7. Ouyang, M., Zhang, W., Wang, E., Yang, F., Li, J., Li, Z. et. al. (2015). Performance analysis of a novel coaxial power-split hybrid powertrain using a CNG engine and supercapacitors. Applied Energy, 157, 595–606. doi: https://doi.org/10.1016/j.apenergy.2014.12.086
8. Saw, L. H., Poon, H. M., Chong, W. T., Wang, C.-T., Yew, M. C., Yew, M. K., Ng, T. C. (2019). Numerical modeling of hybrid supercapacitor battery energy storage system for electric vehicles. Energy Procedia, 158, 2750–2755. doi: https://doi.org/10.1016/j.egypro.2019.02.033
9. Rahman, A. U., Ahmad, I., Malik, A. S. (2020). Variable structure-based control of fuel cell-supercapacitor-battery based hybrid electric vehicle. Journal of Energy Storage, 29, 101365. doi: https://doi.org/10.1016/j.est.2020.101365
10. Yin, C., Wu, H., Locment, F., Sechilariu, M. (2017). Energy management of DC microgrid based on photovoltaic combined with diesel generator and supercapacitor. Energy Conversion and Management, 132, 14–27. doi: https://doi.org/10.1016/j.enconman.2016.11.018

UDC 615.47
DOI: 10.15587/1729-4061.2021.234767

DEVELOPMENT OF AN ALGORITHM FOR SELECTING THE REQUIRED FREQUENCY OF INJECTED CURRENT FOR MULTI-FREQUENCY ELECTRICAL IMPEDANCE TOMOGRAPHY FOR TASKSRELATED TO PREOPERATIVE MONITORING OF HUMAN LUNG FUNCTION

Grayr Aleksanyan
Corresponding author
PhD
Department of Information and Measurement Systems and Technologies
Platov South-Russian State Polytechnic University (NPI)
Prosveshcheniya str., 132, Novocherkassk, Russian Federation, 346428
E-mail: graer@yandex.ru

This paper proposes an algorithm for selecting the required frequency of injected current for problems of personalized multi-frequency electricalimpedance tomography. The essence of the algorithm is to calculate the rate of change in the recorded difference of potentials for the assigned range of frequencies of injected current, followed by determining the frequency after which the rate of a change in potentials is minimal. Subsequently, the injection parameters are readjusted to the chosen frequency and the complete process of electricalimpedance tomography is started. The proposed solutions were studied on four subjects with different fat mass, defined by bioimpedance analysis. Thus, it seems possible to track the dynamics of a change in the lungs of a certain patient by visualizing the reconstructed conductivity field, taking into consideration its internal features. It was established that in the course of studying lungsby using the method of electricalimpedance tomography, it is necessary to take into account the frequency of injected current at an increase in percentage of fat mass. The results of the studies showing a change in the quality of imaging the breathing process at different frequencies of injected current (from 50 kHz to 400 kHz, with a pitch of 50 kHz) are presented. For the test participants with a fat weight of 7.6 kg, 23.3 kg, 15.2 kg and 37.3 kg, the injection frequency was determined as 150 kHz, 200 kHz, 200 kHz, and 350 kHz, respectively.

The proposed algorithm enables visual monitoring of lung function and can be used in the problems of pre- and postoperative monitoring of respiratory function of patients. Its use is particularly relevant for patients connected to an apparatus of artificial lung ventilation

Keywords: multi-frequencyelectrical impedance tomography, selection of injection frequency, information and measuringsystem, fat mass, human lungs

Received date: 10.05.2021
Accepted date: 13.06.2021
Published date: 25.06.2021

***How to Cite**: Aleksanyan, G. (2021). Development of an algorithm for selecting the required frequency of injected current for multi-frequency electrical impedance tomography for tasksrelated to preoperative monitoring of human lung function. Eastern-European Journal of Enterprise Technologies, 3 (5 (111)), 25–28. doi: https://doi.org/10.15587/1729-4061.2021.234767*

1. Introduction

Electrical impedance tomography (EIT) is one of the methods of medical imaging, the principle of which is based on evaluation of a change in the field of conductivity in the assignedcross-section of an object at the injection of high-frequency current of a small amplitude through it [1]. Electrodes, which are either injectable or measuring at a specific moment, are evenly attached on the surface of an object (usually around the perimeter of an object). The state of the electrodes is switchedover by a special control program. The configuration of measuring and injectable electrodes, as well as the switching algorithm, form the system of EIT connections [2]. The mathematical and algorithmic basis of the EIT method is solution ofaninverse problem of reconstructing the conductivity field of an object's cross-section, determined by the plane of the electrodes' attachment. The EIT method was most common during bedside monitoring of lungs of the patients in an intensive care unit and of those connected to devises of respiratory support of external breathing function [3–5].

The EITpersonalization issues are undergoing some changes due to the general trend of the method development. This is caused by fact that, as a rule, the EIT under clinical conditions is based on the application of current of a given frequency without regard to the characteristics of a patient. The only area of consideration for the specificity of an object under study is the length of the electrode belt, which depends on the perimeter of the human chest girth, and a patient's gender [6, 7]. In this case, internal specific features of a person, such as the thickness of the adipose tissue, fluid distribution in the body, percentage of skeletal-muscle tissue, etc. are not taken into account. These circumstances place restrictions on the capabilities of the EIT method, especially when taking respiratory support measures. In this regard, a new approach to addressing the problem is proposed. An algorithm to select the required frequency of injected current for the ETI personalization based onthe multi-frequency EIT (MF EIT) is suggested. In this case, the current of an assigned range of frequencies is injected simultaneously with assessing a change in the distribution of the reconstructed conductivity field. The proposed solutions are relevant and are aimed at expanding the functionality of the MF EIT. The practical implementation of the algorithm for selecting the required frequency will solve one of the important problems of the EIT – obtaining a personalized objective assessment of electrical properties of the internal structures of an object under study. Thus, it becomes possible to determine the boundary frequency of injection current, at which its further increase will not result in an increase in the sensitivity of the method to the specificity of an object.

2. Literature review and problem statement

The results of studies of research into clinical application of the EIT method on patients connected to an apparatus ofartificial ventilation of lungs (AVL) are presented inpapers [8–10]. It is noted that the problems of long-term non-invasive monitoring of human lung function during the pre- and postoperative period are among the important components of improving the quality of medical services of supporting the respiratory function of patients. Thus, paper [8] shows that the optimal values of positive end-expiratory pressure (PEED) in separate lung segments in cardiac patients in the postoperative period were determined with the help of EIT. It was shown that the estimated dead space ishighly correlated with the results of EIT in determining the optimal PEED. There is no assessment of validity of the obtained results with allowance for the characteristics of each of the fifteen test participants. The authors of paper [9] suggested using the EIT to assess the physiological effects of open access to the lungs in patients with early light diffusing acute respiratory distresssyndrome (ARDS).At the same time, the study does not analyze the state of the lungs of the tested before the start of intensive care activities, which does not give an idea of a degree of the EIT personalization for a particular patient and decreases the reliability of obtained results. Similar studies in terms of applicability of the EIT method in clinical practice were carried out in research [10] for premature infants. On the whole, analysis of publishing activity reveals a dynamic increase in the application of the EIT method in clinical practice in a number of areas. Their distinctive feature is the study of issues of monitoring the patient's lungs using the EIT method exclusively in the postoperative period and without taking into consideration the specificity of the object of research. In addition, the authors do not substantiate the selected modes and parameters of the impact of the EIT. At the same time, a set of measures including mainly X-ray hardware and software solutions is used to adequately assess the dynamics of changes in the lung condition in an intensive care unit [11, 12]. Thus, it was proved that, despite its shortcomings, computer tomography provides important information about a patient's condition at the entire stage of medical aid in an intensive care unit. In article [12], a six-year retrospective study allowed making a conclusion that CT is an invaluable method for monitoring and assessing various chest diseases. At the same time, CT provides an accurate diagnosis, which has a great impact on the course of treatment. However, it should be taken into consideration that the number of examinations using CT on a certain patient is limited by side effects and difficulties of practical application(e.g., the need to transport to the site of examination). In addition, CT results cannot be used directly and promptly to optimize EIT parameters.

Research [13–15] shows that there is a practical need to use the technical means of long-term monitoring of vital activity of the patient's lungs at his bedside without ionizing radiation and the need to be transported to specialized premises. Thus, paper [13] contains a review of various methods for breathing monitoring, including the role of traditional and cutting-edge methods in the perioperative period and in patients in critical condition. The most recent methods proposed for monitoring breathing at the bedside of a patient, including lung imaging, are presented and discussed, compared to those that are actually considered gold standards. In [14], analysis and analytical search revealed that two methods of bedside monitoring, such as ultrasonic introscopy of lungs and EIT, are now gaining popularity for problems oflung function monitoring along with traditional methods. These methods do not involve the use of ionizing radiation, are non-invasive and are relatively easy to use, they are also extensively studied as a supplement, and for some uses replace traditional methods.In this case, the problems of EIT personalization and its effectiveness are not explored. The authors of [15] emphasize that it is particularly important to reduce the risk of developing the ARDS after surgery. The strategies for anesthesia and protective apparatus for artificial ventilation of lungs play an important role in this regard. In addition, it is indicated that perioperative treatment of patients with ARDS includes special anesthesia and AVL, hemodynamics monitoring, moderately restrictive introduction of fluid and pain control.

