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REVIEWS

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The use of bio-electrical impedance analysis (BIA) to guide fluid management, resuscitation and deresuscitation in critically ill patients: a bench-to-bedside review

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Abstract

The impact of a positive fluid balance on morbidity and mortality has been well established. However, little is known about how to monitor fluid status and fluid overload.

This narrative review summarises the recent literature and discusses the different parameters related to bio-electrical impedance analysis (BIA) and how they might be used to guide fluid management in critically ill patients. Definitions are listed for the different parameters that can be obtained with BIA; these include among others total body water (TBW), intracellular water (ICW), extracellular water (ECW), ECW/ICW ratio and volume excess (VE)**.** BIA allows calculation of body composition and volumes by means of a current going through the body considered as a cylinder. Reproducible measurements can be obtained with tetrapolar electrodes with two current and two detection electrodes placed on hands and feet. Modern devices also apply multiple frequencies, further improving the accuracy and reproducibility of the results. Some pitfalls and conditions are discussed that need to be taken into account for correct BIA interpretation. Although BIA is a simple, noninvasive, rapid, portable, reproducible, and convenient method of measuring body composition and fluid distribution with fewer physical demands than other techniques, it is still unclear whether it is sufficiently accurate for clinical use in critically ill patients. However, the potential clinical applications are numerous.

An overview regarding the use of BIA parameters in critically ill patients is given, based on the available literature. BIA seems a promising tool if performed correctly. It is non-invasive and relatively inexpensive and can be performed at bedside, and it does not expose to ionising radiation. Modern devices have very limited between-observer variations, but BIA parameters are population-specific and one must be aware of clinical situations that may interfere with the measurement such as visible oedema, nutritional status, or fluid and salt administration. BIA can help guide fluid management, resuscitation and de-resuscitation. The latter is especially important in patients not progressing spontaneously from the Ebb to the Flow phase of shock. More research is needed in critically ill patients before widespread use of BIA can be suggested in this patient population.

Key words: fluid resuscitation, fluid management, fluid balance, monitoring, BIA, bio-electrical impedance analysis, deresuscitation

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The impact of a positive fluid balance on morbidity and mortality has been well established [1–4]. However, little is known about how to monitor fluid status and fluid overload. The human body consists of around 60% water, 18% protein, 16% fat, and 6% minerals. The tissue water content varies from 20% (fat tissue and bones) up to 85% (kidneys, liver, blood). Children may have more water (70%) than adults (50–55%), while women usually have less water and more fat compared to men [5].

Bio-electrical impedance analysis (BIA) measures whole body (or regional or segmental) impedance, phase angle, resistance, reactance and capacitance, by means of an electric current transmitted at different frequencies [5, 6]. New techniques allow measurement of total body water (TBW) with separation into extracellular and intracellular water (ICW) [7]. Data suggests that BIA may provide useful information not only in different well-established patient groups (like dialysis, AIDS, malnutrition) but also in critically ill patients with burns, trauma and sepsis undergoing fluid resuscitation [8–15].

This narrative review summarises the recent literature and discusses the different parameters related to bio-electrical impedance analysis, focusing on their use in guiding fluid management (resuscitation and deresuscitation) in critically ill patients.

DEFINITIONS

Definitions of electrical quantities generated by BIA are reviewed here. More detailed information can be found in some reviews on this topic together with the National Institute of Health (NIH) health technology assessment [5, 16]. The European Society of Enteral and Parenteral Nutrition (ESPEN) also recently published concise guidelines on bioelectrical impedance analysis [17, 18].

Capacitance (C): in electrical terms, is the storage of an electrical charge by a condenser for a short moment in time. Capacitance measurements in a living substance are an indicator of healthy cell membrane. Depending on the health and the number of cells, the electrical capacitance will increase or decrease.

Reactance (X): the opposition of a circuit element to a change of electric current or voltage, due to that element's inductance or capacitance (related to cell mass).

Resistance (R): the resistance of an electrical conductor is the opposition to the passage of an electric current through that conductor (inversely related to the water content).

Insulator: tissue that consists of cells that are not conducting electrical signals, e.g. fat cells where resistance is high and impedance is high.

Conductor: tissue that allows electricity to flow easily, e.g. muscles, water content, where resistance is low and impedance is low.

Impedance (Z): represents the ratio between insulation tissue and conductive tissue.

BIA PRINCIPLE

BIA allows the calculation of body composition and volumes by means of an electric current going through the body considered as a cylinder (Fig. 1). Detailed descriptions of the principles can be found elsewhere [5, 16–18]. In order to obtain reproducible measurements, BIA has to make five assumptions: 1) the human body can be considered as a cylinder; 2) it consists in fact of five smaller cylinders (one central cylinder, two arms and two legs); 3) body composition is assumed to be homogenous; 4) with absence of individual variation; and 5) without impact of environment (temperature, stress, infusions). This of course only holds true in an ideal situation that can differ from real life conditions, especially in the critically ill. These conditions include significant body asymmetry as in amputations, unilateral hemiparesis, and neuromuscular conditions that produce localised changes in perfusion or tissue atrophy [5]. Furthermore, there may be differences between men

