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Modern Trends in Development of Electrical Impedance Tomography in Medicine

Grayr Karenovich Aleksanyan, Nikolay Ivanovich Gorbatenko and Alexander Dmitrievich Tarasov

Platov South-Russian State Polytechnic University (NPI), 132, Prosvescheniya ul., Novocherkassk, 346428, Russian Federation, Russian.

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This article is dedicated to the current state of electrical impedance tomography in medicine. The basic directions of research in this area have been detected. Possible areas of application in clinical conditions have been considered. The main manufacturers of electrical impedance equipment in Russia and abroad have been presented. A list of main dissertations in the Russian Federation on the subject of electrical impedance tomography since 2009 has been presented. Main scientific publications have been presented that publish results of leading groups of researchers. Based on the review and analysis of the subject area, a new approach to the theory of electrical impedance tomography has been proposed.

Key words. Electrical impedance tomography, mathematical model, electrical conductivity, spatial distribution, image reconstruction, reconstruction algorithms, two-dimensional and three-dimensional visualization, internal organs, electrode system.

Currently electrical impedance tomography (EIT) is one of the promising areas in diagnosing functional state of humans[1-6]. Advantages of this method are simplicity of hardware implementation, safety, non-invasiveness, the possibility to study dynamic processes, economic efficiency of its application in clinical practice. In this respect, the EIT technology has significant potential for obtaining necessary results in diagnosing common human functional state[7], studying dynamic processes of cardiovascular activity[8,9], observing cancer formations[10-12], monitoring respiratory system[13, 14], and assessing hyperthermia[15]. Widespread use of EIT in clinical practice will solve a number of medical and social problems, improve quality of health services, reduce the cost of modern medical equipment for health care institutions, and as a result, will make health care more accessible to public.

Main part

Electrical impedance tomography is a method of visualizing distribution of specific resistance of human body (or its internal organs). The EIT method has been theoretically studied since the 70s of the XX century. High frequency electric current is delivered to the studied object by means of surface contact electrodes. By means of recording the voltage measured at the surface of the body, distribution of electrical conductivity of biological object's internal structures is assessed

* To whom all correspondence should be addressed.

[1]. Currently the EIT technology is widely used in a number of countries. Significant results have been achieved by German Dräger company that in 2011 launched the first commercial electrical impedance tomograph PulmoVista® 500 (Figure 1a) intended for use in routine clinical practice for continuous visualization of mechanical ventilation (makes it possible to observe the state of the patient's lungs and to continuously evaluate results of respiratory therapy, thus defining the strategy of sparing ventilation.

In the Russian Federation, the studies are performed at the Institution of the Russian Academy of Sciences, namely, the Institute of Radio Engineering and Electronics named after V.A. Kotelnikov of RAS (Russia). Its employees have made a huge contribution to the theory of EIT. LLC PCC "SIM-technika" (Russia, Yaroslavl)[16] is one of the leaders in development and production of electrical impedance equipment (electrical impedance mammographer "MEIK" (Figure 1b) intended for detecting pathological and non-pathological breast disease in women). LLC "Impedance medical technologies" (Russia, Yaroslavl)[17] manufactures multifrequency electrical mammographers "MEM" (Figure 1) (intended for diagnosing pathological changes in breast tissue). In 2015, sale is planned of the "GIT" gynecologic impedance tomographer that is intended for early diagnosing of cervix oncological diseases and their precursors (Figure 1d). Research in the EIT field is also being performed in the Novosibirsk State

