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Experimental Research the Human Body Impedance in the Chest Area Depending the Frequency of the Injected Current

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Abstract: Present study is devoted to research of living human body impedance in chest area at different frequencies and amplitudes of injection current to define critical conditions for use of device for 2 and 3-dimensional multi-frequency electrical impedance tomography based on natural-model approach. This study describes a method of data obtaining, analyzes the measurement results. Based on this analysis, critical conditions for the use of devices for 2 and 3-dimensional multi-frequency electrical impedance tomography based on natural-model approach are identified. To assess the reproducibility of the measurement results, analysis of measuring data array was performed by calculating the coefficient of variation for each measured value. Based on this analysis, critical requirements for the amplitude of the injection current to a device for the implementation of 2 and 3-dimensional multi-frequency electrical impedance tomography based on natural-model approach were formed. Practical implementation of the approach makes it possible to change the frequency of injection current in the measurement process according to the algorithm which let explore the internal structures of biological object in different ranges of impedance and more accurately identify their type.

Key words: Multi-frequency, electrical impedance tomography, natural-model approach, coefficient of variation calculation, human body chest impedance measuing

INTRODUCTION

Important role is played by frequency and current supplied to the Biological Object (BO) in 2 and 3-dimensional Multi-frequency Electrical Impedance Tomography (MEIT). Due to the fact that the electrical properties of BO tissues are injected current frequency dependent, MEIT use in clinical practice is an important tool of diagnostic information (Aleksanyan *et al*., 2014).

The aim of this study is to study the influence of the frequency of the injected current on the measurement result, i.e., impedance. As MEIT devices work with a limited range of load impedances which in most cases is the impedance of BO then results of this work can be applied to determine the critical conditions for the use of this type of device as well as for the implementation of natural-model approach to problems of 2 and 3-dimensional MEIT generally (Aleksanyan *et al*., 2016).

MATERIALS AND METHODS

To estimate the impedance at the chest surface of the test person (male, 23) is placed an electrode belt, consisting of 16 electrodes of an alloy of cupronickel. (Aleksanyan *et al*., 2015a-c). Electrodes were pressed to the human skin surface by the pulled over rubber belt. To reduce the "skin-electrode" contact resistance gel used for ECG, EEG, defibrillation was applied. The belt is located in infrasternal area. The electrode E1 is placed on the spine, number direction is clockwise. The diagram of electrodes arrangement and a photo of electrode belt placed on test person and connected to the measuring unit shown in Fig. 1. For the measurement conducting the bread board model of hardware and software system of electrical impedance tomography was used (Aleksanyan *et al*., 2015). The model allow to connect the current source to any of 16 electrodes and measure the potential relative to a common point on any of the 16 electrodes (Aleksanyan *et al*., 2014). The structural diagram of the device shown in Fig. 2.

The max output voltage of the device is U_{out} = 10.5 V, the maximum amplitude of the injection current IM = 5 mA, these options are safe for human's body and allow to avoid the undesirable occurrence of biological effects in the tissues of the test BO (Pecker *et al*., 2004). Measurements were made between the electrodes E1→E9; E9→E1; E5→E13; E13→E5. To measure the

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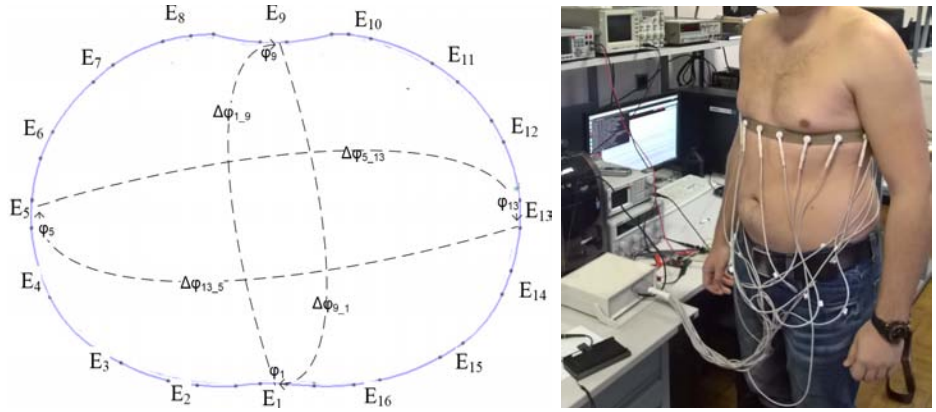

Fig. 1: a) Arrangement of the electrodes for example thorax section and b) the actual mounting on the body

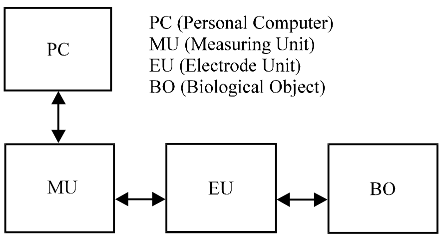

Fig. 2: Block diagram of the breadboard model of EIT device

impedance of the current source connected to these electrodes. Δφ was measured by the difference in potential between the 2 frequencies f_I = 1;5..20 kHz with a step of 5 kHz and amplitudes I_M = 0,1;1..5 mA with a step of 1 mA (Aleksanyan *et al*., 2015a-c). Z was calculated by Eq. 1:

$$Z = \frac{\Delta\varphi}{I_M} \qquad (1)$$

Where:
Z = Impedance value
Δφ = Measured potential difference
I_M = The amplitude of the injected current

