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# EXPERIMENTAL DEPENDENCES OF MEASUREMENT DATA ON THE VOLUME OF INHALED AIR IN MULTI-FREQUENCY ELECTRICAL IMPEDANCE TOMOGRAPHY

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***This paper proposes an approach to modeling the process of artificial ventilation of human lungs by their controlled filling with a fixed volume of air, using an incentive spirometer Coach 2. This makes it possible to simulate the ventilation process for a healthy person and to link the assigned respiratory volume to measurement data. The results of experimental studies of the developed system of multifrequency electric impedance tomography are presented. The tests were performed for the frequency range from 50 kHz to 400 kHz (with a pitch of 50 kHz) at assigned respiratory volumes from 500 ml to 4,000 ml (with a pitch of 500 ml) for five inhalation/exhalation cycles. The scheme of research: active inhalation – passive exhalation, the number of tested volunteers – 3 people from the developers of the system. As a result, the dependences of the measured values of changes in potentials on the frequency of injected current for different respiratory volumes in three test participants without pathologies of the respiratory function and the external respiration function were obtained. The obtained results of the experimental studies show that there is a dependence of the value of the measurement data both on the volume of inhaled air and on the frequency of the injected current. This feature can be used to develop a number of medical devices for personalized monitoring of human lung function. It was also revealed that there are frequencies at which the maximum spread of measurement data according to the results of a series of repeated experiments is observed. At the same time, the nature of the change in the measurement data of the EIT at an increase in the volume of inhaled air is the same for all test participants. It is assumed that this feature can also be used to increase the EIT personalization degree***

***Keywords: electric impedance tomography, multifrequency, measurement data, respiratory volumes, experimental studies, conductivity***

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## 1. Introduction

Electrical impedance tomography (EIT) makes it possible to visualize the distribution of ventilation (that is, air filling) of human lungs by assessing the changes in the reconstructed transthoracic impedance [1]. This method can be used both in assessing the parameters of independent breathing and at artificial ventilation of lungs (AVL) [2]. Based on the obtained measurement data and their processing, a user is given a dynamic image reflecting the change in air filling in the considered areas of the lungs. Since obtained images depend on a change in the air content in the analyzed section, they can be characterized as functional, rather than anatomical (unlike, for example, spiral computed tomography or magnetic resonance tomography). One of the major problems that complicate the clinical application of the EIT method is a low degree of consideration of its parameters of exposure (especially frequency and force of injected current) for a particular patient. The EIT devices existing in the market do not provide this functionality and, accordingly, are limited in their capabilities in terms of advanced monitoring of lung functioning. This is due to differences in the structure and composition of the body, as well as in the activity of the entire respiratory system of a person as a whole and his lungs, in particular.

Overcoming the problems of clinical application of the EIT systems is possible with the introduction into practice of multi-frequency EIT (MF EIT) systems, which allow taking into consideration the dependence of changes in impedance of tissues of a human body on the frequency of the injected current. Thus, it becomes possible to take into consideration additional objective information about the object of study. This makes it possible to differentiate the subjects into groups, as well as to identify the structure of the object and the processes that take place (for example, the function of human lungs, the activity of the cardiovascular system, etc.).

At the same time, there is a problem of preclinical approbation of medical and technical means of the MF EIT and their study on living objects, including humans. This creates a number of difficulties in terms of research into the applicability of the MF EIT for the tasks of assessing the functional state of the lungs of patients with respiratory support. In this regard, there is a need to perform research into the methods and algorithms of the MF EIT not abstractly or using models, but under real conditions. This is especially important for obtaining measurement information in situations where further operation of the MF EIT systems is planned. One of the key areas of clinical use of the EIT is the monitoring of lung function of patients connected to the AVL apparatus.

That is why it is expedient to study and evaluate the work of the developed algorithms and the created MF EIT devices for conditions of intensive care units. At the same time, there is a major contradiction: on the one hand, to obtain initial data, it is necessary to perform the MF EIT simultaneously with the AVL, and on the other hand, it is impossible to connect the ventilator to a healthy person. The relevance of the solutions proposed in the paper lies in the practical implementation of the method for obtaining measurement data using the MF EIT method. The proposed method of controlled filling of lungs with a fixed volume of air while performing multi-frequency electric impedance tomography makes it possible to simulate the process of ventilation on a healthy person. In this case, the active element that controls the processes of inhalation and exhalation is a test participant who uses an incentive spirometer for research purposes. Thus, it becomes possible to conduct the MF EIT on a healthy person without connecting him to the AVL apparatus. This enables expanding the possibilities of studying the method. Thanks to this, it is possible to conduct preclinical studies of new methods, algorithms, and devices of the MF EIT under various AVL modes on healthy people. In addition, this approach allows identification of the problems of the practical use of the MF EIT systems for planning and conducting clinical examinations of the patients in intensive care units.

## 2. Literature review and problem statement

In clinical practice, it is important to be able to conduct non-invasive long-term bedside monitoring of air filling of the lungs of a patient connected to the AVL. Changes in such parameters as respiratory volumes and the magnitude of positive exhalation end pressure (PEEP) in patients with mechanical ventilation of lungs have a significant impact on their functional state [3, 4]. At the same time, an incomparably smaller number of scientific works are devoted to the study of the process of air filling of the lungs at independent breathing of a person with the use of the MF EIT method. Moreover, the problems associated with the simultaneous change in both the parameters of breathing and the parameters of the impact (force and frequency of electric current) almost are not studied. For example, paper [3] studies the relationship between changes in respiratory volume and electrical impedance (obtained using the EIT method) and the changes in positive pressure at the end of exhalation of the studied object who is connected to the AVL. However, the issues related to how various indicators of respiratory volumes affect the recorded EIT data, both at independent and spontaneous breathing, remained unresolved in this paper. This is especially important, as it makes it possible to assess the sensitivity of the EIT method to the problems under consideration. An option for overcoming the relevant difficulties is the study performed in [4]. In it, the authors evaluated the boundary possibilities of the EIT method for visualizing the ventilation process at the AVL with small respiratory volumes. At the same time, within the framework of the research and the obtained results, the authors did not take into consideration the electrical properties of the tissues of the studied objects themselves. This issue is important, as it imposes a number of restrictions in terms of selecting an adequate mode of the EIT injection for a particular field of study and does not take into consideration its composition and structure. It is noted that, despite the known limitations of the method, the EIT has great advantages in monitoring the lungs of a patient with respiratory complications who has mechanical ventilation. At the same time, as well as in [3], the issues of studying the respiratory volumes of patients without lung pathologies during independent breathing, when it is possible to vary the parameters of the effect of EIT in a wider range, remained unresolved. For example, the implementation of the multi-frequency function in EIT systems makes it possible to personalize all EIT activities, taking into consideration objective and reliable information about the object of study.

Papers [5, 6] showed that monitoring based on the EIT can be a source of valuable data on ventilation and perfusion function of lungs. Thus, paper [5] explores the possibilities of monitoring EIT of both the patients on mechanical ventilation of lungs and the patients who retain the function of independent breathing. It should be noted that the paper conducts the research into the parameters of independent breathing of patients with various pathologies of lungs and respiratory tract (asthma, chronic obstructive pulmonary disease, cystic fibrosis). At the same time, the authors did not consider the possibility of applying EIT monitoring of the lungs to the patients who do not have pathologies of the respiratory system. The paper does not disclose the parameters of EIT research, as well as their impact on the data obtained. Article [6] presents the results of studies on the use of the EIT for monitoring the respiratory volumes of animals (anesthetized horses during surgery). The results of clinical studies that confirm the possibility of recording respiratory volumes with the help of EIT are shown. However, like paper [5], it does not study how the obtained data depend on the parameters of exposure during the EIT. The studies similar to [5, 6] explore the problems of joint clinical use of the AVL and EIT systems. However, most of them do not solve the problems of increasing the personalization of the EIT method, including those based on the implementation of the MF EIT function. At the same time, the MF EIT is one of the promising areas for increased reliability. All this suggests that new studies are needed to establish general patterns and features of the MN EIT to solve the problems of monitoring the functional state of the lungs.

