# MAGNETIC RESONANCE-CONDUCTIVITY IMAGING USING 0.15 TESLA MRI SCANNER

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*Abstract-* **A novel imaging method for electrical impedance tomography is implemented. In this method, the magnetic flux density generated by current flowing in a 2D slice is measured using MRI scanner and recorded data is used to reconstruct relative conductivity images. The measurements are done from all parts of the imaging region, and therefore sensitivity is space independent. The magnetic flux density is extracted from phase images of the MRI image and a sensitivity based image reconstruction algorithm is used to reconstruct relative conductivity images. The magnetic flux density measured and the conductivity image reconstructed for an insulator object placed in the middle of the imaging region are presented.**

***Keywords* - electrical impedance tomography, magnetic resonance imaging.**

## I. INTRODUCTION

Electrical impedance tomography (EIT) is an imaging modality to reconstruct the conductivity distribution in a volume conductor. It has applications in biomedical engineering such as solution of bioelectric field problems [1], imaging of physiological function [2] and many other [3], where the information of conductivity is necessary. In order to obtain the conductivity map, a current distribution is generated inside the object to be imaged and peripheral voltage measurements are recorded [4]. The technique is classified as injected-current EIT if electrodes placed at the periphery are used for current generation and it is named as induced-current EIT if the current distribution is generated using coils placed around the object. For both cases, since the voltage measurements are made on the surface, the sensitivity of these measurements is not uniform throughout the object. Specifically, sensitivity is less for inner regions then the peripheral regions. Another limitation is the number of peripheral voltages measured. Although increasing the number of independent measurements can increase the resolution, using more electrodes does not increase the resolution without a limit due to theoretical limitations of EIT [5].

An alternative method for conductivity reconstruction is the use of magnetic flux density generated during current injection. It has been shown that the magnetic flux density due to injected currents can be measured using magnetic resonance imaging (MRI) techniques for dc [6,7], radio frequency (RF) [8] and ac [9] frequency ranges. Since the magnetic flux density measurements can also be done from the inner parts of the volume conductor, the sensitivity of measurements to conductivity perturbations is uniform.

The magnetic flux density measurements can either be used solely to form relative conductivity images [10] or combined with peripheral voltage measurements to reconstruct absolute conductivity images [11]. Both of these techniques can be named as magnetic resonance-electrical impedance tomography (MR-EIT). For two-dimensional case, the current flowing in the imaging plane generates a three dimensional magnetic flux density in general. However, on the imaging plane, only the perpendicular component is nonzero. In the first method, for the two-dimensional problem, measuring one component of the magnetic flux density is sufficient to reconstruct the conductivity distribution [10]. However, the absolute conductivity values can not be found. The second method requires the measurement of the magnetic flux density values at points outside the imaging plane, which is non-zero. The rotation of the object to three different orientations is required even for two-dimensional case [6,7]. The advantage of the latter method is the calculation of the absolute (real) conductivity values.

In this study, the relative conductivity imaging technique proposed in [10] is implemented in 0.15 Tesla Middle East Technical University (METU) MRI System. The direction of the main field is taken as z-direction, so the imaging plane is the x-y plane. The z-component of the magnetic flux density generated by currents flowing in x-y plane is measured using the technique described in [12]. The magnetic flux density distribution recorded and the 2D conductivity image reconstructed for an insulator object placed in the middle of the imaging slice are presented.

## II. METHODOLOGY

### A. Forward Problem

Forward problem is defined as the calculation of magnetic flux distribution for a known conductivity distribution and boundary conditions. The forward problem solution will then be used in the formulation of the reconstruction algorithm.

The relation between the conductivity and potential field is given as

$$\nabla \cdot (\sigma \nabla \phi)(x, y) = 0 \qquad (x, y) \in S \tag{1}$$

together with the Neumann boundary conditions

$$\sigma \frac{\partial \phi}{\partial n} = \begin{cases} J & \textit{on positive current electrode} \\ -J & \textit{on positive current electrode} \\ 0 & \textit{elsewhere} \end{cases} \tag{2}$$

where $\sigma$ is the electrical conductivity, $\phi$ is the electrical potential and $S$ is the slice of the object to be imaged. Once the potential distribution inside the object is found by solving the above boundary value problem, the electric field and the current density are found using

$$\vec{E} = -\nabla\phi \tag{3}$$

and

$$\vec{J} = \sigma\vec{E}\ . \tag{4}$$

respectively. Finally, the magnetic flux density is calculated by the Biot-Savart relation as

$$\vec{B} = \frac{\mu_0}{4\pi}\int_S \frac{\vec{I}\times\vec{R}}{R^3}ds\ . \tag{5}$$

where $\mu_0$ is the permeability of free space and the vector $\vec{R}$ is defined from source point $(x',y',z')$ to the field point $(x,y,z)$.