One of the solutions to the above problems may be the EIT method, which has proven to be an effective means of organizing the treatment process in intensive care units, especially in the AVL implementation [16–18]. For example, article [16] describes the possibility of using the EIT as a treatment monitoring tool in the intensive care unit due to the difficulty of transporting a patient to the radiology department for the control CT. Studies in article [16] have shown that the use of the EIT makes it possible to assess regional lung ventilation continuously in a non-invasive way at the bedside of a patient. It can be used both for mechanically ventilated and for spontaneously breathing patients. This enables effective and dynamic control of the course of a therapeutic process. It is relatively easy to learn to interpret results and does not require special knowledge. Moreover, it is possible to use the EIT in cases where other methods pose a high risk or are contraindicated. The benefits of the EIT are emphasized, the characteristics, technical concepts, and directions of the clinical application of the EIT in patients with respiratory complications are presented in paper [17]. However, the issues of the EIT differentiation depending on the groups of the test participantsare not considered, including the waysof selecting the required parameters of injected current for the EITexamination. It was shown in paper [18] that the EIT is becoming a valuable tool for monitoring patients with mechanical lung ventilation due to its ability to continuously assess regional lung ventilation and aeration. The problems of the mutual impact of the EIT systems on devices and items of an intensive care unit were considered. Thus, the problems of accounting for the influencing factors related to devices and instruments were explored, while the issues of organizing a personalized EIT were not taken into consideration.

Comprehensive use of the EIT and the AVL is a new direction of care in intensive care units [19–21]. This approach makes it possible to detect changes in the functional state of lungs at the early stages of physiological and pathological processes and, as a result, to reduce the total number of complications and postoperative mortality.For example, the EIT during major open operations on the upper abdomen is considered in article [19]. The issues of its intraoperative use for individual optimization of the AVL settings are explored, especially in patients at risk of ventilation and perfusion inconsistency and in patients with gas exchange disorderswho have undergone serious open surgery on the upper abdomen. Paper [20] proposed the integrated system of EIT to improve the usefulness of the AVL monitoring to protect lungs in order to expand the clinical use of EIT. However, the authors both in [19] and in [20] do not consider the ways to improve the quality of EIT research by determining the necessary or optimal parameters of EIT, taking into consideration the electrical properties of the internal structures of the study area. It is pointed out in research [21] that EIT provides useful information in both animal studies and in clinical studies during AVL. EIT has been shown to be useful in recruiting lungs, titrating positive end-exhalation pressure, assessing lung volume, and evaluating the homogeneity of gas distribution in one EIT measurement or in combination with some EIT measurements. Artificial ventilation of lungs, controlled by EIT, preserves the alveolar architecture, and maintains oxygenation and mechanics of lungs better than low-inflow ventilation in animal models. However, data analysis requires a thorough evaluation because of limited understanding of the results of EIT interpretation.

All this suggests that continuous monitoring using the method of EIT of a particular patient's lungs after surgery makes it possible to personalize more the tactics of treatment of respiratory complications. It is possible to evaluate the effectiveness of therapeutic procedures in dynamics at any given time, which cannot be achieved, for example, using ionizing radiation technologies.

However, the issues of practical implementation of EIT personalization algorithms, caused by the complex internal composition of the object of research, a human, remain unresolved. In this regard, personalization of the parameters of the organization and conduction of EIT is a promising direction that will significantly expand its scope in lung function monitoring. This is due to the anatomical and physiological characteristics of an individual, as well as tothe component composition of the body, which, in the end, influences the current flow, and accordingly, affects the distribution of conductivity field. In this regard, there are problems of algorithmic provision of EIT-examinationpersonalization. It is advisable to carry out the research into the above-mentioned problems. One of such approachesis the use of the algorithm of required frequency selection (ARFS) for multi-frequency electric impedance tomography.

3. The aim and objectives of the study

The aim of the research is to develop an algorithm for the selection of frequency of injected current for multi-frequency electricalimpedance tomography, which implies calculating the rate of a change of recorded data by EIT method in the range of frequencies (50–400 kHz, with a pitch of Δf=50 kHz). This will make it possible to select the frequency of injection current for each test participant, at which the maximum sensitivity of the internal structures of the object of research to EIT method will be observed. Practical implementation of this approach will enhance the effectiveness of clinical application of the technology of pre- and postoperative monitoring of lung function by the method of the MF EIT. Positive effect will be achieved due to determining the desired frequency of injection current and its use in the postoperative period at the start of EIT.

To achieve the set goal, the following problems are to be solved:

– to propose a general approach to obtainingsource data for analysis at 3D multi-frequency electricalimpedance tomography;

– to develop the basic principles ofconstructing an algorithm for selecting the required frequency of injected current for two-dimensional and three-dimensional multi-frequency electrical impedance tomography;

– topropose a criterion for selecting the right frequency ofinjected current for a particular person for the problems of multi-frequency electrical impedance tomography;

–to conduct experimental studies on test participants – volunteers who have no health problems;

– to process and analyze the obtained measurement information.

4. Material and methods of research

Theoretical and experimental research was carried out using the methods of 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 means of its reproduction were used.

The equipment used to obtain the original measurement information is given in Table 1. The keysource data for experimental research with the use of the MFEIT method are given in Table 2.

Table 1

Equipment used to obtain the source measurement information

No. of entry	Name	Purpose
1	Information and measuring system of multi-frequency electrical impedance tomography (IMS MF EIT)	Designed to perform EIT examination at different frequencies of injected current. Developed on the base of the Department of Information and Measuring Systems and Technologies, SRSPU (NPI). It is a hardware and software solution that underwent technical testing for human safety. It is used to collect measurement information during EIT
2	Bioimpedance analyzer of metabolic processes and body composition ABC-02 "MEDASS"	It makes it possible to evaluate the indicators of lipid, protein and water metabolism, metabolic rate, and is used in departments of dietetics, hemodialysis, intensive care, rehabilitation, and other areas. It allows making bioimpedance analysis (BIA) of human body composition. In the frameworks of research, it is used to generate BIA protocols for each of the test participants. It is applied to determine fat mass andpercentage of fat mass of a person
3	Personal computer with specialized software to process and analyze measuring information	Designed to organize, store and reproduce the measured differences of potentials to process, analyze, and compare them. It is used as an additional processing power of post-processing of original data. It also contains specialized program packages, such as Statistica, MATLAB, and MS Excel

Table 2

Key source data from experimental research with the use of the MF EIT method

No. of entry	Key source data from experimental research with the use of the MF EIT method	Value
1	Range of frequencies of injected current, kHz	from 50 to 400
2	Form of injected current	Sinusoidal
3	Force of injected current, mA	5
4	Planned duration of monitoring at each frequency, minutes	60
5	Number of the test participants – volunteers	4
6	Received agreement of each volunteer to carry out the studies	Yesin writing
7	Color map ofcross-section image	Ventilation: blue and white
8	Time of research	January, 2021
9	Position of the test participants in space	Lying in bed. The state – calm breathing
10	Electrode system of the IMS MF EIT	Disposable electrodes for the ECG
11	Type of electrode system IMS MF EIT	Electrode belt. 16 electrodes on the belt
12	Type of the MF EIT	Two-dimensional MF EIT
13	Galvanic transfer of the IMS MF EIT	Yes. Transfer by power, information channel, measuring channel
14	Possibility to store results	Yes
15	Continuous control of the quality of electrodesfastening	Yes, automatic

The experiments were conducted at the laboratory "Medical Information and Measuring Systems", the Department of Information and Measuring Systems and Technologies at the South-Russian State Polytechnic University (NPI) named after M. I. Platov (SRSPU (NPI)) (Russian Federation, Novocherkassk).

In advance (2 hours prior), the test participants excluded the intake of food and water. Before the experiments, the works on testing the workability of the IMSMF EIT withthe application of a test program were performed.

The research was carried out on the test participants (volunteers) who independently gave information consent to participate in scientific experiments as part of this work. The obligatory component of the experiment was to provide standard physical conditions excluding any loads on the test participants. Experimental studies were carried out at two successive stages:

1) At stage 1, all test participants underwent BIA [22]. For this purpose, the checked bioimpedance analyzer of the composition of human body "MEDASS"[23, 24] was selected. Disposable electrodes for electrocardiogram (ECG), which are recommended by the manufacturer of the device and come complete with the device, were used. The BIA methodology was implemented in full compliance with the manufacturer's recommendations. The results of the BIA were automatically entered into the protocol (for each participants individually). The results were then copied to a personal computer for further processing.

2) At stage 2, the tested were connected to the IMS MFEIT of human lungs. For each of them, EIT examinationswere performed inthe frequency range from 50 to 400 kHz at current force of 5 mA. The "Pulmonary ventilation monitoring" mode was run. Throughout the entire testing cycle, the quality of electrodes' attachment was continuously monitored, both with the use of embedded software and based on visual observation. During the experimental studies, the position of the body remained constant, the state was calm. Irritating and other factors that may have an impact on the results were excluded. No outside devices, appliances or equipment were used during the research.

The proposed and developed ARFS software module was controlled through an additional functional button that starts the procedure of automatic frequency selectionfor the entire range of the study.

