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Original article

Validity of the methods to assess body fat in children and adolescents using multi-compartment models as the reference method: a systematic review☆

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ABSTRACT

Objective: To analyze the validity of methods to assess body fat in children and adolescents using a systematic review.
Methods: The search was performed by two independent researchers using the MEDLINE, BioMed Central, SciELO, and LILACS electronic databases. For inclusion, the articles should have been written in English or Portuguese, and must have used multi-compartment models as the criterion measure of the model, with body fat measurement of the whole body in non-athlete children and adolescents.
Results: A preliminary search resulted in 832 studies. After all selection steps were performed, 12 articles were included. The selected studies were published between 1997 and 2010, whose samples consisted of children and adolescents with levels of relative body fat ranging from 20.7% to 41.4%. The methods used were: dual energy X-ray absorptiometry (58.3%), isotope dilution (41.6%), skinfold thickness (33.3%), hydrostatic weighing (25%), bioelectrical impedance analysis (25%), air displacement plethysmography (16.6%), and total body electrical conductivity (8.3%).
Conclusions: Based on the analysis of the studies, isotope dilution and air displacement plethysmography methods were the most reliable, despite the limited number of studies. As for clinical use or for population-based studies, the equation of Slaughter et al. (1988), which uses the triceps and subscapular skinfold thickness, showed the best results for assessment of body fat in this population.

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Validade dos métodos para avaliação da gordura corporal em crianças e adolescentes por meio de modelos multicompartimentais: uma revisão sistemática

RESUMO

Objetivo: Analisar a validade de métodos para avaliação de gordura corporal em crianças e adolescentes.
Métodos: A busca foi realizada por dois pesquisadores independentes, nas bases eletrônicas MEDLINE, BioMed Central, SciELO e LILACS. Como critérios de inclusão, os artigos deveriam ser escritos nas línguas inglesa ou portuguesa, ter utilizado como medida critério modelos multicompartimentais, com medida de gordura corporal em crianças e adolescentes não atletas.
Resultados: A busca preliminar resultou em 832 artigos, e após todas as etapas de seleção 12 compuseram esta revisão. Os trabalhos selecionados foram publicados entre 1997 e 2010, com amostras formadas por crianças e adolescentes com níveis de gordura corporal relativa de 20,7-41,4%. Os métodos utilizados foram: absortometria radiológica de dupla energia (58,3%), diluição de isótopos (41,6%), espessura de dobras cutânea (33,3%), pesagem hidrostática (25%), impedância bioelétrica (25%), pletismografia por deslocamento de ar (16,6%) e condutividade elétrica corporal total (8,3%).
Conclusão: A partir da análise dos estudos, concluímos que os métodos diluição de isótopos e pletismografia por deslocamento de ar foram os que se apresentaram mais confiáveis, apesar do número reduzido de investigações. Já para a utilização clínica e em estudos populacionais, a equação de Slaughter et al., que utiliza a espessura das dobras cutâneas tricipital e subescapular, foi a que apresentou melhores resultados para avaliação da gordura corporal nessa população.

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Palavras-chave:
Adiposidade
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Introduction

With the advances in methods and techniques used to assess body composition, together with the development of new equipment that allow for more precise identification of different body components, the use of multi-compartment models has become prevalent in the research field. However, despite the high-quality of data produced, multi-compartment models (four or more compartments) still have some disadvantages compared to the two- or three-compartment models, such as the need for sophisticated, high-cost, and difficult to use equipment, which limits their use in different fields of professional activity, both in clinical settings and in population-based studies.

In this sense, relatively simple and lower financial and operational cost methods have been preferred by professionals from the health care and sports areas for the assessment of body composition in different populations. However, to obtain more reliable diagnoses that are less susceptible to misinterpretation, these methods must be validated through on reliable models, with analysis based on appropriate statistical procedures.

In children and adolescents, body composition assessment appears to be even more challenging, as, depending on the growth and biological maturation, there is a large variation in the different body components (water, protein, minerals, etc.), from birth to adulthood. This variation can significantly affect the estimate of fat mass (FM) and fat-free mass (FFM), especially in two-compartment models. Furthermore, other factors, such as gender and ethnicity, may favor increased estimation errors of these components.[1]

Thus, the purpose of this study was to analyze the validity of the methods used to estimate body fat in non-athlete children and adolescents, through a systematic review.

Methods

In December, 2012, starting with the earliest records, the following databases were searched: MEDLINE, BioMed Central, SciELO, and LILACS. In addition, the references of identified articles were searched manually. The following keywords were used: "review," "validate," "validation," "accuracy," "body fat," "adiposity," and "adolescents," as well as their Portuguese translations. Boolean operators AND and OR were also used. The inclusion criteria were articles written in English or Portuguese; cross-sectional design; use of multi-compartment models as the reference measurement; and measurement of body fat in non-athlete children and adolescents. Two independent reviewers evaluated, selected, and forwarded the articles to a third reviewer. The latter was responsible for verifying agreement, resolving disagreements, and thus establishing the articles included in this review.

