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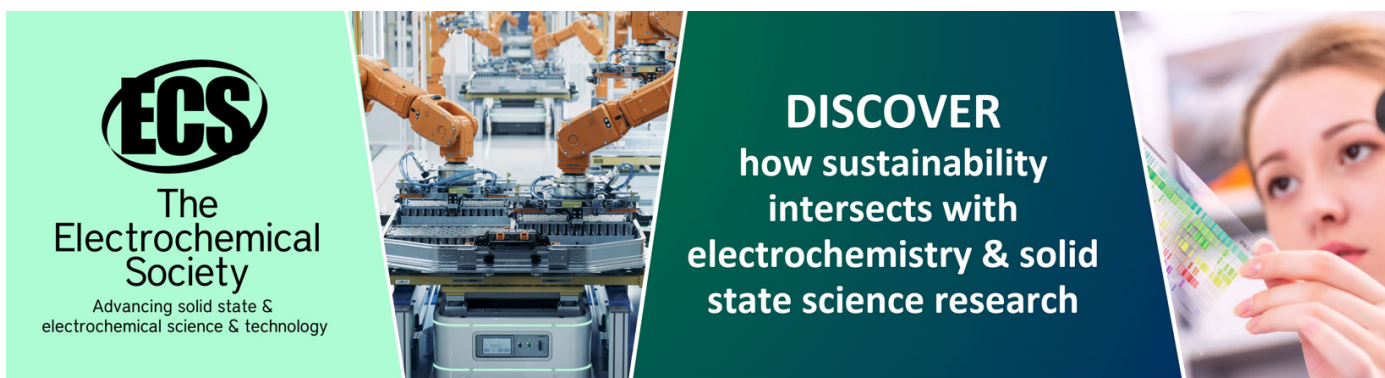
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Applications of Electrical Impedance Tomography (EIT): A Short Review

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Abstract. Electrical Impedance Tomography (EIT) is a tomographic imaging method which solves an ill posed inverse problem using the boundary voltage-current data collected from the surface of the object under test. Though the spatial resolution is comparatively low compared to conventional tomographic imaging modalities, due to several advantages EIT has been studied for a number of applications such as medical imaging, material engineering, civil engineering, biotechnology, chemical engineering, MEMS and other fields of engineering and applied sciences. In this paper, the applications of EIT have been reviewed and presented as a short summary. The working principal, instrumentation and advantages are briefly discussed followed by a detail discussion on the applications of EIT technology in different areas of engineering, technology and applied sciences.

1. Introduction

Electrical impedance tomography (EIT) [1-5] reconstructs the conductivity or resistivity distribution of the object under test within a volume conductor using a voltage-current data measured at the domain boundary (Figure 1). In EIT, a constant sinusoidal current signal is injected to the object and the boundary potentials data are measured through the surface electrodes [1] using an EIT hardware or EIT instrumentation [6-10]. Conductivity or resistivity distribution is reconstructed from the boundary potential data using a computer program known as image reconstruction algorithm [11-13]. Practical phantoms [14-22] which are a model of any targeted object of the real application field are essentially required in EIT to study, calibrate and evaluate the system before applying it in real or practical applications. In EIT, the practical phantoms are developed with non-biological or biological materials with different conductivities. An electronic instrumentation is required for constant current injection and the boundary voltage data measurements in EIT. A constant current source [7] is used to inject a low frequency constant amplitude sinusoidal current to the phantom boundary and develop boundary potentials are measured. Boundary voltage-current data are used to solve the EIT inverse problem and the impedance image reconstruction is conducted to get the tomographic images. The EIT is an ill-posed inverse problem [23-24] has poor signal to noise ratio (SNR) [25-26] and poor spatial resolution [27-28]. Therefore, EIT technique suffers from low spatial resolution compared to conventional tomographic imaging techniques such as [29], CT [29] and MRI [29]. As the quality of the EIT images (especially the spatial resolution) is not yet competitive with CT and MRI, the EIT has not yet been accepted as gold method in medical and clinical imaging. But, EIT is a low cost, noninvasive, non-



ionizing, radiation free and portable imaging modality with high temporal resolution, and hence, for these unique advantages [3-6, 11-13], EIT has obtained enormous attention and interest in diversified fields such as medical imaging [30-38], material engineering [39], Nanotechnology and MEMS [40-41], civil engineering [42-43], chemical engineering [44-46], biotechnology [47-49], and other fields of engineering, technology and applied sciences. In this paper the applications of EIT in different fields have been reviewed and a short summary has been presented for the researchers. The working principal, instrumentation and advantages are briefly discussed followed by a detail discussion on the applications in different areas along with their limitations.

