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Review: Body Composition

MULTI-DIMENSION APPLICATIONS OF BIOELECTRICAL IMPEDANCE ANALYSIS

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ABSTRACT

Khan M, O'Hara R, Pohlman RL, Goldstein DG, Guha SK. Multi-Dimension Applications Of Bioelectrical Impedance Analysis. ***JEP****online* 2005;8(1):56-71. Bioelectrical Impedance Analysis (BIA) has been shown to be an inexpensive, reliable, simple, safe, and noninvasive technique for multiple purposes, such as the prediction and detection of fluids in aviators and aircraft pilots, clinical cardiology settings, and in the estimation of body composition and body water volume in children and adults. In general, when using BIA, a low level electrical current is passed into the body or body segment of a subject using two or more electrodes. A small and constant electrical current flows between the electrodes; same or different electrodes pick up a voltage signal from the body surface of the subject. The detected voltage is expressed in terms of impedance (ohms,Ω). Development of new commercial BIA instruments, such as the body segmental BIA analyzer, multifrequency BIA analyzer, lower body BIA analyzer, upper body BIA analyzer, and laboratory designed BIA analyzers, have greatly expended the utility of this method. The present review paper summarizes some of the applications of BIA in the field of aerospace medicine, research, clinical settings in cardiology, and in the measurement of body composition and body fluid compartmentalization.

Key Words: Aviation, Aircraft pilots, Body composition, Body fluids, BIA.

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INTRODUCTION

A number of researchers have demonstrated bioelectrical impedance analysis (BIA) as a useful, reliable, versatile, safe, simple, and promising noninvasive technique for the detection of physiological events (1,2,3). Prior to reviewing the applications and validity of BIA, it seems suitable to discuss the origin of BIA technique.

Development of BIA Technique

The studies of bioelectric phenomena in human and animal tissue were started in the late 19th century (4,5). Bioelectrical impedance (BI) measurements are based on Ohm's Law: current in a circuit is directly proportional to voltage and inversely proportional to resistance in a DC circuit or impedance in an alternating current (AC) circuit. Two electrodes are used to apply AC into the body or body segment. The voltage signal from the surface of the body is measured in terms of impedance using the same or an additional two electrodes. It is possible to express resistance or impedance information of the body or body segment in terms of physiological events. A considerable amount of work was done between 1930 and1950 to establish the basic uses of impedance for measuring various aspects of human physiology (6-9). The above studies explored relationships of bioelectric impedance and its parameters to physiological variables such as thyroid function, basal metabolic rate, hormone levels, and blood flow (10). The ability of BI to reflect accurately blood volume changes has been the subject of criticism (11). Anderson (12) determined that the confusion concerning the relationship between BIA and blood volume was due to the limitation of a two-electrode system employed in many of the BIA instruments. The introduction of four electrodes (two as current and two as voltage) eliminated the effects of skin impedance and reduced sensitivity to changes close to the electrodes. Technological advancements in BIA instrumentation now enable BIA to measure impedance with a high degree of accuracy (13).

Importance of BIA Technique

The classical techniques based upon air or fluid displacement are cumbersome, which greatly limits their use outside the laboratory. On the other hand, BIA technique is significantly more convenient to use in a routine clinical setting. The BIA using venous occlusion plethysmography has shown wide acceptance as a routine screening test for major deep vein thrombosis (14,15). Ejlersen (16) used BIA to evaluate minimum veno-venous bypass flow for compensating the inferior vena cava clamping during liver transplantation. A veno-venous bypass relieves congestion in the heart and improves cardiac output. The BIA monitoring of the thorax permits continuous determination of stroke volume, indices of contractility such as velocity and acceleration of blood flow, systemic vascular resistance and its index, cardiac output (CO) and cardiac index (CI), and thoracic fluid content. Further, Belott (17) and Gilbert (18) have shown that BIA provides other hemodynamic indices such as systolic time internal, left cardiac work index, and diastolic index in the Pacemaker Clinic and takes only minutes to perform.

BIA has been used widely in the clinical setting for assessment of body composition for the last 20 years. Numerous investigations have demonstrated the usefulness of BIA in assessing body composition, body composition changes and body fluid distribution in a wide range of physiological and clinical conditions (19-21).

