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Total body water by BIA in children and young adults with normal and excessive weight

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Abstract

Background

Estimation of total body water (TBW) is essential for clinical care.

Objective

Evaluation of changes in TBW by bioelectrical impedance analysis (BIA) in children and young adults with excessive weight.

Design

Data was collected in individuals aged 3–21 years with normal (n = 202) or excessive body weight (n = 133). The BIA results from individuals with normal weight were compared with two previously published studies in children by isotope dilution methods.

Results

Individuals with excessive weight had a higher mean TBW (27.87 L, SE 0.368) for height and age as compared to individuals with normal weight (23.95 L, SE 0.298), P<0.001. However, individuals with excessive weight had lower mean TBW (24.93 L, SE 0.37) for weight and body surface area (BSA) as compared to individuals with normal weight (26.94 L, SE 0.287), P<0.001. Comparison with two previously published studies showed no significant differences in mean TBW with one ((p = 1.00) but a significant difference with another study (p = 0.001).

Conclusions

Individuals with excessive weight had 16.5% higher mean TBW for height and age and 7.4% lower TBW for weight and BSA as compared to normal weight individuals. Our study validates the feasibility of data collection in pediatric outpatient setting by BIA.

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Introduction

Estimation of total body water (TBW) is integral to clinical care. It has significant implications for patient care that include dosing of medications, assessment and treatment of dehydration, fluid and energy requirements for parenteral nutrition, and dialysis prescriptions. Although the amount of TBW increases with growth from birth to adulthood, its fraction as a percentage of body weight decreases from about 80% at birth [1] to about 60% in adult men and 50% in adult women [1, 2].

There are several methods for body water estimation [3–7]. Of these, the isotope dilution technique is considered as sufficiently accurate and is used as a reference method for body water estimation. The major limitation with any of these methods is that they can be expensive and time consuming, need appropriate institutional resources, and are not possible in routine outpatient clinic setting, particularly in pediatric patients.

Bioimpedance analysis (BIA) is an alternative method for quantifying body water and its compartmental distribution. A large number of studies have validated the accuracy of BIA for body water estimation by comparing results with simultaneously collected data by dilution methods [5, 8–10]. Studies on TBW by dilution methods are not possible during routine outpatient clinic visits. BIA, in spite of some limitations, offers a potential substitute that deserves further exploration. Very little has been published on a quantitative comparison of TBW for age, weight, height or the body surface area (BSA) in children with normal and excessive weight and, to the best of our knowledge, no study has compared data collected by BIA with the historical data by dilution methods in children. The main objective of our study was to evaluate weight based changes in TBW noninvasively by BIA in ambulatory clinic settings in children and young adults. For validation of our data, we compared our results with two previously published studies in children by dilution methods.

Patients and methods

A total number of 335 BIA studies were done in 312 (93.1%) pediatric patients or their siblings seen in Nephrology Clinic at the Children's Hospital of Michigan and Med-Peds clinic of the University Physician Group over a period of 18 months. In some participants data was collected more than once and the minimum time interval between repeat studies in the same individual was six months. Children and young adults aged 3 years to 21 years with normal or increased body weight were included in the study. Excluded from the study were patients with diabetes, dehydration, hypertension with or without medications, internal defibrillator or pacemakers, missing limb, medications that affect body water content such as diuretics and glucocorticoids, menstruation, pregnancy, moderate exercise, consumption of a big meal within 2 hours before the procedure, and chronic kidney disease or any other co-morbid condition.

The study was approved by the Wayne State University Institutional Review Board. Parents or legal guardians of study participants aged 3–18 years had to sign study consent and those aged 13–18 years had to sign an assent form as well. Participants older than 18 years signed study consent by themselves. The study participant selection process is shown in Fig 1.

Height and weight were measured according to the standardized procedure with shoes and jackets off and only with light clothing [11]. Blood pressure was measured in accordance with the AAP guidelines [12] with manual confirmation of high readings by oscillometric methods.

BIA measurement

Direct segmental multi-frequency bioelectrical impedance analysis device InBody s10 (InBody Co. Ltd) was used for the study. Measurements were made in temperature controlled offices,

