Patterns of Bioelectrical Impedance Vector Analysis: Learning From Electrocardiography and Forgetting Electric Circuit Models

Both electrocardiography and bioelectrical impedance analysis (BIA) aim to transform electrical properties of tissues into clinical information. Electrocardiography is based on several established patterns relating electrical measurements to heart disorders.\(^2\) Conventional BIA is based on electric models supporting quantitative estimates of body compartments.\(^3\)–\(^9\)

In BIA literature, an electrical model (e.g., series, parallel, Cole’s, and Hanai’s models) is used as an electrical equivalent,\(^1\) a circuit that electrically behaves like the original, is expressed through mathematical equations, and represents anatomic structures or physical processes (e.g., 75 trillion cells, three to six body compartments, cellular/vascular fluid shifts, etc.). According to their dictionary definitions, a model is “A representation of the supposed structure of something” and a pattern is “A set of forms used as a guide in making things.” In the clinical setting, operational patterns based on direct laboratory data are more useful than complex, explanatory, or descriptive models of phenomena.

The electrocardiogram (ECG) is a graphic recording through surface electrodes (as in BIA) of electric potentials generated by the heart. Cardiac depolarization and repolarization waves are interpreted with few, time-averaged vectors. An ECG wave (vector) is the complex spatial and temporal summation of electric potentials from multiple myocardial fibers conducted to the surface of the body. Abnormalities of individual waveforms are defined with respect to reference values of healthy subjects. An ECG is interpreted with diagnostic ECG patterns, which are a combination of waveforms associated with specific cardiac disorders in clinical validation studies (e.g., bundle branch blocks, myocardial ischemia, infarction, etc.).\(^2\) Calculations of heart volume, ischemic mass volume, infarction volume, etc., from ECG waveforms are used to estimate body compartments.\(^3\)–\(^9\)

The National Institutes of Health in 1994\(^3\) and an independent panel of BIA experts in 1997\(^7\) continue to recommend (in vain) to manufacturers that they provide both measured data (resistance [R], reactance [Xc], impedance [Z], and phase angle) and prediction equations in their software. The expert panel recommended the use of multifrequency BIA (i.e., R extrapolated to zero and infinite frequency) in estimating total body water (TBW; from R), extracellular water (ECW; from R), and intracellular water (ICW; TBW − ECW) in altered fluid distribution, and a limited use of single-frequency BIA, parallel model, in estimating body cell mass (BCM). Estimation of fat-free mass (FFM) was considered acceptable only with normal fluid status, and derived estimation of fat mass (FM) was considered inappropriate. Single-frequency BIA, series model, was ranked as the least useful BIA technique.\(^4\)

In 2000, Grimnes and Martinsen\(^1\) in their book reported an extensive update of bioimpedance models and techniques making inconsistent previous recommendations of the expert panels. Relevant discrepancies can be summarized in the following statements. 1) Electric circuit models do not take into account the difference between electronic and ionic media, where biological charge carriers cause relaxation processes and, hence, frequency-dependent capacitance and conductance values. 2) When constant-amplitude current is applied to tissues and the corresponding voltage is measured, the raw data and the measured variable are impedance, but the same information can be presented differently as impedance (series circuit models), admittance (parallel circuit models), or immittance (combined term for impedance and admittance). 3) With multifrequency BIA it is impossible to estimate the extracellular electric volume (i.e., ECW) of tissues because an unknown and variable amount of low-frequency current passes through cells (tissue anisotropy), particularly through muscle fibers (parallel direction). 4) In multifrequency BIA, Hanai’s and Cole’s models (including multiple Cole’s systems) are only empirical equations that describe impedance changes with current frequency in suspended spherical cells and in several tissues, other than skin, without any correspondence with tissue structure. 5) For any combination of electrode position, the influence of skin impedance and the path of deep current through tissues are frequency dependent. Hence, in multifrequency BIA, different proportions of tissues and body segments contribute to low- and high-frequency impedance, which prevents any reliable determination of body fluid distribution. 6) BIA with a single-frequency current close to the characteristic frequency (e.g., 50 kHz) provides the best information at a body level because it maximizes the signal-to-noise ratio (maximal Xc values in the order of one-tenth of R values) and minimizes frequency-dependent errors and variability of electric flow paths.

