and body composition between groups.

Next, each of the 2C methods (i.e., isotopic dilution, DEXA, and plethysmography) and the anthropometric equations were compared with the 4C model using the Lin concordance coefficient [43] and the Bland and Altman plot [44]. Significance was set at $P < 0.05$. Data analysis was performed using STATA version 10.0 software.

Results

Table 1 shows the physical characteristics and body composition of the sample by sex and pubertal stage. There were

Table 2
Concordance coefficient between the four-compartment model and the different methods and anthropometric equations for estimating total body fat by sex and pubertal stage

Variable	Boys						Girls					
	Genital stages I and II (n = 19) Stage I (n = 8) Stage II (n = 11)			Genital stages III and IV (n = 14) Stage III (n = 8) Stage IV (n = 6)			Breast stages I and II (n = 5) Stage I (n = 4) Stage II (n = 1)			Breast stages III and IV (n = 22) Stage III (n = 15) Stage IV (n = 7)		
	r	Dif	95% CI	*r*	Dif	95% CI	*r*	Dif	95% CI	*r*	Dif	95% CI
Isotopic dilution	0.968	−0.509	−4.296–3.279	0.984	−0.259	−3.265–2.747	0.948	1.004	−0.407–2.414	0.978	0.344	−2.926–3.613
Dual-energy x-ray absorptiometry	0.971	0.284	−3.510–4.078	0.958	1.523	−2.649–5.696	0.943	0.377	−1.626–2.379	0.965	0.561	−3.563–4.686
Plethysmography	0.958	1.849	−0.955–4.653	0.965	1.967	−1.330–5.264	0.942	0.741	−0.895–2.377	0.970	1.437	−1.838–4.712
Slaughter	0.746	0.899	−11.058–12.856	0.834	2.121	−8.875–13.118	0.638	−2.862	−5.321–0.403	0.849	−3.415	−9.770–2.940
Huang	0.796	−3.901	−11.081–3.280	0.853	−0.752	−9.464–7.959	0.910	−0.275	−1.963–1.413	0.881	−2.410	−8.407–3.588
Ellis	0.627	−6.953	−13.889–0.017	0.707	−4.874	−13.731–3.982	0.814	−1.342	−3.662–0.978	0.948	−1.248	−5.927–3.431
Deurenberg	0.474	−7.334	−15.646–0.977	0.323	−9.330	−21.388–2.729	0.620	−2.587	−5.264–0.091	0.630	−6.570	−13.499–0.360

95% CI, 95% confidence interval; Dif, difference; *r*, correlation

significant differences by sex and by pubertal stage, although there were no interaction effects between the two variables. Age, weight, height, total body water, and bone mineral density were significantly higher for boys as compared with girls. Values were also significantly higher among boys for BF (kg) and FFM (kg) per the 4C model, isotopic dilution, DEXA, and plethysmography as well as per the Huang and Deurenberg equations. Boys had significantly higher values for BF (kg) per the Slaughter equation and for FFM (kg) per the Ellis equation. Alternatively, girls had higher values for BF (%) per the Ellis and Deurenberg equations. In terms of pubertal stage, both boys and girls in more advanced stages had significantly higher values for age, weight, height, total body water, and bone mineral density. Children in more advanced stages of puberty also had significantly greater BF (kg) and FFM (kg) per the 4C model, isotopic dilution, DEXA, and plethysmography as well as per the Slaughter, Huang, Ellis, and Deurenberg equations. However, %BF was greater during the earlier pubertal stages according to the Deurenberg equation.

Table 2 shows the Lin concordance coefficients by sex and pubertal stage for BF (kg) estimates according to the various 2C methods and anthropometric equations as compared with the reference standard 4C model. For boys, the concordance coefficients varied between 0.968 and 0.474 during Tanner pubertal stages I and II, and they were between 0.984 and 0.323 for Tanner stages III and IV. DEXA showed the greatest agreement with the reference standard during the earlier pubertal stages, whereas isotopic dilution produced the highest concordance during the later stages. The Deurenberg equation produced the lowest concordance, regardless of sex or pubertal stage. For girls in all pubertal stages, isotopic dilution showed the greatest agreement with the reference standard. Among the anthropometric equations, the best concordance with the 4C method was for the Huang equation for boys at all pubertal stages and for girls in stages I and II, whereas the Ellis equation produced the highest concordance for girls in stages III and IV. Table 3 shows the concordance coefficients by sex and pubertal stage for FFM (kg) estimates according to the various 2C methods and anthropometric equations as compared with the reference standard 4C model. Isotopic dilution showed the best concordance with the 4C model, regardless of sex or pubertal stage. Among the anthropometric equations, the Huang equation showed the best concordance for boys ($r = 0.730$ for Tanner stages I and II; $r = 0.695$ for Tanner stages III and IV). For girls, the Huang equation also showed the best concordance during early puberty ($r = 0.884$), but the Ellis equation produced the highest concordance during later pubertal stages ($r = 0.917$).

