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Bioelectrical impedance analysis—part I: review of principles and methods

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Summary The use of bioelectrical impedance analysis (BIA) is widespread both in healthy subjects and patients, but suffers from a lack of standardized method and quality control procedures. BIA allows the determination of the fat-free mass (FFM) and total body water (TBW) in subjects without significant fluid and electrolyte abnormalities, when using appropriate population, age or pathology-specific BIA equations and established procedures. Published BIA equations validated against a reference method in a sufficiently large number of subjects are presented and ranked according to the standard error of the estimate.

Bioelectrical spectroscopy;
ESPEN guidelines;
Fat-free mass;
Total body water;
Extracellular water;
Intracellular water;
Body cell mass

The determination of changes in body cell mass (BCM), extra cellular (ECW) and intra cellular water (ICW) requires further research using a valid model that guarantees that ECW changes do not corrupt the ICW. The use of segmental-BIA, multifrequency BIA, or bioelectrical spectroscopy in altered hydration states also requires further research.

ESPEN guidelines for the clinical use of BIA measurements are described in a paper to appear soon in Clinical Nutrition.

Introduction

This review discusses the application of bioelectrical impedance analysis (BIA). BIA is widely used in many clinical situations. Part 1 is a review of the *principles and methods* of BIA, the body compartments evaluated with BIA, selection criteria, and selected BIA equations reported in the literature. Part II will provide guidelines for BIA use in clinical practice.

Historical background

Electrical properties of tissues have been described since 1871.[1] These properties were further described for a wider range of frequencies on larger range of tissues, including those that were damaged or undergoing change after death. Thomasset[2,3] conducted the original studies using electrical impedance measurements as an index of total body water (TBW), using two subcutaneously inserted needles. Hoffer et al.[4] and Nyboer[5] first introduced the four-surface electrode BIA technique. A disadvantage of surface electrodes is that a high current (800 μA) and high voltage must be utilized to decrease the instability of injected current related to cutaneous impedance (10 000 Ω/cm^2).[6] By the 1970s the foundations of BIA were established, including those that underpinned the relationships between the impedance and the body water content of the body. A variety of single frequency BIA analyzers then became commercially available, and by the 1990s, the market included several multi-frequency analyzers. The use of BIA as a bedside method has increased because the equipment is portable and safe, the procedure is simple and non-invasive, and the results are reproducible and rapidly obtained. More recently, segmental BIA has been developed to overcome inconsistencies between resistance (R) and body mass of the trunk.

Principles of bioelectrical impedance

The resistance (R) of a length of homogeneous conductive material of uniform cross-sectional area is proportional to its length (L) and inversely proportional to its cross sectional area (A) (Fig. 1). Although the body is not a uniform cylinder and its conductivity is not constant, an empirical relationship can be established between the impedance quotient (Length^2/R) and the volume of water, which contains electrolytes that conduct the electrical current through the body. In practice, it is easier to measure height than the conductive length, which is usually from wrist to ankle. Therefore, the empirical relationship is between lean body mass (typically 73% water) and height^2/R. Due to the inherent field inhomogeneity in the body, the term height^2/R describes an equivalent cylinder, which must be matched to the real geometry by an appropriate coefficient. This coefficient depends on various factors, among them also the anatomy of the segments under investigation. Therefore, errors occur when there are alterations in resistivity of the conductive material,
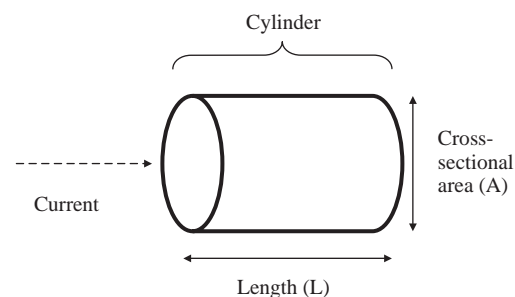
Figure 1 Principles of BIA from physical characteristics to body composition. Cylinder model for the relationship between impedance and geometry. The resistance of a length of homogeneous conductive material of uniform cross-sectional area is proportional to its length (L) and inversely proportional to its cross sectional area (A). Hence resistance $(R) = \rho L/A = \rho L^2/V$; and volume $(V) = \rho L^2/R$, where ρ is the resistivity of the conducting material and V equals AL.

variations in the ratio height to conductive length, and variations in the shape of the body and body segments (body segments behave as if they are in series with each other, with shorter and thicker segments contributing less to the total R).

Another complexity is that the body offers two types of R to an electrical current: capacitative R (reactance), and resistive R (simply called resistance). The capacitance arises from cell membranes, and the R from extra- and intracellular fluid. Impedance is the term used to describe the combination of the two. Several electrical circuits have been used to describe the behavior of biological tissues in vivo.[7] One of them involves arranging R and capacitance in series, another in parallel (Fig. 2), whilst others are more complex. A circuit that is commonly used to represent biological tissues in vivo is one in which the R of extracellular fluid is arranged in parallel to the second arm of the circuit, which consists of capacitance and R of intracellular fluid in series. R and capacitance can all be measured over a range of frequencies (most single-frequency BIA analyzers operate at 50-kHz).

At zero (or low) frequency, the current does not penetrate the cell membrane, which acts as an insulator, and therefore the current passes through the extracellular fluid, which is responsible for the measured R of the body R_0.

At infinite frequency (or very high frequency) the capacitor behaves as a perfect (or near perfect) capacitor, and therefore the total body R (R_∞) reflects the combined of both intracellular and extracellular fluid.

Fricke's circuit
Two parallel electrical conductors:
$R_{(ECW)}$: H_2O-Na
$R_{(ICW)}$: H_2O-K
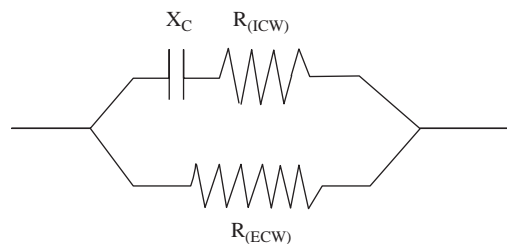isolated by a cell membrane (X_c)

Figure 2 The human body consists of resistance and capacitance connected in parallel or in series. In the parallel model, two or more resistors and capacitors are connected in parallel, with the current passing at high frequencies through the intracellular space and at low frequencies passing through the extracellular space.
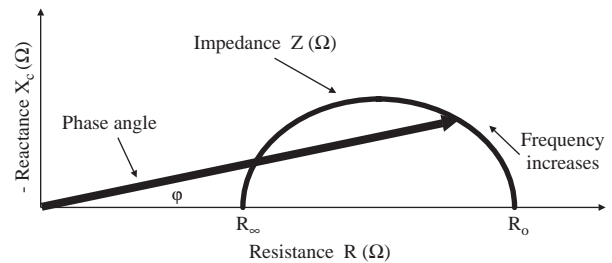

Figure 3 Diagram of the graphical derivation of the phase angle; its relationship with resistance (R), reactance (Xc), impedance (Z) and the frequency of the applied current.

