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Body Fat in Children Measured by DXA, Air-Displacement Plethysmography, TBW and Multicomponent Models: A Systematic Review

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Abstract To conduct a systematic literature review to identify studies that used indirect methods to assess body fat in healthy children. A systematic review was conducted according to the PRISMA guidelines. We conducted a search in the MEDLINE/PubMed, SciELO and Google Scholar databases. Studies in healthy children aged 0–9 years were eligible for inclusion. Studies were kept or excluded from the review according to eligibility criteria defined a priori. Two independent reviewers conducted all steps in the study selection. Initially, 11,246 articles were retrieved, with 3,593 duplicates. After applying the eligibility criteria, 22 articles were selected for review. The methodology of each study was analyzed by each reviewer individually. The indirect methods used to assess body fat in children included dual-energy X-ray absorptiometry (DXA) (14 articles), air-displacement plethysmography (five articles), multicomponent models (two articles), and total body water (one article). Most studies reported absolute (in kilograms) or relative (percentage) body fat measures. Only seven studies reported the fat mass index (FMI) (kg/m^2). DXA was the indirect method most frequently used to assess body fat in healthy children. FMI was seldom reported.

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Introduction

Human body composition reflects the lifetime accumulation of the nutrients that are acquired and retained by the body. It includes chemical elements, tissues and organs that take on forms, shapes, and functions in all living beings. The assessment of body composition allows us to investigate the composition of these sets and how they change with age [1].

Body composition measurement methods can be divided into three groups: direct, indirect, and doubly indirect methods. Direct methods are highly accurate but have limited applicability because they require physical or chemical analysis of human cadavers. Indirect methods [e.g., dual-energy X-ray absorptiometry (DXA), air-displacement plethysmography, hydrodensitometry, and multicomponent models] are expensive and have been primarily used to validate the less accurate doubly indirect methods. Doubly indirect methods (e.g., bioimpedance, body mass index, skinfold thickness measurement) are easily applied, have a low cost and can be used in both the field and clinical research studies [2, 3].

The scientific literature includes many studies that employ doubly indirect methods to assess child body fat. More recently, the indirect methods have attracted interest for their use in children because they can provide more accurate measures [4]. DXA assesses body composition through the principle of X-ray beam attenuation by the different body tissues. The extent to which the energy is attenuated when crossing the body is a function of the thickness, density and chemical composition of the tissues [5]. DXA directly measures the three principal components of the body: fat mass (FM), fat free mass (FFM) and total-body bone mineral (TBBM). It is a non-invasive, safe and suitable method to assess children's body composition. The major advantages of DXA when used to examine children include the short measurement time and the minimal radiation dose [6].

Air-displacement plethysmography is a fairly rapid method of body composition assessment and is easy to use in both adults and children because it demands less individual cooperation compared with hydrodensitometry [5]. Body volume is estimated using an inverse relationship between volume and pressure. The technique provides measurements of two body components: FM and FFM [7]. Both DXA and air-displacement plethysmography may have limited clinical application because of the high price of the equipment required.

Total body water is measured in children through the dilution method of stable isotopes, such as deuterium and oxygen-18. This method is based on the fact that body water is the major component of FFM throughout life. Because of the wide variation in water content in FFM in the first few months of life, some authors do not recommend using this method to assess FM in infants [8].

The multicomponent models use mathematical equations with three or more body components to estimate body measures. Multicomponent models are generally employed in validation studies as gold standards for other methods [9]. The four-component model is considered the most accurate in vivo approach to differentiate FM and FFM in children [10].

The aim of this study was to conduct a systematic literature review to identify relevant studies that used indirect methods to assess body fat in healthy children.

Methods

A protocol using the preferred reporting items for systematic reviews and meta-analyses (PRISMA) standards was completed prior to initiating the literature search. We conducted a literature review in the MEDLINE/PubMed, SciELO and Google Scholar databases and searched for descriptors and keywords applying the medical subject headings (MeSH). The following MeSH descriptors were used: body composition, plethysmography, dual-energy X-ray absorptiometry, DXA, DEXA, densitometry, and the following keywords: BODPOD, BOD POD, PEAPOD, PEA POD, air-displacement plethysmography, deuterium dilution, doubly-labeled water, hydrodensitometry, four-component model, four-component model, four-compartment model, four-compartment model, FM, fat-free mass, lean body mass, lean soft tissue, and lean mass. To increase the sensitivity of the search, assuming that the authors could have employed more than one methodology to assess body composition, we included the descriptors bioelectrical impedance, bioelectric impedance, and skinfold thickness, in addition to the keyword bioimpedance. Two independent reviewers conducted every step of the literature review. If disagreement occurred, a third person determined whether to keep or exclude the article.