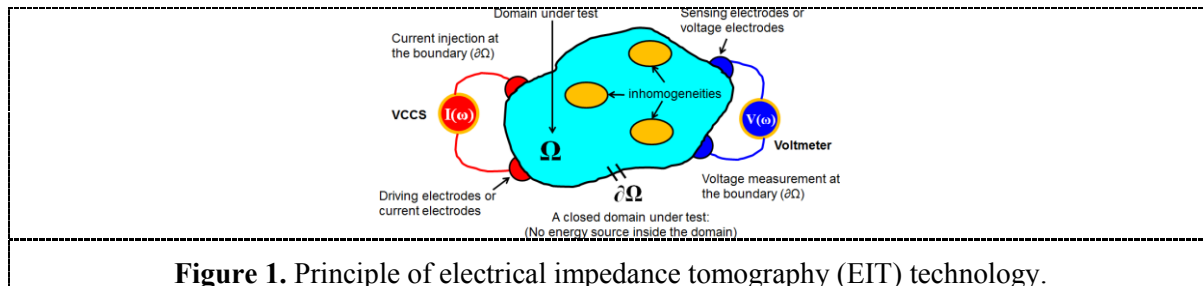


Figure 1. Principle of electrical impedance tomography (EIT) technology.

2. Basics of EIT Technology

In EIT, the electrical impedance of the object under test is reconstructed from a set of voltage current data measured at the boundary by injecting a constant voltage signal or current signal using a constant voltage source [50-51] or constant current source [52-56] using the surface electrodes [1, 57-58]. The surface electrodes are attached to the boundary of the domain under test and are connected to the EIT instrumentation (Figure 2). The boundary potentials are measured by either injecting a constant current signal at a particular frequency (ω) with a single frequency EIT system or at a number of frequencies with a multifrequency EIT system [59-68]. The current injection and the voltage measurement are conducted with, generally, four electrode method [1, 57-58, 69, 75-80] to avoid the electrode-skin interface impedance or contact impedance problem [70-74] in EIT. In four-probe method based EIT data collection scheme, the alternating current signal ($I(\omega)$) is injected through two-electrodes (called driving electrode or current electrodes) as shown by the red electrodes in Fig. 1 and the induced potential ($V(\omega)$) developed is measured across other two-electrodes (called sensing electrodes or voltage electrodes blue electrodes in Fig. 1).

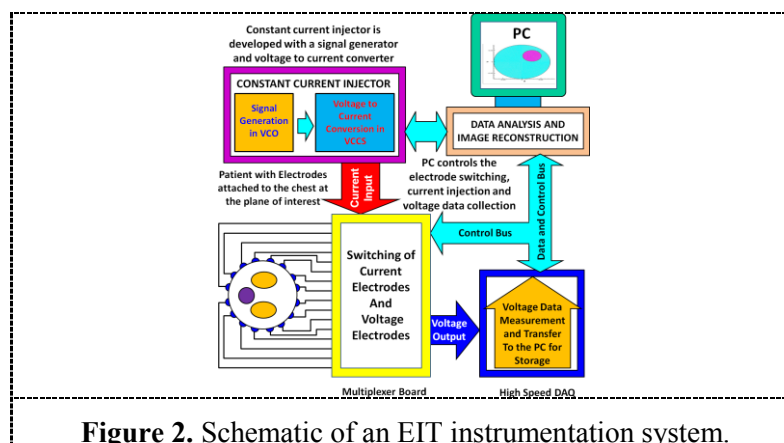


Figure 2. Schematic of an EIT instrumentation system.

3. Applications of EIT Technology

Due to a lot of unique advantages [3-6, 11-13], EIT method has been applied in several fields. The researchers from medical imaging, material engineering, Nanotechnology and MEMS, civil

engineering, chemical engineering, biotechnology, and other fields of engineering, technology and applied sciences have tried to solve their numerous research problems using the EIT technology. The applications of EIT in different fields have been reviewed and a short summary is presented below:

3.1. Medical Imaging

EIT has been found suitable for tomographic imaging in medical field for visualizing body anatomy, physiology and several disease conditions. Few of the medical applications of EIT have been summarized below:

3.1.1. Cranial Imaging in the Newborn

EIT has been applied for cranial imaging in the newborn by Tarrasenko and Rolfe, 1984 [30]. They proposed a sensitivity method to obtain images of resistivity distribution within a body segment to image the spatial distribution of electrical resistivity for cranial imaging in the newborn using a weighted backprojection algorithm.

3.1.2. Lung Imaging

A number of studies on lung imaging with EIT technique have been conducted and reported. Meier et al. [31] studied the suitability of EIT on animal subjects to visualize the acute lung injury. They conducted the EIT experimental studies on six pigs with saline-lavage-induced acute lung injury and investigated whether the EIT procedure could be suitable for monitoring the regional lung recruitment and lung collapse. The incremental and decremental positive end-expiratory pressure (PEEP) trials at ten pressure levels were performed and the ventilatory, gas exchange, and hemodynamic parameters were automatically recorded. EIT and computed tomography (CT) scans of the same slice were simultaneously taken at each PEEP level and the results are compared. Authors found EIT is suitable for monitoring the dynamic effects of PEEP variations on the regional change of tidal volume. Pulmonary Edema is also studied by EIT. Harris et al., 1987 [32] reported that applied potential tomography (APT) [1, 5] is able to produce cross-sectional images of the changes in resistivity distribution within the chest. The authors concluded that the APT may be used to detect ventilatory defects in certain types of lung disease to detect the onset of pulmonary edema in high risk patients and to detect and monitor the edema following treatment. Adler et al., 1995 [33] have conducted a series of EIT experiments on dogs to quantify the capacity of this technology to measure lung tidal volume and fluid content. The authors reported that their results obtained from the experimentations conducted on dogs indicated good correlation with standard reference techniques. They also reported that it was difficult to obtain the long term stability of electrodes on the subject and instrumentation.