The specialized statistical package ofStatistica software, as well as MS Excel software, was used to statistically process the measurement data and the results of EIT study.

5. Results of studying the development of the proposed algorithm

5. 1. General approach to obtaining the source data for analysis at 3D multi-frequency electrical impedance tomography

The practical implementation of 3D multi-frequency electrical impedance tomography (MF EIT) puts forward a number of requirements for the procedure of performing EITexamination. And one of these problems is organization of the process of current injection through the studied object, among which the most important issue is the necessary frequency of injection current. In previous studies, in the case of the single-frequency EIT, the authors observed that the same object of the study had a different degree of quality imaging of the tomographic cross-section, and, accordingly, dynamic imaging of the breathing process. In this case, manual frequency adjustment could eitherimprove or worsen the results. In this regard, the hypothesis was put forward that the quality of the results obtained at EIT and, therefore, the informativeness of the entire procedure, can be possibly enhanced with the application of the multifrequency principle. In this case, it was proposed to use the possibility of automatic change of current frequency to select the injection parameters for a particular person, taking into consideration his anatomical and physiological features. This principle can be used to solve both two-dimensional and three-dimensional EIT problems.

The essence of the proposed approach and the specificity of the practical implementation of ARFSareas follows.

Fig. 1 shows a general scheme for the implementation of MF EIT. It presents the main functional units of IMSMF EIT and potentiallypossible types ofconductivity field imaging (two-dimensional (2D) and three-dimensional (3D)).

The main functional units of IMSMF EIT are:

– an injected current source (CS);
– a switching unit of current source (S_CS);
– aunit to acquire measurement data (M);
– a switching unit of measurement data (S_M);
– amicrocontroller unit;
– apersonal computer (PC);
– the object of study (human chest with lungs) (BO);
– conceptualoptions forvisualizinga change in the conductivity field (variants of imaging EIT results embedded in the IMSMF EIT).

The principle of IMS MF EIT operation is based on the use of a single current source with an algorithm of automatic frequency change, which was developed by the authors taking into consideration the hardware and software features of the *CS* and *M*units. At the same time, electrodes switchingand agreement of injection and measurement moments on the same EL_n electrodes are performed by the switchingunits controlledbythe local computational element (microprocessor unit) by a special control program. Operation of the microprocessor unit and the entire IMS MF EIT is controlled by a personal PC computer, which also stores measurement results, reconstructs conductivity field in all specified cross-sections and visualizes the breathing process.

Assume that we havesome BO with totalconductivitHy ΩBO with the assigned internal structures Ω1, Ω2,..., Ω_k, where k=1...K. For convenience,Fig. 2 shows a simplified circuit of the plane ofattachment ofthe *XY* of the electrode system of the IMS MF EIT.In the case of multi-belt ES for the problems of 3D MF of EIT, there may be several such *P* projections, and their number is equal to the number of electrode belts used. In this regard, the terms "projection" and "belt" are equivalent and can be combined with a general designation (designation"*P*" is accepted in this article).

Non-invasive electrodes$EL1$,$EL2$,...,EL_n, where$n$=1...N, are located on the BO surface. electrodes$EL_n$are not point electrodes.Assume that all electrodesEL_nhave a good contact "skin-electrode", which excludes the influence of transient resistance $R_{sk\text{-}el}$on measurement result, and therefore, on the reconstruction of conductivity field of the BO internal structures.

In the absence of a source of high-frequency injectedcurrent *CS*connected to electrodesEL_n, there will be minor potentials ϕ_n on electrodes EL_n due to the physiological processes occurring in BO. When source *CS* is connected to electrodesEL_n, due to the BO conductivity,on its surface there will be registered potentials ϕ_n, where n=1 ... N, where N is the total number of electrodes EL_n.

In the case of multi-frequency EIT, it is necessary to ensure the impact on the BO of currents of different frequency f_i, where i=2... M. In this regard, several approaches to the implementation of multi-frequency EIT are possible. The first approach is to use one *CS* with $f_i$switching through a control program that determines*m* and the injection circuit. The second approach is determined by using different *CS* with assignedf_i. Both approaches have both positive and negative aspects.

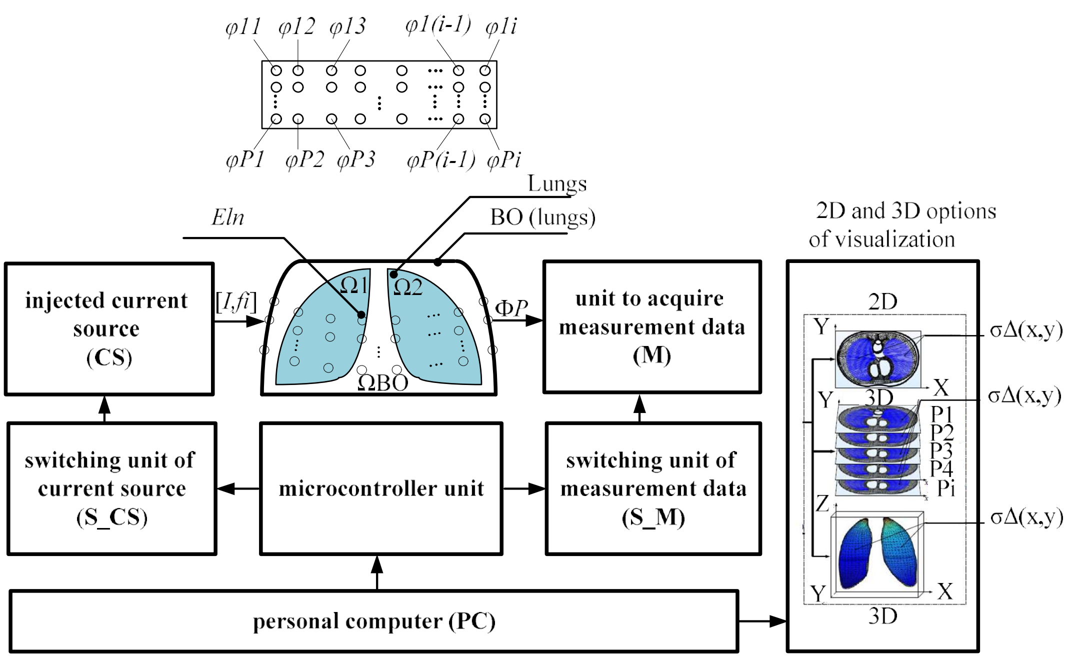


Fig. 1. General scheme of implementingthe multi-frequency electric impedance tomography of human lungs

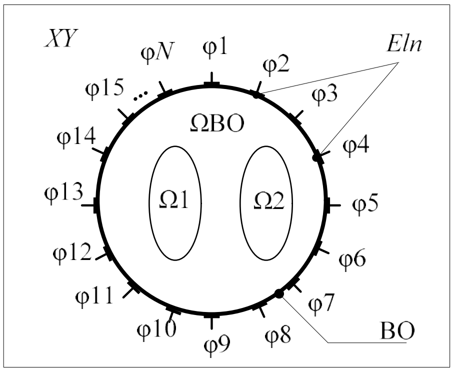


Fig. 2. Simplified circuit of the plane of attachment of electrodes EL_nat the surface of the study object

Consider implementation of the multi-frequency EIT method using the first approach based on the use of a single CS_i, (i=1) with the $f_i$formation through a control program at fixed current force I_1. For this case, in general, the sequence of actions includes the following operations:

1) assignment of the system of EITconnections;

2) connection of CS with parameters (I_1, f_1) to selected EL_n;

3) injection of current f with parameters (I_1, f_1);

4) recording potential sϕ_n from all EL_n;

5) formation of projection Pin accordance with the selected system ofconnections;

6) the actions specified in point 2–5 are repeated until all P are formed. Then new frequency f_i is assigned and these actions are repeated for $CS_1$with parameters (I_1,f_2).

The system of connectionsdetermines the number and configuration of current (injecting) and measuring electrodes. The system of connections is assigned by a user based on the type of research object and the desired results. Thedivergence system of "adjacent electrodes" ("neighboring electrodes") is used.

