Electrical Impedance Tomography Image Reconstruction for Adjacent and Opposite Strategy using FEMM and EIDORS Simulation Models

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***Abstract*— Electrical Impedance Tomography is a low resolution, fast and low-cost, medical imaging technique, which is increasingly catching up both in research and application fields. The main concept includes the usage of electrodes to insert current and measure voltages from the object examined in order to reconstruct the conductivity map of its interior. There are many options to achieve that and the number of the electrodes plays an important role. In this paper, simulation models were generated using the FEMM software tool along with MATLAB to characterize the imaging quality results achieved with respect to the measuring strategy and the electrodes' number.**

Keywords*— *Electrical Impedance Tomography, FEMM, MATLAB, forward problem, inverse problem, adjacent strategy, opposite strategy

I. INTRODUCTION

In biomedical sciences many imaging techniques have been developed in order to acquire imaging parts of the body interior and take valuable information about their structure and functionality. The commonly used techniques achieve high resolution and quality rates, however they are characterized by very high costs, radiation exposure to the patients (CT and MRI), lack of mobility (huge hardware equipment), time consuming preparation and low imaging speeds that deter real time visualization.

The aforementioned disadvantages can be eliminated with Electrical Impedance Tomography (EIT). EIT is an alternative method of imaging that uses current injection driving through electrodes at low frequencies. Despite its low spatial resolution and relatively high noise levels caused by biosignals [1], EIT has the great advantage of its low hardware cost, the patient's safety due to very low current amplitudes, complete lack of radiation, as well as high image reconstruction speed.

In EIT, a lot of basic measurement strategies and some hybrids have been developed to optimize the result of the imaging process and minimize the negative effect of the low resolution and SNR produced [1]. Another method to receive additional information is to increase the number of the electrodes, which will result to increased hardware complexity and cost. Nevertheless, to obtain a high quality result, the hardware used has to be combined sufficiently with an effective measuring strategy, as well as with an efficient image reconstruction algorithm.

In the next session, a summary of an EIT's system common architecture is described, together with the measuring protocols commonly used. In section III, a concise description of the reconstruction problem (forward and inverse) is presented. Furthermore, in section IV, the FEMM and MATLAB interfaces developed are described and simulation results are shown and compared for different strategies and electrode numbers for several human-tissue type objects examined. Finally, the conclusion is discussed.

II. SYSTEM DESCRIPTION & MEASUREMENT STRATEGIES

A. Hardware Architecture

The main architecture of an EIT system includes a sinusoidal signal generator (Direct Digital Synthesizer-DDS followed by a Digital-to-Analog Converter DAC) and a voltage to current converter (current source). The current source is connected to electrode pairs through two 1-to-N analog multiplexers. Note that in analog multiplexers are by-directional. Moreover, the voltage signals, which are differentially measured from the other electrodes, are obtained through two N-to-1 analog mutliplexers followed by appropriate filters and an instrumentation amplifier. The signal produced is sampled from an Analog-to-Digital Converter (ADC) and sent to a processor for further processing. The procedure is usually controlled by a Microcontroller Unit (MCU) [1] [2].

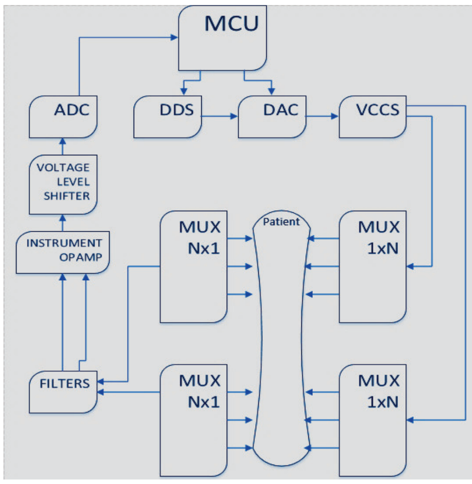

Fig. 1: Block diagram of an EIT system

B. Measurement Patterns

1) Adjacent Pattern:

When the adjacent measurement pattern is used in EIT, the sinusoidal current is applied between a pair of adjacent electrodes and the resulting boundary potential is measured between all other pairs of adjacent electrodes. This is repeated for any possible current electrodes pair, thus as many times as the number of the electrodes used in the system (N). For each current source electrode position, N-3 differential voltage measurements are performed, so a full measurement circle contains N(N-3) measurements, from which only the half are independent. Although this strategy gives the most independent measurements and it is the most commonly used in EIT medical applications, it lacks sensitivity far from the electrodes.