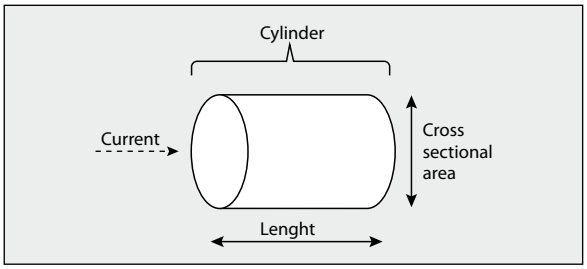

Figure 1. BIA principle. When electric current goes through a cylinder shaped body, the impedance (Z) is related to the length (L) and specific resistivity (ρ) of the tissue and inversely related to the cross-sectional area (A) of the cylinder. The volume of a cylinder (V) can be calculated as L multiplied by A

How does bioelectrical impedance analysis calculate volumes?

$$Z = \rho \times \frac{L}{A}$$

$$Z = \rho \times \frac{L}{A} \times \frac{L}{L}$$

$$Z = \rho \times \frac{L^2}{V}$$

Extrapolated to a patient, L stands for the height (in cm) so that the body composition and volume (V) can be calculated as follows:

$$V = \rho \times \frac{L^2}{Z}$$

where $\frac{L^2}{Z}$ corresponds to the impedance index that can be calculated with bioelectrical impedance analysis

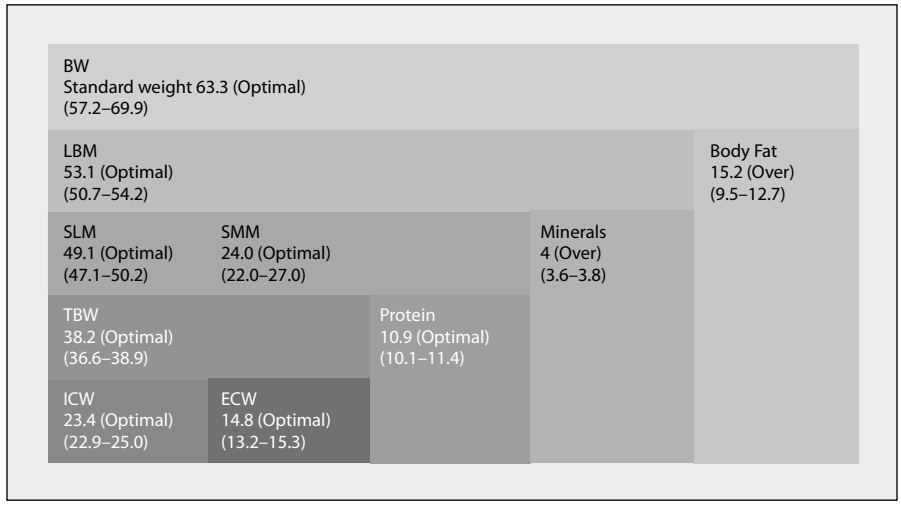

Figure 2. Four compartment body composition analysis with BIA

ICW: Intracellular water (body water that exists inside the cell membrane)

ECW: Extracellular water (body water that exists outside the cell membrane; extracellular can be further subdivided into interstitial, lymphatic, trans-cellular fluid and blood)

TBW: Total body water = ICW + ECW (body water that exists in- and outside of cell membrane)

SLM: Soft lean mass = total body water + protein (skeletal and smooth muscle maintaining body function)

SMM: Skeletal muscle mass

LBM: Lean body mass = SLM + minerals

BW: Body weight = LBM + body fat

The values in between () are the range of standard body composing constituents. Units are expressed in Litres

and women and old and young with regard to evolution of the cylindrical shape.

Therefore, in order to obtain a good BIA measurement, five factors are indispensable: impedance value, height, weight, gender, and age. Of these five, gender and age are the most important in obtaining the highest level of accuracy. Furthermore, body composition is based on genetic (25%), cultural (30%) and non-transmissible (45%) factors. Human body composition measurements can be performed at five levels: atomic (oxygen, carbon hydrogen, nitrogen), molecular (protein, carbohydrate, lipid, minerals, water), cellular (fat cells, body cells, intra- and extracellular fluids, organic and inorganic extracellular solids), tissue (adipose, muscle, bone, blood) and whole body level. BIA allows a four compartment body composition analysis dividing the body into fat, water, mineral, and protein components (Fig. 2)[16].

BIA MEASUREMENT

Reproducible measurements can be obtained with tetrapolar electrodes with two current electrodes (to drive electricity into the human body) and two detection electrodes (to detect impedance) placed on hands and feet. Tetrapolar techniques provide more reproducible results [17, 18]. Although some data is available on segmental measurements of the arm, leg, and trunk, segmental BIA should at present be considered as purely experimental and more information is needed to determine whether additional electrode placement sites offer improvement over standard BIA techniques [5, 19]. Modern devices also apply multiple frequencies, further improving the accuracy and reproducibility of the results. The frequency is the number of repetitions per second of a complete electric waveform (one repetition per second is 1 Hz) [6, 7, 20]. A current with a frequency below 100 Hz will not pass the cell membranes and as such will measure only extracellular water (ECW). Current frequencies above 100 Hz will go through cells and measure total body water (TBW). The intracellular water (ICW) can then be calculated as TBW minus ECW (Fig. 3A).

