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Assessment of Human Arm Bioelectrical Impedance using Microcontroller Based System

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Abstract: In a wide field of research, the devices available based on long-established methods for measurement of bioelectrical impedance are large in size, expensive and low inaccuracy. In this research, a system is developed for the measurement of the segmental bioelectrical impedance of the human body with high accuracy and small of a size. The system also consists real time measurement with cloud interference, which makes it helpful for the subjects who want to check your measurements quickly or online. The developed method uses multi-frequency to measure segmental bioelectrical impedance that follows four electrodes segmental measurement techniques and is equipped as an impedance analyzer and a touch screen. Multi-frequency signals flow to the human body to measure bioelectrical impedance and also compare data measured by the developed device with the standard device. Data have been collected through the developed device and is analyzed. The outcomes show that the relative error of measured amplitude at multi-frequency is less than 1.50% while the absolute error of phase is up to 10. A comparison between the two devices shows that the accuracy parameter of the developed device is more than 98 %. A compatible correlation (~ 0.9993) can be seen between both devices that they measure a nearly equal impedance of left and right arm at the same frequency.
The use of the developed device for the measurement of segmental bioelectrical impedance using multi-frequency adequately enhances all traits of measurement as state-of-the-art facilities, small size and liberated to use due to simplicity with the advancement of online measurements analysis.

Keywords: Bioelectrical impedance, Multi-frequency, Segmental bioelectrical impedance, Impedance analyzer

1. Introduction

In the light of available literature, bioelectrical impedance is used to know corporal conditions of living tissues of human body. In the same line, it is also important to understood ethics and observational measurement of bioelectrical impedance. Further, analysis of blood flow and different parameters related to body composition are also possible by measurement of bioelectrical impedance in field of medical science [1]. Some of the disease affects different body segments of the human body, and make them non-moveable and rigid. The healing of these diseases required regular monitoring; bioelectrical impedance plays an important role for that purpose. The regular measurement of bioelectrical impedance; becomes a marker to know about the internal condition of different body parts [2]. Generally, available

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methods to measure the bioelectrical impedance of human body include two-electrode method, three-electrode method, four-electrode method and eight-electrode method, out of which four-electrode method is widely used, as four-electrode method reduces the interference problem which occurs due to interface between electrode and skin [3]. Bioelectrical impedance of human body use single or multi-frequency for measurement of whole body or segmental impedance, but results shows that segmental body impedance is better to measure in compare to whole body [4]. Thus, segmental impedance can give detailed status of a particular body part or joints, which can be useful for proper treatment and solution. The major or widely used techniques available for measuring bio-electrical impedance are bioelectrical impedance analysis (BIA), dual-energy x-ray absorptiometry (DXA), magnetic resonance imaging (MRI), or computed tomography (CT) [5] etc. Bioelectrical Impedance Analysis (BIA) is the technique that has some real advantages as compared to other techniques that included:

a) It is non-invasive, which is helpful to maintain physiological status of subjects,
b) Very simple for accept,
c) Compact size to carry in pocket,
d) Easily accessed for everyone.
e) It is economical too in compare to other bioelectrical impedance measurement techniques.
f) It is rapid for measurement of data.

All these qualities support that BIA is as a valuable technique too. Comprehensive measurements of fat mass (FM) using BIA had less clinically injurious, if directions of biases be opposite [6]. It was found in a study that BMI significantly correlated with %BF, resistance reactance of several body segments also highly correlated with %BF [7]. In general; under-estimated %BF for normal body mass index (BMI) and over-estimated %BF for over-weights and obese BMIs. Segmental bioelectrical impedance measurement useful to track changes in segments of the body at the time of recovery from any type of disease; also diagnose how each limb is affected, makes it suitable to know about changes in body composition parameters like muscles mass and fat. [8]. The estimation of fat mass and fat-free mass estimated by bioelectrical impedance analysis (BIA), shows a perfect correlation for both sexes [9]. BIA underestimates fat mass for arm and leg and overestimate lean mass for arm and trunk [5].

2. Methods

In this section different methods for measuring bioelectrical impedance are discussed.