The measurements were performed at full inhalation and exhalation. A[3] replicates for each value f_I and I_M. As a result of measurement, the average of three repeated experiments was made. To assess the repeatability of the experiment results, the variation coefficient applied V, defined by the formula (Stiglitz and Rothschild, 1970):

$$V = \frac{\sigma}{\bar{x}} \qquad (2)$$

where, σ is standard deviation, calculated according to the Eq. 2:

$$\sigma = \sqrt{\frac{1}{n}\sum_{1}^{n}(x_i - \bar{x})^2} \qquad (3)$$

Where:
N = Number of measurements
x = Measured value
$\bar{x}$ = The arithmetic mean, calculated according to the Eq. 3

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (4)$$

RESULTS AND DISCUSSION

Figure 3 shows the results of measurement of the impedance Z between the electrode E1 and the electrode E9 depending on frequency f_I and amplitude I_M of injection current during inhalation. Figure shows the graphs of the following:

- Fig. 3a plot of Z on f_I and I_M
- Fig. 3b a plot of Z on I_M
- Fig. 3c plot of Z on f_I

Figure 4 shows measurement results of the Z between the electrode E9 and electrode E1 dependence from f_I and I_M during inhalation. The analysis of the measured data presented in Fig. 3 and 4 shows that with decreasing f_I, Z increases, thus increasing the steepness of the rise in the transition from f_I = 5000-1000 Hz. It is also worth noting that with f_I>Z 5000 Hz frequency practically does not change with the growth of I_M.

Figure 5 shows measurement results of the Z between the electrode E5 and electrode E13 dependence from f_I and I_M during inhalation. Figure 6 shows measurement results of the Z between the electrode E13 and electrode E15 dependence from f_I and I_M during inhalation (Grayr *et al*., 2014).

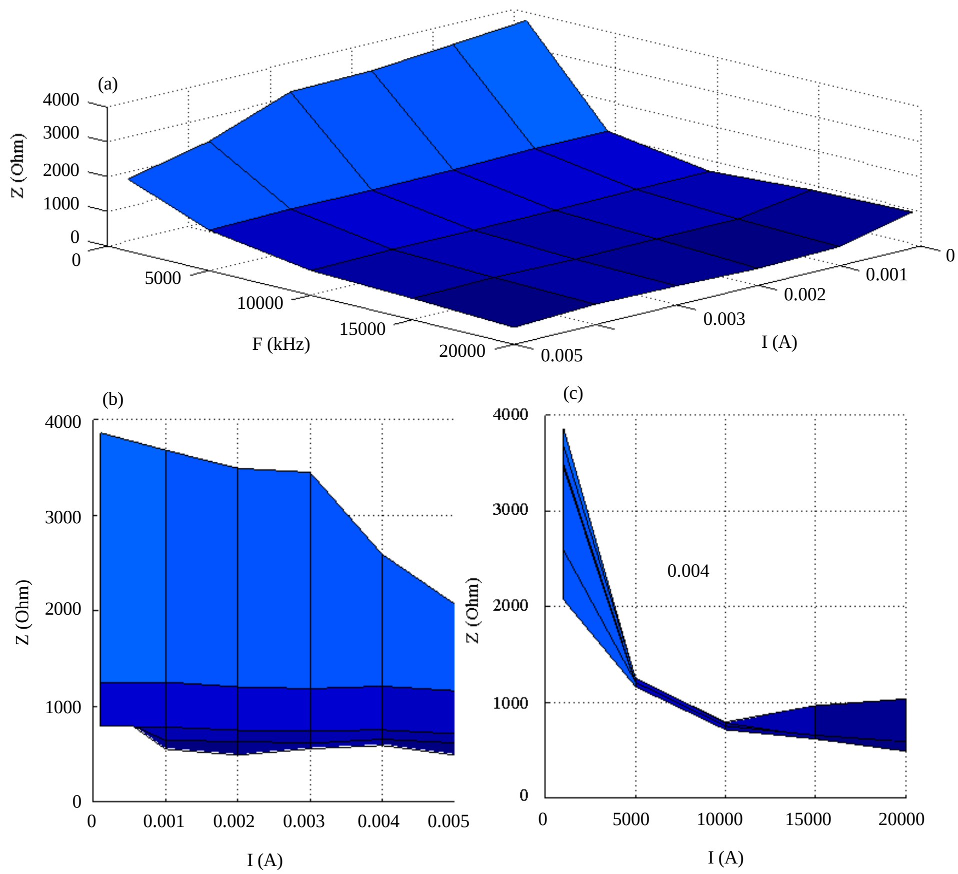

Fig. 3: a) Measurement results of Z between the electrodes E1 and E9 for different values f_I and I_M during inhalation: plot of Z on f_I and I_M; b) a plot of Z on IM; c) plot of Z on f_I