When an electric current passes a cell membrane, a time delay occurs, expressed as *phase angle*. The phase angle is the relationship between resistance and reactance. A phase angle of 0 degrees is an indicator of the absence of cell membranes, whereas 90 degrees represents a capacitive circuit which consists of only membranes with no fluid. Cell membranes cause time delays compared to time taken passing through extracellular water. The greater the number of cell membranes the signal has to pass through, the longer the time delay. The higher the phase angle, the greater the proportion of ICW compared to ECW [16]. So a high phase angle is consistent with high reactance and a large amount of waste cell membrane and body cell mass (BCM) as seen

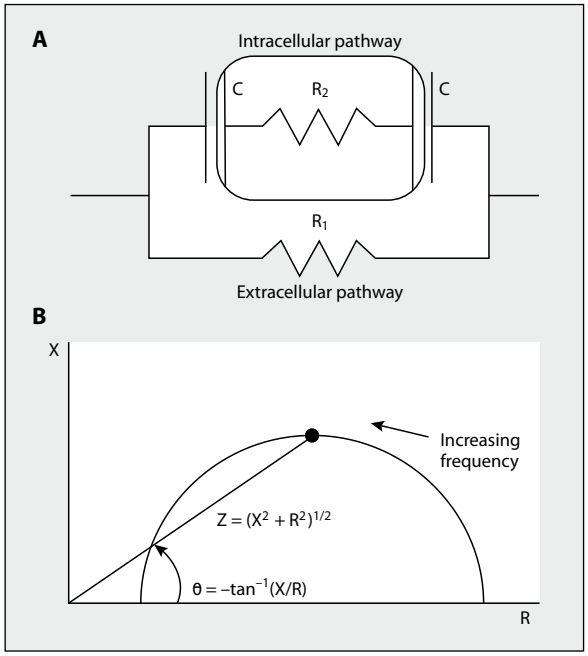

Figure 3. BIA principles. **A** — biological tissues act as conductors or insulators and the flow of current through the body will follow the path of least Resistance (R). Fat Free Mass (FFM) contains large amounts of water and electrolytes and therefore is a better conductor of electrical current than fat and bone, which are poor conductors as they contain low amounts of fluid and conducting electrolytes. The cell membrane of a body consists of a layer of non-conductive lipid (fat, oils and other lipid like substance) material sandwiched between two layers of conductive protein molecules. Cell membranes become reactive elements behaving as capacitors (C) when electrical current is applied; **B** — with BIA the Phase angle (θ), the Reactance (X) and the Resistance (R) are measured. Normal Phase angle is 4–15°. Adapted from Foster and Lukaski [16]

in healthy individuals, whereas (critically ill) patients tend to have a low phase angle (Fig. 3B) [12, 21].

Bio-electrical impedance vector analysis (BIVA) represents the values reactance and resistance in an X-Y plot referencing to a healthy population; as such one can appreciate the evolution of fluid and nutritional status in patients over time (Figure 4). Recent studies have shown a reasonable correlation between BI(V)A parameters and central venous pressure (CVP), brain natriuretic peptide (BNP) and fluid balance [9, 22, 23]. However, in a study on 43 mechanically ventilated patients, House et al. came to the conclusion that BIVA and CVP were not helpful, whereas BNP was the best predictor for poor oxygenation status [22].

BIA PARAMETERS

Table 1 lists the different parameters that can be obtained with BIA. *Absolute measurements* of impedance, reactance, resistance and capacitance have been highly correlated to changes in the human body and have been shown to be good prognostic indicators [24]. Under- and overestimation of *dry weight* is important and has been shown to impair the survival and quality of life of haemodialysis or peritoneal dialysis patients [25, 26]. *Body composition* and *nutritional assessment* of children and adults in clinical settings is important in order to identify potential causes of inadequate nutrition status, including the risk of malnutrition. Performing nutritional assessments in diseased patients enables doctors to identify related disorders and to monitor the effects of treatment [27]. The *glomerular*