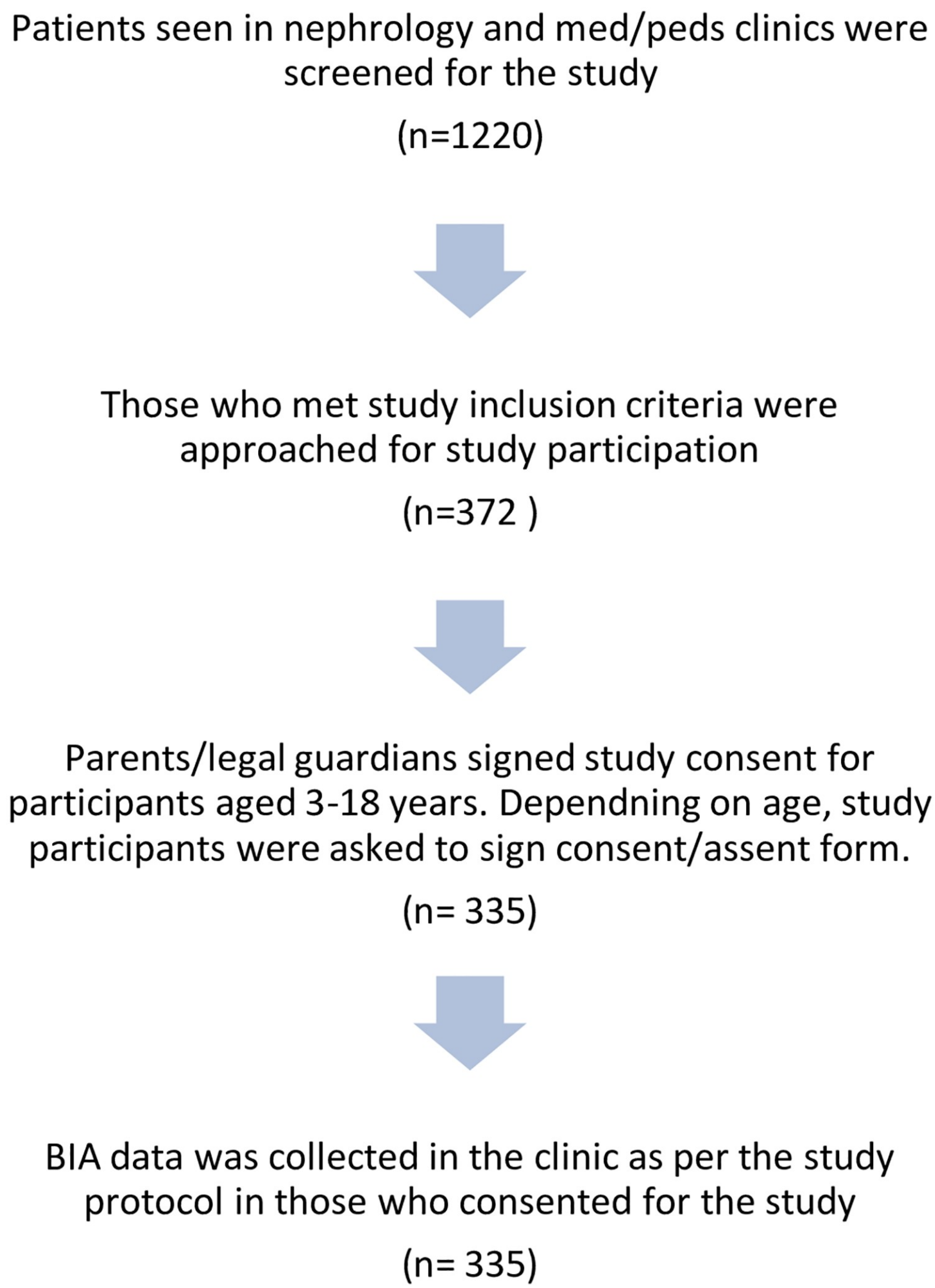

Fig 1. Selection of study participants for bioimpedance analysis (BIA) data collection.

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on examination tables with patient sitting with legs hanging- arms and legs abducted. Before each measurement, study participants were asked to void and sit down for 10 to 15 minutes on the examination table. Touch-type electrodes were placed on participants' feet near ankle and hands near wrist. A current frequency of 50, 100, 500 and 1000 kHz at 5 segments (right arm, left arm, right leg, left leg, and trunk) was applied for a total period of about minute and a half until completion of recording, which was indicated on the screen and with a beeping sound.

Two study investigators used the same BIA machine for data collection from all study participants.

To reduce the risk of measurement error, most patients had three back to back measurements for each study and the mean of three reading was used for data analysis. Studies with coefficient of variation of more than 5% between the three readings were excluded from data analysis. Body weight was defined on the basis of body mass index (BMI) as normal weight BMI<85th percentile), overweight (BMI >85th to 95th percentile), and obesity (BMI >95th percentile) [13]. Excessive weight in our study includes individuals with overweight as well as obesity.

We compared our BIA results with two previously published studies by dilution method in children [14, 15].

Statistical analysis

To express precision and repeatability of BIA measurements, the coefficient of variation was calculated and expressed as a percentage, defined as the ratio of the standard deviation to the mean. Studies with a coefficient of variation of more than 5% between the three readings were excluded from data analysis. Descriptive statistics were reported for both normal and overweight children.

We compared our BIA results with two previously published studies by dilution method in children [14, 15]. The mean of two or three BIA readings for each participant was used for data analysis and the coefficient of variation was calculated and reported for each. Demographic data from study participants was reported using frequencies procedures. Scatterplot graphs and best fit regression equations were reported separately for normal and overweight children, as well as gender. Bioimpedance data obtained from normal weight children was compared to two studies using the isotope dilution methodology. Regression equations were calculated for each study and standardized residual values computed. Median differences in standardized residuals between study groups were examined using a non-parametric Kruskal-Wallis procedure, with pair wise comparisons conducted with a non-parametric Mann Whitney U procedure. Accuracy of prediction models between studies were assessed using explained variance (R2), mean square error (MSE), square root of MSE, and average absolute percent error. The study was approved by our Institutional Review Board. All statistical procedures were conducted using NCSS statistical software Version 11.0.

Study results

A total of 335 studies were done in 312 (93.1%) study participants, one time only in 291 (86.9%), twice in 19 and three times in two participants. Their ages at the time of study ranged from 3 to 21 years with a mean age of 11.0 ± 4.4 years and the mean weight of 47.5 ± 25.9 kg. The gender ratio was almost equal with 173 (52%) males and 162 (48%) females. Of the total number of 335 studies, 202 (60%) were in normal weight and 133 (40%) were in individuals with excessive weight. There were no significant differences in age, gender, race, and height between normal weight and overweight/obese groups. As expected, weight, BMI and BSA are significantly different between the two groups. Demographic details are reported in Table 1.

In 319 (95%) studies, the data used for analysis was a mean of three measurements for each study and in 16 (4.8%) it was a mean of two studies. The coefficient of variation (CV) for three measurements was 0.75% ± 1.0% (Mean ± SD) range 0–3.7%. For two measurements (two each in three combinations), the CV% was 0.58% ± 1.63%, 0.59% ± 0.93%, and 0.79% ± 1.9%, respectively. Only three studies had CV% of more than 5% and they were excluded from data analysis.

Table 1. Demographic data on study participants.

	Total (n = 335)	Normal weight (n = 202)	Overweight & Obese (N = 133)	P value
Age (years) (mean± SD)	11.0 ± 4.39	10.95 ± 4.5	11.2 ± 4.2	0.92
Range	(3–21)	(3.1–21)	(4–19.5)	
Gender				
• Male	173 (51.6%))	95 (47%)	78 (58.6%)	0.048
• Female	162 (48.4%)	107 (53%)	55 (41.4%)	
Race				
• White	90 (26.8%)	54 (26.7%)	36 (27%)	0.78
• African American	98 (29.3%)	54 (26.7%)	44 (33.1%)	
• Other*	147 (43.9%)	94 (46.6%)	53 (39.9%)	
Weight (Kg) (mean± SD)	47.5 ± 25.9	38.5 ± 17.1	61.9 ± 31.5	<0.001
Range	(13.4–167.7)	(13.4–80)	(21–167.7)	
Height (cm) (mean± SD)	144.2 ± 23.5	142.5 ± 23.9	147.3 ± 22.97	0.069
Range	(95–186.6)	(95–186.6)	(96–196.4)	
Body Mass Index (BMI) mean				
± SD	21.4 ± 6.9	18.0 ± 3.9	26.5 ± 7.6	<0.001
Range	(12.9–58.3)	(12.9–24.6)	(17.3–60.86)	
BMI percentile mean ± SD	65.7 ± 30.5	46.6 ± 24.9	94.7 ± 4.3	<0.001
Range	(1–99)	(1–84)	(85–99)	
Body Surface Area (BSA)(m2)				
mean ± SD	1.35 ± 0.46	1.22 ± 0.37	1.55 ± 0.5	<0.001
Range	(0.59–2.56)	(0.59–2.0)	(0.7–2.56)	

Overweight: BMI percentile equal or more than 85th percentile.