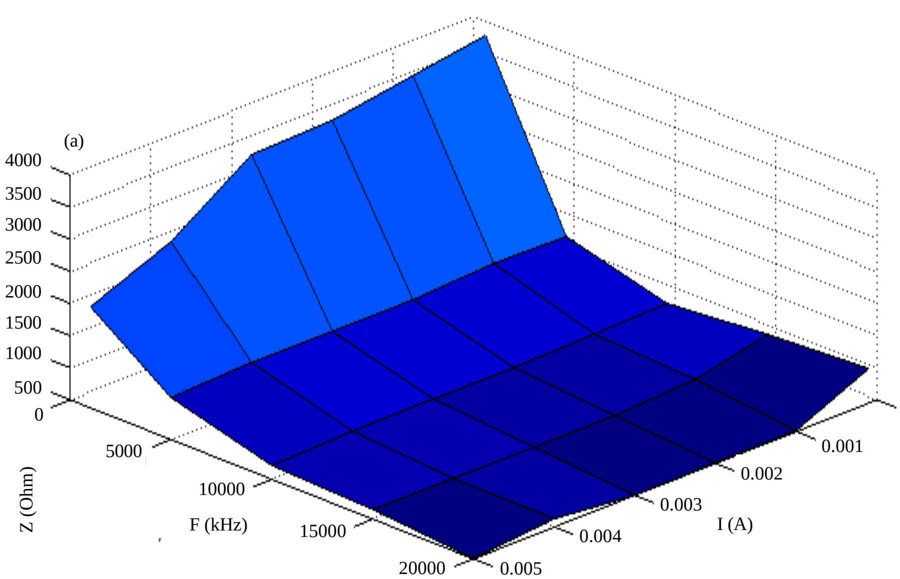

Fig. 4: Continue

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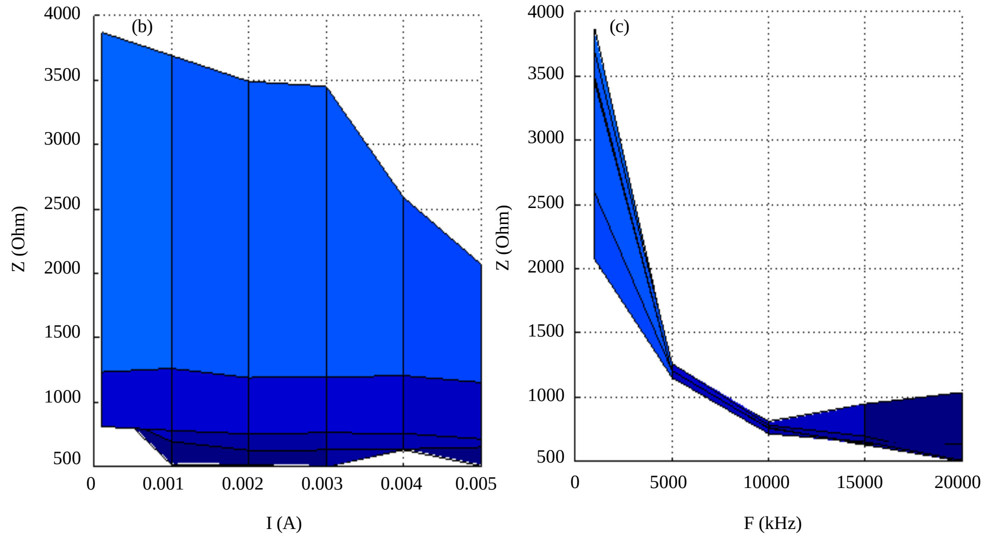

Fig. 4: Measurement results of Z between the electrodes E9 and E1 for different values f_I and I_M during inhalation: a) plot of Z on f_I and I_M; b) a plot of Z on I_M; c) plot of Z on f_I

