MEASURING SYSTEM OF HEMODYNAMIC PARAMETERS USING ELECTRICAL IMPEDANCE

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Abstract - **Tissue bioimpedance measurement technique is currently applied in a wide range of measurements with biomedical applications, such as characterization of human body composition, measurements of hemodynamic parameters, lung, brain, etc. Tissue impedance can be modified function the frequency of the injected current. Therefore, bioimpedance measurement should be performed in a wide range of frequencies. This paper proposes a measurement system which is composed of a microcontroller, a programmable waveform generator and a voltage controlled current source. Microcontroller is controlling the whole system to schedule and to generate a sine wave, the frequency band 100 Hz to 100 kHz. Then, this signal is converted to current using a current controlled voltage source type based on Howland circuit. Bioimpedance signal acquisition on computer was achieved by using a USB data acquisition device NI 6009. For signal processing of bioimpedace, user interface and display LABVIEW and MATLAB were used. The MATLAB software was developed to analyze some vascular hemodynamic parameters. This device is able to acquire and process signals from both the electrical impedance of the central (heart) and peripheral (upper or lower limbs). This technique is a non-invasive and cost-effective method to measure and analyze hemodynamics, which would present for physiologist very important information for critical and continuous care of patients with hemodynamic disorders.**

Keywords: *impedance, microcontroller, current controlled voltage source, virtual instrumentation, Howland circuit.*

1. INTRODUCTION

The bioimpedance technique is applied in many measurements in the medical field, such as a tissue characterization in terms of its composition, measurement of physiological parameters (flow, pulse, blood, and pressure), detection of disease including the field of biosensors. This method has the following advantages: easy to use, relatively low price, fast response and most importantly is a noninvasive method of measurement. The structure of tissues with their content may have different electrical characteristics. There are several models to describe the behavior of these features. Electric models most often used to characterize tissue are those containing three circuit elements (Figure 1).

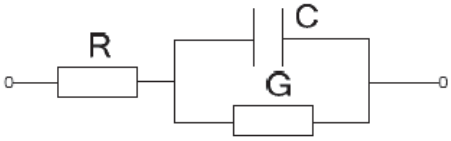

Figure 1. Electrical circuit modeling of tissues.

Due to the nature of tissue, impedance varies with frequency measurement signal, so the impedance will decrease as frequency increases. The relationship between impedance and frequency is linear [2]. Both resistivity and permittivity are frequency dependent. The circuit is AC powered and ensures current limitation at high frequencies. It is possible to obtain the same values for all frequencies with one set of values of elements circuit components. The series circuit characterizes best the impedance, as the time constant is uniquely defined (equations (1) - (7)). It is used as an electrical equivalent of human tissue, with a value of (R) representing the depth of tissue in series with the electrical representation of the superficial tissues (skin) composed of (G) and (C) in parallel. Frequency response of this circuit is represented in Figure 2.

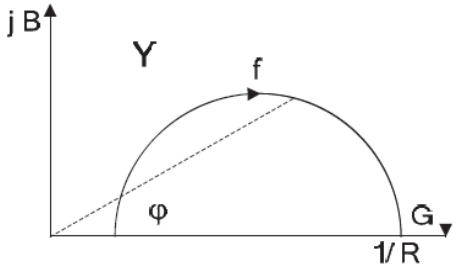

Figure 2. Frequency response of the circuit representation 2R – C

The 2R - 1C series circuit can be described by the following equation:

$$Z = R + \frac{G - j\omega C}{G^2 + \omega^2 C^2} \quad (1)$$

$$Z = R + \frac{1}{C(1+j\omega\tau_z)} \quad (2)$$

$$\tau_z = \frac{C}{G}$$

$$\varphi = \arctan\left(\frac{\omega C}{G(1+RG) + \omega^2 C^2 R}\right) \quad (3)$$

$$\varphi = \arctan\left(\frac{\omega C}{G(1+RG+\omega^2\tau_z\tau_2)}\right) \quad (4)$$

$$Y = \frac{G(1+RG) + \omega^2 C^2 R + j\omega C}{(1+RG)^2 + \omega^2 C^2 R^2}$$

$$Y = \frac{G(1+RG+\omega^2\tau_z\tau_2 + jw\tau_z)}{(1+RG)^2 + (w\tau_2)^2} \quad (5)$$

$$\tau_2 = CR$$

$$C_{ext} = \varepsilon' = \frac{C}{(1+RG)^2 + (\omega\tau_2)^2} \quad (6)$$

$$\varepsilon'' = \frac{G(1+RG+\omega^2\tau_z\tau_2)}{\omega[(1+RG)^2 + (\omega\tau_2)^2]} \quad (7)$$