Since practical constraints and the occurrence of multiple dispersions prevent the use of a direct current (zero frequency) or very high frequency AC currents, the R values at the ideal measurement frequencies are predicted using a Cole–Cole plot[8] (negative reactance versus R plot), with R_0 theoretically representing the R of the extracellular fluid (intracellular water) and R_∞ representing the R of intra- and extracellular fluid (TBW) (Fig. 3).

At 50 kHz, the current passes through both intra- and extracellular fluid, although the proportion varies from tissue to tissue. Another parallel model attempts to take into account the effect of 'mixing'. Mixing theory predicts that the R of conductive fluids increases as the amount of suspended non-conducting material increases (explained simplistically by the increased conductive path taken by the current as it curves around non-conducting particles, which in vivo may be represented by cells). The formula devised by Hanai for in vitro models has been extrapolated for use in vivo, but this requires a number of further assumptions.[9,10] Different conceptual parallel models have been devised for assessing composition of limbs, for example limb muscle mass.[11]

The relationship between capacitance and R is interesting because it reflects different electrical properties of tissues that are affected in various ways by disease and nutritional status and hydration status. The phase angle, which is one measure of this relationship, and other interrelated indices, including R_0/R_∞, have been used to predict clinical outcome.[12–14] Furthermore, when the R and capacitance are plotted graphically after standardising for height, different disease/conditions appear to form distinct clusters (bioelectric impedance vector analysis (BIVA)) as proposed by Piccoli et al.[15–17] (Fig. 4). These may have potential value with respect to diagnosis and prognosis.
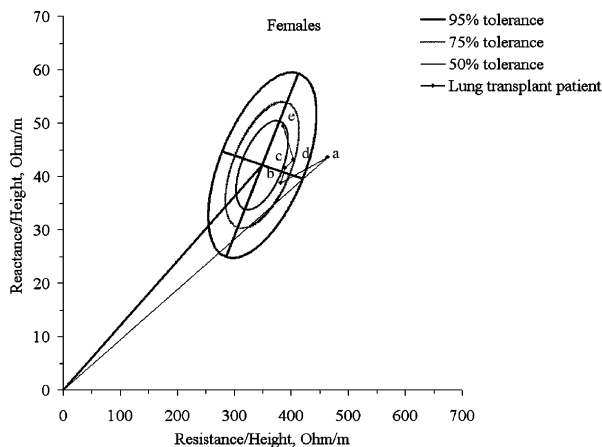
Figure 4 Bioelectrical impedance vector analysis (BIVA) with the *RXc path graph* of one patient following lung transplantation. The gender-specific, bivariate tolerance intervals for the impedance vector are depicted as 50%, 75%, and 95% tolerance ellipses calculated in our healthy Swiss reference population (age 18–59 yr, 2643 women, *R* is the resistance, Xc the negative reactance, and *H* the height). Repeated impedance measurements were obtained after lung transplantation: (a) 1 month, (b) 6 months, (c) 12 months, (d) 18 months, (e) 24 months. The initial vector position (a in woman) indicates soft tissue mass decrease (bioelectrical impedance vector analysis (BIVA) pattern of cachexia). The subsequent vector migration parallel to the minor axis of ellipses toward the target ellipse (b–d in woman) indicates an improvement of nutritional status with increasing hydrated soft tissue mass (i.e. decreasing *R* with increasing Xc). The final vector migration from the lower pole (BIVA pattern of tissue hyperhydration) to the center of the 50% tolerance ellipse, following a trajectory parallel to the major axis (i.e. proportional increase in both *R* and Xc), indicates loss of excess fluid leading to the complete restoration of tissue impedance, which was reached after 24 months in woman (e). Body weight increased from 54.2 to 68.8 kg in woman (156 cm, 47 yr). Unpublished data, adapted from Piccoli et al.[16]

Methods of bioelectrical impedance analysis

Single frequency BIA (SF-BIA)

SF-BIA, generally at 50 kHz, is passed between surface electrodes placed on hand and foot (Fig. 5). Some BIA instruments use other locations such as foot-to-foot[18,19] or hand-to-hand electrodes. At 50 kHz BIA is strictly speaking not measuring TBW but a weighted sum of extra-cellular water (ECW) and intra-cellular water (ICW) resistivities (∼25%). SF-BIA permits to estimate fat-free mass (FFM) and TBW, but cannot determine differences in ICW. BIA results are based on a mixture theories and
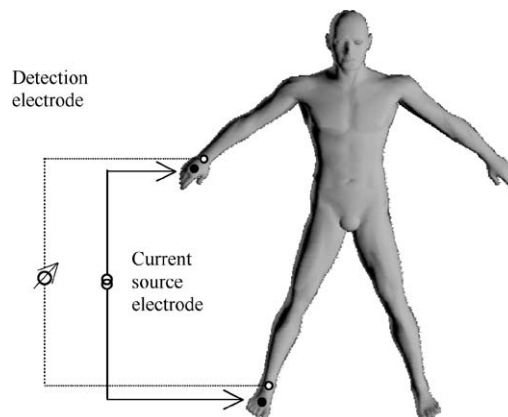

Figure 5 Standard placement of electrodes on hand and wrist and foot and ankle for tetrapolar single (SF-BIA) and multiple-frequency (MF-BIA) BIA.

empirical equations. The latter have been derived in healthy subjects with tight biological homeostasis. Although SF-BIA is not valid under conditions of significantly altered hydration, this does not negate its use to predict absolute FFM or TBW in normally hydrated subjects.[7] The relative merits of the various equations have to be discussed, when the normal relationships are not met.

Multi-frequency BIA (MF-BIA)

As with SF-BIA, MF-BIA uses empirical linear regression models but includes impedances at multiple frequencies. MF-BIA uses different frequencies (0, 1, 5, 50, 100, 200 to 500 kHz) to evaluate FFM, TBW, ICW and ECW. At frequencies below 5 kHz, and above 200 kHz, poor reproducibility have been noted, especially for the reactance at low frequencies.[20] According to Patel et al.[21] MF-BIA was more accurate and less biased than SF-BIA for the prediction of ECW, whereas SF-BIA, compared to MF-BIA, was more accurate and less biased for TBW in critically ill subjects. Hannan et al.[22] noted that MF-BIA, compared to bioelectrical spectroscopy (BIS), resulted in better prediction of TBW and equal prediction for ECW in surgical patients. Olde-Rikkert et al.[23] determined that MF-BIA was unable to detect changes in the distribution or movement of fluid between extracellular and intracellular spaces in elderly patients.

