

*This paper solves the problem of developing and creating multifunctional tools for conducting research into systems of multi-frequency electrical impedance tomography of human lungs. A test bench consisting of modern medical equipment, simulating pre-and postoperative environments to create conditions that are most similar to clinical ones, under which it is planned to operate multi-frequency electrical impedance tomography systems, was proposed and manufactured. This makes it possible to reduce significantly the time for approbation, testing, and elimination of practical inaccuracies and problems of clinical application of the developed medical and technical facilities. A positive result is achieved due to the possibility of forming new test plans with specified conditions and different levels of complexity. This enables enhancing the effectiveness of subsequent clinical tests on patients who are treated in a resuscitation unit or an intensive care unit. The operability of the bench is proved by the repeatability of obtained results of monitoring ventilation and perfusion for each examined person, the continuity of dynamic visualization of the breathing process, as well as a high degree of correlation of obtained values of differences of potentials with the readings of a bedside monitor of a patient. An information and measuring system of multi-frequency electric impedance tomography of human lungs, developed by the author earlier, was used as the EIT device. The EIT tests were performed for the frequency range of 50–400 kHz at a current of 5 mA. All experimental studies involved volunteers who gave written information consent to participate in the tests. The results of the research show that the proposed bench can be used in practice to solve a wide range of scientific and applied problems in the field of electrical impedance tomography*

**Keywords:** *electrical impedance tomography, lungs, perfusion, information and measuring system, bench, visualization, conductivity*

# DESIGNING A BENCH FOR TESTING MEDICALLY AND TECHNICALLY AN INFORMATION AND MEASURING SYSTEM FOR MULTI-FREQUENCY ELECTRICAL IMPEDANCE TOMOGRAPHY OF HUMAN LUNGS

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## 1. Introduction

A sharp positive dynamic in the development of one of the directions, such as multi-frequency electric impedance tomography (MF EIT), is observed in the area of electrical impedance tomography (EIT). This is explained by the fact that existing EIT devices, which entered serial production and were introduced into the medical field, are increasingly often used in the practice of performing resuscitation measures in clinics around the world [1–3]. At the same time, these devices are represented by single items, and the experience of their operation and modern scientific studies have shown that one of the important and promising directions in this area is to extend the methods for increasing the EIT sensitivity to the object of examination. This will allow a significant expansion

of capabilities of the EIT method and the scope of its application in solving important clinical problems. One of the directions of increasing the EIT sensitivity is the implementation of the multi-frequency function. In other words, it is possible to implement in practice a personalized EIT for a particular patient, taking into consideration his physiological characteristics (for example, the size of lungs, the thickness of the subcutaneous fat layer, geometric dimensions, etc.). At the same time, there is a problem consisting of the lack of tools for conducting scientific and technical studies of the MF EIT systems on living research objects with the ability to simulate different operating conditions.

Within the framework of the performed research and applied work, world scientific groups of researchers solve a wide range of tasks to develop the algorithmic and scien-

tific-methodological support and create modern devices of the MF EIT. The experience of development and clinical approbation of medical EIT devices makes it possible to conclude that the process of creation and research into modern medical and technical facilities is inevitably associated with the implementation of preparatory and verification works of scientific, technical, and applied nature. They are aimed at assessing the performance of the proposed hardware and software and algorithmic solutions and make it possible to identify ergonomic requirements for their clinical use.

In addition, the unfavorable sanitary and epidemiological situation, associated with the spread of new coronavirus infection, that occurred in 2020–2021, had a negative impact on the development of new EIT-based systems of medical imaging. It caused adjustments of the plans for the implementation of current work on the creation of the technology for personalized EIT-based monitoring of patients' lung function in the pre-and postoperative periods. They include, for example, restricting access to the intensive care and anesthesiology unit, reducing the number of possible test participants, delaying the deadlines for obtaining permission from the ethics committee to perform experimental clinical studies, etc.

Thus, the studies carried out on this topic make it possible to overcome the above problems. In particular, the problems of eliminating practical inaccuracies and problems of clinical application of multi-frequency EIT systems are resolved. This makes it possible to enhance the effectiveness of examining the patients and directions of time consumption, which is especially important for patients and medical staff in intensive care units. The use of the proposed solutions in practice allows reducing the time of implementation of the EIT examination based on a medical organization since the preparatory time to eliminate inaccuracies and problems of clinical use of the IMS MF EIT decreases significantly.

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## 2. Literature review and problem statement

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Currently, the problem of long-term monitoring of the functional state of human lungs is one of the most important areas of respiratory support for patients. Among them, the possibility of long-term bedside monitoring of the breathing process in the pre-and postoperative period, including patients connected to devices of artificial ventilation of lungs (AVL) [4–6], is of great clinical importance.

Research [4] showed that the application of the EIT method to patients with acute respiratory distress syndrome (ARDS) with mechanical ventilation of lungs makes it possible to obtain bedside information about the alveolar cycle and overdose. The authors used the EIT to individualize positive exhalation end pressure (PEEP) and tidal volume (VT). The obtained results showed that based on the EIT, it is possible to personalize the AVL parameters without causing lung damage and to assess its effect on the compliance of the respiratory system, oxygenation and alveolar cycle. Thus, the study revealed the possibility of personalizing the AVL parameters using the EIT method, but it did not show the possibility of personalizing the EIT examination itself.

Study [5] briefly summarizes the current state of the EIT for visualization of ventilation and perfusion. The authors

made a brief review of the literature on regional ventilation monitoring using the EIT. The paper summarizes past and current research activities aimed at obtaining information about cardiac output and regional perfusion using the EIT method. The authors of article [6] considered and systematized the issues of clinical application of the EIT systems in China since the appearance of similar devices in the medical practice of the state. Possible directions of development of this area were shown. Just as in paper [4], the aspects of personalization of the parameters of the EIT examination itself, such as the parameters of injected current, the type of used electrodes, the place of their imposition, remained unresolved. In these works, the importance of the influence of these factors on the final result of the examination is evidently underestimated.

In research [7, 8], it was shown that the efficiency of artificial ventilation of lungs, as well as the stability of its parameters, increases with the simultaneous use of the method of electrical impedance tomography. Thus, article [7] explores the possibility of using real-time electrical impedance tomography to control protective ventilation of lungs at acute respiratory distress syndrome. The conducted studies revealed that artificial ventilation of lungs using electric impedance tomography provides improved breathing mechanics, better gas exchange, and a decrease in histological signs of lung damage caused by the AVL. In article [8], the studies on the possibility of using the EIT to detect and quantify the effectiveness of recruitment when varying positive end exhalation pressure at acute lung damage were conducted. It was shown that with the help of electrical impedance tomography, it is possible to use the non-invasive measurement of regional delay of ventilation and its visualization with the help of ventilation delay maps. Thus, in the above work, it was shown that the method of electrical impedance tomography can be useful for the individualization of the parameters of artificial ventilation of lungs. It should be noted that articles [7, 8] do not consider the possibility of individualization of the EIT examination itself in clinical practice. This is due to the need for additional preclinical studies to establish the patterns of influence of parameters and modes of the AVL on the EIT results.