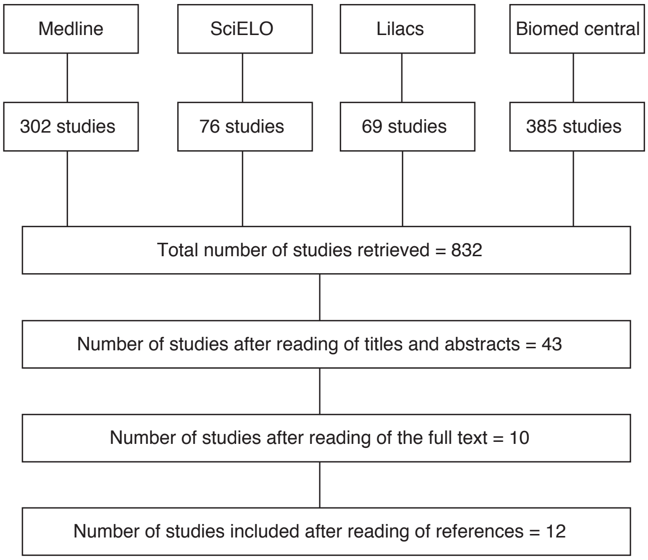

Fig. 1 – Search strategy for validation studies of methods to estimate body fat in children and adolescents (December 2012).

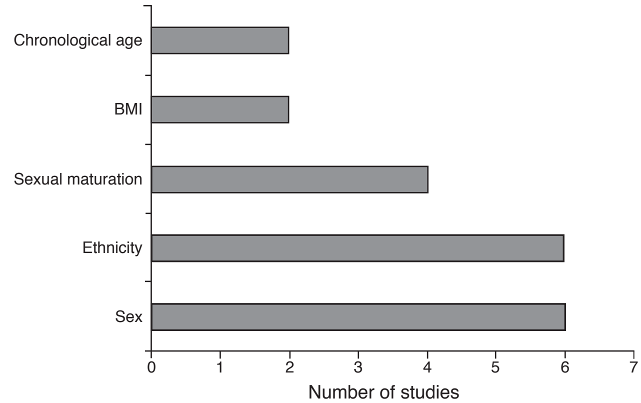

Fig. 2 – Major confounding factors used by the 12 studies selected for this review. BMI, body mass index.

A preliminary search resulted in 832 articles. After the initial selection through the analysis of titles and abstracts, 591 articles were shown to be unrelated to the topic of the review, 153 did not meet the age group of interest, and 45 did not adopt the multi-compartment model as the reference method. Thus, 43 articles were selected for full reading. Of these, seven studies were conducted with athletes, and 26 did not use the established reference method; thus, a total of 10 articles met all previously selected inclusion criteria. Subsequently, based on the analysis of references in these articles, two more studies that met all the criteria were identified, establishing the final total of 12 articles. The study selection process according to the database is shown schematically in Figure 1.

Results

Table 1 shows the description of studies that tested the validity of methods for estimating body fat in children and adolescents that were included in this review.

The 12 studies included and analyzed in the review were published between the years 1997 and 2010. These studies have several distinct characteristics, from the specific characteristics of the study population to the methodological procedures and techniques used for assessing body composition. The samples ranged from 20 to 411 subjects and, with the exception of three studies that investigated only young women,[2-4] all others were performed with individuals of both sexes. Due to the heterogeneity between subjects, a concern for controlling possible confounding variables when interpreting data was observed. The main concerns are shown in Figure 2.

Age range varied from 5 to 21 years. Only five studies had samples consisting only of adolescents (10-19 years). A wide variation was also observed regarding the levels of body fat in young individuals (20.7% to 41.4%).

Six different four-compartment (4C) models were used as reference, 50% of which used the models of Fuller et al.[5] or Boileau et al.[6] Three studies[7-9] that used other three- and four-compartment models were used for comparison.

Among the tested methods, dual X-ray absorptiometry (DXA) (58.3%), isotope dilution (41.6%), skinfold thickness (SFT) (33.3%), hydrostatic weighing (HW) (25%), bioelectrical impedance analysis (BIA) (25%), air displacement plethysmography (ADP) (16.6%), and total body electrical conductivity (TOBEC) (8.3%) were the most often used. In some cases, different formulations and techniques were used to assess relative body fat (RBF).