Bioelectrical spectroscopy (BIS)

In contrast to MF-BIA, BIS uses mathematical modeling and mixture equations (e.g. Cole–Cole plot (Fig. 3) and Hanai formula)[8,24] to generate relationships between *R* and body fluid

compartments or to predict R_0 and R_∞ and then develop empirically derived prediction equations rather than go to mixture modeling.[25] BIS models, constants and equations generated in healthy populations have shown to be accurate, with minimal bias in non-physiologically perturbed subjects.[26] However, modeling techniques need further refinement in disease. As pointed out by Schoeller,[27] body cell mass (BCM), especially muscle mass, constitutes the major current path. These cells are non-spherical, but rather cylindrical, arranged along the current's path. He speculated that the differences in geometry account for the reduction in the mixture effect. Furthermore, the determination of accurate values of resistivity (ρICW and ρECW) presented the most difficulty. Published values are widely discrepant. Ward et al.[10] suggested wide biological variations even in the normal population, may explain the apparent lack of improvement of mixture theory analysis over empirical prediction seen by some.[22,28] Several studies have suggested that resistivity constants used should be adjusted for population measured.[9,29–31] Since the absolute magnitude and biological constancy of resistivity are at present unknown, application of mixture theory for the prediction of both the absolute magnitude of body fluid volume or changes in magnitude of body compartments requires further investigation.[10]

Mixture equations in some studies show improvement in accuracy,[32–34] no improvement[35,36] or worse accuracy[7] than regression approach. The potential of BIS can only be exhausted if the data are interpreted with adequate algorithm that include reliable data fitting and a valid fluid distribution model.[37]

Segmental-BIA

Segmental-BIA is performed by either placing two additional electrode on wrist and foot on the opposite side,[38] or by placing sensor electrodes on wrist, shoulder (acromion), upper iliac spine and ankle,[39] or by placing electrodes on proximal portion of the forearm and the lower leg and trunk electrode on the shoulder and the upper thigh.[7,40] For a detailed review, we refer the reader to De Lorenzo and Andreoli.[41] The trunk of the body with its large cross sectional area contributes as little as 10% to whole body impedance whereas it represents as much as 50% of whole body mass.[42] This implies three aspects for body composition analysis by the whole body BIA approach: (1) changes of the impedance are closely related to changes of the FFM (or muscle mass or body cell mass (BCM)) of the

limbs; (2) changes of the FFM (or muscle mass or BCM) of the trunk are probably not adequately described by whole body impedance measurements, and (3) even large changes in the fluid volume within the abdominal cavity have only minor influence on the measurement of FFM or BCM as could demonstrated in patients with liver cirrhosis and ascites undergoing paracentesis.[43]

Segmental-BIA requires prior standardization, particularly when different approaches and different BIA devices are employed. Standardization of the type of electrodes used and their placement is a major concern. Segmental-BIA has been used to determine fluid shifts and fluid distribution in some diseases (ascites, renal failure, surgery), and may be helpful in providing information on fluid accumulation in the pulmonary or abdominal region of the trunk.

Bracco et al.[44] and Tagliabue et al.[45] found high relative errors with segmental-BIA for arms and legs: 13–17% for arm FFM and 10–13% for leg FFM. Tagliabue et al.[45] noted that frequencies higher than 50 kHz did not improve the segmental BIA results. Additional research is needed to examine the accuracy of the segmental BIA.

Localized bioelectrical impedance analysis

Whole body BIA measures various body segments and is influenced by a number of effects (hydration, fat fraction, geometrical boundary conditions, etc.). Hence the validity of simple empirical regression models is population-specific. For these reasons, localized BIA, which focuses on well-defined body segments and thus minimizes the interference effects, has been proposed. Scharfetter et al.[46] determined local abdominal fat mass by localized BIA. Rutkove et al.[47] determined in patients with neuromuscular disease that phase angle and resistivity of limbs decreased with disease progression and normalized with disease remission and may be useful in the therapeutic evaluation of such diseases.

Bioelectrical impedance vector analysis (BIVA or vector BIA)

The ultimate attractiveness of BIA lies in its potential as a stand-alone procedure that permits patient evaluation from the direct measurement of the impedance vector and does not depend on equations or models. The BIVA approach developed by Piccoli et al.[16,48,49] is only affected by the impedance measurement error and the biological variability of subjects. In BIVA, R and reactance (Xc), standardized for height, are plotted as point

vectors in the *R*–Xc plane. An individual vector can then be compared with the reference 50%, 75%, and 95% tolerance ellipses calculated in the healthy population of the same gender and race (*R*–Xc *graph* method) (Fig. 4). The ellipse varies with age and body size.[50]

Clinical validation studies (renal patients, critical care patients and obese subjects)[17–19] showed that vectors falling outside the 75% tolerance ellipse indicate an abnormal tissue impedance, which can be interpreted as follows: (1) vector displacements parallel to the major axis of tolerance ellipses indicate progressive changes in tissue hydration (dehydration with long vectors, out of the upper pole, and hyperhydration with short vectors, out of the lower pole); and (2) vectors falling above (left) or below (right) the major axis of tolerance ellipses indicate more or less BCM, respectively, contained in lean body tissues. Long-term monitoring of patients has shown combined changes in hydration and soft tissue mass. Fig. 4 shows an example of BIVA follow-up with the *RXc path graph* in a female patient following lung transplantation, using the 50th, 75th and 95th tolerance percentiles of a healthy Swiss reference population (data unpublished). However, Cox-Reijven et al.[51] found a low sensitivity (but high specificity) of BIVA in detecting depletion in gastrointestinal patients. Further validation seems necessary.

Body compartments

Fat-free mass

FFM is everything that is not body fat (Fig. 6). A large number of BIA equations in the literature predict FFM. These equations vary in the parameters included in the multiple regression equations and their applicability in various subjects. Early BIA equations (before 1987) only included height^2/resistance. Later equations include other parameters, such as weight, age, gender, reactance, and anthropometric measurements of the trunk and/or extremities to improve the prediction accuracy. FFM can be determined by SF-BIA provided that hydration is normal and BIA equations used are applicable to the study population, with regard to gender, age, and ethnic group.

Total body water (TBW), extracellular (ECW) and intracellular water (ICW)

O'Brien et al.[52] found that current BIA methods (SF- and MF-BIA) are not sufficiently accurate to assess
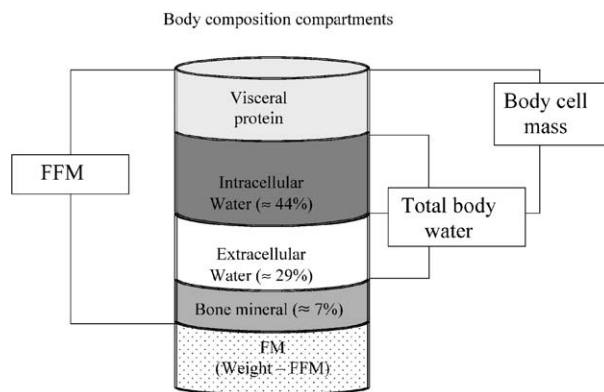

Figure 6 Schematic diagram of fat-free mass (FFM), total body water (TBW), intracellular water (ICW), extracellular water (ECW) and body cell mass (BCM).

