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Design of Automatic Switching Bio-Impedance Analysis (BIA) for Body Fat Measurement

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***Abstract*— Bioelectrical impedance analysis (BIA) is one method of measuring body fat levels by distinguishing the fat mass and non-fat mass based on body composition assessment. This research designs a system to measure the body fat percentage by BIA method. The system is capable of measuring BIA with automatic switching between four different electrode schemes, i.e cross-sectional, hand-to-hand, hand-to-foot, and foot-to-foot. Two electrodes are to conduct current into the body, while other two electrodes are utilized to measure the voltage from the body. The alternating current is injected with frequency of 50 kHz. Automatic switch in the form of multiplexers and demultiplexers controls the sequence of BIA measurement methods. Microcontroller process the data and the result is displayed on LCD. A keypad is used to input related body parameters, i.e height, weight, age, and gender. The measurement tests shows that the BIA works as intended, while the comparison with commercial BIA reveals maximum relative error of 4.6 % and the highest standard deviation of 2.2%.**

Keywords*— *bioimpedance analyzer, automatic switching, cross impedance

I. INTRODUCTION

The needs for healthier life have motivated the development of many tools for health and medical application. In terms of somebody's health status, there have been numerous attempts to detect and maintain it. One simple method is by monitoring the body weight as an early indicator of healthy condition of the body. If the body weight is not drastically change over short period, it is assumed that the overall condition is stable. Moreover, the healthy status can be found from the ratio of weight and height, thus the Body Mass Index (BMI) is coined. The proposition of weight (in kg) in regards of squared height (in meter) shows the number by which somebody is considered underweight, normal, overweight or obese, according to World Health Organization (WHO) criteria[1]. However, the body weight itself cannot completely reflect the composition of either fat and non-fat masses of the body.

Recently, it is deemed important to know the composition of fat and non-fat mass of body, as the fat composition has potential risk on the healt status. According to recent studies, several diseases are heavily linked with disproportionate amount of fat in the body. It is a concern that the risk of type-2 diabetes for people with high body fat composition is higher, even with normal BMI[2]. Correlation of disease with higher body fat percentage is also evident for cardiovascular problems and other metabolic syndrom as well [3], [4]. More detailed information of body composition would be beneficial to identify the health risk as well as to find the suitable way to keep healthy.

There are a number of proposed ways for body composition calculation. According to Tzotzas et al, the method of body composition determination can be classified into two groups, i.e. radionuclide and non-radionuclide methods. The radionuclide methods include total body water (TBW) and total body potassium (TBK) as reference methods, as well as Computed tomography (CT), magnetic resonance imaging (MRI) and neutron activation analysis (NAA). On the other hand, the non-radionuclide include underwater weighing (UWW), air-displacement plethysmography (ADP) and dual energy X-ray absorptiometry (DXA), in addition with bioimpedance analysis (BIA) [5]. BIA is a popular tool to assess body fat for everyday use due to its simple yet reliable operation. Moreover, it is non-invasive and does not require complicated preparation for patient which is the case of densitometry, thus it avoids anxiety during test. In terms of accuracy, BIA performs better than caliper tests. In addition, BIA poses much less radiation risk (if any) than dual energy x-ray absorptiometry (DEXA) [6].

Body fat composition analysis using BIA is based on the difference of impedance Previous development of BIA have been reported in [7], with the application of off-the-shelf components in a bid to get low cost analyzer, without losing the accuracy. It was able to measure bioimpedance with hand-to-hand electrodes. However, the fat distribution in body is not homogeneous that the measurement of total fat from hand to hand cannot provide detailed analysis. Therefore, this paper reports the recent development and improvement by different schemes of measurements. In addition, the automatic switching between sequence of different scheme is presented.

