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REVIEW PAPER

The usability of bioelectrical impedance analysis in overweight and obese children

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ABSTRACT

Obesity, a chronic recurrent disease related to excessive fat tissue accumulation that leads to numerous health problems, is a significant public health concern. Accurate methods to estimate body composition are crucial for diagnosis and treatment of obesity. The purpose of this paper was to evaluate whether bioelectrical impedance analysis (BIA) is a sufficiently reliable method for assessing body composition (BC) in obese children for daily use in clinical practice. Inclusion criteria were English-written studies published between 2018 and February 2024, available in PubMed database, and relating to BIA and its use in pediatric obesity. The review included 31 studies showing that BIA has advantages over body mass index, but exhibits bias in comparison to dual energy X-ray absorptiometry, which can be reduced using multifrequency octopolar devices. BIA-derived measurements are associated with obesity's biochemical and clinical markers. BIA is currently the most easily accessible and sufficiently accurate method for measuring BC.

KEY WORDS:

obesity, bioelectrical impedance analysis, pediatrics.

INTRODUCTION

OBESITY

Obesity is a chronic recurrent disease related to excessive fat tissue accumulation, presenting a risk to health status of an obese individual [1]. Beyond the numerous comorbidities affecting individuals, obesity remains a public health concern, and is one of the most pressing challenges to be addressed in the coming years.

The diagnosis of obesity in children and adolescents depends on anthropometric measurements, such as weight, height, and their calculated derivatives, i.e., body mass index (BMI) assessed via child growth standards for age and sex, specific to a population.

The purpose of this paper was to evaluate whether bioelectrical impedance analysis (BIA) is a sufficiently reliable method for assessing body composition (BC) in the population of obese children for daily use in clinical practice.

Sarcopenic obesity (SO) is defined as sarcopenia (i.e., loss of muscle mass, function, and strength) and obesity occurring together [2]. Sarcopenia causes reduced energy expenditure; it exacerbates obesity and increases the risk of obesity-related disorders [3]. As SO refers to patients with low muscle mass and high fat mass, they are not necessarily 'obese' or 'overweight' when classified by a BMI Z-score. That is why besides the handgrip strength measurement (HGS), muscle-to-fat ratio (MFR) is employed to assess SO [4]. Initially, sarcopenia has been associated with elderly; therefore, diagnostic criteria have been designed for the adult population. For pediatrics, researchers rely on criteria available to the general population [3].

Metabolic-associated fatty liver disease (MAFLD), previously known as nonalcoholic fatty liver disease (NAFLD),

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is a spectrum of liver diseases associated with obesity. New nomenclature was proposed in 2020 because previous terminology no longer reflected current knowledge. Metabolic fatty disease is now understood as a phenotype with heterogenous pathogenesis, manifesting across a wide range of severity and variability [5]. In this article, the current terminology was used, though certain cited references employed former nomenclature. MAFLD can be diagnosed using the gold standard, biopsy. More accessible methods are indirect, but sufficient for screening, one of which is BIA.

BODY COMPOSITION ANALYSIS

BC can be assessed by a variety of field and laboratory methods, which consists of anthropometric measurements (i.e., calculation formulas derived from weight, height, body circumferences, or skinfolds), BIA, ultrasound, magnetic resonance imaging (MRI), air-displacement plethysmography (ADP), dual-energy X-ray absorptiometry (DEXA), and microcompartment models.

BC parameters, such as percent body fat (PBF), fat mass (FM), or fat-free mass (FFM), provide a lot of information on patients' health, serving as a screening test for obesity or a tool for measuring the effectiveness of weight loss programs [6].

Reference methods

Up to date, DEXA remains a reference method for BC assessment. It utilizes X-rays, measuring the attenuation of its beam's energy, which passes through particular body tissue (specific attenuation for any tissue). This method converts BC into FM, lean body mass (LBM), and bone mineral content (BMC). It can be utilized to assess whole body or specific body regions. The estimated margin of error for DEXA is around 3%, which makes it the golden standard [7]. DEXA uses an X-ray generating source, X-ray detector, and a computer with specific software for imaging. The exposure to radiation in the procedure is minimal, and equals to a fraction of typical chest X-ray [8].