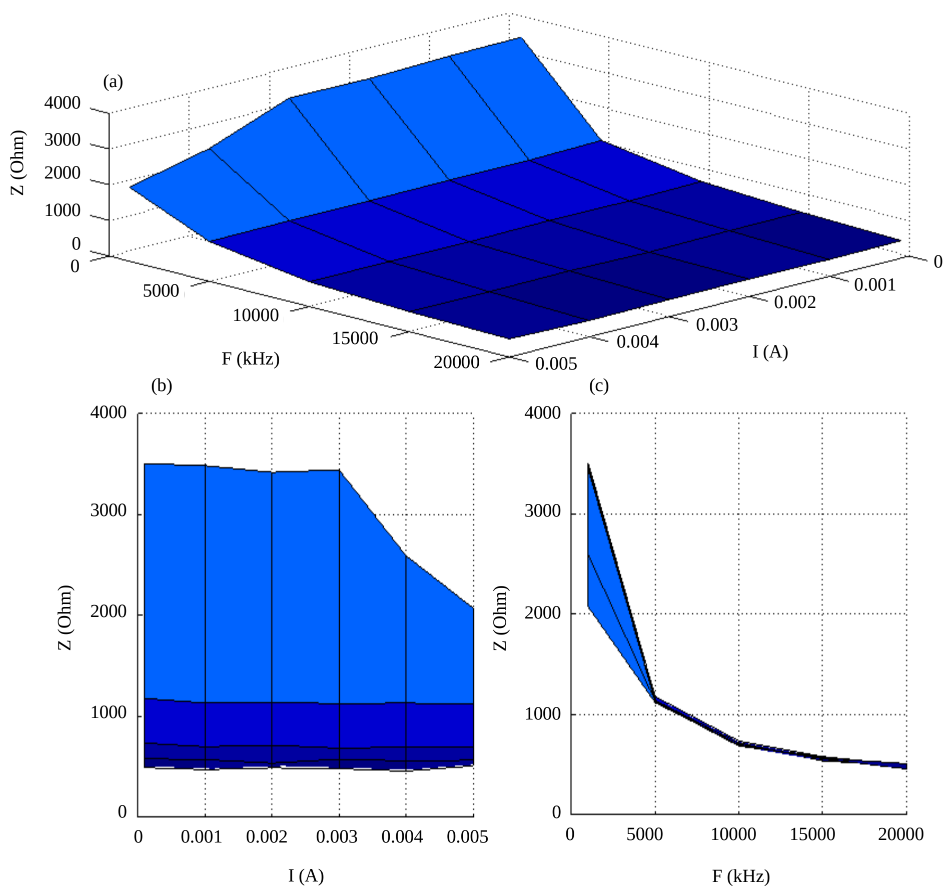

Fig. 5: a) Measurement results of Z between the electrodes E5 and E13 for different values f_I and I_M during inhalation: plot of Z on f_I and I_M; b) a plot of Z on I_M; c) plot of Z on f_I

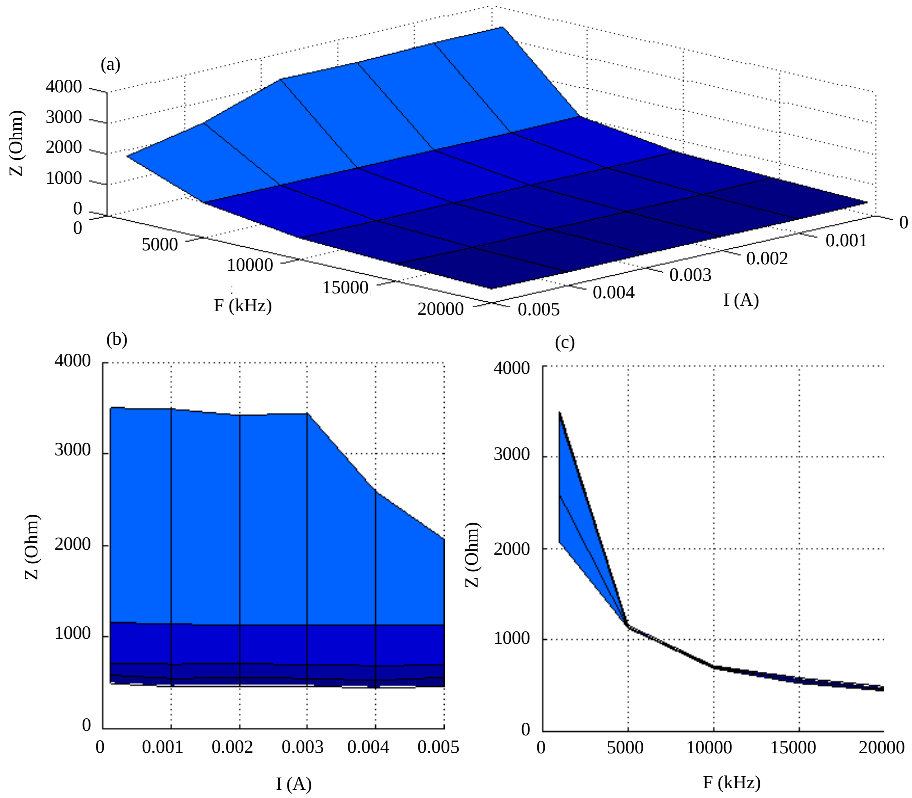

Fig. 6: a) Measurement results of Z between the electrodes E13 and E5 for different values f_I and I_M during inhalation: plot of Z on f_I and I_M; b) a plot of Z on I_M; c) plot of Z on f_I

It should be noted that given on Fig. 3-6 drop of Z with I_M >3 mA at a frequency f_I = 1000 Hz is due to the measurement unit restrictions of the max output voltage U_{out} = 10.5 V: at the maximum amplitude of the injected current I_M = 5 mA measurement Z possible only in the range:

$$Z = 0..Z_{max} = \frac{U_{out}}{I_M}$$

which in this case will be:

$$Z_{max} = \frac{10.5\ V}{0.005\ A} = 2100\ \Omega$$

Figure 7 shows the results of measurement of the impedance Z between the electrode E1 and the electrode E9 depending on frequency f_I and amplitude I_M of injection current during exhalation. Taking into account comments of the test person being feel uncomfortable in places of electrodes adjoining at f_I = 1 kHz, it was decided to limit the amplitude of the current at mentioned frequency to I_M = 2 mA.

Figure 8 shows the results of measurement of the impedance Z between the electrode E9 and the electrode E1 depending on frequency f_I and amplitude I_M of injection current during exhalation. Analysis conducted of the resulting measurement data presented in Fig. 6 and 8 shows that the nature of the change the Z impedance, measured at a "forward" direction of the injection current, similar to the data measured with a "reverse" the direction of the injection current electrodes and a common point.