3.1.3. Hyperthermia Treatment

EIT has been also used for thermal monitoring of hyperthermia treatment. Conway et al. 1985 [34] and Conway, 1987 [35] presented an impedance imaging method to display the induced thermal gradients during hyperthermia treatment. They presented the results obtained with EIT method applied with the experimentations both in vitro and in vivo. A time series of conductivity images showed the distribution of thermal changes and suggested a temperature resolution better than 1 °C. They reported that the spatial resolution was limited to approximately 10% of the circular array diameter by the 104 independent measurements from 16 electrodes used in the EIT system.

3.1.4. Paediatric Lung Disease

EIT has also been applied for paediatric lung disease. Pham et al., 1994 [36] used the EIT technique to study the regional ventilation distribution in neonatal and paediatric lung disease. EIT has been applied on spontaneously breathing infants in their neonatal period, at 3 and 6 months of age during their non-rapid eye movement sleep and the data on regional ventilation distribution and regional filling characteristics were obtained. It is reported that the regional impedance amplitudes increased

with the age but regional ventilation distribution remained unchanged in all infants at any age, with the dependent (posterior) lung always better ventilated. Authors also reported that the regional ventilation distribution and regional filling characteristics remained unchanged over the first 6 months of life, and the results obtained on regional ventilation distribution with EIT were found very similar to those in adult subjects.

3.1.5. Breast Imaging

Breast Imaging has been studied with EIT by several research groups. Zain and Chelliah, 2014 [37], applied EIT technique on one hundred and fifty mammography patients above 40 years. Visual interpretation of the images was conducted using the breast imaging - electrical impedance (BI-EIM) classification for detection of abnormalities. Quantitative assessment was carried out by comparison of the breast average electric conductivity with the norm and correlations with visual interpretation of the images, made by a radiologist, were determined using Chi-square. The one-way analysis of variance (ANOVA) was used to compare the mean electrical conductivity between groups and t-test was used for comparisons with pre-existing Caucasians statistics. Authors reported that the Quantitative assessment of electrical impedance tomography was significantly related with visual interpretation of images of the breast.

3.1.6. Brain Imaging

Holder et al., 1996 [38] reported their studies on EIT for imaging the impedance changes of several per cent over tens of seconds, known to occur during evoked activity of the cerebral cortex. The results demonstrated that, for the first time, reproducible impedance changes of few per cent can be seen in EIT images during functional cerebral stimulation and they concluded that EIT may eventually be suitable for imaging evoked responses or epilepsy in human subjects.

3.2. *Material Engineering*

EIT has been also studied in material engineering and the manufacturing technology such as semiconductor manufacturing. Michiel and Kruger, 2003 [39] applied EIT procedure to study the semiconductor manufacturing. The author used the standard EIT technique to estimate the conductivity distribution of the thin film of a conductive polysilicon across a wafer and the estimated conductivity distribution is related to the thickness of the polysilicon film. Results showed that the EIT is suitable to visualize the conductivity changes occurred due to the physical and chemical effects inside the interior of a wafer during semiconductor manufacturing. Author reported that the differential thickness measurements from the EIT based prototype etch rate sensor correlated very well with optical thickness measurements. Author also proposed a novel EIT based sensor which was capable of providing temporal and spatial wafer surface potential information during plasma processing. Promising results are obtained from the simulation studies conducted on the prototype sensor using the depletion mode NMOSFETs as transduction elements and justified the suitability of the EIT based metrology technique.

3.3. *Nanotechnology and MEMS*

EIT has been studied in thin film technology and nanotechnology such as imaging of Carbon Nanotube (CNT) composite thin films. Hou et al. 2007 [40-41] applied EIT to reconstruct the spatial conductivity distribution to visualize the structural defects in CNT thin films and its response to various pH environments. The ability of the EIT to image the spatial distribution of conductivity of CNT thin films was found advantageous to develop the multifunctional CNT-based sensing skins.

3.4. *Civil Engineering*

EIT has been also studied in several civil engineering applications and a number of research works have been reported such as imaging leaks from buried pipes by Jordana et al. 2001 [42], brick walls imaging by Hola et al., 2008 [43]. Jordana et al. 2001 [42] applied EIT to detect the leaks in buried

pipes using a surface linear electrode array perpendicular to the axis of the pipe. The author tested their proposed system in the laboratory using a stainless steel tube immersed in water and covered by a rubber sleeve to simulate a non-conductive leak. The system has also been studied with the field measurements involved with the simulated leaks of water from a plastic tube buried in a farm field. Author reported that the simulated leak was successfully distinguished with EIT based pipe leakage detection system. Hola et al., 2008 [43] studied the applicability of EIT for detection of brick wall dampness in real building structures. The EIT setup was applied to determine the dampness of test brick walls on a specially built laboratory test rig and the results obtained from the EIT based studies are compared with the results obtained from the conventional destructive dry-weight method. Author reported that, a satisfactory agreement was found between the results and the further research aimed to apply the EIT method in building engineering practice.

