A DUAL MODALITY SYSTEM FOR HIGH RESOLUTION - TRUE CONDUCTIVITY IMAGING

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Abstract. In this study, a dual modality imaging system which utilises the magnetic flux density measurements, acquired using Magnetic Resonance Current Density Imaging (MRCDI) techniques, and the surface potential measurements, obtained from conventional Electrical Impedance Tomography (EIT) techniques, to reconstruct high resolution absolute conductivity images. An iterative algorithm is developed to minimise the difference between the current densities calculated based on the potential and the magnetic field measurements. The proposed technique is tested on simulated data with/without noise. The conductivity error is approximately 5% with noise free data and 13% when 10% noise is added to the measurements. The spatial resolution is limited by the worst of the finite element size or half the MRI resolution.

1. INTRODUCTION

Electrical properties of biological tissues vary between different tissues and with the physiological status of the same tissue type. Conventional Electrical Impedance Tomography (EIT) has been developed to make use of this property of the tissues. In EIT, body surface electrical measurements are used to reconstruct images of conductivity distribution inside (Boone et al 1997). Quantitative accuracy of the reconstructed EIT images is poor and space dependent since the sensitivity of the surface measurements to internal conductivity changes is poor and space dependent. Spatial resolution of EIT is worse than 10% of the array diameter and position dependent since the current density is a function of conductivity distribution and position in the body. These drawbacks of conventional EIT technique limit its usage when high accuracy and resolution is required, despite EIT's advantages such as good soft tissue contrast, portability and non-invasiveness. One should also note that, the *in-vivo* tissue conductivity distribution can be imaged with no other conventional imaging modalities. The need for accurate knowledge of electrical properties of tissues in analysis of bioelectric field problems is well known (Ferree et al 2000).

Within the last decade, Magnetic Resonance Current Density Imaging (MRCDI) has been proposed to image current density and magnetic flux density generated by externally applied currents to a volume conductor (Scoot et al 1991, Eyuboglu et al 1998). In this new modality, MRI techniques are employed to measure the magnetic flux density hence the current density at dc and RF frequency (Scoot et al 1995). Using MRCDI, the magnetic flux density and the current density can be imaged with a spatial resolution equal to the MRI resolution and half the MRI resolution, respectively (Eyuboglu et al 1998). Since the MRI main magnetic field and the RF field are highly homogeneous inside the sample the magnetic flux density and the current density can be imaged with almost equal sensitivity throughout the sample. Another technique to measure magnetic fields generated by low frequency ac (less than 100Hz) currents has been proposed by Ider and Muftuler (1997) however the spatial resolution of this technique is poor due practical limitations such as long data acquisition time.

A sensitivity based algorithm to reconstruct conductivity images using the measurements of magnetic flux density has been developed by Ider and Birgul (1998). Their algorithm reconstructs images of changes in conductivity with respect to a reference distribution not the absolute (true) conductivity.

Magnetic Resonance – Electrical Impedance Tomography (MR-EIT) technique reconstructs electrical conductivity distribution, combining peripheral potential measurements from EIT and magnetic flux density measurements from MRCDI to reconstruct accurate absolute conductivity values with high resolution (Birgul et al 1999, Eyuboglu et al 2000). In this paper, a dual modality imaging system MR-EIT is described. The proposed technique was tested on simulated data with and without noise and it has been shown that absolute conductivity images can be reconstructed with high resolution.

2. MR-EIT TECHNIQUE

An iterative algorithm is developed to reconstruct the conductivity distribution, minimising the difference between the current density distributions, calculated based on the surface potential measurements and the magnetic flux density measurements.

2.1 Surface Potential Measurements Using EIT Techniques

An EIT set up with 16 electrodes is used. The probing current is applied between opposite pairs of electrodes. Developed potentials are measured on the body surface at all electrodes except the current injecting electrodes. This process is repeated until all opposite pairs of electrodes are activated for current injection. This results in total number of 104 surface potential measurements. In addition to the potential measurements, magnetic flux density inside the body is measured using MRCDI techniques for each current drive configuration, as summarised in the following section.