Figure 9 shows the results of measurement of the impedance Z between the electrode E5 and the electrode E13 depending on frequency f_I and amplitude I_M of injection current during exhalation. Figure 10 shows the results of measurement of the impedance Z between the electrode E13 and the electrode E5 depending on frequency f_I and amplitude I_M of injection current during exhalation.

The results of impedance measurements on human chest surface during inhalation shown in Table 1. The measurement results of Z during exhalation shown in Table 2. Calculation of the coefficient of Variation (V) has been performed for evaluation of measurement results

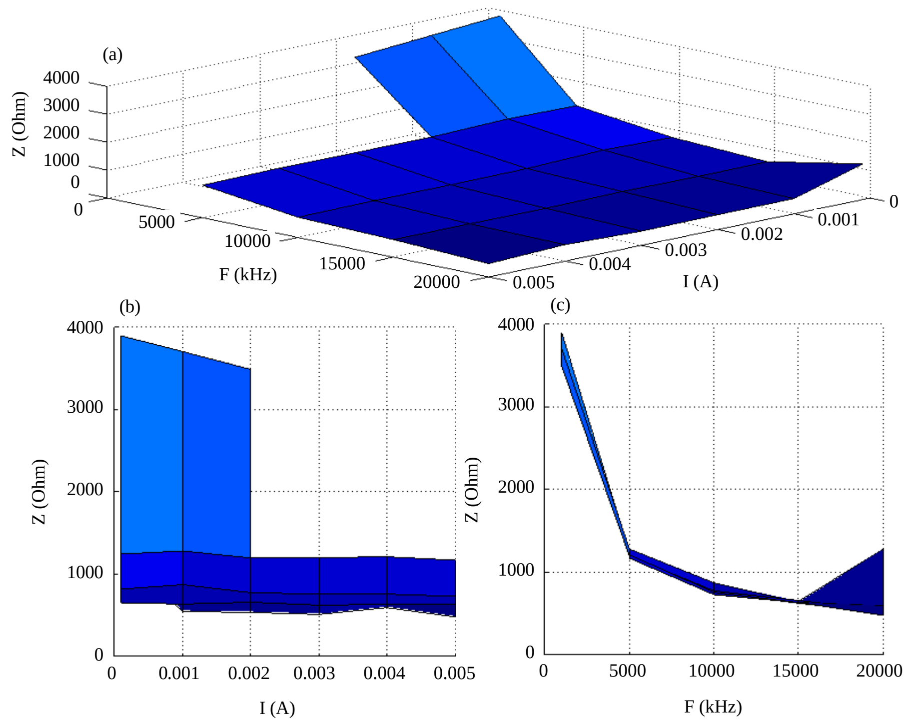

Fig. 7: Measurement results of Z between the electrodes E1 and E9 for different values f_I and I_M during exhalation: a) plot of Z on f_I and I_M; b) a plot of Z on I_M c); plot of Z on f_I

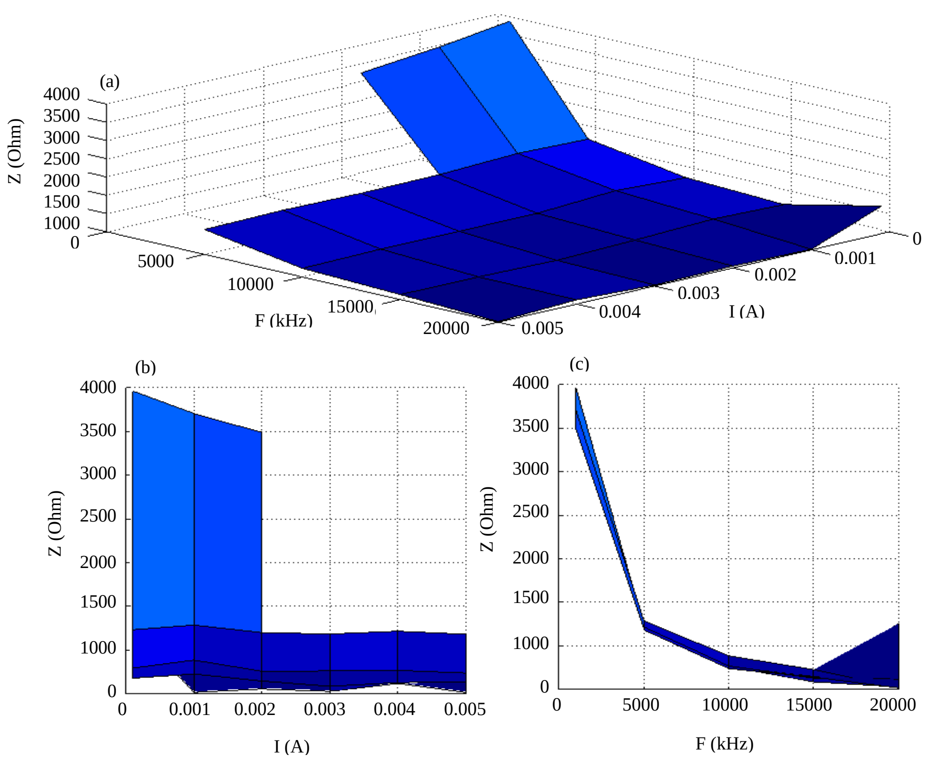

Fig. 8: a) Measurement results of Z between the electrodes E9 and E1 for different values f_I and I_M during exhalation: plot of Z on f_I and I_M; b) a plot of Z on I_M; c) plot of Z on f_I