Paper [7] solves the issues of using a portable EIT device for monitoring the respiratory function of a person during apnea and subsequent hypoventilation. The importance and necessity of quantitative methods of assessment in the diagnosis of diseases are shown. The authors have developed a device that determines the respiratory volumes, the position of the body of the examined patient, the sounds made by a patient. The device also records the electrical activity of the heart (ECG) and pulse oximetry (SPO2). Analyzing the obtained results, it can be concluded that the measurement data of the EIT can complement the existing tools for monitoring lung activity. Accordingly, there is a practical need for methods and algorithms of EIT personalization. This will make it possible to overcome one of the main shortcomings of the device proposed by the authors – to assess the ventilation function of the lungs. Thus, the capabilities of the device and the scope of its application will be significantly expanded.

Research [8] explores one of the directions of the MF EIT, its diagnostic value both at mechanical ventilation and at independent breathing. The disadvantages of the paper include a narrow range of frequencies of injected current and the declared possibility of applying current up to 10 mA. In addition, the possibility and degree of influence of the EIT parameters on the results of the study are not disclosed and are described in general phrases. Research [9] is devoted to the study of the process of independent breathing using the EIT after extubating a patient. The paper shows the diagnostic and prognostic value of the obtained measurement data. This article, due to the natural causes, does not reflect the effect of variation of respiratory volumes on recorded data, nor discloses the parameters of the EIT examination.

Thus, the conducted analysis of the current state of the problem revealed a number of unresolved issues related to the assessment of the dependence of respiratory volumes and parameters of the EIT examination. It does not pay sufficient attention to conducting EIT examination of the healthy objects without pathologies with the ability to change the parameters of air filling of lungs within a wide range with a simultaneous change in the frequency of the injected current. This is important for determining additional technical limitations of the EIT method, as well as for improving the efficiency of using the MF EIT systems. The current situation may be the result of the understandable focus of teams of researchers and developers primarily on the problems of patients with pathologies. However, as noted earlier, this approach does not make it possible to obtain additional data on the range of sensitivity of the EIT method to changes in respiratory volumes and the frequency of injected current for a given object of research.

All this makes it possible to assert that continuous monitoring lungs using the method of the MF EIT allows personalizing the tactics of treatment of respiratory complications in the postoperative period to a greater extent. However, the issues of practical implementation of the MF EIT remain unresolved, taking into consideration the specifics of the field of application. The greatest attention should be paid to the postoperative period, in which the main changes in lung function are observed. In this regard, there are problems of theoretical and algorithmic support for the personalization of the EIT research. It is advisable to conduct studies devoted to the exploration of the features of recorded EIT data at different frequencies of injected current and at different values of respiratory volume.

## 3. The aim and objectives of the study

The purpose of the study is an experimental assessment of the dependence of recorded measurement data on the volumes of inhaled air at the MF EIT. This will make it possible to assess the applicability of the proposed IMS of MF EIT in the problems of personalized MF EIT of lungs at the preclinical stage of trials. The practical implementation of the obtained research results will enhance the effectiveness of the clinical application of the technology of pre-and postoperative monitoring of lung function using the MF EIT method.

To achieve the set goal, it is necessary to solve the following problems:

– to propose a general plan of experimental research;

– to conduct experimental studies to determine the dependence of measurement data on the volume of inhaled air and the frequency of injected current;

– to perform processing and analysis of the obtained measurement information;

– to assess the applicability of the obtained results for clinical use.

## 4. Materials and methods of research

Recorded changes in potentials from the surface of the human chest obtained at different frequencies $f_i$ of injected current $I$ in accordance with the program of experimental studies are used as the source data for theoretical studies. The organization of the process of collecting measurement data, their processing and visualization were performed using a multi-zone information and measurement system of multi-frequency electric impedance tomography (IMS of MF EIT).

To simulate ventilation measures, we used a load testing procedure, which was performed using the Coach 2 medical incentive spirometer. This device is widely applied in the clinical practice of intensive spirometry to restore lung function of patients in the postoperative period (in the clinic or at home).

Computational experiments were performed using the Statistica applied software package (USA), MS Excel environment (USA), MATLAB (USA).

Experimental studies were conducted on volunteers from the developers of the IMS of MF EIT. All of them gave individual information written consent to participate in the tests on the basis of the laboratory of information and measuring systems for medical purposes of the SRSPU (SPI) (Novocherkassk). The basic source data for experimental studies are shown in Table 1.

Table 1

Basic source data for experimental studies

| No. by order | Name | Description |
|---|---|---|
| 1 | 2 | 3 |
| 1 | Number of test participants | 3 people, volunteers (who gave written consent to participate in experimental studies). For convenience, each test participant was assigned the following designations – $P1$, $P2$, and $P3$ |
| 2 | Distinctive features of test participants | Young people under 35, having different physiques. Males. Without pathologies of respiratory function and breathing function. The SpO2 level before and after doing research in all subjects is not less than 99 % |
| 3 | Range of inhaled air, $V$ | from 500 ml to 4,000 ml. It is determined by the functionality of the used device to perform breathing maneuvers. Pitch of increase $\Delta V$=500 ml |
| 4 | Device for breathing maneuvers | Incentive spirometer Coach 2 |
| 5 | Contraindications to the use of the device | There are no contra indicators to apply this incentive spirometer |
| 6 | Specificity of respiratory movements when performing breathing maneuvers | Active inhalation, passive exhalation |

Continuation of Table 1

| 1 | 2 | 3 |
|---|---|---|
| 7 | Tested EIT device | Information-measuring system of multi-frequency electric impedance tomography (IMS of MF EIT). Includes a current source proposed in [10], but modified for use in the IMS of MN EIT |
| 7. 1 | Amplitude of injected current, $I$ | 5 mA (at each frequency from the specified frequency range) |
| 7. 2 | Frequency of injected current, $f_i$ | from 50 kHz to 400 kHz, with the pitch $\Delta f$=50 kHz |
| 7. 3 | System of connections of the EIT (Circuit of injection and measurement) | To perform research at all frequencies, the circuit of «adjacent electrodes» was used |
| 7. 4 | The type of the used electrode belt of the EIT | The electrode belt consisting of single-use electrodes was manufactured. The number of electrodes in the belt is 16 pcs |
| 8 | Place of theoretical and experimental research | Laboratory of «Information and Measurement Systems for Medical Purposes». Novocherkassk, Rostov region, SRSPU (SPI) |
| 9 | Principal researcher | Grayr Karenovich Alexanian |
| 10 | The position of the test participant in space when performing a breathing maneuver and EIT examination | Only in the standing position. Holding a load spirometer in the hand |
| 11 | Terms of experiments | December 2020 |
| 12 | Duration of any cycle of experiments | 1 (one) day per one test participant, no more than 8 hours for the entire complex of EIT examination in order to observe the minimum spread of time of physiological parameters of vital activities of an organism |
| 13 | Number of repeated tests at each frequency and in established respiratory volume | 5 (five) tests followed by their simple averaging at each frequency and in the established respiratory volume |

All manipulations and activities related to the research involving healthy volunteers were performed only after obtaining their written consent. The criteria for inclusion of volunteers in the studies were the following: healthy adult young people chosen from the developers of the IMS MF EIT, who themselves gave written informed consent to participate in the tests. The criteria for exclusion from participation in experimental studies were the existence of an implanted pulse generator, surgeries in the chest area, existence of skin injuries, health deterioration. The process of performing experimental studies was accompanied by continuous recording of the obtained data, taking into consideration all the specific features of the experiment. Simultaneously with the automatic registration of changes in the potentials of the MF EIT for each subject ($P1$–$P3$), the results of the EIT examination at a given frequency of injected current were recorded manually.

