TETRA-POLAR BIOELECTRICAL IMPEDANCE ANALYZER

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ABSTRACT

The paper introduces a tetra-polar bioelectrical impedance analyzer design using microcontroller which can provide information regarding body composition based on bioelectrical impedance analysis (BIA). The primary objective of this development is to provide a non-invasive, valid, and reliable technique of estimating human body composition. In this research, body composition is divided into body fat (BF), body water (TBW), and body muscle (BM) which is displayed in percentage using character liquid crystal display (LCD). The analyzer uses Fricke’s electrical circuit to model the behavior of biological tissues in vivo. From current stimulus perspective, the analyzer is categorized multi-frequency BIA means the circuit uses different frequencies to evaluate body composition. The method of injecting current to body and measure the voltage drop is tetra-polar method. A prototype has been developed and the performance has been evaluated. The system was tested on the human body repeatedly over certain period and the gathered data set is analyzed. The data analysis indicates that BF, TBW, and BM estimation has maximum error 2.82%, 0.65%, and 0.88% respectively.

Keywords: BIA, body fat, body water, body muscle, microcontroller.

1 INTRODUCTION

Assessment of human body composition is an important factor in determining the nutritional status of an individual and of populations. Although a variety of body composition methods is available, the majority are limited to the research or clinical laboratory. It includes densitometry [1], determination of total body water (TBW) [2], potassium (TBK) [3], nitrogen [4], and calcium [5], tomography [6], and electrical conductivity [7]. Other techniques that have been developed for field use, such as skinfold thickness [8] and ultrasound [9], are less reliable predictors of human body composition. Thus, there is a need for a technique that provides reliable and valid estimates of human body composition. The method should be non-invasive and suitable for use outside of the laboratory. Measurement of whole body bioelectrical impedance is a approach that may meet this need.

The method for determining body impedance is based upon the condition of applied current in the organism. In biological structures, application of a constant alternating current results in an impedance to the spread of the current that is frequency dependent. The living organism consists of intra- and extracellular fluids that behave as electrical conductors, and cell membranes that act as electrical capacitors. These capacitors are regarded as imperfect reactive element. At low frequencies, the current passes mainly through the extracellular fluid while at higher frequencies; it passes through extra- and intracellular fluids [10,11]. In this manner, body fluids and electrolytes are responsible for electrical conduction and cell membranes are involved in capacitance.

The pioneering work of relating electrical impedance measurements to biological function has been conducted since 1871. Thomasset [10,11] conducted the original studies using electrical impedance measurements as an index of total body water (TBW), using two subcutaneously inserted needles. Hoffer et al.[12] and Nyboer [13] first introduced the four-surface electrode bioelectrical impedance analysis (BIA) technique. A disadvantage of surface electrodes is that a high current (800 mA) and high voltage must be utilized to decrease the instability of injected current related to cutaneous impedance (10 000 Ω/cm²) [14].

By the 1970s the foundations of BIA were established, including those that underpinned the relationships between the impedance and the body water content of the body. A variety of single frequency BIA analyzers then became
commercially available, and by the 1990s, the market included several multi-frequency analyzers. The use of BIA as a bedside method has increased because the equipment is portable and safe, the procedure is simple and noninvasive, and the results are reproducible and rapidly obtained.

The purpose of this research is to develop a tetra-polar bioelectrical impedance analyzer for assessing total body water (TBW), body fat (BF), and body muscle (BM), to determine the reliability of impedance measures, and investigate the validity of this measurements by comparison with commercially available instrument.

2 PRINCIPLES, DESIGN, AND IMPLEMENTATION

In this chapter, the fundamental principles of bioelectrical impedance analysis are reviewed first in order to enable better understanding upon design and implementation section that described subsequently.

