Influence of Frequency of Excitation Signal and Electrode Position on the Transthoracic Impedance Measurement

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***Abstract*—In this paper an analysis of influence of electrode position and frequency of excitation signal on the transthoracic impedance is described. In the conducted study, positions of ECG electrodes, placed on the thorax of male volunteers, were changed while bioimpedance was monitored with a developed AD5933-based impedance measurement device. The measurement system is controlled with the custom PC software and all results are stored on a local hard disk of computer, which allows easy offline analysis. Each electrode configuration was tested on 10 frequencies in the range of 10-100 kHz during 10 minutes of normal breathing, in sitting positions of volunteers. All tested subjects did not consume food or water at least two hours prior to the measurement. Temperature and relative humidity of the ambient were monitored with SHT-11 sensor. Obtained results show that the magnitude of transthoracic impedance is decreased with increasing of the frequency, while the phase angle is increased. The biggest relative change is in lower frequency range, while on higher frequencies this change is significantly smaller. Moreover, changes caused by different electrode positions were noticed and discussed.**

Keywords—AD5933, bioimpedance, ECG electrodes, transthoracic impedance

I. INTRODUCTION

Nowadays, with the rising cost of healthcare and an aging worldwide population, there are growing demands on health services, which require big investments in expanding infrastructure of hospitals and increasing number of clinical staff. Because of that, remote monitoring technologies in combination with home-based analysis performed with diagnostic medical devices, can reduce cost of healthcare in general. Thus, there is a strong motivation for many industrial and academic institutions to develop smart home health care devices and systems. These devices are usually designed to monitor blood pressure, temperature, heart rate and breathing.

Adequate respiratory activity is critically important for the human life. Breathing is spontaneous reaction, and its rate is changed many times during the day and/or night, with strong dependency on physical activities (such as sport) or mental conditions (stress, fear, etc.). Normal adult human has a respiratory rate of 12–15 *breaths/min* in rest, inspiring and expiring 6–8 *l/min* of air [1].

The mortality related to acute respiratory failure is significant [2], because respiratory failure can be difficult to predict. It can develop into a life threatening condition in just a few minutes, or it can build up more slowly [1]. Based on this fact, it is obvious that continuous monitoring of respiratory activity is very important for identifying or predicting high-risk situations.

Respiratory monitoring is also very important for many clinical reasons such as cardiac arrhythmias [3], synchronization and compensation of MRI scans of sequences of the heart and thorax [4, 5], detection of sleep apnea [6] and in general postoperative care.

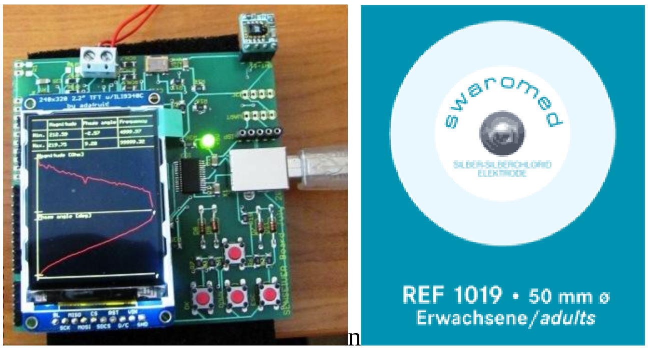
Approaches designed to measure respiration can be divided into two main groups: direct (for example, nasal thermistors measure the temperature changes in the air and carbon dioxide sensors measure the change in carbon dioxide in inhaled and exhaled air), and indirect methods (such as transthoracic inductance and impedance plethysmographs). Each method has advantages and disadvantages [7].

Main purpose of our study is to investigate influence of electrode placement and frequency selection on the transthoracic impedance measurement. Similar study was described in [8] where lung water detection using bioimpedance spectroscopy was investigated by finding the optimal frequency range and electrode position. More detailed discussion regarding influence of electrode type, size and placement in bioimpedance monitoring is presented in [9]. In [10], transthoracic measurement device based on the integrated circuit AD5933 [11] is described. It is shown that AD5933 can be used in continuous acquisition such as impedance cardiography and respiration monitoring. Our study covers complete pipeline from development of multi-frequency measurement and data acquisition device to analysis of measured data according to the ECG electrodes position on the thorax. Compared to the similar work, contribution of our study is also that ambient temperature and relative humidity are monitored. This was implemented to ensure that all test subject were treated in the same environmental conditions.

