BIOPHYSICS AND MEDICAL PHYSICS

Conference materials
UDC 616-71
DOI: https://doi.org/10.18721/JPM.163.250

Implementation of electrical impedance tomography

A.I. Levin[1]✉, E.A. Pecherskaya[1], Yu.A. Varenik[2], J.V. Shepeleva[1]

[1] Penza State University, Penza, Russia;

[2] Penza State University of Architecture and Construction, Penza, Russia

✉ levin.alescha2013@yandex.ru

Abstract. The method of electrical impedance tomography, which calculates images of the electrical conductivity inside the body based on surface measurements is considered. The basis of the method is an alternating electric current, which is supplied to various configurations of injecting and detecting electrodes located on the body surface and the potential field that arises in its volume is measured. It is shown that each link of the hardware that implements the electrical impedance tomography method has an impact on the final visualization. The implementation essence of the software part of the method based on the Laplace equation is stated. It is advisable to use the results of the work when monitoring the respiratory and cardiovascular systems using a chest belt with electrodes.

Keywords: EIT, ADC, biological object, impedance

Citation: Levin A.I., Pecherskaya E.A., Varenik Yu.A., Shepeleva J.V., Implementation of electrical impedance tomography, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (3.2) (2023) 288–293. DOI: https://doi.org/10.18721/JPM.163.250

Материалы конференции
УДК 616-71
DOI: https://doi.org/10.18721/JPM.163.250

Реализация электроимпедансной томографии

А.И. Левин[1]✉, Е.А. Печерская[1], Ю.А. Вареник[2], Ю.В. Шепелева[1]

[1] Пензенский государственный университет, г. Пенза, Россия;

[2] Пензенский государственный университет архитектуры и строительства, г. Пенза, Россия

✉ levin.alescha2013@yandex.ru

Аннотация. Электроимпедансная томография (ЭИТ) — это метод томографической визуализации, который рассчитывает изображения электропроводности внутри тела на основе измерений поверхности, который нашел свое применение в различных сферах, в частности, в неинвазивном мониторинге биологических функций в режиме реального времени. Основой медицинской ЭИТ является переменный электрический ток, который подается на различные конфигурации инжектирующих и детектирующих электродов, расположенных на поверхности тела и измеряемое возникающее в его объеме потенциальное поле. Однако для медицинских приложений ЭИТ все еще находится на экспериментальной стадии; она еще не использовалась для регулярного ухода за пациентами.

Ключевые слова: ЭИТ, АЦП, биологический объект, импеданс

Ссылка при цитировании: Левин А.И., Печерская Е.А., Вареник Ю.А., Шепелева Ю.В. Реализация электроимпедансной томографии // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 16. № 3.2. С. 288–293. DOI: https://doi.org/10.18721/JPM.163.250

Implementation of the EIT hardware

The hardware implementation of electrical impedance tomography (EIT) is as important as the image reconstruction algorithm. It plays a decisive role in the excitation of a part of the body and, accordingly, is in direct contact with the tested biological object (patient). When receiving and transmitting data, due to nonlinearity and extremely incorrect formulation of the inverse problem, the image reconstruction quality is sensitive to the error measured by an analog-to-digital converter (ADC)in this case. In the last decade, a variety of high-precision automatic measuring devices and advanced measurement methods have been proposed to reduce measurement noise, but with inherent systematic errors. Meanwhile, data transfer mode and speed, convenience, power consumption and cost are also key indicators in EIT medical imaging, where this medical imaging method is required to monitor changes in the impedance of physiological and pathological conditions in real time [1].

It is shown that each link of the hardware has an impact on the final EIT visualization. For example, electrodes located at the front end of a highly sensitive detection system. The electrodes are in direct contact with the human body, thus, any signals on them, including useful information, noise, artifacts, contact resistance, polarization voltage, etc., will be amplified and processed in the subsequent circuit and ultimately affect image reconstruction results. Therefore, the calculation of the electrode parameters, its dimensions, quantity and sensory ability is especially important. A small number of electrodes (< 16) in the EIT will reduce the measurement sensitivity, and too many electrodes will reduce the measurement speed (> 16). The Standard EIT configuration uses 16 electrodes.

Electrodes in direct contact with the human body can detect noise, contact transient resistance, polarization voltage, etc. These interferences will be amplified and processed in the subsequent circuit and ultimately affect the results of calculating the electrical conductivity of biological tissues. In addition, different contact force of the working electrodes surface with the human body also leads to different readings of bioimpedance measurements. Therefore, the calculation of the electrode parameters, its dimensions, quantity and noise immunity is especially important. A small number of electrodes (less than 16) in the EIT reduces the measurement sensitivity, since the maximum display matrix is built by dividing the plane into 256 segments [2], and an increase in the number of electrodes to 32 reduces the measurement speed [3], but the display matrix is already built by the plane into 1024 segments. At the same time, 16 electrodes are used in the standard EIT configuration.