Papers [9, 10] present the results of the studies on the use of the EIT for monitoring physiological parameters during anesthesia. In paper [9], the possibility of individualization of the parameters of positive exhalation end pressure in patients with obesity during general anesthesia using electric impedance tomography was studied, a randomized controlled clinical research was conducted. It was shown that it is necessary to develop various strategies to protect the lungs, including the case after extubation and in the postoperative period, especially for patients with obesity of varying degrees. Research [10] indicates that a higher positive exhalation end pressure controlled by the EIT method can improve lung ventilation during recruitment maneuvers, ensuring enhanced regional lung protection. A prospective randomized cross-trial on intubated adult patients with various lung injuries showed that at a higher positive exhalation end pressure, the success of recruitment maneuvers was evident in all areas of lungs, and heterogeneity of ventilation distribution decreased.

Despite the significant variability in the choice of parameters of the EIT examination, the considered works did not show how the initial test conditions affect the choice of

these parameters. Thus, the main results of the conducted analysis are unresolved issues related to the selection of parameters of the EIT examination and the conditions for its implementation. In the considered works, attention is not paid to the personalization of the EIT examination itself, the data source for which is both the parameters of the EIT examination itself (parameters of injected current, the type of used electrodes, the place of their imposition) and the psycho-physiological state of a patient (sex, weight, build, measured body dimensions, found and assumed pathologies in the field of research), its spatial position and other conditions.

The reason for this may be a non-obvious choice of suitable parameters for the EIT examination for patients with different electrical properties of tissues of the internal structures of the chest. To select the appropriate parameters of EIT monitoring, the conditions of medical hospitals and intensive care units may be needed. However, due to various circumstances, including the poor epidemiological situation, access to such medical facilities for experimental research may be difficult.

An option for overcoming the relevant difficulties may be the creation of an experimental bench for research into the effects of varying the parameters of the EIT use outside medical institutions. A similar approach is used in paper [11]. Thus, article [11] represents a description of the development of a portable system for monitoring lung ventilation by electric impedance tomography. The possibility of creating a portable system is achieved by organizing wireless data transmission from the active electrode belt to the processing unit. With the help of the developed system, the optimal parameters of EIT monitoring, which vary from person to person, are chosen. At the same time, this paper did not show the use of the developed device under clinical conditions together with the appropriate equipment. The authors of paper [12] conduct a study of the dependence of results of the EIT examination on the applied parameters. The study was conducted on healthy animals and animals with acute respiratory distress syndrome. A change in the amplitude, frequency, and phase parameters of the EIT examination was shown to contribute to improving the efficiency of detection of affected areas of the lungs. It is worth noting that the study is aimed at detecting differences in the visualization of healthy and damaged tissues when applying various parameters of the research. Thus, it is impossible to say that the paper explores the possibility of personalizing the EIT parameters under clinical conditions.

All this suggests that it is expedient to conduct a study on the development of tools that make it possible to research information and measuring systems of electrical impedance tomography under conditions close to the conditions of medical institutions.

In this regard, it was decided to simulate the pre-and post-operative situation and the situation for the creation of the most appropriate conditions for the use of the developed medical and technical facilities of the MF EIT. At the same time, special attention was paid to the issues related to the exclusion of negative impact and influence on the test participants.

In particular, the issues related to the organization and performance of measures of artificial ventilation of lungs (AVL) and defibrillation were excluded.

Thus, a research bench, which makes it possible to create a platform for experimental studies of the information and

measuring system of multi-frequency electric impedance tomography (IMS MF EIT) of human lungs, was proposed and manufactured.

There are no research facilities for problems of the MF EIT that are similar to those discussed in the article. The solutions proposed by the authors make it possible to localize in a single space the necessary instrumental tools for unambiguous determining a person's condition by his multi-parameter measurements and compare them with the results of the MF EIT. This ensures a reliable array of measurement and analytical information for the correct interpretation of the results of the EIT examination. The proposed bench forms the groundwork for subsequent comprehensive studies in terms of the EIT personalization, formalization of results classification by the types of patients taking into consideration their individual morphological body composition.

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### 3. The aim and objectives of the study

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The aim of the research is to develop a bench for medical and technical tests of the information and measuring system of multi-frequency electric impedance tomography of human lungs. This will allow conducting experimental studies of technical systems of the MF EIT under conditions as similar as possible to clinical ones.

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

- to propose the general principles of construction of the IS MTI EIT and to substantiate the basic requirements for the bench;
- to determine the instrument composition of the IS MTI EIT;
- to develop a plan of experimental studies of the IMS MF EIT on the proposed bench;
- to perform experimental studies of the IMS MF EIT on the proposed bench;
- to process and analyze measuring information obtained using the IS MTI EIT.

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### 4. The study materials and methods

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When developing the ISMTI EIT, the methods for searching for relevant scientific and technical information in existing reference and bibliographic databases were used. The analytical review of modern mass-produced EIT devices used in clinical practice is based on analysis of the largest exhibitions and conferences of medical instrumentation, as well as the review of the official websites of manufacturers of specialized EIT devices.

Theoretical studies were carried out using the methods for collecting medical and technical information, experiment planning, the methods of mathematical statistics, and modern approaches to archiving and recording the measurement procedure. In particular, the results of automatically generated research protocols, principles and means of backing up information, as well as the methods for its reproduction, were used.

Experimental studies of the IS MTI EIT were carried out using modern certified medical devices given in Table 1.

These devices were used to perform experimental studies of the IMS MF EIT, close to clinic conditions. The basic source data of the tests using the method of the MF EIT are given in Table 2.