ADP is a method assessing mass and volume of a human body, and therefore can estimate body density, which can be further calculated into FM and FFM. This method has a high level of agreement with DEXA, but requires expensive equipment [6].

Another reference method is the 4-compartment model, which integrates data from DEXA, ADP, and bioimpedance spectroscopy (BIS) or hydrometry (isotope dilution). In this model, the human body is divided into four categories, such as fat, protein, mineral, and water. The degree of complication and variety of techniques used guarantees both best results and low accessibility in field research [9].

Bioelectrical impedance analysis

BIA is another BC analysis method. The principle of bioimpedance is to estimate BC parameters, including FFM (consisting of BMC), extracellular water (ECW), intracellular water (ICW), visceral protein, FM, and total body water (TBW), by measuring electrical resistance (R) and reactance (Xc) of different body segments. In this method, low level electrical current is used at a particular frequency (or frequencies) flowing through patient's body. The time in which the current passes a particular segment differs based on the tissue's electrical properties. The higher the tissue's hydration, the smaller resistance, as body water with diluted electrolytes has low resistance and conducts electrical current rapidly in comparison with adipose tissue, which has a much higher resistance [8].

BIA units can use a single-frequency current, typically 50 kHz, or multiple frequencies, such as 1, 5, 50, 250, 500, and 1,000 kHz, and consist of different amounts of electrodes, up to eight (2 for each foot and hand). The most accurate results are obtained by multifrequency octopolar devices [6, 10–12].

TBW parameter is calculated from R and body anthropometrics, including height and limb length, with several assumptions regarding body shape, limbs, and trunk considered as cylinders, water displacement, and intracellular fluid composition. Raw electrical data are converted into BC components, with manufacturer-dependent regression equations, and involve height, weight, age, sex, assessment of athletic body type, and health status [12]. Certain clinical conditions, such as patient's ethnicity and age, can influence the outcome of estimation, resulting in overestimation or underestimation of BIA parameters, so the better the regression equation supplied by the manufacturer, the more accurate the result [13].

Apart from calculated BIA parameters, prone to over- or underestimation, some raw BIA-derived data can be interpreted without further equations. Bioelectrical impedance vector analysis (BIVA) is the first example. Through BIVA, patient's hydration status and body cell mass (BCM) can be evaluated using R (resistance) and Xc (reactance) normalized by height (R/H and Xc/H) in the form of a graph R/Xc [13]. A longer vector in the graph indicates a greater resistance, hence dehydration and vice versa. BIVA, as a predictor of BCM and hydration, is employed as a prognosis in certain clinical conditions, such as chronic kidney disease, heart failure, various cancer types, or anorexia nervosa [13].

Another example of a directly measured BIA variable is phase angle (PhA), which is calculated from resistance and reactance from BIA reading. PhA is considered an index of hydration (ECW : ICW ratio), BCM, and cellular integrity, and is related to FFM. Moreover, it is associated with muscle strength and overall health. A lower PhA is correlated with a cell's low ability to store energy, indicating breakdown of cellular membranes. A higher PhA indicates a high amount of intact cell membranes and BCM [14]. Furthermore, PhA value is related to sex and age; it increases with the presence of obesity, but also with physical fitness (measured by HGS); however, these correlations need further verification [14].

Body mass index

BMI is an anthropometric index calculated from patients' weight (in kilograms) divided by their height (in meters) squared. Currently, the diagnosis of obesity in pediatric patients is based on BMI, standardized by growth charts for age and sex. Overweight is diagnosed as BMI over 85th percentile (> 1 SD), and obesity as BMI over 97th percentile (> 2 SD) [1].

MATERIAL AND METHODS

For this systematic review, on February 2, 2024, a search was conducted in the PubMed database for articles on combined bioelectrical impedance or BC, children or adolescents or pediatrics, and obesity or adiposity. Only English-written articles issued in the past 5 years were considered, providing 490 records. One author (A.K.) investigated manually all abstracts and relevant full-text papers, and excluded articles combining both adults and pediatric population, and those not focusing on obesity. The final search resulted in 31 full-text articles, which were included in the review (Figure 1).

RESULTS

The comparison between BIA and other BC analysis methods are presented in Table 1 [6, 7, 9–13, 15–20]. The results of studies on BIA used for various purposes in the obese children population are summarized in Table 2 [2–4, 15, 18, 19, 20–32].