When CS is connected to $EL_n$and current is injectedthrough BO on the BO surface, the set ϕ_n– Φ. (1) is recorded on the BO surface with the use of surface electrodes EL_n. Each column in (1) determines projection P.

$$\Phi=\begin{vmatrix}
\phi_3 & \phi_4 & \phi_5 & \phi_6 & \cdots & \phi_{n-1} & \phi_n \\
\phi_4 & \phi_5 & \phi_6 & \phi_7 & \cdots & \phi_n & \phi_1 \\
\phi_5 & \phi_6 & \phi_7 & \phi_8 & \cdots & \phi_1 & \phi_2 \\
\phi_6 & \phi_7 & \phi_8 & \phi_9 & \cdots & \phi_2 & \phi_3 \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
\phi_{n-4} & \phi_{n-3} & \phi_{n-2} & \phi_{n-1} & \cdots & \phi_{n-6} & \phi_{n-5} \\
\phi_{n-3} & \phi_{n-2} & \phi_{n-1} & \phi_n & \cdots & \phi_{n-5} & \phi_{n-4} \\
\phi_{n-2} & \phi_{n-1} & \phi_n & \phi_1 & \cdots & \phi_{n-4} & \phi_{n-3} \\
\phi_{n-1} & \phi_n & \phi_1 & \phi_2 & \cdots & \phi_{n-3} & \phi_{n-2} \\
\phi_n & \phi_1 & \phi_2 & \phi_3 & \cdots & \phi_{n-2} & \phi_{n-1}
\end{vmatrix}. \quad (1)$$

To construct the tomographic cross-section of the reconstructed field from Φ it is necessary to form connections. Tothis end,according to the assigned system of connections, the difference ofϕ_n between the selected EL_n is calculated.

$$U_{ij}=\phi_i-\phi_j. \quad (2)$$

Thus, recalculation of Φinto U^{f_1} is performed (3)

:

$$U_{I_1}^{f_1}=\begin{vmatrix}
U_{3,4} & U_{4,5} & U_{5,6} & U_{7,8} & . & U_{n-2,n-1} & U_{n-1,n} \\
U_{4,5} & U_{5,6} & U_{6,7} & U_{8,9} & . & U_{n-1,n} & U_{1,2} \\
U_{5,6} & U_{6,7} & U_{7,8} & U_{9,10} & . & U_{1,2} & U_{2,3} \\
U_{6,7} & U_{7,8} & U_{8,9} & U_{10,11} & . & U_{2,3} & U_{3,4} \\
. & . & . & . & . & . & . \\
U_{n-5,n-4} & U_{n-4,n-3} & U_{n-3,n-2} & U_{n-2,n-1} & . & U_{n-7,n-6} & U_{n-6,n-5} \\
U_{n-4,n-3} & U_{n-3,n-2} & U_{n-2,n-1} & U_{n-1,n} & . & U_{n-6,n-5} & U_{n-5,n-4} \\
U_{n-3,n-2} & U_{n-2,n-1} & U_{n-1,n} & U_{1,2} & . & U_{n-5,n-4} & U_{n-4,n-3} \\
U_{n-2,n-1} & U_{n-1,n} & U_{1,2} & U_{3,4} & . & U_{n-4,n-3} & U_{n-3,n-2} \\
U_{n-1,n} & U_{1,2} & U_{3,4} & U_{4,5} & . & U_{n-3,n-2} & U_{n-2,n-1}
\end{vmatrix}. \quad (3)$$

Thus, during the injection and measurement procedure, array U^{f_1} that corresponds to connectionsatfixed frequency f_1 of current I_1 is formed. The measurement process described above is repeated for frequency f_2 at current I_1. As a result, one obtains $U_{I_1}^{f_2}$.

In a general form, during the implementation of this approach, it is necessary toforesee a change in the force of probing current I. Then, given that both the force of current of the probing signaland its frequency may be changed, it is necessary to introduce the concept of "injection strategy at multi-frequency EIT" that is assigned by matrix (4):

$$STR_{I_j}^{f_p}=\begin{vmatrix}
f_1 & I_1 \\
f_1 & I_2 \\
\ldots & \ldots \\
f_1 & I_n \\
f_2 & I_1 \\
f_2 & I_2 \\
\ldots & \ldots \\
f_2 & I_j \\
f_p & I_j
\end{vmatrix}. \quad (4)$$

Then, at the assigned strategy $STR_{I_j}^{f_p}$, Uin the general form is as follows (5):

$$U=\left[U_{I_j}^{f_p}\right]_{\substack{j=1\ldots J\\ p=1\ldots P}}. \quad (5)$$

Knowing U, one can reconstruct the conductivity field depending on the chosen injection strategy. In this study, to assess the effectiveness of the proposed ARFS, it was decided to use only one fixed value of current force for all analyzed frequencies.

5. 2. Development of the basic principles of construction ofthe algorithm for selection of the required injected current frequency

5. 2. 1. Problem statement

For practical implementationof the proposed approach, it is necessary to perform works to develop and implement the algorithm in the form of a program module (PM) as part of IMSMF EIT. The input data of ARFS should be the data obtained from formula (5), and output data should be the recommended current injection frequency. In this work, the results of interim calculations and estimates obtained during ARFS should not be displayed to a user.

5. 2. 2. Problem solving

To solve the set problem, an algorithmic description of ARFS was drawn up and the PM, integrated into the interface of IMS MF EIT, was developed. The PM was designed in the C++programming language. The programming environment was Visual Studio Code 1.54.3. This PM does not have a dedicated interface window.

5. 2. 3. Development of an algorithm for selectingth-erequired frequency of injected current

Fig. 3, *a*shows the general block-diagrams for the use of ATFS for problems related totwo-dimensional EIT, Fig. 3, *b* – for three-dimensional EIT. The main difference of theseschemes is the choice of the number of electrode belts *P*. In general, the two-dimensional MN EIT is supposed by default to use one plane of electrodes (electrode belts *P*) attachment.In the case of 3D MF IET, the problem is to localize the number and assign tomographic cross-sections within the specified belts. It is implied that the entire process of EIT examination will be performed for a given system of connections"adjacent electrodes", which does not change throughout the implementation of the MFEIT. The start of the measurement process is standard and consists in establishing the fact that the hardware units and software of IMS MF EIT are ready to give commands to turn on current source *CS* with set values of frequency $f_i$and current force *I*.

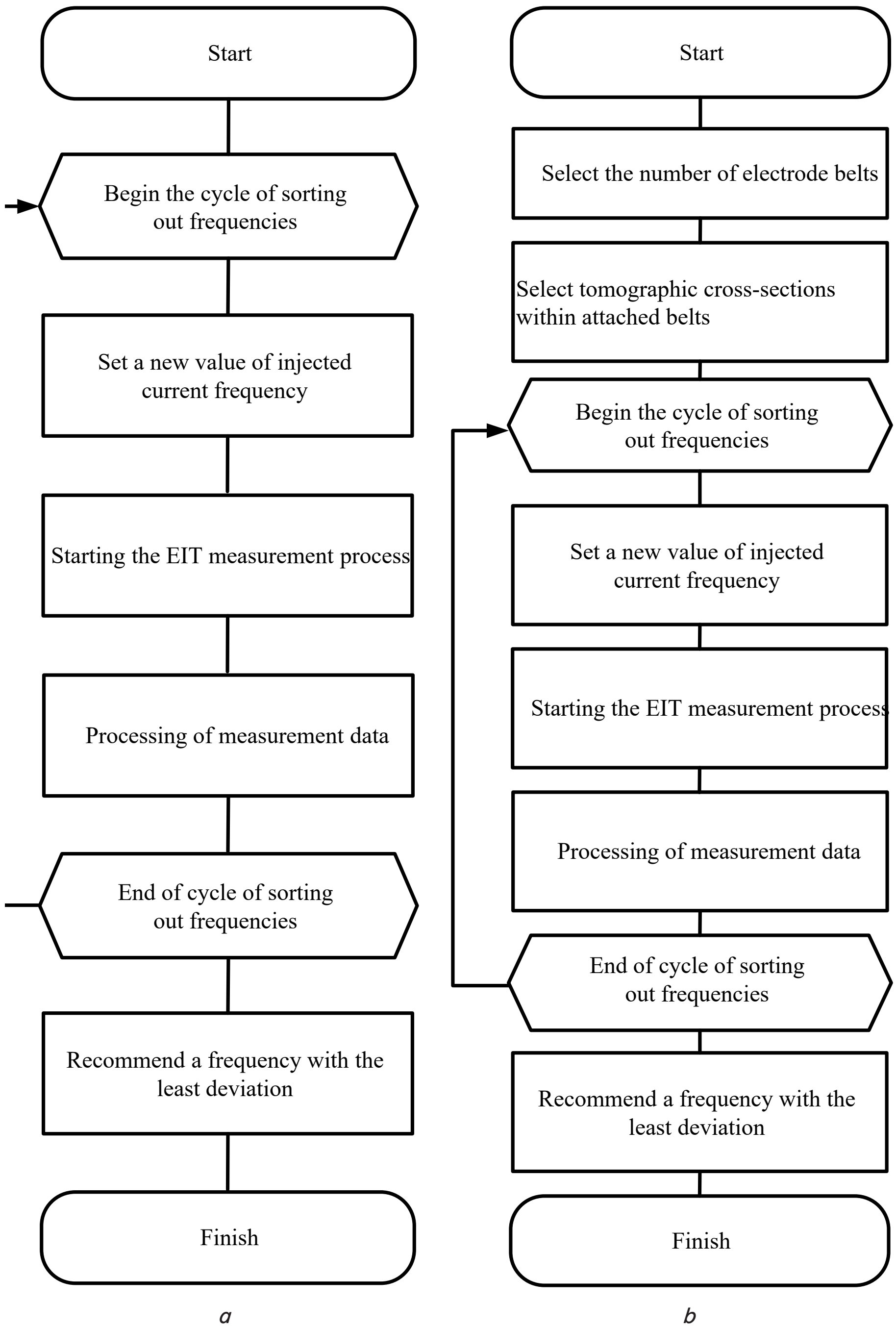


Fig. 3. General block-diagramfor the application of an algorithm to select theinjected current frequency: *a* — for two-dimensional electrical impedance tomography; *b* — for three-dimensional electrical impedance tomography

It is proposed to perform EIT procedure at a set current frequency within a 15-second time interval, followed by an automatic switch to the frequency that is next in order. The pitch of setting the frequency of injected current Δϕ that is equal to 50 (kHz) is considered in the article. At the same time, the total active range of current frequency for the developed IMS MF EIT is 50–400 kHz. After completing the procedure of sorting out frequencies in the predefined range, the problem on recommending-EIT at a specific fixed frequency is solved.An algorithm has been developedfor calculating the rateof changing recorded data by EIT method in a range of frequencies determined as the mean value of changes in the difference of recorded potentials over the injection interval at the present frequency. It is followed by choosing the required frequency, after which the specified rate ofchange is minimal.

