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Electrical Bioimpedance: Methods and Applications

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Abstract

Bio-electrical impedance analysis (BIA) is an inexpensive, quick and non-invasive technique for measuring body composition. Unlike other various complicated methods, bioimpedance measurement technique is simple and less time consuming for various applications including medicine, biotechnology and security system. BIA is a promising method for predicting changes in body composition and has the potential to replace the conventional methods of detection and diagnosis of diseases in near future. The results are reproducible and rapidly obtained. However it suffers from a lack of standardized methods and quality control procedures. This paper describes the theory and practical implementation of various methods to measure complex impedance of biological tissues. By reviewing the current development status of bioimpedance technology, the paper analyses the future emphasis of development and technology direction, in order to make bioimpedance technology gain wider clinical applications.

1. Introduction

Electrical Bioimpedance Monitoring is an emerging technique for biomedical research and for medical practice. It constitutes one of the diagnostic methods based on the study of the passive electrical properties of the biological tissues. These properties have been the object of study since Luigi Galvani (1737-1789) discovered that while an assistant was touching the sciatic nerve of a frog with a metal scalpel, the frog's muscle moved when he drew electric arcs on a nearby electrostatic machine. However, it was not until the end of 19thcentury [1]that these properties started to be measured; thanks to the development of new instrumentation and the setup of the electromagnetic field theory by James Clerk Maxwell (1831-1879).

The practical use of the electrical passive properties started in the middle of the 20thcentury.Different properties and techniques resulted in a collection of methods that are now used for multiple applications. Usually, these methods have three advantages in common i.e. require low-cost instrumentation, easily applicable in practice, enable on-line monitoring.

2. Equivalent Circuit of A Biological Tissue

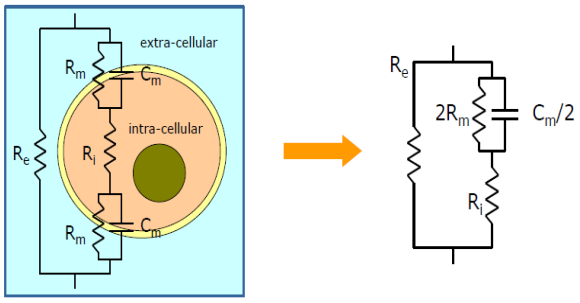

Fig: 1. Equivalent Circuit of a Cell

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It is desirable to depict equivalent circuit models of the tissue bio impedance because they are useful to attribute a physical meaning to the impedance parameters. With the help of the main constituents of the cell, a simple electrical model for the cell can be induced (see the figure below). The current injected into the extracellular medium can flow through the cell across the bi-layer lipid membrane (BLM) (C_m) or across the ionic channels (R_m) or can circulate around the cell (R_e). Once the current is into the cell it 'travels' trough the intracellular medium (R_m) and leaves the cell across the membrane (R_m‖C_m) [2].

The circuit on the right is equivalent to the left model after performing some simplifications. The same simplifications can be applied to reduce a tissue composed by many cells to a single cell equivalent circuit. Usually, the membrane conductance is very low and R_m is ignored. In this case, the equivalent circuit is very simple and a single dispersion exists. At low frequencies (<1 kHz) most of the current flows around the cell without being able to penetrate into the cell. At high frequencies (> 1 MHz) the membrane capacitance is no impediment to the current and it flows indiscriminately through the extra and intracellular media [3].

3. Frequency Dependency: The Dispersion Windows

Living tissue is considered as a dispersive medium: both permittivity and conductivity are functions of frequency. This observed frequency dependence is denominated dispersion and it arises from several mechanisms (identified and named three major dispersions: α-, β-, and γ-dispersions. Another subsidiary dispersion was noted at first in 1948 and later identified and termed δ-dispersion.

A. α-Dispersion

The understanding of the α-dispersion remains incomplete. A multitude of various mechanisms and

elements contribute to this frequency dependence, three well-established ones being [4]:

- The frequency-dependent conductance of the channel proteins present in the cell membrane.
- The frequency dependence of the surface conductance and capacitance largely caused by the effect of the counter-ion atmosphere existing near charged cell surfaces.
- The effect of the endoplasmic reticulum, when it exists.

B. β-Dispersion

The β-dispersion is caused mostly by the cellular structures of tissue, due to the low conductivity of the plasma membrane of the cells forming the tissue. It takes time to charge the membranes through the conducting mediums, the extracellular and intracellular fluids. The introduced time constant is determined by the plasma membrane capacitance, cell radius and the fluid conductivities. Contributing to the β-dispersion caused by the cell structure, there are other tissue constituents: proteins, amino acid residues and organelles [5].