### B. *Inverse Problem*

In the previous section, forward problem of finding magnetic flux density given a conductivity distribution and boundary conditions was stated. In this part, the inverse problem is defined as the calculation of conductivity distribution using magnetic flux density measurements.

The relation between conductivity and magnetic field generated by the internal distribution of current is non-linear. Due to this non-linearity, either iterative techniques should be used or linearization around some initial value should be applied. In this study, the second alternative is used. A linear relation between conductivity perturbations and magnetic field perturbations is derived using the forward problem solution.

Analytical solution to forward problem (FP) does not exist for complex conductivity distributions, therefore, a numerical technique must be applied. Finite Element Method (FEM) is used to calculate the electric potential and corresponding magnetic flux density distribution for a given conductivity distribution and boundary conditions. A FEM mesh for the 2D rectangular phantom in Fig 1 with 875 nodes and 1632 first order triangular elements is used. The conductivity is assumed to be constant within each element.

A linear matrix equation between the change in conductivity and the change in magnetic flux density is obtained using linearization and FEM as:

$$\Delta\mathbf{b} = \mathbf{S}\Delta\sigma \tag{6}$$

where $\Delta\mathbf{b}$ is the vector containing magnetic flux density values at measurement points, $\Delta\sigma$ is the vector containing conductivity perturbation in each element and $\mathbf{S}$ is the mapping between these two quantities and is called the *sensitivity matrix*. Once the sensitivity matrix is found, the conductivity perturbation distribution can be obtained for a given magnetic flux densiy measurement by matrix inversion and multiplication. The sensitivity matrix is not square in general and is singular for most cases. Therefore, generalized matrix inverse (or *pseudo-inverse*) of $\mathbf{S}$ is used. Singular Value Decomposition (SVD) is used to find the pseudo-inverse, $\mathbf{S}^+$. Using SVD, the sensitivity matrix is decomposed as

$$\mathbf{S} = \mathbf{U}\Lambda\mathbf{V}^\mathbf{T} \tag{7}$$

where $\mathbf{U}$ and $\mathbf{V}$ are two orthonormal matrices whose columns are left and right singular vectors respectively and $\mathbf{\Lambda}$ is a diagonal matrix with entries $\lambda_i$ being the $i^{th}$ singular value. Using generalized inverse, (6) can be rewritten as

$$\Delta\mathbf{b} = \mathbf{U}\Lambda\mathbf{V}^T\Delta\boldsymbol{\sigma} \tag{8}$$

Since $\mathbf{U}$ and $\mathbf{V}$ are orthonormal matrices, their inverses are their transposes and the inverse of the diagonal matrix $\Lambda$ is obtained by replacing $\lambda_i$ with $1/\lambda_i$. The conductivity perturbation is then obtained as

$$\Delta\sigma = \mathbf{V}\Lambda^{-1}\mathbf{U}^\mathbf{T}\Delta\mathbf{b} \tag{9}$$

This matrix equation can be written in summation form as:

$$\Delta\sigma = \sum_{i=1}^{r}\lambda_i^{-1}\mathbf{v}_i\mathbf{u}_i^T\mathbf{b} \tag{10}$$

where $\mathbf{u}_i$ and $\mathbf{v}_i$ are the columns of matrices $\mathbf{U}$ and $\mathbf{V}$ and they can also be called as measurement and image basis vectors respectively. In this summation, if some $\lambda_i$ are very close to zero, $\lambda_i^{-1}$ will grow drastically and cause errors in the reconstructed image. In order to avoid this, singular vectors corresponding to small singular values are not included in image reconstruction. The optimum number of basis to be included depends on the object and the noise level.