2.1 Basic principle of segmental bioelectrical impedance measuring

Using theory of Ohm's Law, in respect of human body, the voltages generated between different points in the body volumes are termed as Source (which is used to inject/supply the current) and current passes through two electrodes are termed as sink (which is employed to detect the corresponding response) [10]. According to the basic theory of measurement of bioelectrical impedance, small amount of current is being injected into the human body through the touching electrodes and the corresponding voltage across electrodes touching the human body are being measured (in term of impedance). Refer Fig. 1 where electrical nature of a cell has been displayed. In the cell of human body, intracellular water (ICW) and extracellular water (ECW) is available that acts or considered as resistance. In the same line, cell membrane is being treated as capacitance. With this, biological tissues of the human body can be represented by three-element RC model in which capacitance C is equal to membrane; resistance R_i is equal to the ICW and R_e is equal to the ECW. Here, capacitor C is connected with R_i in series and resistance R_e is connected in parallel.

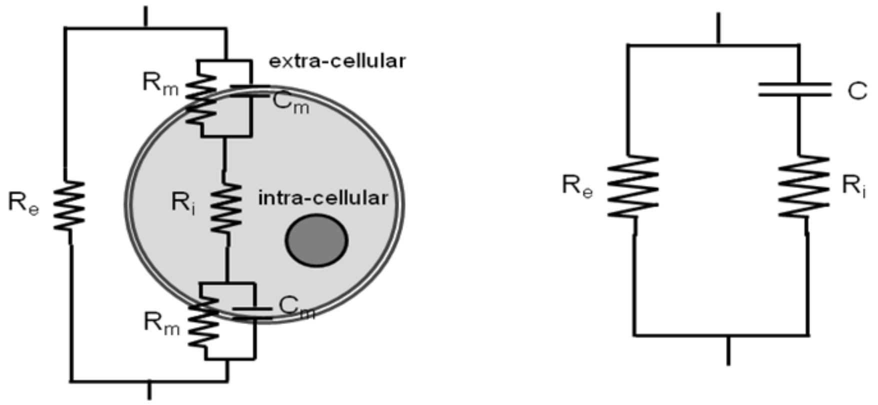

Fig.1 - (a) Model of bioelectrical impedance measurement with intra cellular water and extra cellular water; (b) Basic model of body's equivalent circuit [4]

Biological tissues have different impedance characteristics with different current frequencies; the electrode system Z_X composed of the electrode and human tissues connects with a standard resistor R_S in series [11]. The model for the measurement of bioelectrical measurement is shown in Fig. 2. The voltage across Z_X and R_S becomes U_Z and U_S after signal processing when there is the excitation current in the circuit. The current through Z_X and R_S are I and the relationship between U_Z and U_S is as follows:

$$\frac{U_Z}{U_S} = \frac{I.Z_X}{I.R_S} = \frac{Z_X}{R_S} \quad (1)$$

Using equation (1), it is concluded that,

$$Z_X = R_S \frac{U_Z}{U_S} = R_S \frac{|U_Z| \angle \phi_1}{|U_S| \angle \phi_2} = R_S \frac{|U_Z|}{|U_S|} \angle \theta \quad (2)$$

where $\angle \theta$ is the phase difference of U_Z and U_S.

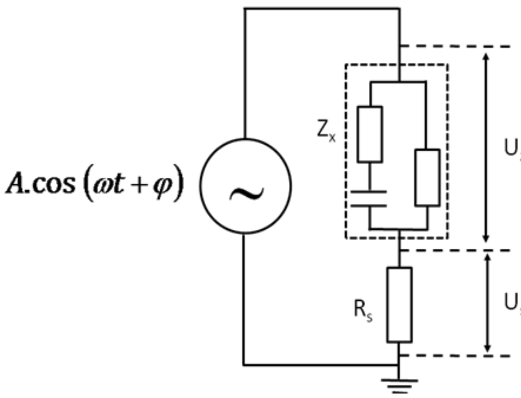

Fig. 2 - Model of bioelectrical impedance measurement

Bioelectrical impedance of tissues varies with the frequency range of current applied to them. The relationship between frequency and impedance is inversely proportional. Means, if there is any increment in the frequency, there will be decrement in corresponding value of impedance [12]. The relation of capacitive inductance against frequency shows that if the frequency is increased the overall capacitive reactance would be decreased. As the frequency reached to high or infinity level, the capacitors would reduce practically up to zero, but if frequency reached zero levels, capacitive inductance rapidly increases up to infinity and act as an open circuit condition. It means that capacitive reactance is "inversely proportional" to frequency.