Table 1

Equipment used during experimental studies of the IMS MF EIT

No. by order	Name	Purpose
1	Patient's bedside monitor COMEN-STAR-8000D (BMP) (1 unit)	Allows monitoring parameters of SpO <sub>2</sub> , ECG, breathing rate (BR), heart rate (HR)
2	Bioimpedance analyzer of metabolic processes and body composition ABC-02 «MEDASS» (1 unit)	They make it possible to assess the indicators of lipid, protein, and water metabolism, the rate of metabolic processes, and are used in the departments of dietetics, hemodialysis, intensive care, rehabilitation, and other areas. Enable performing bioimpedance analysis (BIA) of human body composition
3	Medical instrument bench SMPP-01 Medtrede, (1 unit)	It is intended to accommodate medical equipment in medical institutions, contains shelves and boxes
4	Functional bed «Armed SAE-201» with electric drive (with mattress), (1 unit)	It is intended to place the test participants in the «lying» position. Disposable sheets are used for the mattress
5	Medical monounit AdvantecPOC-615, (1 unit)	High-performance computing unit (terminal) for a variety of healthcare applications. It is used as the main computing power as part of the IMS MF EIT
6	Information and measuring system of multi-frequency electric impedance tomography (IMS MF EIT), (1 unit)	It is designed to perform an EIT examination. It was developed on the basis of the Department of Information and Measuring Systems and Technologies of the SRSPU (NPI). It provides injecting fixed-amplitude current (5 mA) in a given frequency range

Table 2

Basic source data of experimental studies using the MF EIT method

No. by order	Basic source data of multi-frequency electric impedance tomography	Value
1	Range of frequencies of injected current, [ $f_i$ ] kHz	from 50 to 400
2	Force of injected current, mA	5
3	Planned duration of monitoring at each frequency, minutes	60
4	Number of tested volunteers, people	4
5	Conditional designations of volunteers	$P1, P2, P3, P4$
6	Obtaining consent from each volunteer to perform research	Yes, in writing
7	Color map of a cut image	Ventilation: blue and white Perfusion: red and black VPR: black and white
8	Terms of research	November 2020 – January 2021
9	Position of a test participant in space	–
10	Electrode system of the IMS MF EIT	Disposable electrodes for the ECG
11	Type of the MF EIT	Two-dimensional MF EIT Three-dimensional MF EIT
12	Galvanic connection of IMS MF EIT	Yes
13	Possibility of storing results	Yes
14	Continuous control of quality of electrode attachment	Yes, automatic
15	Apparatus voltage limitation on electrodes, V	Yes 12.5

All manipulations and activities to carry out research involving healthy volunteers were performed only after obtaining their written agreement. The criteria for the involvement of volunteers in the studies were the following features: healthy adult young people from the developers of the IMS MF EIT, who themselves gave written informed consent to participate in the tests. The criteria for the exclusion from participation in experimental studies were the existence of an implanted pulse generator, chest surgeries, the existence of skin damages, health deterioration.

A pulse oximetry channel was connected to each test participant (the sensor was placed on the index finger of the right hand), ECG electrodes (three patient's cables). The structure of the electrode system (ES) of the EIT included surface disposable electrodes located along the chest perimeter at the same distance from each other.

The process of performing experimental studies was accompanied by making continuous protocols of the recorded data, taking into consideration all the features of the experiment. Simultaneously with automatic recording of the changes in potentials of the MF EIT for each test participant (1 – P4), the results of the EIT examination at a given frequency of injected current were recorded manually. It was possible to automatically generate BIA protocols for each P1–P4.

Processing of measurement data of the MF EIT, reconstruction of conductivity field, dynamic visualization of results of calculation of ventilation, perfusion and ventilation-perfusion ratio were made based on the software developed by the authors to control the operation of the IMS MF EIT and the user interface. Secondary additional statistical processing was performed using the specialized software package STATISTICA.

**5. Results of the research into designing a bench for the medical and technical tests of systems of multi-frequency electric impedance tomography**

**5.1. General principles of construction of the IS MTI EIT and basic requirements for the bench**

In general, the process of creating the IS MTI EIT implies the development of a single complex of interrelated medical devices used for testing the MF EIT facilities. It is a specialized medical and technical tool that makes it possible to simulate various conditions for the implementation of the MF EIT, including living objects. At the same time, the main purpose of creating this bench is to reduce the time for bringing the projected hardware and software facilities of the MF EIT to the stage of experimental and clinical approbations based on

a medical organization. Since the subject area of the study in the article is the implementation of tests of the IS MF EIT of human lungs, it is proposed to limit the scope of research to the conditions of units of intensive care and resuscitation, in which the further use of the device is planned.

In this regard, when developing the IS MTI EIT, it is necessary to adhere to the following principles specified in Table 3.

The practical implementation of the proposed principles enables developing a multifunctional technical tool for conducting comprehensive experimental studies of the systems of the MF EIT. At the same time, it makes it possible to conduct multi-level testing and approbation of new MFEIT devices with the performance of the tasks of clinical application, as well as a direct comparison of the obtained results with the readings of other medical devices.

Table 3

General principles of constructing IS MTI EIT

No. of entry	Principle of construction of IS MTI EIT	Basic requirements for the bench
1	2	3
1	Principle of simulating the situation in pre- and postoperative periods	1. 1. Application of certified medical items in the structure of IS MTI EIT. 1. 2. Availability in the IS MTI EIT of medical equipment that is mandatory for use in the departments of resuscitation and anesthesiology, intensive care, and postoperative wards. 1. 3. Ensuring the possibility of changing the body position in space. 1. 4. Simulation of situations and development of the main directions of application of the IMS MF EIT
2	Principle of simulating the body position in space	2. 1. The need to change the spatial positions of test participants using the outside means that exclude the effort of test participants themselves. 2. 2. Comfortable placement of test participants, excluding a negative impact on performance and results of the MF EIT. It is possible to ensure this principle with the use of a modern multifunctional bed in the bench structure as an invariable component of the IS MTI EIT
3	Principle of objective monitoring of the functional state of test participants	3. 1. Monitoring of vital indicators that could be potentially taken into consideration in processing and analyzing the data of the MF EIT. 3. 2. Exclusion of subjective factors of researchers from the monitoring process. A simple solution to ensure this criterion is to use a bedside patient's monitor
4	Principle of differentiation of test participants	4. 1. Study of people with various geometric sizes, the various body builds, and internal composition. 4. 2. Taking into consideration the physiological, anatomical and anthropometric features of test participants in problems of MF EIT. This criterion is ensured by the use in the structure of the IS MTI EIT of a bioimpedance analyzer of human body composition. With the help of this toolkit, it is possible to divide test participants according to the criterion of total electrical resistance of the internal structures of a human to the flow of electric current
5	Possibility to perform research to solve a wide range of scientific and technical problems	5. 1. Existence of several channels for obtaining information about the condition of test participants. For example, BR, HR, blood oxygenation, and photo plethysmography (SpO2), etc. 5. 2. Possibility of conducting simultaneous combinatorial research with a wide range of problems to be solved. 5. 3. Taking into consideration the multifactorial impact on a test participant. 5. 4. Assessment of a degree of influence of the IMS MF EIT on other medical devices. 5. 5. Assessment of the ergonomic degree of the proposed IMS MF EIT. 5. 6. Ensuring the operability of the IS MTI EIT of the developed MF EIT devices, regardless of their modification
6	Principle of mobility and compactness	6. 1. The need for local movements of the hardware of the IS MTI EIT during the tests to comply with the most comfortable conditions for test participants and researchers. 6. 2. Reduction and elimination of the negative impact of the bench equipment on each other
7	Ensuring the safety of tests	7. 1. The use of certified medical devices. 7. 2. Continuous visual monitoring. 7. 3. Self-control and feedback from test participants
8	Assessment of the impact of the operation of the developed IMS MF EIT on other medical devices	8. 1. Assessment of the degree of influence of the MF EIT systems on other medical devices. 8. 2. Ensuring the possibility of excluding/reducing the impact of the operation of the IMS MF EIT on medical devices connected to a patient. 8. 3. Control of subjective sensations to the parameters of the EIT impact (for example, force and frequency of injected current)
9	Principle of obtaining information in real-time mode	9. 1. Implementation of current monitoring of changes in the functional state of the lungs in accordance with the research plan. 9. 2. Multiparameter control of physiological indicators of test participants when performing the MF EIT in real-time mode
10	Principle of storage and making protocols of the MF EIT procedure	10. 1. Storage of the MF EIT results. 10. 2. Generation of protocols of the BIA and MF EIT results. 10. 3. Formation of experimental tables and other supporting documents for fixing the conditions for the implementation of experimental studies