We searched for articles with the above descriptors/keywords in the title and/or abstract. No restrictions of language and year of publication were set. All human studies in children aged 0–9 years that were published prior to September 2014 were eligible for inclusion. Two different search strategies were applied. First, we searched each individual method of assessment of body composition in each database by applying the above-mentioned restrictions and created 23 separate EndNote® libraries. Second, we searched articles that appeared only in MEDLINE/PubMed using a combination of all of the above descriptors/keywords, e.g., body composition or BODPOD or BOD POD or pletysmography or air-displacement pletysmography… and FM or fat-free mass or lean mass. The library obtained from these combinations was merged with the previous libraries to obtain a single list.

Finally, the two reviewers conducted a methodology evaluation of the selected articles. We evaluated the following aspects: definition of outcome measures; definition of inclusion/exclusion criteria, study period and setting, sampling procedures (target population and description of all steps to the final sample), description and/or reporting of losses, description of body fat measurement methods (staff training, instrument calibration, requirement of fasting for the deuterium oxide dilution method, and appropriate clothing), and statistical analysis (measures of central tendency and dispersion and significant differences).

Results

A total of 11,246 references were found; 3,593 were duplicates, which resulted in 7,653 references for reading titles (Fig. 1). After reading the titles, 7,300 references were excluded, resulting in 353 for the abstract analysis. Of these, 95 were selected for full-text evaluation. The following exclusion criteria were used for the selection of titles: anthropometry or skinfold thickness measurement as the single method used to measure body fat; body composition (bone, water, cells, nutritional status or BMI exclusively), specific populations (obese or premature children or children with any other condition), age group

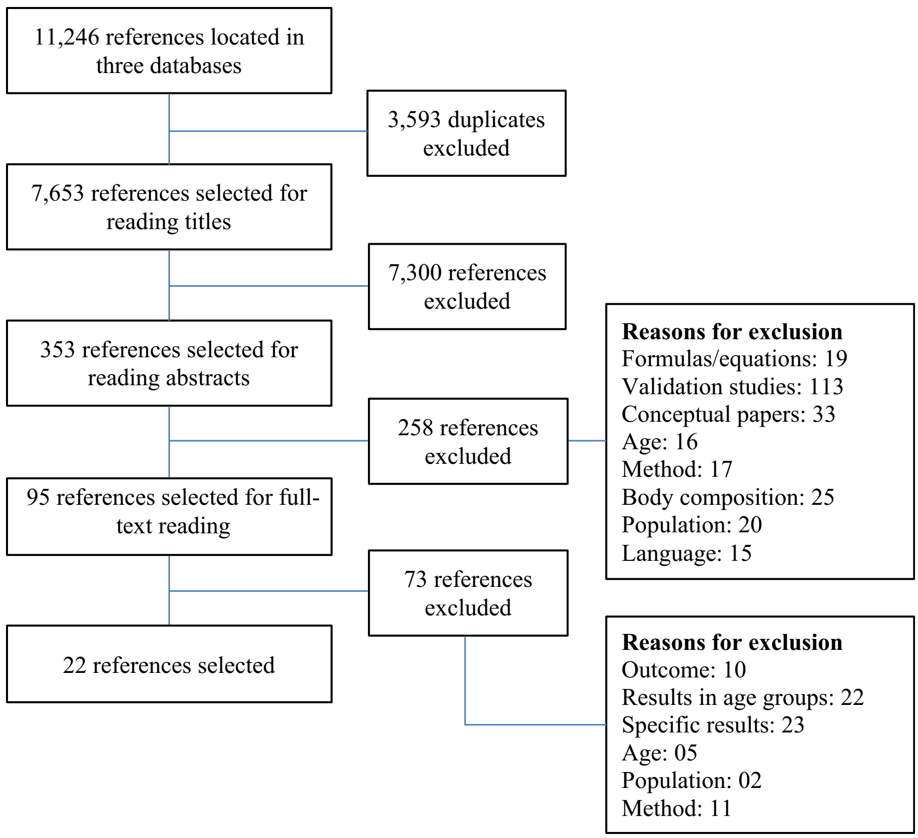

Fig. 1 Flowchart of the systematic literature review of studies on body fat measured by indirect methods in children

(studies exclusively in children aged ≥10 years), and adiposity analyzed as the exposure variable.