* Includes Hispanics, Asian and those who refused to reveal their race.

P values are based on the comparison of normal weight group and overweight/obese group.

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TBW according to the various age groups is shown in Table 2. Scatterplots of TBW individuals with normal weight (n = 202) in relation to their age, body weight, height, and body surface area (BSA) are shown in Fig 2. Separate simple linear regressions and R-squared values were obtained for age (72.2%), body weight (94.1%), height (95.5%), and BSA (97.0%).

A scatterplot of TBW between genders of normal weight is shown in Fig 3. Females had a slightly higher R-squared value (94.4%); TBW = 6.878 + 0.359 (x) compared to males (92.9%); TBW = 5.056 + 0.456 (x). In terms of feasibility, both equations were highly predictive for both females and males with normal weight using BIA estimation. When controlling for body weight, age, BSA, and height males (97.3%) and females (97.8%) had almost identical R-squared values (97.3%). Results from the General Linear Model (GLM) revealed a significant

Table 2. Total body water according to various age groups.

Age Groups	Male			Female		
	Normal Weight	Excessive Weight	P Value	Normal Weight	Excessive Weight	P Value
3–7 Years	12.5±2.5 (n = 23)	15.0±3.7 (n = 21)	0.011	12.2±2.2 (n = 36)	15.1±3.7 (n = 13)	<0.01
8–12 Years	20.7±4.6 (n = 32)	26.5±7.6 (n = 27)	<0.01	21.6±3.8 (n = 35)	25.3±5.8 (n = 25)	<0.01
13–17 Years	37.8±7.5 (n = 37)	45.1±8.7 (n = 21)	<0.01	28.4±4.3 (n = 30)	37.5±9.0 (n = 15)	<0.01
18–21 Years	42.0±1.7 (n = 3)	46.8±5.8 (n = 7)	0.21	27.5±4.1 (n = 6)	40.1±9.0 (n = 4)	0.015

Excessive weight: Overweight and obese.

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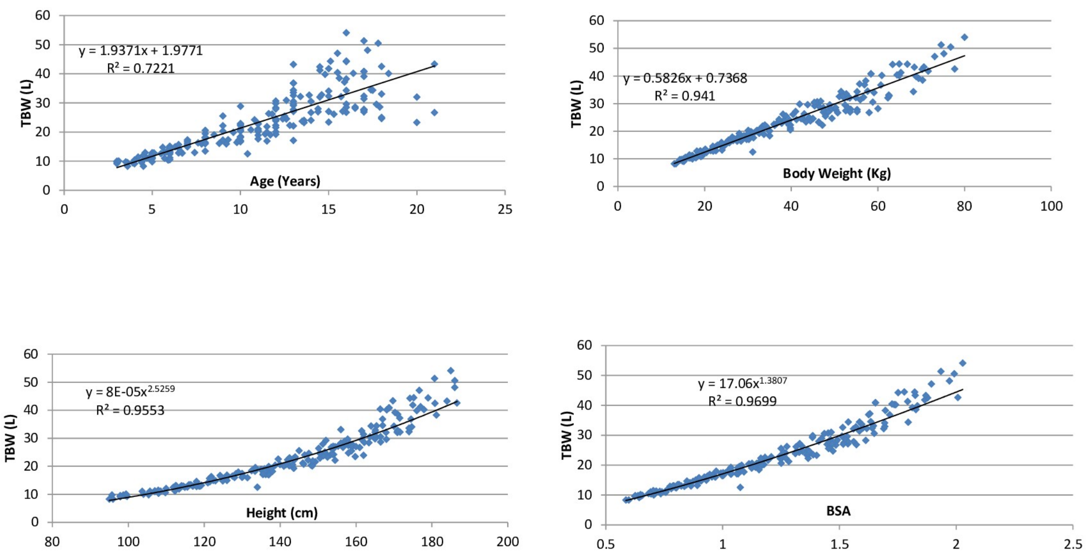

Fig 2. Correlation between total body water and age, weight, height, and BSA in normal weight individuals. TBW: Total Body Water; BSA: Body Surface Area in m^2.

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($P<0.01$) difference in the mean TBW in males (24.04, SE 0.20) versus females (22.47, SE 0.19) with normal weight. Covariates appearing in the model were evaluated at the following values: body weight = 38.57, height = 142.49, BSA = 1.22, age = 10.96. No significant mean differences in TBW were found between ethnicity groups.

Scatterplots of TBW in normal (n = 202) and individuals with excessive weight (n = 133) in relation to their age, body weight, body surface area, and height (BSA) are shown in Fig 4. Individuals with excessive weight had higher mean TBW (27.87, SE 0.368) for height and age as compared to individuals with normal weight (23.95, SE 0.298), $P<0.001$ (covariates age = 11.0, height = 144.2). However, the mean TBW for weight and BSA was lower in individuals with excessive weight (24.93, SE 0.37) as compared to individuals with normal weight (26.94, SE 0.287), $P<0.001$ (covariates weight = 47.5, BSA = 1.353).