The block-diagram of the operation ofthe proposed ARFS is shown in Fig. 4. In the development of this algorithm, variables that should be taken into consideration when solving the problem were determined. First of all, it is the frequency range, the pitch of increasing frequency Δf and measurement data processed using formulas (3) and (5) and injection time at each frequency t. The value of 50 kHz is assigned as the initial frequency f_0, as mentioned above. Next, EIT-examination cycle is run with a gradual increase in frequency of injected current at pitch Δf.

During EIT process, the recorded values ϕ_n are automatically stored with the possibility to be reproduced. After running all frequencies from the assigned range, ϕ_n is averaged to obtain magnitude Φ_{cp} for each frequency. Then all Φ_{cp} are compared to determine the frequency, at which one starts to observe the lowest rate of changing Φ_{cp}. Tothis end, $H_i$values are calculated and their changes are analyzed as frequency $f_i$increases.

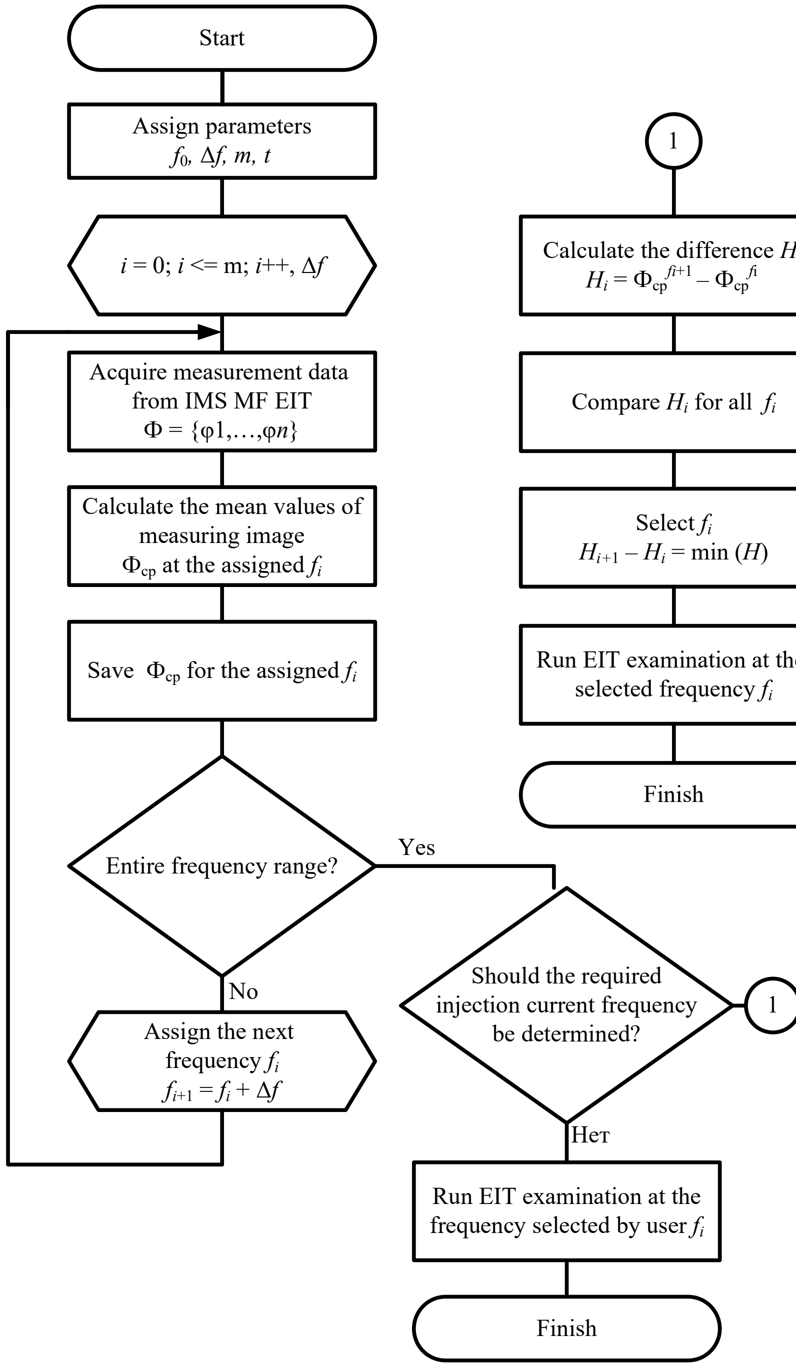


Fig. 4. Block-diagram of the algorithm for selecting the required frequency of injected current

The structure of the algorithm provides for the possibility of running an EIT examination both at the frequency determined by the results of the ARFSoperation and at the frequency chosen by a user. This is useful, for example, in cases where a user has decided on a certain frequency during visual monitoring, at which he wants to perform an EIT in future. In this way, the ARFS can work both under adecision support mode and in the automatic mode.

The block-diagram, shownin Fig. 4, reflects the main stages of ARFS operation and makes it possible to visualize the computational procedures performed.

5. 3. Criterion for selecting the required frequency of injected current for a particular person

The required injected current frequency is determined by the criterion of finding a minimum deviation of mean values of recorded difference in H potentials for the entire frequency range of the IMS MF EIT. In ageneral form, this condition can be described as (6):

$$H = \left(\Phi_{cp}^{(f_{i+1})} - \Phi_{cp}^{f_i}\right) \to \min. \qquad (6)$$

It is proposed to implement the algorithm at which the rate of change inthe recorded data is calculated as the mean value of changes in the difference of the potentials measured at the surface of an object over the interval of injection time at the current frequency. The required frequency, after which the change rate is minimal, is then selected.

Thus, one determines and assess the boundary frequency at which its further increase does not result in theincreased sensitivity of the method to the specificity of the tested BO object.

Studies were carried out to estimate the required averaging range, in this case, the window size from 10 seconds to 1 minute with the pitch of 10 seconds was analyzed. The obtained results showed that an increase in the size of the averaging window for a specified frequency range (from 50 to 400 Hz) did not lead to qualitative and quantitative changes that had a significant impact on the decision to choose the recommended frequency.

At the same time, an increase in the window by more than 15 seconds made it difficult to apply the algorithm in the IMS MF IIT and significantly increased the time of EIT study. This circumstance is not applicable under conditions of intensive care units during the performance of postoperative monitoring oflung function, as the time of preparatory procedures and settings of IMS MF EIT increases significantly.

5. 4. Experimental studies to monitor the process of human lungs ventilation during multi-frequency electrical impedance tomography

5. 4. 1. Development ofthe plan of tests

The experimental studies were aimed at assessing and provingthe possibility of personalization of EITexamination of the volunteers' lungs based on the proposed ARFS. To do this, it is necessary to perform the following works:

– to obtain original measurement data of the MF EIT of a patient;

– to perform imaging of the ventilation process of the volunteers' lungs at the MF EIT with the use of the proposed ARFS.

In this regard, the following plan of tests was proposed:

1) selection of test participants;

2) execution of BIA of each of them. Generation of BIA protocols;

3) carrying out the MF EIT with the use of the developed IMS;

4) processing and analyzing the obtained measurement information.

5. 4. 1. 1. Selection of test participants for experimental research

Four males with different body mass indices were selected from the volunteers to take part in the tests. All of them gave written informational consent to participate in the research. By the time of the tests, they were conscious, healthy, denied any problems with respiratory function of the lungs. Each of them had no problems with the respiratory system.

5. 4. 1. 2. Bioimpedance analysis of body composition with the generation of the test protocol

At stage 1, each of them went through the procedure for determining bioimpedance analysis of body composition (BIA). In Table 1, the summary data of all BIA protocols obtained at the ABC "MEDASS"device for P1, P2, P3, and P4 were grouped.

Table 1

BIA results of test participants obtained before MF EIT

No. by order	BIA parameter	P1	P2	P3	P4
1	Body mass index	19.2	23.7	21.9	26.1
2	Fat mass, kg	7.6	23.3	15.2	37.3
3	Lean fat-free body mass, kg	55.4	58.7	58.8	40.7
4	Active cell body mass, kg	32.6	35.5	39.2	44
5	Skeletal-muscular mass, kg	30.9	30.7	31.9	16.8
6	Total water of the organism, kg	40.5	43.0	43.1	29.8
7	Extracellular fluid of the organism, kg	15.7	17.0	16.5	13.1
8	Percentage of fat mass, %	12.1	28.4	20.5	47.8

Five independent BIA for each test participant were performed, which showed a minimal variation of determined parameters, which indicates consistency of the current physiological state and bioimpedance composition of the body before the performance of MF EIT. In Table 1, attention should be paid to the readings in rows 2 and 8. These parameters can serve as an objective means of differentiating between the test participants.