2.2 Magnetic Flux Density Measurements using MRCDI Techniques

Static electric current applied to a conductor generates a constant magnetic field. The component of the magnetic flux density parallel to the main magnetic field accumulates a phase term in the echo signal during a spin-echo imaging protocol (Eyuboglu et al 1998),

$$S = \int_x \int_y K(x,y) M(x,y) \exp\left\{ j\gamma \left[G_x x t + G_y y t_y + \vec{B}_j T_c \right] \right\} dx dy \qquad (1)$$

where, *K(x,y)* represents the inhomogeneities in the imaging magnetic field, *M(x,y)* is the transverse magnetisation, G_x and G_y are the magnetic field gradients applied along *x* and *y* axis respectively, *t* and t_y are the duration of these gradients, γ is the gyromagnetic ratio, $\vec{B}_j$ is the component of the current-induced-magnetic-flux-density parallel to the main imaging field and T_c is the duration of the current pulse. In order to extract the phase introduced by $\vec{B}_j$, the phase image acquired with a current pulse is normalised by the phase image acquired without a current pulse. Then the phase component caused by the current injection can be expressed as:

$$\Phi_{jn} = \gamma B_j(x,y) T_c \qquad (2).$$

$\vec{B}_j$ can be calculated based on equation (2). Current density is related to the magnetic flux density by Biot-Savart law: $\vec{J} = \mu_o^{-1}(\nabla \times \vec{B})$ (3).

In order to calculate the current density in one direction, the components of the flux density in two orthogonal directions, perpendicular to the direction of the current density are needed. To determine components of the current density in all directions, components of the magnetic flux density in three directions are required. This is achieved by repeating the MR imaging sequence three times. The details of MRCDI techniques used in this study can be found in Eyuboglu et al (1998).

2.3 MR-EIT Image Reconstruction Algorithm

Image reconstruction algorithm is an iterative algorithm, which uses a Finite Element (FE) grid composed of 1089 nodes and 2048 triangular elements, during the forward problem solution. MRCDI measurements are employed to acquire the magnetic flux anywhere in the object. Based on the flux density information, $\nabla\times\vec{B}$ and the current density $\vec{J}_{MR}$ are calculated throughout the object (Eyuboglu et al 1998). Iterations start with an initial conductivity distribution and the forward problem is solved to calculate the node potentials of the FE grid by using the measured surface potentials and known probing currents. Based on the potentials at all nodes and the estimated conductivity, the potential gradient and the current density distribution are calculated. In the third step of the algorithm, a new conductivity distribution is estimated to minimise the error between the current density estimates calculated based on the potential measurements and the magnetic filed measurements. The error function to be minimised is defined as,

$$R=\sum_{N}\int_{S}\left\|\vec{J}_{EIT}-\vec{J}_{MR}\right\|dS=\sum_{N}\sum_{j}\int_{S_j}\left\|-\sigma_j\nabla\phi_{EIT}-\vec{J}_{MR}\right\|dS \qquad (4)$$

where N is the number of independent current injection patterns, j is the number of elements in the FE model. Subscripts *EIT* and *MR* stand for values calculated based on EIT and MRCDI measurements, respectively. The new estimate of the j^{th} element's conductivity is obtained as:

$$\sigma_j=-\frac{1}{\mu_o}\left(\sum_{N}\int_{s_j}\nabla\phi\cdot\nabla\times B\ dS\Big/\sum_{N}\int_{s_j}\nabla\phi\cdot\nabla\phi\ dS\right) \qquad (5)$$

Second and third steps of the algorithm are repeated, replacing the initial conductivity estimate with the calculated conductivity estimate of the previous iteration. The convergence behavior of the algorithm is given in Eyuboglu et al (2000).