TBW under conditions of hydration change. Equations that were developed in euhydrated populations have not been shown to be valid for individuals with altered hydration. Data from both hypo- and hyper-hydration studies suggest that electrolyte balance influences BIA measurements independently of fluid changes. Such effects may be difficult to predict, as fluid and electrolyte changes will also affect the ratio of intra- to extracellular water which, in turn, influences resistivity. The ECW:ICW ratio is a factor known to limit the applicability of predictive equations generated by BIA to external populations.[53] Furthermore, BIA does not allow to accurately assess TBW and ECW when body water compartments are undergoing acute changes.[54,55] In addition, the average body hydration of the FFM varies with age (newborns 80%; 10-yr old children 75%,[56] healthy adults 73%).

According to Ellis et al.[57] 50 kHz SF-BIA primarily reflects the ECW space, which represents a constant proportion of TBW in normal condition. An increase in ECW or in the ECW/TBW ratio may indicate edema and/or malnutrition. MF-BIA appears to be sensitive to such changes, even if there are no significant changes in body weight. On the other hand, the parallel-transformed, SF-BIA model[58] appears to be sensitive to changes in ICW (or BCM),[7] but not to changes in ECW. Therefore this model may have limited use for estimating FFM or body fat when there is an abnormal hydration state.[57]

Among the MF-BIA and BIS models, the 0/∞ parallel (Cole–Cole) model is considered more precise and accurate for the measurement of ECW and ICW than variables obtained by SF-BIA. Gudivaka et al.[7] found the 0/∞ parallel (Cole–Cole) model accurately predicted changes in TBW, ECW and ICW in subjects receiving Ringer's solution or

diuretic therapy with proximally placed detector electrodes (elbow and knee). Scharfetter et al.[59] estimated that, due to electrolyte changes, at the end of dialysis, the error with respect to the volume change was large ($\leqslant 15\%$ for the ECW and $> 20\%$ for ICW). They concluded that a correction of the fluid distribution model for resistivity changes is necessary to obtain more reliable ICW data. The potential of BIS can only be exhausted if the data are interpreted with adequate algorithm that include reliable data fitting and a valid fluid distribution model which considers tissue non-homogeneities.[37] A valid model must guarantee that ECW changes do not corrupt the ICW and vice versa.[37] Standardization of BIS method remains a concern.

The meta-analysis by Martinoli et al.[60] concluded that SF-BIA and BIS significantly overestimated TBW in healthy individuals, whereas there was no overestimation by MF-BIA. MF-BIA seems to be a more accurate method for determining the TBW compartment for healthy and obese adults and for persons with chronic renal failure.

Body cell mass (BCM)

Whereas FFM is everything that is not body fat, there is no consensus on the physiological meaning of measures of "cellular mass", "BCM" or "metabolically active tissue" and "ICW". The BCM is the protein rich compartment which is affected in catabolic states, and loss of BCM is associated with poor clinical outcome.[61,62] In overhydrated patients, even precise determination of FFM might fail to detect relevant protein malnutrition because of expansion of the ECW. Estimating the size is difficult because it is a complex compartment, comprising all nonadipose cells as well as the aqueous compartment of adipocytes. Future research is needed to define BCM and the role of BIA in its clinical evaluation.

In patients with severe fluid overload, such as patients with ascites, inter-individual differences of lean tissue hydration are probably too high to develop uniform equations to assess BCM. Pirlich et al.[63] concluded that in patients with large alterations of body geometry or hydration status the application of standard BIA is not appropriate to assess BCM.

Ward and Heitmann[64] evaluated assessment of BCM and ECW by BIA without the need for measurement of height and found that the significant differences in the mean values and wide limits of agreement compared to reference data for BCM and ECW do not permit to predict these body compartments without inclusion of height in spite of obvious advantages of not requiring an accurate measurement of height.

BIA measurements and equations

BIA measurements must be standardized in order to obtain reproducible results (see BIA—part 2). Reported mean coefficients of variation for within-day R measurements are ≈ 1–2%; daily or weekly intra-individual variability is slightly larger ranging from $\approx 2\%$ to 3.5%.[65–68] Day-to-day coefficients of variation increases for frequencies lower than 50 kHz.[69] Overall reproducibility/precision is 2.7–4.0%.[67] Prediction errors were estimated to be 3–8% for TBW and 3.5–6% for FFM, respectively.[70,71]

Early BIA equations were validated in inadequate populations, as demonstrated in respiratory insufficiency patients.[72] Large variations in results were noted with many formulas published in the literature that precluded clinical interpretation. The use of "general" prediction equations across different age and ethnic groups without prior testing of their validity should be avoided. Choosing a BIA equation that is adapted to the populations studied continues to be a limiting factor of BIA.

Standardization of future studies with regard to methodological considerations (such as inclusion and exclusion criteria, standardization of BIA methods etc.) as discussed by Gonzalez et al.[73] should help to improve BIA results in the future.

Table of validated equations

Selected BIA equations published since l990 for *adults* for FFM (Table 1);[6,58,70,74–88] body fat (Table 2),[38,82,86,88,89] TBW (Table 3),[20,25,32,58,65,70,78,88,90–94] ECW (Table 4),[20,25,32,90,92,93,95] ICW (Table 5)[96,97] and BCM (Table 6)[58,98] are shown in order of increasing standard error of the estimate (SEE). They are limited to studies in healthy subjects that include at least 40 subjects and are validated against a criterion measure. For discussion of BIA equations in specific diseases, we refer the reader to "Bioelectrical impedance analysis—part II: utilization in clinical practice". The equation for TBW by Kushner and Schoeller[65] is included because it is frequently cited in the literature. For BIA equations for FFM, TBW and body fat published prior to l990, we refer the reader to Houtkooper et al.[99]

How to choose a BIA equation

Houtkooper et al.[99] suggested that prediction error (SEE) of 2.0–2.5 kg in men and 1.5–1.8 kg in women

Table 1 Bioelectrical impedance analysis equation reported in the literature since 1990 for fat-free mass (FFM) classified according to subject category (adult, elderly, overweight) and standard error of the estimate (SEE).