Measurement data of the MF EIT were processed, conductivity field was reconstructed, dynamic visualization of the results of calculation of ventilation, perfusion, and the ventilation-perfusion ratio was performed based on the software for controlling the operation of the IMS of MF EIT and the user interface developed by the authors. Secondary additional statistical processing was performed using a specialized software package STATISTICA.

## 5. Experimental evaluation of dependence of measurement data on the volume of inhaled air

### 5. 1. General plan of experimental studies

The essence of experimental studies is controlled filling of lungs with fixed air volume $V_i$ while performing multi-frequency electric impedance tomography. This makes it possible to simulate the AVL process involving a healthy person and to link the assigned respiratory volume to measurement data. In this case, the active element that controls inhalation and exhalation processes is the test participant himself, who uses an incentive spirometer for research purposes. The general circuit explaining the basic principles of obtaining and processing measurement data is shown in Fig. 1.

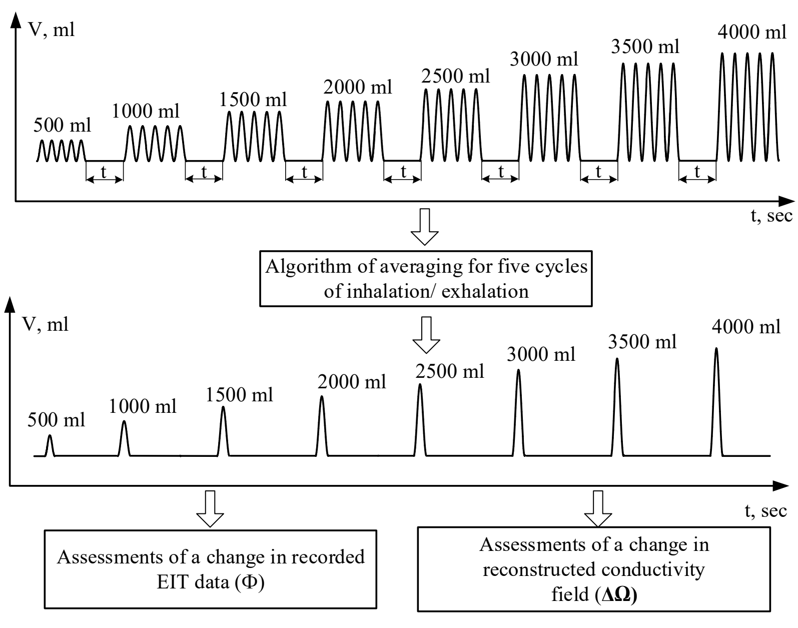



Fig. 1. General circuit explaining the basic principles of obtaining and processing measurement data in the framework of experimental studies

It schematically shows the breathing pattern used in the study. During the experiment, each test participant (code designation $P1$, $P2$, and $P3$ is accepted) must perform a controlled series of five inhalations/exhalations on each of the volumes set on the incentive spirometer $V_i$ (from 500 ml to 4,000 ml, with a pitch of increase of 500 ml). To decrease the methodological error and filtration of interference associated with the subjective features of using Coach 2, caused by the failure to reach or by exceeding the set volume of $V_i$. the measurement data for each volume of $V_i$ were averaged. The standing position was chosen for the convenience of the test participant performing a breathing maneuver and the MF EIT. In subsequent studies, only averaged data were used as the source data to reconstruct the conductivity field and to assess a change, as well as to estimate changes in measurement information.

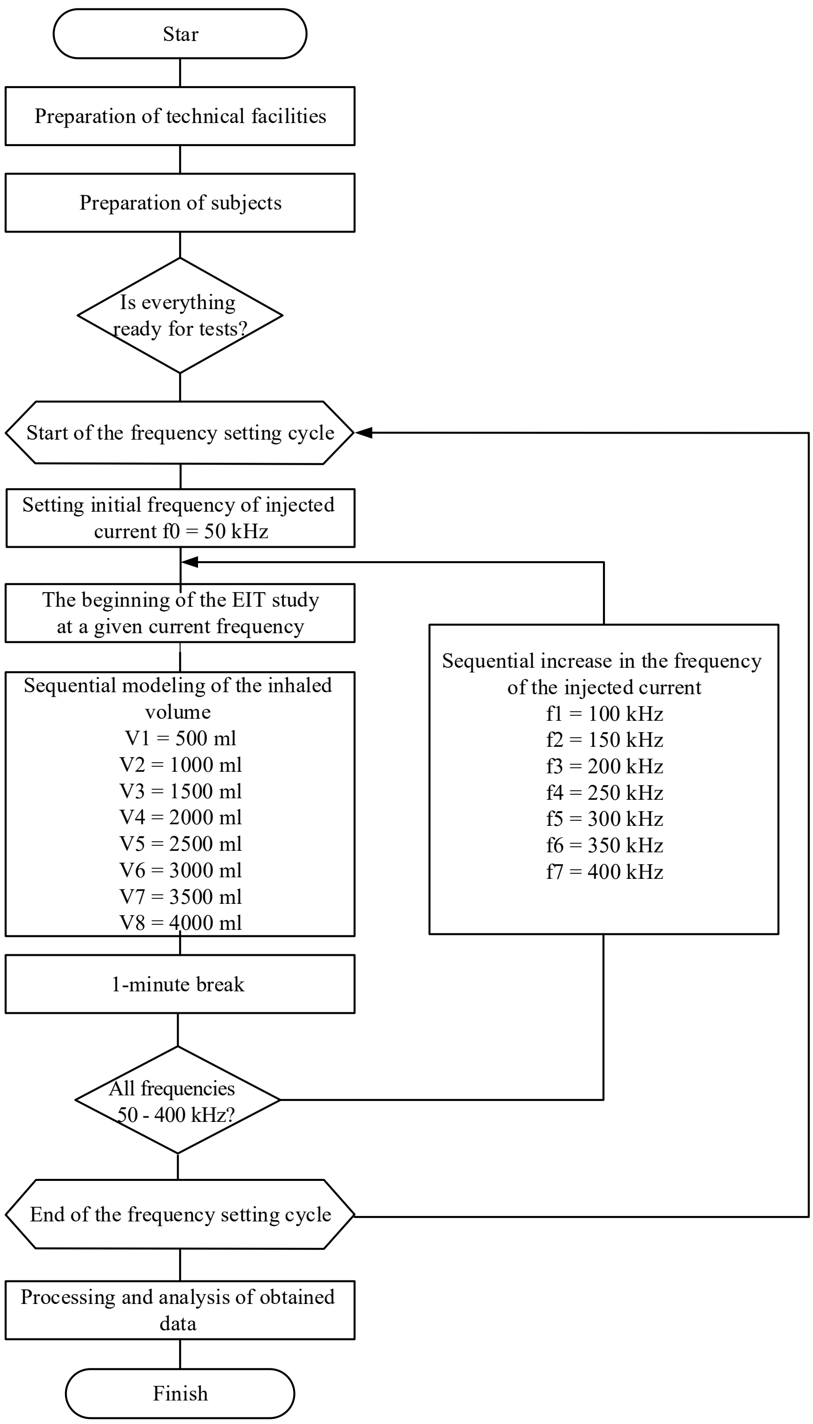



Fig. 2. Block-diagram of the generalized algorithm for obtaining measurement data

Each test participant performed breathing maneuvers using the Coach 2 simulator for three weeks (with a frequency of repetition of 1 time in 3 days) performed breathing maneuvers using the Coach 2 simulator. This was done in order to eliminate discomfort, improve the convenience and predictability of the experiment, as well as study the problematic moments that may occur during tests. For each test participant *P*1, *P*2, and *P*3, new incentive spirometers Coach 2 and the means for their cleaning and disinfection were purchased. During the tests, it was found that between controlled breathing maneuvers, it is desirable to choose an interval of at least $t$=1 minute. A general block diagram of the implementation of experimental studies, adjusted according to the results of tests, is shown in Fig. 2.