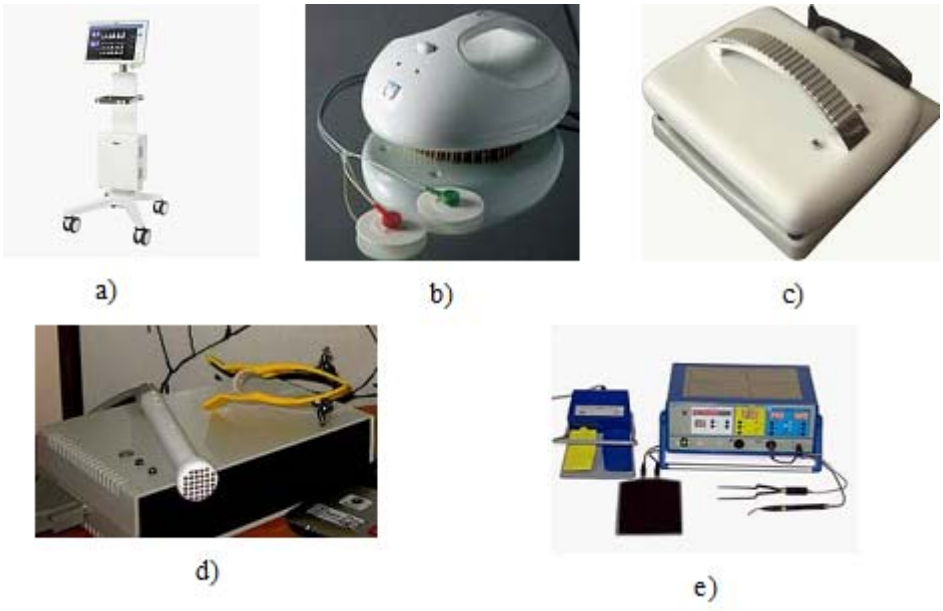

Fig. 1. Modern devices for EIT

Technical University[18], where the technology of non-invasive electrical impedance oncological diagnostics has been developed (Figure 1e) that is protected by patents and is currently being tested. The Moscow Scientific Research Oncological Institute named after P.A. Herzen[19] of the Health Ministry of Russia has been working for a long time on the problems of diagnostics and imaging in EIT.

Over 100 research groups in 21 countries perform research in this field, namely, Canada, the USA, Brazil, UK, Spain, South Africa, Italy, France, Germany, Poland, Russia, China, India, Singapore, Slovenia, Czech Republic, Taiwan, Vietnam, South Korea, Japan and Australia.

International conferences in the area of EIT are held on a regular basis

The XI International Conference on biomedical applications in EIT was held on April 4-8, 2010 at the University of Florida (Gainesville, USA)[20].

The XII International Conference "Electrical Impedance Tomography (EIT 2011)" was held on May 4-6, 2011, at the University of Bath

(UK). At the conference, issues of medical use of EIT, magnetic induction tomography and magnetic resonance imaging were discussed[21].

The XIV International Conference on EIT was held on April 22-25, 2013, in Heilbad Heiligenstadt (Germany). Leading scientists in the field of impedance biological measurement delivered their lectures[22].

The XV International Conference on EIT Biomedical Applications was held on April 24-26, 2014, in Carleton University (Canada)[23].

Research groups publish their main results in international magazines that deal with electrical impedance tomography. The main ones are: Physics in Medicine and Biology, Physiological Measurement, Measurement Science and Technology, Electronics Letters, IEEE Transactions in Biomedical Engineering, IEEE Transactions in Medical Imaging, Medical and Biological Engineering and Computing, SIAM Journal of Applied Mathematics, British Medical Journal, The Lancet, New England Journal of Medicine, Journal of Physiology, Biomedical electronics, Bulletin of the Russian Research Center of Radiology, Medical Radiology and Radiation Safety, New Scientist, Scientific American, Inverse Problems in Science and Engineering, Progress In Electromagnetics Research, Journal of Electromagnetic Waves and Applications.

Free software products have been developed, such as EIDORS[24], GREIT[25], RES2DINV[26], which implement the forward and inverse modeling algorithms for electrical impedance tomography in medical and industrial use, as well as for exchanging information and facilitation of collaboration between groups working in these areas.

It has been established that in the algorithms of tomography images reconstruction used in clinical practice, methods of inverse projections methods of solving inverse problems, and iterative methods are used[27, 28]. However, significant drawback of inverse projection method is low sensitivity, and methods for solving inverse problems require significant computation power.

There are four basic ways to use EIT in clinical conditions: visualization of resistance distribution in body (object); imaging frequency of resistance change inside body (object); visualization of impedance change in course of physiological changes (e.g., respiration); and imaging of changes in impedance in case of pathological changes (e.g. cerebral haemorrhage and oncological disease.)

Scientific research in the area of EIT is conducted in the following areas: brain EIT, including newborn, diagnosis of cerebral hemorrhage[29]; EIT of adipose tissue in abdominal cavity[30]; EIT of heart, monitoring of intraventricular hemorrhage[31]; EIT in gynecology and urology[32,33]; EIT of lungs, diagnostics of pulmonary edema[34]; EIT of liver tissue[35]; EIT of stomach; EIT of female breast[6]; impedance spectroscopy[36]; detecting temperature during hyperthermia in cancer treatment[15].