II. METHODS

In the measurement of bioelectrical impedance analysis (BIA), the human body is modeled into an equivalent circuit consisting of resistors and capacitors as shown in Figure 1 [2]. The human body is made up of a collection of cells that each cell is

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composed of intracellular water, extracellular water, and cell membranes. Intracellular water (R_i) and extracellular water (R_e) have conductive properties so that they represent the properties of a resistor. In contrast, the cell membrane comprises non-conductive fat and is enclosed by a conductive protein representing the properties of capacitor (X_c) [8].

The BIA method passes an alternating current at a certain frequency into the human body. Then by measuring the voltage generated from the current back and forth we can know the magnitude of the body impedance value. The relationship between current, voltage, and also impedance used in BIA can be seen in Eq. 1.

$$Z = \frac{V}{I} \qquad (1)$$

Where Z is body impedance (in ohm), V is measured voltage (in volt) and I is the applied current (ampere).

The current used in the BIA to flow into the human body ranges from 0.2-0.8 mA. The use of the current between 0.2-0.8 mA is intended so that users do not feel electric stimulation so safe to use, but the current is also still below the human body's current threshold of 1-5 mA [4]. The current flow into the body is strongly influenced by the amount of frequency used. At BIA, the frequency used is 50 kHz. At this frequency, the capacitance properties of the cell membrane are transformed into resistance so that the current is capable of passing through the intracellular water section [9]. In BIA, two electrodes are used to insert current into the body commonly referred to as a current electrode, while two other electrodes are used to measure the resulting voltage or so-called voltage electrode as shown in Fig. 2.

In this research, a body fat percentage measuring device using bioelectrical impedance analysis (BIA) method with automatic switch. The design of the authors using whole body measurement method that can perform measurements in several electrode schemens, e.g. hand-to-hand, hand-to-foot, and foot-to-foot. Four electrodes are used in this design which consists of two electrodes to enter the AC current into the body and two electrodes to measure the voltage generated from the body. The automatic switch mechanism is designed as a sequence control method of measuring the percentage of body fat, with the additional parameters of height, weight, age, and gender are keyed-in.

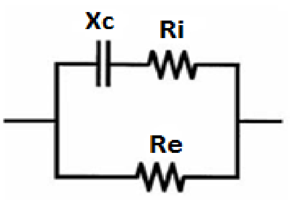

Fig. 1. Equivalent circuit of body composition

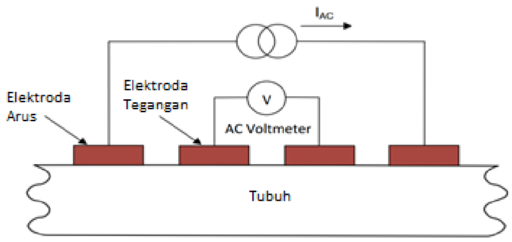

Fig. 2. Impedance measurement method using four electrodes [6]

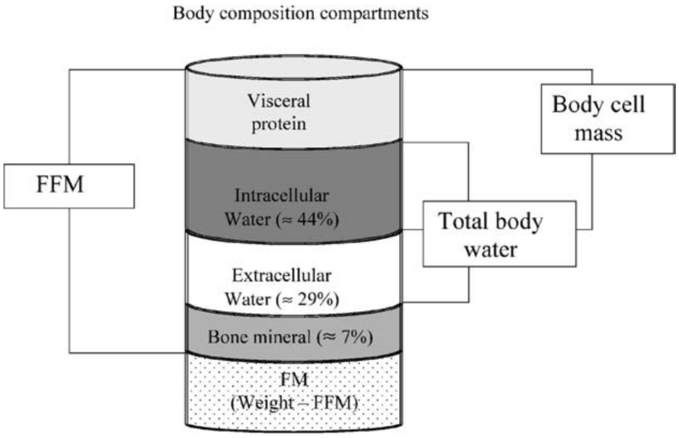

Fig. 3. Body composition [9]

The composition of the human body can be modeled in the form of two compartments, namely fat free mass and fat mass. Figure 3 shows the composition of the human body in which the fat free mass (FFM) is composed of approximately 73% fluid, 20% metabolic tissue, and 7% of minerals in bone [9].