In addition to using the same criteria employed at the title reading step, the following studies were excluded: validation research or comparison of methods with no quantitative body fat data reported, clinical reviews or updates on assessment methods with no quantitative results reported (conceptual papers), studies specifically planned to generate formulas or equations to predict body composition measurements, and specific languages (German, Italian, Japanese, Czech, Polish, and Chinese).

The exclusion criteria for the articles used in the full-text reading step were the same as those used in the title and abstract reading steps, and results reported for very large age groups beyond the age range of childhood; body composition assessed exclusively through bioimpedance, bioelectrical impedance or bioelectric impedance; and body fat results reported according to only specific child characteristics other than sex and age. After applying the eligibility criteria, 22 articles were selected for review (Table 1). To reduce losses, the lists of references in the selected articles were searched, but none were included.

The 22 articles selected were published between 1997 and 2013. The studies were conducted worldwide: 4 in North America [11–14]; 11 in Europe [10, 15–24]; 2 in Asia [25, 26]; 2 in Africa [27, 28]; and 3 in Oceania [29–31]. Twelve articles had a cross-sectional design, with the sample sizes ranging from 40 to 16,973 individuals, and ten articles had a longitudinal design, with the sample sizes ranging from 76 to 7,336 individuals.

The methodology evaluation of the 22 articles underlined their similarities and differences and allowed us to draw comparisons. Most studies had clearly defined outcome measures, except for two [16, 25]. If percent fat mass (%FM) and fat mass index (FMI) were defined as outcome measures, the studies described how they were calculated, except for two [16, 25]. Most studies established inclusion/exclusion criteria (except for three [14, 30, 31]) and defined the study setting (except for three [14, 16, 31]). Main inclusion criteria were full-term healthy children born to single pregnancies from mothers without morbidities. Information on the calendar time of data collection was not available in approximately 50 % of the studies [14–16, 19, 21, 24, 25, 27, 30, 31]. Concerning the statistical analyses, all studies reported the means in addition to any measure of dispersion (standard deviations, standard errors, confidence intervals and/or ranges).

Overall, most studies showed incomplete descriptions of sampling procedures, which prevented an assessment of sample representativeness. Furthermore, information concerning losses to follow-up in cohort studies and refusals in cross-sectional studies was not available in almost all publications (although they were not reported in the body text,

Table 1 Articles selected for systematic review after full-text reading (n = 22)