Why is BIA based on models and prediction equations? During stable periods, relations between body components are constant and correlated with each other, which allows investigators to estimate an unknown body component (e.g., TBW, ICW, ECW, FFM, FM, and BCM) from a related measured property (bioimpedance) through regression equations.\(^5\)–\(^9\),\(^10\) Hundreds of excellent validation studies have established a solid relation between body impedance and body fluid volume (isotope dilution), but with population-specific accuracy of prediction. However, because criterion methods have their own errors, the standard error of the estimate of the best BIA regression equations is too large (95% prediction interval greater than ±3 to 6 kg or L) to be useful in the clinical setting.\(^6\)–\(^9\),\(^10\) The expert panel also invited investigators to find new ways of expressing results to improve the clinical utility of BIA.\(^4\)

Clinical utility of BIA can be achieved by following the methodology of ECG interpretation, i.e., using vector BIA (bioelectrical impedance vector analysis, BIVA) as a stand-alone procedure based on patterns of direct impedance measurements (impedance vectors).\(^1\)–\(^9\) Body soft tissues (lean plus fat soft tissues, or the FFM without bone plus the FM)\(^7\) actually generate the body impedance and therefore can be evaluated directly with vector BIA. Contribution of bone to impedance is negligible, and lean contributes more than fat soft tissue because adipocyte droplets of triacylglycerols are non-conductors.\(^1\)–\(^7\)

Impedance at 50 kHz is represented with a complex number (a point) in the real–imaginary plane (Z vector), which is a combination of R (i.e., the opposition to flow of an alternating current through intra- and extracellular ionic solutions, representing the real part of Z) and Xc (i.e., the capacitive component of tissue interfaces, and cell membranes and organelles, representing the imaginary part of Z).\(^1\)–\(^7\),\(^9\) R and Xc components are significantly, positively correlated in humans, at any age, in healthy and disease,\(^11\)–\(^19\) indicating a binding of ionic solutions to containing
From clinical validation studies in adults,11,13,16–19 vectors falling out of the 75% tolerance ellipse indicate an abnormal tissue impedance, which is interpreted and ranked by following two directions: 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 apparent edema 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 cell mass, respectively. Different trajectories indicate combined changes in hydration and tissue mass. This method of vector BIA, known as the RXc graph method, allows an evaluation of soft tissues through patterns based on percentiles of their electrical properties without prior knowledge of body weight.

A necessary condition for vector BIA pattern identification is a statistically significant difference in mean vector position among groups of subjects, i.e., when their 95% confidence ellipses do not overlap on the R–Xc plane (P < 0.05, equivalent to a significant Hotelling’s T² test).20,21 For instance, vectors from obese or edematous subjects are shorter than normal, with comparable R value and a higher or lower Xc value, respectively. Different trajectories indicate combined changes in hydration and tissue mass. This method of vector BIA, known as the RXc graph method, allows an evaluation of soft tissues through patterns based on percentiles of their electrical properties without prior knowledge of body weight.

In the present issue of Nutrition, Buffa et al. describe an interesting BIVA pattern in puberty.22 They document a significantly shorter mean impedance vector with increased phase angle in postmenarcheal compared with premenarcheal girls. This vector displacement, indicating more soft tissue mass, has been observed in adult populations with increased BMI11,13,17 and in growing children, in particular boys, between ages 10 and 15 y.14 In the menarche study, after correction for BMI (as a covariate), the mean vector displacement, although reduced, was still significant, indicating an increased soft tissue mass after menarche.22 However, a precise assessment of vector pattern associated with puberty should be based on the comparison of two groups of girls strictly matched for BMI and age. The size of vector displacement attributed to menarche is of interest in interpretation of physiologic processes within the wide “normal” intersubject variability.19,22 Indeed, complex feminine hormonal influences on soft tissues may account for the greater tolerance intervals of women compared with men of different races.11–13 Accordingly, pre-menopause vector position and variability might also differ from post-menopause.

Conventional BIA equations, at any current frequency, based on percentiles of their electrical properties without prior knowledge of body weight. Clinical validation studies are necessary to map on the R–Xc plane more regions discriminating between population-specific, physiologic, and abnormal body impedance changes.

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