One of the equations used to determine FFM is the result of an experiment conducted by Myloot et al as shown in Eq. 2 [10]

$$FFM = 0.36\frac{h^2}{z} + 0.16h + 0{,}29w - 0{,}13a + 4{,}8g - 6{,}83 \qquad (2)$$

where FFM is fat free mass (kg), h is height (cm), z is impedance (Ω), w is weight (kg), a is age (year) and g is gender (1 for man and 0 for woman). The typical composition of the human body is shown in Fig. 3. The fat mass can be known in accordance with Eq. 3.

$$FM = Weight - FFM \qquad (3)$$

Having known the value of fat mass (fat mass) then the value of body fat percentage (body fat percentage) can be known by comparing the value of fat mass to body weight in accordance with Equation 4.

$$BF = \frac{FM}{Weight} X\ 100\% \qquad (4)$$

Differences in the fat ratio of body composition between men and women results in the different criteria of determination of body fat status in BIA. It is affected by the gender and age of person [10].

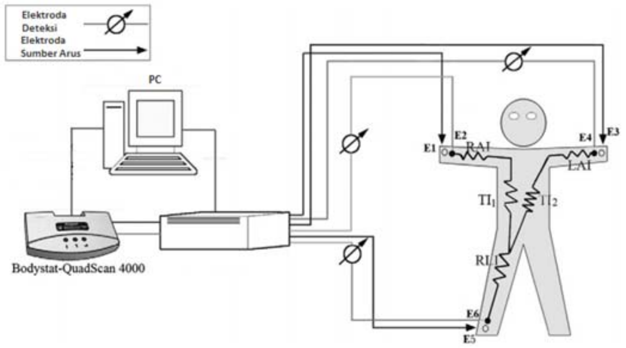

Fig. 4. H*and-to-foot* and *cross-sectional impedance* measurement techniques [11]

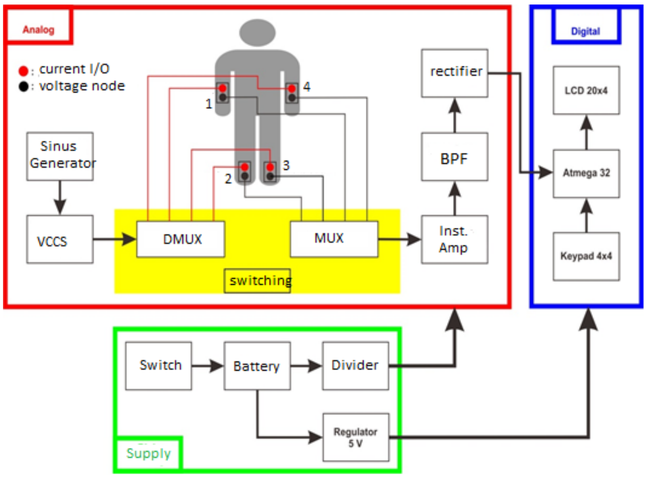

Fig. 5. Block diagram of automatic switching 4-electrode BIA

III. DESIGN

This system consists of 3 blocks, namely analog blocks, digital blocks, and power supply blocks. The analog block aims to transmit the current into the human body and measure the difference in body impedance produced in the form of voltage. Digital block is enabled to control the whole system. While the power supply block is used to provide voltage to analog and digital blocks. The block diagram of the system can be seen in Figure 5.

Fig. 5 reveals the block diagram of the system. Sine wave generator IC 80838 is used to produce 50-kHz AC voltage. A voltage controlled current source IC LF353P is selected to produce constant current of 0.2 mA. IC 74HC4052 is an analog/digital mux/dmux IC, and is used to determine which electrode to use for body fat measurement. Instrumentation amplifier is required to strengthen the measured voltage of the body as it has high CMRR. The active Sallen-Key filter topology is used to remove the noise signals at a certain frequency range. The desired middle frequency of BPF is 50 kHz with a cut off frequency value of 33-70 kHz. At the heart of the system, low-cost ATmega 32 microcontroller is used to control the whole system. In addition, the interface of the system is added with 4x4 keypad to enter human data for further calculation, and 20x4 LCD to display calculated impedance.