DISCUSSION

The results presented in Table 1 demonstrate that, although BIA is not a flawless method for assessing BC, it seems to be sufficient in daily pediatric practice.

Firstly, BIA is a better tool than BMI for diagnosing obesity. Anthropometric indices have many advantages, such as simplicity, low cost, repeatability, and accessibility, which is why they are still the most commonly used tools in Poland. On the other hand, they may be misleading in certain conditions, such as exceeding muscle tissue in athletes and obesity, providing the same result on BMI percentile charts, though the discrepancy of these two conditions is evident. Moreover, a higher BMI position on percentile charts gives no information regarding the amount of fat tissue or its distribution, which affects obesity health hazard [1]. BMI as a tool for weight loss monitoring is incapable of determining whether it is due to reduction of FM, FFM, or TBW. In summary, various disadvantages of BMI, including low specificity to adiposity or sarcopenia and insufficient correlation to obesity complications, suggest the necessity for a more specific tool.

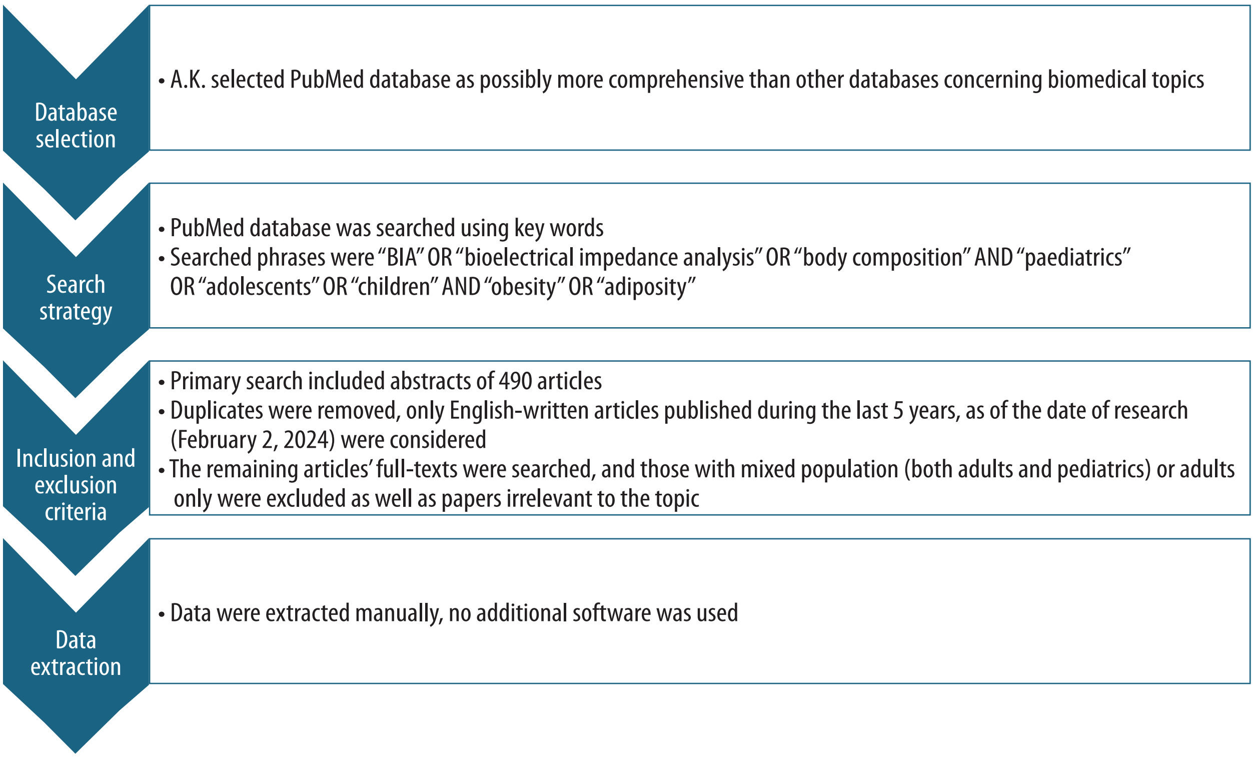

FIGURE 1. Methodology used in the review

TABLE 1. Comparison of bioelectrical impedance analysis (BIA) versus other body composition (BC) analysis methods