5. 4. 1. 3. Obtaining measurement data from each test participant using IMS MF EIT in accordance with the experiment plan

Then, all test participants P1, P2, P3, and P4 were in turn connected to IMS MF EIT. The test participants were in the "lying"position. Thesystem of EIT connections"neighboring electrode" was employed. The type of breathing is calm independent without additional effort on the part of the test participants. The current force is 5 mA. The injection current frequency is from 50 to 400 kHz. A software module on selectionof the required injection frequency with an automatic consecutive increase in frequency of injected current with the step of 50 kHz was run. The results of measurements were automatically stored in the memory of IMS MF EIT. Disposable ECG electrodes were used in EIT study. The number of electrodes in one belt was 16. The MF EIT examination lasted at least 1 hour for each test participant(P1, P2, P3, and P4).

5. 5. Processing and analysisof obtained measurement information

At stage 1, the measurement data of EIT examinationwere downloaded from memory and processed in accordance with expression (6). Fig. 4 shows the results of experimental studies of the mean values for each test participant. Analyzing the information of Table 1 and Fig. 5, one can conclude the following:

– at an increase in body fat mass or in percentage of fat mass,an increase in Φ_{cp} is observed;

– the value Φ_{cp} of every test participant*Pi*is inversely proportional to frequency of injection current;

– each test participant*Pi*can be characterized by its own dependence Φ_{cp} on frequency of injection current.

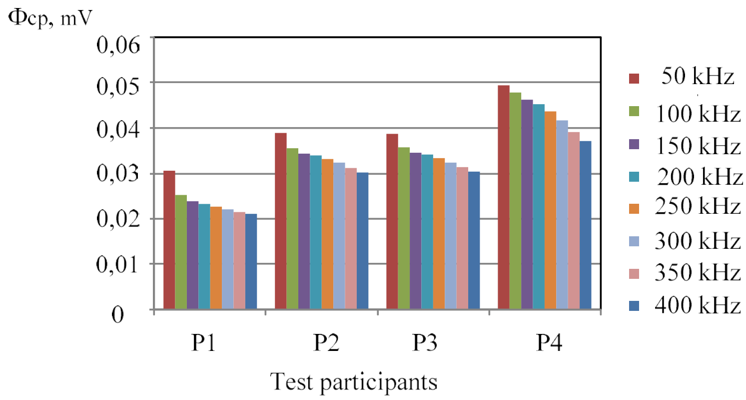


Fig. 5. Results of experimental research. Measured values of difference in potentials for each test participantduring multi-frequency electrical impedance tomography

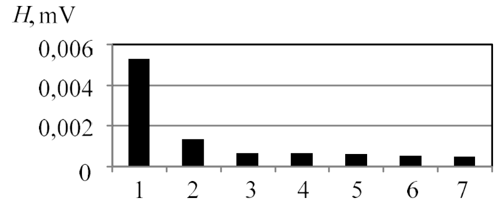


Fig. 6. Estimated value of H for test participant P1

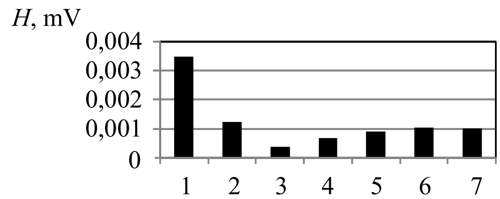


Fig. 7. Estimated value ofH for test participant P2

Values *H*for test participants P1–P4 were calculated from formula (6). The results of calculations are shown in Fig. 6–9. The x-axison all chartsrepresents a dimensionless value, which characterizes the iteration of problem-solving using expression (6) and contains the following designations (Table 2).

Table 2

Conditional designations accepted for convenience of presenting information on charts

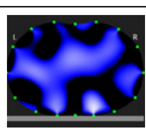
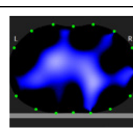
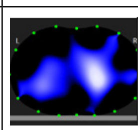
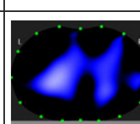
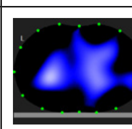
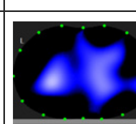
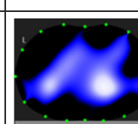
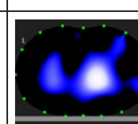
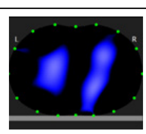
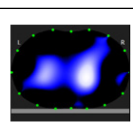
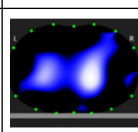
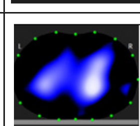
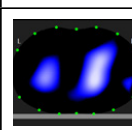
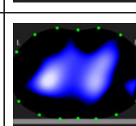
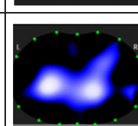
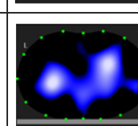
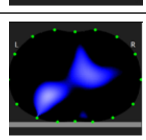
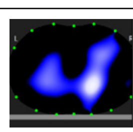
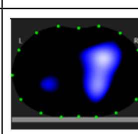
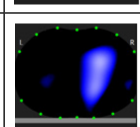
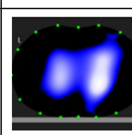
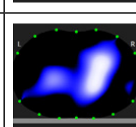
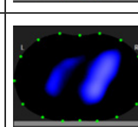
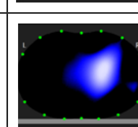
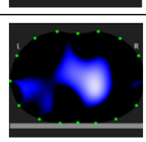
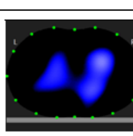
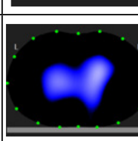
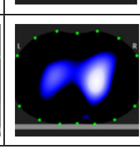
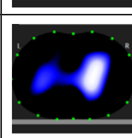
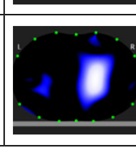
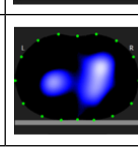
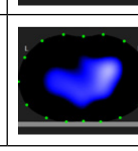
Designation on x-axis	Explanation to designation
1	100–50 kHz
2	150–100 kHz
3	200–150 kHz
4	250–200 kHz
5	300–250 kHz
6	350–300 kHz
7	400–350 kHz

The data reflected in Fig. 6–9 show that by applying expression (6) to measurement data, it is possible to determine the boundary frequency of injection current, in which its further increase does not lead to an increase in the sensitivity of the method to the specificity of an object. That is, there is a frequency, after which the minimum deviation of mean values of recorded difference of H potentials (for the entire range of frequencies) practically does not change at an increase in frequency. In addition, it is clearly seen that for P1, P2, P3, and P4, one should not perform EITat the current rate of 50 kHz and 100 kHz, and P4 has high volatility H even at the end of the frequency range, which indicates the need to increase the injection rate by a magnitude greater than 400 kHz.

Table 3 gives an illustration of the ventilation process of test subjects P1, P2, P3, and P4 at different frequencies of injected current. In fact, the IMS MF EIT operation involves dynamic visualization of the breathing process. However, due to the impossibility to put all the images on paper, Table 3 gives the stop-frames for the stage of maximal inhalation for the sake ofconvenient presentation and enhanced visibility.

Table 3

Results of monitoring the air filling of lungs of tested participants in frequency range of 50 to 400 kHz (Stage of maximum inhalation with calm breathing)

Test partici-pants	Frequency of injected current							
	50 kHz	100 kHz	150 kHz	200 kHz	250 kHz	300 kHz	350 kHz	400 kHz
P1								
P2								
P3								
P4								

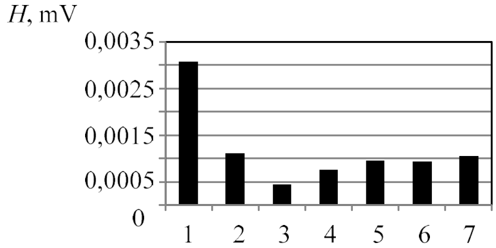


Fig. 8. Estimated value ofH for test participant P3

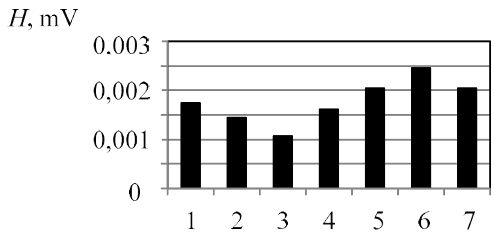


Fig. 9. Estimated value ofH for test participant P4

Analysis of the data in Table 3 reveals that the quality of breathing process imaging depends on the frequency of injected current. Moreover, each of the test participants has such a frequency range, in which the air filling is visualized as clearly as possible relative to other frequencies (out of the range). It can also be seen that at frequencies of 50 kHz and 100 kHz, the quality of visualization of ventilation is unstable and unsatisfactory, artifacts are observed, especially in P1.

Further, by applying the ARFS to source measurement data, and comparing the calculations with the data, specified in Table 3, the following results were obtained (Table 4).

Thus, it can be concluded that the proposed algorithm helps to enhance the quality of imaging of the human breathing process.