2) Opposite Pattern:

The opposite pattern is characterized by the opposite placement of the current source electrodes. The voltage measurements then can be taken in two ways. The first one is by measuring the voltages between the adjacent electrodes and the second one is measuring between the opposite electrodes (adjacent or opposite stimulation). This result into N(N-3) measurements, in which $\frac{3N^2}{8}-\frac{N}{4}$ of them are independent. The independent measurements, are less than the ones from the adjacent pattern when the number of electrodes is N >5. This strategy has very recently started to be used in medical EIT applications and gains more and more popularity.

3) Cross pattern:

Also called *diagonal pattern*. The Nth electrode is used as a current reference, while the first electrode is used as a voltage reference. Then, current is applied to the second electrode and voltage measurements are performed between the pairs 1-3, 1-4,...,1-(N-1). The process is repeated for applying the current to the fourth, 8^{th} till the N-2th electrode. The number of independent measurements is less than that of the opposite-side strategy. The pattern is very rarely used because of its complexity and low sensitivity near the electrodes [1] [2] [3].

Of course the aforementioned measuring methods have a lot of variants and the electrode numbering can be done clockwise or counter-clockwise either. Furthermore, many other strategies in EIT have been proposed e.g. the trigonometric one, which also has gained popularity. A lot of research has also recently begun to be done in hybrid strategies in order to achieve more valuable information and minimize the imaging errors.

Assuming that a reliable circuitry has been developed, the final image quality is depended on the strategy selected, the number of the electrodes and the reconstruction algorithm. In [2] a 64-electrode adjacent strategy EIT system was proposed and developed in order to receive additional measurements than other traditional EIT systems with 16 or 32 electrodes. However, the challenge is not only to increase the electrode number, but also to exploit the information that could be taken at the most efficient way. Thus, tests need to be done for different measuring patterns and object setups in order to find whether to use each pattern and when it is worth increasing the electrode number (so as the hardware costs and time-processing).

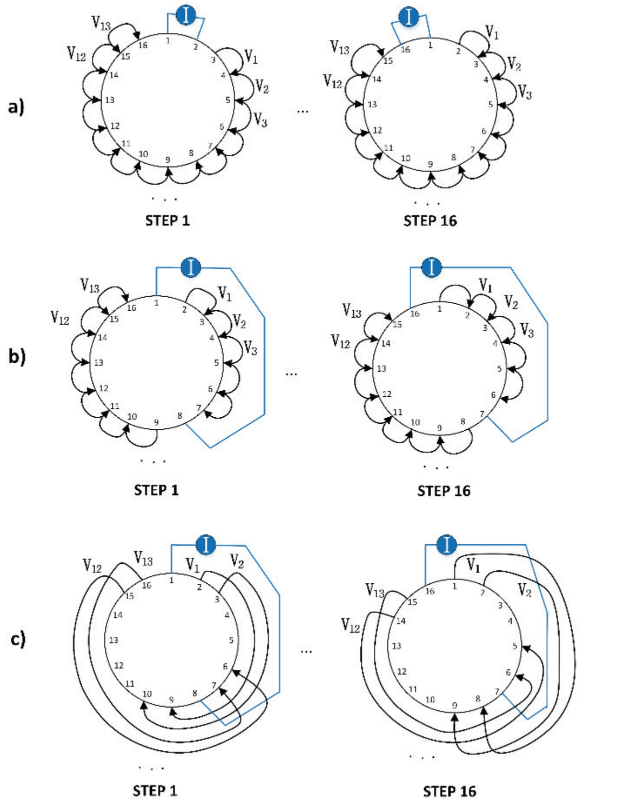

Fig. 2: Measuring protocols: a) adjacent b) opposite with adjacent voltage measurements c) opposite with opposite voltage measurements [3]

