Low-Cost Body Impedance Analyzer for Healthcare Applications

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Abstract – **Bioimpedance has been widely used in many health areas. The ability of the human body cells, as the response for the alternate electric current flow, can provide valuable information about health status of the subject. This work presents a low-cost body impedance measuring system. The system is composed by the impedance meter AD5933, a four-electrode front-end circuit, a microcontroller system and a computer system for processing, visualization and data storage. The developed system calculates the resistance, reactance and phase angle (PA) from measured impedance spectra. Two subjects were assessed and the bioimpedance data was compared with data encountered in the literature. Predictive equations were used to calculate fat-free mass (FFM), fat mass percentage (%FM) and total body water (TBW). Preliminary results describe consistent with the reference values in the literature, indicating that the developed device is proper to body impedance measurement. The body impedance analyzer developed in this work was conducted according to the requirements of healthcare applications, such as portability and low cost. It can be concluded that the developed system can be used for body composition assessment over a wide aging range.**

Keywords – **Impedance Analyzer, AD5933, Body composition.**

I. Introduction

The human body is composed by about 60 to 100 trillion cells that are grouped by function to form tissues and organs [1]. The health status of the body depends on the cell functions. Most laboratorial imaging diagnosis applies invasive and expensive technologies in order to assess the state of the body health. Bioimpedance Analysis (BIA) has been widely used as a noninvasive and low cost alternative in many medical areas [2,3,4]. The cells react to the alternate current flow according to their health status. The technique consists of injecting an alternate current of low amplitude (≤ 1 mApp), over a frequency range of tens of kHz, into the body and measures the resulting voltage. The voltage and current ratio (V/I) is a complex impedance (Z) composed by a resistance and a capacitive reactance part. The resistance (R) depends on the electric conducting characteristics of the body fluids. The capacitive reactance (Xc) is caused by the cell membranes, actuating as capacitors that change with the frequency. Figure 1 illustrates the current path through the cells and their respective electrical model. At lower frequencies, cell membranes block the current flow. At higher frequencies (≥ 50 kHz), the current also flows through the cell membranes and then it causes a delay in the current phase due to capacitive effects.

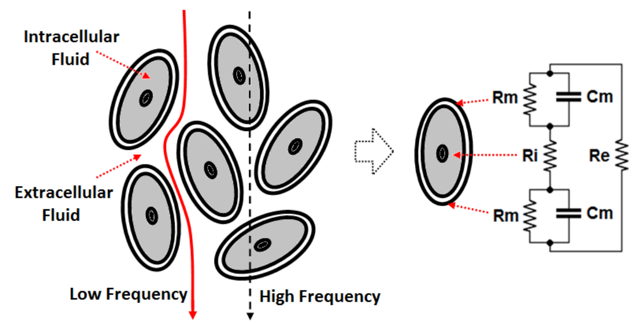

Fig. 1 Electrical current path through the cells, where Rm is the membrane resistance, Cm is the membrane capacitance, Ri is the intracellular resistance and Re is the extracellular resistance

Researches have associated BIA data with many diseases, which are caused by cells modification and then it changes the body impedance [5,6]. The phase angle is obtained from the geometric relationship between R and Xc, which has been used as an important indicator of cellular integrity. PA below 5% indicates some damage to the selective permeability of cell membranes. This characteristic is compatible with cell death caused in some types of cancer [7]. PA higher than 12% indicates large amounts of body mass and intact cell membranes, which is related to healthy subjects. It is shown in Figure 1 that, at low frequency, current does not flow through the cellular membranes, where extracellular fluid information is obtained. On the other hand, at higher frequencies, the current flows through the extracellular and intracellular fluids, allowing the determination of its reactance [2].

In order to better characterize tissue, a wide frequency range is required, as for example the body mass composition. Body mass is composed of high-conductivity tissues (lean body mass) and low conductive tissues (body fat). Excess body fat can lead to obesity and therefore increase the risk of serious health complications, such as heart disease and stroke [3]. BIA technologies used in body mass may vary according to the number of electrodes, signal excitation (voltage or current) and frequency range. Most

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system use single-frequency excitation at 50 kHz (SF-BIA). Multi-frequency systems (MF-BIA) use few discrete frequency excitation ranging from 1 to 500 kHz in a four-electrode configuration [8].

The objective of this work is to develop a low-cost system for body impedance measurement in healthcare applications.

II. METHODOLOGY

In order to measure the body impedance, it was developed a homemade hardware and software. The system, shown in Figure 2, consists of the impedance meter AD5933 (from Analog Devices), an Analogue Front-End (AFE) circuit and a microcontroller for the computer interface.