II. Materials and Methods

During previous studies, we developed an automated system for electrical impedance measurement and data acquisition [12]-[14]. The main features of that system are low price, small dimensions and full standalone operation (including a TFT display, embedded keypad, SD card for data storage and the self-calibration system) as well as PC software for remote control. Impedance measurement device is based on the integrated circuit AD5933, which is a high precision impedance converter system, and it is designed to meet requirements for bioimpedance applications: amplitude of the output voltage can be changed from 200 mV to 2000 mV while frequency sweep can be performed in the range from 1 to 100 kHz in maximum 511 points with minimum frequency step of 0.1 Hz. Other characteristics of developed system are high overall accuracy (max. error in impedance magnitude and phase angle measurement is 2 %), a wide measurement range (100 Ω - 1 MΩ), small dimensions and USB power supply option. The PCB of the device is shown in Fig. 1a.

For bioimpedance measurement, the impedance measurement device should be connected with appropriate electrode system. In this study, standard Ag/AgCl ECG electrodes from Nessler Medizintechnik Gmbh were used (Fig. 1b).



(a) (b)

Fig. 1. (a) The PCB of the developed impedance measurement device. (b) Used ECG electrode

Developed analog front end for AD5933 [14] is composed in such a way that proposed system operates in two-electrode mode, which means that the same pair of ECG electrodes is used for stimulation and sensing.

To create appropriate profile of testing conditions, ambient conditions (temperature and relative humidity) were monitored with digital SHT11 sensor from Sensirion [15].

Device is controlled with software [14], which has been developed in such a way that ensures easy usage as well as that all steps in configuration, measurement and data acquisition are done automatically. Received results of measurement are presented in real-time on magnitude and phase angle graphs. Temperature and relative humidity are also graphically presented. All results of the measurement are stored automatically on the hard disk of the computer.

Although system accuracy has been examined earlier [12]-[14], in this study one additional test is performed. The magnitudes ($|Z_R|$, $|Z_C|$) and phase angles (θ_R, θ_C) of impedances of a resistor with resistance of R=220 Ω and a capacitor with capacitance of C=1 nF are measured using the developed system. The electrical conditions are the same as will be used in bioimpedance measurements: amplitude of excitation AC voltage is V_{out}=200 mV, while each test frequency (10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 kHz) is repeated 60 times, approximately one time per second. Mean values (m) and standard deviation (SD) of measurements are computed and presented in Table I. and Table II.

TABLE I. Mean value and standard deviation of impedance magnitude and phase angle measurement of resistor

	$|Z_R|$ [Ω]		θ_R [°]	
f [Hz]	**m**	**SD**	**m**	**SD**
10k	221.45	0.19	0.83	0.05
20k	220.33	0.36	0.91	0.07
30k	221.22	0.28	1.23	0.06
40k	221.62	3.93	1.79	1.03
50k	222.27	0.28	1.84	0.05
60k	223.20	0.28	2.08	0.06
70k	223.06	0.26	2.26	0.07
80k	223.37	2.30	2.40	0.60
90k	223.32	0.28	2.57	0.06
100k	223.59	0.37	2.84	0.07

TABLE II. Mean value and standard deviation in impedance magnitude and phase angle measurement of capacitor

	$|Z_C|$ [Ω]		θ_C [°]	
f [Hz]	**m**	**SD**	**m**	**SD**
10k	12475	198.1	-82.9	0.85
20k	6937.8	110.9	-88.6	0.78
30k	4706	19.4	-87.6	0.30
40k	3511.3	150.9	-87.4	3.02
50k	2886	16.1	-87.6	0.30
60k	2426.8	13.5	-87.4	0.26
70k	2093.4	6.6	-88.2	0.17
80k	1841.2	43.7	-88.4	1.20
90k	1642.8	7.6	-89.1	0.30
100k	1473.7	13.2	-89.1	0.52

As can be seen from the Table I. and II, the ratio of standard deviation and mean value of impedance magnitude and phase angle is the biggest on frequencies of 40 and 80 kHz, while on the other frequencies is significantly smaller. This behavior was not expected in the case of passive components so it was concluded that is consequence of the noise in measurement loop and it has to be considered in analysis of the obtained results in bioimpedance measurement.

III. Results

As mentioned above, the main purpose of this study is to investigate effects of frequency of excitation signal and electrode placement on the measured impedance of the thorax. ECG electrodes (in the Fig. 2. marked with A, B, C and D) were placed on thorax of the tested subject and each configuration (AB, AC and AD) was kept during one minute on every test frequency (10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 kHz), so entire measurement took 10 minutes in total.