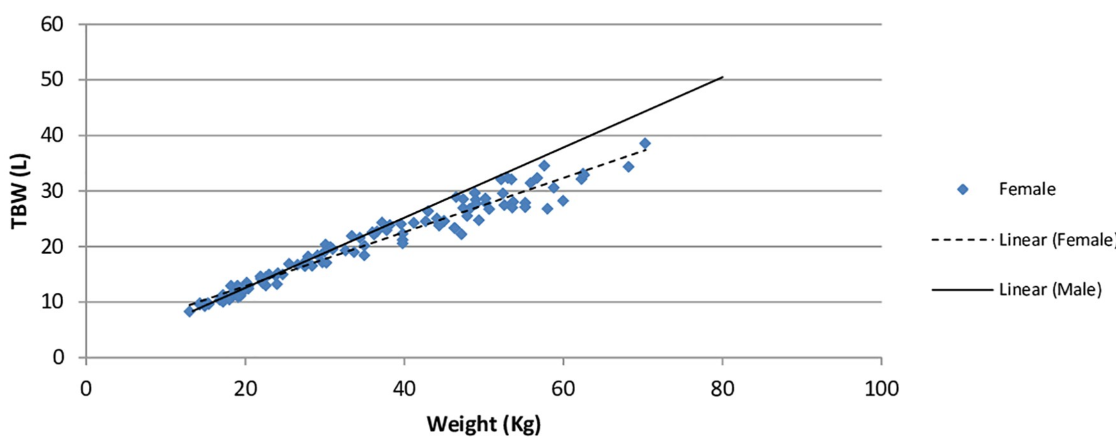

Fig 3. Total body water (TBW) in males and females with normal weight.

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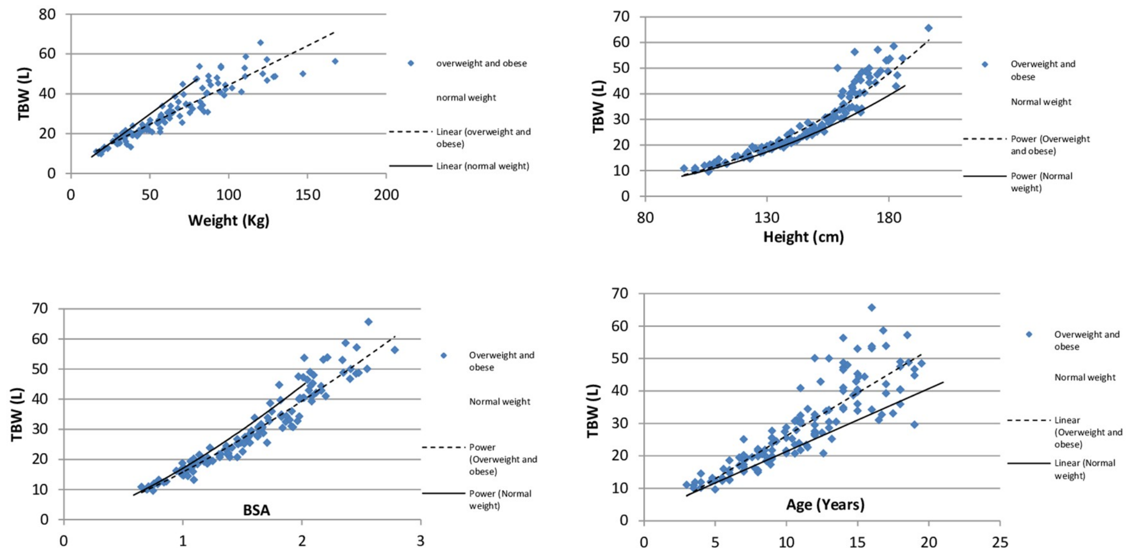

Fig 4. Total body water in overweight and obese individuals as compared to those with normal weight. TBW: Total Body Water; Overweight includes obese participants; BSA: Body Surface Area in m^2.

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The correlation coefficients of TBW with participant age, weight, height and BSA were (rounded) 0.72, 0.94, 0.96, and 0.97, respectively. The mean TBW (L) in males and females with normal as well as excessive weight was 26.52 L (SE) 0.21 and 24.46 L (SE) 0.22 ($P<0.001$), respectively; covariates appearing in the model were evaluated at the following values: Body Weight = 47.51, Height = 144.15, BSA = 1.35.

A comparison of our demographic data in children with normal weight with the two studies by isotope dilution methods that either published individual patient data (Cheek et al.) [14] or made it available to us on request (Dasgupta et al.) [15] is shown in Table 3. It reveals that there were no significant differences in all standardized median residual values predicting TBW between our data and that produced the two isotope dilution studies (BSA: p = 1.00; body weight: p = 0.93; height: p = 0.57; age: p = 0.87).

Fig 5 reveals that our data very closely replicated the scatterplot graphs by dilution methods of TBW. Data from all three investigations revealed that the relationship between TBW and body weight best fit a linear function but the relationship between TBW with height and TBW with BSA best fit a power curve function.

Fig 6 displays the regression residual plot graphs for TBW by BSA between our data and that produced by the two dilution methods. Residuals from the BIA method and the dilution

Table 3. Standardized residual median regression values for total body water by each single predictor by study investigator.

	Our Study	Dasgupta et al. [15]	Cheek et al. [14]	P-Value
BSA	0.08	0.03	0.04	1.00
Weight	0.11	-0.02	-0.05	0.93
Height	-0.15	0.03	0.11	0.57
Age	-0.05	-0.02	-0.13	0.83

BSA: Body surface area.

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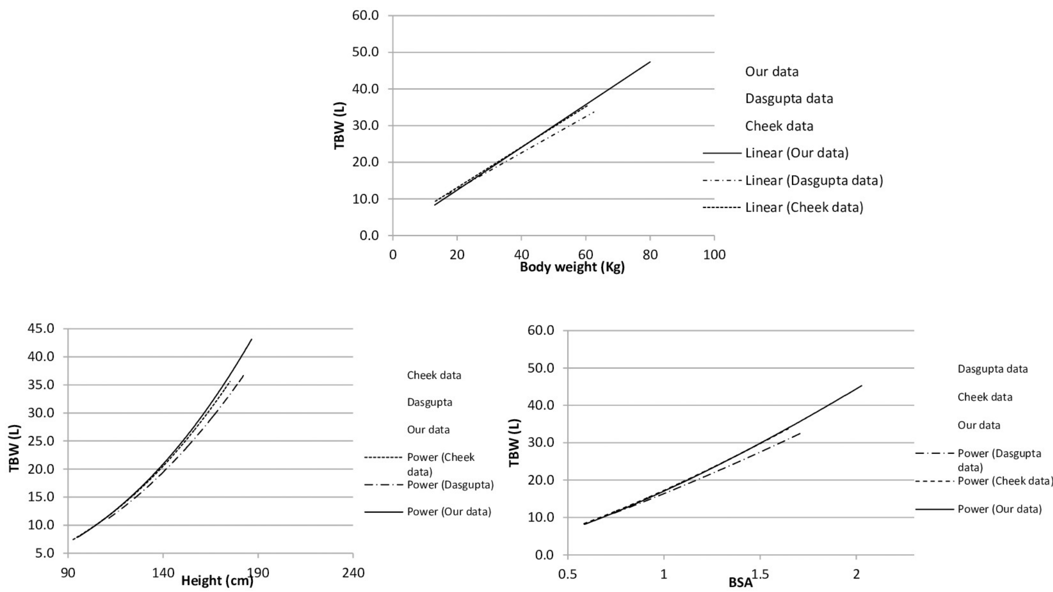