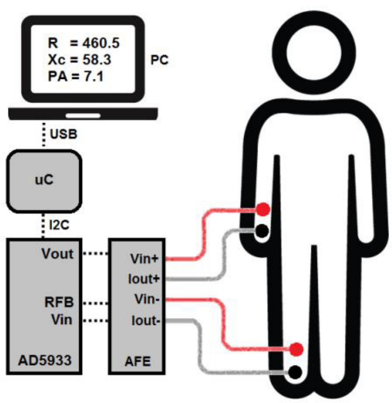

Fig. 2 Schematic of the body impedance analyzer, where PA is the phase angle, Iout+ is the inject current and Iout- is the return current.

A. System main characteristics

AD5933 – It is a high precision impedance meter, which includes frequency generator (from 1 to 100 kHz), digital-to-analog converter, analog-to-digital converter (12 bits) at 1 MSPS, digital signal processor (DSP) and auxiliary circuits [9]. The impedance data are processed by using a Discrete Fourier Transform (DFT) algorithm, which returns both real and imaginary part of the measured impedance at each selected frequency. Data are accessed by the I2C interface.

Analog Front-end – The output signal excitation of the AD5933 is a sinusoidal constant amplitude voltage with a DC level. It was manufactured to perform a two-electrode measurement. In order to use the AD5933 for human tissue measurements, it was used a four-electrode AFE circuit which complies according to safety regulations set by IEC-60601. A high pass filter removes the DC level of the reference voltage (V_{out}) to be converted into a current by a mirrored-modified Howland current source [10]. The output current is set to 800 µA over a frequency range of 5 to 100 kHz. The voltage across the load is measured by an instrumentation amplifier (INA118) and read by the AD5933.

Microcontroller and Computer Systems – The Arduino Nano board (from Atmel) is used as the interface between AD5933 (I2C) and the computer (USB). The embedded software in the microcontroller executes special commands to configure operating parameters of the AD5933 and data read are sent to the computer. The software allows the setting of some parameters of the AD5933, such as frequency sweep; number of collecting data, time between data collection, V_{out} amplitude and resistor calibration value. Impedance data are processed, converted in terms of R, Xc and PA values, which are stored in a text format.

B. Bioimpedance measurements

During the calibration process it is used a resistive load of 1 kΩ in order to calculate the system gain. Electrodes are placed in the right hemi-body of the subject and at the dorsal region of the foot and hand (see Figure 2). Current electrodes are connected at distal positions (near the toes) and the voltage electrodes are placed in the proximal positions away from the current electrodes at a distance of approximately 5 cm. The subject is rested in a supine position for 5 minutes before data acquisition. Also, the arms forms a 30° angle with the torso whereas the legs an angle of 45° between each other [8]. It was performed 5 measurements with an interval of 30 seconds between each other. Both mean R and Xc values are calculated in the frequency range from 5 to 100 kHz at 1 kHz intervals.

C. Body Composition

Both R and Xc values are used to calculate the body components, such as FFM, %FM and TBW. Two predictive equations from literature were used in this work, as shown in equations 1 and 2. The first one was obtained by using gold standard instruments, such as dual energy x-ray absorptiometry [11], which evaluated the bioimpedance and DXA data of 5225 healthy white subjects aging from 15 to 98 years old by determining the FFM (kg).

$$FFM = -4.104 + \frac{0.518 \times Height^2}{R_{50}} + 0.231 \times Weight + 0.130 \times Xc_{50} + 4.229 \times Sex \quad (1)$$

Where *Height* is expressed in centimeters, *Weight* in kilograms, both R_{50} and Xc_{50} values are at 50 kHz and *Sex* is 1 for male and zero for female.

The second prediction equation used a database from five North American research centers containing the body composition of 1774 white subjects aging from 12 to 94 years old by predicting the TBW [13].

$$TBW = 1.203 + \frac{0.449 \times Height^2}{R_{50}} + 0.176 \times Weight \qquad (2)$$

Both results from prediction equations are compared to the measured data at 50 kHz by using the proposed BIA system.

III. Results

In order to validate the proposed BIA system, two healthy male white subjects were assessed. Table 1 shows the anthropometric characteristics of the subjects, as well as the measured impedance values and the literature ones based on the predictive equations 1 and 2.

Table 1 Anthropometric and bioimpedance characteristics at 50 kHz in comparison to the predictive equations 1 and 2 (Mean ± STD)

	Subject 1	Subject 2	Ref. [11]	Ref. [13]
Age (year)	45	47	45 – 54	40 – 49
Height (cm)	180	177	174.0 ± 6.4	178.9 ± 8.1
Weight (kg)	84.5	77.2	73.0 ± 9.2	82.2 ± 11.7
BMI (kg/m^2)	26.1	24.5	24.4 ± 2.6	25.7 ± 3.3
FFM (kg)	59.6	60.2	58.1 ± 5.1	61.7 ± 7.4
%FM	29.4	21.9	20.3 ± 5.1	24.3 ± 7.8
TBW (liter)	41.3	44.0	–	45.7 ± 6.7
R (Ω)	575.4	481.2	469.0 ± 43.0	–
Xc (Ω)	83.1	66.0	58.8 ± 8.4	–
PA (degree)	8.2	7.8	7.2 ± 0.9	–

Figures 3, 4 and 5 show the frequency response of the measured R, Xc and phase angle from two subjects, respectively. It can be observed in figure 3 that the spectra of the resistance R from subject 1 are higher than the subject 2, which might indicate a greater amount of fat mass. It can be observed in figure 4 that the reactance Xc represents approximately 14.4 and 13.7%, respectively, from subjects 1 and 2. In terms of phase angle from figure 5, it can be observed higher PA values in subject 2, which is compatible with BMI from literature [12].