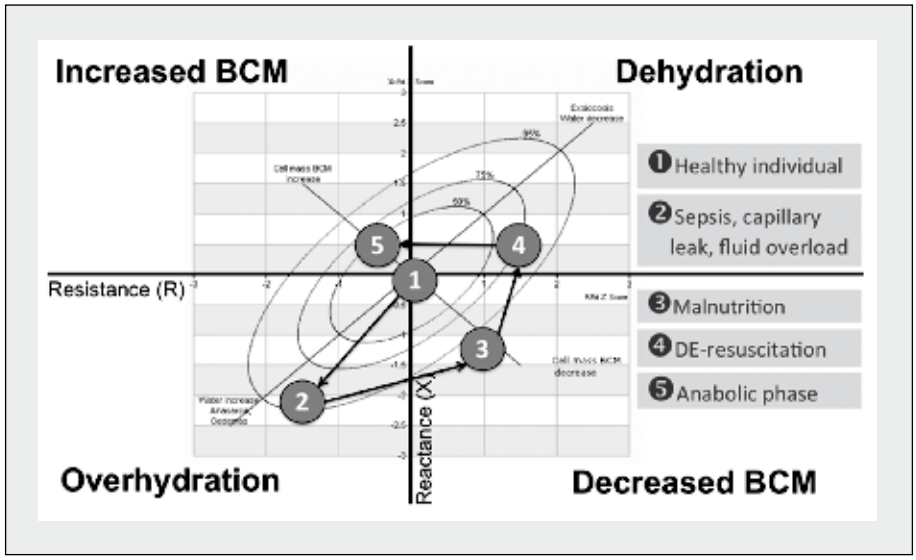

Figure 4. Bio-electrical impedance vector analysis (BIVA). Illustrative case of a 56-year-old man admitted to ICU after bowel perforation and four quadrant peritonitis. Bio-electrical impedance vector analysis (BIVA) plot of individual BIA measurements with Resistance (R) on X-axis and Reactance (X) on Y-axis; the centre point with coordinates (0,0) refers to the healthy population. Points 1 to 5 show evolution of obtained values from baseline to recovery of the acute illness. (BCM: body cell mass)

Table 1. Different parameters that can be obtained with BIA

ABSOLUTE MEASUREMENTS
• Impedance (Z)
• Phase Angle (θ)
• Resistance (R)
• Reactance (X)
• Capacitance (C)
DRY WEIGHT
• Dry Weight
BODY COMPOSITION
• Fat%
• Fat Mass
• Fat Free Mass (FFM, L or %)
• Fat Free Mass Hydration (FFMH,%)
• Body Volume
• Body Density
• Body Mass Index (BMI)
• Resting Metabolic Rate
• Target Fat (min/max)%
• Target Weight (min/max)
• Target Water (min/max)%
KIDNEY FUNCTION
• Glomerular Filtration Rate (GFR)
MINERALS AND PROTEIN
• Total Body Potassium (TBK)
• Total Body Calcium
• Protein Mass
• Mineral Mass
GLYCOGEN
• Glycogen Mass
FLUID STATUS
• Extracellular Fluid
• Intracellular Water Volume (ICW, L or %)
• Extracellular Water Volume (ECW, L or %)
• Total Body Water Volume (TBW, L or %)
• Extracellular Mass
• Extracellular Solids
• Extracellular/Intracellular Water, ECW/ICW ratio
• Extracellular Water/Total Body Water
• Intracellular Water/Total Body Water
• Interstitial-Fluid Extravascular
• Plasma-Fluid (Intravascular)
• Intracellular Water/Total Body Water
• Body Cell Mass (BCM)
• Muscle Mass

filtration rate (rate at which waste is removed from our kidneys) is an important indicator of kidney function. Studies have shown a good correlation between BIA and other techniques in the estimation of GFR, avoiding the need for 24 hour urine collection (gold standard creatinine clearance) or using other calculations (Cockroft-Gault, MDRD (modification of diet in renal disease), or CKD-EPI (Chronic Kidney Disease Epidemiology Collaboration) formula) [28, 29]. BIA can obtain information on *mineral* (bone, soft tissue) and *protein* content of the body. In some patients, assessment of the loss of minerals can be very important. *Glycogen mass* is the primary storage form of carbohydrates found in the cytoplasma of most cells. Intracellular and extracellular body *fluid status* in both healthy and diseased patients is of significant importance. Extracellular Water (ECW) increases in different diseases and oedema is the most common sign of ECW expansion. Monitoring these changes in patients can provide us with detailed information and understanding of changes as a result of disease. *Body cell mass* (BCM) is an accurate method of establishing a healthy subject's nutritional status or a patient's degree of malnutrition. BCM is used for calculation of energy expenditure and other metabolic measures.

VALIDATION

Although BIA is a simple, noninvasive, rapid, portable, reproducible, and convenient method of measuring body composition and fluid distribution with fewer physical demands (than anthropometric techniques for instance), it is still unclear whether it is sufficiently accurate for clinical use in critically ill patients [30]. BIA measures TBW and as such it needs to be validated through comparison with other means of determining TBW or methods (such as densitometry) used to derive the components of the two-compartment model of the body composition, namely fat free mass, and body fat. Because BIA disproportionately considers the extremities, the relationship between impedance and TBW can only be empirical. As explained in the NIH health technology assessment, this places an important constraint on the derived value: TBW must be altered in the torso and the extremities in a fixed relationship in health and disease in order to retain predictive value [5]. This relationship probably exists in most normal subjects and in those with mild disease perturbations such as mild-to-moderate obesity and other chronic illnesses not producing local fluid accumulation.