3.5. Chemical Engineering

EIT has large potential in the chemical engineering applications and hence EIT has been also studied in this area. Dickin and Wang, 1996 [44] presented an overview of the important aspects of an ERT system for use in process applications by focusing on the design and operation of flexible ERT instrumentation. A few of the research works reported so far could be summarized as visualizing combustion by Waterfall et al., 1997 [45] and Tapp et al. 2003 [46].

3.6. Biotechnology

Cell culture imaging has been studied by several research groups such as Linderholm et al. 2008 [47], Sun et al. 2008 [48] and Sun et al. 2010 [49]. In EIT based cell culture imaging, the microtechnology is used to develop the microelectrodes which are housed in a small domain where the cell culture is process and monitoring is conducted. A biological culture media of living cells or tissue is used as the object and small amount of electrical current has been injected and the boundary data are collected. The collected boundary data are fed to the computer and the impedance images are reconstructed using a reconstruction algorithm. Linderholm et al. 2008 [47], presented a novel, inexpensive, and fast microimpedance tomography system capable of four-electrode measurements using 16 planar microelectrodes integrated into a culture chamber for two-dimensional imaging of cell and tissue cultures. Impedance measurements are conducted with an Agilent 4294A impedance analyzer combined with a front-end amplifier and 2D images are obtained using a reconstruction algorithm. The shape and position of a human hair, yielding vertical cross sections of the object and the human epithelial stem cells (YF 29) grown directly on the device surface are studied. The rapid resistivity decrease caused by permeabilized cell membranes is monitored by EIT system which suggested that the technique can be used in electroporation studies. Sun et al. 2008 [48] and Sun et al. 2010 [49] presented a miniaturized EIT system that can image the electrical conductivity distribution within a two-dimensional cell culture. A chip containing a circular 16-electrode array is fabricated with PCB technology and used to inject current and to measure spatial voltage across a multi-nuclear single cellular organism, *Physarum Polycephalum*. An impedance analyzer operating in four-electrode mode is used to collect the voltage –current data and the impedance images are reconstructed with the open source software, EIDORS. Author claimed that the developed system providing a non-invasive lab-on-a-chip (LOC) technology for mapping the spatially distribution of electrical properties of single cells will be significantly useful for diagnostic and clinical applications.

4. Discussion

Due to a number of advantages, the researchers from a number of research fields are applying EIT to solve their problems. Though the EIT technology has number advantages, but the technology suffers from poor SNR and poor spatial resolution. Increasing the number of electrodes increases the spatial resolution but housing a lot of electrodes is not always possible in all the real applications. Increasing FEM mesh with large number of elements also improves the image quality but computation time and cost may increase. Electrodes used in medical imaging are generally found as the surface electrodes in

most of the cases. In other field the electrodes can be soldered or penetrated to the object. The injected current amplitude and frequency are required to be chosen very carefully for the medical EIT whereas the amplitude could be increased more for the non-biological sample imaging with EIT. Contact impedance is found a crucial issue in EIT in most of the applications and hence the four electrode method is preferred. Being an ill-posed inverse problem the EIT produces a large noise at the output in response to the small error or noise at the input. Also, the solution process of the inverse problem needs a suitable regularization technique to get the better solution. Therefore, we need to carefully design the system to get the optimum images in a particular application. Therefore, a lot of studies are still required to be conducted to solve all the challenges in sensors design, instrumentation developments, and the reconstruction process.

5. Conclusions

EIT has been applied in different filed of engineering, technology and applied sciences. The research works conducted on the application of EIT in medical imaging, material engineering, Micro and Nanotechnology, civil engineering, chemical engineering, biotechnology have been reviewed and presented as a short summary. In all the fields the EIT technology is found as a low cost portable and fast tomographic imaging modality along with some other advantages and limitations. Due to number of advantages, EIT is possible to apply in several research problems. In this paper a number of research works conducted on the application of EIT in different areas have been discussed and summarized. The paper provides a short summary of the application of EIT and the summary of the EIT applications may help to cultivate the new ideas to apply the EIT technology in new fields where the technology has not yet been applied or studied so far.