III. THE EIT IMAGE RECONSTRUCTION PROBLEM

The elliptic Laplace's equation which describes the EIT's problem is $\vec{\nabla}\left(\sigma\vec{\nabla}V\right)=0$, where σ(**x**) is the conductivity and V(**x**) is the voltage [1] [2] [4]. **x** is a coordinate vector (2-D or 3-D). The boundary conditions are the following:

- $\int_{El}\sigma\frac{\partial V}{\partial n}ds=I_i$, where El is the ith electrode's surface and n the vertical vector to that surface.
- $V_{boundary}+z_i\sigma\frac{\partial V}{\partial n}=V_i$, which means that the voltage measured on the ith electrode is the sum of the electrode's boundary potential and the potential drop across the electrode's contact impedance [4] [5].

That differential equation is non-linear and cannot typically be solved analytically. Voltages and conductivities through this area are unknown. The most common solution is solving the forward model (known conductivities with unknown voltages) and then the inverse problem (known voltages with unknown conductivities). To perform this, an initial conductivity (usually constant-homogeneous model) is defined. After the first area voltage calculation (forward solution), a new conductivity map is calculated (inverse solution). This is repeated until the conditions of convergence are met.

A. *The forward problem*

The forward problem is usually solved with Finite Elements Method (FEM). According to the FEM, the examination area is discretised to a number of canonical shapes (commonly triangles or rectangles), called elements. Each element is defined by some points, called nodes. Every element's potential can be written as a polynomial function $V_e(x,y)$ (assuming two-dimensional area), thus the area's potential is $V(x,y)=\sum_{e=1}^{N} V_e(x,y)$ for each element e. If V_{ei} is the potential on each node i of the element e, the element's potential is written $V_e(x,y)=\sum_{i=1}^{N} a_i(x,y)V_{ei}$, where $a_i(x,y)$ are the shape functions (one on the node i, zero else). Defining a potential Laplacian functional, it is possible to convert the problem to a linear equation system and solve for all the potentials [5] [6].

B. *The inverse problem*

For each voltage solution found and conductivity defined, a Jacobian matrix is first calculated: $J_{i,j}=\frac{\partial V_i}{\partial \sigma_j}$. A conductivity change is then calculated:

$$\delta\sigma=\left(J^T WJ+\lambda^2 Q\right)^{-1}\left(J^T W\Delta V-\lambda^2 Q\Delta\sigma\right)$$ [1] [3] [5],

where W and Q are inverse covariance parameters, λ the hyper-parameter and ΔV (or $\Delta\sigma$) the difference between estimation and measurements. The problem does not have unique solution, but depends on the selection of the appropriate parameters.

IV. SIMULATIONS AND RESULTS

MATLAB code was developed, communicating with the Lua console of the FEMM tool, in order to simulate certain EIT models. A circular geometry was defined with the electrodes attached at the perimeter. The test case area includes a homogeneous material (sea water), and five discrete random conductivity areas. The code takes as inputs the number of the electrodes (16, 32 or 64), the strategy (adjacent of opposite) and the inhomogeneous materials which fill the five corresponding areas. That materials have chosen to behave just as human tissues and are described below [7]:

Table 1: Estimated conductivity and relative permittivity of the materials chosen at 10kHz

Material	Conductivity (S/m)	Relative Permittivity
Lungs	0.1	5000000
Bones	0.03	40000
Heart	0.3	15000000

Those materials were chosen because EIT has a great percentage of application on chest imaging and ventilation function monitoring. The FEMM for the defined geometry, creates the mesh needed to solve the forward problem.