Continuation of Table 3

1	2	3
11	Exclusion of application of life support systems	11. 1. Exclusion of a defibrillator from the structure of the IMS MF EIT. 11. 2. Exclusion of the device of artificial ventilation of lungs from the structure of the IMS MF EIT ventilator. This restriction is due to the fact that only healthy people who do not need intensive care will be allowed to take part in the research at the proposed bench. At the same time, it is not possible to connect healthy people (including those outside a clinical organization) to this kind of device

**5. 2. Determining the instrument composition of the test bench**

A block diagram of the IS MTI EIT for performing examination using the MF EIT method was developed. It was shown in Fig. 1. It was obtained based on an analytical review of the current global state of the direction of EIT of human lungs, as well as on the analysis of publication activity in the field of medical applications of modern EIT tools. To manufacture the bench in accordance with the proposed block diagram, the work was performed to search for and acquire new medical devices. In particular, to assemble and arrange the bench, medical equipment was purchased in the amount and composition specified in Table 1.

In the proposed version of the construction of the IS MTI EIT, all devices (except for a functional medical bed) are located on a mobile medical board bench SMPP-01. This makes it possible to localize the tools and increase the mobility of the entire IS MTI EIT. The information and measuring system of multi-frequency electric impedance tomography is implemented based on a modern monounit for medical purposes manufactured by Advantech. Structurally, this

monounit is attached to the bracket of the hardware bench. The hardware and software unit is located on the top of the bench and is connected to the mono unit via a USB interface.

The problems of the bench structure, review of necessary and available devices, their acquisition, delivery, and assembly were solved, and trial experiments were conducted in the period of August 2020 – November 2020. The physical appearance of the assembled bench is shown in Fig. 2.

An analyzer of bioimpedance processes and body composition ABC-02 is located on the lower shelf of the bench. It is designed to perform the first stage of research in order to differentiate the test participants by the body mass index (BMI). At the same time, the list of evaluation parameters is not closed. It is determined by built-in protocols, which are automatically generated based on the BIA results and are subject to further accounting in order to assess the dynamics of their change. This is necessary to perform works on studying the trends in the results of MF EIT of lungs and the nature of changes in electrical properties of separate organs and tissues. The power supply of components of the IS MTI EIT is carried out from the built-in socket unit connected to the power supply network of a laboratory. The bench is equipped with a grounding element.

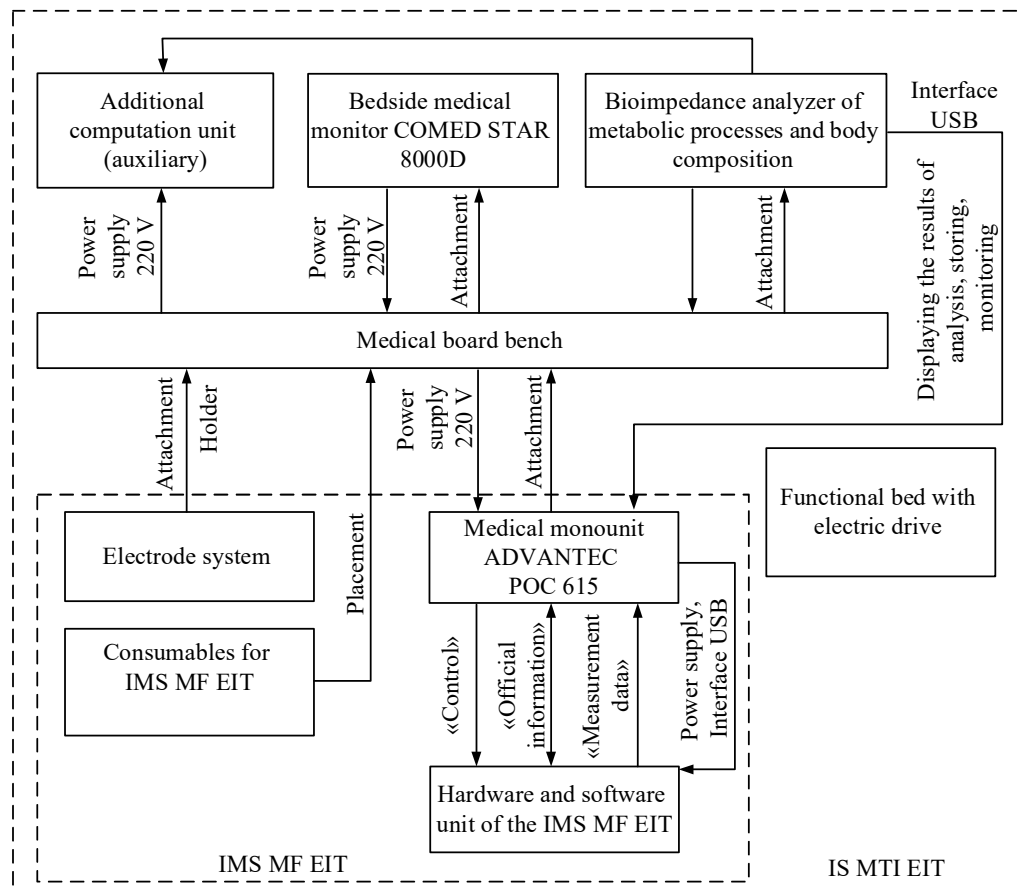


Fig. 1. Block diagram of the experimental bench for research



Fig. 2. General view of the IS MTI EIT for solving the MF EIT problems

**5. 3. Development of a plan for experimental studies of IMS MF-EIT at the proposed bench**

The purpose of the experimental studies of the IS MTI EIT is to solve the following scientific and technical problems:

- assessment of the operability of the developed and created technical solutions and algorithms of the MF EIT in practice as part of a single bench under conditions close to clinical;
- assessment of the possibility to perform a long-term MF EIT on the developed bench under conditions of the laboratory base and with the involvement of volunteers;
- assessment of the influence of injected current of the IMS MF EIT on the ECG channels of a bedside patient's monitor, which is an integral element of the bench;
- study of the possibility of differentiating patients according to the results of BIA when performing MF EIT;
- identification of problem areas for monitoring the results of the EIT research and the user interface of the IMS MF EIT;
- assessment of compliance of BR, HR, and VPR calculated using the IMS MF EIT with the values determined by the BMP;
- formation of a vector of directions for further refinement of algorithmic and hardware-software tools that were identified with the help of the proposed bench.