6. References

- [1] J.G. Webster, *Electrical impedance tomography*. Adam Hilger Series of Biomedical Engineering, Adam Hilger, New York, USA. 1990.
- [2] M. Cheney, D. Isaacson, J.C. Newell, *Electrical Impedance Tomography*, SIAM Review, 1999; 41(1): 85–101.
- [3] R.H. Bayford, *Bioimpedance Tomography (Electrical Impedance Tomography)*, Annual Review of Biomedical Engineering. 2006; 8: 63–91.
- [4] C.W.L. Denyer, *Electronics for Real-Time and Three-Dimensional Electrical Impedance Tomographs*, PhD Thesis, Oxford Brookes University, 1996.
- [5] D.S. Holder, *Electrical impedance tomography: methods, history and applications (Series in Medical Physics and Biomedical Engineering)*, 1st Ed. Institute of Physics Publishing Ltd., UK. 2005.
- [6] Bera TK and Nagaraju J, A Multifrequency Electrical Impedance Tomography (EIT) System for Biomedical Imaging, IEEE International Conference on Signal Processing and Communications (SPCOM 2012), India, IISc - Bangalore, India pp 1-5.
- [7] Bera TK and Nagaraju J, A Multifrequency Constant Current Source for Medical Electrical Impedance Tomography, Proceedings of the IEEE International Conference on Systems in Medicine and Biology 2010 (IEEE ICSMB 2010), India, 2010, pp 278-283.
- [8] Riu PJ, Rosell J, Lozano A, Pallàs-Areny R, Multi-frequency static imaging in electrical impedance tomography: Part 1. Instrumentation requirement, Med Biol Eng Comput. 1995 Nov;33(6):784-92.
- [9] Oh TI, Wi H, Kim do Y, Yoo PJ, Woo EJ, A fully parallel multi-frequency EIT system with flexible electrode configuration: KHU Mark2, Physiol Meas. 2011 Jul;32(7):835-49. doi: 10.1088/0967-3334/32/7/S08. Epub 2011 Jun 7.
- [10] 13K G Boone and D S Holder, Current approaches to analogue instrumentation design in electrical impedance tomography, TOPICAL REVIEW, Physiol. Meas. 17 (1996) 229–247. Printed in the UK
- [11] W.R.B. Lionheart, EIT reconstruction algorithms: pitfalls, challenges and recent developments, Review Article, Physiol. Meas. 2004; 25: 125–142.
- [12] T.K. Bera, S.K. Biswas, K. Rajan and Nagaraju J, Improving Conductivity Image Quality Using Block Matrix-based Multiple Regularization (BMMR) Technique in EIT: A Simulation Study, Journal of Electrical Bioimpedance, vol. 2, pp. 33–47, 2011.
- [13] T.K. Bera, S.K. Biswas, K. Rajan and Nagaraju J, Improving Image Quality in Electrical Impedance Tomography (EIT) Using Projection Error Propagation-Based Regularization (PEPR) Technique: A Simulation Study, Journal of Electrical Bioimpedance, vol. 2, pp. 2–12, 2011. DOI:10.5617/jeb.158
- [14] Holder, D. S., Hanquan, Y., & Rao, A. (1996). Some practical biological phantoms for calibrating multifrequency electrical impedance tomography. *Physiological measurement*, 17(4A), A167.
- [15] P.J. Vauhkonen, M. Vauhkonen, T. Makinen, P.A. Karjalainen and J.P. Kaipio, Dynamic electrical impedance tomography—phantom studies, *Inverse Problems in Engineering*, 2000, Vol. 8, pp. 495–510.
- [16] T.K. Bera and Nagaraju J, Resistivity Imaging of A Reconfigurable Phantom With Circular Inhomogeneities in 2D-Electrical Impedance Tomography, Measurement, Volume 44, Issue 3, March 2011, Pages 518-526. DOI:10.1016/j.measurement.2010.11.015
- [17] H. Griffiths, Z. Zhang and M. Watts, A constant-perturbation saline phantom for electrical impedance tomography, *Phys. Med. Biol.*, 1989, Vol. 34, No 8, 1063-1071. Printed in the UK
- [18] T.K. Bera, J. Nagaraju and G. Lubineau, Electrical impedance spectroscopy (EIS)-based evaluation of biological tissue phantoms to study multifrequency electrical impedance tomography (Mf-EIT) systems. *Journal of Visualization*, Vol. 19(4), pp 691-713, 2016