BIA versus BMI	A positive association was found between PBF measured by BIA and CMR, but there was no such association between CMR and BMI *Z*-score [15]. The research demonstrated poor agreement between BMI *Z*-score and PBF *Z*-score in obese patients. The superiority of FMI, calculated as BIA-derived FM (in kilograms) divided by height (in meters) squared was highlighted as a more effective tool for distinguishing obese from non-obese patients compared with BMI [13]. The BMI *Z*-score underestimated the prevalence of overweight and obesity compared with BIA-derived PBF [16]. One study showed that BMI overestimates the prevalence of obesity in adolescents in comparison with BIA method [17].
BIA versus DEXA	Though there was a bias in BIA results in comparison with DEXA (bias increases with higher PBF), it may be substantially reduced when certain regression equation (developed by the authors) is utilized [9]. Proportional changes in BC parameters (FM, FFM, and PBF) were comparable; also BIS was shown a viable alternative to DEXA, but only on group level [19]. A good agreement between BIA and DEXA results was found, suggesting that BIA may be a feasible alternative to DEXA in determining BC [18]. A well-known bias, BIA-derived FM, and PBF, were overestimated while FFM was underestimated in comparison with DEXA. Despite this bias, BIA was concluded a viable method of BC analysis in obese children [11]. BIA and DEXA demonstrated a strong correlation in tracking changes in BC among obese children participating in a weight loss program [19]. The authors of the review of BC assessment techniques reported that BIA, as a technique, showed a statistically high bias in comparison with the 4-compartment model or DEXA, but the reviewed articles' results differed [6]. The results revealed greater bias in tetrapolar, single-frequency BIA device, while small bias was shown in multifrequency octopolar BIA device in comparison with DEXA [12]. The results showed poor agreement between DEXA and an automated BIA device (cheap, accessible, and tetrapolar) [7].
BIA versus MRI	Magnetic resonance imaging may be used to assess visceral and subcutaneous fat thickness. Some specific equations can then be used to calculate FM or FFM. Compared with DEXA, MRI showed a good level of agreement [6]. There was a strong correlation between MRI and BIA in pediatric obese patients using MAFLD, but only with a multifrequency octopolar BIA device [20].
BIA versus ADP	Multifrequency octopolar BIA devices were confirmed as a valid method to assess BC in comparison with ADP [10].

ADP – air-displacement plethysmography, BC – body composition, BMI – body mass index, CMR – cardiometabolic risk factors, DEXA – X-ray absorptiometry, FFM – fat-free mass, FM – fat mass, FMI – fat mass index, MAFLD – metabolic-associated fatty liver disease, MRI – magnetic resonance imaging, PBF – percent body fat

DEXA, the gold standard for BC assessment, still has advantages over bioimpedance techniques. Further studies confirm a well-known bias, i.e., BIA-derived FM and PBF are overestimated and FFM is underestimated in comparison with DEXA [11]. However, bias is less significant using higher-quality BIA units, with multifrequency octopolar models suggesting to have negligible bias. In general, most of the cited researchers agree that BIA can be successfully used as an alternative to DEXA [9, 12, 20, 21]. Orsso *et al.* [6] in their review of BC assessment techniques in obese children were less optimistic regarding BIAs relevance in comparison with DEXA. BIA, as a technique, showed a statistically high bias in comparison with the 4-compartment model or DEXA, but the reviewed articles results were inconsistent [6].

Although DEXA has a clear advantage over BIA in terms of measurement accuracy, it has several limitations, including cost of equipment, requirement of qualified staff, possible contradictions, low accessibility, long scanning time, and for obese patients, limited acceptable size of a body possible to scan. Another limitation is unavailability to use DEXA as a field technique, as the size of the machine excludes its portability [7, 33].

Other methods, such as MRI or ADP, have rarely been directly compared with BIA. Based on the available literature, it can be concluded that the agreement between these methods is sufficient [10, 20]. The same applies when comparing these methods with DEXA. MRI compared with DEXA shows a good level of agreement. Also, ADP has a good level of agreement with DEXA, but requires expensive equipment [6].

Table 2 summarizes the results of the available literature regarding different applications of BIA in the obese pediatric population, showing evidently that BIA has already been used in various studies.