The gold standard techniques for measuring body composition and TBW are isotope dilution (labelled deuterium), followed by dual energy X-ray absorptiometry (DEXA), underwater weighing, and air-displacement plethysmography. Abdominal and visceral fat can also be measured with computed tomography (CT) and magnetic resonance imaging (MRI). These techniques require special facilities and cannot be used for daily bedside measurements. Previous studies showed varying results and in some cases BIA could not provide additional information [6, 19, 31, 32]. Total body potassium (TBK) has been found to be linearly correlated with body cell mass (BCM) [31]. However, laboratory techniques such as total body potassium (40K and 42K) are not practical for everyday bedside monitoring. Portable methods consist of infrared analysis, skinfold caliper measurement, and dual contact BIA. Tetrapolar BIA falls in between basic and advanced methods. Different studies comparing BIA to DEXA have shown good correlation [19]. For clinical purposes, two devices are available to be used in (critically

Table 2. Effects of disease states on body composition

Impact of illness on tissue	Impact of illness on fluid status
• Loss of or low body fat • Excessive weight gain • Loss of body weight • Loss of fat free mass • Low muscle tissue mass • Loss of or low bone mineral • Loss of body cell mass • Malnourishment • Increased catabolism • Delayed anabolism • High body density • Clinical muscle wasting (cachexia wasting syndrome, sarcopenia) • Higher bone mass and mineral density • Reduced lean trunk mass	• Fluid imbalance • Positive daily fluid balance • Positive cumulative fluid balance • Peripheral oedema • Altered fluid status — changes in total body water, extracellular and intracellular fluids • Increase or decrease in intracellular water (decreased body cell mass and total body potassium) • Increase in extracellular water (oedema) • Plasma volume increases and fluid accumulates in the lungs, abdominal organs and peripheral tissues • Changes in water, mineral and protein contents • Increase in ECW/ICW ratio • Increase in total body water • Change in fat free mass hydration • Variations in TBW-to-FFM ratio • Variations in impedance-to-TBW ratio

ill) patients: the Fresenius Medical Care Body Composition Monitor (BCM) (Fresenius Medical Care, Bad Homburg, Germany) (http://www.bcm-fresenius.com/index.html), and the Maltron BioScan 920 (Maltron International Ltd, Rayleigh, UK) (http://www.maltronint.com/products/bioscan920-2S.php). However, no head-to-head comparison has been performed in a large sample of critically ill patients.

CLINICAL APPLICATIONS

NUTRITIONAL ASSESSMENT

As suggested by ESPEN: *"BIA is an important clinical tool for evaluating the metabolic status of intensive care unit (ICU) patients. It is inexpensive and noninvasive, and it provides useful information concerning altered body composition and membrane potential at the tissue level measured by phase angle, as well as fluid imbalance"* [17, 18]. Disease states can have a profound impact on body composition as listed in Table 2. As a consequence, from a theoretical point of view, the clinical applications for BIA could be numerous: AIDS, muscle wasting, anorexia, postmenopausal women, obesity, pregnancy, Crohn's disease, cystic fibrosis, diabetes, paediatric diseases, enteral and parenteral nutrition, elderly, rheumatoid disease, tropical disease, sepsis and septic shock. Studies have shown that fat-free mass (FFM) was lower and fat mass was higher in, respectively, acutely ill and chronically ill patients than in controls [21]. Sarcopenia is the backdrop against which the drama of disease is played out, a body already depleted of protein because of ageing or starvation is less able to withstand the protein catabolism that comes with acute illness or inadequate protein intake [33]. BIA may be clinically useful for demonstrating sarcopenic obesity in women at normal BMI, with additional studies necessary to determine the metabolic reasons underlying this change in body composition [34]. BIA can be helpful in burn patients, cardiovascular diseases, peripheral oedema, gastroenteritis, haemodialysis, continuous veno-venous haemofiltration (CVVH), peritoneal dialysis, liver disease, second and third spacing (segmental analysis), lung disease (like ARDS with capillary leak), malnutrition, bariatric surgery, postoperative fluid status, renal failure, and stroke.

CHRONIC KIDNEY DISEASE

BIA can detect changes in body composition even in the early stages of kidney disease and in patients with cardio-renal syndromes, showing lower resistance, abnormal impedance vectors, reduced phase angle, and higher TBW together with a lower BCM. Importantly, patients do need to have overt signs of overhydration or malnutrition for BIA to detect these alterations [35, 36]. These changes in body composition continue during the entire spectrum of chronic kidney disease, being most evident in end-stage renal disease (ESRD). Compared to the National Health and Nutrition Examination Survey (NHANES) III population, ESRD patients (chronic maintenance dialysis patients) had lower resistance, reactance, phase angle, intracellular water and body cell mass values, in contrast to a 17% higher extracellular water value [37]. In chronic haemodialysis patients, multifrequency whole body BIA can give an objective measure of fluid and nutritional status, calculating overhydration within one to two litres [38]. It can therefore provide an appropriate and noninvasive method for the determination of dry weight (especially compared to other methods such as deuterium dilution technique, anthropometry, or the Watson equation) [39]. Using BIA as a guide to achieving dry weight results in an improved fluid status and the control of blood pressure [40]. In the long term, this means a greater decline in arterial stiffness, (chronic) fluid overload and systolic blood pressure and even all-cause mortality [41]. In peritoneal dialysis patients, who often have a significant residual kid-

ney function, BIA-guided fluid management with measurements performed after draining the intraperitoneal cavity [42] can help restore diuresis in underhydrated patients and improve tension and weight control in overhydrated patients [8, 43].