2.1 Principles of Bioelectrical Impedance Analysis

The resistance (R) of a length of homogeneous conductive material of uniform cross sectional area is proportional to its length (L) and inversely proportional to its cross sectional area (A), as illustrated in figure below.

\[ R = \frac{\rho L}{A} = \frac{\rho L^2}{V} \]  \hspace{1cm} (1)

and volume:

\[ V = \frac{\rho L^2}{R} \]  \hspace{1cm} (2)

where \( \rho \) is the resistivity of the conducting materials and \( V \) equals AL. Although the body is not a uniform cylinder and its conductivity is not constant, an empirical relationship can be established between the impedance quotient (length²/R) and the volume of water, which contains electrolytes that conduct the electrical current through the body. In practice, it is easier to measure height than the conductive length, which is usually from wrist to ankle. Therefore, the empirical relationship is between lean body mass (typically 73% water) and height²/R.

Due to the inherent field in-homogeneity in the body, the term height²/R describes an equivalent cylinder, which must be matched to the real geometry by an appropriate coefficient. This coefficient depends on various factors, among them also the anatomy of the segments under investigation. Therefore, errors occur when there are alterations in resistivity of the conductive material, variations in the ratio height to conductive length, and variations in the shape of the body and body segments (body segments behave as if they are in series with each other, with shorter and thicker segments contributing less to the total R).

Another complexity is that the body offers two types of R to an electrical current: capacitive R (reactance), and resistive R (simply called resistance). The capacitance arises from cell membranes, and the R from extra- and intracellular fluid. Impedance is the term used to describe the combination of the two. Several electrical circuits have been used to describe the behavior of biological tissues in vivo [15]. One of them involves arranging R and capacitance in series, another in parallel, whilst others are more complex. A circuit that is commonly used to represent biological tissues in vivo is one in which the R of extracellular fluid is arranged in parallel to the second arm of the circuit, which consists of capacitance and R of intracellular fluid in series, as illustrated below.
Figure 2. The human body consists of resistance and capacitance connected in parallel or in series.

R and capacitance can all be measured over a range of frequencies (most single-frequency BIA analyzers operate at 50 kHz). At zero (or low) frequency, the current does not penetrate the cell membrane, which acts as an insulator, and therefore the current passes through the extracellular fluid, which is responsible for the measured R of the body $R_0$. At infinite frequency (or very high frequency) the capacitor behaves as a perfect (or near perfect) capacitor, and therefore the total body R ($R_\infty$) reflects the combined of both intracellular and extracellular fluid. Since practical constraints and the occurrence of multiple dispersions prevent the use of a direct current (zero frequency) or very high frequency AC currents, the R values at the ideal measurement frequencies are predicted using a Cole–Cole plot [16] (negative reactance versus R plot), with $R_0$ theoretically representing the R of the extracellular fluid (intracellular water) and $R_\infty$ representing the R of intra- and extracellular fluid (TBW), as illustrated in Figure 3.

According to the Figure 4, human body can be divided into two major partitions, fat mass (FM) and fat-free mass (FFM). FFM is everything that is not body fat. It is mainly composed of body water and small portion of protein and mineral. This portion will be used to derive body water and body muscle percentages. Whereas FFM is everything that is not body fat, there is no consensus on the physiological meaning of measures of body cell mass (BCM). The BCM is the protein rich compartment, which is affected in catabolic states, and estimating the size is difficult because it is a complex compartment, comprising all non-adipose cells as well as the aqueous compartment of adipocytes.

BIA measurements must be standardized in order to obtain reproducible results. Reported mean coefficients of variation for within-day R measurements are $\approx 1\% - 2\%$; daily or weekly intra-individual variability is slightly larger ranging from $\approx 2\%$ to $3.5\%$ [17 - 20]. Day-to-day coefficients of variation increases for frequencies lower than 50 kHz [21]. Overall reproducibility/precision is $2.7\% - 4.0\%$ [19]. Prediction errors were estimated to be $3\% - 8\%$ for TBW and $3.5\% - 6\%$ for FFM, respectively [22, 23].

Subjects must be measured (recall values are not acceptable) for height and weight at the time of the BIA measurement. Standardized conditions with regard to body position, previous exercise, dietary intake and skin temperature must be respected. No interference with pacemaker or defibrillators is anticipated [24]. Although there are no known incidents reported as a result of BIA measurements, the possibility cannot be eliminated that the induced...
field of current during the measurement could alter the pacemaker or defibrillator activity.