- [19] B.S. Kim, K.Y. Kim, T.J. Kao, J.C. Newell, D. Isaacson, and G.J. Saulnier, Dynamic electrical impedance imaging of a chest phantom using the Kalman filter, *Physiol Meas.* 2006, 27(5): S81–S91.
- [20] A. Kimoto and K. Shida, Imaging of Temperature-Change Distribution in the Brain Phantom by Means of Capacitance Measurement, *IEEE Trans. on Instrumentation and Measurement*, Vol. 49, No. 3, 2000
- [21] Bera, T. K., Bera, S., Nagaraju, J., & Chakraborty, B. (2017, March). Multiple inhomogeneity phantom imaging with a LabVIEW-based Electrical Impedance Tomography (LV-EIT) System. In *Computer, Communication and Electrical Technology: Proceedings of the Int. Conf. on Advancement of Computer Comm. and Electrical Technology (ACCET 2016)*, India, 2016 (p. 273). CRC Press.
- [22] Bera, T. K., Chowdhury, A., Mandai, H., Kar, K., Haider, A., & Nagaraju, J. (2015, February). Thin domain wide electrode (TDWE) phantoms for Electrical Impedance Tomography (EIT). In *Computer, Communication, Control and Information Technology (C3IT)*, 2015 Third International Conference on (pp. 1-5). IEEE.
- [23] O'Sullivan, F. (1986). A statistical perspective on ill-posed inverse problems. *Statistical science*, 502-518.
- [24] Tikhonov, A. N., & Goncharsky, A. V. (Eds.). (1987). *Ill-posed problems in the natural sciences* (p. 344). Moscow: Mir.
- [25] A T Tidswell, A Gibson, R H Bayford, and D S Holder, Electrical impedance tomography of human brain activity with a two-dimensional ring of scalp electrodes, *Physiol. Meas.* 22 (2001) 167–175.
- [26] Andy Adler and Robert Guardo, A Neural Network Image Reconstruction Technique for Electrical Impedance Tomography, *IEEE Trans Med Imaging*, Vol. 13, No. 4, December 1994, pp 594-600.
- [27] A M Sinton, B H Brown, D C Barber, F J McArdle and A D Leathard, Noise and spatial resolution of a real-time electrical impedance tomograph, *Physiol. Meas.* 1992 Vol. 13, Suppl. A, 125-130.
- [28] James L Wheeler, WeiWang and Mengxing Tang, A comparison of methods for measurement of spatial resolution in two-dimensional circular EIT images, *Physiol. Meas.* 23 (2002) 169–176.
- [29] Bushberg, J.T., Seibert, J.A., Leidholdt, Jr.E.M., Boone, J.M.: *The Essential Physics of Medical Imaging*. 2nd Edition, Lippincott Williams & Wilkins, USA (2001).
- [30] Tarrasenko L and Rolfe P, Imaging spacial distributions of resistivity - an alternative approach, *Electronics Letters*, 20, pp574-5, 1984.
- [31] Meier, T., Luepschen, H., Karsten, J., Leibecke, T., Großherr, M., Gehring, H., & Leonhardt, S. (2008). Assessment of regional lung recruitment and derecruitment during a PEEP trial based on electrical impedance tomography. *Intensive care medicine*, 34(3), 543-550.
- [32] Harris ND, Suggett AJ, Barber DC and Brown BH, Applications of applied potential tomography (APT) in respiratory medicine, *Clin Phys. Physiol. Meas.*, 8 Suppl. A, pp 155-65, 1987
- [33] Adler, A., Berthiaume, Y., Guardo, R., & Amyot, R. (1995, September). Imaging of pulmonary edema with electrical impedance tomography. In *Engineering in Medicine and Biology Society, 1995., IEEE 17th Annual Conference* (Vol. 1, pp. 557-558). IEEE.
- [34] J. Conway, M. S. Hawley, A. D. Seagar, B. H. Brown, D. C. Barber, *Applied Potential Tomography (APT) For Noninvasive Thermal Imaging During Hyperthermia Treatment*, *Electronics Letters*, 1985, Vol. 21 No. 19, 836-838.
- [35] J. Conway, *Electrical impedance tomography for thermal monitoring of hyperthermia treatment: an assessment using in vitro and in vivo measurements*, *Clin. Phys. Physiol. Meas.*, 8, Suppl. A, pp 141-6, 1987
- [36] T.M.T. Pham, M. Yuill, C. Dakin and A. Schibler, Regional ventilation distribution in the first 6 months of life, *European Respiratory Journal (ERJ)* April 1, 2011 vol. 37 no. 4 919-924.
- [37] Zain, N. M., & Chelliah, K. K. (2014). Breast imaging using electrical impedance tomography: correlation of quantitative assessment with visual interpretation. *Asian Pacific Journal of Cancer Prevention*, 15(3), 1327-1331..
- [38] D S Holder, A Rao and Y Hanquan, Imaging of physiologically evoked responses by electrical impedance tomography with cortical electrodes in the anesthetized rabbit, *Physiol. Meas.* 17 (1996) A179–A186.
- [39] Michiel Victor Paul Kruger, *Tomography as a Metrology Technique for Semiconductor Manufacturing*, PhD Thesis, University of California, Berkeley, 2003.
- [40] Tsung-Chin Hou, Kenneth J Loh and Jerome P Lynch, Spatial conductivity mapping of carbon nanotube composite thin films by electrical impedance tomography for sensing applications, *Nanotechnology* 18 (2007) 315501 (9pp).
- [41] Tsung-Chin Hou, Kenneth J. Loh, Jerome P. Lynch, *Electrical impedance tomography of carbon nanotube composite materials, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2007*, edited by Masayoshi Tomizuka, Chung-Bang Yun, Victor Giurgiutiu, *Proc. of SPIE Vol. 6529*, 652926, (2007).
- [42] Josep Jordana, Manel Gasulla and Ramon Pall`as-Areny, Electrical resistance tomography to detect leaks from buried pipes, *Meas. Sci. Technol.* 12 (2001) 1061–1068.
- [43] Jerzy Hola, Zygmunt Matkowski, Krzysztof Schabowicz, Jan Sikora, Stefan Wójtowicz, *New Method of Investigation of Rising Damp in Brick Walls by means of Impedance Tomography*, 17th World Conference on Nondestructive Testing, 25-28 Oct 2008, China.
- [44] Fraser Dickin and Mi Wang, Electrical resistance tomography for process applications, *Meas. Sci. Technol.* 7 (1996) 247–260.
- [45] Roger C. Waterfall, Ruhua He and Christopher M. Beck, Visualizing combustion using electrical impedance tomography, *Chemical Engineering Science*, Vol. 52, No 13, pp. 2129-2138, 1997.
- [46] H.S. Tapp, A.J. Peyton, E.K. Kemsley, R.H. Wilson, *Chemical engineering applications of electrical process tomography*, *Sensors and Actuators B* 92 (2003) 17–24.
- [47] Pontus Linderholm, Laurent Marescot, Meng Heng Loke, and Philippe Renaud, *Cell Culture Imaging Using Microimpedance Tomography*, 138 *IEEE Trans Biomed Eng.*, Vol. 55, No. 1, 2008, pp 138-146.
- [48] T. Sun, S. Tsuda, N.G. Green, K.P. Zauner and H. Morgan, *On-Chip Electrical Impedance Tomography for Monitoring The Kinetics in The Cell Culture*, Twelfth International Conference on Miniaturized Systems for Chemistry and Life Sciences, 2008, USA, pp 973-975.
- [49] Tao Sun, Soichiro Tsuda, Klaus-Peter Zauner, Hywel Morgan, *On-chip electrical impedance tomography for imaging biological cells*, *Biosensors and Bioelectronics* 25 (2010) 1109–1115.