Positive correlations between BIA-derived parameters, such as PBF, FM, and FFM, and obesity-related laboratory and clinical parameters, have been observed by numerous researchers. These correlations highlight the potential role of BIA-derived measurements in diagnosing and monitoring obesity and its comorbidities.

Another important condition in which BIA is utilized is SO. As mentioned, SO refers to patients with low muscle mass and high fat mass, so they are not necessarily "obese" or "overweight" when classified by BMI *Z*-score; thus, measuring BC is the most effective way to diagnose this condition. Diagnostic criteria were designed for the adult population only, while for pediatrics, researchers rely on criteria available to the general population, which needs further research in this area.

Dehydration is a significant concern in obese children. Studies showed that it can affect up to half of this

TABLE 2. Bioelectrical impedance analysis (BIA) advantages in managing obese children

BIA indices and biochemical parameters	Baseline FM measurements correlated with homeostatic model assessment, with insulin resistance (HOMA-IR), HbA_{1c}, Tg, and SBP [21]. A higher dietary inflammatory index was associated with a higher PBF. Anti-inflammatory-rich diet components can help improving BC in obese adolescents [22]. There was a positive correlation between ALT level and BMI *Z*-score, PBF, and FMI. This suggests that individuals with greater levels of obesity are at a higher risk of experiencing more severe liver diseases [2]. A strong correlation was discovered between BIA-derived PBF and biochemical markers related to CMR. Higher PBF values were linked to adverse biochemical markers, such as Tg, LDL-C, and reduced levels of HDL-C. Also, an increased PBF was associated with elevated FBG levels, higher SBP, and DBP [15]. Significant associations were found between stress biomarkers, such as salivary cortisol and inflammation markers, i.e., hsCRP with metabolic dysregulation. BIA-derived PBF was positively correlated with hair cortisol concentrations, indicating a link between chronic stress and adiposity. Inflammation markers, such as hsCRP, ferritin, and white blood cell count, also showed significant positive correlations with PBF, highlighting the association between adiposity and systemic inflammation [23]. There were strong associations between BIA-derived PBF and specific biochemical markers linked to CMR, such as fasting serum insulin, Tg, GGT, uric acid, hsCRP, and HDL-C. These biochemical markers showed a high diagnostic capacity in identifying children with pediatric MetS and increased CMR [24]. A link between BIA values and vitamin D and leptin levels in adolescents was examined. In boys with a PBF below 40%, there was a negative correlation between leptin and 25(OH)D levels, while in girls, an inverse relationship between leptin and 25(OH)D was found only in those with PBF below 30%, who exhibited higher leptin and lower 25(OH)D levels. Unexpectedly, participants with a higher PBF (≥ 40%) presented increased 25(OH)D levels, which was contrary to previous research [25]. Excessive fat accumulation measured by BIA-derived PBF and WHtR was correlated with a higher TC, LDLc, and non-HDLc levels, especially in boys. PBF was the best predictor of dyslipidemia [26]. A higher PBF was linked to an increased risk of MetS components, while a lower MFRs were associated with a higher risk of MetS, emphasizing the significance of muscle mass in metabolic health. Patients with MetS showed a higher PBF, lower MFR, and EBP, glucose, Tg, and thyroid-stimulating hormone. The study highlighted the predictive value of MFR *Z*-scores in identifying MetS risks in advance [27].
BIA in MAFLD	Muscle mass and FM measured by BIA correlated with total psoas muscle surface area and fat compartments measured by abdominal MRI [20]. There was a reversed association between muscle mass measured by BIA and severity of hepatic steatosis (confirmed by biopsy) in children with MAFLD. No association was found between BIA-derived PBF and hepatic steatosis [28]. BC charts created with BIA can also serve as valuable tools for assessing risk in diseases associated with obesity, such as MAFLD [2].
BIA in hypertension	Cited research discovered association between sarcopenia, defined by MFR criterion, and a higher DBP in overweight and obese children [4]. A higher PBF was associated with an increased SBP and DBP levels. This correlation was shown more in girls and older-aged children. The study highlighted a graded association between BP categories and high PBF, indicating that as the BP levels increased, the risk of having high PBF also increased significantly. This association was particularly notable for the highest quartile of SBP, emphasizing the relevance of PBF in understanding EBP risks [18]. There was a significant positive correlation between PBF and BP levels in both males and females. Their analysis demonstrated that males and females classified as overweight or obese based on PBF had increased risks for EBP compared with non-overweight children [15].
BIA in SO	The presence of sarcopenia was associated with higher levels of GGT, CRP, higher DBP, and lower cardiorespiratory and muscular fitness [4]. In children with SO, correlations were reported between the distance of six-minute walk test and appendicular muscle mass divided by weight, MFR, PBF, and BMI *Z*-score [3]. No associations were found between six-minute walk test results and BC when sarcopenia was not present [29].
BIA in fitness assessment	A significant relationship was demonstrated between HGS, standing broad jump, and five broad jump, and PhA, while there was no association between PhA and six-minute walking test (which measures CRF). FFM is a significant predictor of HGS, while PhA can be used as a predictor of muscle strength in obese pediatric population [29]. Improving physical fitness was positively correlated with decrease in FM and increase in FFM (both in absolute terms and percentages) [19].