Each frequency of injection current was set by the principal researcher on the sensor monitor IMS of MF EIT. The principal researcher also monitored the progress of the experiment, recorded the results, and monitored compliance with the sequence of actions according to the plan formed in advance. The pitch of increasing the injection frequency $\Delta f$ was 50 kHz. The pitch of setting the respiratory volume $\Delta V$ was 500 ml. Upon completion of the experimental studies, as well as after each test participant, the IMS of the MN EIT was turned off, the electrode system was disassembled and sent for disinfection, the used electrodes were disposed of.

**5. 2. Determining the dependence of measurement data on the volume of inhaled air and frequency of the injected current**

**5. 2. 1. Instrument base and source data for research**

Table 2 shows the list of the equipment and the components that are directly used to obtain measurement data of the MF EIT.

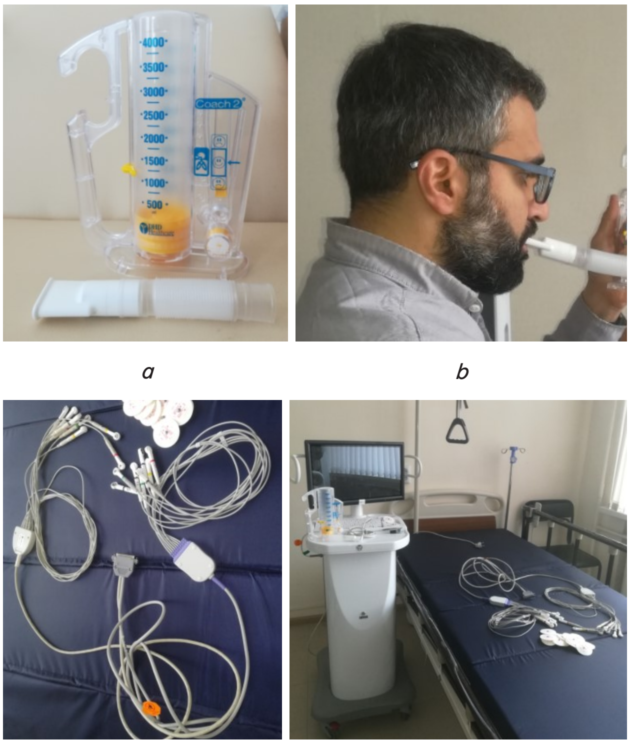
Table 2

Basic source data for experimental studies

| Type of equipment/parts | Type of equipment/parts |
|---|---|
| Incentive spirometer | Coach 2 |
| Information and measurement system of multifrequency electric impedance tomography of human lungs | IMS MF EIT |
| Disposable ECG electrodes | produced by *Scintac* (re-sticking to the surface of the body is not allowed) |

Fig. 3 shows the view of the experimental setup and its main parts.

New spirometers were purchased for each test participant. Disposable electrodes were used as part of the electrode system (Fig. 3, *c*).




*a* *b*

*c* *d*

Fig. 3. General view of the experimental setup and its parts: *a* — view of the incentive spirometer Coach 2; *b* — example of using incentive spirometer Coach 2 in the framework of these studies (the photo shows the author); *c* — view of the electrode system with disposable electrodes; *d* — view of the developed information and measurement system of electric impedance tomography

**5. 2. 2. Features of participation of volunteers in experimental studies**

We wrote a brochure of the experiment, with which each of the participants got acquainted. We received written consent from each participant *P*1, *P*2, and *P*3 to take part in the experiment. The incentive spirometer Coach 2, which is a non-sterile product for individual use of respiratory therapy and has an inhalation port, was chosen to perform controlled breathing maneuvers. Incentive spirometers Coach 2 are designed to be used in intensive spirometry. The product helps to restore patients after operations and/or if necessary, to do deep breathing exercises with the possibility of subjective control of inhaled volume. In accordance with the instruction manual, incentive spirometers Coach 2 are designed to be used in medical institutions or at home.

During the measurements, *P*1, *P*2, and *P*3 did not eat, drink water, perform any physical exercises and other actions that could distort the results. The obtained data were automatically saved with the possibility of reproduction and processing in outside specialized packages of applied programs.

**5. 2. 3. General principles of obtaining measurement information**

Measurement information is obtained based on the EIT algorithms, which include injecting current through an object and recording the response to this influence. Their practical implementation is aimed at performing the following main stages:

– superimposition of electrodes distanced from each other and closely connected to each other along the perimeter of an object;

– connection of the current source to a pair of adjacent electrodes and injection of high-frequency current of small amplitude *I* through an object;

– recording the changes of potentials on all other electrodes that are not injectable at the given moment;

– connection of the current source to the next pair of adjacent electrodes and recording the changes of potentials Φ on all electrodes that are not currently injected.

The stages of switching electrodes, injection, and collection of measurement data Φ are continuous and are repeated until the device stops working. As a result, an array of measurement information, which is the changes of the potentials Φ from the surface of an object obtained during the observation period, is collected. Their magnitude depends on the functioning of an object and its structure. Further, based on this information, the inverse problem is solved in order to reconstruct changes in the internal conductivity field of object Ω. The EIT method is most widely used in medicine for monitoring the lung function of a person connected to an AVL apparatus or having respiratory support. This is caused by the fact that the intake of air in the lungs is a periodic process in which an object with low resistance (lung tissue) receives a volume of the respiratory mixture or air $V_i$ with resistance that is many times greater than its own. As a result of monitoring the changes in conductivity field Ω in the plane of putting of the electronic system, it is possible to visualize those parts of the lungs that, for example, are not involved in ventilation. At the same time, pain is excluded, a test participant does not feel the passage of current, and the monitoring itself can be performed for a long time, at the bedside and in conjunction with other medical products connected to a patient (except for the defibrillator of an electrosurgical knife).

In the general case, the fixed-frequency current is injected through a patient. In the case of the MF EIT, it is proposed to use a frequency range with a fixed pitch of increase. Due to this, it is possible to read measurement data, which contain, among other things, information about the dependence of the electrical properties of a research object on frequency. Thus, one can get an additional channel of useful diagnostic information, which is peculiar to a particular person, and personalize the EIT examination.