$$X_C = \frac{1}{2\pi f C} = \frac{1}{\omega C} \quad (3)$$

where X_C = capacitive reactance
C = capacitance in farads
f = frequency in hertz

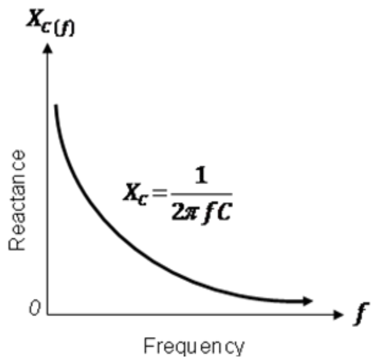

Fig. 3 – Capacitive Reactance against Frequency

Referring the graph shown in Fig. 3, it can be interred that a hyperbolic curve between capacitive reactance and frequency. The reactance value of a capacitor is high at low frequency but as frequency starts to increase its decreases quickly. The relation between frequency and impedance is inversely proportional as impedance will be decreased with increment in frequency.

2.2 Multi-frequency and segmental bioelectrical impedance measurement

Bio-electrical measurement using multi-frequency measurement technique is more favourable with respect to single frequency measurement. The measurement of ECW and ICW is required on low and high range of frequency respectively because at low frequency, current cannot penetrate cells of body and flow only in ECW although high frequency penetrates cell membrane and flows in both ECW and ICW. The human body's impedance could be measured at the wide range of frequency and the resulting determination of ECW and ICW compartment is more helpful to improve the calculation of total body water (TBW) as compared to single-frequency [12]. The use of single-frequency cannot identify the difference in ICW although satisfactory results are obtained for the estimation of FFM and TBW.

Single frequency can be used to determine unquestioning measurement of fat free mass (FFM) and TBW in hydrated subjects, but that cannot be applied in the condition of variable hydration. Contrary to this, multi-frequency is very useful and accurate to measure different parameters related to body composition as FFM, ICW, ECW and TBW at different frequencies [13]. Thus, in this research, multi frequency is being used.

2.3 System architecture

Basic theory of bioelectrical impedance analyzer is shown in Fig. 4. The system consists of a PmodIA impedance analyzer, Arduino microcontroller, Temperature sensor, sub-miniature version A (SMA) and alligator coaxial cables for the connections of electrodes.