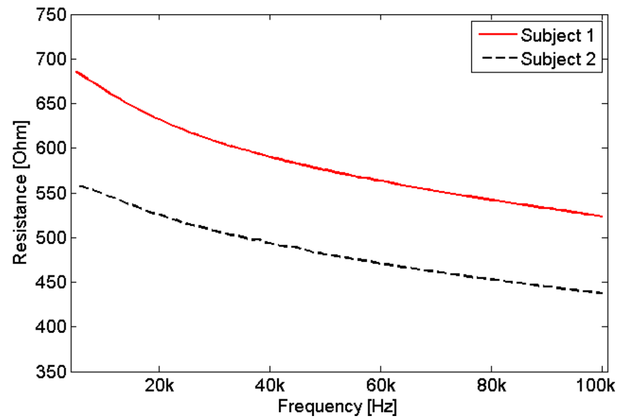

Fig. 3 Resistance R as a function of frequency from subjects 1 and 2

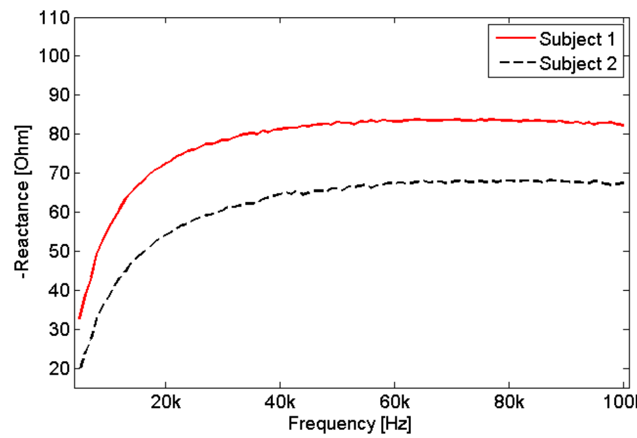

Fig. 4 Reactance Xc as a function of frequency from subjects 1 and 2

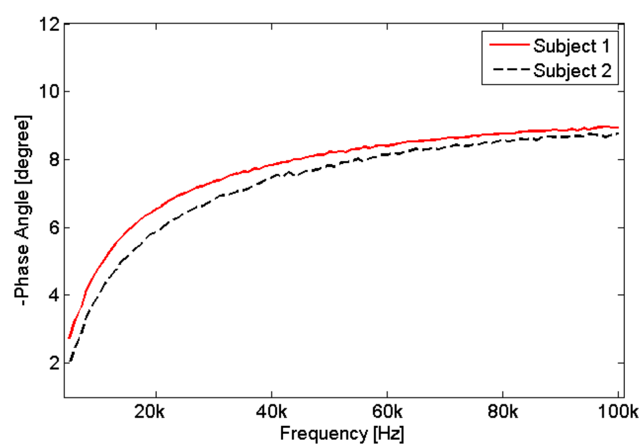

Fig. 5 Phase Angle as a function of frequency from subjects 1 and 2

IV. DISCUSSIONS

BIA is a simple and low-cost technique for body composition diagnosis. The correct use of R and Xc with the predictive equations is important for calculating the body components, such as FFM and TBW. However, the estimation of the body composition by BIA depends on the collected data from DXA, for example. Although the predictive equations can change according to target population, there are many works in the literature that show equations with good correlation between bioimpedance and standardized methods [14].

The predictive equations used in this work presented small errors over the age range. FFM, %FM and TBW, based on measured R and Xc, were consistent with the ones reported in the literature [11,15]. In addition, other works have indicated that the phase angle is important for evaluating health status [7,16]. It is important to emphasize that PA value depends only on the R and Xc measurements and it is free from the statistical regression effects contained in the predictive equations. Barbosa-Silva *et al* (2005) determined PA values from 6.5 to 9.0 degrees of healthy adults aging from 40 to 49 years old. These findings are compatible with the results of this work. Caution has to be taken due to the fact that bioimpedance is a limited technique for body composition due to population differences. Even so, it is still considered an important tool for health professionals [8].

V. CONCLUSION

Bioimpedance is a non-invasive, safe and relatively inexpensive technique to assess body composition of both healthy and illness patients. The body impedance analyzer developed in this work was conducted according to the requirements of healthcare applications, such as portability and low cost. These characteristics are considered very important for large-scale use, benefiting the National Health System (NHS) and homecare users. It can be concluded that the developed system can be used for body composition assessment over a wide aging range.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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