Predictions of leg-segment electrical impedance (LEI) are extremely useful for aviators when determining medical diagnosis and therapy in aerospace medicine. Khan (22) investigated a unique application of BIA in a study of blood pooling in the simulated leg segment of an aircraft pilot under G-stress. In another study, BIA was also used to simulate and measure arm blood pooling of an aircraft pilot under G-stress. The results of the studies may then lead to practical designs and develop countermeasures to reduce or remove arm pain of aircraft pilot.

BIA INSTRUMENTS

There are a number of manufacturers who make BIA instruments for commercial scale. A panel of BIA experts emphasized the need for standardization of equipment and recommended that all BIA instruments should report resistance, reactance, and prediction equations as well as calculated body composition values (23). The panel also noted that raw data such as source current, frequency, range, and accuracy should be made available. The technological advances and changes in theoretical modeling have resulted in a number of variations in the traditional BIA instruments. Additionally, user-friendly BIA analyzers have been designed for home use and individual monitoring of health fitness (24).

CLASSIFICATION OF BIA INSTRUMENTS

BIA instruments have been classified into different types of models:

Traditional or Series BIA Model

The traditional or series BIA model assumes that there is only one conductive path and that the body consists of a series of resistors. An electrical current, injected at a single frequency, is used to measure whole body impedance (i.e., wrist to ankle) for the purpose of estimating total body water and fat free mass. Its impedance (Z) is equal to $\sqrt{(R^2 + Xc^2)}$. Whole body bio-impedance (Z,R, and Xc) are used in BIA prediction equations to estimate total body water (TBW) and fat free mass (FFM). The equations are either population specific or generalized. A number of researchers have developed predictive equations that are age-specific, ethnic-specific, fatness-specific, and physical activity level-specific (25-30).

Parallel BIA Model

In this model of impedance, the resistors and capacitors are oriented both in series and in parallel in the human body (31). It has been suggested that the arrangement is more consistent with human physiology. Its impedance is simply the reciprocal of the series model ($Z^{-2} = R^{-2} + Xc^{-2}$). The parallel model is thought to be most useful in estimating intra-cellular water or body cell mass. This model is also preferred when assessing patients who are malnourished or have a fluid imbalance (32,33). The values of Rp and Xc_p of the parallel model may be transformed from the series model.

$Rp = Rs + [(Xc_s)^2 / (Rs)]$

$Xc_p = Xc_s + [(Rs)^2 / (Xc_s)]$

Where subscript letter p and s indicate parallel and series, respectively.

Segmental BIA Model

The forearm only accounts for slightly more than 1 % of body weight, but contributes 25 % to whole body impedance (34). Similarly the trunk region represents most of the fat free mass, but it contributes relatively little to whole body resistance. The theoretical upper limb-trunk-lower limb resistance ratio is 13.8:1:11.8. Thus, whole body BIA is relatively insensitive to changes in the trunk region. It has been determined that a segmental BIA model is more useful in patients with altered fluid distribution. Organ (35) described the theory of segmental BIA and placement of electrodes. Cornish (36) further simplified and standardized the procedure for the segmental BIA model. Research conducted so far suggests that segmental BIA is the preferred approach in the evaluation of regional fluid changes and in monitoring extra cellular water in patients with abnormal fluid distribution, such as those undergoing hemodialysis (37-39).

Multi-Frequency BIA Model

A BIA instrument operating at the single frequency of 50 KHz reflects primarily the extra cellular water compartment as a very small current passes through the cell. Because low frequency (~1 KHz) current does not penetrate the cells and that complete penetration occurs only at a very high frequency (~1 MHz), multi-frequency BIA or bioelectrical impedance spectroscopy devices have been developed. These devices are able to scan a wide range of frequencies.

The Cole model is a parallel model that uses resistance values at zero and infinite frequencies. The model was designed to analyze multi-frequency data in the assessment of total body water (TBW), intracellular water (ICW), and extracellular water (ECW) of patients with abnormal fluid distribution (40,41). It has also been reported to be the best model for predicting changes in ECW, ICW, and TBW (42).

Lower Body Model

The development of a lower body analyzer for home use began in 1992. Tanita Corporation, USA, is marketing about 20 different models of lower body analyzers that vary in weight capacity, software and memory, and data output. Its footpad has two electrode plates; one for the foot and other for the heel. The subject stands barefoot on a footpad similar to a bathroom scale and lower body impedance is measured with pressure contact electrodes. The current is applied by the anterior electrodes (ball of the foot) and impedance is measured by the posterior electrodes (heel). Research has reported good agreement with the impedance as measured by pressure contact and commercial gel electrodes (43).