Regarding statistical procedures used, all studies performed Bland-Altman analysis of agreement[10] among the measures, and only four did not use the parameters obtained in the multiple regression analysis. It was observed that there was a wide variation in slope (–4.80 to 4.13) and intercept (–8.33 to 19.26) values, depending on the method analyzed. For the coefficient of determination (R^2) values, 27% were higher than 0.95, 58% were greater than 0.89, and 79% were higher than 0.80. Furthermore, only 48% of the standard errors of estimate (SEEs) could be considered excellent.[11] Biases ranged from near zero (3C – Fuller et al.[7]) to 23 percentage points[2] (TOBEC – Equation 2), whereas only 20% of the limits of agreement (LA) (2SD) analyzed were less than 5%. Regarding the main confounding variables, it was observed that the tendency to measurement deviation varied widely (r = –0.77 to r = 0.69) depending on the variable, as well as the order used (reference/alternative method) in the agreement analysis.

Discussion

Throughout time, many differences can be observed in the validation studies of methods for reliable estimation of the

Table 1 – Description of validation studies of methods for estimating body fat in children and adolescents (December, 2012).

Reference	N	Sample	Age	RBF	Reference method	Tested method	Results						
							Analysis of regression				Analysis of agreement		
							Slope	Intercept	R2	SEE	Bias (p.p.)	LA (2SD) (%)	Tendency
Bray et al.[9]	114 (61 M)	CAU and AA	12	27.8%	4C (Bray et al. 2002)	4C (Bray et al. 2001)	0.05	–2.81	0.99	NR	–1.52	NR	NR
						4C (Wells et al. 1999)	–0.02	–2.69	0.98	NR	–3.13	NR	NR
						4C (Heymsfield et al. 1990)	–0.007	–2.88	0.97	NR	–3.08	NR	NR
						4C (Friedl et al. 1992)	–0.008	–3.15	0.97	NR	–3.35	NR	NR
						3C (Wells et al. 1999)	–0.02	–1.13	0.96	NR	–1.76	NR	NR
						$H_2{}^{18}0$ dilution (Bray et al. 2001)	–0.06	1.95	0.95	NR	0.34	NR	NR
						DXA	0.11	–4.79	0.95	NR	–1.73	NR	NR
						HW (Bray et al. 2001)	–0.08	0.97	0.92	NR	–1.33	NR	NR
						PH (Siri 1961)	0.02	–3.66	0.92	NR	–3.11	NR	NR
						EDC (Bray et al. 2001)	–0.04	–0.14	0.85	NR	–1.35	NR	NR
						EDC (Slaughter et al. 1988)	0.07	–5.53	0.85	NR	–3.77	NR	NR
						ANT (Ellis et al. 1997)	–0.03	–6.58	0.51	NR	–7.31	NR	NR
						BIA (Bray et al. 2001)	–0.16	4.45	0.85	NR	0.03	NR	NR
						BIA (Deurenberg et al. 1990)	–0.29	10.21	0.87	NR	1.91	NR	NR
						BIA (Goran et al. 1993)	–0.56	7.40	0.88	NR	–6.45	NR	NR
						BIA (Schaefer et al. 1994)	0.18	–4.72	0.86	NR	0.22	NR	NR
						BIA (Suprasongsin et al. 1995)	–0.39	–3.82	0.80	NR	–12.28	NR	NR
Fields and Goran[12]	25 (14M)	CAU and AA	11.4 ± 1.4	28.0%	4C (Lohman 1986)	DXA	0.84	0.95	0.95	2.00 kg	1.70	NR	0.47
						HW (Lohman 1989)	1.09	0.94	0.95	2.10 kg	–2.10 kg	NR	–0.53
						ADP (Lohman 1989)	1.03	0.88	0.97	1.70 kg	–0.50 kg	NR	–0.34
						${}^2H_2O$ dilution	0.85	–0.89	0.98	1.50 kg	3.60 kg	NR	0.61
Gately et al.[13]	20 (18M)	Overweight and obese	11 to 17	41.2%	4C (Lohman 1986)	DXA	M = 1.05; F = 1.13; T = 1.06	M = –3.90; F = –8.04; T = –4.39	M = 0.96; F = 0.90; T = 0.94	M = 1.97%; F = 2.14%; T = 2.02%	M = 1.70; F = 2.20; T = 1.90	NR	NR

Table 1 – Description of validation studies of methods for estimating body fat in children and adolescents (December, 2012). *(Continuation)*