Fig 5. Comparison of regression line fits between bioimpedance and dilution methods. BSA: Body surface area Cheek et al[14], Dasgupta et al[15].

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method are not systematically different in range until approximately 15 years of age when a greater spread is seen in all predictive variables examined in the BIA graphs.

Accuracy of prediction statistics from the regressions from the three studies are shown in Table 4. R-squared values for predicting TBW with BSA, body weight, height, and age was 96% for the BIA method and 91% and 95% for the dilution method. The square root of MSE

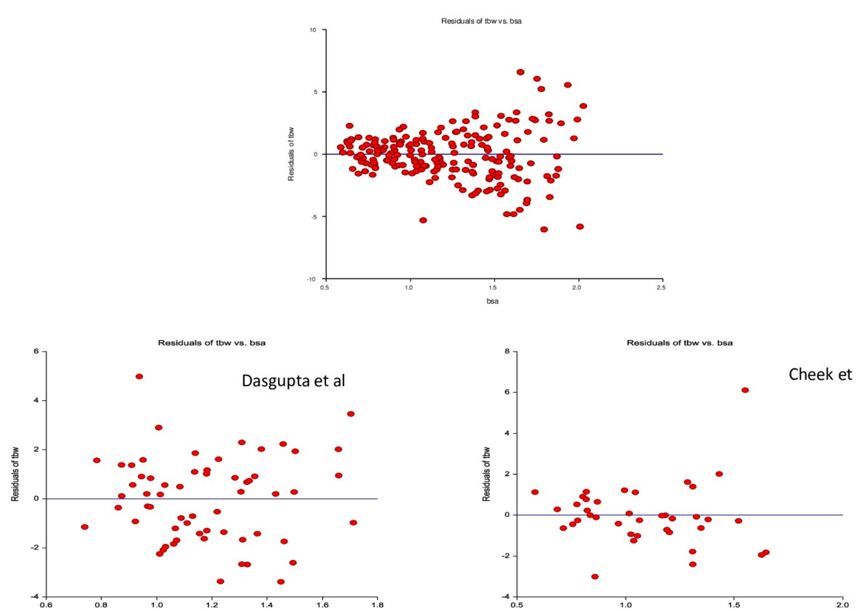

Fig 6. Comparison of regression residuals between bioimpedance and dilution methods. BIA: Bioimpedance analysis; TBW: Total body water; BSA: Body surface area; Studies by dilution method (Cheek[14], Dasgupta[15]).

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Table 4. Accuracy of prediction statistics by study investigator.

	Our Study	Dasgupta et al. [15]	Cheek et al. [14]
R^2	0.9610	0.9097	0.9535
Adjusted R^2	0.9602	0.9032	0.9481
Mean Squared Error	4.1882	3.1892	2.4950
Square Root of MSE	2.0465	1.7858	1.5796
Mean Abs Pct Error*	6.473	7.104	5.151

*Mean Abs Pct Error: Average Absolute Percent Error.

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was slightly higher for the BIA method (2.05) than for the two dilution methods (1.79 and 1.58). Mean absolute percent error (MAPE) calculated from the BIA data (6.47) was between the two calculated using the dilution method (7.10 and 5.15).

Discussion

BIA is the most practical method for TBW estimation in children in the outpatient clinic setting. Previously considered as less accurate, the introduction of a multi-frequency BIA has helped enhance its accuracy [16]. The major advantages of BIA over other methods of body water estimation are that the equipment is non-invasive, inexpensive, portable, easy to use, and takes five minutes to complete. Furthermore, the results are immediately available and it is possible to have multiple readings. In 1994, the Technology Assessment Conference Statement by the National Institutes of Health concluded that the BIA provides a reliable estimate of TBW in most conditions and in view of its ease of measurement, expense, safety, portability, and reproducibility is preferred over logistically complex techniques [17]. According to the European Society for Clinical Nutrition and Metabolism Guidelines, the BIA works well in healthy subjects and in patients with stable water and electrolyte balance [18–22].

A large number of studies have been done to validate BIA against reference techniques for the measurement of TBW and ECW [5, 8–10]. These studies have revealed a good overall agreement between dilution techniques and BIA in healthy children as well as adults [23–25], hospitalized elderly patients [26] pregnant women [27], diabetic patients [28], children with obesity [29], and during rehydration for cholera [30]. A study in healthy as well as malnourished children revealed that the BIA method was accurate within 4% of the mean body water measured by isotope dilution [31]. BIA's accuracy in detecting changes in blood volume was also demonstrated in adults [32–34] and children on dialysis [16, 35–38].

Apart from the ease of data collection in children by BIA, our study revealed excellent reproducibility of BIA readings with a very low coefficent of variation between the three readings. A high reproducibility with <1% error on repeated measurements for TBW and ECW has been reported previously also [23, 39]. Our study revealed a significant correlation of body water content with height, weight and BSA, but not patient age. It showed a linear relationship with age and weight and a curvilinear relationship with height and BSA. This is similar to the study by Cheek et al. [14] that showed a linear relationship of TBW with weight and a curvilinear relationship with height, the latter because of growth spurt.