To perform experimental studies, a test plan was developed, the block diagram of which is shown in Fig. 3.

This block diagram describes the sequence of actions necessary to perform experimental studies based on the proposed IS MTI EIT.

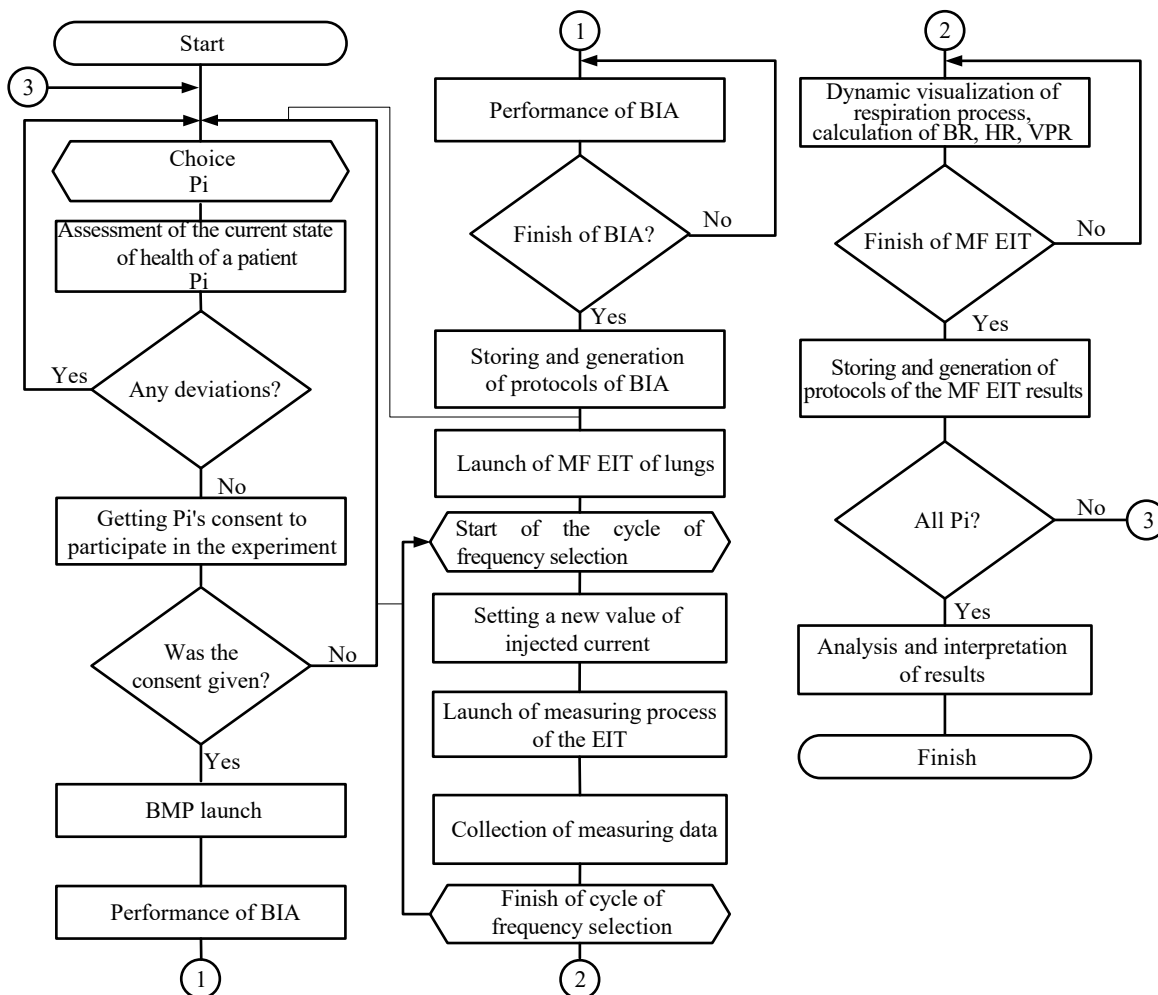


Fig. 3. Block diagram of experimental studies of the MF EIT systems on the developed IS MTI EIT

**5.4. Experimental studies of IMS MF-EIT on the proposed bench**

The developed IS MTI EIT was used to perform experimental studies in accordance with the plan of tests and the information specified in Table 2 and Fig. 3. Fig. 4 shows the photos of the process of experimental research on the IS MTI EIT.



a



b



c



d



e

**Fig. 4.** Photographic images of the process of performing experimental studies: *a* – for test participant *P1*; *b* – for test participant *P2*; *c* – for test participant *P3*; *d* – for test participant *P4*; *e* – an example of attaching sensors and electrodes of devices that are part of the bench

The test participants (*P1–P4*) were sequentially connected to the constituent elements of the IMS MF EIT. All of them were in a calm state, did not eat or drink water. They were in the position of “lying” on the bed (on the back). Physical and emotional loads were excluded.

Experimental studies were carried out in accordance with the information specified in Table 2 and Fig. 4. Table 4 shows the summary average values of the monitored parameters for each of the *P1–P4* during the observation time (60 minutes). At the same time, to give an objective assessment of the performance of the IS MTI EIT, it was proposed to

compare the values of BR, HR and VPR, determined indirectly using IMS MF EIT and BMP.

Simultaneously with the quantitative assessment, continuous dynamic visualization of the breathing process was provided for *P1, P2, P3*, and *P4*. The results of the examination of all test participants at each frequency  $f_i$  were recorded and archived for further reproduction and analysis.

**5.5. Processing and analysis of measurement information obtained with the use of IS MTI EIT**

**5.5.1. Assessment of operability of the developed and created technical solutions and algorithms of MF EIT in practice as part of a unified bench**

Summary results of experimental data are shown in Table 4. It presents the information obtained for all test participants  $P_i$  using the constituent elements of the IS MTI EIT.

An array of observations of BR and HR using the IMS MF EIT and BMP for *P1, P2, P3*, and *P4* was used to calculate the relative errors in assessment  $\delta$  (BR) and  $\delta$  (HR). The results of their calculation are shown in Table 5. The values determined on the BMP were used as a reference measure.