**5. 3. Processing and analysis of the obtained measurement information**

The process of obtaining an array of measurement data Φ for given volume $V_i$ is a continuous cycle of obtaining changes in the difference of potentials from the electrodes in accordance with the selected system of EIT connections (1).

$$\Phi_{f_i}^{V_i} = \sum \left| \phi_{j+1} - \phi_j \right|, \qquad (1)$$

where $\left(\phi_{j+1} - \phi_j\right)$ is the recorded measurements of the difference of potentials of the EIT, $j$=1...$N$, where $N$ is the total number of electrodes, $N$=16; $V_i$=[500 ml; 1000 ml; 1500 ml; 2000 ml; 2500 ml; 3000 ml; 3500 ml; 4000 ml]; $f_i$=[50 kHz; 100 kHz; 150 kHz; 200 kHz; 250 kHz; 300 kHz; 350 kHz; 400 kHz].

The results of experimental data at different values of respiratory volumes and at different frequencies of injected current were obtained for each of the test participants $P1$, $P2$, and $P3$. The data were obtained. Subsequently, according to the circuit presented in Fig. 1, the array of measurement data $\Phi_{f_i}^{V_i}$ was averaged according to formula (2).

$$\Phi_{cp} = \frac{\sum \Phi_{f_i}^{V_i}}{K}, \qquad (2)$$

where $K$ is the number of all $\Phi_{f_i}^{V_i}$, obtained at assigned $V_i$ and $f_i$.

Fig. 4–6 show the dependence of $\Phi_{cp}$ (ordinate axis) on the magnitude of respiratory volume $V_i$ (abscissa axis) at different frequencies of injection current $f_i$ for each test participant $P1$, $P2$, and $P3$.

Analyzing the content of Fig. 4–6, *a*, it can be concluded that there is an increase in the value of $\Phi_{cp}$ depending on the magnitude of respiratory volume $V_i$. At the same time, within the fixed $V_i$, a decrease in the magnitude of $\Phi_{cp}$ is clearly noticeable, in this case, each of $P1$, $P2$, and $P3$ has his own rate of its change. If we consider the change of conductivity field $\Omega$ of the test participants performing breathing maneuvers, it is possible to observe a decrease in its magnitude at an increase in $V_i$. Within a fixed $V_i$. there is a clearly noticeable increase in $\Omega$ at an increase in the frequency of injection current $f_i$.

Fig. 7 shows the dependence of the measured values of changes in the EIT potentials on the frequency of injected current $f_i$ for different respiratory volumes $V_i$ in three test participants.

The results of processing the measuring data shown in Fig. 7, make it possible to conclude that the results obtained fully comply with theoretical studies on changing the electrical properties of living biological tissues when an alternating electric current passes through them. It is noticeable that each test participant, under fixed conditions of the experiment, is different as for the levels of measurement data. This is due to the internal structure and composition of the tissues of the body (thickness of adipose tissue, geometric dimensions of lungs, the perimeter of the chest girth, etc.) of each out of $P1$, $P2$, and $P3$.

Fig. 7 demonstrates that possible artifacts in the course of obtaining measurement data can lead to misinterpretation of the data (the lower group of diagrams for $P3$ has a surge at a frequency of 150 kHz). In this regard, it is necessary to introduce a unit for tracking and analyzing the correctness of data at the MF EIT (for example, along with control of the quality of electrode fastening) into the algorithms for performing MF EIT

Based on the obtained measurement data $\Phi_{f_i}^{V_i}$ at different frequencies of injected current and inhaled volumes, the conductivity field was reconstructed using the EIT method. In general, this stage of processing measurement data can be represented in the form of (3):

$$\Phi = \Phi_{f_i}^{V_i} \to \Omega_{f_i}^{V_i} = \Omega. \qquad (3)$$

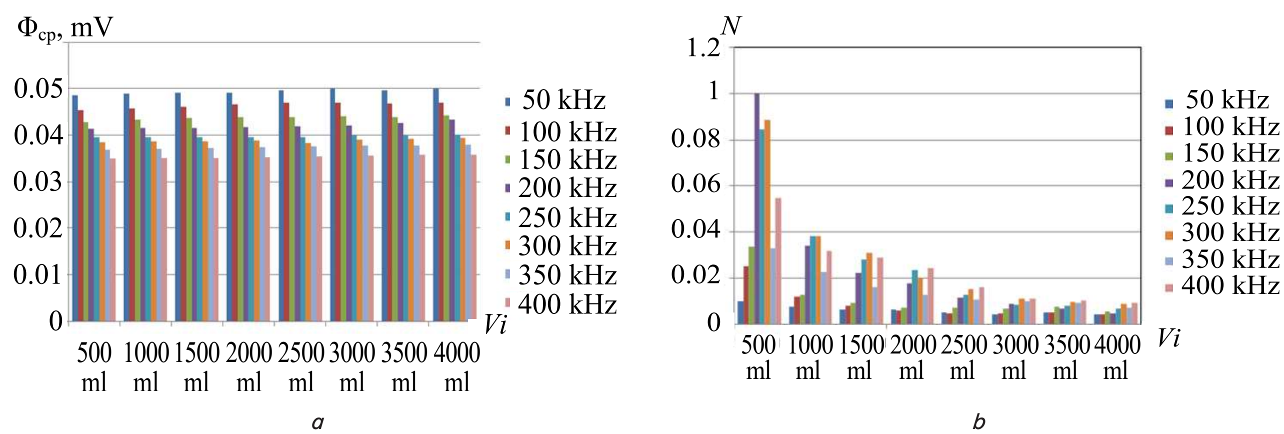



Fig. 4. For test participant $P1$: *a* — dependence of $\Phi_{cp}$ on the magnitude of respiratory volume $V_i$ at different frequencies $f_i$; *b* — the normalized values of a change in conductivity $\Omega$ of the region of placing the electrode system ($N$) at different frequencies of injection current $f_i$ at assigned $V_i$

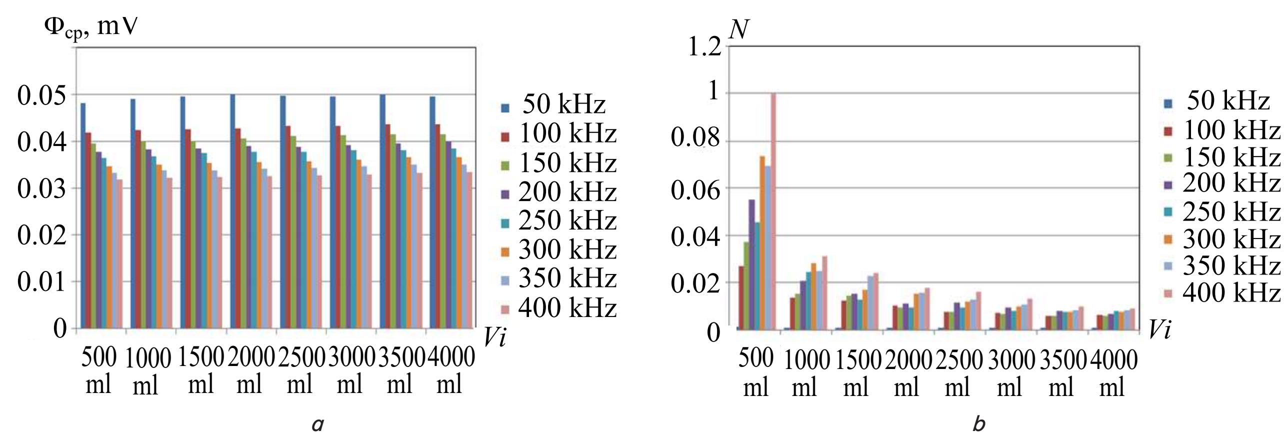



Fig. 5. For test participant $P2$: *a* — dependence of $\Phi_{cp}$ on the magnitude of respiratory volume $V_i$ at different frequencies $f_i$; *b* — the normalized values of a change in conductivity $\Omega$ of the region of placing the electrode system ($N$) at different frequencies of injection current $f_i$ at assigned $V_i$