Males with normal weight in our study showed 9% more mean TBW as compared to females with normal weight. When combined with those with overweight and obesity, the males had 7.7% more TBW than females. The reported gender difference for TBW by dilution method in children is variable. It ranges from about 6% higher TBW in males aged 7–9 years [40] to about 15% in males aged 5–8 years [41]. The TBW increases with growth and our study revealed that the TBW was very similar in boys and girls with normal weight in 3–7 year age group and it was significantly lower ($p<0.01$) in females as compared to males in 18–21 year age group. For those with excessive weight, the TBW was similar in 3–7 year age group, but it did not show any significant difference (p 0.16) in 18–21 age group. However, the number of patients in 8–21 year age group in our study is very small and will need further validation.

Studies in adults have revealed that individuals with overweight and obesity have lower TBW for weight and hence are hypohydrated as compared to those with normal weight [42–44]. Very little has been published about weight related changes in TBW in children and the observations made are very similar to adults [29, 45, 46]. A weight related decrease in TBW in obesity is a result of relatively higher percentage of body fat in such individuals with a net decrease in fat-free mass and TBW for weight. Body fat has only 20–30 percent water as compared to about 70% in fat-free body mass [47]. In our study, individuals with excessive weight had 16.5% higher mean TBW for height and age and 7.4% lower TBW for weight and BSA as compared to normal weight individuals.

Body water measurement by BIA is affected by multiple factors. These include room temperature, electrode placement, skin temperature, posture, recent physical activity, full bladder, changes in plasma osmolality or sodium concentration, hydration status, consumption of food and beverages, conductance of examination table, ethnicity, menstruation, and underlying medical conditions [5, 17, 48–51]. The accuracy of measurement is also affected by the variability of prediction equations for a particular patient population [26]. In our study, we overcame some of these limitations by using strict study inclusion/exclusion criteria and standardizing methods for data collection as elaborated previously, and by using the same BIA machine for all participants. Our study cohort consisted of healthy children and young adults with no suspected systemic or fluid and electrolyte abnormality.

Our study explored the feasibility of BIA data collection in routine pediatric outpatient clinic setting. Instead of validating our data by comparing it with a reference method, which would have been impossible in our setting, we compared our data with the two studies that either published individual patient data [14] or made it available to us on request [15]. Our results showed no significant mean differences in TBW with the former but a significant difference with the latter. It is interesting to note that the two studies, both by dilution method, showed significant difference amongst themselves, which might be indicative of some inherent limitations even with indirect method for body water estimation. The study cohort for these studies, including ours, were not age, weight, race or gender-matched, which may explain the differences. However most of the individuals, 90% in one study [15] and 93% in the other study [14], had normal weight and hence comparable to our study cohort with normal weight.

As in adults, hypohydration in children and young adults with excessive weight has clinical implications. These include increased risk of dehydration, assessment and management of dehydration, calculation of volume of distribution for medications, and management of renal failure, including dialysis. In 2004, The European Society of Clinical Nutrition and Metabolism (ESPEN) recommended to use BMI for TBW measurement only for BMI between16-34. Higher BMI in some of our patients could be a study limitation. However, studies published after the publication of ESPEN guidelines have reported that BIA accurately estimates TBW in overweight and obese subjects [52, 53] and this may be due to an increasing use of multi-frequency BIA for data collection. Not having a concurrent reference method to validate BIA results in our study cohort could be seen as a study limitation. However, our study results are consistent with observations made in children, who were studied by dilution methods. Our observations are based on a single-center study cohort and a larger multi-center study will be needed to see if the results are any different in a national cohort. Being an observational, exploratory and a pilot study, we did not do power analysis for the estimation of our sample size. However, a post hoc power analysis using the SE of TBW and BSA, which was 0.287, with a 95% level of confidence and the margin of error set at 3.1%, the sample size would be n = 333.

In conclusion, children and young adults with excessive weight are hypohydrated, which may increase their risk of dehydration. Further studies are needed to evaluate the clinical significance of hypohydration in this population.

Supporting information

S1 Data.
(XLSX)

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Author Contributions

Conceptualization: Tej K. Mattoo.

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Funding acquisition: Tej K. Mattoo.

Investigation: Tej K. Mattoo, Hong Lu, Eric Ayers.

Methodology: Tej K. Mattoo, Hong Lu, Ronald Thomas.

Project administration: Tej K. Mattoo.

Resources: Eric Ayers.

Software: Ronald Thomas.

Supervision: Tej K. Mattoo.

Writing – original draft: Tej K. Mattoo.

Writing – review & editing: Hong Lu, Ronald Thomas.

References

1. Friis-Hansen BJ, Holiday M, Stapleton T, Wallace WM. Total body water in children. *Pediatrics* 1951; 7 (3): 321–7. PMID: 14827634
2. Virgili F, D'Amicis A, Ferro-Luzzi A. Body composition and body hydration in old age estimated by means of skinfold thickness and deuterium dilution. *Ann Hum Biol* 1992; 19(1): 57–66. https://doi.org/10.1080/03014469200001922 PMID: 1734823
3. Kyle UG, Earthman CP, Pichard C, Coss-Bu JA. Body composition during growth in children: limitations and perspectives of bioelectrical impedance analysis. *Eur J Clin Nutr* 2015; 69(12): 1298–305. https://doi.org/10.1038/ejcn.2015.86 PMID: 26039314
4. Mellits ED, Cheek DB. The assessment of body water and fatness from infancy to adulthood. *Monogr Soc Res Child Dev* 1970; 35(7): 12–26. PMID: 5508380
5. Armstrong LE. Hydration assessment techniques. *Nutr Rev* 2005; 63(6 Pt 2): S40–54. https://doi.org/10.1111/j.1753-4887.2005.tb00153.x PMID: 16028571
6. Wells JC, Fewtrell MS. Measuring body composition. *Arch Dis Child* 2006; 91(7): 612–7. https://doi.org/10.1136/adc.2005.085522 PMID: 16790722
7. Ellis KJ. Human body composition: in vivo methods. *Physiol Rev* 2000; 80(2): 649–80. https://doi.org/10.1152/physrev.2000.80.2.649 PMID: 10747204