Table 4

Results of experimental data

N	IMT	$t_i$ , min	$f_i$ , kHz	IMS MF EIT			Bedside patient's monitor		
				BR	HR	VPR	BR	HR	SpO2
P1	19.2	60	50	11–12	69–78	0.93–1.1	10–11	90–92	98–99
		60	100	12–13	80–82	0.86–1.14	11–13	93–95	98–99
		60	150	13–16	87–92	0.85–1.0	13–14	95–96	98–99
		60	200	12–15	71–78	0.86–1.02	13–14	96–97	98–99
		60	250	11–13	82–85	0.86–1.06	13–14	89–90	98–99
		60	300	16–17	83–87	0.95–1.02	14–16	86–90	98–99
		60	350	11–12	68–72	0.98–1.08	12–15	90–99	98–99
		60	400	13–15	82–83	0.98–1.09	14–16	95–96	98–99
P2	23.7	60	50	17–18	71–73	1.06–1.18	16–17	74–75	98–99
		60	100	18–19	70–71	0.93–1.01	18–20	71–72	97–98
		60	150	17–18	65–72	1.11–1.19	16–17	74–76	97–98
		60	200	16–17	76–77	1.12–1.18	17–19	74–76	97–98
		60	250	20–21	64–66	1.11–1.19	18–19	77–79	98–98
		60	300	18–19	67–74	1.12–1.16	17–18	72–78	98–98
		60	350	16–17	60–71	1.03–1.12	17–18	72–74	99–99
		60	400	10–12	71–72	1.04–1.12	12–14	72–74	99–99
P3	21.9	60	50	14–15	70–72	0.96–1.07	7–10	76–78	98–99
		60	100	15–16	63–69	1.02–1.06	9–11	74–78	99–99
		60	150	13–15	78–79	0.96–1.04	14–15	75–77	98–99
		60	200	18–19	70–71	1.01–1.07	16–18	78–79	99–99
		60	250	18–19	72–73	1.03–1.07	15–16	75–76	98–99
		60	300	18–20	62–63	1.02–1.07	17–18	76–78	99–99
		60	350	17–18	75–76	1.18–1.19	15–16	73–75	99–99
		60	400	18–19	77–78	1.02–1.05	15–16	74–75	98–99
P4	26.1	60	50	17–18	75–80	0.95–1.00	19–20	78–82	98–99
		60	100	16–17	58–60	0.99–1.10	15–16	86–87	97–98
		60	150	14–16	80–82	0.89–1.04	12–14	81–83	97–98
		60	200	14–15	70–71	0.97–1.08	11–14	84–88	97–98
		60	250	14–15	62–64	0.96–1.04	14–15	89–91	97–98
		60	300	16–17	72–74	0.99–1.10	13–15	87–88	97–98
		60	350	16–17	62–64	0.97–1.03	12–13	87–92	97–98
		60	400	12–14	89–92	0.93–1.00	11–13	91–92	97–98



Table 5

Results of assessing the error in determining BR and HR for  $P1-P4$

$P_i$	$P1$		$P2$		$P3$		$P4$	
$f_i$ , kHz	$\delta(BR)$ , %	$\delta(HR)$ , %	$\delta(BR)$ , %	$\delta(HR)$ , %	$\delta(BR)$ , %	$\delta(HR)$ , %	$\delta(BR)$ , %	$\delta(HR)$ , %
50	9.52	19.23	6.06	3.36	70.59	7.79	10.26	3.13
100	4.17	13.83	2.63	1.40	55.00	13.16	6.45	31.79
150	7.41	6.28	6.06	8.67	3.45	3.29	15.38	1.22
200	0.00	22.80	8.33	2.00	8.82	10.19	16.00	18.02
250	11.11	6.70	10.81	16.67	19.35	3.97	0.00	30.00
300	10.00	3.41	5.71	6.00	8.57	18.83	17.86	16.57
350	14.81	25.93	5.71	10.27	12.90	2.03	32.00	29.61
400	6.67	13.61	15.38	2.05	19.35	4.03	8.33	1.09
$ \delta(M) $ , %	0.19	13.97	0.43	5.80	23.89	5.58	10.72	16.43

Analyzing the data of Table 5, it can be concluded that the mean value of the error of indirect estimation of BR  $\delta_{CP}(BR)$  does not exceed 17 % (except for the output at injection frequency of 50 kHz in  $P3$ ). The error of indirect estimation of HR  $\delta_{CP}(HR)$  is about 16 %. Taking into consideration the duration of monitoring (60 minutes at each  $f_i$ ), continuity of the study, conditions for performing MF EIT, as well as the data of Table 5, it can be concluded that the created IS MTI EIT makes it possible to do research to assess the performance of technical solutions and algorithms of the MF EIT.

**5. 5. 2. Assessment of the possibility of performing a long-term MF EIT on the developed bench under conditions of the laboratory base with the involvement of volunteers**

The workability of the IS MTI EIT was maintained throughout the time of the collection of measurement data and dynamic visualization of the breathing process for all test participants. During the experiments, failures and other disruptions of the structural elements of the IS MTI EIT were not observed. Given the duration of the process of experimental research, there was a need for local movements of the IS MTI EIT. However, these manipulations did not affect the process of collecting measurement data and visualization of the breathing process by the MF EIT method with simultaneous monitoring of parameters of vital activity of a test participant. Switching between the BIA, MF EIT, and BMP devices, replacement of failed electrodes, etc. were carried out without any interference into experimental studies.

**5. 5. 3. Assessment of compliance of BR, HR, and VPR, calculated for IMS MF EIT, with the values determined by the BMP**

For each  $P_i$ , standard statistical diagrams of the spread of the BR and HR values determined on the IMS MF EIT and BMP were constructed. The designations specified in Table 6 are shown in Fig. 5.

Analyzing the data in Fig. 5, 6, it can be concluded that there is a pattern of dependence of the obtained values within each test participants  $P_i$ . Moreover, the nature of the dependence of the values of BR and HR for each test participant regardless of the type of the research (IMS MF EIT or BMP) is clearly visible.

Table 7 gives the examples (freeze frames) of the results of dynamic visualization of changes in conductivity field due to the process of lung ventilation ( $\Omega_v$ ), changes in conductivity field due to the process of lung perfusion ( $\Omega_p$ ), the results of calculation and visualization of the VPR for all test participants ( $P1, P2, P3$  and  $P4$ ). These images were obtained using the IMS MF EIT.

Table 7 shows that the proposed bench can be used for problems of long-term monitoring and visualization of cycles of breathing, lungs perfusion, and derivatives based on them (for example, VPR). The information given in Table 7 demonstrates that the areas of human lungs involved in the process of air exchange are visualized, and the proposed technical solutions can be used in subsequent research.