Reference	N	Sample	Age	RBF	Reference method	Tested method	Results						
							Analysis of regression				Analysis of agreement		
							Slope	Intercept	R2	SEE	Bias (p.p.)	LA (2SD) (%)	Tendency
						ADP (Siri 1961)	M = 0.98; F = 0.84; T = 0.94	M = –0.77; F = 5.58; T = 1.02	M = 0.97; F = 0.93; T = 0.96	M = 1.61%; F = 1.86%; T = 1.74	M = 1.80; F = 1.80; T = 1.80	NR	NR
						ADP (Lohman 1989)	M = 0.99; F = 0.81; T = 0.94	M = 0.00; F = 8.33; T = 2.45	M = 0.97; F = 0.94; T = 0.95	M = 1.67%; F = 1.68%; T = 1.81%	M = 0.20; F = –0.40; T = –0.04	NR	NR
						^2H_2O dilution (Pace and Rathbun 1945)	M = 0.94; F = 1.09; T = 0.97	M = 3.99; F = –0.97; T = 3.06	M = 0.95; F = 0.91; T = 0.93	M = 2.06%; F = 2.03%; T = 2.12%	M = –1.60; F = –2.70; T = –2.00	NR	NR
						^2H_2O dilution (Lohman 1986)	M = 0.95; F = 1.14; T = 0.99	M = 1.98; F = –5.26; T = 0.65	M = 0.96; F = 0.92; T = 0.95	M = 1.89%; F = 1.93%; T = 1.95%	M = –0.10; F = –0.60; T = –0.30	NR	NR
Ramirez et al.[21]	60 (30M)	Overweight and obese	6 to 14	34.7%	4C (Lohman e Chen 2005)	^2H_2O dilution	NR	NR	0.98	1.20 kg	3.10	9.9	NR
Roemmich et al.[8]	47 (24M)	Different sexual maturation stages	10.4 ± 0.4 to 13.4 ± 0.5	21.0%	4C (Lohman 1992)	PH (Siri 1961)	NR	NR	0.78	NR	–5.15*	NR	0.39
						PH (Lohman 1989)	NR	NR	0.78	NR	–1.14*	NR	0.28
						3C (Lohman 1992)	NR	NR	0.81	NR	–0.40*	6.06	0.20
						3C (Siri 1961)	NR	NR	0.99	NR	–0.75*	0.99	0.14
						DXA	NR	NR	0.71	NR	–1.88*	8.30	0.28
						SFT (Slaughter et al. 1988) TR+MC	NR	NR	0.61	NR	–0.31*	8.10	0.14
						SFT (Slaughter et al. 1988) TR+SS	NR	NR	0.62	NR	–0.09*	9.88	0.14
						BIA (Houtkooper et al. 1982)	NR	NR	0.43	NR	0.68*	11.04	0.47
						BIA (Boileau 1984)	NR	NR	0.40	NR	2.18*	12.02	0.37
Sopher et al.[14]	411 (236M)	Heterogeneous	6 to 18	21.7%	4C (Lohman 1992)	DXA	4.13	0.77	0.85	3.66%	–1.01 kg*	8.89	NR
Wells et al.[7]	30 (16M)	Swimmers	8 to 12	20.7%	4C (Fuller et al. 1992)	SFT (Slaughter et al. 1988)	NR	NR	NR	NR	–3.50	8.00	–0.55

Table 1 – Description of validation studies of methods for estimating body fat in children and adolescents (December, 2012). (*Continuation*)