Population	Source	n	Criterion measure	Equation	r^2	SEE*	BIA instrument
Adults							
Healthy subjects, 18–94 yr	Kyle et al.[74]	343	DXA	$-4.104 + 0.518\, Ht^2/R_{50} + 0.231$ weight $+0.130\, Xc + 4.229$ sex	0.97	1.8	Xitron
Healthy adults, 18–29 yr	Lohman[75]	153	Densitometry[85],[†]	Women $= 5.49 + 0.476\, Ht^2/R_{50}$ $+0.295$ weight	NR	2.1	Valhalla
Healthy adults, 30–49 yr	Lohman[75]	122	Densitometry[85],[†]	Women $= 11.59 + 0.493\, Ht^2/R_{50}$ $+0.141$ weight	NR	2.5	Valhalla
Healthy, ethnic divers	Kotler et al. SF parallel[58]	126	DXA	Women $= +0.07 + 0.88\,(Ht^{1.97}/Z_{50}^{0.49})$ $(1.0/22.22) + 0.081$ weight	0.71	6.56% (≈ 2.6)	RJL-101
Healthy subjects, >16 yr	Deurenberg et al.[76]	661	Multi-C,[87] densitometry[86],[‡]	$-12.44 + 0.34\, Ht^2/R_{50} + 0.1534$ height $+0.273$ weight -0.127 age $+4.56$ sex	0.93	2.6	RJL-101
Healthy subjects, 12–71 yr	Boulier et al.[6]	202	Densitometry	$6.37 + 0.64$ weight $+0.40\, Ht^2/Z_{1\,MHz} - 0.16$ age -2.71 sex (men $= 1$, women $= 2$)	0.92	2.6	IMP BO-1
Women 18–60 yr	Stolarczyk et al.[77]	95	Multi-C[§]	$20.05 - 0.04904\, R_{50} + 0.001254\, Ht^2$ $+0.1555$ weight $+0.1417\, Xc - 0.0833$ age	0.75	2.6	Valhalla
Healthy adults, 50–70 yr	Lohman[75]	72	Densitometry[85],[†]	Women $= 6.34 + 0.474\, Ht^2/R_{50} + 0.180$ weight	NR	2.8	Valhalla
Healthy adults, 18–29 yr	Lohman[75]	153	Densitometry[85],[†]	Men $= 5.32 + 0.485\, Ht^2/R_{50} + 0.338$ weight	NR	2.9	Valhalla
Healthy subjects, 12–94 yr	Sun et al.[70]	1095	Multi-C	Women: $-9.529 + 0.696\, Ht^2/R_{50}$ $+0.168$ weight $+0.016\, R_{50}$	0.83	2.9*	
Healthy, ethnic divers	Kotler et al. SF parallel[58]	206	DXA	Men $= +0.49 + 0.50\,(Ht^{1.48}/Z_{50}^{0.55})$ $(1.0/1.21) + 0.42$ weight	0.92	5.45% (≈ 3.2)	RJL-101
Healthy adults, 30–49 yr	Lohman[75]	111	Densitometry[85],[†]	Men $= 4.51 + 0.549\, Ht^2/R_{50}$ $+0.163$ weight $+0.092\, Xc$	NR	3.2	Valhalla
Healthy subjects, 35–65 yr	Heitmann[78]	139	Multi-C,[88] ^3H_2O, TBK	$-14.94 + 0.279\, Ht^2/R_{50} + 0.181$ weight $+0.231$ height $+0.064$ (sex weight) -0.077 age	0.90	3.6	RJL-103
Healthy adults, 50–70 yr	Lohman[75]	74	Densitometry[85],[†]	Men $= -11.41 + 0.600\, Ht^2/R_{50}$ $+0.186$ weight $+0.226\, Xc$	NR	3.6	Valhalla
Healthy subjects, 12–94 yr	Sun et al.[70]	734	4 compart	Men : $-10.678 + 0.652\, Ht^2/R_{50}$ $+0.262$ weight $+0.015\, R$	0.90	3.9*	RJL-101

Overweight

Overweight women 25–45 yr	Jakicic et al.[79]	123	DXA	$2.68 + 0.20\,Ht2/R_{50} + 0.19$ weight $+2.55$ ethnicity(Caucasian $= 0$, AfricanAmerican $= 1) + 0.1157$ height	0.65	8.8*	RJL-101
Overweight women 25–45 yr	Jakicic et al.[79]		DXA	$2.04 - 0.02\,R_{50} + 0.19$ weight $+2.63$ ethnicity(Caucasian $= 0$, AfricanAmerican $= 1$) $+0.2583$ height	0.65	8.8*	

Elderly

Elderly women 62–72 yr	Haapala et al.[80]	93	DXA	$-128.06 + 1.85\,BMI - 0.63$ weight$+1.07$ height $- 0.03\,R_{50} + 10.0$ waist–hip ratio	0.83	1.6	RJL-101
Elderly	Roubenoff et al.[81]	294	DXA	Women : $7.7435 + 0.4542\,Ht^2/R_{50} +0.1190$ weight $+ 0.0455$ Xc	0.77	2.09	RJL-101
Elderly, 65–94 yr	Baumgartner et al.[82]	98	Multi-C[82,¶]	$-1.732 + 0.28\,Ht^2/R_{50} + 0.27$ weight $+4.5$ sex $+ 0.31$ thigh circ	0.91	2.5	RJL-101
Elderly	Dey et al.[83]	106	4 compart	$11.78 + 0.499\,Ht^2/R_{50} + 0.134$ weight $+3.449$ sex	0.91	2.6	RJL-101
Elderly, 60–83 yr	Deurenberg et al.[84]	72	Densitometry[86,‡]	$7.0 + 0.360\,Ht^2/R_{50} + 4.5$ sex $+0.359$ weight $- 0.20$ thigh circ	0.92	2.5	RJL-101
Elderly, 60–83 yr	Deurenberg et al.[84]	72	Densitometry[86,‡]	$3.9 + 0.672\,Ht^2/R_{50} + 3.1$ Sex	0.88	3.1	RJL-101
Elderly, 65–94 yr	Baumgartner et al.[82]	98	Densitometry[86,‡]	$15.44 + 0.34\,Ht^2/R_{50} + 0.36$ weight $+4.3$ sex $- 0.57$ ankle circ	0.87	3.2	RJL-101
Elderly	Roubenoff et al.[81]	161	DXA	Men: $9.1536 + 0.4273\,Ht^2/R_{50} +0.1926$ weight $+ 0.0667$ Xc	0.72	3.4	RJL-101
Elderly	Roubenoff et al.[81]	445	DXA	$5.741 + 0.4551\,Ht^2/R_{50} + 0.1405$ weight $+0.0573$ Xc $+ 6.2467$ sex			RJL-101

BIA equations are shown in order of increasing standard error of the estimate (SEE). They are limited to studies in healthy subjects that include at least 40 subjects and are validated against a criterion measure.