In boys, DEXA, plethysmography, and the Slaughter equation overestimated BF (kg). In girls, all 2C methods overestimated BF, whereas the anthropometric equations underestimated BF. Isotopic dilution and the Huang, Ellis, and Deurenberg equations overestimated FFM (kg) as compared with the 4C model. In girls, all equations overestimated FFM.

Table 3
Concordance coefficient between the four-compartment model and the different methods and anthropometric equations for estimating fat-free mass, by gender and pubertal stage

Variable	Boys						Girls					
	Genital stages I and II (n = 19) Stage I (n = 8) Stage II (n = 11)			Genital stages III and IV (n = 14) Stage III (n = 8) Stage IV (n = 6)			Breast stages I and II (n = 5) Stage I (n = 4) Stage II (n = 1)			Breast stages III and IV (n = 22) Stage III (n = 15) Stage IV (n = 7)		
	r	Dif	95% CI	*r*	Dif	95% CI	*r*	Dif	95% CI	*r*	Dif	95% CI
Isotopic dilution	0.964	0.509	−3.279–4.296	0.972	0.259	−2.747–3.265	0.946	−1.004	−2.414–0.407	0.970	−0.344	−3.613–2.926
Dual-energy x-ray absorptiometry	0.963	−0.284	−4.078–3.510	0.918	−1.523	−5.696–2.649	0.912	−0.377	−2.379–1.626	0.950	−0.561	−4.686–3.563
Plethysmography	0.955	−1.849	−4.653–0.955	0.912	−1.967	−5.264–1.330	0.911	−0.741	−2.377–0.895	0.950	−1.437	−4.712–1.838
Slaughter	0.661	−0.899	−12.856–11.058	0.588	−2.121	−13.118–8.875	0.471	2.862	0.403–5.321	0.806	3.415	−2.940–9.770
Huang	0.730	3.901	−3.280–11.081	0.695	0.752	−7.959–9.464	0.884	0.275	−1.413–1.963	0.862	2.410	−3.588–8.407
Ellis	0.635	6.953	0.017–13.889	0.530	4.874	−3.982–13.731	0.760	1.342	−0.978–3.662	0.917	1.248	−3.431–5.927
Deurenberg	0.583	7.334	−0.977–15.646	0.367	9.330	−2.729–21.388	0.428	2.587	−0.091–5.264	0.651	6.570	−0.360–13.499