Table 6

Explanation to the data shown in Fig. 5, 6

Designation	BR	HR
$P1\_IMS$	The score was obtained according to the data of IMS MF EIT for test participant $P1$	The score was obtained according to the data of IMS MF EIT for test participant $P1$
$P2\_IMS$	The score was obtained according to the data of IMS MF EIT for test participant $P2$	The score was obtained according to the data of IMS MF EIT for test participant $P2$
$P3\_IMS$	The score was obtained according to the data of IMS MF EIT for test participant $P3$	The score was obtained according to the data of IMS MF EIT for test participant $P3$
$P4\_IMS$	The score was obtained according to the data of IMS MF EIT for test participant $P4$	The score was obtained according to the data of IMS MF EIT for test participant $P4$
$P1\_BMP$	The score was obtained according to the data of BMP for test participant $P1$	The score was obtained according to the data of BMP for test participant $P1$
$P2\_BMP$	The score was obtained according to the data of BMP for test participant $P2$	The score was obtained according to the data of BMP for test participant $P2$
$P3\_BMP$	The score was obtained according to the data of BMP for test participant $P3$	The score was obtained according to the data of BMP for test participant $P3$
$P4\_BMP$	The score was obtained according to the data of BMP for test participant $P4$	The score was obtained according to the data of BMP for test participant $P4$

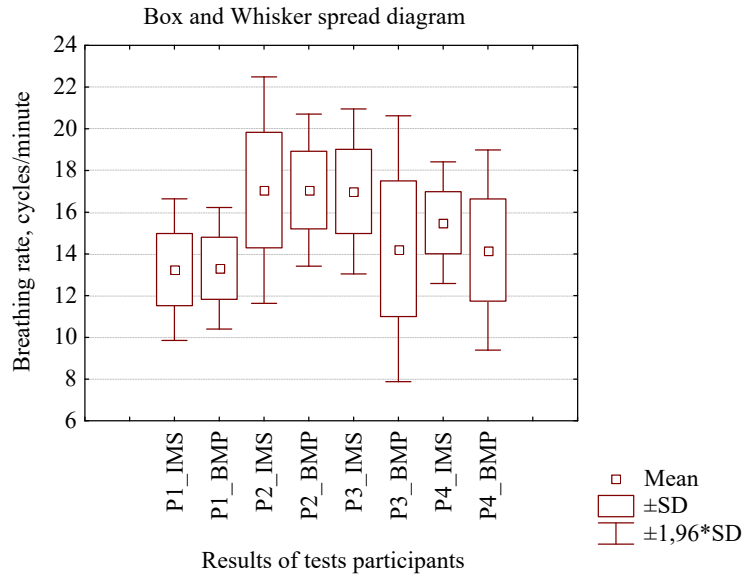


Fig. 5. Diagram of the spread of BR values determined by IMS MF EIT and BMP for test participants  $P1$ ,  $P2$ ,  $P3$  and  $P4$

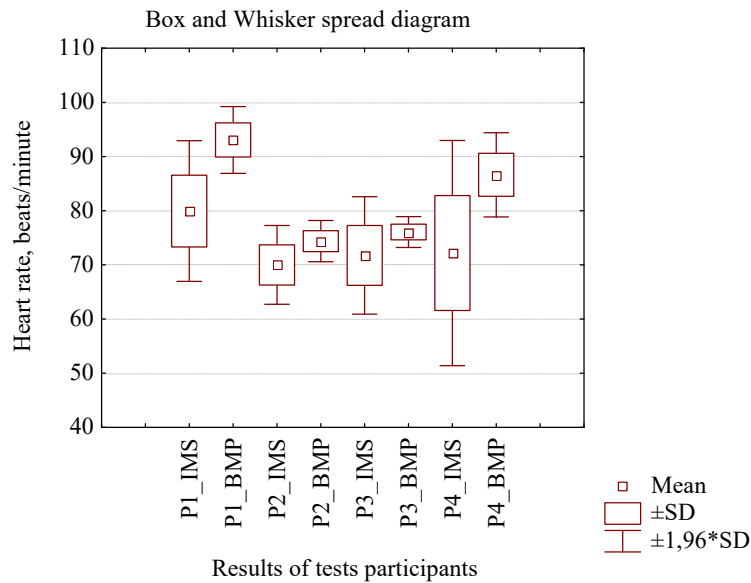


Fig. 6. Diagram of the spread of HR values determined by the IMS MF EIT and BMP for test participants  $P1$ ,  $P2$ ,  $P3$  and  $P4$

Table 7

Results of visualization of changes  $\Omega_V$ , changes of field  $\Omega_P$  and VPR, obtained using the IMS MF EIT

$P_i$	$P1$			$P2$		
$f_i$ , kHz	$\Omega_V$	$\Omega_P$	VPO	$\Omega_V$	$\Omega_P$	VPR
1	2	3	4	5	6	7
50						
100						

Continuation of Table 7

1	2	3	4	5	6	7
150						
200						
50						
300						
350						
400						
$P_i$	$P_3$			$P_4$		
$f_i$ , kHz	$\Omega_V$	$\Omega_P$	VPO	$\Omega_V$	$\Omega_P$	VPR
50						
100						
150						
200						

Continuation of Table 7

1	2	3	4	5	6	7
250						
300						
350						
400						

**5. 5. 4. Evaluation of the influence of injected current of the IMS MF EIT on the ECG channels of a bedside patient’s monitor as part of the bench**

It was found that the implementation of the MF EIT does not affect the recording of the ECG signal. It should be noted that the moment of current injection, which is visualized as the appearance of an additional short-term high-frequency signal, is visualized on the ECG curve (Fig. 7).

At the same time, this feature of the operation of the IMS MF EIT was observed at all frequencies of injected current and on the ECG data of all the examined volunteers. Thus, there is a transient process when the EIT examination gets started. This problem was related to the problems of organizing the process of the IMS MF EIT control and was promptly eliminated. Nevertheless, the obtained results show that the IS MTI EIT can be used to identify problem areas in the developed MF EIT systems and their prompt elimination.



*a*

*b*



*c*

*d*

**Fig. 7.** Influence of the process of current injection on the channel of recording ECG of a bedside patient’s monitor:

- a* – on the results of recording the ECG of test participant *P1*;
- b* – on the results of recording the ECG of test participant *P2*;
- c* – on the results of recording the ECG of test participant *P3*;
- d* – on the results of recording the ECG of test participant *P4*

**6. Discussion of the results of experimental studies of the developed bench**

The results obtained in the course of experimental studies indicate that the manufactured IS MTI EIT can be used in the problems of the MF EIT of human lungs. The proposed solutions make it possible to perform experimental studies of technical systems of the MF EIT under conditions as similar as possible to clinical ones. In addition, they can significantly reduce the time for testing, approbation, and evaluation of the developed devices for EIT of lungs. A positive result is achieved due to the possibility of forming new test plans with specified conditions and different levels of complexity. This makes it possible to enhance the effectiveness of subsequent clinical tests on the patients who are treated in a resuscitation unit or an intensive care unit. In general, the proposed IS MTI EIT provides a decrease in time for the elimination of practical problems of a clinical nature, electronic filling, and algorithmic support of the developed medical and technical facilities of the MF EIT.