*RSME, root mean square error; R, resistance; Ht^2/R, height^2/resistance, Xc, reactance; V, body volume; Z, impedance; Z_5, impedance at 5 kHz; Z_{100}, impedance at 100 kHz; 1 for men, 0 for women, unless otherwise stated, NR, not reported, height in cm, weight in kg, thigh circumference in cm, resistance in ohm, reactance in ohm). RJL Systems, Inc, Clinton Twp, MI; Xitron Technologies, San Diego, CA; Valhalla Scientific, San Diego, CA; BIA-2000-M, Data Input, Hofheim, Germany; IMP BO-1, (2 subcutaneous electrodes), I'Impulsion, Caen, France. All subjects are Caucasian, except Jakicic (Caucasian and African-American), Stolarczyk et al. (Native American), and Sun (Caucasian and African-American).

†%BF $= ((4.570/\text{body density}) - 4.142)\,100$.

‡%BF $= (4.95/\text{body density}) - 4.5)\,100$.

§%BF $= (6.38/\text{body density}) - 3.961\,\text{bone mineral mass} - 6.090)\,100$.

¶%BF $= ((1.34/\text{body density}) - 0.35\,\text{age} + 0.56\,\text{mineral content} - 1)\,205$.

Table 2 Bioelectrical impedance analysis equation reported in the literature since 1990 for body fat (BF) classified according to standard error of the estimate (SEE).

Comments	Source	n	Criterion measure	Equation	r^2	SEE	BIA instrument
Body fat (%)							
Elderly, 65–94 yr	Baumgartner et al.[82]	98	Multi-C[82],*	$-23.58 + 20.03\,(R_{50}$ weight$)/$Ht^2 $+0.29$ *thigh* circ -4.99 *sex* $+ 0.52$ *arm* circ	0.73	3.80%	RJL-101
Elderly, 65–94 yr	Baumgartner et al.[82]	98	Densitometry[86],†	$-18.89 + 22.12\,(R_{50}$ weight$)/$Ht^2 $+0.64$ *calf* circ -4.13 *sex*	0.55	5.00%	
Body fat (kg)							
Healthy subjects, 21–64 yr, segmental BIA	Organ et al.[38]	104	Underwater weighing, ^{2}H$_2$O	Women : $-5.9150 + 0.7395$ weight -0.3327 *height* $+ 0.0846$ *age* $+0.048$ *upperlimb* $R_{50}+0.2705$ trunk R_{50} $+0.0384$ lowerlimb $R_{50}-0.1219$ lowerlimb Xc	0.93	1.9	Na
Healthy subjects, 21–64 yr, segmental BIA	Organ et al.[38]	96	Underwater weighing, ^{2}H$_2$O	Men : $-4.2422 + 0.7368$ weight $- 0.0482$ height $+0.1170$ *age* $+ 0.0393$ *upperlimb* $R_{50}+0.5110$ trunk R_{50} $+0.0654$ lowerlimb $R_{50}-0.2560$ lowerlimb Xc	0.93	2.8	Na
Healthy subjects, 35–65 yr	Heitmann[89]	139	FM multi-C[88]	$14.94 - 0.079$ Ht$^2/R_{50}+0.818$ weight $- 0.231$ height -0.064 *sex* weight $+ 0.077$ *age*	0.90	3.6	RJL-103

BIA equations are shown in order of increasing standard error of the estimate (SEE). They are limited to studies in healthy subjects that include at least 40 subjects and are validated against a criterion measure.

R, resistance; Ht^2/R, height^2/resistance; Xc, reactance; V, body volume; Z, impedance; Z_5, impedance at 5 kHz; Z_{100}, impedance at 100 kHz; 1 for men, 0 for women, unless otherwise stated; circ, circumference.

RJL Systems, Inc, Clinton Twp, MI; Xitron Technologies, San Diego, CA; Valhalla Scientific, San Diego, CA; BIA-2000-M, Data Input, Hofheim, Germany.

*%BF $= ((1.34/$body density$) - 0.35$ age $+ 0.56$ mineral content $-1)\,205$.

†%BF $= (4.95/$body density$) - 4.5)\,100$.

Table 3 Bioelectrical impedance analysis equation reported in the literature since 1990 for total body water (TBW), classified according to standard error of the estimate (SEE)*.

Comments	Source	n	Criterion measure	Equation	r^2	SEE	BIA instrument
Healthy subjects	Deurenberg et al.[90]	139	^2H_2O	$6.69 + 0.34573\ Ht^2/Z_{100} + 0.17065$ weight -0.11 *age* $+ 2.66$ *sex*	0.95	1.73	Human-IM scanner
Healthy subjects	Deurenberg et al.[90]	139	^2H_2O	$6.53 + 0.36740\ Ht^2/Z_{50} + 0.17531$ weight -0.11 *age* $+ 2.83$ *sex*	0.95	1.74	
Healthy subjects	Cornish et al.[25]	60	^2H_2O	$0.6 + 0.50\ Ht^2/R_0 + 0.186$ weight		2.1 or 6.1%	SEAC
Healthy subjects, 35–65 yr	Heitmann[78]	139	Multi C,[88] ^3H_2O, TBK	$-17.58 + 0.240\ Ht^2/R_{50} - 0.172$ weight $+0.040$ *sex weight* $+ 0.165$ *height*	0.85	3.47	RJL-103
Healthy subjects, ethnic divers	Kotler et al. SF parallel[58]	206	^3H_2O, TBK	Men $= (-3.66 + 0.58\ (Ht^{1.62}/Z_{50}^{0.7}\ 1.0/1.35) +0.32$ *weight*$)$	0.83	7.80%	RJL-101
Healthy subjects, ethnic divers	Kotler et al. SF parallel[58]	126	^3H_2O	Women $= (-0.86 + 0.76\ (Ht^{1.99}/Z_{50}^{0.58}\ 1.0/18.91) +0.14$ *weight*$)$	0.67	8.20%	RJL-101
Healthy subjects, 17–66 yr	Kushner and Schoeller[65]	40	^2H_2O	Men $= 8.399 + 0.396\ Ht^2/R_{50} + 0.143$ weight	0.96	M 1.66	RJL-101
				Women $= 8.315 + 0.382\ Ht^2/R_{50} + 0.105$ weight	0.95	F 0.88	
Healthy subjects, 17–66 yr	Kushner and Schoeller[65]	40	^2H_2O	$1.726 + 0.5561\ Ht^2/R_{50} - 0.0955$ weight	0.97	1.75	
Healthy subjects, 12–94 yr	Sun et al.[70]	734	Multi-C	Men : $1.203 + 0.449\ Ht^2/R_{50} + 0.176$ weight	0.84	3.8*	RJL-101
	Sun et al.[70]	1095	Multi-C	Women : $3.747 + 0.450\ Ht^2/R_{50} + 0.113$ weight	0.79	2.6*	
Elderly subjects	Vache et al.[91]	58	^{18}O	$3.026 + 0.358\ Ht^2/R_{50} + 0.149$ weight $+ 2.924$ sex			Analycor3
Elderly subjects	Vache et al.[91]	58	^{18}O	$2.896 + 0.366\ Ht^2/R_{100} + 0.137$ weight $+ 2.485$ sex	0.97	1.3	
Healthy subjects, 19–65 yr	Van Loan and Mayclin[92]	60	^2H_2O	$14.0107 + 0.29753\ Ht^2/R_{224} + 0.14739$ weight -3.63734 *sex*(*men* $= 0$, *women* $= 1$) $- 0.07299$ *age*	0.86	3.58	Xitron
Elderly, 63–87 yr	Visser et al.[93]	117	^2H_2O	Men $= 8.3 + 0.3228\ Ht^2/Z_{50} + 0.1652$ weight	0.66	3.1	Xitron
				Women $= 11.9 + 0.2715\ Ht^2/Z_{50} + 0.1087$ weight	0.41	2.7	
Healthy non-obese and obese subjects	Cox-Reijven and Soeters[32]	90	^2H_2O	$0.08 + 0.458\ Ht^2/R_{tbw} + 0.06$ weight	0.91	1.9	Xitron
Obese women	De Lorenzo et al.[94]	55	^2H_2O	$23.1898 + 0.0154\ (V/Z_1) + 0.3315\ V/((Z_1\ Z_{100})/(Z_1 - Z_{100})$	0.94	2.8	
Surgical patients	Hannan et al.[20]	43	^3H_2O	$5.82 + 0.446\ Ht^2/R_{50} + 0.129$ weight	0.90	2.5	Xitron
Surgical patients	Hannan et al.[20]	43	^3H_2O	$5.69 + 0.399\ Ht^2/R_{500} + 0.114$ weight	0.90	2.5	Xitron
Surgical patients	Hannan et al.[20]	43	^3H_2O	$-1.04 + 0.45\ Ht^2/R_{500} + 0.46$ APT $+ 0.0119\ Ht^2/Xc_{50} - 0.0106\ Ht^2/Xc_{500}$	0.93	2.2	Xitron