- [50] T R Qureshi, C R Chatwin and W Wang, Design of Wideband Voltage Source Having Low Output Impedance, Flexible Gain and Controllable Feedback Current for EIT Systems, 2012 2nd International Conference on Biomedical Engineering and Technology, IPCBEE vol. 34 (2012), IACSIT Press, Singapore, 45-50.
- [51] Youssoufa Mohamadou, Tong In Oh, HunWi, Harsh Sohal, Adnan Farooq, Eung Je Woo and Alistair Lee McEwan, Performance evaluation of wideband bio-impedance spectroscopy using constant voltage source and constant current source, Meas. Sci. Technol. 23 (2012) 105703 (10pp).
- [52] Alexander S Ross, G J Saulnier, J C Newell and D Isaacson, Current source design for electrical impedance tomography, Physiol. Meas. 24 (2003) 509–516.
- [53] Jeong Whan Lee, Tong In Oh, Sang Min Paek, Jae Sang Lee, and Eung Je Woo, Precision Constant Current Source for Electrical Impedance Tomography, Proceedings of the 25th Annual International Conference of the IEEE EMBS, Mexico, 2003, 1066-1069.
- [54] José Antonio Gutiérrez Gnechi, Voltage Controlled Current Source (VCCCS) for Electrical Impedance Tomography (EIT) Measurements in the α and β Dispersion Frequency Ranges, 2010 Electronics, Robotics and Automotive Mechanics Conf., 677-681.
- [55] Bera TK and Nagaraju J, A Multifrequency Constant Current Source Suitable for Electrical Impedance Tomography (EIT), Proceedings of 2010 International Conference on Systems in Medicine and Biology, 2010, India, pp 278-283.
- [56] Engr. Angelito A. Silverio, M.S., Engr. Angelina A. Silverio, M.A., M.S., A High Output Impedance Current Source for Wideband Bioimpedance Spectroscopy Using 0.35 μ m Tsmc Cmos Technology, International Journal of Engineering and Applied Sciences, 2012, December 2012. Vol. 1, No.2. 68-75.
- [57] Malmivuo, J. & Plonsey, R. (1995). Bioelectromagnetism: Principles and Applications of Bioelectric and Biomagnetic Fields, New York, Oxford: Oxford University Press.
- [58] J. G. Webster, Medical Instrumentation: Principle and design, John Wiley & Sons, Hoboken, NJ, USA, 1995
- [59] Romsauerova, A., McEwan, A., Horeh, L., Yerworth, R., Bayford, R. H. & Holder, D. S. (2006). Multi-frequency electrical impedance tomography (EIT) of the adult human head: initial findings in brain tumours, arteriovenous malformations and chronic stroke, development of an analysis method and calibration, Physiol. Meas. 27, S147–S161.
- [60] Soni, N. K., Hartov, A., Kogel, C., Poplack C. S. & Paulsen, K. D. (2004). Multi-frequency electrical impedance tomography of the breast: new clinical results, Physiol. Meas. 25, 301–314.
- [61] Bera TK and Nagaraju J, A Battery Based Multifrequency Electrical Impedance Tomography (BbMf-EIT) System for Impedance, Imaging of Human Anatomy, 15th International Conference on Electrical Bio-Impedance (ICEBI) and 14th Conference on Electrical Impedance Tomography (EIT), Germany, April 22–25, pp 217.
- [62] Wi, H., Kim, T. E., Oh, T. I. & Woo, E. J. (2012). Expandable Multi-frequency EIT System for Clinical Applications, In, Progress In Electromagnetics Research Symposium Proceedings (49-52). KL, MALAYSIA.
- [63] Bera TK and Nagaraju J, A LabVIEW Based Multifunction Multifrequency Electrical Impedance Tomography (MfMf-EIT) Instrumentation for Flexible and Versatile Impedance Imaging, 15th International Conference on Electrical Bio-Impedance (ICEBI) and 14th Conference on Electrical Impedance Tomography (EIT), Germany, April 22–25, 2013, 216.
- [64] Oh, T. I., Koo, H., Lee, K. H., Kim, S. M., Lee, J., Kim, S. W., Seo, J. K. and Woo, E. J. (2008). Validation of a multi-frequency electrical impedance tomography (mfEIT) system KHU Mark1: impedance spectroscopy and time-difference imaging, Physiol. Meas. 29, 295–307.