Reference	N	Sample	Age	RBF	Reference method	Tested method	Results						
							Analysis of regression				Analysis of agreement		
							Slope	Intercept	R2	SEE	Bias (p.p.)	LA (2SD) (%)	Tendency
						SFT (Johnston et al. 1988)	NR	NR	NR	NR	–7.80	8.60	–0.33
						SFT (Deurenberg et al. 1990)	NR	NR	NR	NR	1.40	8.40	–0.59
						SFT (Brook 1971)	NR	NR	NR	NR	5.20	10.50	–0.06
						BIA (Deurenberg et al. 1989)	NR	NR	NR	NR	5.90	8.60	–0.77
						BIA (Davies et al. 1988)	NR	NR	NR	NR	13.70	8.50	–0.29
						BIA (Houtkooper et al. 1989)	NR	NR	NR	NR	–2.70	7.90	0.43
						BIA (Danford et al. 1992)	NR	NR	NR	NR	6.70	7.20	–0.45
						HW (Weststrate and Deurenberg 1989)	NR	NR	NR	NR	–2.00	5.60	–0.07
						HW (Lohman 1989)	NR	NR	NR	NR	–1.15	5.20	–0.04
						DXA	NR	NR	NR	NR	–0.20	6.50	0.08
						^2H_2O dilution	NR	NR	NR	NR	0.60	4.90	0.30
						3C (Fuller et al. 1992)	NR	NR	NR	NR	0.00	0.90	–0.30
Wells et al.[15]	153 (96F)	Overweight	5 to 21	40.8%	4C (Fuller et al. 1992)	DXA	NR	NR	NR	NR	M = 0.6 9kg; F = 0.96 kg; T = 0.86kg	M = 3.07; F = 4.74; T = 4.10	M = –0.19; F = 0.30; T = 0.17
Williams et al.[16]	89 (48F)	O and NO	5 to 18	O = 41.4% NO= 22.0%	4C (Fuller et al. 1992)	DEXA	NR	NR	NR	NR	NOB = –1.74; NOG = –0.03; OB = 1.41; OG = 1.03	NOB = 3.52; NOG = 3.51; OB = 2.59; OG=3.50	NOB = 0.09; NOG = 0.44; OB = –0.54; OG = –0.52
Wong et al.[4]	112F	CAU and AA	9 to 17	23.9%	4C (Boileau et al. 1985)	SFT (Durnin and Wormersley 1974)	CAU = 0.30; AA = –0.29	CAU = 10.05; AA = 10.62	NR	CAU = 3.90%; AA = 4.00%	CAU = 2.80; AA = 3.80	CAU = 15.70; AA = 16.10	NR
						EDC (Brook 1971)	CAU = 0.16; AA = 0.01	CAU = –1.28; AA = 2.55	NR	CAU = 4.70%; AA = 4.90%	CAU = 2.60; AA = 4.60	CAU = 18.80; AA = 19.60	NR
						SFT (Durnin and Rahaman 1967)	CAU = –0.40; AA = –0.48	CAU = 13.83; AA = 17.35	NR	CAU = 3.60%; AA = 3.70%	CAU = 4.40; AA = 5.80	CAU = 14.30; AA = 14.90	NR
						SFT (Slaughter et al. 1988)	CAU = –0.09; AA = 0.04	CAU = 2.25; AA = 0.04	NR	CAU = 5.10%; AA = 4.50%	CAU = 0.10; AA = 2.10	CAU = 20.40; AA = 17.70	NR
						SFT (Jackson et al. 1980)	CAU = –0.003; AA = 0.01	CAU = –7.00; AA = –4.78	NR	CAU = 4.50%; AA = 4.00%	CAU = –7.10; AA = –4.60	CAU = 17.80; AA = 16.00	NR

Table 1 – Description of validation studies of methods for estimating body fat in children and adolescents (December, 2012). (*Continuation*)

Reference	N	Sample	Age	RBF	Reference method	Tested method	Results						
							Analysis of regression				Analysis of agreement		
							Slope	Intercept	R2	SEE	Bias (p.p.)	LA (2SD) (%)	Tendency
						EDC (Slogan et al. 1962)	CAU = –0.28; AA = –0.33	CAU = 3.84; AA = 6.33	NR	CAU = 3.80%; AA = 3.70%	CAU = 2.90; AA = –1.70	CAU = 15.40; AA = 14.80	NR
						SFT (Wilmore and Behnke 1970)	CAU = –0.78; AA = –0.69	CAU = 19.26; AA = 18.25	NR	CAU = 3.20%; AA = 3.10%	CAU = 0.50; AA = 1.60	CAU = 12.80; AA = 12.40	NR
						SFT (Katch and McArdle 1973)	CAU = –0.62; AA = –4.80	CAU = 5.21; AA = 3.74	NR	CAU = 4.50%; AA = 4.90%	CAU = 9.70; AA = –7.80	CAU = 18.40; AA = 19.50	NR
Wong et al.[2]	114F	CAU and AA	12.7 ± 1.9 to 13.5 ± 1.7	23.7%	4C (Boileau et al. 1985)	Electrical conductivity							
						TOBEC equation 1	CAU = 0.88; AA = 0.78	CAU = 3.40; AA = 5.64	CAU = 0.72; AA = 0.81	CAU = 3.90%; AA = 2.90%	CAU = 0.60; AA = 0.30	CAU = 16.00; AA = 13.10	CAU = 0.06; AA = 0.30
						TOBEC equation 2	CAU = 1.32; AA = 0.85	CAU = 1.94; AA = 14.79	CAU = 0.48; AA = 0.64	CAU=10.20%; AA=4.80%	CAU = 23.00; AA = 11.20	CAU = 46.10; AA = 22.40	CAU = 0.69; AA = 0.11
Wong et al.[3]	141F	CAU, AA, HIS and ASI	9 to 17	24.0%	4C (Boileau et al. 1985)	DXA	0.95	5.08	0.81	3.30%	3.90	13.40	NR