6. Discussion of results from applying the developed algorithm

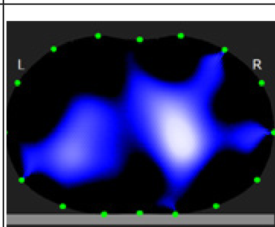
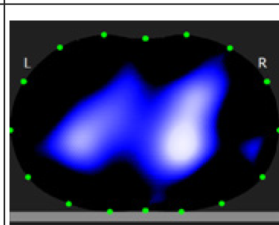
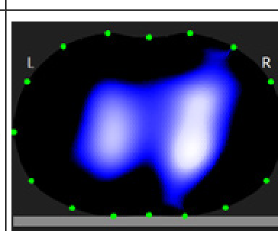
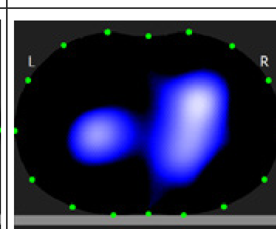
The results of the studies show that measurement data for MF EIT can be used to initially adjust EIT parameters. Thus, without resorting to analysis of the reconstructed field (which is resource-intensive), but based only on measurement information, it is possible to effectively determine the source data for the start of EIT examination. Subsequent reconstruction can be performed on the data obtained at the chosen frequency. This makes it possible to expand the capabilities of the entire EIT method and, in comparison with the existing approaches, to enhance the effectiveness of a separate EIT examination dependingon characteristics of a person.

The general approach to obtaining source data at two-dimensional and three-dimensional MF EIT, explored in the paper, does not contain any key changes in comparison with today's level of algorithmic development of EIT. However, this makes it possible to formalize the process of development and subsequent refinement of the results. This ensures widening the possibilitiesof enhancement of EIT effectiveness in practice by full localization of calculation procedures based on the finished device (without the use of specialized data processing packages).

In general, conducted experimental studies show that the developed IMS MF EIT allows long-term monitoring of human lungs ventilation by analyzing and imaging the changes in conductivity field of the chest cross-section. The dynamic imaging of the breathing process observed on the IMS MF EIT monitor completely repeats the inhalation/exhalation cycles, making it possible to observe the air filling of lungs (including the right and left one separately). The results of processing and analyzing the measurement information obtained at the MF EIT are fully correlated with modern ideas about the electrical properties of biological tissues and the nature of their change depending on the exposure parameters [25, 26].

Table 4

Summary data of the proposedARSF operation

Parameters	The tested			
	P1	P2	P3	P4
Percentage of fat mass, %	12.1	28.4	20.5	47.8
Fat mass, kg	7.6	23.3	15.2	37.3
Required frequency of injection current	150 kHz	200 kHz	200 kHz	350 kHz
Visualization ofchange of conductivity field, caused by the lung ventilation process				

The research results show potential possibility of automatic setting of parameters of EIT examination. In this case, analyzing the data presented in Fig. 5–9, it can be concluded that it is possible to personalize EIT examination for a particular patient, taking into consideration his physiological characteristics.Bioimpedance analysis, performed for all the test participantsusing the device specified in paper [26] (Table 1), shows that there is a direct correlation between EIT results on the amount of fat mass (percentage of fat mass) of a person. Thus, as its content increases, the frequency of injection current should be increased. The problem of the upper limit of the injection frequency is open and requires more research, as the developed IMSMF EIT is intended to operate in the frequency range of 50–400 kHz.

The proposed personalization approach, based on the ARFS, solves one of the main problems of EIT – to obtain objective non-invasive assessment of the electrical properties of internal structures of the tested object. This makes it possible tostate initial conditions at the run of EIT examination, which is important in the implementation of the technology of monitoring lung function in the pre- and postoperative period.

At the same time, it should be taken into consideration that this study has a series of limitations. These include a small size of the sample of the test participants, which is why it is required to check performancein a larger group. It also includes the absence of the test participants with external breathing problems. However, these works are planned to be carried out based onthe medical organization on real patients atan intensive care unit. The Ethics Committee of a major medical organization gave consent to conduct research and collect statistical information. Thus, in the short- term perspective, the performance of ARFS will be tested on patients with complications or those who need hardware respiratory support. Further studies will result in the formationof control groups of the tested, in planning the clinical tests and the procedure of execution with appropriate developed hypotheses and expected results. Particular attention should be paid to ARFSoperation in end-to-end monitoring of the lung function of a particular person in the pre- and postoperative period. The problem of the ARFSapplication for the problems of assessing lung perfusion by EIT method remains unclear.

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

The main difficulties in the development of this area include a weak methodological study of the subject area, a small number of studies of the MF EIT under clinical conditions on apparatus patients. This imposes a limitation of algorithmic nature on obtaining objective information about the possibility of the ARFSoperation under actual clinical conditions.

In particular, the issues of the rapid operation of the algorithm, age limits, gender specificity, which should be taken into consideration when organizing the MFAIT with the use of ARFS remain open. Specific attention should be paid to the use of several current sources (its own current source for each frequency) as part of the IMS MF EIT.

7. Conclusions

1. A general approach to obtain data during 3D multi-frequency electrical impedance tomography was proposed, which implies injecting a patient with high-frequency current of small amplitude involving the algorithm of a gradual increase in frequency at the assigned pitchΔfin the required frequency range. Within the framework of this work, the values of frequency of injection current from 50 kHz to 400 kHz with a pitch of an increase Δf=50 kHz were considered. The obtained results enhance the effective use of EIT in practice by full localization of computing procedures based on a fully-fledged device (without the use of specialized data processing packages).

2. The basic principles forconstructinganalgorithm for selecting the required frequency of injected current for two-dimensional and three-dimensional multi-frequency electrical impedance tomography were developed. The main stages of the algorithm's operation and the necessary calculation procedures were defined. A description of the algorithm was drawn up and a software module that implements the proposed principles was developed. The general schemes for applying the algorithm for selectingthe required frequency of injected current for thetasks of two-dimensional and three-dimensional electrical impedance tomography were developed. In particular, the sequence of actions on its practical application as part of the technical toolswithin multi-frequency EIT was shown;the block-diagrams illustratingthe operation of those devices that implement the proposed algorithm were drawn up.

3. A criterion was proposed for selecting the desired frequency of injected current for a particular person for the tasksrelated tomulti-frequency electrical impedance tomography, which is an addition to the developed algorithm and makes it possible to determine the final injection current frequency for further EIT examinations. It is proposed to calculate the minimum deviations in the mean values of recorded differences of potentials for each injection frequency with a subsequent selection of the frequency after which the specified rate of change is minimal. That makes it possible to choose for each test participant the injection current frequency at which the maximum sensitivity ofthe internal structures of a test participant to EIT methodwould be observed.

4. The results of the experimental studies show that the proposed algorithm makes it possible to personalize EIT examination. It was established experimentally that with an increase in the percentage of a person's fat mass, it is necessary to increase an injected current frequency. In addition, it was shown that the quality of ventilation process visualizationdepends on the frequencies of the injected current and the internal structure of a test participant. The proposed algorithm for selecting the required frequency of injected current makes it possible to state the initial conditions at the start of EIT examination for a particular person, which is important in the implementation of the technology of lung function monitoring in the preoperative and postoperative periods.

5. The results of processing and analyzingthe measurement information acquired during the experimental studies involving healthy test participantssubstantiatethe conclusion that the proposed algorithm for selecting the required frequency of injected current could be used as part of the technical toolsetfor electrical impedance tomography. It provides for accounting the features of a test participant, which, ultimately, has a positive effect on the quality of monitoring the human breathing process. That creates an opportunity to enhance the quality of medical services based on EIT method.

Acknowledgement

This research was carried out under the grant of the Russian Science Foundation (Project No. 19-79-00322).