2.2 Design and Implementation of Bioelectrical Impedance Analyzer

The analyzer design involves mixed circuitry, both analog and digital. Primarily, the analog circuit is used to perform signal conditioning upon bio-potential signal picked up by electrodes. The digital counterpart is used to administer signal injection to human body through electrodes and process the acquired signal from analog circuit into human readable form with the help of analog to digital converter (ADC). The block diagram of bioelectrical impedance analyzer is illustrated in Figure 5. The heart of the system is microcontroller MPC82G516A from Megawin Technology.

Although the block diagram looks complicated, the working mechanism is quite straightforward. As it is reflected from the name, the sensing target for BIA estimation is body impedance. Like the impedance in the electrical circuit, the common measurement technique is to inject a certain amount of alternating current to target impedance and measure the voltage drop due to impedance. The impedance is then simply voltage per current. This technique is also applicable to BIA estimation, with slight modification.

In this research, the method of injecting current to body and measure the voltage drop is known as tetra-polar method. Current is injected through the electrode pads under the front of each foot and the voltage measured by the electrodes under the heel. Since the aim in BIA is to measure the impedance of the deep tissues, the tetra-polar method is preferred as the voltage drop measured using a separate set of electrodes will be that of the deep tissues, since negligible current is drawn through the electrode. The tetra-polar arrangement is illustrated in Figure 6.

A circuit model called Fricke’s circuit [Figure 2] is used to represents body impedance. There are four additional resistors included to the model due to skin resistance. The electrode pads are made from particular conductive material deposited on glass surface.

From current stimulus perspective, this BIA circuit is categorized multi-frequency BIA means the circuit uses different frequencies to evaluate FFM, TBW, ECW, and ICW. In this research, the lower frequency is set at 5 kHz while the higher frequency is set at 50 kHz. The microcontroller is responsible for these signals generation. Timer 2 and timer 2 interrupt is used to address this task. The timer is set to auto-reload mode and appropriate reload value is assigned to timer register. Each time timer 2 overflows; the routine in timer 2 ISR alternates the state of PA3. Therefore, as long as timer 2 runs, continuous square wave signal generated and outputted to PA3.

The signal gating is governed by PC4 and PC5. When PC4 at logic "high", 5 kHz signal is delivered to the system and PC5 does likewise with 50 kHz signal. The requirement for BIA circuit is sine wave signal; therefore the square wave signal should be converted using converter 1 and converter 2. These blocks have similar construction, only differ in component values. Before injected to target impedance, this signal is amplified and filtered using active low-pass filter.

Each complete impedance measurement takes three consecutive steps. This sequence is performed by multiplexer, which is controlled by PA7 and PC2. The better understanding about this sequence can be obtained by simplifying BIA block diagram, as illustrated in Figure 7.
Tetra-Polar Bioelectrical Impedance Analyzer-Daniel Santoso

R301 and R302 serve as reference resistances; the value is 300 Ω and 600 Ω respectively. The sequence is quite straightforward, and also applies both to 5 kHz and 50 kHz impedance measurement. Firstly, the multiplexer’s inputs are directed to measure voltage drop between two reference resistances ($v_{AC}$). Secondly, the multiplexer’s inputs are then directed to measure voltage drop between single reference resistance ($v_{BC}$). Finally, to obtain the target impedance value, the multiplexer’s inputs are directed to measure voltage drop between target impedance ($v_{DC}$). It is required to measure impedance at 50 kHz and impedance at 5 kHz. Therefore, the complete sequence to estimate body composition takes 6 steps.

The output of multiplexer is connected to the input of differential amplifier to be amplified with certain gain. Up to this stage the signal is still alternating current (ac). Therefore a circuit to get direct current (dc) equivalent is inserted in between differential amplifier and ADC. In addition, this circuit also adjusts the dc output to a certain level that is within the range of ADC input.