The main method for implementing EIT is to supply a stable probing current to the object and evaluate the impedance distribution by measuring the potential difference between two active electrodes. Methods for measuring the potential difference can be based on two-electrode and four-electrode methods. Current injection and voltage measurement are performed from the same pair of electrodes in the first method, and the measurement values are always inaccurate due to the contact impedance. In comparison, the four-electrode measurement method can effectively reduce the effect of contact impedance [4].

Implementation of the EIT software

A number of scientists have proved the presence of a significant capacitive component in the final complex bioimpedance [5], therefore, a sinusoidal probing current signal will have a phase shift, which leads to an additional measurement error.

Thus, the results of bioimpedance measurements contain measurement errors due to the voltage between the electrodes on the body surface, random capacitances and impedances of the contacts themselves and the supply cables, as well as the presence of polarization in the measured tissues. The measurement error increases significantly with frequency, cable length and the number of used electrodes and multiplexers, if the circuit is built on their basis. Therefore, it is required to carry out a thorough calibration of measuring instruments in the EIT system [6].

Undoubtedly, EIT has always been and remains a rather controversial topic of study, of importance for both scientific and clinical applications. The main reason for it is directly related to the fundamental problem of the low-energy electromagnetic field when applied to complex biological systems: low contrast and spatial resolution due to the mechanisms underlying the interaction of EMF with biological tissues. This problem was recognized over 40 years ago and remains a major drawback of low energy electromagnetic imaging techniques. Recently, there have been many reports about approaches to overcome the shortcomings or at least reduce their impact [7].

To solve this problem, the authors propose new circuit solutions that allow EIT to be carried out in a wide frequency range from 1 kHz to 100 kHz, which will improve the accuracy of measuring the electrical conductivity of biological tissues of human internal organs. It is proposed to use three sets of electrodes arranged parallel to each other instead of one set of electrodes arranged along the circumference (Fig. 1). It makes it possible to increase the number of planes for measuring the distribution of electrical conductivity (up to 9) through the applied electrodes. Software analysis of the obtained distributions of electrical conductivity will reduce the methodological error of measurements, and, accordingly, the display of electrical conductivity in the measured planes. Fig. 1 illustrates the new methodology for conducting EIT [8].

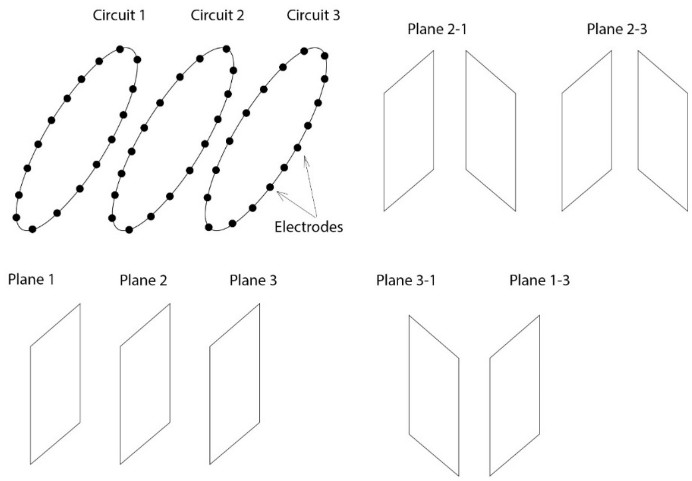

Fig. 1. Proposed scheme for applying electrodes for EIT

Their location on the patient is also important. It is a competent arrangement that determines the amount of high-quality information contained in the measurement processes, the conditionality of the inverse EIT problem and the EIT measurements reliability. The electrodes position affects the reconstruction quality of the resulting image. Typically, electrodes are placed in the intercostal space between the 4th and 6th ribs. A number of researchers in their works claim that the most favorable angles between the injecting and detecting electrodes are in the range from 60 to 150 degrees [9].

The EIT essence is the inverse problem of determining the impedance, where the relationship between the electric field and the electric current is determined. There are two methods for obtaining electrical impedance. The first method is to establish a stable voltage across the object's surface and then evaluate the impedance distribution over the current flowing through the object. The main EIT method is to apply a stable current to the object and evaluate the impedance distribution by measuring the boundary voltage, which is discussed in this summary. Measurement methods are usually divided into two-electrode and four-electrode approaches. Current injection and voltage measurement are performed from the same pair of electrodes in the first approach, where the strategy can be easily implemented, but the measurement values are always inaccurate due to the contact impedance [10].

Usually, a number of mathematical methods: Newton–Gauss, the method of finding a unique solution of the Laplace equation under the Newman boundary condition are used to construct the EIT image.

In particular, based on Maxwell's equation, Ohm's law and the law of charge conservation, Laplace's equation can be obtained as follows:

$$\nabla\left[\sigma(r)\nabla\varphi(r)\right]=0,\ \ r\in\Omega, \tag{1}$$

where φ is the electric potential, Ω is the measured area.