95% CI, 95% confidence interval; Dif, difference; *r*, correlation

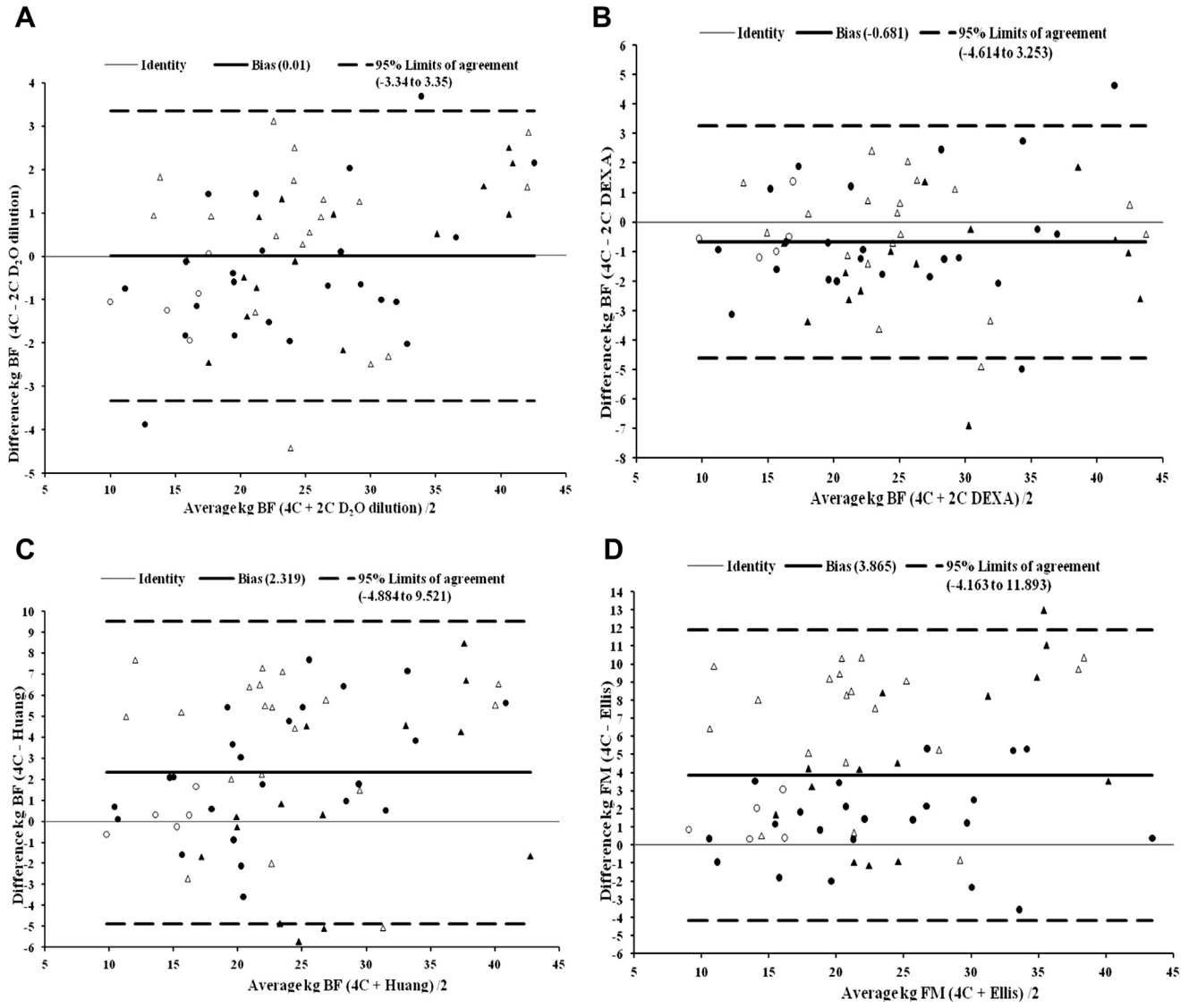

Fig. 1. (A) Difference in kg of body fat (BF) between four-compartment (4C) model and two-compartment (2C) model as measured via isotopic dilution (D_2O dilution), plotted against the average kg of BF per the two methods (4C + 2C D_2O dilution)/2. (B) Difference in kg of BF between 4C model and 2C model as measured via dual-energy x-ray absorptiometry (DEXA), plotted against the average kg of BF per the two methods (4C + 2C DEXA)/2. (C) Difference in kg of BF between 4C model and equations of Huang and colleagues (Huang), plotted against the average kg of BF per the two methods (4C + Huang)/2. (D) Difference in kg of BF between 4C model and equations of Ellis and colleagues (Ellis), plotted against the average kg of BF per the two models (4C + Ellis)/2. ○, Breast stage I and II female subjects; ●, breast stage III and IV female subjects; Δ, genital stage I and II male subjects; ▲, genital stage III and IV male subjects.

Figure 1 shows the concordance analysis according to the Bland and Altman plots for BF (kg) for the 4C model versus the 2C methods (i.e., isotopic dilution and DEXA) and the Huang and Ellis anthropometric equations, which showed the greatest extent of agreement with the gold standard. In boys, isotopic dilution underestimated BF, whereas DEXA overestimated BF by +0.284 during pubertal stages I and II and by +1.523 during pubertal stages III and IV. In girls, both methods overestimated BF. The Huang and Ellis equations underestimated BF in all subjects, regardless of sex or pubertal stage.