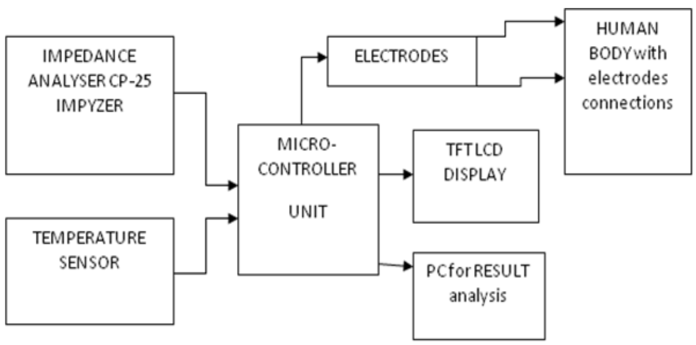

Fig. 4 - Block diagram of proposed system

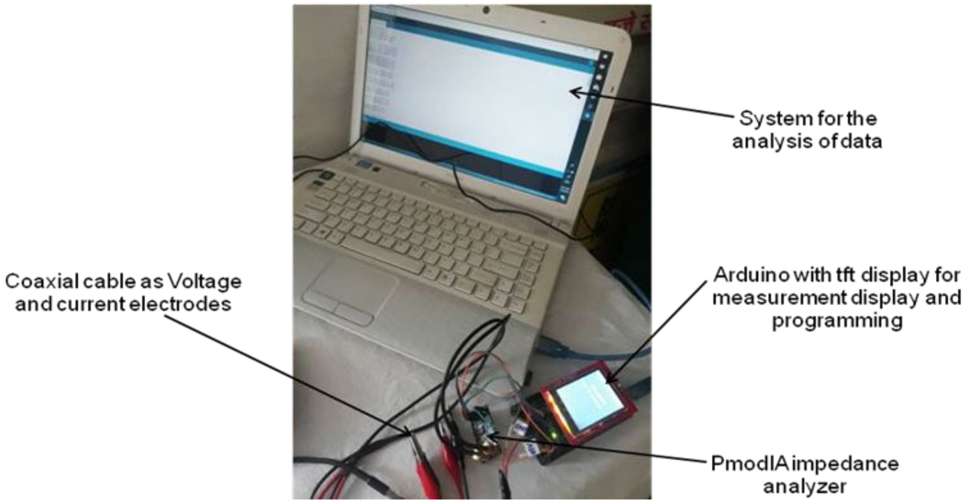

Fig. 5 - Experimental set up for the impedance measurement system

2.4 PmodIA impedance analyzer

PmodIA impedance analyzer [14] is a combination of AD5933 frequency generator and analog to digital converter (ADC). It is a 12-bit impedance converter. External unknown impedance is being generated at a known frequency using ADC. This known frequency is transferred by a SMA connector called current electrodes to human body and the response of corresponding frequency is picked in form of voltage response by other SMA connector called voltage electrodes. Captured response is being sent to ADC and the specimen data is being converted in to discrete Fourier transform. The output impedance of AD5933 depends on the excitation amplitude. The linearity and the calibration process of the AD5933 chip affect the range of measurable impedance [15]. On-chip data registers are used to store real and imaginary parts of the results.

2.5 Arduino microcontroller

The Arduino Mega 2560 [16] is an ATmega2560 base microcontroller board. To make small size of prototype developed in this research, Mega2560 PCB is used with length and width of 4 and 2.1 inches, respectively. In combination of 14 pulse width modulation (PWM) outputs and 16 analog inputs, it has total 54 inputs and output ports. It consists of 4 hardware serial ports as universal asynchronous receiver and transmitter (UART), 16 MHz crystal oscillator, a universal serial bus (USB) port for easy connections, a reset button, a power jack and an ICSP header. This system can be powered by USB or external supply and the feature of self selection of source of power is also provided. ATMega 2560 have all such required facilities related to microcontroller that included connection with USB, power it by AC to DC transcribed or battery for started. It can work on a supply of 6 to 20 volts, and consists of 256 KB flash memory to store the codes.

2.6 Electrodes connections

In the developed hardware, two square electrodes are being used for the analysis of samples during measurement and to monitoring the response of measured signals. A device presented in [17] uses multi-lead or multi-electrodes for more accurate results. It also measures volume at different locations of the body concerning time. Shape of electrodes is being selected based on the requirement. In full range of frequency, about 200 ohm unchanging impedance can be provided by impedance analyzer, using spherical electrodes. The spherical electrodes show zero phases with resistive behavior in entire range. Instead of this, quadrate electrodes are complex and show high impedance at low frequency, because of a less conductive pasting layer [18]. Most of the electrodes used by bio-impedance manufacturers must be used to minimize error in equipment at the right side of the body at 50 kHz, but error becomes large at high frequency when measuring low impedance. The prevention of this error is the use of lower impedance electrodes [19]. SMA to alligator, a coaxial cable is used to connect the electrodes with human body for the measurement of bio-electrical impedance. One port of cable is connected with impedance analyzer chip and another is attached with the body, with the help of round electrode.

2.7 TFT LCD screen

Data measurement is being done by 2.4” inch TFT LCD screen. Thin-film-transistor is a 2.4" colored display as shield available for Arduino UNO with micro SD card. It consists of a resistive touch screen, SD card slot, an easy Arduino UNO shield, and a reset switch. Arduino requires a preinstall TFT library in which Arduino IDE uses SPI interface to use this TFT shield. LCD display needs the 8-bit for use of parallel data bus as input pins, a notation for DI as data input and DO as data output. Two more actions; select and SCK data clock consist of SD card. To control 8-bit data bus, a display needs five more pins, known as RST, CS, RS, WR, and RD.