CRITICAL CARE

Many conditions exist in critical illness (ascites, anasarca, severe peripheral oedema, pleural effusions, the massively overhydrated patient, as well as other clinical conditions in which there are severe disturbances in water and electrolyte distribution) where conventional BIA may be a poor measure of TBW [17, 18]. Therefore, for the time being BIA can only be considered as a research tool in critically ill patients because the TBW-to-FFM ratio is variable and the body impedance-to-TBW ratio may often vary during the above-cited conditions [5, 17, 18].

It is important for the clinician to be aware that the normal ECW/ICW ratio is less than 1. An increase in ICW is seen in patients with heart failure, liver cirrhosis and chronic renal failure (especially early stage). A decrease in ICW is generally related to osmotic factors, while increases in ECW are mostly due to a shift from intra- to extracellular space as seen with second (interstitial) and third space (ascites, pleural effusion) oedema, in the late stages of the above-cited conditions (heart, or liver or kidney failure).

Critically ill patients, especially those with sepsis or severe sepsis, are prone to develop changes in body fluid distribution with migration of fluid from the intravascular to the extravascular space. Furthermore, the systemic inflammatory response produces changes between the FFM and TBW distribution [44]. In addition, oxidative stress and production of reactive oxygen species is associated with damage of the cell membrane and loss of cell wall integrity, which may result in a drop in the phase angle, as discussed above. Raw impedance data can provide information on hydration and cell mass integrity [45].

Plank found that although changes in TBW were similar, patients with peritonitis and sepsis (n = 12) had higher ECW values compared to those with blunt trauma (n = 18) [11]. In a study on the use of continuous veno-venous haemofiltration to adjust fluid volume excess in 30 septic shock patients with acute kidney injury (AKI), Dabrowski et al. found a sustained increase in TBW, ECW (Fig. 5A) and ECW/ICW ratio (Fig. 5B) in nonsurvivors [46]. Volume excess (VE) was also associated with increased intra-abdominal pressure (IAP) and worse outcomes. The use of CVVH with net ultrafiltration (UF) successfully reduced IAP, TBW, ECW, and ICW in those patients who survived 96 h of CVVH. A similar study in 68 ICU patients with sepsis (n = 51) compared to patients without sepsis (n = 17) showed that ECW and FFM hydration were increased in severe sepsis compared

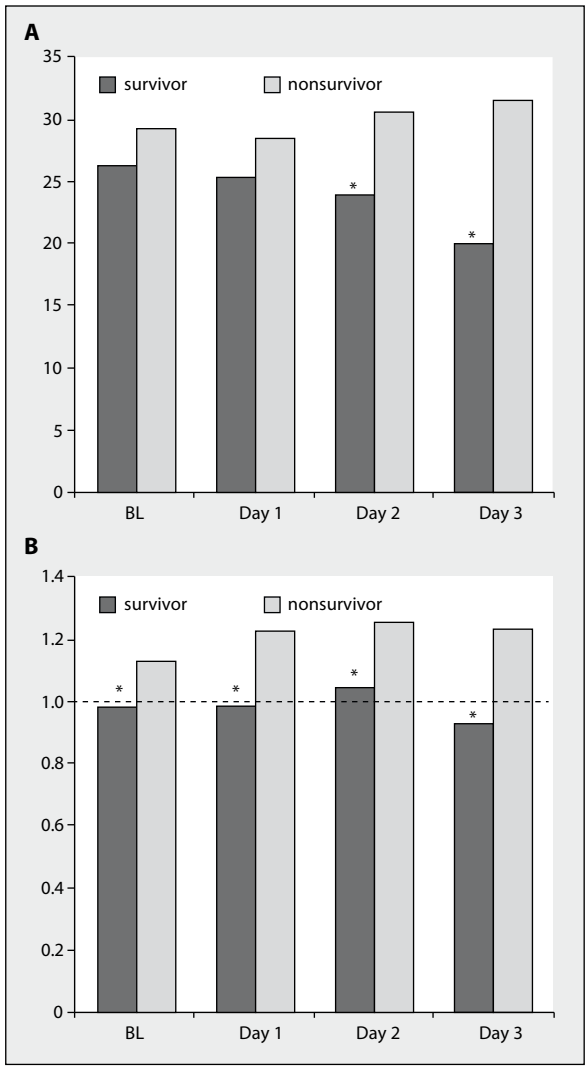

Figure 5. Day-by-day evolution of BIA parameters in survivors vs nonsurvivors; **A** — day-by-day evolution in ECW between survivors and nonsurvivors; **B** — day-by-day evolution in ECW/ICW ratio between survivors and nonsurvivors (normal ratio, < 1, as indicated by the dotted line). Adapted from Dabrowski et al. [46]; * denotes *P*-value < 0.05; BL — baseline

to sepsis [47]. Raw impedance data analysis showed that patients without sepsis had significantly lower resistance values (401.1 ± 129.56 Ω vs 490.4 ± 142.06 Ω, $P = 0.025$) and resistance normalised by height than patients with confirmed sepsis (241.16 ± 80.3 Ω m^{-1} vs 293.05 ± 89.35 Ω m^{-1}; $P = 0.037$). Changes in tissue physiology and integrity during sepsis may produce changes in electrical properties; as such, the use of raw data obtained with BIA seems promising. Indeed, raw data is not influenced by assumptions that can affect body composition results, and BIVA provides information on tissue hydration and BCM independent of regression equations, even in overhydrated patients [24]. The study by Slotwinski showed that patients with sepsis had significantly higher raw impedance (566 ± 98.66 Ω vs 423.86 ± 149.7 Ω; $P = 0.0003$) and resistance normalised