Tyrrel (44) derived a fat free mass predictive equation for children using foot-to-foot impedance measures obtained from a Tanita analyzer. Utter (45) has shown that the accuracy of lower body BIA model is similar to the hydrodensitometry for assessing changes in % BF over time.

UPPER BODY BIA MODEL

The development of an upper body analyzer for home use began in the late 1990s. Omron Health Care, USA, developed a low cost hand-to-hand BIA analyzer (model HBF-306BL). Handles of the device contain plate electrodes, which are held by both hands with arms outstretched parallel to the ground while standing erect. Recently, it has been modified to estimate the body composition of active and non-active adults and children. Predictor variables of the manufacturer’s equation will provide upper body impedance, age, gender, height, weight, and physical activity level. The device has been tested on ethnically diverse samples of European and Asian populations.

The human body composition is based primarily on the chemical analysis of organs and quantified as fat, mineral (bone and soft tissue), protein, and water. Such quantified approach is called four-compartment (4-C) model. The standard error estimation (SEE) of upper body BIA is 4.5 % in body fat (%BF) compared to the 4-C model. The SEE in % BF is also related to age, body fatness level, and arm span to height ratio of the subjects (46). A proprietary equation has been cross-validated on a large, diverse, and heterogeneous sample from three laboratories using hydrodensitometry to obtain a two compartment model reference measures of % BF and fat free mass (47). The average difference between reference and predicted % BF values is slightly smaller for the Omron analyzer (2.2 % BF) compared to the whole body analyzer (3.3 % BF) and lower body analyzer (3.2 % BF) (48).

LABORATORY DESIGNED BIA MODEL

Both bipolar and tetrapolar electrode systems are being used practically in BIA instruments. Of these, the tetrapolar system has a definite advantage as it provides a uniform current density distribution in the body segment and measures impedance with less electrode interface artifact and impedance errors. A new BIA instrument was designed and developed to assess simulated blood pooling of an aircraft pilot under G-stress. In the tetrapolar system, a pair of surface electrodes (I_1, I_2) is used as current electrodes to introduce a low intensity constant current at high frequency into the leg segment. A separate pair of electrodes (E_1, E2) measures changes accompanying physiological events. Voltage measured across E_1-E_2 is directly proportional to leg-segment electrical impedance (LEI) of the human subject. Use of surface circular flat electrodes as well as band type electrodes has been advocated. These types of electrodes insignificantly affect the EIP output. Therefore, four band electrodes were used for convenience. Current electrodes (I_1, I_2) were placed around the bottom of leg and below the knee joint to drive 3 mA at 20 K Hz of constant current onto the leg segment. Potential electrodes E_1–E_2 were placed towards the inner side maintaining a distance of 2 cm from each other. Constant spacing was kept between each current and voltage electrode for repeatable results. All four electrodes were connected to a Kelvin's Double Bridge to quantify impedance value. The Bridge was balanced by varying the resistive and capacitive component alternatively. Thereafter, the LEI of human leg were observed on the digital output display of BIA instrument.

SELECTION OF CURRENT AND FREQUENCY FOR BIA

The applied current levels from 20 μA to 10 mA rms at a frequency range of 20-100 K Hz have been used in the literature of the BIA technique (49). An adequate constant current source and high input impedance circuit should be used in conjunction with the tetrapolar electrode configuration to avoid the contact pressure effects at the electrode-skin interface. Anderson (12) has shown usefulness of BIA with an operating current of 1mA at 22 K Hz. Placement of four electrodes was optimized for impedance pneumography using the increased excitation current of 2 mA at 78.8 K Hz (50). Even 4 mA excitation current at 100 K Hz was employed in EIP to evaluate venovenous bypass flow (16). A number of other investigators have used different excitation current levels at different frequencies keeping 5 mA as the maximum harmless current intensity.

RECOMMENDED USES OF BIA

The different bioelectrical impedance analysis (BIA) methods are being recommended for a variety of clinical applications. Table 1 summarizes the different BIA methods and their recommended uses. The BIA technique has been demonstrated to be valuable because it is noninvasive, with multi-dimensional applications in diverse research fields and clinical settings. Thus far, BIA has been used to increase G tolerance of aircraft pilots in aerospace medicine, to estimate body composition, to determine total body water, to assess compartmentalization of body fluids, to provide cardiac monitoring, measure blood flow, and deep vein thrombosis.