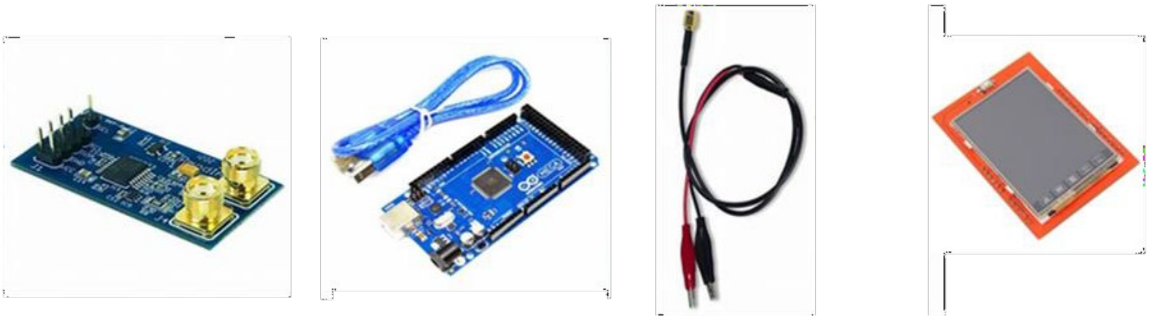

Fig. 6 - (a) PmodIA impedance analyzer; (b) Arduino microcontroller; (c) SMA to alligator coaxial cable; (d) TFT LCD screen

3. Results

In this section major results of this paper are elaborated hereunder.

3.1 Fidelity proof

For the reliability check of the proposed system, the developed hardware was compared with a simulated circuit through Digital Storage Oscilloscope (DSO). Same experimental conditions such as waveform, amplitude, and frequency were given to DSO and observations were recorded. Further, data obtained from DSO and developed hardware is being compared. Data obtained through the developed device under 500 KHz frequencies and DSO is presented in table 1.

Table 1 - Measured results compare with 500 KHz frequency

DSO	**CP-25 IMPYZER**	**Error**
Amplitude(ohm)		**(in %)**
426.3	420.8	1.29
580.8	574.3	1.12
648.6	653.9	0.82
750.2	755.7	0.73
Phase(degree)		Error
-33.5	-34.5	1.00
-22.8	-22	0.80
-11.8	-12.4	0.60
-6.3	-7.0	0.70

The comparison of observations reflects that the relative error of amplitude is less than 1.5%, although the absolute error of phase is up to 1degree. With this, it can be said that the developed device is highly accurate.

3.2 Measurement of bioelectrical impedance

The proposed device was employed to measure a bioelectrical impedance of right and left arm at multi frequency. The obtained results are presented in table 2. With this, it can be observed that there is no more difference in data obtained by both arms but the impedance of right arm is less than an impedance of left arm, although muscles of right arm are stronger than left arm. The impedance of both arms measured at the same frequencies.

Multi-frequency is useful for the measurement of Intracellular and extracellular resistance. Further, the difference in the ratio of intracellular and extracellular resistance (Ri/ Re) is also helpful to detect diseases as early in a group of subjects [20].

Table 2 - Data of human Impedance measurement using CP-25 IMPYZER

Frequency(KHz)	Left Arm (Ω)	Right Arm(Ω)
5	398.9	389.8
50	356.1	350.1
100	338.8	333.1
200	320.5	316.2
400	310.9	306.3
500	307.6	302.4

3.3 Limitations during measurement

Measurement of segmental bioelectrical impedance needs utmost carefulness while recording the data from the human body. Although segmental impedance shows achievements in medical practice to overcome demerits of conventional BIA techniques, but it is necessary to instruct subjects not to perform any heavy physical activity on experiment day and to remove all metal accessories from the contact of body as presence of metal may attract flow of current and an additional resistance might be incorporated into the observations recorded by device [21].

4. Discussion

The present study analyzes the accuracy of designed system CP-25 IMPYZER for the measurement of segmental bioelectrical impedance at multi-frequency. Table 3 shows attractive similarities between two systems, first is CP-25 IMPYZER and second prototype machine used in [1]. The prototype used by [1] is being considered as a standard device. Comparative study of both devices shows that both devices are in a line of each other. Accuracy parameter of the system prototype machine (CP-25 IMPYSER) is more than 98% with the standard device. CP-25 IMPYZER could be a useful tool in different field as daily routine life, research field, and medical research field. The developed device can most be liked due to its tiny size, low cost, and easy understanding.