Impedance is an important parameter that characterizes this circuit, as defined by a single time constant (τ_Z). This time constant is independent of (R) if the circuit is carrying current. Measured impedance parameter is in close correlation with characteristic frequency, determination of (τ_Z) is directly related to capacity and a conductance (such as effects of membrane tissues) connected in parallel. The same is not valid for admittance, which is dependent on (τ_Z) and (τ_2), and therefore of (R) and (G) [3]. Equation (6) is of particular interest. (C_{ext}) terminal capacity is measured, for example, a deck or an amplifier. At high frequencies the susceptible (B) = (Y) is small and (C_{ext}) is strongly dependent on frequency ($\frac{1}{\omega^2}$). In this frequency range, high capacity increases by decreasing frequency. But this does not reflect any function depending on the frequency components that acts as an internal capacitor. This reflects the simple fact that we have direct access to the condenser, but only the resistance at high frequencies. Human tissue may be seen as parallel conductor model containing muscle and blood. In this case, the bioimpedance relationship can be expressed by:

$$Z = \frac{L}{\sigma_m S_m + \sigma_b S_b} = \frac{L}{\sigma_m S_m + \sigma_b \frac{V_b}{L}} \quad (8)$$

where σ_m - muscle conductivity; σ_b - blood conductivity, S_m - sectional area of muscle tissue, S_b - blood vessel section area, L - measured length, V_b - blood volume. The method we use in determining the impedance is the method of four electrodes. This method consists of applying a current (I) between two electrodes and voltage detection between the other two electrodes. By this method, the impedance electrode is removed from the final impedance calculation. This applies as long as the electrodes have relatively low impedance compared to the input impedance voltage detector circuit. In surface measurements, skin impedance is also reduced because it is in series with each electrode [5].

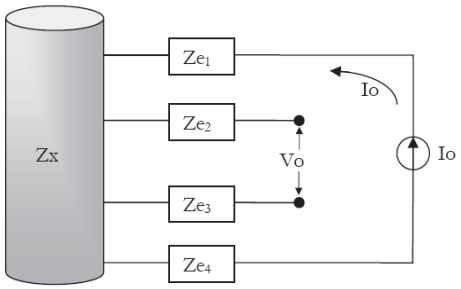

Figure 3. Four electrodes Method.

2. MATERIAL AND METHOD

Block diagram of the proposed system is shown in Figure 4. Microcontroller is used as a generator to produce sinusoidal wave of voltage range of frequencies from 100 Hz to 100 kHz. Then it is converted to current by a voltage controlled current source. With electrodes I_1 and I_4 the injection current is applied in the measurement region. Electrodes E_2 and E_3, at the distance (L) between them, collect and send the signal data acquisition device NI USB 6009, which communicates via USB with the PC that has the software.

Microcontroller is used to set the output signal amplitude and frequency. In addition, it is used as a control circuit for the converter D / A. Microcontroller - can communicate with the programmable waveform generator through a serial data transmission.

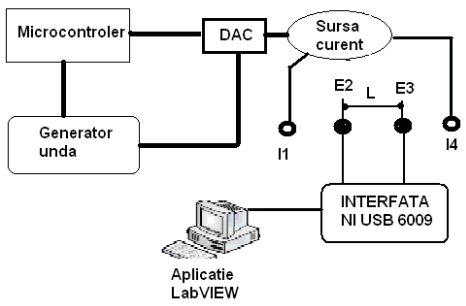

Figure 4. Block diagram of measuring system.

We used the MSP430F169 microcontroller because the total power consumption is reduced. The Texas Instruments MSP430 series is an ultra low - power microcontroller family consisting of several devices featuring different sets of modules targeted to various applications. The microcontroller is designed to be battery operated for use in extended - time applications. The MSP430 achieves maximum code efficiency with its 16 - bit RISC architecture, 16 - bit CPU-integrated registers, and a constant generator. The digitally-controlled oscillator provides wake - up from low - power mode to active mode in less than 6 µs. The MSP430x16x series are microcontroller configurations with two built - in 16 - bit timers, a fast 12 - bit A/D converter, dual 12 - bit D/A converter, two universal serial synchronous/asynchronous communication interfaces (USART), I^2C, DMA, and 48 I/O pins [8].

For multifrequency bioimpedance applications, the power source must generate different frequencies. This can be achieved with programmable waveform generator. We used for this purpose AD9833.