3C, three-compartment model; 4C, four-compartment model; AA, African-American; ADP, air displacement plethysmography; ANT, anthropometry; ASI, Asian; BIA, bioelectrical impedance analysis; CAU, Caucasian; DXA, dual energy X-ray absorptiometry;
F, female; HIS, Hispanic; HW, hydrostatic weighing; LA, limits of agreement; M, male; NO, non-obese; NOB, non-obese boys; NOG, non-obese girls; NR, not reported; OG, obese girls; pp, percentage points; O, obese; OB, obese boys; RBF, relative body fat measured by the reference method; SEE, standard error of estimate; SFT, skinfold thickness;
T, total;
TR + MC, skinfolds of the triceps + medial calf region;
TR + SS, skinfolds of triceps and subscapular regions;
TOBEC, total body electrical conductivity.
*4C alternative method.

different components of body composition, whether regarding the sample, methods and techniques used, or the treatment of information. Thus, when analyzing the data available in the literature, it is essential to verify the method used, the quality of measurements, and the statistical analysis employed for data treatment. In this sense, the statistical procedures most often used for this purpose have historically been Student's *t*-test and coefficients of correlation (r) and determination (R^2). However, the main researchers in the field of body composition have shown that these methods, when used alone, do not appear sufficient to discriminate the quality of the measurements, especially because they do not allow for any inference about the agreement of individual values. Therefore, the method should be submitted to an analysis, not only within the set of values, but also on the basis of individual assessment, so that clinical decision-making can be safer in different situations.

All the studies that met the inclusion criteria of this review used the analysis of agreement proposed by Bland and Altman.[10] However, although all bias values were identified (mean difference between the scores of the investigated method and the reference method), limits of agreement and trend analysis could not be extracted from all studies due to the lack of information or data inaccuracy. Therefore, the importance of presenting all parameters of this analysis for better understanding and interpretation of results is highlighted.

The Bland and Altman plotting method[10] has been used to assess agreement between two methods employed to measure the same data (same measurement unit). This analysis allows for the comparison of the magnitude of the differences between the scores of the two methods, and whether the difference between the means is related to intersubject variations. Another important advantage is the possibility to verify this association in each individual that comprises the sample. This difference indicates the average discrepancy between the two methods. Obviously, the bias is expected to be low, the limits of agreement relatively low, and the trend not confirmed (r values close to zero), showing low inter-subject variability.

Regarding regression analyses, eight studies showed R^2 values and seven had intercept and slope values. The expectation of regression analysis is that the values of the intercept and slope fit the characteristics close to the so-called line of identity (intercept = 0 and slope = 1), that the coefficient of determination (R^2) is high, and that the standard error of estimate is reduced.

Dual energy X-ray absorptiometry

Among all methods for estimating body fat in healthy children and adolescents, the most tested in the analyzed studies was DXA (58.3%). In general, this method appears to underestimate RBF[3,8,12-16] when compared to the multi-compartment methods. However, no statistically significant difference was observed in any of the investigations.[7] The bias in the estimate of RBF by DXA may be partly explained by the assumption of constant values for FFM hydration (73.2%), which can range from 67% to 85%,[17] mainly according to individual characteristics and biological maturation phase. Thus, the higher the values of body hydration, the higher the overestimation of RBF values. It is noteworthy that the criterion values for body water may vary according to the equipment manufacturer. Thus, FM is an important intervening factor in the bias magnitude, as it tends to be overestimated in fatter individuals[14-16] and underestimated in thinner ones.[12,14,16]

Moreover, the amount of FM and FFM may also influence the bias due to differences in tissue thickness.[18] In this sense, deep tissues (> 20-25 cm) result in an increase in the attenuation of low-energy photons and can lead to an overestimation of body fat.[19] Although some studies have reported that this bias may also be related to sex and stage of sexual maturation,[8,15,16] other studies have not confirmed this hypothesis for gender,[13-15] sexual maturation,[3,14] or even ethnicity.[3,14]

This conflicting information may be associated with important methodological differences between the studies, such as the type and size of the selected sample, as well as the instruments used, as equipment produced by different manufacturers use different algorithms to convert the radiographic information into of body fat values, and additionally, some devices do not have specific algorithms for young populations. Furthermore, the precision can also vary if the beams are emitted in the form of pencil or fan.[20] Thus, generally speaking, when compared to the 4C model, it has been observed that DXA shows high LA, which, when added to the bias, especially when analyzing individuals with extreme fat percentage, limits its validity in the assessment of body fat in children and adolescents, thus requiring caution in its use.

Isotope dilution

The second most commonly used method in the validation studies analyzed was isotope dilution (deuterium or oxygen-18). Of the studies selected in this review, five compared the results obtained by isotope dilution with the 4C model. Of these, four found good estimates of FM,[7,9,13,21] and only one had an unfavorable outcome.[12] In the latter, Fields and Goran[12] assessed children of different ethnicities and observed a tendency to underestimate body fat in leaner individuals and overestimate in fatter individuals. However, the sample had a lower body hydration value when compared to other studies, which may have caused errors in the constants used by the method, thus contributing to the finding of biased RBF values. Therefore, in spite of the reduced number of studies, the use of isotope dilution, when compared to 4C models, was shown to be reliable for the assessment of body fat in young individuals.