Figure 2 shows the concordance analysis according to the Bland and Altman plots for FFM (kg) for the 4C model versus the 2C methods (i.e., isotopic dilution and DEXA) and the Huang and Ellis anthropometric equations. In boys of all pubertal stages, isotopic dilution overestimated FFM, whereas DEXA underestimated FFM. In girls, both isotopic dilution and DEXA underestimated FFM. The Huang and Ellis equations overestimated FFM in all subjects, regardless of sex or pubertal stage.

Discussion

Several studies in children have agreed that increased BF and the central distribution of BF are responsible for early cardiometabolic alterations and premature mortality during adulthood [3–7]. For this reason, it is necessary to properly assess BF and its distribution to establish the biological risk associated with adiposity [9,10]. This research provides a background for the measurement of BF in schoolchildren, thereby helping to increase the evidence available for both the country and the region studied. Although some methods are ostensibly more exact than others, there is no true gold standard for measuring body composition in vivo. All methods rely on assumptions that

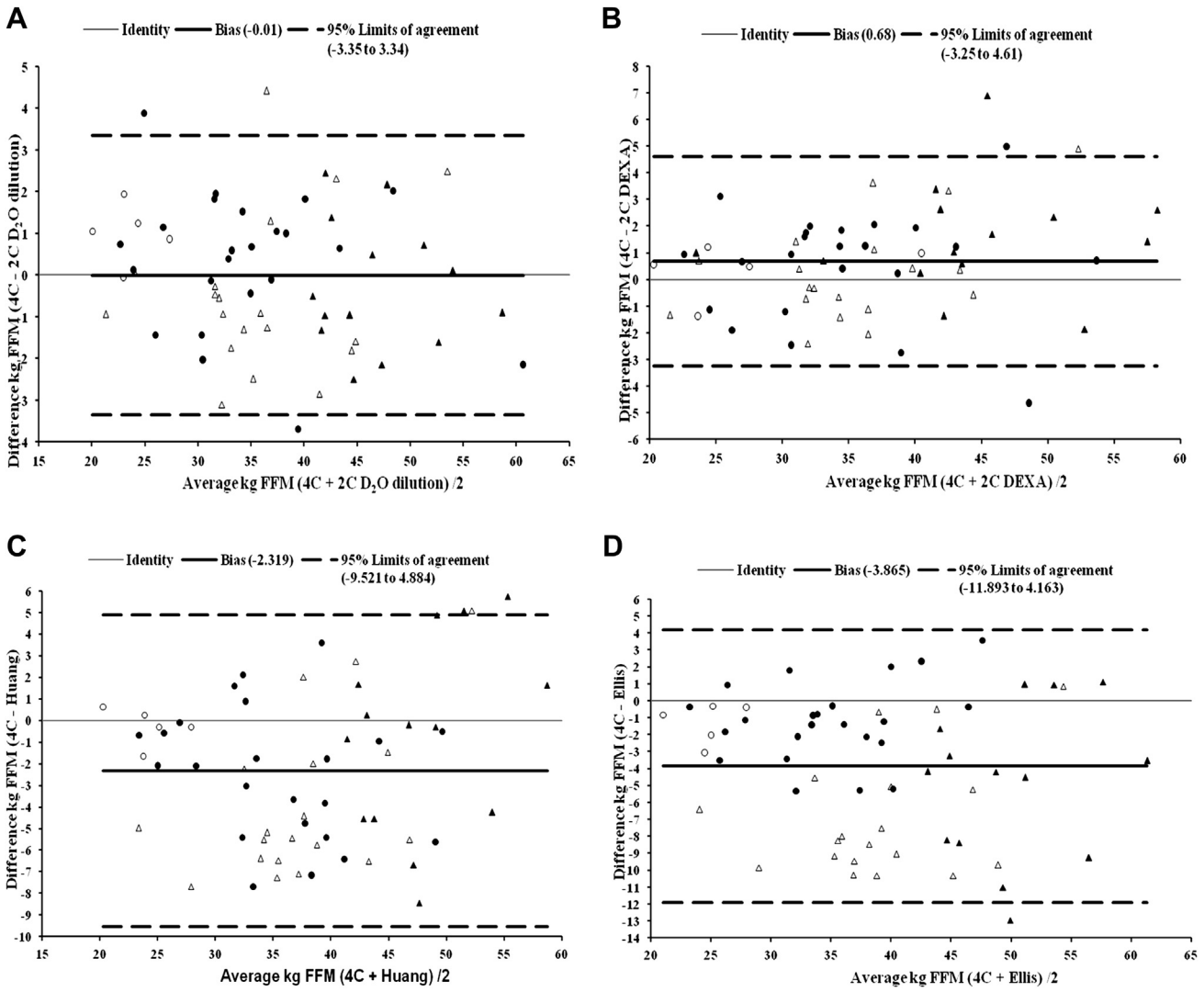

Fig. 2. (A) Difference in kg of fat-free mass (FFM) between four-compartment (4C) model and two-compartment (2C) model as measured via isotopic dilution (D_2O dilution), plotted against the average kg of FFM per the two methods (4C + 2C D_2O dilution)/2. (B) Difference in kg of FFM between 4C model and 2C model as measured via dual-energy x-ray absorptiometry (DEXA), plotted against the average kg of FFM per the two models (4C + 2C DEXA)/2. (C) Difference in kg of FFM between 4C model and equations of Huang and colleagues (Huang), plotted against the average kg of FFM per the two methods (4C + Huang)/2. (D) Difference in kg of FFM between 4C model and equations of Ellis and colleagues (Ellis), plotted against the average kg of FFM per the two models (4C + Ellis)/2. ○, Breast stage I and II female subjects; ●, breast stage III and IV female subjects; Δ, genital stage I and II male subjects; ▲, genital stage III and IV male subjects.

may not be valid in all cases; therefore, the best model is the one that minimizes assumptions. The 4C model quantifies BF and FFM more precisely than other methods because it directly measures mineral, water, and protein content rather than assuming a constant density of FFM [45]. In this study, we chose the 4C model as the reference standard to validate the sensitivity of other methods to estimate body composition (i.e., BF and FFM) in obese schoolchildren at various stages of secondary sex development. Isotopic dilution and DEXA showed the greatest extent of agreement with the reference standard 4C model for both BF and FFM, regardless of sex or pubertal stage, whereas the Deurenberg equation consistently produced the lowest concordance.