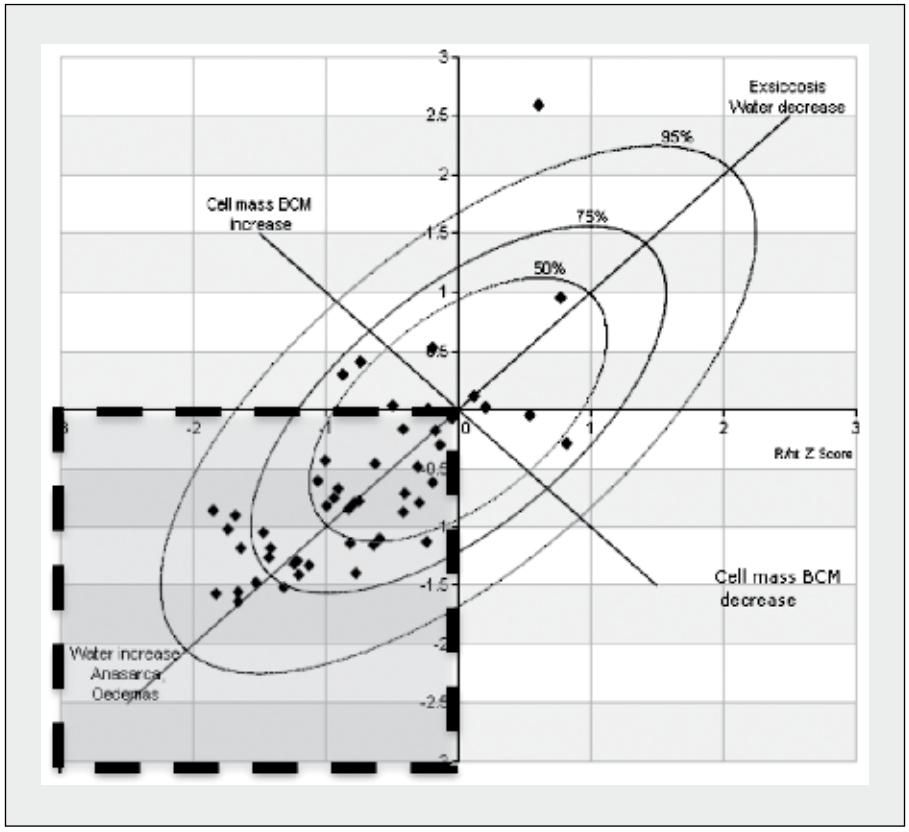

Figure 6. Bioelectrical impedance vector analysis (BIVA) showing patients with sepsis plotted on three tolerance ellipses. Resistance (R) on X-axis and Reactance (X) on Y-axis; the centre point with coordinates (0.0) refers to the healthy population. About 49% of sepsis cases were located above the 50th percentile, suggesting fluid accumulation (within grey shaded square), see text for explanation. Adapted from Slotwinski et al. [47]

by height (336.69 ± 66.9 Ω m^{-1} vs 259.94 ± 90.9 Ω m^{-1}; $P = 0.00165$) than those with severe sepsis [47]. However, the % ECW was lower in sepsis vs severe sepsis (45.95 ± 2.97% vs 49.2 ± 6.11%; $P = 0.026$). The sepsis population was positioned mainly on the lower left side of the BIVA tolerance ellipses, characterised by fluid retention and drop in BCM [24]. In the abovementioned study, 49% of sepsis cases were located above the 50th percentile, suggesting fluid accumulation as shown in Figure 6 [47]. The lower mean phase angle of the patients with sepsis being above the 50th percentile in the study by Slotwinski could be related to a low body cell mass and high ECW/ICW ratio, as observed by other investigators [48]. Piccoli et al. [49] previously found that cardiac patients with dyspnoea falling on the lower side of the 50% tolerance ellipse presented with increasing fluid volume and CVP. A retrospective study comparing BIA data from critically ill patients (n = 15) with healthy volunteers (n = 25) showed significant differences in body water composition between patients and healthy individuals [50]. In this study, patients had higher values for TBW (45 ± 7.7 vs 38 ± 9.7 L, $P = 0.01$), ECW (24.1 ± 5.4 vs 16.9 ± 5.3 L, $P < 0.0001$) and ECW/ICW ratio (1.2 ± 0.2 vs 0.8 ± 0.2, $P < 0.0001$) while