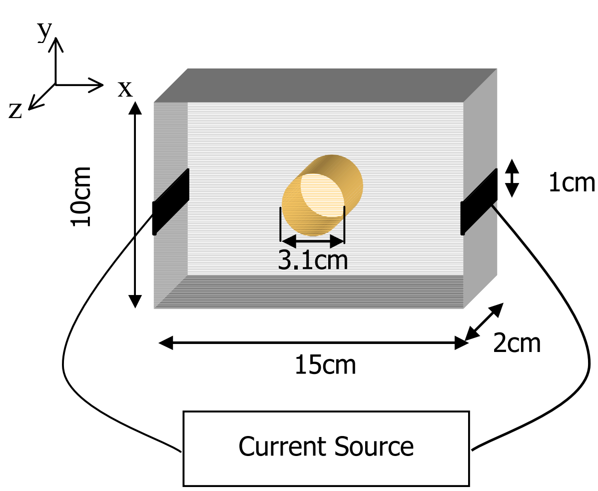



Figure 1 Definitions for the phantom and the coordinate system

## III. Experimental Setup

The magnetic flux density is measured using magnetic resonance imaging techniques as used in current density imaging [12]. A spin echo pulse sequence is applied together with a bipolar DC current pulse [13]. The current source is voltage controlled and the triggering pulses are generated synchronous with the pulse sequence. An additional phase term is introduced in the MRI image when current is applied. The magnetic flux density is extracted from phase images by taking the ratio of MRI image with current to the MRI image without current. The details of data acquisition can be found in [13].

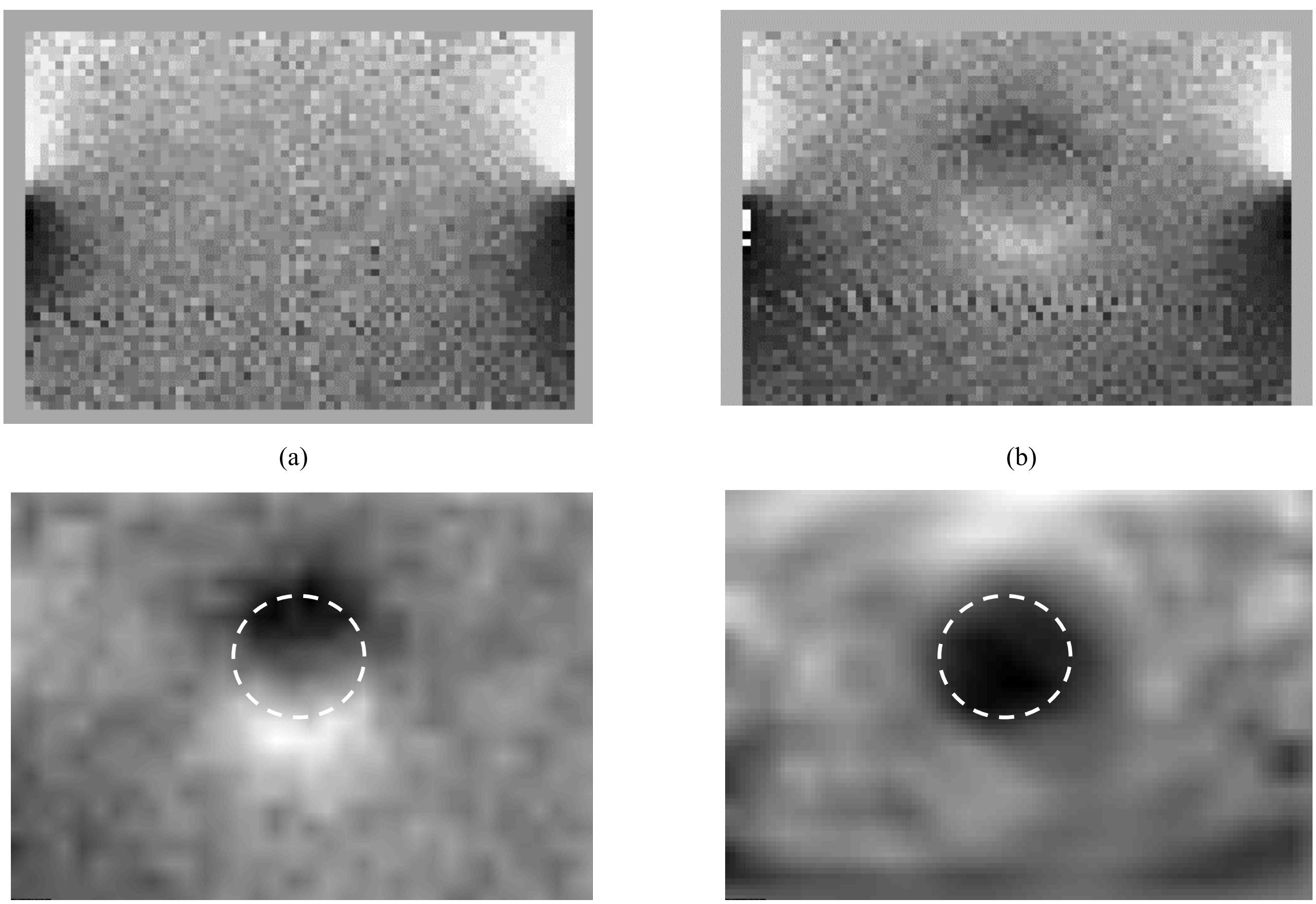
The experimental phantom is given in Fig 1. The depth of the rectangular phantom is 2cm and the current is assumed to flow in x-y direction only. The circular shell-object with negligible shell thickness is placed in the middle of the imaging region. The center of the object is at (0mm, 4mm) where the center of the phantom is defined as origin. The object is made of a plastic insulator, and therefore, no current exists in the inner region. The inner part of the object is filled with phantom solution so that MR signal can be recorded.