References, country	Design (n)	Age group of interest	Indirect method	Measure
Andersen et al. [27], Ethiopia	Longitudinal (378)	0–6 months old	PEA POD	FM (kg) %FM FMI (kg/m^2)
Collings et al. [15], United Kingdom	Cross-sectional (398)	4 years old	DXA	FM (kg) %FM FMI (kg/m^2)
Forsum et al. [16], Sweden	Longitudinal (76)	4 years old	BOD POD	%FM
Khadgawat et al. [25], India	Cross-sectional (1,640)	7–9 years old	DXA	%FM
Weber et al. [11], United States	Cross-sectional (8,961)	8–9 years old	DXA	FMI (kg/m^2)
Lakshmi et al. [17], United Kingdom	Cross-sectional (888)	7 years old	DXA	%FM
Wells et al. [10], United Kingdom	Cross-sectional (565)	5–9 years old	Multicomponent model	FM (kg) FMI (kg/m^2)
Borrud et al. [12], United States	Cross-sectional (16,973)	8–11 years old	DXA	FM (kg) %FM
Carberry et al. [29], Australia	Longitudinal (77)	0–4.5 months old	PEA POD	FM (kg) %FM
Eriksson et al. [18], Sweden	Longitudinal (108)	1–12 weeks old	PEA POD	FM (kg) %FM
Ay et al. [19], Netherlands	Longitudinal (252)	6 months old	DXA	FM (kg) %FM
Fields et al. [13], United States	Longitudinal (117)	1–6 months old	PEA POD	FM (kg) %FM
Lim et al. [26], Korea	Cross-sectional (449)	5–9 years old	DXA	FM (kg) %FM
Robinson et al. [20], United Kingdom	Longitudinal (536)	4 years old	DXA	FM (kg) FMI (kg/m^2)
Griffiths et al. [28], South Africa	Longitudinal (281)	9–10 years old	DXA	FM (kg) FMI (kg/m^4)
Henche et al. [21], Spain	Cross-sectional (1,113)	0–10 years old	DXA	FM (kg) %FM
Shaw et al. [22], United Kingdom	Cross-sectional (1,251)	5–6 years old	DXA	%FM
Rogers et al. [23], England	Longitudinal (7,336)	9–10 years old	DXA	FM (kg)
Taylor et al. [30], New Zealand	Cross-sectional (661)	3–10 years old	DXA	%FM
Wells et al. [24], United Kingdom	Cross-sectional (69)	8 years old	Deuterium oxide dilution method	FM (kg) FMI (kg/m^2)
Butte et al. [14], United States	Longitudinal (76)	0–2 years old	Multicomponent model	FM (kg) % FM
Taylor et al. [31], New Zealand	Cross-sectional (40)	3–8 years old	DXA	FM (kg) %FM

DXA dual energy X-ray absorptiometry, *BOD POD* plethysmography, *PEA POD* plethysmography (for babies), *FM* fat mass, *%FM* percent fat mass, *FMI* fat mass index

some studies provided the information that was used to calculate these losses), except for two [27, 29]. The equipment used for body fat evaluation was generally described by the authors, but the calibration and operation procedures and the patient positioning and use of appropriate clothing were scarcely reported.

Dxa

Fourteen studies used DXA to assess body fat [11, 12, 15, 17, 19–23, 25, 26, 28, 30, 31]. Seven reported results by specific age groups [12, 21–23, 28, 30, 31], and seven reported them by age [11, 15, 17, 19, 20, 25, 26]. Most studies reported FM (kg), [12, 15, 19–21, 23, 26, 28, 31] and %FM as outcome measures [12, 17, 19, 21, 22, 25, 26, 30, 31]. Only four studies provided data on FMI [11, 15, 20, 28]. The fact that studies assessed children at different ages and used different age groups made it difficult to compare their findings. However, the studies primarily found a higher mean FM among girls than boys at all stages of child development and that FM increases with age.

Air-Displacement Plethysmography

Five studies used air-displacement plethysmography to assess FM in children. The four studies conducted in Ethiopia [27], Australia [29], Sweden [18], and the United States [13] used the PEA POD system to assess body fat in babies. They evaluated full-term children aged 0–6 months. The PEA POD measures body volume in children, which is used to calculate fat-free mass (FFM) and FM. All four studies reported FM (kg) and %FM by sex and age, and only one provided data on FMI [27]. The findings of these studies suggest that there are no clear sex differences in body fat in this stage of life.

The other study was conducted in Sweden and evaluated children at the age of 4 years using the BOD POD system [16]. Similar to PEA POD, the BOD POD estimates the FM using the body volume measure, but the first equipment is specifically intended for babies. The results of the study suggest that at the age of 4 years, girls show a higher %FM; however, it was not possible to assess whether the difference was statistically significant (the authors did not provide p values or confidence intervals).

Total Body Water (TBW)

A study conducted in the United Kingdom used the deuterium oxide dilution method to assess body fat in 8-year-old children from the Avon Longitudinal Study of Parents and Children (ALSPAC) cohort [24]. They measured total body water in the children and then converted this value to FFM. FM was calculated as the difference between body weight and FFM. The mean FM (kg) and FMI (kg/m^2) were higher among girls than boys, which is consistent with the results obtained using other methods.