BIA equations are shown in order of increasing standard error of the estimate (SEE). They are limited to studies in healthy subjects that include at least 40 subjects and are validated against a criterion measure.

TBK, total body potassium; ^3H_2O, triterium; ^2H_2O, deuterium oxide.

RJL Systems, Inc, Clinton Twp, MI; Xitron Technologies, San Diego, CA; Human-IM Scanner, Dietosystem, Milan, Italy; Analycor3, Spengler, France, SEAC, Brisbane, Australia.

*RMSE, root mean square error; R, resistance; Ht^2/R, height^2/resistance; Xc, reactance; V, body volume; Z, impedance; APT, maximum thickness long full length of sternum, measured with calipers; $R_{TBW} = (R_{ICW}\ R_{ECW})/R_{ICW} + R_{ECW})$; Z_5, impedance at 5 kHz; Z_{100}, impedance at 100 kHz; 1 for men, 0 for women, unless otherwise stated.

Table 4 Bioelectrical impedance analysis equation reported in the literature since 1990 for extracellular water (ECW), classified according to standard error of the estimate (SEE).

Population	Source	n	Criterion measure	Equation	r^2	SEE	BIA instrument
Healthy subjects	Deurenberg et al.[90]	139	KBr	$2.30 + 0.19528\, Ht^2/Z_1 + 0.06987$ weight -0.02 *age*	0.87	0.98	Human-IM
Healthy subjects	Deurenberg et al.[90]	139	KBr	$2.53 + 0.18903\, Ht^2/Z_5 + 0.06753$ weight -0.02 *age*	0.86	1.02	scanner
Healthy subjects, 19–65 yr	Van Loan and Mayclin[92]	60	NaBr	$-5.17753 + 0.09989\, Ht^2/R_{224} + 0.09322$ weight $- 1.3962$ *sex(men = 0, women = 1)*	0.92	1.06	Xitron
Healthy[22] and ill subjects[18]	Sergi et al.[95]	40	NaBr	$-7.24 + 0.34\, Ht^2/R_1 + 0.06$ weight $+2.63$ *(healthy = 1, ill = 2)* $+ 2.57$ *sex(men = 0, women = 1)*	0.89	1.75	RJL-101 and 103
Healthy[22] and ill subjects[18]	Sergi et al.[95]	40	NaBr	$-5.22 + 0.20\, Ht^2/R_{50} + 0.005\, Ht^2/Xc_{50} + 0.08$ *weight* $+ 1.9$ *(healthy = 1, ill = 2)* $+ 1.86$ *sex(men = 0, women = 1)*	0.89	1.75	
Healthy non-obese and obese subjects	Cox-Reijven and Soeters[32]	90	NaBr	$-3.511 + 0.351\, Ht^2/R_{ecw} + 0.05$ weight	0.77	2.0	Xitron
Healthy subjects	Cornish et al.[25]	60	NaBr	$-6.3 + 0.352\, Ht^2/R_0 + 0.099$ weight $+ 3.09$ sex(0 = male, 1 = female)	0.7	2.1 or 11.7%	SEAC
Healthy subjects	Cornish et al.[25]	60	NaBr	$1.2 + 0.194\, Ht^2/R_0 + 0.115$ weight	0.65	2.2 or 12.7%	SEAC
Healthy subjects	Cornish et al.[25]	60	NaBr	$-5.3 + 0.480\, Ht^2/R_0 + 3.5$ sex(0 = male, 1 = female)	0.66	2.2 or 12.6%	SEAC
Elderly, 63–87 yr	Visser et al.[93]	117	KBr	Men $= 4.8 + 0.2249\, Ht^2/Z_5$ Women $= 1.7 + 0.1998\, Ht^2/Z_5 + 0.0571$ weight	0.39 0.65	2.2 1.0	Xitron
Surgical patients	Hannan et al.[20]	43	NaBr	$5.75 + 0.01\, Ht^2/Xc_{50} + 0.165\, Ht^2/R_5$	0.87	1.7	Xitron
Surgical patients	Hannan et al.[20]	43	NaBr	$6.15 + 0.0119\, Ht^2/Xc_{50} + 0.123\, Ht^2/R_{50}$	0.87	1.7	Xitron

BIA equations are shown in order of increasing standard error of the estimate (SEE). They are limited to studies in healthy subjects that include at least 40 subjects and are validated against a criterion measure.

R, resistance; Ht^2/R, height^2/resistance; R_{ecw}, Resistance by Cole–Cole plot; Xc, reactance; V, body volume; Z, impedance; Z_5, impedance at 5 kHz; Z_{100}; impedance at 100 kHz; 1 for men, 0 for women, unless otherwise stated.

NaBr = sodium bromide, KBr = Potassium bromide.

Human-IM Scanner, Dietosystem, Milan, Italy; Xitron Technologies, San Diego, CA; RJL Systems, Inc, Clinton Twp, MI; SEAC, Brisbane, Australia.