## IV. Results

Four MR images are recorded successively to obtain the change in the magnetic flux density distribution when the object is placed in the imaging region. These images can be listed as:

*Data 1*: no object, no current
*Data 2*: no object, current applied
*Data 3*: object placed, no current
*Data 4*: object placed, current applied

The magnetic flux density when there is no object is calculated by taking the ratio of Data 2 to Data 1. In order words, the difference of phase images for two cases is obtained. If there exists any phase wrap in the difference phase images, they are unwrapped using a model based phase unwrapping algorithm [14].



(a) (b) (c) (d)

Figure 2 (a) Magnetic flux density when there is no object. (b) Magnetic flux density when circular insulator shell is placed in the middle of the imaging region. (c) Difference in magnetic flux density when object is placed. (d) Reconstructed conductivity perturbation when 155 image basis functions are used. In the color-scale, black corresponds to insulator and white corresponds to conductor.

The magnetic flux density for no-object case is given in Fig. 2(a). Similarly, taking the ratio of Data 4 to Data 3 and applying the phase unwrapping algorithm, the magnetic flux density with the insulator perturbation is found (Fig. 2(b)). The difference of images in Fig 2(b) and Fig 2(a) is then obtained (Fig. 2(c)) because the proposed algorithm uses the change in magnetic flux density. Finally, using the inverse sensitivity matrix, the conductivity perturbation that generates the recorded magnetic flux perturbation is calculated (Fig 2(d)). In the image reconstruction, 155 basis functions are used. Magnetic flux data close to electrodes are not included in the image reconstruction.

## V. Discussion

In this study, a novel imaging method, MR-EIT is implemented using a low field MRI scanner. Relative conductivity images are reconstructed using a sensitivity based image reconstruction algorithm. The results show that it is possible to reconstruct conductivity images with higher resolution compared to conventional EIT methods. Since magnetic flux density measurements are done from the entire object, the sensitivity of measurements is equal throughout the imaging region. Magnetic flux density in the finite elements just near the electrodes is very high. These values are excluded in image reconstruction since the linearization assumption is not valid for these regions.

The proposed algorithm generates 2D relative conductivity images using only one component of the magnetic flux density measurements. Absolute conductivity values can not be reconstructed using the magnetic flux density measurement only. However, it is possible to reconstruct absolute conductivity images using peripheral voltage measurements together with the magnetic flux density measurements. The method described in [11] uses magnetic flux density in all three dimensions as well as peripheral voltage measurements as a means for further improvement Using MRI, only one component of the magnetic field can be measured at a time; therefore, the object needs to be rotated for this method. Current studies involve the improvement of the relative conductivity images and the implementation of the absolute conductivity imaging method.

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