The workability of the bench is proved by the repeatability of the obtained results of monitoring ventilation, perfusion and VPR for each test participant,

the continuity of dynamic visualization of the breathing process, as well as a high degree of correlation of the obtained values of differences of potentials with the BMP indicators. Thus, it becomes possible to solve a wide range of scientific and applied problems to create new tools for non-invasive monitoring and evaluation of the parameters of the function of external respiration and the effectiveness of apparatus ventilation of lungs based on the MF EIT.

The medical and technical instrument composition proposed in Table 1 has significant potential for a wide range of research in the field of the EIT of human lungs. Implemented principles of construction, reflected in Table 3, ensure the possibility of long-term safe bedside monitoring of a patient's condition with the possibility to simulate the conditions of clinical examinations.

The obtained test results prove the possibility of using the ISMTI EIT for subsequent scientific and technical research in the field of the MF EIT.

However, this study has a series of limitations:

1) theoretical studies show that the proposed principles for determining VPR at EIT reflect modern ideas about this parameter. However, VPR monitoring is a procedure of indirect assessment and requires additional research in terms of assessing the adequacy and reliability of obtained data;

2) the boundaries of applicability of the proposed solutions are limited to healthy test participants. The paper did not contain the examination of people who have pathologies in the system of external respiration;

3) the conditions of applicability of the proposed solutions are limited by the features of the laboratory, on the basis of which experimental studies were conducted. In particular, conditions that are close to clinical, but do not replace them, were created;

4) the procedures of performing the MF EIT are limited by technical characteristics and functionality of the IMS MF EIT;

5) the limited instrument composition of the bench, excluding the existence of the AVL and a defibrillator. This is due to the fact that when drawing up the research plan, the features of the bench, which are characterized by the complete absence of devices with an increased level of the influence of the human body, were taken into account;

6) the lack of studies of long-term bedside monitoring with the time of continuous monitoring of the lung condition of a test participant for more than 24 hours;

7) a small sample of test participants and the absence of a control group, although all test participants performed self-control of their own well-being, discomfort, and the existence of side effects. Nevertheless, the obtained results make it possible to conclude that the proposed technical solutions enable performing the MF EIT for a sufficiently long period of time. During testing, the IMS MF EIT did not fail, the workability was ensured throughout the test on all test participants.

The disadvantages of this study include the following features: a limited frequency range (from 50 kHz to 400 kHz), a frequency increase pitch multiple of 50 kHz, a fixed current force of 5 mA, as well as the absence of tests using electrode systems based on reusable metal electrodes. These problems and limitations are the subjects of further research and developments, require separate algorithmic and hardware solutions and go beyond the scope of this research.

The development of the results of the article is inevitably associated with the expansion of the apparatus and algorithmic

content of the IS MTI EIT. In particular, it is necessary to include in the structure of the bench a number of other medical items used in resuscitation practice, as well as to consider the potential possibility of organizing a multi-user platform for the problems of the MF EIT based on the developed bench. This will allow increasing the efficiency of examination using the MF EIT method and reducing the time for obtaining primary measurement information.

The development of procedure description and methodological approaches may consist in the organization and performance of the MF EIT of lungs at different positions of a patient's body, taking into consideration the whole complex of possibilities of the IS MTI EIT. In particular, a number of similar studies should be performed in the "lying", "standing" and "sitting" positions, as well as using load testing technologies. In this regard, in the future, it is advisable to include in the structure of the bench the items for simulating load procedures, which are widespread in the postoperative period.

Expanding the functionality of the proposed bench is possible by including new medical items, as well as appropriate software, in its structure. In particular, it is promising to obtain estimates of the degrees of relationship between the results of the MF EIT and the results of other medical methods implemented based on the IS MTI EIT. Thus, it is possible to manufacture a single non-invasive bedside technology for multiparameter assessment of the functional state of patients' lungs based on the proposed bench.

One of the areas of research in the short-term perspective is to obtain permission from the committee of the ethics of a medical organization to perform experimental and clinical testing of the bench involving the patients with confirmed respiratory function disorders, as well as the patients connected to the AVL devices. This set of studies is mandatory and is aimed at clarifying the capabilities of the bench for its use on apparatus patients.

It became possible to expand the functionality of the bench by including new medical items in its structure. Equipment of the IS MTI EIT with a computer spirometer seems promising.

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## 7. Conclusions

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1. The general principles of construction of the IS MTI EIT were proposed and the basic requirements for the bench that allow creating the tools for performing medical and technical studies of devices for the EIT of lungs were stated. The considered approaches have the scientific and technical potential for simulating the conditions of application of the EIT systems with the possibility of expanding the required hardware. The obtained results of theoretical research enable choosing the main modules of the bench and forming a program for subsequent experimental research.

2. The instrumental composition of the IS MTI EIT was determined. The hardware and software bench designed for planning, organizing, and performing research into both new technical EIT facilities and specialized software solutions under conditions close to clinical was assembled. The manufactured IS MIT EIT has novelty and significant potential for solving a wide range of experimental problems of the MF EIT.

3. A plan of experimental studies of the IMS MF EIT was developed on the proposed bench. It contains a sequence

of actions necessary to perform tests using the equipment of the IS MF EIT. The main distinctive features of the proposed plan are mutually related operations performed taking into consideration the instrumental composition of the bench for solving the problems of the two-dimensional and three-dimensional MF EIT.

4. Experimental studies of the IMS MF EIT were carried out on the proposed bench with the involvement of 4 volunteers. The monitoring duration is 60 minutes at each frequency of the injected current. The obtained results demonstrated the capability of the proposed IS MF EIT to perform safely and successfully long-term non-invasive monitoring of the functional state of human lungs with simultaneous dynamic visualization of the processes of ventilation, perfusion and the ventilation-perfusion ratio. All structural elements of the assembled bench remained operational throughout the test cycle.

5. Measurement information obtained with the use of the IS MTI EIT was processed and analyzed. The obtained results showed that the developed and assembled IS MTI EIT can be

used to solve the problems of the MF EIT of human lungs. It makes it possible to perform long-term bedside monitoring of the human breathing process based on the EIT with the possibility to visualize changes in the conductivity field due to the process of air filling of lungs. The results of processing the data of the IMS MF EIT and their comparison with the readings of a bedside monitor show that the average value of the error of indirect assessment of the BR does not exceed 17 %, and that of the HR is about 16 %.

In particular, it was found that the implementation of the MF EIT does not affect the recording of the ECG signal. In this case, it should be noted that the moment of current injection, which is visualized as an additional short-term high-frequency signal, is visualized on the ECG curve.

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