Subjects were sitting and were instructed to have normal breathing. Temperature and relative humidity of ambient were also measured. SHT-11 sensor was placed on the measurement board, very close to the tested subject and all measurements were performed in indoor environment (temperature: 27±0.8 ºC, relative humidity: 48±3 %RH). Before the measurements, parts of the skin where electrodes will be placed were cleaned with 70 % diluted ethanol.

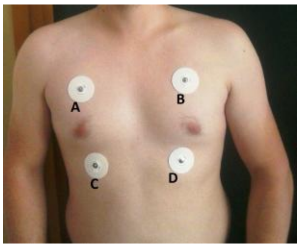


Fig. 2. Electrode position on the thorax of the test subject

Tested subjects were male, white race and aged between 23 and 26. More detailed description is given in Table III.

TABLE III. CHARACTERISTICS OF VOLUNTEERS INVOLVED IN THE EXPERIMENT

	Gender	Age	Weight [kg]	Height [cm]
Subject 1	Male	23	78	185
Subject 2	Male	24	68	170
Subject 3	Male	26	89	176

In the following tables, obtained mean values (m) and standard deviations (SD) of impedance magnitudes (|Z|) and phase angles (θ) for all three test subjects are given.

TABLE IV. MEAN VALUE AND STANDARD DEVIATION OF IMPEDANCE MAGNITUDE - SUBJECT 1

	AB		AC		AD	
	|Z| [Ω]		|Z| [Ω]		|Z| [Ω]	
f [Hz]	m	SD	m	SD	m	SD
10k	1267.3	5.42	1275.6	3.27	1086.2	2.68
20k	787.13	2.71	778.27	3.17	701.25	1.66
30k	628.53	2.03	610.51	2.39	573.88	1.71
40k	547.99	10.61	524.94	12.37	509.26	11.08
50k	502.15	1.39	477.02	1.86	470.44	3.02
60k	472.68	1.54	443.74	2.19	443.91	1.55
70k	449.65	4.35	422.77	2.24	426.08	4.73
80k	431.93	5.5	406.30	4.17	414.86	4.96
90k	419.35	1.35	391.75	1.70	403.65	1.13
100k	409.62	2.19	380.34	1.34	395.42	1.06

TABLE V. MEAN VALUE AND STANDARD DEVIATION OF IMPEDANCE PHASE ANGLE - SUBJECT 1

	AB		AC		AD	
	θ [º]		θ [º]		θ [º]	
f [Hz]	m	SD	m	SD	m	SD
10k	-61.49	0.33	-62.07	0.14	-56.82	0.16
20k	-51.33	0.24	-54.01	0.17	-47.18	0.13
30k	-44.04	0.19	-47.24	0.21	-40.25	0.18
40k	-38.82	1.18	-42.17	1.08	-35.25	1.14
50k	-35.19	0.18	-38.21	0.20	-31.96	0.26
60k	-32.13	0.13	-35.07	0.22	-29.11	0.16
70k	-29.89	0.63	-32.37	0.27	-26.91	0.44
80k	-27.85	0.80	-30.38	0.63	-25.15	0.76
90k	-26.11	0.20	-28.50	0.22	-23.60	0.19
100k	-24.62	0.21	-26.84	0.22	-22.30	0.15

TABLE VI. MEAN VALUE AND STANDARD DEVIATION OF IMPEDANCE MAGNITUDE - SUBJECT 2

	AB		AC		AD	
	|Z| [Ω]		|Z| [Ω]		|Z| [Ω]	
f [Hz]	m	SD	m	SD	m	SD
10k	1135.7	6.87	1242.0	6.58	1241.5	12.52
20k	747.13	2.15	793.24	1.90	807.45	2.31
30k	625.18	2.29	649.79	2.36	670.26	2.40
40k	566.89	12.54	580.18	11.42	601.76	13.50
50k	534.01	1.54	539.74	1.49	565.45	1.42
60k	513.04	1.60	514.12	1.97	541.19	1.46
70k	497.21	1.55	494.05	1.80	522.47	2.95
80k	485.38	4.71	479.01	5.64	508.75	7.04
90k	475.04	1.40	468.54	1.15	497.77	1.57
100k	468.16	1.51	459.66	1.61	490.07	1.94