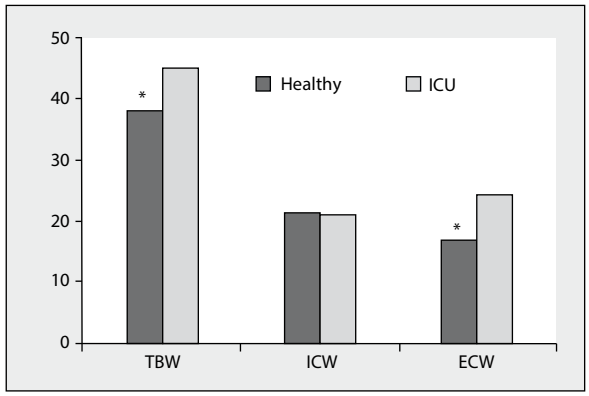

Figure 7. Bar graph showing mean values for total body water (TBW), intracellular water (ICW) and extracellular water (ECW) in 15 ICU patients compared to 25 healthy volunteers. Adapted from Huygh et al. [50]; *denotes *P*-value < 0.05

ICW was lower 20.9 ± 3.8 vs 21.2 ± 5 L, P = NS) (Fig. 7) [50]. Patients had a VE of 7.8 ± 5.7 vs –0.2 ± 0.6 L in healthy volunteers ($P < 0.0001$). Patients also had a significantly lower phase angle (at 100 kHz) compared to healthy individuals, respectively 8.7 ± 2.8 vs 10.4 ± 1 ($P = 0.008$).

FLUID STATUS ASSESSMENT

Recent studies have shown that a positive daily, or cumulative positive, fluid balance is an independent predictor for poor outcome [1–4, 51–53]. It is beyond the scope of this review to discuss the pathophysiologic implications of fluid overload in detail as this has been discussed previously elsewhere [54, 55]. However, BIA parameters like TBW, ICW, ECW, ECW/ICW ratio and VE have a clinical potential and can easily be used with other indices of capillary leak and fluid overload like daily and cumulative fluid balance, body weight, serum capillary leak index (CLI = serum C-reactive protein (CRP) divided by serum albumin), renal leak index (RLI = urinary albumin divided by serum creatinine), serum osmolality and colloid oncotic pressure, extravascular lung water and pulmonary vascular permeability index (as can be obtained with transpulmonary thermodilution), serum total protein, albumin and haemoglobin levels (as measured for haemoconcentration *vs* haemodilution) to name just a few [56].

BIA PITFALLS AND LIMITATIONS IN CLINICAL PRACTICE

Pitfalls one has to take into account during BIA measurement are changing posture (the best position being supine), incorrect position of arms (should be next to body), incorrect contact with the electrodes, and contact with another person or object during measurement. Other factors that may interfere with BIA measurements that are currently not yet well understood are: infusions with large amounts of normal saline, peripheral oedema and overhydration (a frequent observation in critically ill patients), changes in ambient air and skin temperature or fever, sweating, nutrition and oral feeding, nutritional status, changes in Na and K content, a body mass index (BMI) > 34 kg m^{-2}, specific conductance of hospital bed, etc. It is wise to advise anyone with a (temporary) pacemaker or an implanted defibrillator to avoid BIA evaluation until this issue has been reviewed, because even small currents could potentially provoke an incorrect defibrillator response [5].

Whole-body bioimpedance analysis measures the bioelectrical properties between the wrist and the ankle under the assumption of a steady fluid distribution. This configuration forces the division of the body on three electrical independent segments with different cross-sectional areas and lengths: the arm, the trunk, and the leg. The geometrical differences of these three segments importantly influence their contribution to overall whole-body bioimpedance [57]. Moreover, water is not evenly distributed in the human body. The same volume of extracellular fluid in the leg leads to different results in whole-body bioimpedance than does a similar volume of extracellular water in the trunk. An increase in abdominal water content following ascites or intra-peritoneal inflammation significantly disturbs whole-body bioimpedance findings. Therefore, whole-body bioimpedance is much more sensitive to volume changes in the limbs than in the trunk [58].

As previously stated, the body position has also a significant impact on whole-body bioimpedance findings. Ideally, the measurement of body compartments should be performed in the supine position. Trunk elevation, which is widely used in patients with traumatic brain injury, can change body water distribution, reducing the credibility of whole-body bioimpedance measurements [59].

It is worth noting that an increase in IAP also affects whole-body bioimpedance findings. Third or fourth grade of intra-abdominal hypertension significantly congest abdominal vessels reducing blood outflow from the limb [60]. An increase in intravenous volume and a decrease in venous compliance lead to interstitial oedema in the limb, which increases the electrical conductivity disturbing whole-body bioimpedance findings [61]. Therefore, the credible measurement of body water distribution should always be seen in relation to measurement of IAP.

CONCLUSIONS

The recommendations for fluid monitoring can at best be described as open for discussion and debate. Any measurement stands or falls on its accuracy and reproducibility. Nevertheless, bioelectrical impedance analysis seems a promising tool if performed correctly. BIA has numerous advantages as it is non-invasive and relatively inexpensive and can be performed easily at the bedside, while it does not expose to ionising radiation as do other techniques. Modern BIA devices have very limited between-observer variations. However, BIA parameters are population-specific and one must be aware of clinical situations that may interfere with the measurement. BIA allows assessment of different parameters related to the patient's fluid status such as TBW, ICW, ECW, ECW/ICW ratio and VE and as such it can help guide resuscitation and de-resuscitation (perhaps something of even greater importance) in patients not progressing spontaneously from the Ebb to the Flow phase of shock [62]. More research is needed in critically ill patients before widespread use of BIA can be suggested in this patient population.

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