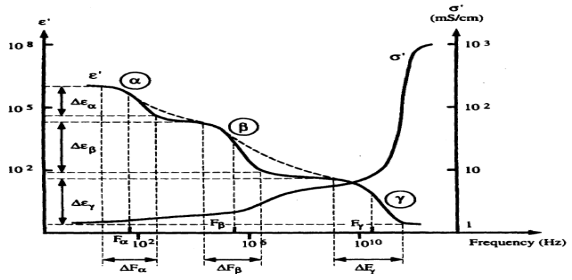

Fig: 2. Dispersion of Conductivity and Permittivity

C. γ-Dispersion

This frequency dependence is caused by the high content of water incell and tissue. Tissue water is identical to normal water, which relaxes at20 GHz, except for the presence of proteins and amino acids, etc. Tissuewater displays a broad spectrum of dispersion from hundreds of MHz tosome GHz.

D. δ -Dispersion

This is a weak subsidiary dispersion effect observed around 100 MHz caused by proteins bonded to water.

4. Bia Instruments

BIA instruments have been classified into different types of models:-

A. 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 √(R^2+〖X_c〗^2). Whole body bio-impedance (Z, R andX_c) 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 [6-7].

B. 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)+〖X_c〗^(-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. The values of R_p andX_(C_p)of the parallel model may be transformed from the series model[7-8].

$$R_p=R_s+[(X_(C_s))^2/((R_s))] \quad (1)$$

$$X_(C_p)=X_(C_s)+[(R_s)^2/((X_(C_s)))] \quad (2)$$

C. Segmental BIA Model

The forearm only account for slightly more than 1 % of body weight, but contributes 25 % to whole body impedance. 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 described the theory of segmental BIA and placement of electrodes [9-10]. Cornish 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.

D. 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 previous model works reasonably well for dilute cell suspensions. However, the tissue bioimpedance tends to be more complex than that and it is not unusual to observe two superimposed dispersions in the frequency band from 10 Hz to fewMHz.

An example is the myocardial muscle[2]. This fact means that another resistance-capacitance couple should be added to mimic the bioimpedance results. In the case of the myocardium, this second dispersion is attributed to the significantpresence of gap junctions[11].

Furthermore, it is necessary to substitute the capacitance in the previous dispersion models by a part called Constant Phase Element (CPE) in order to fit accurately the modeled impedance values to the actual bioimpedance measurements. The CPE is not physically realizable with ordinary lumped electric components but it

is usually described as a capacitance that is frequency dependent. The impedance of the CPE is:

$$Z_{CPE} = \frac{1}{(j\cdot 2\pi\cdot f\cdot C)^{\alpha}} \quad (3)$$

The α parameter usually is between 0.5 and 1. When it is 1 the behaviour of the CPE is exactly the same of an ideal capacitance.

The physical meaning of the CPE is not clearly understood. Some authors suggest that α can be regarded as a measure of a distribution of resistance-capacitance combinations. That is, the tissue is not homogeneous and the sizes of the cells are randomly distributed, thus, the combination of the equivalent circuits can differ from the simple RC model.

When the CPE is included in the simple bioimpedance equivalent circuit (a resistance-capacitance series combination in parallel with a resistance), the expression of the impedance is:

$$Z = R_{\infty} + \frac{\Delta R}{1+(j\cdot 2\pi\cdot f\cdot \tau)^{\alpha}} \quad (4)$$

This expression, called Cole equation, was found by Cole in 1941 and is used by most authors in the bioimpedance field to describe their experimental results. Hence the tissue bioimpedance is characterized with four parameters: R∞, ΔR, α and τ. The parameter R∞ represents the impedance at infinite frequency (only resistive part), R0 (= R∞ + ΔR) is the impedance at frequency 0 Hz, τ is the time constant (ΔR.C) and α is the parameter of the CPE.

The resistive values (R∞, ΔR, R0) are usually scaled to resistivity values by using the cell constant. The αand τ are not dependent on the cell dimensions and, therefore, do not need to be scaled.

In the representation of the Cole equation on the Wessel diagram, the arc is no longer a semicircle centred in the real axis. Instead of that, the semicircle centre is above the real axis and the arc is apparently flattened. That displacement depends on the value of α (α =1 ⇒ semicircle centred on the real axis).