With that, the main areas of research are the following: optimal placement of electrodes and lead system; effective materials for electrodes; optimal amperage; optimal frequency; defining necessary and sufficient number of electrodes; use of the finite element method and of nonlinear optimization; studying feasibility of using internal electrodes for improving accuracy; calibration of information and measurement systems; numerical interpolation methods; combined influence of electrical impedance tomography with ultrasound[37]; studying sensitivity and modeling electrode systems; algorithms for 2D and 3D reconstruction; increasing repeatability, reducing errors.

Over the past few years in the Russian Federation the following dissertations have been defended (Table 1).

Based on the review performed, and on the analysis of the current state of the problem, it has been revealed that today there is no common effective approach in the theory of EIT. There is a need to develop new approaches, mathematical models and devices for improving measurement accuracy, for developing and studying spatial distribution visualization and reconstruction algorithms. A promising field in this area is comprehensive use of experimental studies, modeling and computer technologies for obtaining necessary information.

Use of natural simulation approach (NSA) is proposed for these purposes. Use of NSA can significantly extend the theory of electrical impedance tomography and functional capabilities of hardware. In course of implementing NSA, measurement results are used as input data for solving the inverse problem of calculating

Table 1. Dissertations in EIT defended in the Russian Federation

Name of institution	Year	Author	Paper title	Specialty	Type
Institution of the Russian Academy of Sciences Institute of Radio Engineering and Electronics named after V.A. Kotelnikov of the RAS	2009	Korzenevsky A.V.	Quasi-static electromagnetic imaging for biomedicine	01.04.01 - Devices and methods of experimental physics	Doctoral dissertation, physical and mathematical sciences
Saint Petersburg State Electrotechnical University "LETI" named after V.I. Ulyanov (Lenin)	2013	Semchenkov A.A.	Method and system if electrical impedance mammography	05.11.17 - Medical devices, systems and units	MPhil dissertation, Engineering Sciences
Moscow State University named after M.V. Lomonosov	2013	Gavrilov S.V.	Numeric methods for solving the problem of electrical impedance tomography in case of piecewise-constant conductivity	05.13.18 - Mathematical modeling, numerical methods and program suites	MPhil dissertation, Physical and mathematical sciences
Moscow State Technical University named after N.E. Bauman	2012	Timokhin D.P.	Developing a biotechnical system for multichannel electrical impedance mapping of heart biomechanical activity	05.11.17 - Medical devices, systems and units	MPhil dissertation, Engineering Sciences
Tomsk Polytechnic University	2009	Fokin A.V.	Methods and technical tools for visualizing electric impedance distribution in brain	05.11.17 - Medical devices, systems and units	MPhil dissertation, Engineering Sciences
Moscow State Technical University named after N.E. Bauman	2012	Kirpichenko Y.E.	Development of biotechnical system of precardiac vector electric impedance rheography	05.11.17 - Medical devices, systems and units	MPhil dissertation, Engineering Sciences
Institution of the Russian Academy of Sciences Institute of Radio Engineering and Electronics named after V.A. Kotelnikov of the RAS	2010	Tuykin T.S.	Experimental methods of electric field tomography	01.04.01 - Devices and methods of experimental physics	MPhil dissertation, physical and mathematical sciences

Novosibirsk State Technical University	2010	Belik K.D.	Methods and means of multi-frequency electric impedance measurement of human tissues for oncosurgery	05.11.17 - Medical devices, systems and units	MPhil dissertation, Engineering Sciences
Moscow State Technical University named after N.E. Bauman	2012	Astapenko E.M.	Biotechnical system for multichannel electrical impedance study of brain hemodynamic parameters	05.11.17 - Medical devices, systems and units	MPhil dissertation, Engineering Sciences