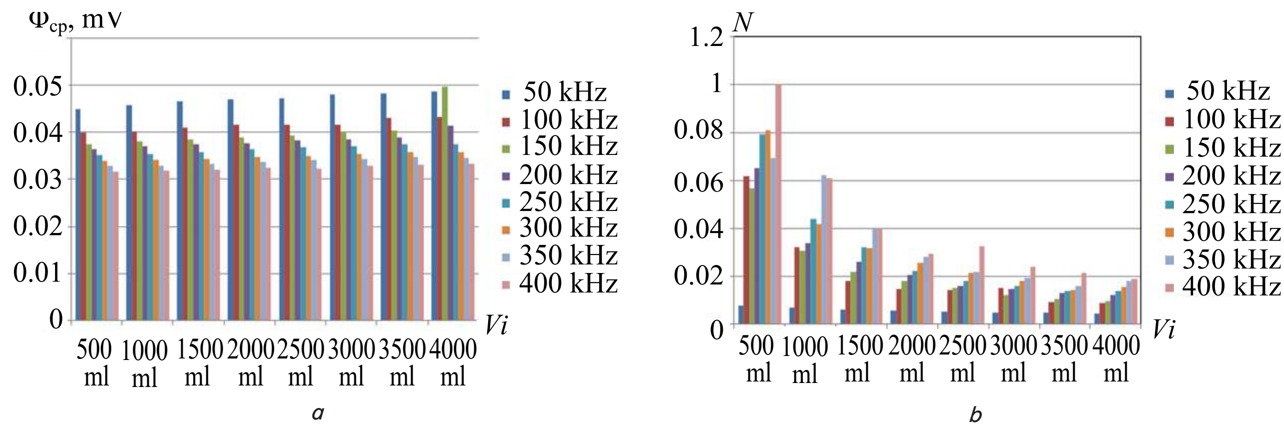



Fig. 6. For test participant $P3$: $a$ – dependence of $\Phi_{cp}$ on the magnitude of respiratory volume $V_i$ at different frequencies $f_i$; $b$ – the normalized values of a change in conductivity Ω of the region of placing the electrode system ($N$) at different frequencies of injection current $f_i$ at assigned $V_i$

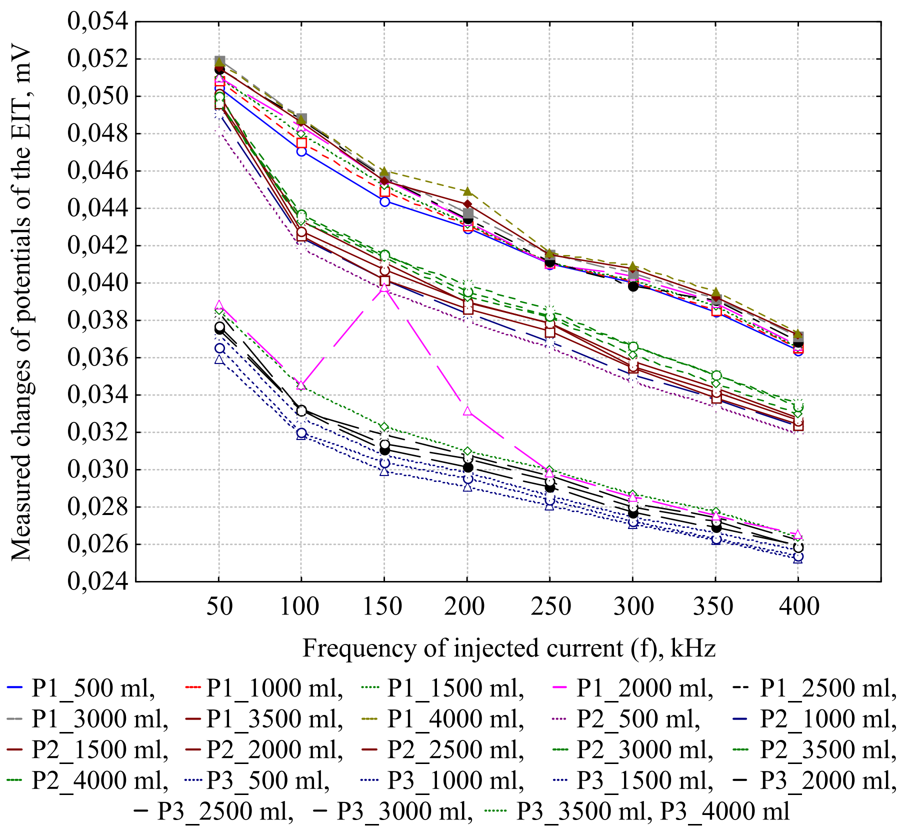



Fig. 7. Dependence of the measured values of changes of potentials in electrical impedance tomography on the frequency of injected current $f_i$ for different respiratory volumes $V_i$ in three test participants ($P1$, $P2$, and $P3$)

As a result, we obtained an array $\Omega_{f_i}^{V_i}$, reflecting the relative change in conductivity field (in the cross-section of placing the electrode system) for different frequencies of injected current and inhaled volumes. Here and further, for the convenience of designating the axes of the diagram, a simplified designation was adopted – Ω and Φ.

Fig. 8, *a* shows the diagrams of the spread of the dependence of recorded changes in EIT potentials on the volume of inhaled air *Vi*. Fig. 8, *b* shows the dependence of the calculated values of a change of the reconstructed conductivity field Ω of the test participants. The data in Fig. 8 are presented for all test participants *P*1, *P*2, and *P*3.

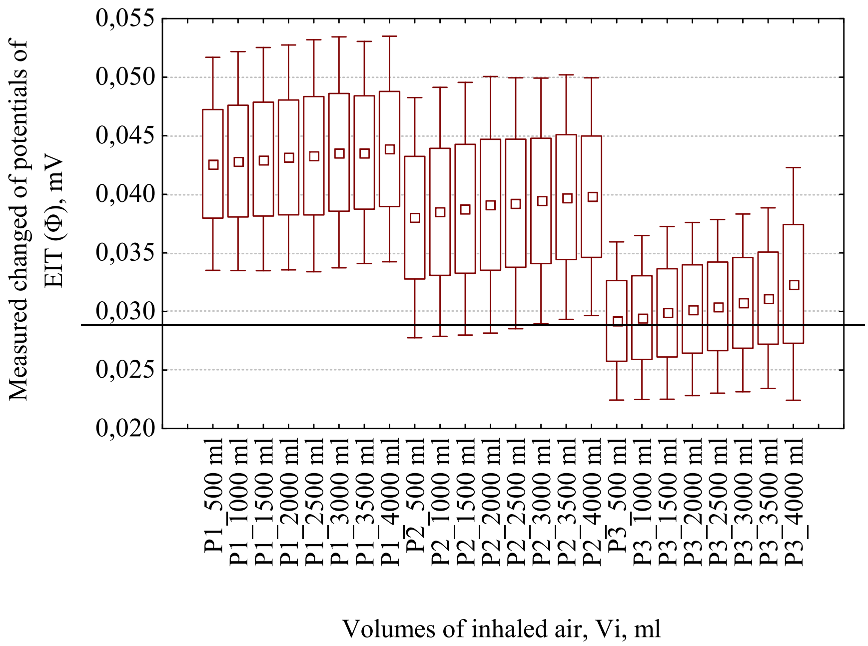
Analyzing the data in Fig. 8, it can be concluded that a characteristic feature for all test participants is a large spread at the lower frequencies, especially at injection frequency $f_0$=50 kHz. This will lead to the conclusion that for *P*1, *P*2, and *P*3 the MF EIT should not be performed at low injection frequencies, especially at frequency $f_0$. In this regard, it is necessary to correct the algorithm for performing MF EIT with adjustment for possible injection frequencies, at which the greatest spread is observed. This recommendation requires more detailed scientific theoretical and applied research, including physiological studies. In addition, the spread (sweep) diagrams reflect differences between *P*1, *P*2, and *P*3 as for electrical properties. At the same time, the nature of the change in the measurement data of the EIT at an increase in the volume of inhaled air is the same for all subjects. Thus, the implementation of the multi-frequency principle makes it possible to differentiate between the subjects in order to increase the degree of personalization of the EIT examination.