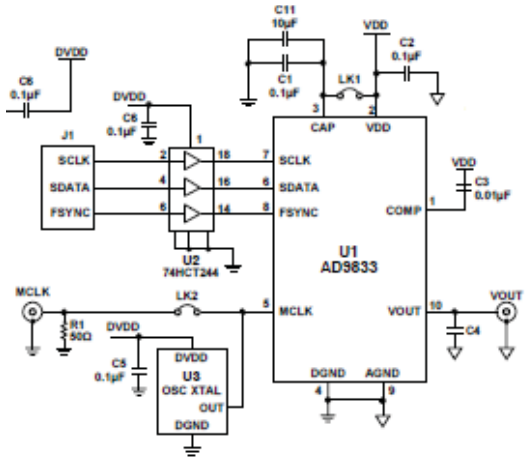

Figure 5. AD9833 circuit.

Microcontroller transmits data to the AD9833 internal registers through SPI interface. AD9833 can generate a voltage waveform with different frequency.

Current controlled voltage source was designed using a modified Howland circuit as required. It was chosen because this scheme is simple and of high performance.

If the circuit satisfies the condition:

$$\frac{R_2}{R_1} = \frac{R_4}{R_3} \tag{9}$$

The output impedance and load current and can be calculated using the following equation:

$$I = \frac{V_{AD5933}}{R_5} \tag{10}$$

Results that output impedance will approach to infinite. As a result, the performance of the current source may be very good for bioimpedance applications.

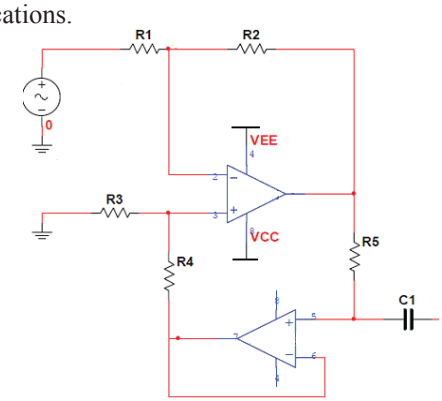

Figure 6 Howland circuit.

Bioimpedance signal acquisition on computer was made using a device data acquisition National Instruments, NI USB 6009. This card is positioned between the device and PC, provides signal digitization and transfers it to computer for further processing.

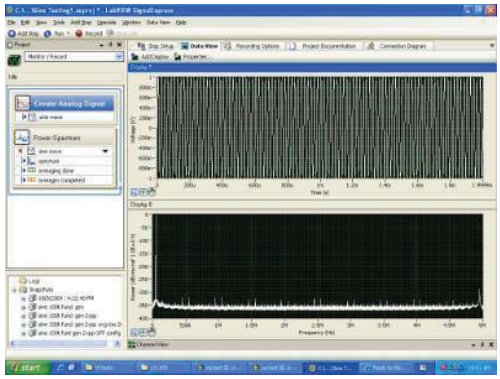

Figure 7 User interface in Lab VIEW.

Calibration process is a mechanism applied to the measurement of impedance to compensate for systematic errors caused by electronic components, differences in frequency responses etc. It is necessary for the system to be calibrated in order to achieve a correct signal. Calibration block was made in LABVIEW and is required before any measurement.

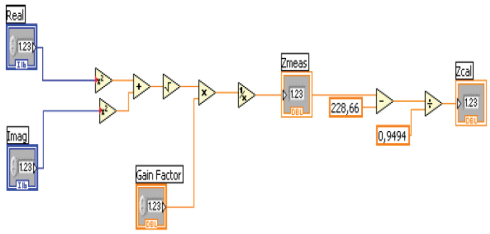

Figure 8. Block diagram of calibration system.

To check the dynamic range of the frequency of the system, several known resistance values were tested (Figure 9).

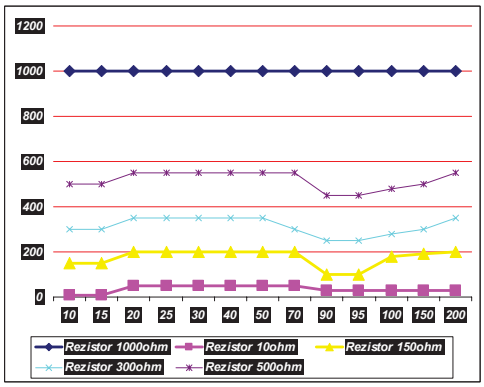

Figure 9. Calibration system - impedance depending function frequency variation.