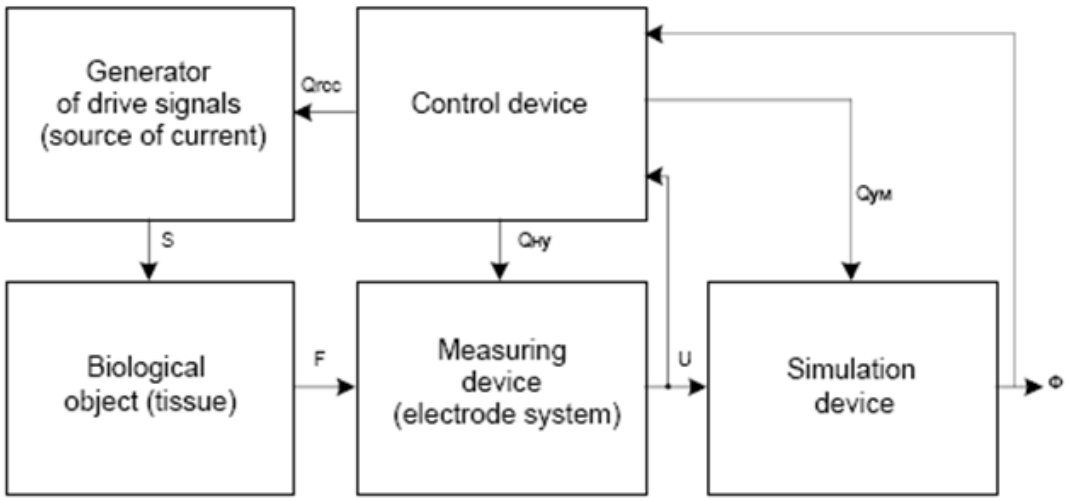

Fig. 2. The block diagram of the device that implements natural simulation approach in EIT

the electrical conductivity, and as a criterion of calculation correctness. With that, it is necessary to simultaneously develop models adjustment algorithms. The advantage of the proposed approach is the ability to obtain accurate diagnostic information about status of internal organs using non-invasive recording voltages on the surface of human body without direct electrical measurements on the object (e.g., heart). This is achieved by measuring electrical conductivity directly on the object and further adjustment of the mathematical model until simulation values of the entire object match experimental values. Under these conditions, parameters of the internal structures of objects (bodies) are further determined by means of simulation.

The general form, the block diagram of the device that implements the proposed method in the theory of EIT is shown in Figure 2[38].

Future research in this area is aimed at optimizing the electrode system, source of current, defining the scheme of biological object probing and selecting the most suitable lead system. On the basis of these results it is planned to develop an algorithm for reconstruction and visualization of spatial distribution of biological object's internal structures.

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REFERENCES

1. Pekker, Y.S., Electrical impedance tomography. Tomsk: NTL Publishers, 2004; 298.
2. Webster, J., Electrical impedance tomography, Adam Hilger series of biomedical engineering. New York (USA): Adam Hilger, 1990; 199-223.
3. Pekker, Y.S., K.S. Brazovsky, O.S. Umansky, M.P. Plotnikov and V.Y. Usov, First experience of clinical use electrical impedance tomography in detection of brain vascular injuries. *Medical Imaging*, 2002; **3**: 88-91.
4. Gulyaev, Y.V., A.V. Korzenevsky, S.A. Sapetsky, O.V. Trohanova, T.S. Tuikin and V.A. Cherepenin, Electrical impedance tomographer. Utility model RF patent # 109394, published on 20.10.2011, 2011.
5. Isaacson, D. and J. Mueller, Biomedical applications of electrical impedance tomography. *Physiological Measurement*, 2003; **24**: 3-5.
6. Karpov, A. and M. Korotkova, Standards for Electrical Impedance Mammography. Technical Aspects and Clinical Implication. Croatia: InTech Publishing, 2012; 159-179
7. Korzenevsky, A.V., Quasi-static electromagnetic imaging for biomedicine, thesis of a Dr. of Physical and Mathematical Sciences, Kotel'nikov Institute of Radioengineering and Electronics of the RAS, Moscow, 2009; 326.
8. Kirpichenko, Y.E., D.P. Timokhin and S.I. Schukin, Study of features and accuracy of determining parameters of heart activity based on the impedance mapping technology. *Biomedical Electronics*, 2011; **10**: 23-27.
9. Schukin, S.I., Assessing movements heart ventricles projection borders on the basis of technology of multi-channel electrical impedance mapping. *Biomedical Radio Electronics*, 2012; **10**: 8-11.
10. Rozhkov, N.I., D.K. Fomin, A.A. Nazarov, O.E. Jacobs and O.A. Borisova, Opportunities of electric impedance tomography in identifying structural changes in biological tissues: experimental data. Bulletin of the Russian Research Center of Radiology and Nuclear Medicine, 9. Date Views: 09.10.2014 http://vestnik.rncrr.ru/vestnik/v9/papers/roshkova_v9.htm, 2009.
11. Trohanova, O.V., M.B. Okhapkin and A.V. Korzenevsky, Mammography for detecting benign and malignant tumors in female breast. *Surgeon*, 2009; **2**: 43-51.
12. Trohanova, O.V., Assessing the state of female breast using electrical impedance mammography. AG-info, 2008; **4**: 2-7.
13. Zhang, J. and P. Patterson, Analysis on the influence of tissues/organs' movements in EIT images of lung ventilation using finite difference thorax models. In the Proceedings of IEMBS'04, San Francisco, CA, 2004.
14. Zhao, Z. and K. Moller, Evaluation of an electrical impedance tomography-based global in homogeneity index for pulmonary ventilation distribution. *Intensive Care Med*, 2009; **11**: 1900-6.
15. Wessalowski, R. and R. Van Heek-Romanowski, Estimated number of children with eligible for hyperthermia based on population and treatment-related criteria. *Intensive CareMed*, 1999; **6**: 455-466.
16. Official website of LLC PCC "SIM-technika". Date Views: 10.10.2014 http://www.impedance.ru.
17. Official website of LLC "Impedance medical technologies". Date Views: 08.10.2014 http://www.medimpedance.ru.
18. Official website of the Novosibirsk State Technical University. Date Views: 10.10.2014 http://www.nstu.ru.
19. Official website of the Moscow Research Oncological Institute named after P.A. Herzen. Date Views: 13.10.2014 http://www.mnioi.ru.
20. Official website of the conference. Date Views: 04.10.2014 http://conferences.dce.ufl.edu.
21. Official website of the conference. Date Views: 07.10.2014 http://www.bath.ac.uk/elec-eng/invert/conference/eit_2011.html.
22. Official website of the conference. Date Views: 05.10.2014 http://www.icebi-conference.org.
23. Official website of the conference. Date Views: 07.10.2014 http://eit2014.org.
24. Internet resource EIDORS. Date Views: 12.10.2014 http://eidors3d.sourceforge.net.
25. Internet resource GREIT. Date Views: 12.10.2014 http://eidors3d.sourceforge.net/GREIT/index.shtml.
26. Official website of developer organization. Date Views: 01.10.2014 http://www.geotomosoft.com.
27. Castillo, P.R. and V. Krvachenko, Solution of boundary and eigenvalue problems for second-order elliptic operators in the plane using pseudoanalytic formal powers. *Mathematical Methods in the Applied Sciences*, 2011; **4**: 445-468.
28. Sarode, V. and P. Chimurkar, Electrical Impedance Tomography (EIT) based Medical Imaging using Finite Element Method (FEM). *International Journal of Engineering Sciences & Emerging*