Multicomponent Models

Of the 22 selected studies, two used a multicomponent model. A study conducted in the United States assessed children aged 0–2 years [14]. The measures of TBW (deuterium oxide dilution method), total body potassium (whole body counter) and bone mineral density (DXA) were used to estimate FFM and FM. FM and %FM were reported for all ages investigated. The authors found that body fat increased with age in both sexes. %FM was higher in girls at all ages, except at 24 months, when there was no sex difference. Another study in the United Kingdom included 5–9-year-old children [10]. FM and FFM were estimated from TBW (deuterium oxide dilution method), bone mineral content (DXA) and body volume (air-displacement plethysmography). FM and FMI Z-scores were calculated for all ages separately. The measures increased with age in both sexes.

Discussion

In this review, we found that DXA is the indirect method most frequently used to assess body fat in children. It is widely accepted in research and clinical settings to use different methods to assess body composition in children, but most such methods have limitations, are costly, are inconvenient to use, or are not generally available for clinical purposes. DXA is a suitable method to assess body composition in children and adolescents [32] because it is safe and incurs minimum radiation exposure. DXA can be used in children to assess bone mineral content, lean body mass and body FM and is an alternative approach to the four-component model [6].

Methods requiring participant compliance cannot be used in infants and young children (e.g., hydrostatic weighing with head submersion in the water that requires breath holding and subsequent air exhalation) [8, 33]. Air-displacement plethysmography is a substitute approach in these cases. In this review, we verified that this method was reported in five studies; four used the PEA POD system that was specifically designed for babies (weighing between 1 and 8 kg), and one used different equipment, the BOD POD. The BOD POD is a newer method that has more limited clinical applicability than DXA, which can provide bone mass measurements in addition to body fat and lean body mass measurements. This factor may, in part, explain the few studies that are currently available and used this equipment.

Another aspect worth mentioning is the unit of measurement of FM. Most studies reported their results in kilograms and/or as a percentages, whereas indexes adjusted for height were not frequently used [34]. The usefulness of measuring percentage of body fat has been recently reevaluated. This measure is estimated by adjusting the fat content for body weight, but it disregards the fact that FFM varies among individuals [35]. Wells and Cole [24] argued that same-height children can have different percentages of FM due to different absolute amounts of FM but equivalent amounts of FFM or different absolute amounts of FFM and equivalent amounts of FM. The normalization of these measures for height squared (kg/m^2) may improve the sensitivity of this method in detecting changes in body composition measurements [24].

Most studies reviewed reported estimates of mean FM by age, allowing for comparisons between studies. Only six studies [12, 22, 23, 28, 30, 31] showed the results of FM grouping children at different ages (e.g., 0–5, 6–10, and 8–11 years). The analysis of aggregated sets of FM data makes it difficult to draw comparisons between studies because it is well established that body composition varies significantly during childhood [14].

Because of the wide variety of methods used and the different age groups investigated in the studies, the body fat results could not be directly interpreted. For instance, the studies conducted in the United States in children aged 6 months found similar mean FM values when measured using the multicomponent model [14] and the PEA POD system [13], but these measures were higher than those obtained by DXA [19] in Dutch children. In comparing %FM among 6-month-old children from various countries measured with PEA POD, infants from the United States [13] presented a higher mean compared with those from Ethiopia [27]. Additionally, children younger than 8 years of age assessed using the deuterium oxide dilution method in the UK [24] had a higher mean FM than did same-age Korean children assessed by DXA [26]. Children aged 5–6 years in the UK assessed by DXA [22] showed a higher mean FM than did Korean children [26]. The different results may be due to the method used or to the specific characteristics of each population. Additionally, some aspects of the methodology should be considered: in studies without a clear description of the sampling procedures, selection bias cannot be ruled out. Because a description of the operating procedures of DXA was not available in most articles, we could not assess whether measurements were taken properly [i.e., children wearing appropriate clothes, staff properly trained to operate the equipment and frequency of instrument calibration (daily/weekly)]. Adherence to these procedures and protocols is essential to guarantee the reliability of body composition measurements. Failure to do so may have resulted in biased body fat measurements in an unpredictable direction.

In conclusion, we found that DXA was the indirect method that was most employed for assessing body fat in children. FMI was seldom reported and should be more frequently used to control the effect of different heights. Additionally, providing a proper description of the procedures adopted before taking the examination, if reported, would help the readers assess the methodological quality of the studies. Finally, different results can be obtained in children of the same age and sex, depending on the method used and the population studied.

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