The ADC circuit doesn’t refer to embedded ADC inside Megawin MPC82G516A. Instead, it refers to external mixed circuit serves as dual-slope integrating ADC – like. The primary function of this circuit is to translate a certain level of DC input voltage to a pulse-width modulated square wave signal. Clearly, in this ADC the change of input voltage will modulate the signal’s duty cycle. The duty cycle is then fed to microcontroller and interpreted using particular algorithm. By doing this way, voltage information (volt) is conveyed to microcontroller in time unit (second). The waveform fed to microcontroller’s INT0 (interrupt port 0) is illustrated in Figure 8.

For this application, $t_2$ is used to obtain the target impedance ($Z_L$) value. The measurement concept is illustrated in Figure 9.

At first step, microcontroller obtains $t_a$ as representation of $v_{AC}$. Secondly; $t_b$ is then obtained as representation of $v_{BC}$. It is commonly understood that value of $v_{AC}$ is twice the value of $v_{BC}$ since the same current flows through those resistances. However, it is not relevant to $t_a$ and $t_b$. Finally, at third step, $t_c$ which is representation of $v_{DC}$ is obtained.

The first two steps are used to establish reference line. The slope of this line must be calculated using equation (3) to enable impedance measurement.

$$m = \frac{y_2 - y_1}{x_1 - x_2}$$  \hspace{1cm} (3)

The $m$ in equation (3) can be also expressed using equation (4).

$$m = \frac{y_2 - y_1}{x_1 - x_2}$$  \hspace{1cm} (4)
By rearranging equation (4), the actual impedance (\(x_3\)) can be obtained.

\[ x_3 = x_1 - \frac{y_3 - y_1}{m} \]  

(5)

The impedance at 5 kHz and impedance at 50 kHz, along with weight, height, age, and gender information will be used to estimate body composition. The final result of this estimation is percentage of body fat (BF), total body water (TBW), and body muscle (BM) which is displayed on character liquid crystal display (LCD). The formulas are not shown due to proprietary right.

Impedance measurement at 50 kHz is used to estimate body fat and total body water while impedance measurement at 5 kHz is used to estimate body muscle. Actually, impedance measurement at 50 kHz means TBW estimation. TBW itself consists of ECW and ICW. Information about body muscle percentage is derived from ICW, meanwhile the impedance at 5 kHz only represents ECW. Therefore, ICW value must be obtained from TBW – ECW.

3 RESULT

The design considerations and implementation regarding bioelectrical impedance analyzer has been elaborated in previous sub-chapter. A prototype of the analyzer has been successfully developed and tested.

Basically there are two tests have been conducted upon the prototype to determine its reliability of impedance measures, and investigate the validity of the measurements. The purpose of the first test is to ensure that the analyzer can measure impedance of electric circuit model of human body properly. It is reasonable to assume that if BIA section shows correct result in measuring impedance of electric circuit, it will remain correct for measuring impedance of human body as well. After that, at the second test, the analyzer applied to human body to investigate its performance in the real-world application.

The circuit model for human body impedance used in the first test is Fricke’s circuit. This model is further improved by incorporating skin resistance on each terminal to simulate real application, as illustrated in Figure 6 previously. The circuit model is basically a simple RC network with impedance Z. The value of Z can be calculated using (6).

\[ Z = (X_C + R_{ICW}) || R_{ECW} \]  

(6)

In the first test, \(R_{ICW} = 560 \Omega\), \(R_{ECW} = 560 \Omega\), \(C = 4.7\) nF, \(R_C = 820 \Omega\) were used. The impedance both at 5 kHz and 50 kHz were then measured. The experiment was repeated 10 times to ensure the repeatability. The BIA results (BF, TBW, and BM) were obtained by plugging in \(Z_{50\text{kHz}}\) and \(Z_{5\text{kHz}}\) in BIA formula inside the microcontroller. The other parameters needed to compute BIA (gender, age, height, and weight) were manually inputted. The result is based on reading of LCD screen located on front panel of the analyzer as illustrated in Figure 9.

![Figure 9. LCD screen when measuring impedance in Fricke’s circuit](image)

The result of 10 consecutive experiments is summarized in Table 1.