Technologies, 2012; **2**: 83-89.

29. Yerworth, R. and B. Bayford, Electrical impedance tomography spectroscopy (EITS) for human head imaging. *Physiological Measurement*, 2003; **24**: 477-489.
30. Fusehng, Y. and C. Hua, Measurement the resistivity-temperature properties of liver tissue and applying EIT to monitor hyperthermia treatment based on phantom. In the Proceedings of the 12th International Conference in Electrical Impedance Tomography (EIT 2011), University of Bath, 2011; 49-53.
31. Xuetao, S. and Y. Fusheng, Preliminary Research on Monitoring of Cerebral Ischemia Using Electrical Impedance Tomography Technique. In the Proceedings of the 29th Annual International Conference IEEE/EMBS, 2008; 1188-1119.
32. Brown, B. and S. Milnes, Detection of cervical intraepithelial neoplasia using impedance spectroscopy: a prospective study. *British Journal of Obstetrics and Gynaecology*, 2005; **112**: 802-806.
33. Korjenevsky, A. and V. Cherepenin, Gynecologic electrical impedance tomograph. In the Proceedings of the Journal of Physics: Conference Series, 2010; 802-806.
34. Mayer, M. and P. Brunne, Monitoring of lung edema using focused impedance spectroscopy: a feasibility study. *Physiological Measurement*, 2005; **4**: 185-192.
35. Demirkaz1k, F.B. and E. SalihEmri, Radiation-induced liver injury and foreign body reaction secondary to the diaphragmatic Teflon patch in an operated malignant pleural mesothelioma patient: CT, MRI and PET-CT findings. *Magnetic Resonance Imaging*, 2000; **6**: 707-714.
36. Kerner, T. and K. Paulsen, Electrical impedance spectroscopy of the breast: clinical imaging results in 26 subjects. *IEEE Transactions on Medical Imaging*, 2002; **21**: 638-645.
37. Wan, Y. and R. Paulsen, Sensitivity study of an ultrasound coupled transrectal electrical Impedance Tomography system for prostate imaging. *Physiological Measurement*, 2010; **31**: 17-29.
38, Gorbatenko, N.I., Natural-simulation tests of articles made of ferromagnetic materials. Rostov-on-Don: SKNC VSh Publishing House, 2001; 392.