The test is performed to find out whether the output of the sine wave generating circuit designed to produce a sinusoidal signal with a frequency of 50 kHz. The test is done by looking at the output signal of the sine wave generator circuit using oscilloscope. Figure 8 is the output signal output from a sinus generator circuit which is capable of producing a sinusoidal signal with a frequency of 50.01 kHz and a VPP voltage of 2.16 V. The resulting 50.01 kHz frequency corresponds to the system design.

IV. RESULT AND ANALYSIS

The test was performed to determine whether the voltage controlled current source (VCCS) is capable of producing a constant current of 0.2 mA with the load varied. The load variation uses 1-k Ω potentiometers whose values are adjusted to the human body impedance ranging from 0 – 1530 Ω. Test results from the VCCS block can be seen in Table 2.

Table 1. VCCS test result

R_{load} (Ω)	V_{out} (mV)	V_{load} (mV)	Output Current (mA)		Relative error (%)
			Measured	Simulated	
100	2640	20	0,20	0,22	9,1
150	2650	30	0,20	0,22	9,1
200	2660	40	0,20	0,22	9,1
250	2670	50	0,20	0,22	9,1
300	2690	70	0,23	0,22	4,5
350	2700	80	0,23	0,22	4,5
400	2710	90	0,23	0,22	4,5
450	2720	100	0,22	0,22	0,0
500	2730	110	0,22	0,22	0,0
550	2740	120	0,22	0,22	0,0

Table 1 shows the result of measured current value has the lowest value of 0.20 mA and the highest is 0.23 mA. The resulting current value is still at a safe limit that ranges from 0.2 - 0.8 mA and its value is relatively stable. The result of this VCCS block test is also in accordance with system design.

The automatic switch test was conducted to determine whether the circuit able to work as the electrode sequence controller used in each measurement mode of body fat percentage. The test is performed by matching the logic value of the selectors on pins 9 and 10 IC 74HC4052 with LED flash indicator based on sequence of measurement mode of body fat percentage. The switching block testing scheme for each measurement mode of body fat percentage can be seen in Figure 9.

Table 3 shows the automatic block switch testing as the electrode sequence controller used in each measurement mode of body fat percentage is working well. For example, to find out whether the body fat percentage measurement mode is hand-to-hand (H-H), then we need to test it according to the test scheme in Fig. 6 by first determining the selector logic by pressing the switch. When the body fat percentage measurement mode is hand-to-hand (H-H) then the respective LED will light up. The same is true for other body fat percentage measurement modes. To find out if the output of IC 74HC4052 affects the constant current value of 0.2 mA generated by a voltage controlled current source, it is necessary to compare between the input and output of the automatic switch block on the hardware. Test results can be seen in Table 4.

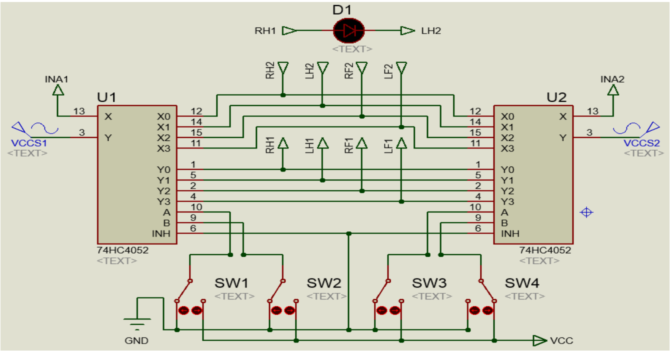

Fig. 6. Test scheme for each operation mode

Table 1. Test of selector sequence for 6 different modes

Selector				Electrode pairs Mode	LED
S1$_1$	**S0$_1$**	**S1$_2$**	**S0$_2$**		
0	0	0	1	*hand-to-hand* (H–H)	√
0	0	1	0	*right hand-to-right foot* (RH–RF)	√
0	0	1	1	*right hand-to-left foot* (RH–LF)	√
0	1	1	0	*left hand-to-right foot* (LH–RF)	√
0	1	1	1	*left hand-to-left foot* (LH–LF)	√
1	0	1	1	*foot-to-foot* (F–F)	√