8. Sun SS, Chumlea WC, Heymsfield SB, et al. Development of bioelectrical impedance analysis prediction equations for body composition with the use of a multicomponent model for use in epidemiologic surveys. *Am J Clin Nutr* 2003; 77(2): 331–40. https://doi.org/10.1093/ajcn/77.2.331 PMID: 12540391
9. Ritz P, Investigators. Body water spaces and cellular hydration during healthy aging. *Ann Ny Acad Sci* 2000; 904: 474–83. https://doi.org/10.1111/j.1749-6632.2000.tb06502.x PMID: 10865791
10. Ritz P, Vol S, Berrut G, Tack I, Arnaud MJ, Tichet J. Influence of gender and body composition on hydration and body water spaces. *Clinical nutrition* 2008; 27(5): 740–6. https://doi.org/10.1016/j.clnu.2008.07.010 PMID: 18774628
11. CDC. National Center for Health Statistics. National Health and Nutrition Examination Survey (NHANES) anthropometry procedures manual. 2013. http://www.cdc.gov/nchs/data/nhanes/nhanes_13_14/2013_Anthropometry.pdf.
12. The fourth report on the diagnosis, evaluation, and treatment of high blood pressure in children and adolescents. Pediatrics 2004; 114(2 Suppl 4th Report): 555–76.
13. Centers for Disease Control and Prevention; https://www.cdc.gov/growthcharts/
14. Cheek DB, Mellits D, Elliott D. Body water, height, and weight during growth in normal children. *Am J Dis Child* 1966; 112(4): 312–7. https://doi.org/10.1001/archpedi.1966.02090130086007 PMID: 5925616
15. Dasgupta I, Keane D, Lindley E, et al. Validating the use of bioimpedance spectroscopy for assessment of fluid status in children. *Pediatr Nephrol* 2018; 33(9): 1601–7. https://doi.org/10.1007/s00467-018-3971-x PMID: 29869117
16. Furstenberg A, Davenport A. Assessment of body composition in peritoneal dialysis patients using bioelectrical impedance and dual-energy x-ray absorptiometry. *Am J Nephrol* 2011; 33(2): 150–6. https://doi.org/10.1159/000324111 PMID: 21293116
17. NIH Consensus statement. Bioelectrical impedance analysis in body composition measurement. National Institutes of Health Technology Assessment Conference Statement. December 12–14, 1994. Nutrition 1996; 12(11–12): 749–62.
18. Kyle UG, Bosaeus I, De Lorenzo AD, et al. Bioelectrical impedance analysis-part II: utilization in clinical practice. *Clinical nutrition* 2004; 23(6): 1430–53. https://doi.org/10.1016/j.clnu.2004.09.012 PMID: 15556267
19. Lewy VD, Danadian K, Arslanian S. Determination of body composition in African-American children: validation of bioelectrical impedence with dual energy X-ray absorptiometry. *J Pediatr Endocrinol Metab* 1999; 12(3): 443–8. https://doi.org/10.1515/JPEM.1999.12.3.443 PMID: 10821224
20. Stupnicki R, Tomaszewski P, Milde K, Czeczelewski J, Lichota M, Glogowska J. Body fat-based weight norms for children and youths. *Pediatr Endocrinol Diabetes Metab* 2009; 15(3): 139–43.
21. Meleleo D, Bartolomeo N, Cassano L, et al. Evaluation of body composition with bioimpedence. A comparison between athletic and non-athletic children. *Eur J Sport Sci* 2017; 17(6): 710–9. https://doi.org/10.1080/17461391.2017.1291750 PMID: 28319679
22. Resende CM, Camelo JS Junior, Vieira MN, et al. Body composition measures of obese adolescents by the deuterium oxide dilution method and by bioelectrical impedance. *Braz J Med Biol Res* 2011; 44(11): 1164–70. https://doi.org/10.1590/s0100-879x2011007500122 PMID: 22052374
23. Segal KR, Burastero S, Chun A, Coronel P, Pierson RN Jr., Wang J. Estimation of extracellular and total body water by multiple-frequency bioelectrical-impedance measurement. *Am J Clin Nutr* 1991; 54 (1): 26–9. https://doi.org/10.1093/ajcn/54.1.26 PMID: 2058583
24. Aglago KE, Menchawy IE, Kari KE, et al. Development and validation of bioelectrical impedance analysis equations for predicting total body water and fat-free mass in North-African adults. *Eur J Clin Nutr* 2013; 67(10): 1081–6. https://doi.org/10.1038/ejcn.2013.125 PMID: 23839666
25. El Harchaoui I, El Hamdouchi A, Baddou I, et al. Development and validation of bioelectrical impedance analysis equations for prediction total body water and fat-free mass using D2O technique in Moroccan children aged between 8 and 11 years old. *Eur J Clin Nutr* 2018.
26. Powers JS, Choi L, Bitting R, Gupta N, Buchowski M. Rapid measurement of total body water to facilitate clinical decision making in hospitalized elderly patients. *J Gerontol A Biol Sci Med Sci* 2009; 64(6): 664–9. https://doi.org/10.1093/gerona/glp018 PMID: 19228780
27. Lukaski HC, Hall CB, Siders WA. Assessment of change in hydration in women during pregnancy and postpartum with bioelectrical impedance vectors. *Nutrition* 2007; 23(7–8): 543–50. https://doi.org/10.1016/j.nut.2007.05.001 PMID: 17570642
28. De Lorenzo A, Sorge RP, Candeloro N, Di Campli C, Sesti G, Lauro R. New insights into body composition assessment in obese women. *Can J Physiol Pharmacol* 1999; 77(1): 17–21. https://doi.org/10.1139/cjpp-77-1-17 PMID: 10535661

29. Bedogni G, Bollea MR, Severi S, Trunfio O, Manzieri AM, Battistini N. The prediction of total body water and extracellular water from bioelectric impedance in obese children. *Eur J Clin Nutr* 1997; 51(3): 129–33. https://doi.org/10.1038/sj.ejcn.1600351 PMID: 9076401

30. McDonald JJ, Chanduvi B, Velarde G, et al. Bioimpedance monitoring of rehydration in cholera. *Lancet* 1993; 341(8852): 1049–51. https://doi.org/10.1016/0140-6736(93)92410-u PMID: 8096957

31. Fjeld CR, Freundt-Thurne J, Schoeller DA. Total body water measured by 18-O dilution and bioelectrical impedance in well and malnourished children. *Pediatr Res* 1990; 27(1): 98–102. https://doi.org/10.1203/00006450-199001000-00024 PMID: 2104972