Table 3 - Comparative analysis of impedance measured by CP-25 IMPYZER and standard device for female

Frequency (KHz)	Left Arm (Ω)			Right Arm (Ω)		
	Standard Device	CP-25 IMPYZER	Error (in %)	Standard Device	CP-25 IMPYZER	Error (in %)
5	394.3	398.9	1.17	388.6	389.8	0.31
50	351.6	356.1	1.28	348.3	350.1	0.52
100	334.5	338.8	1.29	330.8	333.1	0.70
250	315.5	320.5	1.58	310.2	316.2	1.93
500	308.3	310.9	0.84	301.2	306.3	1.69

Table 4 - Comparative analysis of impedance measured by CP-25 IMPYZER and standard device for male

Frequency (KHz)	Left Arm (Ω)			Right Arm (Ω)		
	Standard Device	CP-25 IMPYZER	Error (in %)	Standard Device	CP-25 IMPYZER	Error (in %)
5	290.6	294.4	1.31	283.4	284.8	0.49
50	279.9	283.7	1.36	273.6	275.7	0.77
100	272.5	277.6	1.87	267.4	270.2	1.05
250	254.8	259.7	1.92	249.3	252.4	1.24
500	235.5	238.1	1.15	229.2	231.7	1.09

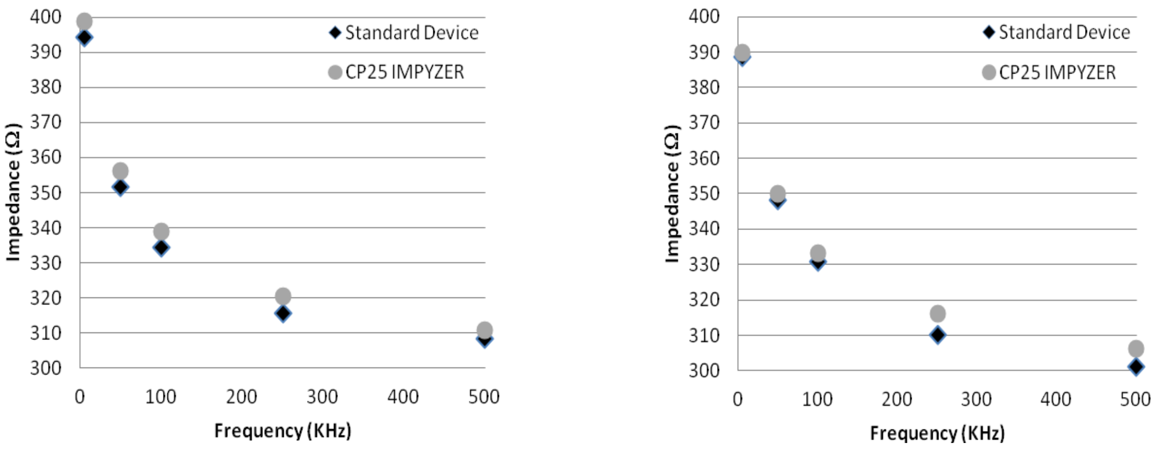

Fig. 7 - Plot represents comparative analysis of impedance measured by system prototype machine and standard device of female. (a) for Left Arm and (b) for Right Arm

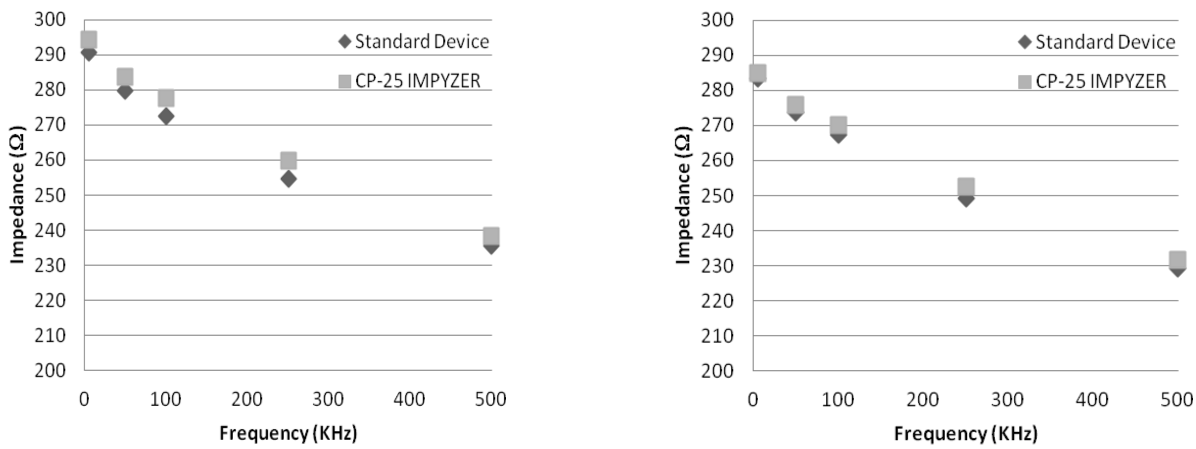

Fig. 8 - Plot represents comparative analysis of impedance measured by system prototype machine and standard device of male. (a) for Left Arm and (b) for Right Arm