Further, to enhance the visibility of the results of experimental tests, cluster analysis was applied to the obtained array of measurement data Φ for each *P*1, *P*2, and *P*3. Cluster analysis makes it possible to objectively systematize the obtained results of the study and give a simplified idea of the nature of a change in measurement data and a change in reconstructed conductivity field at an increase in the frequency of injected current $f_i$.

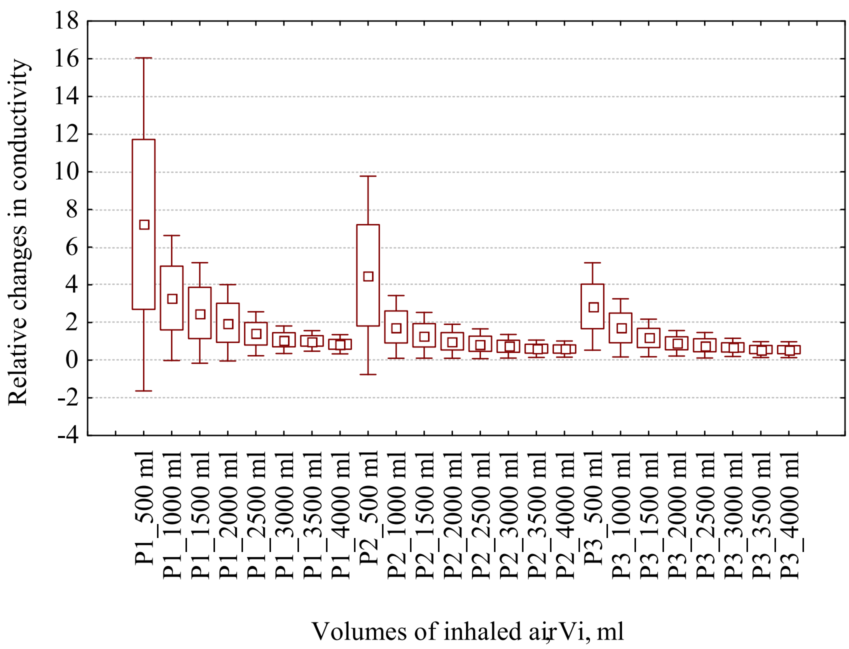
Fig. 9 shows the results of cluster analysis of measurement data at different frequencies of injected current. Fig. 10 shows the results of cluster analysis of changes in the reconstructed conductivity field at different frequencies of injected current.

The results of processing and analysis of Φ and Ω make it possible to conclude that at MF EIT, the measurement data obtained directly from the MF EIT device and not subjected to post-processing reflect the characteristics of the object of research. They can serve as an additional channel for obtaining basic information to account for artifacts, as well as to increase the correctness of reconstruction tasks.

Analyzing the content of Fig. 7–10, it can be concluded that the MF EIT is an effective tool for objective reliable differentiation of patients. Its application in the tasks of EIT of human lungs makes it possible to increase the degree of personalization of the procedure and minimize artifacts in the source data of the EIT.




*a*




*b*

Fig. 8. Spread diagrams for test participants *P*1, *P*2, and *P*3: *a* — dependence of recorded changes in EIT potentials (Φ) on the volume of inhaled air; *b* — dependence of calculated values of changes in reconstructed conductivity field (Ω) on the volume of inhaled air *Vi*

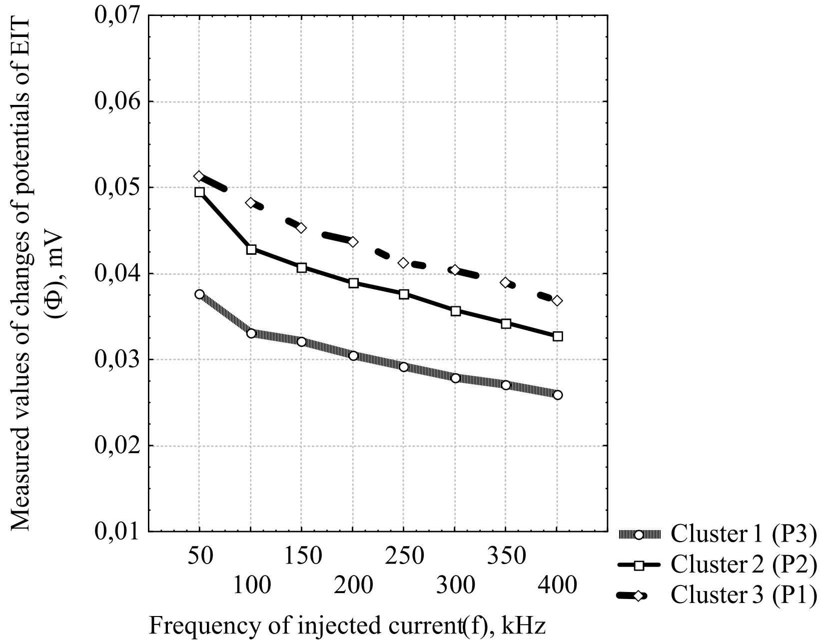



Fig. 9. Results of cluster analysis of measurement data Φ at different frequencies of injected current $f_i$

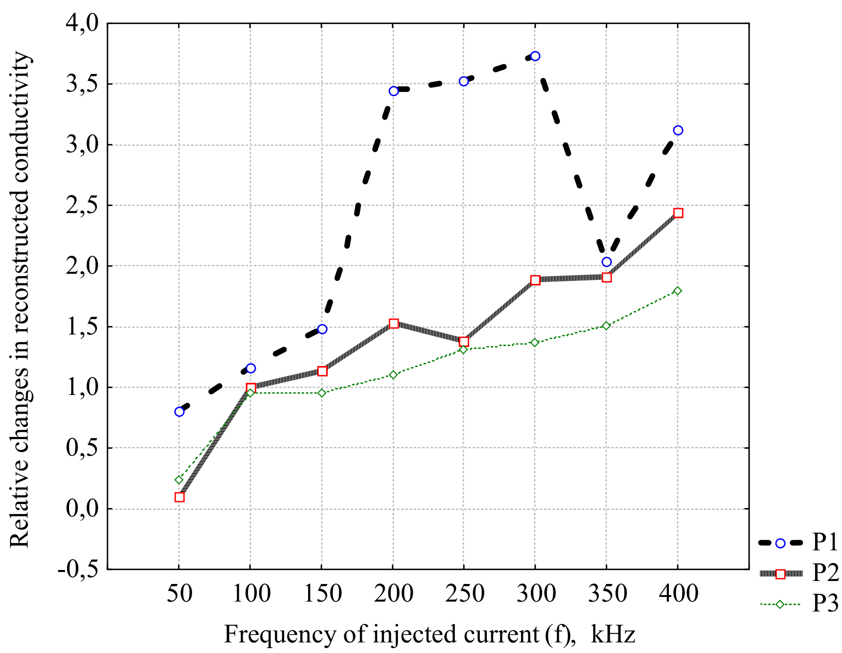



Fig. 10. Results of cluster analysis of reconstructed conductivity field Ω at different frequencies of injected current $f_i$

**5. 4. Assessment of applicability of obtained results for clinical use**

The obtained results can serve as the basis for the development of a method for personalization of the EIT activities, including those in solving problems of pre-and postoperative monitoring of human lung function. The essence of the method is as follows. Initially, before performing surgical interventions, an adequate injection rate for a particular patient is evaluated. Then, in the postoperative period, it is considered as a reference for the launch of the EIT examination. This makes it possible to overcome the problem associated with the fact that when performing resuscitation measures, there is inevitably a distortion of objective information about the state of a patient and the parameters of the impedance of the field of research peculiar to him. This can be caused for various reasons, for example, under the influence of drug therapy, drop infusion, or various kinds of manipulation with the patient's position in space, etc. Multifrequency electric impedance tomography can serve as one of the ways to solve the above problems.