32. Moissl U, Arias-Guillen M, Wabel P, et al. Bioimpedance-guided fluid management in hemodialysis patients. *Clin J Am Soc Nephrol* 2013; 8(9): 1575–82. https://doi.org/10.2215/CJN.12411212 PMID: 23949235

33. O'Lone EL, Visser A, Finney H, Fan SL. Clinical significance of multi-frequency bioimpedance spectroscopy in peritoneal dialysis patients: independent predictor of patient survival. *Nephrol Dial Transplant* 2014; 29(7): 1430–7. https://doi.org/10.1093/ndt/gfu049 PMID: 24598280

34. Raimann JG, Zhu F, Wang J, et al. Comparison of fluid volume estimates in chronic hemodialysis patients by bioimpedance, direct isotopic, and dilution methods. *Kidney Int* 2014; 85(4): 898–908. https://doi.org/10.1038/ki.2013.358 PMID: 24067432

35. Oh G, Wong C, Begin B, Salsbery K, Sutherland S, Chaudhuri A. Whole-body single-frequency bioimpedance analysis in pediatric hemodialysis patients. *Pediatr Nephrol* 2014; 29(8): 1417–23. https://doi.org/10.1007/s00467-014-2778-7 PMID: 24570069

36. Schaefer F, Wuhl E, Feneberg R, Mehls O, Scharer K. Assessment of body composition in children with chronic renal failure. *Pediatr Nephrol* 2000; 14(7): 673–8. https://doi.org/10.1007/s004670000353 PMID: 10912541

37. Zaloszyc A, Schaefer B, Schaefer F, et al. Hydration measurement by bioimpedance spectroscopy and blood pressure management in children on hemodialysis. *Pediatr Nephrol* 2013; 28(11): 2169–77. https://doi.org/10.1007/s00467-013-2540-6 PMID: 23832099

38. Yang EM, Park E, Ahn YH, et al. Measurement of Fluid Status Using Bioimpedance Methods in Korean Pediatric Patients on Hemodialysis. *J Korean Med Sci* 2017; 32(11): 1828–34. https://doi.org/10.3346/jkms.2017.32.11.1828 PMID: 28960036

39. Milani GP, Groothoff JW, Vianello FA, et al. Bioimpedance and Fluid Status in Children and Adolescents Treated With Dialysis. *Am J Kidney Dis* 2017; 69(3): 428–35. https://doi.org/10.1053/j.ajkd.2016.10.023 PMID: 28089477

40. Al-Ati T, Preston T, Al-Hooti S, et al. Total body water measurement using the 2H dilution technique for the assessment of body composition of Kuwaiti children. *Public Health Nutr* 2015; 18(2): 259–63. https://doi.org/10.1017/S1368980013003534 PMID: 26263176

41. Leman CR, Adeyemo AA, Schoeller DA, Cooper RS, Luke A. Body composition of children in south-western Nigeria: validation of bio-electrical impedance analysis. *Ann Trop Paediatr* 2003; 23(1): 61–7. https://doi.org/10.1179/000349803125002887 PMID: 12648327

42. Rosinger AY, Lawman HG, Akinbami LJ, Ogden CL. The role of obesity in the relation between total water intake and urine osmolality in US adults, 2009–2012. *Am J Clin Nutr* 2016; 104(6): 1554–61. https://doi.org/10.3945/ajcn.116.137414 PMID: 27935519

43. Stookey JD, Barclay D, Arieff A, Popkin BM. The altered fluid distribution in obesity may reflect plasma hypertonicity. *Eur J Clin Nutr* 2007; 61(2): 190–9. https://doi.org/10.1038/sj.ejcn.1602521 PMID: 17021599

44. Hankin ME, Munz K, Steinbeck AW. Total body water content in normal and grossly obese women. *Med J Aust* 1976; 2(14): 533–7. PMID: 994955

45. Battistini N, Brambilla P, Virgili F, et al. The prediction of total body water from body impedance in young obese subjects. *Int J Obes Relat Metab Disord* 1992; 16(3): 207–12. PMID: 1317830

46. Maffeis C, Tommasi M, Tomasselli F, et al. Fluid intake and hydration status in obese vs normal weight children. *Eur J Clin Nutr* 2016; 70(5): 560–5. https://doi.org/10.1038/ejcn.2015.170 PMID: 26463726

47. Gundersen K, Shen G. Total body water in obesity. *Am J Clin Nutr* 1966; 19(2): 77–83. https://doi.org/10.1093/ajcn/19.2.77 PMID: 5916037

48. Androutsos O, Gerasimidis K, Karanikolou A, Reilly JJ, Edwards CA. Impact of eating and drinking on body composition measurements by bioelectrical impedance. *Journal of human nutrition and dietetics: the official journal of the British Dietetic Association* 2015; 28(2): 165–71.

49. Beckmann L HS, Medrano G, Kim S, Walter M, Leonhardt S., Monitoring change of body fluids during physical exercise using bioimpedance spectroscopy. Conf Proc IEEE Eng Med Biol Soc 2009; 2009. p. 4465–8

50. Dehghan M, Merchant AT. Is bioelectrical impedance accurate for use in large epidemiological studies? *Nutr J* 2008; 7: 26. https://doi.org/10.1186/1475-2891-7-26 PMID: 18778488

51. Kyle UG, Bosaeus I, De Lorenzo AD, et al. Bioelectrical impedance analysis—part I: review of principles and methods. *Clinical nutrition* 2004; 23(5): 1226–43. https://doi.org/10.1016/j.clnu.2004.06.004 PMID: 15380917

52. Sartorio A, Malavolti M, Agosti F, et al. Body water distribution in severe obesity and its assessment from eight-polar bioelectrical impedance analysis. *Eur J Clin Nutr* 2005; 59(2): 155–60. https://doi.org/10.1038/sj.ejcn.1602049 PMID: 15340370

53. Thurlow S, Taylor-Covill G, Sahota P, Oldroyd B, Hind K. Effects of procedure, upright equilibrium time, sex and BMI on the precision of body fluid measurements using bioelectrical impedance analysis. *Eur J Clin Nutr* 2018; 72(1): 148–53. https://doi.org/10.1038/ejcn.2017.110 PMID: 28722029