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 filed 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 invers 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 special 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.

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(ω)) 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(ω)) developed is measured across other two-electrodes (called sensing electrodes or voltage electrodes blue electrodes in Fig. 1.

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

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