3. RESULTS AND DISCUSSIONS

The software for data analysis was developed in MATLAB, a powerful software environment, mathematical, based on matrix operations. It offers the chance to create user interfaces with GUIDE Graphical User Interface Tools. The purpose of implementing the graphical user interface (GUI) for this project was to obtain usable programs through visual elements associated with stock control and the sliding display, buttons, menus, graphics [7]. For its realization it was necessary to build a tree structure, focusing on two directions: one associated with each patient's specific personal data and other related to analysis and calculation of specific parameters plethysmographyc waves (Figure 10).

The electrical impedance of the thorax can be thought of as composed of two types of impedances:

1. The base impedance (Z_0) corresponding to non-time varying tissues, such as muscle, bone and fat. (Z_0) is measured when the pulsatile volume is minimal.
2. The impedance (ΔZ) corresponding to time varying fluid volume (blood) [9].

The electrical impedance of the thorax Z (t) cyclically drops with each pulsatile volume of blood ejected from the heart. The relation between Z (t) and Z_0 is shown in equation (10).

$$Z(t) = Z_0 - \Delta Z \tag{11}$$

where: Z_0 = base impedance corresponding to non-time varying tissues; ΔZ = impedance corresponding to time varying fluid volume.

In the case of cardiac output, ΔZ is empirically determined to be as is shown by equation (11):

$$\Delta Z = T \cdot \frac{dZ}{dT} \tag{12}$$

where: T = Systolic (LVET) ejection time (seconds); $\frac{dZ}{dt}$ = magnitude of the largest impedance change during systole (Ohms/sec).

The pulsatile volume of blood ejected by the heart is called the stroke volume (SV). The expression relating SV to Z_0, T and $\frac{dZ}{dt}$ is:

$$SV = R \cdot \left(\frac{L^2}{Z_0^2} \right) \cdot T \cdot \frac{dZ}{dT} \tag{13}$$

where: SV = Stroke volume (mL); R = Resistivity of blood (Ohms * cm); L = Length between inner band electrodes (cm). To determine heart rate (HR), ECG was recorded simultaneously. Cardiac Output (CO) is related to SV as follows:

$$CO = SV \cdot HR \tag{14}$$

where: CO = Cardiac Output (liters / minute); HR = heart rate (BPM) [11].

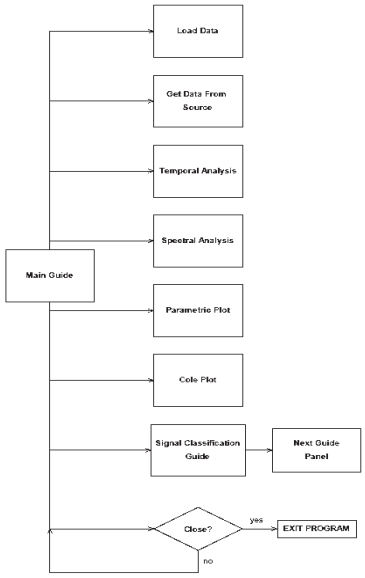

Figure 10. Flowchart of operation of the processing software.

The numerical values of hemodynamic parameters obtained from the analysis of signals are displayed according to user requirements. Parameters measured at the central level: SV = Stroke Volume; SVI = Stroke Volume Index; CO = Cardiac Output; CI = Cardiac Index; HR = Heart Rate; LVET = Left Ventricular Systolic Ejection; PM = Mean arterial Pressure.

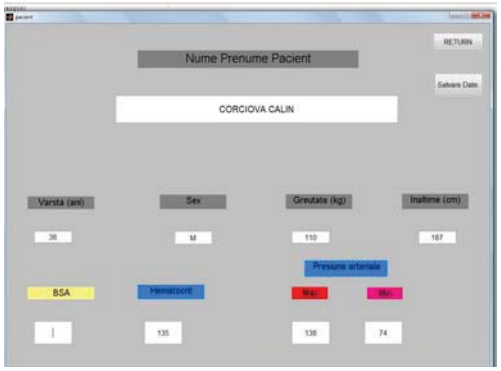

Figura 11. Patient data input window.

Parameters measured at regional level are the vascular flow, vascular compliance and vascular resistance. After choosing the type of file and its loading, the application provides users with three graphics specific to each patient and collected statements from the file: electrocardiogram, plethysmographyc wave and derivative order I of the plethysmographyc wave (Figure 12)

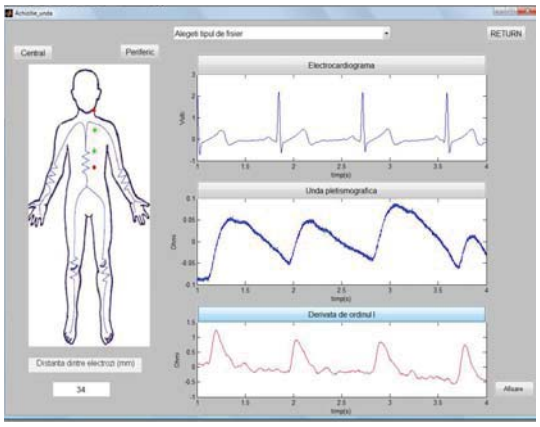

Figure 12. Presentation window of the waveform.