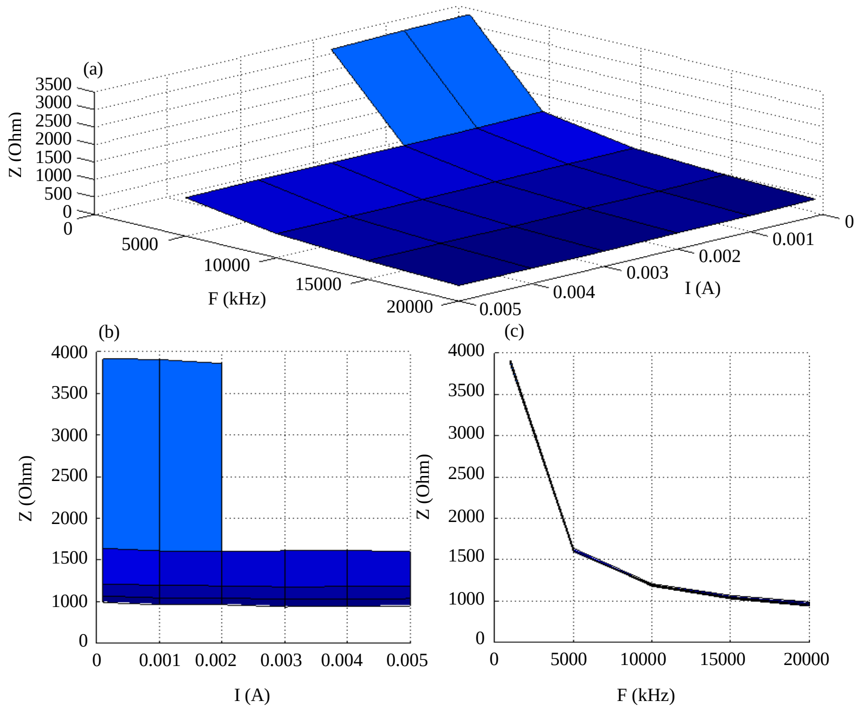

Fig. 9: a) Measurement results of Z between the electrodes E5 and E13 for different values f_I and I_M during exhalation: plot of Z on f_I and I_M; b) a plot of Z on I_M; c) plot of Z on f_I

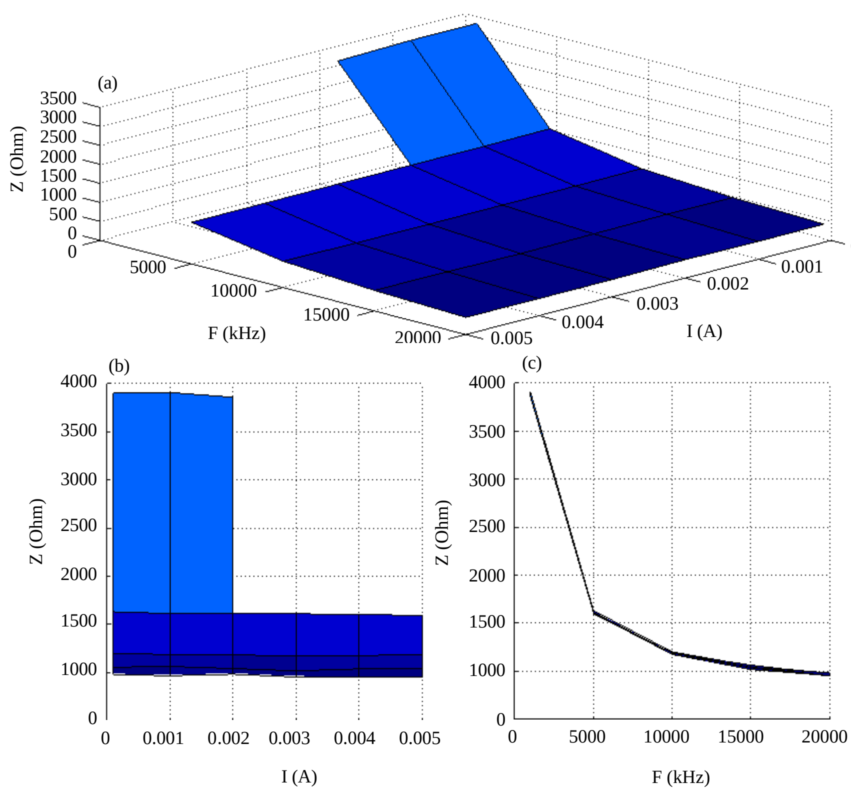

Fig. 10: a) Measurement results of Z between the electrodes E13 and E95 for different values f_I and I_M during inhalation: plot of Z on f_I and I_M; b) a plot of Z on I_M; c) plot of Z on f_I