The range of measured impedance at 5 to 500 kHz frequency is less than 400Ω and greater than 300Ω (300 < impedance < 400 Ohm) for female and the range of measured impedance at 5 to 500 kHz frequency is less than 300Ω and greater than 200Ω (200 < impedance < 300 Ohm) for male. Increments in impedance are done by the decrement of frequency. Measured reading have a relationship between left and right arm, that are same as obtained through standard device (as at 5kHz frequency, impedance is 398.9 Ohm – measured through CP-25 IMPYZER and at same frequency, standard device measures 394.3Ohm impedance). The impedance of the right arm is always less than the left arm in both device but the overall measured impedance of CP-25 IMPYZER is greater than the previous device. The relation between frequency and impedance is inversely proportional as impedance will be decreased with increment in frequency.

A compatible correlation (for Left Arm – 0.9997 and for Right Arm– 0.9995) can be observed between both devices that they measure a nearly equal impedance of left and right arm at the same frequency but the developed device in present study shows relatively high impedance as compare than a standard device. With the help of some more improvement in the future, this developed device can be made more accurate so that it can be used clinically. This study was aimed to develop a system with compact size, lightweight, easily handled and affordable for the measurement of the segmental bioelectrical impedance of the human body accurately. We also compared this device with a previously developed device designed in [1]. It is necessary to understand its measuring parameters compared to the standard device. CP-25 IMPYZER compares with the standard device in table 3 and 4 indicate that it is strongly connected for segmental measurement at different frequencies.

4.1 Advantages of proposed device

1. It is a portable and versatile device.
2. It is very simple to use for quick responses.
3. It is compact in size as handy with light in weight and can carry in your pocket.
4. It is a low-cost device that has been developed to evaluate the phenomenon of bioelectrical impedance.
5. The system can be configured as multi-frequency bioelectrical impedance analyzer for BIA purpose,
6. The system allowing rapid and accurate measurement of the electrical impedance over a wide frequency range.
7. The measured signals can be analyzed by transferring them to a PC through USB transmission; it is also useful for further processing.

4.2 Disadvantages of proposed device

1. The system needs a PC for the analysis of measured data.
2. Some of the parameters as weight and height measurements are not available in the system they feed manually.

5. Conclusion

Overall study summarizes that BIA is one of the most popular and easy to hand technique to measure bio-electrical impedance and is extensively used in the field of medical and daily routine life of normal person. Inspiring from the application of BIA, a system using PmodIA impedance analyzer and Arduino microcontroller, is being developed in this research. To reduce its cost, minimizing the error and for high accuracy, a circuit with Arduino 2560 microcontroller was designed. With the help of obtained results, it can be established that the developed system is accurate with low cost and compact size. Future researches have lots of ideas in medical profession and allied research field. However, some improvement may make this developed system more reliable and widen its application for measurement of more parameters. Proposed device can be modified by increasing number of measured parameters related to body composition and bioelectrical impedance. However, further validation of this instrument should include more clinical testing on subjects for more parameters related to bioelectrical impedance and body composition.

Appendix A:

Table of Abbreviation

FM	-	Fat Mass
BIA	-	Bioelectrical Impedance Analysis
DXA	-	Dual-energy X-ray Absorptiometry
CT	-	Computed Tomography
MRI	-	Magnetic Resonance Imaging
ICW	-	Intra-Cellular Water
ECW	-	Extra-Cellular Water
FFM	-	Fat Free Mass
TBW	-	Total Body Water
ADC	-	Analog-to-Digital Converter
SMA	-	Sub-Miniature version A
TFT	-	Thin Film Transistor
PWM	-	Pulse Width Modulation
UART	-	Universal Asynchronous Receiver and Transmitter
USB	-	Universal Serial Bus

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