Table 2. Test of input and output of automatic switching

R (Ω)	Vin 1 (mV)	Vin 2 (mV)	Vout 1 (mV)	Vout 2 (mV)
100	2640	2620	2660	2640
150	2650	2620	2670	2640
200	2660	2620	2680	2640
250	2670	2620	2690	2640
300	2690	2620	2710	2640
350	2700	2620	2720	2640
400	2710	2620	2730	2640
450	2720	2620	2740	2640
500	2730	2620	2750	2640
550	2740	2620	2760	2640

Table 4 shows that between the input and output currents of IC 74HC4052 did not change. The resulting current is relatively stable with a low value of 0.20 mA and the highest is 0.23 mA, but its value is still at a safe limit ranging from 0.2 - 0.8 mA. So, it can be concluded that the automatic switch block is able to work well in accordance with system design.

The linearity test is performed to know the characteristic of analog block system from sin sinus generator, voltage controlled current source, auto switch, instrumentation amplifier, field pass filter, and AC to DC converter. The test is done by looking at the effect of the load increase to the output voltage on the AC to DC converter block.

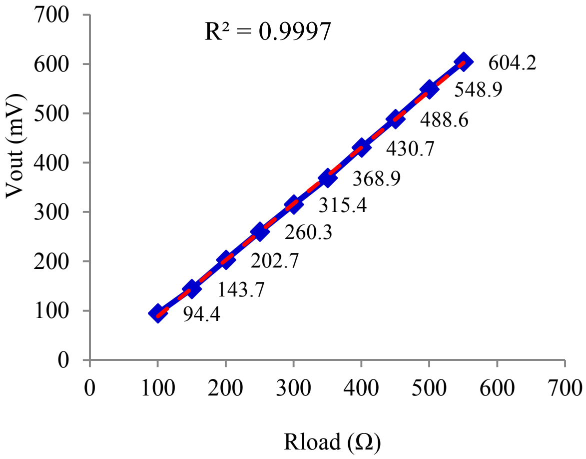

Fig. 7. Linearity test between load and output voltage

Fig. 7 shows the result of linearity test between load resistance which represents the body impedance and the output voltage. As indicated by the result, the output voltage is linear with the increment of resistance (R^2=0.997), thus the system can be viewed as having linear response.

The overall test was done by measuring 10 respondents (5 males, 5 females). The test was done by comparing the measurement using our BIA with other commercial BIA. Table 8 shows the comparison of the results of each method of measuring body fat percentage with the highest average relative error rate of 4.6% and the lowest of 1.9%, while for standard deviation has the highest value of 2.2% and the lowest is 1.1%. The tolerance limit for an acceptable error is 5%, so that the percentage of body fat measurement made is appropriate to the design.

Table 5. Test result for different scheme

Electrode pairs	Relative error (%)	Std. dev
right hand to left foot (RH *to* LF)	1.9	1.1
left hand to right foot (LH *to* RF)	1.9	1.2
hand to hand (H *to* H)	2.2	1.8
foot to foot (F *to* F)	4.6	2.2

V. CONCLUSION

Based on the results and analysis described earlier, it can be concluded that the body fat percentage measurement system designed is working well. The average relative error resulting from each measurement methods consisting of cross method, hand-to-hand, and foot-to-foot have the highest error of 4.6% and the lowest of 1.9%, while the standard deviation has the highest value of 2.2% and the lowest is 1.1%. For further development, the design of the system needs to pay attention to contact resistance resulting from the measurement of body fat percentage.

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