Table 1. BIA methods and their recommended uses.

Method	*Model*	*Frequency(s)*	*Theory*	*Recommended Use*
Traditional BIA (Whole body)	Series	50 KHz	Body represents resistors (R) in series	To estimate TBW and FFM in healthy subjects.
	Parallel	50 KHz	Body represents R and capacitors (C) in parallel	To estimate intracellular water (ICW) and body cell mass (BCM)
High-low BIA	Dual frequency	5 & 500 KHz	Low and high frequency currents penetrate extracellular and intracellular body respectively	To estimate extracellular water (ECW) and total body water (TBW)
Multi-frequency BIA	Cole-Cole	Multiple	Plot of reactance versus resistance to identify theoretical value of R_0 and R_∞ at zero and infinite frequency.	To estimate ECW, ICW, and TBW; to monitor changes in the ECW/BCM and ECW/TBW ratios in clinical populations.
Multifrequenc y BIA	Hanai Mixture	Multiple	Tissue resistivity and body geometry alter Cole-Cole model	Based on model developed for use in suspended, spherical cells.
Segmental BIA	Series	Single or multiple	Body represented by up to five cylinders and resistance is measured separately	To measure fluid distribution or regional fluid accumulation in clinical populations.
Upper-body and Lower-body BIA	N/A	50 KHz	System employs stainless steel pressure-contact pad and plate electrodes	To estimate % BF in healthy subjects with normal hydration status and fluid distribution
Laboratory designed BIA	Series	20 KHz	Bridge circuit employed was balanced by varying R and C alternatively.	To predict and analyze simulated parameters of aircraft pilot or aviator under G stress.

USE OF BIA IN AEROSPACE MEDICINE

Khan (2) has described the use of BIA to predict electrical impedance parameters for simulated leg segment of aircraft pilot under G stress. The leg segment of aircraft pilots was simulated in a laboratory by placing a blood pressure cuff around the thigh of the human volunteers. When the cuff was inflated to pressures beyond venous pressure, but below arterial pressure, blood pooling in the leg below the cuff was recorded. The induced blood pooling of aircraft pilots was studied using a computer model and human model. In the computer model, the leg segment of the pilot was modeled as a cylinder containing a fat layer, bone (tibia and fibula), muscles, and blood volume present in arteries, arterioles, capillaries, venules, and veins. The finite element analysis (FEA) was applied to the 3D model of leg segment to compute electric field, current density patterns, and their vector plots. A specified voltage of 90 volts was applied between end points of the model using suitable boundary conditions.

Khan (2) further found a relative contribution of admittance for the leg constituents of fat, muscle, bones, and blood volume as 2.96, 75.58, 0.33, and 11.13 %, respectively. Analyses of the results were also carried out for following cases:

Case I: The resistivities of leg constituents, fat, muscle, bone (tibia and fibula,) and blood volume were taken as 1400, 200, 10,000 and 150 Ω-cm respectively. The LEI has been predicted to be 46.7 Ω, the value corresponds well with the experimental value of 46.0 Ω and a predicted value of

1.58 % higher. A ratio of current density between end points of the leg segment has been found to be 86.49.

Case II: The resistivity of particular leg constituent such as muscle was reduced to 175 from 200 Ω-cm keeping the blood volume and resistivity of other regions as in Case I. The purpose of Case II was to evaluate the effect of change in the conductivity of muscle on current density distribution. The electrical impedance of fat, bone, muscle, and blood volume was calculated and compared with predicted electrical impedance of leg constituents as in Case I. These parameters were also computed for the change of blood resistivity from 150 to 125 Ω-cm. The electrical impedance values of leg-constituents predicted for blood resistivity change and are shown in Figure1.

Case III: Blood pooling was simulated in the FE model for a 7 % increase in blood volume monitoring the length of the blood vessel and the same length of leg segment. The overall LEI was predicted to be 44.2 Ω. The electrical impedance of fat, bone, muscle, and blood volume, were calculated and compared with predicted electrical impedance of leg constituents as in Case I.