TABLE 2. Cont.

BIA and hydration status	Significant dehydration was observed in over half of the participants of the study, which were obese children. This study also highlighted a correlation between dehydration and higher BIA-derived FM and BMI in obese children [30]. Overweight children were more exposed to dehydration. The study also noted consistent TBW predictions between BIA and dilution methods, highlighting BIA's reliability [31].
BIA as a weight-loss monitoring tool	A strong correlation was found between BIS and DEXA results in baseline and follow-up measurements during a weight loss program. The agreement between both the methods improved at follow-up [32]. Improvements in the percentage of muscle mass measured by BIA were associated with enhancements in the Kasch pulse recovery test score. Also, a correlation was observed between the reduction in fat mass percentage and improvement in physical fitness [19].

ALT – alanine transaminase, BC – body composition, BMI – body mass index, CMR – cardiometabolic risk factors, CRF – cardiorespiratory fitness, DBP – diastolic blood pressure, DEXA – X-ray absorptiometry, EBP – elevated blood pressure, FBG – fasting blood glucose, FFM – fat-free mass, FM – fat mass, FMI – fat mass index, GGT – γ-glutamyl transferase, HbA_{1c} – glycated hemoglobin, HDL-C – high-density lipoprotein cholesterol, hsCRP – high sensitivity C-reactive protein, HGS – handgrip strength measurement, LDL-C – low-density lipoprotein cholesterol, MAFLD – metabolic-associated fatty liver disease, MetS – metabolic syndrome, MFR – muscle-to-fat ratio, MRI – magnetic resonance imaging, non-HDLc – non-HDL cholesterol, PBF – percent body fat, PhA – phase angle, SO – sarcopenic obesity, SBP – systolic blood pressure, TBW – total body water, TC – total cholesterol, Tg – triglycerides, WHtR – waist-to-height ratio

population. Dehydration can have a negative impact on metabolic functions and impair physical performance. In addition, pharmacokinetics of drugs in the obese pediatric population remains an underexplored area due to altered BC.

The recent field of research on the obese children population where BIA has been utilized, involves monitoring weight loss and assessing fitness levels. The cited studies demonstrate that BIA can be successfully used in childhood obesity treatment programs.

The strength of this review is the broad investigation, which eventually resulted in detecting a whole spectrum of obesity-related comorbidities, linked to various BIA parameters. Another strength is comparing various BC measurement methods regarded as the gold standards with BIA, and establishing the role of the bioimpedance method among other BC measuring techniques.

The limitation of our review is its timing. Conducting another review in the future, investigating the relation between BIA parameters in obese pediatric children using pharmaceutical therapy would enrich the results. Another possible limitation is choosing only one database, and including only English-written articles.

Despite the considerable amount of new literature, many aspects of BIA's usability in overweight and obese children remain to be explored. For example, the subject of puberty and its impact on BIA-derived parameters, appears challenging to study and standardize.

CONCLUSIONS

Obesity, understood as a disease related to excessive fat tissue accumulation, requires a better diagnostic method than the currently widely used BMI. BIA, despite possible inaccuracies compared with reference methods, is presently the most easily accessible and sufficiently accurate method for measuring BC. It is useful in diagnosing and monitoring obesity and its associated comorbidities.

DISCLOSURE

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