The following Wessel diagram shows an actual bioimpedance multi-frequency measurement (bioimpedance spectrometry) from a rat kidney. Observe that the Cole model fits the actual data and that it is equivalent to a semicircle centered below the real axis (take into account that the imaginary axis has been inverted)

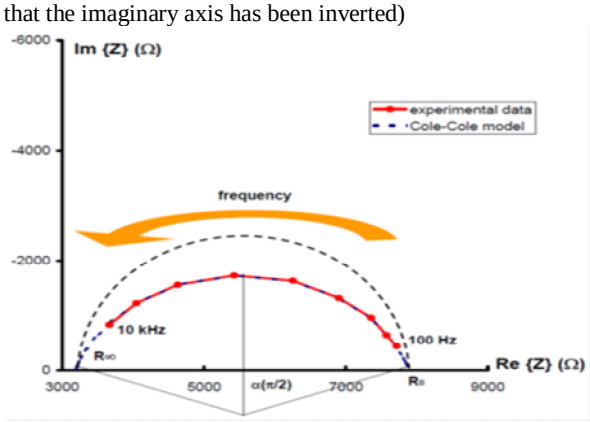

Fig: 3. Wessel diagram of an actual bioimpedance measurement and the superimposed Cole model results.

In the case that two or more dispersions are observed (e.g. in the myocardium), the above equation is expanded to include the model of eachdispersion.

$$Z = R_{\infty} + \frac{\Delta R_1}{1+(j\cdot 2\pi\cdot f\cdot \tau_1)^{\alpha_1}} + \frac{\Delta R_2}{1+(j\cdot 2\pi\cdot f\cdot \tau_2)^{\alpha_2}} + \cdots \quad (5)$$

Table: BIA methods and their recommended uses.

Method	Model	Frequency	Theory	Recommended use
Tradition-al BIA	Series Parallel	50 KHz 50 KHz	Body represents resistors(R) In series Body represents R and capacitors	To estimate TBW and FFM in healthy subject To estimate intracellular water and body cell mass
High-low BIA	Dual frequency	5 & 500 KHz	Low and high frequency currents penetrate extracellular and intracellular body respectively	To estimate extracellular water and TBW
Multifrequency BIA	Cole-Cole	Multiple	Plot the reactance versus resistance to identify theoretical values of Ro 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
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 population.

5. Applications

A. 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. Kubicekintroduced the first practical method for determination of cardiac function in a clinical setting. Patterson 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.

Newman [12] et al. 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 developed an equation for stroke volume that has become widely used and accepted. The Kubicek equation is given by the following expression:

$$SV = \rho.[L^2]/[Z_o^2].dZ/dt.t \quad (6)$$

Where SV= stroke volume (mls), ρ = electrical resistivity of blood (Ω-cm), L = distance between inner electrodes, Z_0 = Average thoracic impedance (Ω), $\frac{dz}{dt}$= peak value of dZ/dt waveform (Ω/s), t = ventricular ejection time (s)[13]. Several authors have offered refinements in the Kubicek's original equation and modified Kubicek model [14]. Other equation used to determine SV is that of modified Sramek equation generally known as Sramek-Bernstein equation. Its expression is as follows [15]:

$$SV = \delta.[(0.17H)^3/4.2].dZ/dt.t/Z_o \quad (7)$$

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.CO can be easily calculated according to the following expression:

$$CO = SV * HR \quad (8)$$ Where HR = heart rate

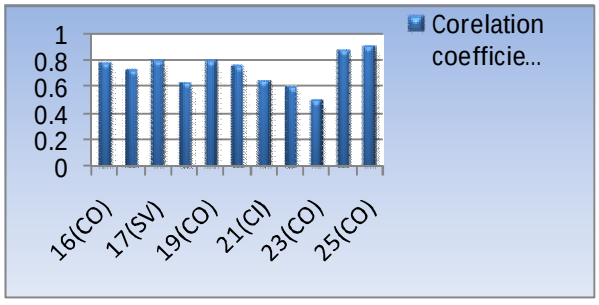

Fig: 4. Comparison of ICG with Thermo Dilution Invasive Technique in Assessment of SV, CO, and Cardiac index (CI)

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.

B. Body Composition Determination

BIA was first used for body composition analysis between 1960 and 1970. Thomassett [26] 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. Hofferand [27] Jenindeveloped 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[28-31].