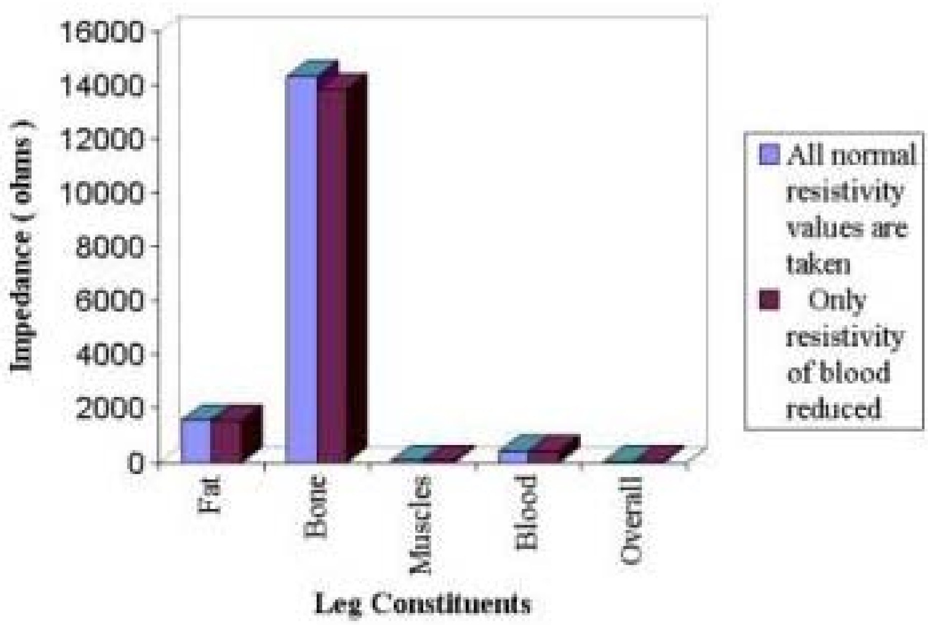

Fig.1 Electrical impedance of different leg constituents for physiologically normal and reduced resistivity blood from 150 to 125 ohm-cm.

Hatsell (51) derived an analogue of Cohn's theorem for bulk conductor using the Quasi-Power theorem and presented comments on rheoencephalography. Equation 1 states an analogue of Cohn's theorem applied to resistivity change that is frequently more convenient for research. Resistivities of leg constituents, such as blood and muscles, were reduced from 150 to 125 Ω-cm and 200 to 175 Ω-cm, respectively. The predicted impedance parameters satisfied the Cohn's theorem.

$$\left|\frac{\partial R_I}{\partial \ell_I}\right| \leq \frac{\left|J_m\right|^2}{(i_I)^2}\Delta V \qquad -------------- \quad (1)$$

Where $\partial R_I = Small \quad change \quad in \quad resistance.$

$\partial \ell_I = Small \quad change \quad in \quad resistivity \quad of \quad leg \quad constituent.$

$J_m = Maximum \quad current \quad density \quad within \quad region.$

$i_I = Input \quad current \quad to \quad the \quad region, \quad and \quad \Delta V = Change \quad in \quad volume.$

Khan (22) modified laboratory designed BIA model to test a simulated arm segment of aircraft pilot. The modified BIA instrument was used to make electrical impedance analysis of simulated arm blood pooling of the pilot under G-stress. The blood pooling was simulated in the computer model using finite element analysis (FEA). A commercial software package for FEA called NISA/EMAG was used to predict simulated blood pooling. Later on, the blood pooling an arm segment was simulated in the laboratory by placing a blood pressure cuff around the upper arm of human volunteers. When the cuff was inflated to pressures beyond venous pressure, but below the arterial pressure, blood pooling in the arm below the cuff was observed. This simulated blood pooling has been measured using electrical impedance plethysmography and oil filled plethysmography. Arm pain was also experienced during simulation of blood pooling and may be analyzed in the laboratory in future studies.

The overall electrical impedance of an arm segment has been predicted to be 83.1 Ω using finite element method. The value corresponds well with the experimental value of 81.5 Ω of the same dimensions, the predicted value being 1.94 % higher. The predicted value of electrical impedance on simulated blood pooling in the computer model lowered to 79.93 Ω. The impedance change was used to assess the blood pooling and found to be 14.90 ml. Various curves were plotted for all five sets of experimental data of simulated blood pooling of the arm segment assessed by electrical impedance plethysmography (EIP) and oil filled plethysmography (OFP). A linear correlation was observed between the values of simulated blood pooling measured by EIP and OFP. A correlation factor of 0.99 was found between blood pooling measured by both EIP and OFP techniques.