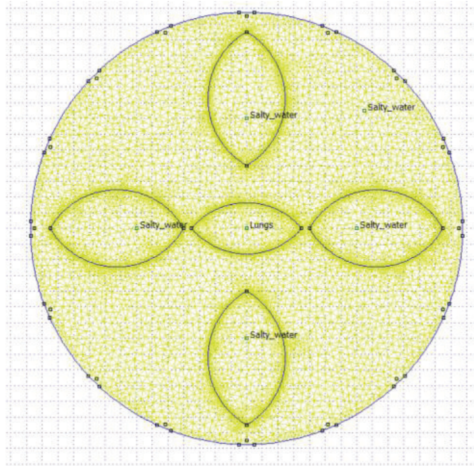

Fig. 3: The geometry mesh created by the FEMM tool (for 16 electrodes)

From the solution of the forward problem the voltage distribution in the examination area for each current injection is available. FEMM then finds the average potential on each electrode surface and returns it to MATLAB, which stores all the measurements in a vector. That measurements represent the expected voltage electrode potentials when the selected objects are inserted in the circular tank. Then, the measurement vectors are used as inputs to the EIDORS tool of MATLAB to reconstruct the conductivity map. The purpose is to examine the quality of imaging for each strategy and number of electrodes, by comparing the reconstructed image with the conductivities set as inputs in the FEMM tool.

Firstly, a bone tissue was defined at the right area segment, while the whole area was defined homogeneous. Measurements were simulated with FEMM for both adjacent and opposite strategies. The resulting voltages were sent to MATLAB for conductivity map reconstruction (EIDORS tool).

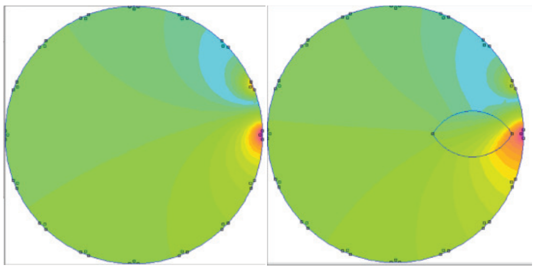

Fig. 4: 1st current pair adjacent voltage distribution simulated by FEMM a) In homogeneous area b) With a bone tissue right. It is observed that inhomogeneity causes local changes in voltage distribution and to the measurements taken.

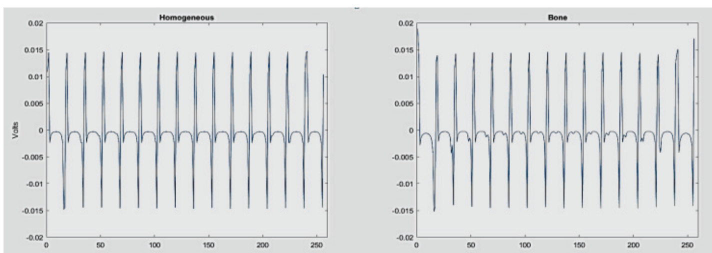

Fig 5: Homogeneous (left) and inhomogeneous (right) adjacent simulation measurements. Current input is 1mA p-p and frequency 10kHz.

Reconstructions for the right-sided bone tissue were made for 16, 32 and 64 electrodes for both strategies (adjacent and opposite with adjacent voltage measuring), shown in Fig. 6. (Red colors represent lower conductivities). It is observed that when using adjacent strategy, increasing the electrodes number, eliminates the reconstruction noises and improves the distinctive ability, whereas when using opposite strategy, the noise eliminates but the shaping and the overall quality is worse and does not improve by using more electrodes. However, the opposite strategy gives more accurate shape of the object.

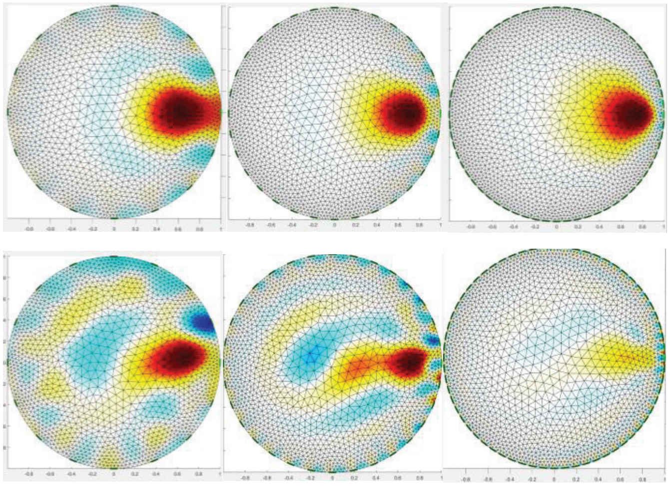

Fig. 6: Conductivity reconstructions with adjacent strategy (up) and opposite strategy (down), using 16, 32 and 64 electrodes (from left to right)