Table 5 Bioelectrical impedance analysis equation reported in the literature since 1990 for intracellular water (ICW), classified according to standard error of the estimate (SEE).

Comments	Source	n	Criterion measure	Equation	r^2	SEE	BIA instrument
Elderly, 60–80 yr	Dittmar and Reber, SF_{BIA}[96]	159	TBK	$9.182 + 0.285\ Ht^2/Z_5 + 7.114\ PA_5 + 2.113\ sex$	0.93	0.9	BIA-2000-M
Healthy men, 23–53 yr	De Lorenzo et al.[97]	57	TBK	$12.2 + 0.37065\ Ht^2/R_{icw} - 0.132\ age + 0.105\ weight$	0.69	1.9	Xitron

BIA equations are shown in order of increasing standard error of the estimate (SEE). They are limited to studies in healthy subjects that include at least 40 subjects and are validated against a criterion measure.
TBK, total body potassium; R_{icw}, intracellular resistance; Ht^2/Z_5, height^2/impedance at 5 kHz; PA_5, phase angle at 5 kHz; 1 for men, 0 for women.
Xitron Technologies, San Diego, CA; BIA-2000-M, Data Input, Hofheim, Germany.

Table 6 Bioelectrical impedance analysis equation reported in the literature since 1990 for body cell mass (BCM), classified according to standard error of the estimate (SEE)*.

Comments	Source	n	Criterion measure	Equation	r^2	SEE	BIA instrument
Elderly, 60–90 yr	Dittmar and Reber, SF_{BIA}[98]	160	TBK	$1.898\ Ht^2/X_{cp50} - 0.051\ weight + 4.180\ sex + 15.496$	0.84	1.71*	BIA-2000-M
Elderly, 60–90 yr	MF_{BIA1}	160	TBK	$1.118\ Ht^2/R_{ic5/50} + 4.250\ sex + 14.457$	0.84	1.73*	
Elderly, 60–90 yr	MF_{BIA2}	160	TBK	$0.822\ Ht^2/R_{ic5/100} + 4.158\ sex + 14.096$	0.84	1.73*	
Healthy, ethnic diverse	Kotler et al. SF parallel[58]	206	TBK	$Men = 1/120\ ((0.76\ (59.06\ Ht^{1.6}/X_{cp50}^{0.5}) + (18.52\ weight) - 386.66)$	0.83	9.96%	RJL-101
Healthy, ethnic diverse	Kotler et al. SF parallel[58]	126	TBK	$Women = 1/120\ (0.96\ (1.3\ Ht^{2.07}/X_{cp50}^{0.36}) + (5.79\ weight) - 230.51)$	0.56	12.30%	

BIA equations are shown in order of increasing standard error of the estimate (SEE). They are limited to studies in healthy subjects that include at least 40 subjects and are validated against a criterion measure.
BIA-2000-M, Data Input, Hofheim, Germany; RJL Systems, Inc, Clinton Twp, MI.
*RMSE, root mean square error; TBK, total body potassium; R, resistance; Ht^2/X_{cp50}, height^2/parallel reactance at 50 kHz; $R_{ic5/50}$, $R_5\ R_{50}/(R_5 - R_{50})$; $R_{ic5/100}$, $R_5\ R_{100}/(R_5 - R_{100})$; 1 for men, 0 for women.

and actual error of 0.0–1.8 kg is considered ideal. Prediction error of less than 3.0 kg for men and 2.3 kg for women would be considered very good. BIA equations chosen should not be used without prior verification against reference methods in the subject population studied.

Limitations of BIA equations

BIA integrates various body segments with variable physical effects of hydration, fat fraction, geometrical boundary conditions etc. on tissue conductivity (see Part II). This explains, in part, why empirical regression models are population-specific. Furthermore, the trunk contributes only a small proportion to whole body impedance because it is relatively short and has a large cross-sectional area. Limitations of BIA measurements in case of body water alterations or body geometry abnormalities are described in Part II. ECW:ICW ratio is a factor known to limit the applicability of predictive equations generated by BIA to populations with varying hydration.[53]

The difficulties of validating BIA in different age and ethnic groups, and clinical conditions with abnormal hydration states has resulted in a plethora of BIA equations that confuse, rather than aid in the interpretation of BIA results. Tables 1–6 try to facilitate this selection by presenting equations according to the respective value of standard error of the estimate. Specific BIA measurement errors associated with clinical conditions are discussed in Part II.

Reference methods

Validation of BIA equations must be done against reference methods, including multi-compartment model,[100,101] densitometry (underwater weighing),[102] dual-energy X-ray absorptiometry (DXA),[102] isotope dilution[102,103] and total body potassium (TBK). Each of these reference methods has limitations and makes assumptions (such as total body potassium (TBK)/FFM is constant with age, constant hydration of FFM of 73%, constant density for FFM with densitometry) that are not valid in all situations.[104] Although DXA is not yet considered a "gold" standard method, it is included as reference method because of its wide availability and it can be used in patients. A limitations of DXA is that results by different manufacturers do not agree.[105,106] Although TBK is a reference method for body cell mass (BCM),[107] it is limited in the determination of FFM because TBK content varies with sex and age.[108,109] The two-compartment model makes assumptions regarding the constancy of composition of FFM, which is not true in all ethnic groups and across the life. These limitations can be overcome with a multi-compartment model.[104]

Thus, some of the discrepancies reported in the literature are due to different reference methods and different software versions of the reference methods used in the validation process. This leaves us with the dilemma of choosing a BIA equation for a specific population that was considered valid based on a reference method that may or may not have been accurate and may or may not be comparable to other reference methods.

Study population

Most studies were done on Caucasian subjects. Kotler et al.[58] and Sun et al.[70] include African-American and Hispanic subjects. Stolarczyk et al.[77] includes native American Indians. Ethnic-specific impedance-based equations for body composition are justified because of differences in body build among ethnic groups.[110] Relative leg lengths,[111] frame size[112] and body build[113] are factors responsible for ethnic differences in the body mass index (BMI) to % body fat relationship. Failing to adjust for differences in FFM density in ethnic groups may result in systematic biases of up to 3%.[111] Future body composition research should include non-Caucasian subjects.

Conclusion

Whole-body BIA allows the determination of the FFM and TBW in subjects without significant fluid and electrolyte abnormalities, when using appropriate population, age or pathology-specific BIA equations and established procedures. The determination of changes in BCM, ECW and ICW requires further research using a valid model that guarantees that ECW changes do not corrupt the ICW and vice versa. The use of segmental, MF-BIA or BIS in altered hydration states also requires further research.

ESPEN guidelines for the use of BIA measurements (see Bioelectrical impedance analysis—Part II) are described in another paper to be published soon in Clinical Nutrition.

Acknowledgements

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