USE OF BIA TO MONITOR CARDIAC FUNCTION

An ideal method of assessing information on the cardiovascular system should be noninvasive, simple, atraumatic, inexpensive, reliable, and also applicable in long-term surveillance outside the cardiac monitoring laboratory. Use of BIA to monitor cardiac function is called a conventional impedance cardiography (ICG) technique. The ICG provides a single impedance tracing, from which parameters related to the pump function of the heart, such as cardiac output (CO), are estimated. Most of the properties of ICG render results superior to other methods. Kubicek (52) introduced the first practical method for determination of cardiac function in a clinical setting. Patterson (53) produced an original CO formula based on elementary physics. Several variations in electrode configurations and CO equations have been presented over the years to improve the method (54-56). Computer models designed to calculate the current flow in the thorax have been used more recently in examining the ICG measurement configurations, producing supporting data for the anticipated conception of the complexity of the signal origin (57-59).

Newman (60) conducted a review of a non-invasive assessment of stroke volume and cardiac output by impedance cardiography (ICG). They also described accuracy of ICG in terms of absolute value of stroke volume (SV) and CO. Kubicek (61) developed an equation for stroke volume that has become widely used and accepted. The Kubicek equation is given by the following expression:

$SV = \rho.[L^2]/[Zo^2].dZ/dt.t$ --------------------- (2)

Where SV= stroke volume (mls), ρ = electrical resistivity of blood (Ω-cm), L = distance between inner electrodes, Zo = Average thoracic impedance (Ω), dZ/dt = peak value of dZ/dt waveform (Ω/s), t = ventricular ejection time (s).

Several authors have offered refinements in the Kubicek's original equation and modified Kubicek model. Other equation used to determine SV is that of modified Sramek equation generally known as Sramek-Bernstein equation. Its expression is as follows:

$SV = \delta.[(0.17\ H)^3/4.2].\ dZ/dt.\ t\ /Zo$ ------------------ (3)

Where δ = Bernstein scaling factor or weight correction factor = $\beta.\ (W_{OBSERVED} / W_{IDEAL})$, W= subject weight, β = relative blood volume index and its details in Bernstein's original paper (Bernstein (54).

Once SV has been determined, CO can be easily calculated according to the following expression:

$CO = SV * HR$ ----------------------------------- (4)

Where HR = heart rate

CO can be determined for every heart-beat. This ability to determine SV and CO on a beat-to-beat basis is one of the most appealing and important advantages of ICG.

Gilbert (18) managed congestive heart failure and the effect of prescribed ACE inhibitors, β-blockers, and diuretics on cardiac functions, such as cardiac output (CO), systemic vascular resistance (SVR), and stroke volume (SV). The thoracic electrical bioimpedance (TEB) technique is nothing more than BIA applied to the thorax. An increase in thoracic fluid content detected by TEB can warrant a prompt increase in diuretic dosage to treat fluid retention associated with the initiation of β-blockers (62). Descriptions of only three out of eight subjects are presented in Table 2 due to a word limit for review papers.

An important question surrounding ICG concerns how well it compares with conventional technique of thermodilution. There are a number of studies that have attempted to answer this question (63). The conventional method that determines stroke volume (SV) and cardiac output (CO) rely on invasive maneuvers and has significant risk of experimental morbidity. Thermodilution has become widely accepted as an accurate means of determining CO, particularly in coronary care clinical settings. One of the disadvantages of this and other invasive methods is that they are capable of providing only intermittent estimates of CO. On the other hand, ICG provides beat-to-beat assessment of CO noninvasively. Figure 2 shows the results of a number of studies comparing ICG with the thermodilution invasive technique in the assessment of stroke volume, cardiac output, and cardiac index (37,64-72).

Table. 2. Response of pharmacologic therapy using TEB data on patients during 1998.