The practical implementation of the MF EIT of the human lungs does not create additional inconvenience to a patient and medical personnel. All the test participants pointed out the absence of discomfort and inconvenience. In addition, the process of air filling of lungs was intuitively and clearly visualized in a dynamic image in accordance with the volume of incoming air at all frequencies and at all specified volumes.

## 6. Discussion of results of experimental studies of the dependence of measurement data on the volume of inhaled air

The proposed approach to performing the MF EIT with the simultaneous task of controlled respiratory volume showed positive results of the practical use of an incentive spirometer for simple modeling on a healthy person of the AVL mode. This significantly expands the range and directions of further non-invasive studies of the EIT method to solve the problems of long-term bedside monitoring (both pre-and postoperative). Nevertheless, the obtained results enable us to conclude that healthy subjects in the conscious state may well act as a measure of objective control, and their subjective assessments can be systematized for subsequent comprehensive analysis.

The obtained results of experimental studies (Fig. 4–6) show that there is a dependence of the magnitude of measurement data both on the volume of inhaled air and on the frequency of the injected current. This feature can be used to develop a number of medical devices for personalized monitoring of human lung function. This is achieved due to the identified sensitivity of the MF EIT itself to the internal structure of the research object and to the modes of its functioning.

The results of the studies, systematized in Fig. 7, 8, reflect the full compliance of analytical expressions – an increase in the difference in recorded potentials is associated with an increase in the volume of supplied air. At the same time, at an increase in the frequency of the injected current, we observe a decrease in the magnitude of measurement data.

Analyzing the diagrams of dependences shown in Fig. 7, 10, it can be concluded that it is necessary to introduce a unit for tracking and analyzing the data correctness at the MF EIT (for example, along with control of the quality of electrode fastening) into the algorithms of performing the MF EIT. This will make it possible to select problem areas in the array of measurement data before launching processing and to take them into consideration when analyzing the reconstructed field.

It was revealed that there are frequencies at which the maximum spread of measurement data is observed according to the results of a series of repeated experiments (Fig. 8). At the same time, the nature of a change in measurement data of the EIT at an increase in the volume of inhaled air is the same for all test participants. It is assumed that this feature can also be used to increase the degree of EIT personalization. For example, identification of the frequency range with the maximum spread may indicate the inadequacy of the specified parameters of the EIT examination for a particular test participant. Or vice versa, the search for the frequency (or frequency range), after which there is a minimum standard deviation of the measurement data of the MF EIT.

It should be noted that the previously developed IMS of MF EIT showed high operation stability, regardless of the physiological characteristics of a test participant. It was experimentally established that it can be applied to perform an EIT examination on ventilation volumes from 500 ml to 4,000 ml. Obtaining the dependence of changes of potentials at different frequencies and at different respiratory modes make it possible to conclude that the proposed IMS of MF EIT can be used in further work on the study of the modes and features of the MF EIT.

It should be noted that these studies have a series of limitations. These include a small sample size of test participants, which requires a performance check on a larger group, as well as the absence of test participants with problems with external respiratory function. However, these works are planned to be performed on the basis of a medical organization with the involvement of real patients of an intensive care unit. In addition, within the framework of these studies, the tasks were set for the study of the MF EIT on healthy subjects who do not have problems with lung function. This was done in order to assess the sensitivity of the EIT method.

The issue of using the MF of EIT for the tasks of assessing lung perfusion by the MF EIT method, as one of the directions of application of the multi-frequency mode, remains unclear. It is important to conduct experimental and clinical studies and to explore the problem of the use of the MN EIT in intensive care units. In particular, it is necessary to assess the impact of third-party medical devices on the results of the MF EIT.

The disadvantages of this study include the following features: a limited frequency range (from 50 kHz to 400 kHz), a frequency increase pitch that is multiple of 50 kHz, fixed current force of 5 mA. These problems and limitations are the subjects of further research, require separate algorithmic solutions, and go beyond the scope of this paper.

Among the main difficulties in the development of this direction, it is possible to single out a weak methodological study of the subject area due to the relatively short terms of research in the direction of the MF EIT under clinical conditions.

## 7. Conclusions

1. A general plan of experimental studies, involving the controlled filling of lungs with a fixed air volume while performing the MN EIT, was proposed. This makes it possible to simulate the AVL process on a healthy person and link the specified respiratory volume to measurement data. In this case, the active element that controls the processes of inhalation and exhalation is a test participant himself, who uses an incentive spirometer for research purposes. Thus, the proposed method enables conducting preclinical studies of systems and methods of the MF EIT on healthy people and to obtain measurement information with maximum adequacy to the object of study.

2. Experimental studies were carried out to determine the dependence of measurement data on the volume of inhaled air and the frequency of the injected current. The tests were conducted involving three volunteers from the developers of the IMS of MF EIT, who gave written informed consent to participate in the experiment. Experimental studies were conducted at the frequency of the injected current from 50 kHz to 400 kHz (with an increase pitch of 50 kHz) and at respiratory volumes from 500 ml to 400 ml (with an increase pitch of 500 ml). As a result, measurement information was collected and systematized in the form of changes in EIT potentials for these frequencies and volumes. Thus, experimental data on the simultaneous performance of the MF EIT at different respiratory volumes were collected. Various algorithms of processing and analysis can be applied to them in order to identify existing dependences and features.

3. The obtained measurement information for each test participant at different values of respiratory volumes and at different frequencies of injected current was processed and analyzed. It was established that there is an increase in the value of measurement data depending on the magnitude of respiratory volume. At the same time, within a fixed volume, a decrease in the magnitude of changes of the EIT potentials is clearly noticeable, and the rate of its change is different for all test participants. When assessing the change in the reconstructed conductivity field, it was found that there is a decrease in its magnitude at an increase in respiratory volume. At the same time, within a fixed respiratory volume, an increase in conductivity field is clearly noticeable with an increase in the frequency of the injected current.

It was revealed that for all test participants, the maximum spread of changes in EIT potentials is observed at low frequencies, especially at the injection frequency of 50 kHz. This means that for these people, EIT should not be performed at low injection rates. A recommendation on the need to adjust the algorithm for performing the MF EIT taking into consideration possible injection frequencies, at which the greatest variation is observed, was made.

4. The main directions of applicability of the obtained results for clinical use were considered. It was shown that at the MF EIT, measurement data obtained directly from the MF EIT device and not subjected to post-processing reflect the features of the object of study. They can serve as an additional channel for obtaining basic information for accounting for artifacts, as well as for increasing the correctness of algorithms for solving inverse problems that are used to reconstruct the conductivity field.

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