- [65] Griffiths, H. (1988). A phantom for electrical impedance tomography, Clin. Phys. Physiol. Meas., 9 (Suppl. A), 15-20.
- [66] S. Kaufmann, A. Latif, W. C. Saputra, T. Moray, J. Henschel, U. G. Hofmann, M. Ryschka, Multi-frequency Electrical Impedance Tomography for Intracranial Applications, World Congress on Medical Physics and Biomedical Engineering May 26-31, 2012, Beijing, China, IFMBE Proceedings Volume 39, 2013, pp 961-963.
- [67] Robitaille, N., Guardo, R., Maurice, I., Hartinger, A. E. & Gagnon, H. (2009). A multi-frequency EIT system design based on telecommunication signal processors, Physiol. Meas. 30, S57–S71.
- [68] Kerner, T. E., Williams, D. B., Osterman, K. S., Reiss, F. R., Hartov, A. & Paulsen, K. D. (2000). Electrical impedance imaging at multiple frequencies in phantoms, Physiol. Meas. 21, 67–77.
- [69] Bera TK and Nagaraju J, Electrical Impedance Spectroscopic Study of Broiler Chicken Tissues Suitable for The Development of Practical Phantoms in Multifrequency EIT, Journal of Electrical Bioimpedance, vol. 2, pp. 48–63, 2011. DOI:10.5617/jeb.174
- [70] E. J. Woo, P. Hua, Dr J. G. Webster, W. J. Tompkins, R. Pállás-Areny, Skin impedance measurements using simple and compound electrodes, Medical and Biological Engineering and Computing, January 1992, Volume 30, Issue 1, pp 97-102
- [71] Hua, P., Woo E.J., Webster J.G., Tompkins Willis J., An electrical impedance tomograph using compound electrodes, An electrical impedance tomograph using compound electrodes, Date of Conference: 9-12 Nov 1989, vol.2, Page(s): 472 – 473.
- [72] Ping Hua, Eung Je Woo, John G. Webster, and Willis J. Tompkins, Using Compound Electrodes In Electrical Impedance Tomography, IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING, VOL. 40, NO.1, JANUARY 1993, 29-34.
- [73] B H Cornish, A Jacobs, B J Thomas and L C Ward, Optimizing electrode sites for segmental bioimpedance measurements, Physiol. Meas. 20 (1999) 241–250.
- [74] A. Hinton and B. Sayers. (1998). “Advanced Instrumentation for Bioimpedance Measurements,” Solartron Analytical, Farnborough, U.K., Technical Note. [Online]. Available: <http://www.solartronanalytical.com/downloads/technotes/ap04.pdf>
- [75] Zhang WB, Jeong DM, Lee YH, Lee MS., Measurement of subcutaneous impedance by four-electrode method at acupoints located with single-power alternative current, Am J Chin Med. 2004;32(5):779-88.
- [76] Alberto Yúfera and Adoración Rueda, A Method for Bioimpedance Measure With Four- and Two-Electrode Sensor Systems, 30th Annual International IEEE EMBS Conference, Vancouver, British Columbia, Canada, August 20-24, 2008, pp 2318-2321.
- [77] Padma Batra1 , Sukwinder Singh1, Satyendra Pratap Singh1, A New Method for Measurement of Bioelectrical Impedance, 2011 International Conference on Communication Systems and Network Technologies, pp 740-743.
- [78] Fernando Seoane1,2, Javier Ferreira1, Juan Jos’e Sanch’ez1 and Ramon Brag’os3, An analog front-end enables electrical impedance spectroscopy system on-chip for biomedical applications, Physiol. Meas. 29 (2008) S267–S278 doi:10.1088/0967-3334/29/6/S23.
- [79] A. Kežionis, P. Butvilas, T. Šalkus, S. Kazlauskas, D. Petruionis, T. Žukauskas, E. Kazakevičius, and A. F. Orliukas, Four-electrode impedance spectrometer for investigation of solid ion conductors, Rev. Sci. Instrum. 84, 013902 (2013).
- [80] H Asfour, W Soller, NG Posnack, AE Pollard and MW Kay, Low frequency impedance spectroscopy of cell monolayers using the four-electrode method, Journal of Physics: Conference Series 224 (2010) 012085 doi:10.1088/1742-6596/224/1/012085.