Among the various techniques used to estimate adiposity, DEXA ($r = 0.971$) and isotopic dilution ($r = 0.984$) showed the greatest agreement with the 4C model in boys during pubertal stages I and II. In girls, isotopic dilution showed the greatest agreement with the 4C model ($r = 0.948$ for Tanner stages I and II; $r = 0.978$ for Tanner stages III and IV). This finding is consistent with results from a study of 30 obese adolescents, which reported an r value of 0.96 for boys for both DEXA and isotopic dilution as well as r value of 0.90 and 0.92, respectively, for girls for the two methods [46]. Another study in a group of Mexican adolescents between the ages of 9 and 14 y also found a high concordance of DEXA with the reference standard, regardless of sex or pubertal stage ($r = 0.95$). Furthermore, a study of 25 children (14 boys and 11 girls) involving similar methodology found that isotopic dilution produced the best concordance with the reference standard ($r = 0.98$); this was followed by plethysmography ($r = 0.97$) and DEXA ($r = 0.95$) [47].

The anthropometric equations produced the lowest concordance with the reference model, regardless of sex or pubertal stage. This finding is consistent with the results of Roemmich and colleagues [27] in a study that compared multicompartmental models with the Slaughter equation ($r = 0.621$) in 47 adolescents by pubertal stage [39]. In another study that looked at a sample of

114 children who were 12 y old, the lowest concordance with the 4C model was with the Ellis ($r^2 = 0.51$) and Slaughter ($r^2 = 0.85$) equations [48].

BF (kg) estimates obtained with the use of the 2C models (i.e., isotopic dilution, DEXA, and plethysmography) were no more than 2 kg different from those calculated with the use of the 4C model for both sexes and for all pubertal stages. This discrepancy is lower than reported by Bray and colleagues [48], who found an average difference of −1.73% (−2.21; −1.26) [40].

Isotopic dilution overestimated FFM (kg), which is consistent with the findings of a study of 60 schoolchildren between the ages of 6 and 14 y by Ramirez and colleagues [49], in which isotopic dilution overestimated FFM by 0.75 and 1.41 kg in boys and girls, respectively. In the present study, isotopic dilution overestimated FFM equally in boys and girls and by less than 1 kg during all stages of pubertal development.