<table>
<thead>
<tr>
<th>(Z_{50\text{kHz}}(\Omega))</th>
<th>(Z_{5\text{kHz}}(\Omega))</th>
<th>BF(%)</th>
<th>TBW(%)</th>
<th>BM(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>550</td>
<td>380</td>
<td>8.0</td>
<td>67.3</td>
<td>55.5</td>
</tr>
<tr>
<td>550</td>
<td>385</td>
<td>8.3</td>
<td>66.8</td>
<td>54.8</td>
</tr>
<tr>
<td>550</td>
<td>382</td>
<td>8.1</td>
<td>67.3</td>
<td>55.5</td>
</tr>
<tr>
<td>548</td>
<td>381</td>
<td>8.0</td>
<td>67.3</td>
<td>55.5</td>
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<tr>
<td>550</td>
<td>381</td>
<td>8.0</td>
<td>67.3</td>
<td>55.5</td>
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<td>8.1</td>
<td>66.8</td>
<td>54.8</td>
</tr>
<tr>
<td>550</td>
<td>387</td>
<td>8.4</td>
<td>66.8</td>
<td>54.8</td>
</tr>
<tr>
<td>549</td>
<td>386</td>
<td>8.3</td>
<td>66.8</td>
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<td>550</td>
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<td>387</td>
<td>8.4</td>
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</tbody>
</table>

Based on hand calculation, \(Z_{50\text{kHz}}\) and \(Z_{5\text{kHz}}\) equals to 554 \(\cong 4\) \(\Omega\) and 376 \(\cong 19\) \(\Omega\). In average, the test result indicates \(Z_{50\text{kHz}}\) and \(Z_{5\text{kHz}}\) equals to 549 \(\Omega\) and 383 \(\Omega\) which is close to the result from hand calculation. The analyzer only measures the real part from the complex impedance while the imaginary is omitted. Based on data analysis of the first test, the impedance measurement at 5 kHz has maximum error 0.1 % while 50 kHz counterpart has 0.45 %.

The second test can be regarded as simple clinical test since it was conducted on human body
over a period of time. This test was conducted in 10 consecutives days. Each day, the test was conducted in two sessions, morning and evening, repeated for 10 times per session. It is assumed that during repetition, the environmental factors will not change drastically thus any variation on the result shall be caused by the internal mechanism of the system. In average, one session takes 15 minutes. On every session, subject’s weight and height were measured using traditional weight scale and ruler since recall values are not acceptable in BIA. A commercial product from SOEHNLE, namely Body Balance was used as reference instrument. Totally, the system has been tested at least for 200 times thus it also provides reliability information of the analyzer. According to test scheme, there are vast amount of data set that can be analyzed to evaluate the performance of the system. However, those data are not shown in this paper because of the limited space. From data analysis, it can be concluded that BF, TBW, and BM estimation has maximum error 2.82%, 0.65%, and 0.88% respectively.

4 CONCLUSION AND FUTURE DIRECTIVES

A prototype of tetra – polar bioelectrical impedance analyzer has been designed and implemented based on Megawin 82G5126A microcontroller. The analyzer uses tetra-polar method for injecting current to body and measure the voltage drop. From current stimulus perspective, the analyzer is categorized multi-frequency BIA which uses 5 kHz as lower frequency and 50 kHz as higher frequency. Using Fricke’s circuit model, the impedance measurement at 5 kHz has maximum error 0.1 % while 50 kHz counterpart has 0.45%. A simple clinical test has been conducted as well on human body repeatedly over a period of time. From data analysis upon the tests, it can be concluded that BF, TBW, and BM estimation has maximum error 2.82%, 0.65%, and 0.88% respectively. Thus far, the analyzer has capability of determining body composition based on bioelectrical impedance analysis. The composition which consists of body fat, body water, and body muscle are displayed on LCD in terms of percentage. This can further be improved by implementing algorithm to compare acquired body composition with a particular standard. Based on the comparison and analysis, the analyzer is then generates recommendation regarding diet and exercise for user.

REFERENCES