A second comparison test was performed for an elliptic-shaped lung tissue in the center of the area. As above, adjacent and opposite strategy for 16, 32 and 64 electrodes were simulated and reconstructed. The results are shown in Fig. 7. It is observed that although both strategies are capable of detecting the object, they show difficulties reconstructing the shape, size and conductivity in contrast to the homogenous backgrounds. This can be improved with additional number of electrodes. However, it is shown that the opposite strategy has more sensitivity near the center of the area [3]. Finally, it is worthmentioning that high noise reconstruction occurs near the electrodes in both strategies.

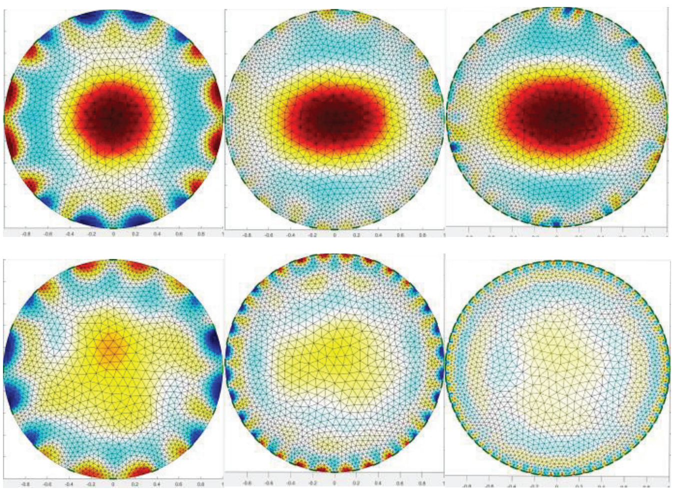

Fig. 7: Conductivity reconstructions with adjacent strategy (up) and opposite strategy (down), using 16, 32 and 64 electrodes (from left to right)

Another aspect that needs to be discussed is the distinctive ability of different objects of adjacent and opposite method (both with adjacent and opposite voltage measuring). To test that, two bone tissues were defined right and down in the examination area. Simulations were performed for 32 electrodes and the results are shown in Fig 8. The images show that both strategies have approximately the same distinctive ability, while in the opposite strategy the object shapes are more approximate. Furthermore, using the opposite pattern with opposite voltage measures causes an undesirable mirror effect to the produced image due to the symmetry of the current-voltage projections.

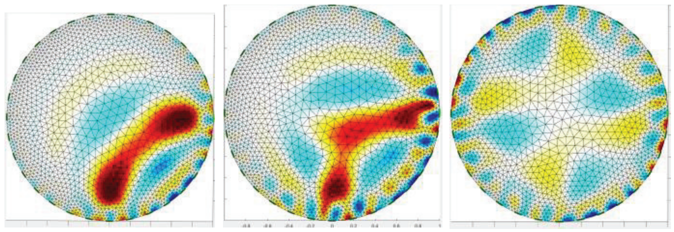

Fig. 8: Conductivity reconstructions of two bone tissues with adjacent strategy (left), opposite strategy with adjacent voltage measuring (center) and opposite strategy with opposite voltage measuring (right), using 32 electrodes

V. CONCLUSIONS

EIT is a tomography technique that could remarkably assist the effort for interior object imaging, as it is relatively cheap and easy to perform. The measuring strategy and the number of electrodes recommended depends on the application. For example, since the adjacent protocol gives better results for objects near the surface, it could be used at skin sensing. However, for very interior objects (heart, lungs, liver), each strategy produces unique information and both of them could be used complementary with at least 32 electrodes, since they do not have enough reliability for 16 electrodes. Using more than one strategies and crossing the information produced is something accessible, because it does not need any changes at hardware. However, more research has to be done in order to find more efficient hybrid methods.

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