Case History	*Date*	*CO L / min*	*CI $L/m^2.min$*	*SVR $dy/sec.cm^{-5}$*	*BP/ MAP mmHg*
54 yr male having CHF with shortness of breath, 10 mg Enalapril, an ACE inhibitor, twice daily. After TEB data, ACE inhibitor dosage was doubled to 20 mg twice daily.	June 19	3.9	-	1977	96 MAP
TEB enabled physician to target drug therapy and evaluated patient's response	June 26	5.9	-	835	61 MAP
63 yr male with coronary artery disease with fatigue, β-blockers. After TEB data, inhibitor dosage of 10 mg was initiated.	April 24	3.4	-	1870	85 MAP
Patient has no symptoms of fatigue. After TEB data, dosage upward to 20 mg.	May 8	6.0	-	1034	83 MAP
No symptoms and proved an excellent response to pharmacologic therapy.	July 9	7.6	-	722	75 MAP
71 yr male with severe CHF. Blood pressure correlated poorly with other hemodynamic indices in patients with heart failure. The cardiac index (CI) and SVR values from the TEB data provided objective goals of therapy.	July 9	-	2.3	1525	88/60
	July 23	-	1.8	1960	92/60
	Aug 4	-	2.2	1614	98/60
	Oct 6	-	1.8	2335	94/60
	Oct 20	-	2.3	1813	102/72
	Nov 17	-	3.3	1318	104/78
	Dec 1	-	2.3	1675	94/64

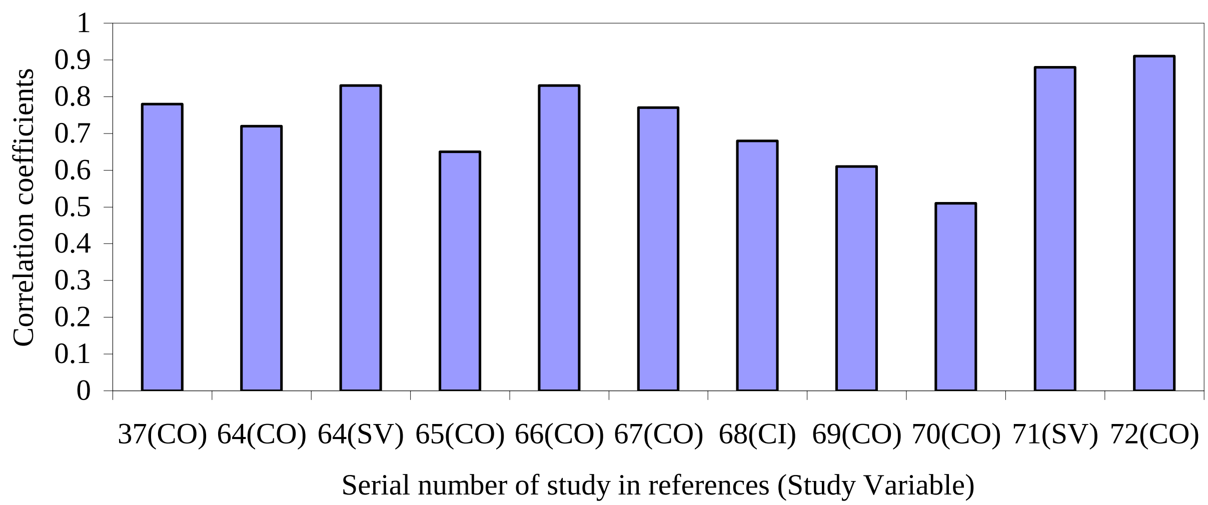

Fig. 2 Comparison of ICG with thermodilution invasive technique in assessment of SV, CO, and Cardiac index (CI).

The broad range (0.41 to 0.91) of correlation coefficients reflects the wide diversity of methodologies employed with different subject groups and BIA techniques used. It has been found that ICG is a reliable means of monitoring CO. Similarly, others have concluded that ICG is a satisfactory method with a probability of error similar to other established techniques. But a few concluded that BIA technique was inadequate due to low reliability.