Table 1: Measured values Z during inhalation at different values f_I and I_M

Fl (Hz)	I_M (mA)	Z_{1-9} (Ohm)	Z_{9-1} (Ohm)	Z_{5-13} (Ohm)	Z_{13-5} (Ohm)
20000	5.0	490.661133	506.859	508.251	460.5854
15000	5.0	618.683533	651.965067	564.6906	561.484667
10000	5.0	714.647533	715.406867	696.256267	695.581333
5000	5.0	1164.6874	1154.0576	1116.93733	1133.68367
1000	5.0	-	-	-	-
20000	4.0	591.075333	631.201	456.725667	445.020167
15000	4.0	657.19575	637.370083	557.751583	527.538667
10000	4.0	754.267083	757.588917	695.001333	688.621333
5000	4.0	1211.4145	1206.88	1131.53242	1134.69608
1000	4.0	-	-	-	-
20000	3.0	555.326222	500.067778	480.101556	463.369333
15000	3.0	615.365222	629.707	575.573556	550.264222
10000	3.0	746.832444	763.635	684.051556	701.275889
5000	3.0	1186.50956	1194.10233	1125.27533	1128.79044
1000	3.0	-	-	-	-
20000	2.0	490.260333	512.406	488.8895	464.318333
15000	2.0	635.788333	627.562833	535.711667	557.857
10000	2.0	751.999667	754.636	714.141333	709.817833
5000	2.0	1205.351	1190.9035	1139.336	1137.33233
1000	2.0	3492.03767	3490.1395	3418.85183	3420.96083
20000	1.0	552.162667	516.097	471.384	460.627333
15000	1.0	642.524667	695.058	571.052	548.858667
10000	1.0	784.523	781.062	698.309	704.759667
5000	1.0	1254.86967	1262.15867	1131.47533	1139.28933
1000	1.0	3683.54367	3690.92567	3485.07767	3489.92833
20000	0.1	1036.36333	1036.47667	491.34	491.9
15000	0.1	967.07	947.316667	578.976667	587.03
10000	0.1	795.45	811.49	734.203333	718.36
5000	0.1	1245.80333	1234.58667	1177.15333	1162.81
1000	0.1	3864.48667	3870.75	3506.07	3503.06667

Table 2: Measured values Z during exhalation at different values f_I and I_M

Fl (Hz)	I_M (mA)	Z_{1-9} (Ohm)	Z_{9-1} (Ohm)	Z_{5-13} (Ohm)	Z_{13-5} (Ohm)
20000	5.0	477.500333	516.603	445.610667	452.1068
15000	5.0	631.380333	639.141733	536.976933	542.4606
10000	5.0	727.428733	738.353867	686.934	690.814733
5000	5.0	1167.76673	1181.93987	1099.34747	1095.21367
1000	5.0	-	-	-	-
20000	4.0	591.39175	617.491917	440.64375	450.451083
15000	4.0	631.253667	627.352	535.86975	538.822417
10000	4.0	755.7435	768.45075	681.344917	675.123
5000	4.0	1209.2	1216.10733	1116.13592	1102.05775
1000	4.0	-	-	-	-
20000	3.0	508.574444	528.329667	437.638333	454.440889
15000	3.0	622.114333	585.626889	526.150333	518.417
10000	3.0	754.776778	762.088222	677.724333	674.701333
5000	3.0	1199.79689	1183.97867	1110.01967	1111.77722
1000	3.0	-	-	-	-
20000	2.0	533.075333	554.377	461.7875	482.984
15000	2.0	657.301167	647.1775	545.940667	542.038833
10000	2.0	772.879833	759.065333	689.148667	683.032
5000	2.0	1195.86	1200.3945	1103.2705	1112.44483
1000	2.0	3488.97933	3488.5575	3358.95333	3359.4805
20000	1.0	544.781	517.151333	461.260333	467.798333
15000	1.0	634.855333	726.68	545.232667	564.112
10000	1.0	870.789333	885.001	697.837667	686.562333
5000	1.0	1280.04133	1286.02	1109.18767	1113.54033
1000	1.0	3705.68933	3706.11133	3406.83	3407.88433
20000	0.1	1277.22333	1254.21	489.53	478.513333
15000	0.1	649.713333	678.82	568.186667	556.39
10000	0.1	815.856667	794.41	709.396667	701.803333
5000	0.1	1243.1	1232.24333	1139.63667	1132.13667
1000	0.1	3897.52	3963.58667	3418.06667	3408.40333