Hydrostatic weighing

The HW method was tested in only three[7,8,12] of the selected studies. However, five other studies[2-4,8,14] used

HW as a measure of body volume/density for the multi-compartment models. The estimate of body fat by this method is based on the measurement of body density to discriminate the components of body composition. In this sense, there are different equations to estimate RBF from body density. Two equations are frequently used for this purpose, that of Brozek et al.[22] and that of Siri.[23] However, both equations were obtained from samples comprising adults, and therefore, they assume constant values for FM (0.9007 g/cm^3) and FFM (1.100 g/cm^3) densities that are not accurate, particularly during the processes of growth and sexual maturation.[1]

Another important limitation is the assumption that the FFM components are equally distributed and have similar densities in different populations. In this sense, Lohman[24] proposed an adaptation in the constants of the formula of Siri,[23] according to age and sex, and the results were more reliable.[13]

In the present study, it was observed that different equations to estimate RBF based on body density were used, and Lohman's[25] equation was most frequently used (two studies). Overall, it was observed that equations developed in adults showed less reliable estimates. However, even when using an equation adapted for the age group,[25] it was not possible to establish a pattern of behavior, and, although both studies showed a negative bias (criterion – alternative), Fields and Goran[12] identified a tendency to underestimate in individuals with higher RBF and overestimate in leaner peers, while Wells et al.[7] did not observe any indications regarding this effect.

The small number of validation studies on HW in children and adolescents can be explained, at least partially, by the fact that several researchers still consider it the gold standard for measuring body fat.

Air displacement plethysmography

Of the selected articles, five used ADP, all through the BOD POD® – Body Composition Tracking System – plethysmographic chamber. Among them, only two[12,13] aimed to verify the validity of this method, while others used the measurement of body volume/density in the multi-compartment models. ADP, although a more expensive method when compared to HW, eliminates the discomfort of submersion in water, and requires less cooperation of the evaluated individual. These characteristics have made ADP gradually gain more interest, especially in studies with pediatric populations.

As in the HW method, the equation most often used to estimate RBF was that by Lohman.[25] As expected, the most important bias was observed in the generalized equation.[23] Estimates based on Lohman's equation[25] did not differ from the line of identity, presented low standard errors of estimate and reduced biases, and did not appear to be affected by body fat levels or sex. Thus, it is suggested that plethysmography, when the standard procedures and specific equation are followed, can be a reliable method for the measurement of body fat in children and adolescents. However, it is worth mentioning that only two studies verified this finding. Thus, although the preliminary results are promising, further studies with representative samples are needed.

Bioelectrical impedance analysis

The estimation of body fat by the BIA method was compared to the 4C model in three[7-9] of the analyzed studies. This method provided the least satisfactory assessment of RBF, when compared to other methods tested. Many equations inappropriately estimate RBF, both individually and in groups.[26-30] The major confounders in the analysis of data obtained from this method are the amount of body fat,[9] sex, and sexual maturation.[8] In general, the equations overestimate RBF in lean subjects and underestimate it in fatter individuals. One explanation for this problem are the characteristics of the method.

BIA was developed to estimate body water based on the data provided by the impedance of an electric current. Therefore, the data suggest that, with the increased amount of body fat, the electrical conductivity is systematically changed, as the FM has lower hydration than the FFM. Additionally, other factors can affect the quality of results, among which are the level of hydration, skin temperature, time of collection, menstrual cycle, and the presence of metal objects close to the body.[1] Therefore, although it is a simple, easy to use, and low-cost method, BIA apparently does not provide a good estimate of body fat in young individuals. However, the most often accepted equations appeas to be that of Bray et al.[31] and that of Schaefer et al.[32]

Total body electrical conductivity

The body fat assessment method based on different levels of electrical conductivity in tissues, known as TOBEC, was compared to the 4C model in only one study. Wong et al.,[2] when testing two equations for predicting FFM in girls based on TOBEC data, one based on a quadratic model and the other in a linear model, observed better indicators of validity (bias, SEE, and LA) in the former. However, it is an incipient method and requires a larger number of studies.

Skinfold thickness

The SFT method was compared with the 4C model for estimating body fat in four studies. In these, 12 different predictive equations were tested, eight of which were developed in young individuals, and only one[33] was based on the 4C model. These characteristics probably contributed to the fact that the equation of Slaughter et al.[33] was the only one present in all four studies. This equation has two models: one that uses the triceps and subscapular folds (TR + SS), and another that replaces the subscapular skinfold with the medial calf (TR + MC).