BODY COMPOSITION DETERMINATION

BIA was first used for body composition analysis between 1960 and 1970. Thomassett (73) developed a method for estimating total body water (TBW) and extracellular water using a two-needle electrode technique. This approach has not become popular because of the patient's discomfort. Hoffer (74) and Jenin (75) developed a four surface electrode method for the study of body composition. They reported a strong relationship between total body impedance measures and TBW suggesting that this BIA method may be a valuable tool for analyzing body composition in the clinical setting. Nyboer (76) extended the tetrapolar electrode technique to estimate fat free mass (FFM) and percent body fat. The present use of BIA to estimate body composition is based upon greater electrolyte content and conductivity of FFM as compared to adipose tissue or bone (72,77) and upon geometrical relationship between impedance and volume of the conductor (78). A number of researchers have developed BIA prediction equations for TBW, FFM, and % BF. Houtkooper (79) summarized 55 BIA prediction equations (18 for TBW, 29 for FFM, 8 for % BF or fat mass). They reported that the typical prediction estimating error (SEE) ranged from 0.9 to 1.8 kg TBW, 2.0 to 3.0 kg FFM, and 3.0 % to 4.0 % BF in adults.

It is generally assumed that an electrical current at 50 KHz is conducted by electrolytes contained in the body water. An excitation current (200-800 micro ampere) is applied at current electrodes on the hand and foot, and a voltage drop due to impedance is detected by the voltage electrodes on the wrist and ankle. Commonly used population specific and generalized BIA prediction equations are available to estimate body composition and may be used to obtain R and Xc directly from BIA analyzer. Baumgartner (80) and Spinale (81) also used BIA methods for determining body composition at research and clinical levels.

The composition of leg sections was predicted with anthropometry and bioelectrical impedance analysis using magnetic resonance imaging (MRI) as the reference (82). Impedance measurements obtained from a multi-frequency BIA model (Make: SFB2, SEAC, Brisbane, Australia) to estimate muscle and adipose tissue (AT) mass within the thigh and calf accounting for specific resistivities of all constituent tissues at 50 KHz. The multi-frequency BIA model reads to one decimal place in the range of 10 to 2000 Ω, accuracy is within 1% as claimed by the manufacturer, and has been verified experimentally (83). The mean ± SD impedance for a 20 cm thigh section was 22.8 ± 5.3 Ω and that for a 10 cm calf section was 25.2 ± 7.0 Ω. Table 3 shows that there was a small mean overestimation of thigh muscle and underestimation of AT, both for cross sectional area and volume, by the fundamental BIA method compared with the MRI reference measures. Whereas mean calf muscle values were slightly underestimated and AT values overestimated.

Table 3. Percentage change for area and volume of muscle and AT measured by MRI and BIA in thigh and calf sections

	MRI	*BIA*	*% change*
Thigh			
Muscle (cm^2)	123.5	128.9	- 4.37
Adipose Tissue (cm^2)	76.8	71.4	4.37
Muscle volume	2.30	2.58	-12.17
AT volume	1.68	1.43	14.88
Calf			
Muscle (cm^2)	62.7	57.1	9.09
Adipose Tissue (cm^2)	26.5	36.2	-36.60
Muscle volume	0.60	0.57	5.0
AT volume	0.26	0.36	-38.46

SUMMARY

The results of studies conducted on BIA show that simplicity and non-invasiveness of the technique are two of its most significant advantages. The shortcoming of BIA has been addressed using computer modeling and predicted BIA equations appropriately. The BIA technique with a computer model using the finite element software package has been investigated in aerospace medicine. The study conducted on the simulated leg segment of aircraft pilot under G stress has reported the following:

1. Relative contribution of different leg constituents to the overall leg segment electrical impedance (LEI).
2. Effect of change in resistivity of a particular leg constituent on the overall LEI keeping other parameters constant.
3. Effect of blood pooling on the resistivities of leg constituents.

The computer model of BIA also computed admittance of leg constituents such as fat, bones, muscles, and blood volume. The predicted leg segment electrical impedance (LEI) value is also verified experimentally by BIA technique with tetrapolar electrodes system.

BIA offers a variety of applications for the noninvasive measurement of body composition, including % BF, FFM, TBW, and compartmentalization of body fluids. The BIA technique has been validated by many investigators and is being used extensively for the assessment of TBW and FFM in healthy adults and children. The operator should be familiar with the principles and applications of BIA for the effectiveness of the technique. Additionally, the subject's height, weight, standardized conditions with respect to body position, previous history, dietary intake, and skin temperature, must be assessed with consistence and accuracy. Collectively, minor errors in these measurements may result in significant error in the results of BIA methods.

The development of new commercial BIA models has extended clinical applications of BIA greatly. Therefore, BIA methods have relevance in every direction of research and clinical settings with multi-dimensional applications.

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