References

1. Abboud, M., Guardo, R., Martineau, R., Taillefer, J., Pelletier, C. (1995). Monitoring of peripheral edema using electrical bioimpedance measurements. Proceedings of 17th International Conference of the Engineering in Medicine and Biology Society. doi: https://doi.org/10.1109/iembs.1995.575290
2. Pekker, Ya. S., Brazovskiy, K. S., Usov, V. Yu. (2004). Elektroimpedansnaya tomografiya. Tomsk: NTL, 192.
3. Pomprapa, A., Schwaiberger, D., Pickerodt, P., Tjarks, O., Lachmann, B., Leonhardt, S. (2014). Automatic protective ventilation using the ARDSNet protocol with the additional monitoring of electrical impedance tomography. Critical Care, 18 (3), R128. doi: https://doi.org/10.1186/cc13937
4. Liu, S., Tan, L., M ller, K., Frerichs, I., Yu, T., Liu, L. et. al. (2016). Identification of regional overdistension, recruitment and cyclic alveolar collapse with electrical impedance tomography in an experimental ARDS model. Critical Care, 20 (1). doi: https://doi.org/10.1186/s13054-016-1300-y
5. Nestler, C., Simon, P., Petroff, D., Hammerm ller, S., Kamrath, D., Wolf, S. et. al. (2017). Individualized positive end-expiratory pressure in obese patients during general anaesthesia: a randomized controlled clinical trial using electrical impedance tomography. British Journal of Anaesthesia, 119 (6), 1194–1205. doi: https://doi.org/10.1093/bja/aex192
6. Buzkova, K., Roubik, K. (2015). The effect of electrode belt size selection upon evaluation of the distribution of ventilation using electrical impedance tomography. 2015 E-Health and Bioengineering Conference (EHB). doi: https://doi.org/10.1109/ehb.2015.7391453
7. Karsten, J., Stueber, T., Voigt, N., Teschner, E., Heinze, H. (2015). Influence of different electrode belt positions on electrical impedance tomography imaging of regional ventilation: a prospective observational study. Critical Care, 20 (1). doi: https://doi.org/10.1186/s13054-015-1161-9
8. Blankman, P., Shono, A., Hermans, B. J. M., Wesselius, T., Hasan, D., Gommers, D. (2016). Detection of optimal PEEP for equal distribution of tidal volume by volumetric capnography and electrical impedance tomography during decreasing levels of PEEP in post cardiac-surgery patients. British Journal of Anaesthesia, 116 (6), 862–869. doi: https://doi.org/10.1093/bja/aew116
9. Cinnella, G., Grasso, S., Raimondo, P., D'Antini, D., Mirabella, L., Rauseo, M., Dambrosio, M. (2015). Physiological Effects of the Open Lung Approach in Patients with Early, Mild, Diffuse Acute Respiratory Distress Syndrome. Anesthesiology, 123 (5), 1113–1121. doi: https://doi.org/10.1097/aln.0000000000000862
10. Hough, J. L., Shearman, A. D., Liley, H., Grant, C. A., Schibler, A. (2014). Lung recruitment and endotracheal suction in ventilated preterm infants measured with electrical impedance tomography. Journal of Paediatrics and Child Health, 50 (11), 884–889. doi: https://doi.org/10.1111/jpc.12661
11. Gross, B. H., Spizarny, D. L. (1994). Computed Tomography of the Chest in the Intensive Care Unit. Critical Care Clinics, 10 (2), 267–275. doi: https://doi.org/10.1016/s0749-0704(18)30128-3
12. Adeniji-Sofoluwe, A. T., Adekanmi, A. J., Efidi, R. (2017). Imaging Findings in Chest Computed Tomography: Initial Experience in a Developing Country. Open Journal of Clinical Diagnostics, 07 (04), 113–123. doi: https://doi.org/10.4236/ojcd.2017.74012
13. Ball, L., Sutherasan, Y., Pelosi, P. (2013). Monitoring respiration: What the clinician needs to know. Best Practice & Research Clinical Anaesthesiology, 27 (2), 209–223. doi: https://doi.org/10.1016/j.bpa.2013.06.004
14. Ball, L., Vercesi, V., Costantino, F., Chandrapatham, K., Pelosi, P. (2017). Lung imaging: how to get better look inside the lung. Annals of Translational Medicine, 5 (14), 294–294. doi: https://doi.org/10.21037/atm.2017.07.20
15. Battaglini, D., Robba, C., Rocco, P. R. M., De Abreu, M. G., Pelosi, P., Ball, L. (2019). Perioperative anaesthetic management of patients with or at risk of acute distress respiratory syndrome undergoing emergency surgery. BMC Anesthesiology, 19 (1). doi: https://doi.org/10.1186/s12871-019-0804-9
16. Białka, S., Copik, M., Rybczyk, K., Misio ek, H. (2017). Electrical impedance tomography for diagnosis and monitoring of pulmonary function disorders in the intensive care unit – case report and review of literature. Anaesthesiology intensive therapy, 49 (3), 222–226. doi: https://doi.org/10.5603/ait.2017.0040
17. Bachmann, M. C., Morais, C., Bugedo, G., Bruhn, A., Morales, A., Borges, J. B. et. al. (2018). Electrical impedance tomography in acute respiratory distress syndrome. Critical Care, 22 (1). doi: https://doi.org/10.1186/s13054-018-2195-6
18. Frerichs, I., Pulletz, S., Elke, G., Gawelczyk, B., Frerichs, A., Weiler, N. (2011). Patient examinations using electrical impedance tomography—sources of interference in the intensive care unit. Physiological Measurement, 32 (12), L1–L10. doi: https://doi.org/10.1088/0967-3334/32/12/f01
19. Schaefer, M. S., Wania, V., Bastin, B., Schmalz, U., Kienbaum, P., Beiderlinden, M., Treschan, T. A. (2014). Electrical impedance tomography during major open upper abdominal surgery: a pilot-study. BMC Anesthesiology, 14 (1). doi: https://doi.org/10.1186/1471-2253-14-51
20. Jang, G. Y., Ayoub, G., Kim, Y. E., Oh, T. I., Chung, C. R., Suh, G. Y., Woo, E. J. (2019). Integrated EIT system for functional lung ventilation imaging. BioMedical Engineering OnLine, 18 (1). doi: https://doi.org/10.1186/s12938-019-0701-y

21. Shono, A., Kotani, T. (2019). Clinical implication of monitoring regional ventilation using electrical impedance tomography. Journal of Intensive Care, 7 (1). doi: https://doi.org/10.1186/s40560-019-0358-4
22. Ward, L. C. (2018). Bioelectrical impedance analysis for body composition assessment: reflections on accuracy, clinical utility, and standardisation. European Journal of Clinical Nutrition, 73 (2), 194–199. doi: https://doi.org/10.1038/s41430-018-0335-3
23. Shchelykalina, S. P., Nikolaev, D. V., Kolesnikov, V. A., Korostylev, K. A., Starunova, O. A. (2020). Data Views Technology of Bioimpedance Vector Analysis of Human Body Composition. 17th International Conference on Electrical Bioimpedance, 77–83. doi: https://doi.org/10.1007/978-981-13-3498-6_12
24. Nikolaev, D. V., Schelykalina, S. P. (2016). Lektsii po bioimpedansnomu analizu sostava tela cheloveka. Moscow: RIO TSNIIOIZ MZ RF, 152.
25. Martirosov, E. G., Nikolaev, D. V., Rudnev, S. G. (2006). Tekhnologii i metody opredeleniya sostava tela cheloveka. Moscow: Nauka, 248.
26. Nikolaev, D. V., Smirnov, A. V., Bobrinskaya, I. G., Rudnev, S. G. (2009). Bioimpedansniy analiz sostava tela cheloveka. Moscow: Nauka, 392.

UDC 534.26
DOI: 10.15587/1729-4061.2021.234657

ESTIMATING THE INFLUENCE OF DOUBLE-SIDED ROUNDED SCREENS ON THE ACOUSTIC FIELD AROUND A LINEAR SOUND SOURCE

Vitalii Didkovskyi
Doctor of Technical Sciences, Professor*
Vitaly Zaets
Corresponding author
PhD, Associate Professor*
E-mail: zaetsv@i.ua
Svetlana Kotenko
PhD, Junior Researcher
Department of Building Physics and Energy Efficiency
State Enterprise «State Research Institute of Building Constructions»
Preobrazhenska str., 5/2, Kyiv, Ukraine, 03037
Volodymyr Denysenko
PhD, Associate Professor**
Yuriy Didenko
PhD, Associate Professor**
*Department of Acoustic and Multimedia Electronic Systems
National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute»
Peremohy ave., 37, Kyiv, Ukraine, 03056
**Department of Higher and Applied Mathematics
Kyiv National University of Trade and Economics
Kyoto str., 19, Kyiv, Ukraine, 02156

This paper reports a study into the acoustic field of transport flow around noise protection screens located on both sides of the sound source.

Most research on noise protection involving noise protection screens relates to the assessment of the effectiveness of screens located on one side of the noise source. The influence of the second screen on the effectiveness of the first one has been investigated only experimentally. Therefore, it is a relevant task to assess the mutual impact of the two screens between which the linear sound source is located.

A problem was stated in such a way that has made it possible to derive an analytical solution and find a sound field around a linear sound source. In this case, the sound source was limited on both sides by acoustically rigid screens with finite thickness. The screens' cross-sections were shaped as part of a ring with arbitrary angles and the same radius.

The problem was solved by the method of partial domains. This method has made it possible to obtain an infinite system of algebraic equations that were solved by the method of reduction. Such an approach to solving a problem allows a given solution to be applied for different cases of the mutual location of screens, source, and territory protected from noise.

The study results help estimate a field between the screens, the dependence of increasing sound pressure on the road on the geometric size of the screen and the width of the road. In addition, the solution resulted in the ability to assess the impact of one screen on the efficiency of another in the frequency range of up to 1,000 Hz. It has been shown that the mutual impact of screens could reduce the screen efficiency by 2 times.

The study reported here could make it possible to more accurately calculate the levels of the sound field from traffic flows when using noise protection screens, which is often performed in practice when designing new and reconstructing existing highways

Keywords: rounded noise protection screen, method of partial domains, two-sided noise protection screens, noise reduction

Received date: 04.05.2021
Accepted date: 05.06.2021
Published date: 25.06.2021

***How to Cite**: Didkovskyi, V., Zaets, V., Kotenko, S., Denysenko, V., Didenko, Y. (2021). Estimating the influence of double-sided rounded screens on the acoustic field around a linear sound source. Eastern-European Journal of Enterprise Technologies, 3 (5 (111)), 38–46. doi: https://doi.org/10.15587/1729-4061.2021.234657*

1. Introduction

Noise is one of the undesirable environmental factors. The largest sources of noise are transporting highways [1, 2]. Noise protection screens are one of the most effective means of reducing transport noise.

The levels of the sound field behind a screen are influenced by a large number of parameters, primarily the geo-