Roemmich et al.[8] compared both equations with the 4C model and observed that both overestimated body fat, although the TR + SS equation presented better results. The TR + MC equation was shown to be more influenced by body adiposity, in which the predictions tended to be worse in fatter individuals. Furthermore, the trend analysis also showed sex as a potential confounder regarding data interpretation. The TR + MC equation overestimated RBF more often in boys than in girls, while the equation TR + SS tended to underestimate RBF in girls and overestimate it in boys.

Wong et al.,[4] when testing eight predictive equations in girls, observed that the equation of Slaughter et al.[33] (TR + SS) showed the highest validity (relative bias = 0.1%), although the equation of Jackson et al.[34] was the most accurate (SEE = 4.5%), but it underestimated RBF. Additionally, both showed no tendency to data distortion with RBF variation, indicating that despite the low accuracy, the equation by Slaughter et al.[33] can be considered a good alternative for this population. It is noteworthy that, in addition to having been developed specifically for young populations, this equation uses only two skinfolds, which makes it simpler and less error-prone when compared to that of Jackson et al.,[34] which uses four skin folds and one circumference measure.

In general, it was observed that some predictive equations tend to underestimate RBF,[4,7,9] whereas others tend to overestimate.[4,8,9] The estimation of body fat by SFT is widely used in clinical practice and population studies; however, this method is one of the most susceptible to measurement errors, such as the indiscriminate use of equipment from different manufacturers, often without proper calibration, as well as the fact that it critically depends on the skill and experience of the examiner.[35,36] The bias of this method also depends on the level of body fat (difficulty in performing the measurement), and it is not specifically indicated for obese individuals. Moreover, another limitation to be considered is that the prediction equations use FFM density as the constant; however, it tends to differ among ethnic groups, and change with age.

Over the years, several SFT-based equations were developed to predict RBF. These equations can be generalized, when developed from population studies with heterogeneous groups, or specific, when they are based on studies of homogeneous groups. In theory, generalized equations can be used in all types of individuals, but the results are not as accurate as would be desired. Regarding specific equations, they should only be used in individuals or groups that have very similar characteristics to those of the population for which they were developed. When this is not taken into account, a great variability in the results with the different equations is observed.[24,25] Thus, to prevent marked errors, it is very important, when choosing an equation, to ascertain what kind of population the equation was designed: men, women, children, young adults, elderly, active individuals, athletes, etc.[35,36]

The data obtained indicates the existence of a few SFT equations that are appropriate to estimate the RBF in children and adolescents. Thus, new equations must be developed and validated using reference methods as the gold standard, considering ethnicity, sex, and chronological and biological age, as well as the specific densities of the components of the MLG.

Final considerations

To the best of the authors' knowledge, this is the first systematic review of the validity of methods for assessing body fat in children and adolescents. In the present study, only 12 articles were selected.

Considering the existence of a wide range of methods and the importance of assessing body fat in this population, there are a limited number of studies in the literature. This finding can be explained by the use of the 4C-model as the criterion for study selection, which limited the inclusion of several validation studies of weaker methods. Many studies use DXA- or HW-criterion methods.[37] However, based on the information of this review, caution should be exercised in using these methods, both in assessment and in their use as the gold standard for the validation of alternative methods for estimating body fat in young individuals.

The 4C model is recognized as the gold standard for the assessment of body composition at the tissue level. This model is developed by using the reference methods for each component of body composition, allowing for the isolation and identification of body fat. Nevertheless, most of the regression equations of multi-compartment models were developed in adult individuals, which limits their use in young individuals.[9] In the studies that comprised this review, there was concern regarding the use of specific models. Of the six 4C models used as reference measures, four were developed in adolescents. However, in addition to the concern with the models, measurement errors (intra- and inter-observer, inter-equipment, and inter-laboratory) must be carefully controlled.

Based on the analyzed data, it was observed that, among the currently used laboratory methods to estimate body fat in children and adolescents, isotope dilution and plethysmography methods are the most reliable. Among the methods that are more applicable in clinical practice or population-based studies, the equation of Slaughter et al.,[33] which uses the TR +SS and considers ethnicity and sexual maturation stage, is suggested. According to the results, thus far no equation for BIA has satisfactorily predicted body fat in young individuals and, therefore, this method is not recommended for this population. Finally, it is suggested that further studies should be performed and that, within the limitations of the methods, alternative model adjustments should be made in order to minimize analysis biases, as well as to avoid the tendency toward deviation of estimates in certain population groups.

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Conflicts of interest

The authors declare no conflicts of interest.

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