TABLE VII. MEAN VALUE AND STANDARD DEVIATION OF IMPEDANCE PHASE ANGLE - SUBJECT 2

	AB		AC		AD	
	θ [º]		θ [º]		θ [º]	
f [Hz]	m	SD	m	SD	m	SD
10k	-56.83	0.23	-58.97	0.19	-57.05	0.7037
20k	-43.96	0.13	-47.65	0.15	-45.43	0.1556
30k	-35.70	0.16	-39.66	0.14	-37.57	0.2032
40k	-30.04	1.21	-34.14	1.20	-32.21	1.1456
50k	-26.40	0.14	-30.31	0.17	-28.63	0.1607
60k	-23.50	0.14	-27.32	0.19	-25.80	0.1483
70k	-21.38	0.13	-25.03	0.20	-23.69	0.2786
80k	-19.70	0.69	-23.13	0.65	-21.88	0.7106
90k	-18.38	0.17	-21.68	0.16	-20.67	0.1677
100k	-17.16	0.15	-20.34	0.19	-19.41	0.1576

TABLE VIII. MEAN VALUE AND STANDARD DEVIATION OF IMPEDANCE MAGNITUDE - SUBJECT 3

	AB		AC		AD	
	|Z| [Ω]		|Z| [Ω]		|Z| [Ω]	
f [Hz]	m	SD	m	SD	m	SD
10k	1224.1	5.24	1150.1	3.48	1119.3	3.19
20k	843.05	3.92	761.73	2.0	763.67	2.63
30k	725.87	2.69	644.49	2.23	657.34	2.58
40k	670.01	13.53	587.11	12.02	606.51	12.19
50k	640.43	2.09	558.24	1.80	577.61	1.33
60k	619.89	2.40	539.86	2.06	561.01	1.86
70k	604.22	4.37	525.30	7.32	546.86	9.76
80k	594.75	7.24	517.27	6.30	537.72	6.01
90k	586.69	1.81	507.76	2.11	528.34	1.63
100k	579.66	1.79	501.25	1.70	524.92	1.87

TABLE IX. MEAN VALUE AND STANDARD DEVIATION OF IMPEDANCE PHASE ANGLE - SUBJECT 3

	AB		AC		AD	
	θ [º]		θ [º]		θ [º]	
f [Hz]	m	SD	m	SD	m	SD
10k	-52.34	0.20	-56.62	0.15	-54.17	0.17
20k	-39.09	0.20	-43.14	0.16	-40.47	0.15
30k	-31.12	0.28	-34.49	0.20	-32.16	0.20
40k	-26.1	1.25	-28.73	1.20	-26.82	1.19
50k	-22.73	0.16	-25.01	0.19	-23.5	0.16
60k	-20.3	0.17	-22.06	0.25	-20.9	0.16
70k	-18.44	0.42	-20.05	0.78	-18.97	1.01
80k	-17.12	0.80	-18.27	0.95	-17.33	0.73
90k	-15.90	0.26	-17.09	0.26	-16.42	0.19
100k	-14.88	0.17	-15.98	0.16	-15.29	0.16

From Tables IV.-IX, it can be concluded that in the conducted study:

- the values of impedance magnitude decrease, while the values of impedance phase angle increase with increasing frequency, as discussed in [16];
- the biggest relative change of impedance magnitude and phase angle is in frequency step from 10 kHz to 20 kHz;
- at high frequencies (higher than 60 kHz) there is very small relative change in impedance magnitude and phase angle from one to next frequency step;
- magnitude and phase angle of transthoracic impedance are changed when electrode position is changed, but from the obtained results, no unique relationship between electrode placement and measured values for impedance magnitude and phase angle for all subjects can be found;
- the measurement results at 40 and 80 kHz have the biggest standard deviation due to the limitations of the measurement device, this should not be connected with patient behavior.

IV. Conclusion

Main aim of this study was to investigate analysis of electrode position and frequency of excitation signal on the transthoracic impedance measurement. Position of the pair of ECG electrodes, placed on the thorax of male volunteers, was changed in three different configurations while bioimpedance was monitored with a developed AD5933-based impedance measurement device. Each electrode configuration was tested on 10 frequencies in the range 10-100 kHz during 10 minutes of normal breathing, in sitting positions of volunteers. Temperature and relative humidity of the ambient were monitored with SHT-11 sensor.

Obtained results show that transthoracic impedance magnitude decreases with increasing of the frequency, while the phase angle increases. The biggest relative change of impedance magnitude and phase angle is in frequency step from 10 kHz to 20 kHz, while at high frequencies this change is significantly smaller.

In further studies, improvement of the measurement system will be done to remove noise present at 40 and 80 kHz. System can also be realized as handheld device with wireless data transmitting so remote monitoring of transthoracic impedance will be possible.

Furthermore, more test subjects will be involved in experiments so breathing patterns can be created, with the aim to detect when the subject is healthy and relaxed or under heavy physical or mental load.

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