3. RESULTS

The performance of the proposed technique is tested using simulated potential and magnetic flux density measurements with and without noise. A high contrast point object is used to test the spatial resolution and accuracy of the technique for a concentric and an eccentric inhomogeneity. The object diameter is 1/16 of the electrode array diameter and the conductivities of the object and the background are 0.004S/cm and 0.002S/cm, respectively. Random noise with a uniform distribution and a maximum value equal to 5%, 10% and 20% of the maximum value of the measurements is added to the measurements to test the noise performance. Error in the reconstructed conductivity and the calculated surface potentials for the reconstructed conductivity are calculated as $e_\sigma=\sqrt{1/M\left(\sum_{j=1}^{M}\left(\sigma_{jr}-\sigma_{jc}\right)^2/\sigma_{jr}^2\right)}\times 100$ and $e_\phi=\sum_N\left(\left\|\phi_m-\phi_c\right\|/\left\|\phi_m\right\|\right)\times 100$, respectively. Where M is the total number of elements in the FE mesh, subscripts j, r, c, m represent the j^{th} element, true, calculated and measured values, respectively. Table 1 shows these errors for both conductivity distributions at different noise levels.

Noise level	e_σ (%) concentric	e_ϕ (%) concentric	e_σ (%) eccentric	e_ϕ (%) eccentric
Noise-free	5.4	8.4	5.3	9.6
5%	9.6	10.5	9.6	11.4
10%	13.3	16.7	13.2	17.1
20%	20.7	30.3	20.7	30.7

Table 1. Error values in reconstructed images for the concentric and the eccentric point objects.

The error in surface potentials is larger than the error in conductivity. This is due to the fact that, a small error in conductivity close to the surface result in a higher error in surface potentials. Figure 1 shows the image reconstructed for the concentric and the eccentric object with 10% noise after 10 iterations and the profiles through the centre of the object along the horizantal direction. The full-width-at-half-maximum (FWHM) values for both inhomogeneity cases are equal to the size of a pixel.

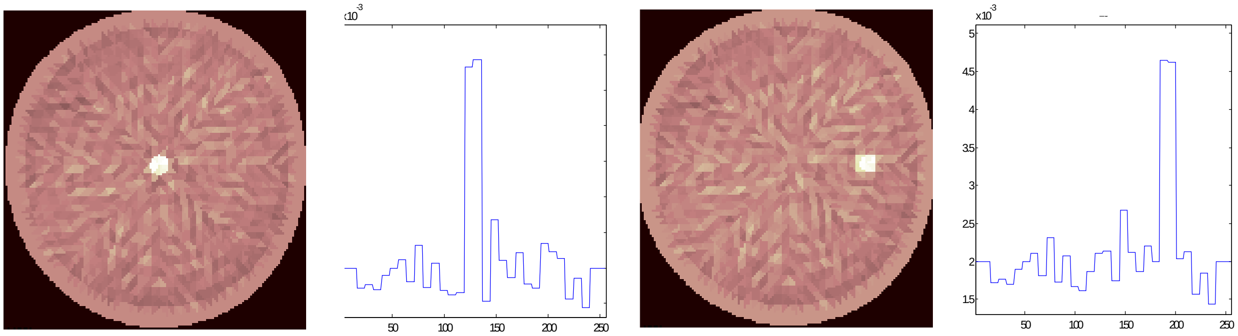

Figure 1: Reconstructed images (the point object appears as a white spot) and the profiles through the object centre along the horizantal direction for the concentric and the eccentric inhomogeneities.

4. CONCLUSION

In this paper, a dual modality imaging system combining conventional EIT measurements with MRCDI measurements to reconstruct accurate, absolute and high resolution, conductivity images is presented. The conductivity estimates and the FWHM values for small objects, placed at different locations, show that the sensitivity and the spatial resolution of the technique is independent of position. For the point objects, absolute conductivities can be reconstructed with at most 10 to 15 % error and the spatial resolution is limited by the worst of the finite element size or half the MRI resolution. The technique is also tested for a more complex thorax phantom and similar results are obtained. These results will be presented at the conference. Further work is underway for practical realisation and extension of the technique for 3-dimesional imaging.

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