When comparing girls with boys in Tanner stages I and II, an overestimation of BF was found for girls, and an underestimation was found for boys. Similar results were found when comparing the results obtained for girls and boys in Tanner stages III and IV.

DEXA overestimated BF in both sexes and during all pubertal stages (+0.284–1.523 kg in boys and +0.377–0.561 in girls). Another study reported similar results in a group of obese schoolchildren, in whom DEXA overestimated BF by $+1.7\% \pm 3.8\%$ for boys and $+2.2\% \pm 4.4\%$ for girls [46]. DEXA underestimated FFM in both sexes and during all pubertal stages as compared with the reference 4C model. These results are consistent with findings reported by Wells and colleagues [45], who found that DEXA underestimated FFM by −0.7% as compared with the 4C model.

Among the anthropometric equations, only the Slaughter equation overestimated BF in boys; it did so by +0.899 kg during pubertal stages I and II and by +2.121 kg during stages III and IV, which was contrary to the findings reported by Roemmich and colleagues [27], Bray and colleagues [48], and Wells and colleagues [50], with the last study reporting a discrepancy of −3.77% (−4.53, −3.02). The other equations (including the Slaughter equation for girls) underestimated BF for both sexes. This finding is consistent with the studies noted previously [27,48,50].

With the exception of the Slaughter equation for boys, all equations overestimated FFM (kg). A previous study of 41 children between the ages of 8 and 12 y reported similar results, with all anthropometric equations overestimating FFM as compared with the 4C model [45].

The literature suggests that anthropometric measures (i.e., skinfold measurements) for obese subjects may be unreliable as a result of the size of the skinfold and the inconsistent level of skill among evaluators. Webber and colleagues [51] compared FFM estimates in 21 obese subjects by using body mass index and skinfolds as compared with bioelectrical impedance analysis (BIA) and DEXA methods. The authors found high correlations between some of the methods ($r^2 = 0.94$ for DEXA versus BIA), but agreement was low among other measures, particularly among skinfolds as compared with DEXA measurements (concordance coefficient, −21.9 to −1.5 kg for estimated FFM).

Another method that is useful for determining body composition is BIA; however, various factors limit its application in an obese population. For example, body geometry and the distribution of body water differ in obese subjects as compared with individuals of normal nutritional status [45]. Anthropometric equations developed for eutrophic subjects generally overestimate FFM in obese children [52].

This study has validated the use of 2C models (i.e., isotopic dilution and DEXA) and anthropometric equations for estimating BF and FFM as compared with the gold standard 4C model in a sample of obese schoolchildren. The high cost and the need for sophisticated equipment associated with the use of the 4C model prevents its wide application in clinical practice; therefore, it is essential to validate other, lower-complexity and lower-cost techniques. The most widely used of these techniques are skinfold measurement, DEXA, and BIA, which rely on various assumptions to convert raw measurements into body composition estimates [53]. These methods represent an improvement over the body mass index, because they provide information about fat versus lean components.

One limitation of this study is that it included only obese children, so the findings cannot be extrapolated to the entire pediatric population. However, it is precisely these children with malnutrition by excess who would benefit most from the evaluation of the fat-to-lean tissue ratio to predict their risk of future cardiovascular disease.

Another limitation is the age group included, which was limited to children between the ages of 8 and 13 y. Future studies should expand the sample to children of a broader age range.

In summary, the results show that there are simpler methods for the evaluation of body composition in obese children that produce high levels of agreement with the ideal 4C model. These methods include isotopic dilution and DEXA, and, as somewhat less preferable options, anthropometric equations.

Conclusion

Both isotopic dilution and DEXA 2C methods demonstrate acceptable levels of agreement with the reference 4C model in obese schoolchildren between the ages of 8 and 13 y. Because of its greater availability, lower cost, and more rapid administration, DEXA is the recommended method for a pediatric population. If groups of children are to be measured, deuterium dilution is suggested, because several children can be dosed and sampled at the same time. As compared with the reference methods used, the anthropometric equations of Slaughter, Huang, Ellis, and Deurenberg showed the lowest concordance with the gold standard for the measurement of BF and FFM. However, anthropometry remains a useful measure of body composition for group or population studies if there are no other methods available.

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