In this case, the boundary condition on the electrodes will be as follows:

$$\sigma(r)\frac{\partial\varphi(r)}{\partial n}=j,\ r\in\Omega, \tag{2}$$

where j is the current density at the electrodes, Ω is the boundary of the body.

The relationship between excitation, system response and measurement can be easily represented as follows:

$$\bar{V}=F\left(\sigma(r)\right)\Big|_j, \tag{3}$$

where $\sigma(r)$ is the conductivity distribution, V is the theoretical boundary stress, and F is a nonlinear function representing the conductivity distribution space in the measurements space [11].

As a result of the application of the new proposed scheme for applying electrodes, the number of matrices for the distribution of the electrical conductivity of the human body increases (up to 9 pieces).

a) *b*)

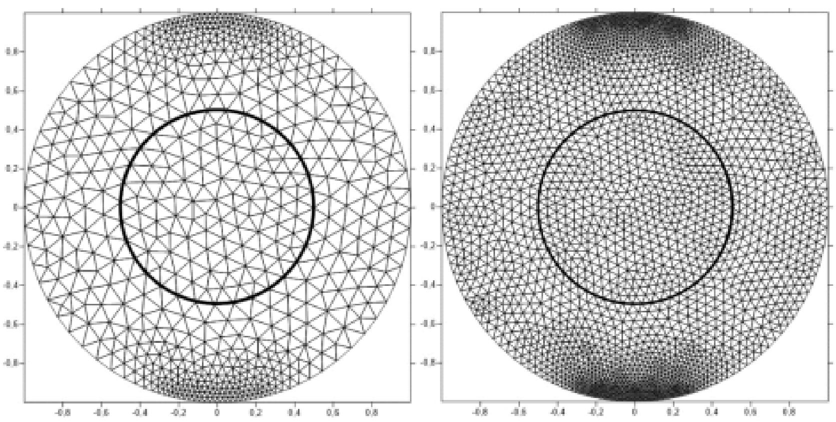

Fig. 2. Calculation grid: (*a*) thickening on the electrodes (1256 cells); (*b*) thickening to the entire boundary of the region (2804 cells)

Table 1

Deviation of numerical results from the analytical

Net	Deviation
No thickening	0.03017
Condensation on the electrodes	0.01435
Condensation at the border with air	0.01681
Condensation on the entire border	0.02062

Step-by-step processing of these matrices in comparison with the electrical conductivity distribution of the human body (as shown in Fig. 2) will allow, using mathematical processing methods, to build a more adequate model of the electrical conductivity distribution and determine the foci of blood clots and edema in the vessels and internal organs at the site of electrode application much more accurately [12].

In order to obtain high-quality solutions in places with large gradients of changes in the parameters of the distribution of electrical conductivity of tissues of various kinds, grids (unstructured and structured) for mathematical calculation need to be thickened.

A number of researchers [13–14], having carried out work on the construction and calculation of grids with different grid density (at the electrodes, at the boundary with air and along the entire boundary of the volume), came to the conclusion that the smallest deviation of the numerical results from the analytical one occurs when the grid is thickened precisely at the electrodes (Table 1).

Thus, based on these results, we came to the conclusion that in order to increase the speed and quality of mathematical calculations of the electrical conductivity of tissues during EIT, it is required to implement in an applied way this grid thickening on the electrodes by applying them in three rows around a circle with a displacement angle $\varphi = 30$ degrees. In this work, studies were carried out between two electrodes located diametrically along the circumference. The use of three rows of electrodes with an offset by an angle φ makes it possible to implement two variants of thickening: both on the electrodes and along the entire boundary. This improves the efficiency of the control program by eliminating time and technical resources for mesh modeling and subsequent calculations.

Conclusions

The EIT ability to detect conductivity changes finds application in the monitoring of the respiratory and cardiovascular systems using a chest belt with electrodes.

The conductivity changes are caused by the lung's expansion with each breath and the blood movement with each heartbeat. Continuous monitoring of vital physiological parameters of ventilated patients in the intensive care units or operating rooms will provide healthcare professionals with additional information about the patient's health status or the therapy effectiveness, which can improve patient outcomes. According to the business plan of startup company Swisstom, 3.8 million people are ventilated annually in developed countries, about 15% of them receive acute lung injury, and about 5% (190,000 patients) of ventilated patients eventually die from acute lungs injury.

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THE AUTHORS

LEVIN Alexis I.
levin.alescha2013@yandex.ru
ORCID: 0000-0003-0428-2319()

VARENIK Yuriy A.
yurik_ru@mail.ru
0009-0009-6455-3011

PECHERSKAYA Ekaterina A.
pea1@list.ru
ORCID: 0000-0001-5657-9128

SHEPELEVA Juliya V.
eduard.shepelev.67@mail.ru
ORCID: 0000-0001-5075-2727

Received 03.07.2023. Approved after reviewing 06.09.2023. Accepted 07.09.2023.