Table 3: Values of V during inhalation depending on f_I and I_M

Fl (Hz)	I_M (mA)	V_{1-9} (%)	V_{9-1} (%)	V_{5-13} (%)	V_{13-5} (%)
20000	5.0	1.20	1.23	0.49	1.16
15000	5.0	1.34	0.87	0.59	1.29
10000	5.0	1.38	1.21	1.78	0.66
5000	5.0	0.99	1.17	0.71	1.51
1000	5.0	-	-	-	-
20000	4.0	0.93	1.12	0.59	0.83
15000	4.0	0.54	1.35	1.40	0.64
10000	4.0	0.10	0.99	0.88	0.56
5000	4.0	1.05	0.65	1.51	1.07
1000	4.0	-	-	-	-
20000	3.0	1.41	1.37	0.86	1.49
15000	3.0	1.34	0.97	0.94	1.43
10000	3.0	1.50	0.41	0.30	0.27
5000	3.0	1.38	1.69	1.09	1.09
1000	3.0	-	-	-	-
20000	2.0	0.31	0.25	0.14	0.14
15000	2.0	0.83	1.59	1.46	0.95
10000	2.0	1.83	0.90	0.21	0.12
5000	2.0	0.91	1.00	0.38	0.50
1000	2.0	0.35	0.19	1.05	1.02
20000	1.0	1.83	0.64	1.28	1.03
15000	1.0	0.61	1.51	0.28	1.04
10000	1.0	0.82	1.19	0.68	0.90
5000	1.0	1.13	1.25	0.72	1.02
1000	1.0	0.68	0.80	1.49	1.58
20000	0.1	4.11	4.29	4.27	3.34
15000	0.1	4.46	3.91	4.31	4.03
10000	0.1	4.43	4.13	4.24	3.69
5000	0.1	3.83	3.98	3.97	4.20
1000	0.1	3.43	4.32	3.88	4.00

Table 4: Values of V during exhalation depending on f_I and I_M

Fl (Hz)	I_M (mA)	V_{1-9} (%)	V_{9-1} (%)	V_{5-13} (%)	V_{13-5} (%)
20000	5.0	1.15	0.09	0.30	1.07
15000	5.0	0.12	0.64	0.42	0.47
10000	5.0	0.36	0.68	0.36	0.07
5000	5.0	1.38	0.53	0.74	0.65
1000	5.0	-	-	-	-
20000	4.0	0.66	0.43	0.94	1.17
15000	4.0	1.13	1.05	0.04	0.29
10000	4.0	0.42	0.02	0.74	1.33
5000	4.0	0.76	0.36	0.36	0.96
1000	4.0	-	-	-	-
20000	3.0	0.51	1.08	0.73	1.38
15000	3.0	1.07	1.51	0.80	0.94
10000	3.0	0.21	0.42	0.56	0.57
5000	3.0	0.45	0.82	0.71	0.72
1000	3.0	-	-	-	-
20000	2.0	0.39	0.81	0.72	0.70
15000	2.0	1.03	0.15	0.32	0.43
10000	2.0	1.13	0.06	0.51	0.68
5000	2.0	1.14	0.76	0.45	0.94
1000	2.0	0.50	0.48	0.30	0.32
20000	1.0	1.23	0.34	1.36	0.55
15000	1.0	0.39	1.39	1.07	0.78
10000	1.0	1.16	1.10	1.81	1.45
5000	1.0	0.90	0.84	0.63	1.05
1000	1.0	0.35	0.33	1.35	1.39
20000	0.1	3.97	3.22	3.56	3.20
15000	0.1	3.01	2.31	2.54	2.64
10000	0.1	2.36	2.95	3.26	3.21
5000	0.1	3.63	3.00	2.89	2.57
1000	0.1	3.12	2.59	2.77	2.41

repeatability for each of the measured value Z. V calculation results during inhalation are presented in Table 3. The results of calculation of V during exhalation are presented in Table 4. Analysis of the coefficient of variation V presented in Table 3 and 4 shows that with I_M = 0.1 mA V increases which indicates a low repeatability of measurements at this value injected of current.

CONCLUSION

As the result of research on Z dependence from f_I and I_M using the breadboard model of hardware and S system of electrical impedance tomography, measurement data Z on the surface of the chest of a living human, measured on the inhale and exhale at several points ranging f_I = 1;5..20 kHz in steps of 5 kHz and I_M = 0,1;1..5 mA with 1mA increment were obtained.

Dependences of impedance Z on frequency f_I amplitude I_M were obtained from the measured data. Analysis of the dependencies suggests that thoracic impedance Z of living human chest increases with decreasing frequency f_I of injecting current. The dependences obtained demonstrate the efficacy of the 2 and 3-dimensional multi-frequency electrical impedance tomography as an imaging tool for applications of non-invasive study of the internal structures of BO.

To assess the reproducibility of the measurement results were analyzed measurement data array by calculating the coefficient of variation Values (V) measured for each Z. The analysis revealed a lower reproducibility of measurements for I_M = 0.1 mA, based on that the critical requirements for the injection amplitude current to a device for the implementation of 2 and 3-dimensional MEIT based natural-model approach were formed.

Also, worth noting is that during the measurements revealed a significant increase in the impedance Z on f_I <5 kHz as the result of the amplitude of I_M reducing as a result due to restrictions of the maximum output voltage of the device which makes a significant error in the result of the measurement process. Taking this into account as well as the discomfort feeling of the test person during measurement at f_I <5 kHz, the critical requirements for the frequency of the injection current to a device were formed for the implementation of 2 and 3-dimensional MEIT based on natural-model approach. These requirements are consistent with the results obtained, for example (Pecker *et al*., 2004).

The practical realization of natural-model approach to the problems of 2 and 3-dimensional MEIT allows to change the frequency of the injection current in the measurement process according to the algorithm which will explore the internal structure of BO in different ranges of impedance and more accurately identify their type.

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