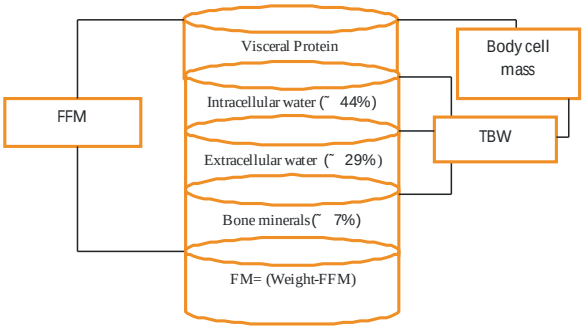

Fig: 5. Body Composition Compartments

A number of researchers have developed BIA prediction equations for TBW, FFM, and % BF. Houtkoopersummarized 55 BIA prediction equations (18 for TBW, 29 for FFM, 8 for % BF or fat mass). They reported that the typical prediction estimating error 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 amperes) 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 X_c directly from BIA analyzer. Baumgartner and Spinalealso 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. The multi-frequency BIA model reads to one decimal place in the range of 10 to 2000 Ω, accuracy is within 1%, and has been verified experimentally. 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 [32-33].

A. Detection of Fake Fingers in Security System

According to a survey, 80% of security systems can be easily fooled with fake fingers. Fingerprint recognition

system is now not only used in high security application but also used in consumer applications [34].

A proper method would be to use a live finger detection technique based on simultaneous measurement of impedance of various skin layers.

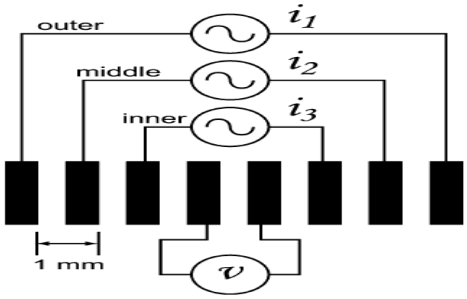

Fig: 6. Electrode Array with Three Alternative Current Injecting Electrode Sets and one Set of Voltage Pickup Electrodes

The figure shows that the differential output voltage is connected to an impedance analyzer, and internal oscillator is connected to three other electrode pairs. The analyzer performs three successive four electrode measurements. In this method, three frequency scans were done using root mean square voltage of 10mV at different frequencies from 10kHz to 1 MHz. Inner electrode produces a higher impedance dominated by the properties of stratum corneum, while those electrodes which are far apart allow more current through them, thus lesser impedance.

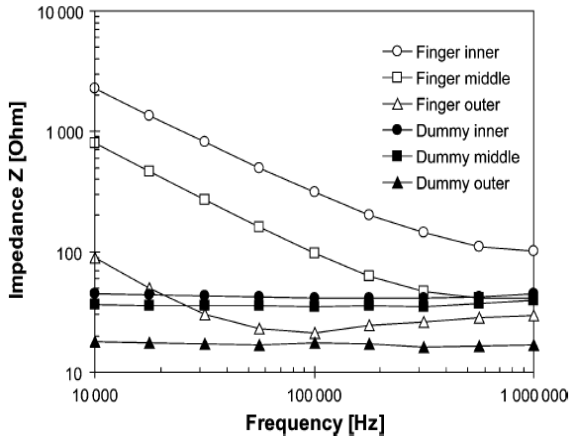

Fig: 7. Measured Impedance Modulus Response for one Live Finger and Fake Finger

Sofinger print recognition along with a frequency analyzer using electrical bio impedance of different skin layers provides a reliable method for the detection of a fake finger in biometric fingerprint [35].

6. Conclusion and Future Scope

BIA-applied currents flow throughout all conducting tissue within the body and thereby do not uniquely reflect the properties of any single tissue, compartment, or region. BIA measurements are linked with output variables such as TBW or body fat through statistical association rather than on the basis of biophysical principles. BIA values are affected by numerous variables including body position, hydration status, consumption of food and beverages, ambient air and skin temperature, recent physical activity, and conductance of the examining table. Reliable BIA requires standardization and control of these variables.

A specific, well-defined procedure for performing routine BIA measurements is not practiced. Therefore, it is recommended that a committee of appropriate scientific experts and instrument manufacturers be formed with the goal of setting instrument standards and procedural methods.

Instruments used for BIA should provide electrical specifications and calibration verifications that confirm a measurement accuracy within ± 1 percent over the broad range of resistance expected for biological systems. The instrument should report the primary resistance and, if measured, reactance values and the frequency(s) at which these measurements were made.

Calculations of body composition parameters from the basic electrical measurements should include population-specific equations and report the standard errors of the estimate for the individual.

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