Extracting information from graphs, mathematical operation and the processing dates will be done in a new window (Figure 13).

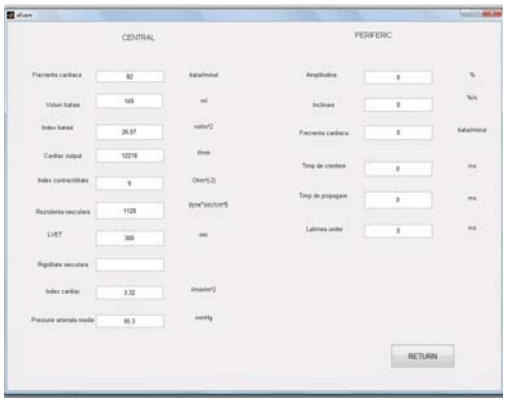

Figure 13. Processed data display window

A measurement was made on 20 clinically normal volunteers. The study has the approval of the Committee of Ethics of the university. Every calculation was performed as an average over 10 heart beats.

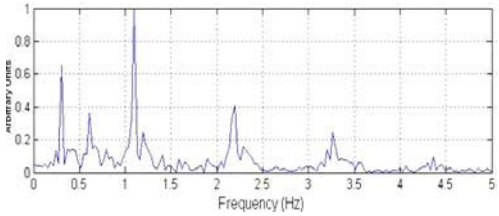

Figure 14 Power spectral density of the plethysmographic wave.

Heart rate (beats/min)	Distance from $E_2 - E_3$ (cm)	LVET (ms)	Stroke volume (ml)	Cardiac index (ml/m^2)	Cardiac output (ml/min)
62	34	288	137	39.9222924	8494
65	35	298	122	35.8823529	7930
68	34	278	121	36.8216399	8228
70	32	248	113	40.3571429	7910
69	34	280	114	42.8840125	7866
63	35	292	145	43.104872	9135
66	33	258	133	52.5	8778
63	32	270	130	54.1666667	8190
68	35	276	127	32.6571429	8636
63	33	260	125	32.6797386	7875
82	36	300	149	26.0768109	12218
75	33	290	143	31.7777778	10725
68	30	260	115	31.3636364	7820
80	33	283	130	27.3684211	10400
91	34	282	128	27.6806632	11648

Table 1: Central parameters and their calculated values

For peripheral plethysmography wave analysis we developed a software processing module corresponding figure 13.

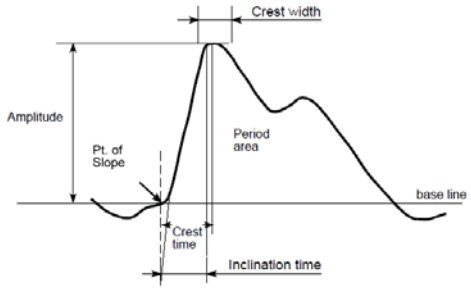

Figure 15. Analysis of peripheral plethysmographyc wave.

	Arm	Leg
Flow / beat (ml)	0.95 – 4.30	1.58 – 7.10
Flow/minute (ml)	92 - 283	103 - 480
Z_0 (ohm)	42.0 - 81	37 - 70

Table 2 Values of the blood flow measurements in normal limbs.

Heart rate (beats min)	Crest time (ms)	Impedance quotient (p.m.)	Slope quotient (p.m.)	Crest width (ms)
71	120	1.18	23.9	69
69	118	1.00	20	65
82	127	1.20	25	76
70	119	1.11	23.4	71
91	130	1.24	28	72

Table 3 Peripheral parameters calculated.

4. CONCLUSIONS

Tissue electrical impedance measurement technique is a method of diagnosis and study that brings to the medical staff a set of advantages over the traditional methods for determining cardio - vascular parameters. It largely meets the qualities of an ideal method for determining hemodynamic parameters: to be noninvasive, can be used for any patient, to be easily reproducible, can be used immediately for diagnostic and therapeutic procedures.

The final solution chosen in the design and construction of the signal acquisition system for electrical impedance proved to be viable and meets the technical criteria.

The software used in calculating the central and peripheral vascular parameters was performed using accessible environment software. The proposed system can be easily applied in a variety of clinical investigations.

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