A new approach to Current Density Impedance Imaging

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Abstract—Current density impedance imaging (CDII) is a new impedance imaging technique that utilizes current density vector measurements made using magnetic resonance imager (MRI). CDII provides a simple mathematical expression for the gradient of the logarithm of conductivity, ∇ln(σ), at each point in a region where two current density vectors has been measured. From the images of the gradient of the logarithm of conductivity, ln(σ) can be reconstructed through integration and of σ by a priori knowledge of the conductivity at a single point in the object. The CDII technique was tested on a conductivity phantom made from tissue mimicking gel. The results showed accurate reconstruction of the gel conductivity from two current density measurements. This study, for the first time, has demonstrated a local reconstruction technique to calculate sample conductivity inside the phantom non-invasively.

I. INTRODUCTION

Imaging tissue conductivity has long been the goal of Electrical Impedance Tomography (EIT). Previous EIT methods generally used only boundary voltage and current measurement to create a conductive image. Due to the ill-posedness of the EIT problem, there are limitations to EIT resolutions deep inside the sample away from the boundary. Recently, a new magnetic resonance Electrical Impedance Tomography (MREIT) method, based on Current Density Imaging (CDI) [1], has been proposed to overcome the ill-posedness of EIT [2]. The proposal method solves nonlinear boundary value problem, however, the iterative solution to this problem is computationally intensive and requires measurement of current density (CD) at all points inside and on the boundary. In practice, CD cannot be obtained in all places within the body (in the lung for example) or near severe susceptibility artifacts. This paper presents a new approach to impedance imaging that utilizes a simple explicit mathematical formula to produce the logarithm of conductivity. CDII employs two independent current densities, $J_1$ and $J_2$, in a region of interest in an isotropic conductive material. This new approach, therefore, does not require an iterative solution or a global knowledge of CD or its concomitant magnetic field except in the region of interest.

II. THEORY

CDII operates on two independent current density vector measurements acquired using different current electrode arrangements on the object surface ($J_1$ and $J_2$). The following expression for the conductivity can be derived from the steady state approximations of Maxwell’s equations:

$$\nabla \ln(\sigma(x,y,z)) = \left(\frac{1}{M^2}\right) \{ \nabla \times J_2 \cdot M \nabla \times J_1 - (\nabla \times J_1 \cdot M) J_2 + (\nabla \times J_1) M \}$$ (1)

Where, $\sigma(x,y,z)$ is the conductivity of the sample and the vector $M = J_1 \times J_2$ is assumed not to equal to zero at the point $(x,y,z)$. Note that $J_1$, $J_2$, and $M = J_1 \times J_2$ form a basis if $J_1$ and $J_2$ are not parallel.

This expression $\nabla \ln(\sigma(x,y,z))$ can be integrated from any starting point to provide relative conductivity, $\ln(\sigma(x,y,z))$, at any point within the region of interest.

III. METHOD

In addition to a mathematical scrutiny, CDII was tested on a rectangular phantom filled with tissue mimicking gel made from agar, animal hide and water (Figure 1) [3]. This gel was made conductive by adding NaCl to match typical saline concentration (0.9% by weight). The gel was then allowed to cross-link for approximately 24 hours. After the complete cross-linking, the gel was removed from the plastic container (cube in shape) and cut into three equal thickness slabs. In the middle slab, two voids of differing shapes were introduced by cutting out a part of the slab (Figure 2). These slabs were then put back together into the plastic container with saline filling the voids. Same concentration of NaCl was used for both the gel and the saline, to prevent the diffusion of Na⁺ or Cl⁻ molecules. A four-electrode direct impedance measurement using HP 4285A LCR meter (Palo Alto, CA) showed the conductivity of the saline 50% higher than that of the gel (both contains the same amount of NaCl). After the phantom was reassembled with gel slabs, four coin-shaped copper electrodes (12.2 mm in dia.) were placed over the top of the gel for the current delivery during CDI. An o-ring sealed top plate was used to prevent water leakage and evaporation.
Figure 1 A rectangular plastic phantom containing tissue mimicking gel (100mm x 100mm x 80mm). Four circular copper plate electrodes (12.2mm in dia.) were positioned near the corner of the gel for the current application. The electrodes were compressed against the gel to ensure good contact. Once closed, the phantom remained watertight to prevent evaporation and leakage.

Figure 2 A photograph of the two voids cut out of the middle gel slab. These voids were eventually filled with saline to create regions with 50% higher conductivity. A white bar indicates 10mm in size.

For the current density vector measurement, two opposing electrodes were used to apply the current to the gel. The phantom was then placed inside GE Signa® 1.5T magnetic resonance imager for the current density vector measurements. A standard low frequency current density imaging (LFCDI) sequence was employed to measure two current density vector distributions, \( J_1 \) and \( J_2 \) (1.9 mm cubic voxel, TR=3600ms, TE=50ms, Tc=34ms, 2 averages) [1]. Each measurement took approximately 19 minutes to complete.

Using \( J_1 \) and \( J_2 \), \( \nabla \ln(\sigma) \) was calculated using the equation 1. All processing was done in Matlab® software and MayaVI® software was used to visualize and perform streamline analysis of the data [4]. The resulting \( \nabla \ln(\sigma) \) data was then integrated to provide the relative conductivity distribution. In order to avoid integrating over noisy areas of the image, a quality-guided integration method was employed using \([J_1 \times J_2]\) as a predefined quality map [5].

IV. RESULTS

The MR magnitude data (measuring the proton density) provided structural information to visualize the gel and the voids in the middle (Figure 3). The areas filled with saline (marked by * in Figure 3) were clearly identified by the stronger MR signal. The streamline analysis of the current density data revealed current pathways between each set of electrodes (Figure 4). As expected, current density magnitude was the highest near the electrodes and quickly decreased in a radial fashion (290 A/m² max).

Figure 3 An MR magnitude image of the phantom in the middle gel slab. The two areas filled with saline (marked with *) displayed higher proton density due to the higher water content.
Figure 4 A visualization of current flow thorough the phantom using streamline analysis. The two sets of streamlines indicate some of the current flowing between two opposing electrodes. The green intersecting plane indicates the approximate location of the saline filled voids within the phantom.

The calculated $\nabla \ln(\sigma)$ data showed high magnitude near the edges of the voids (Figure 5). Despite the noisy areas near the corner, the rest of the image displayed low values throughout. The $\nabla \ln(\sigma)$ inside the void (filled with saline) showed same value as the gels surrounding the void. Width of the high magnitude areas varied from 3.8mm to 9.5mm and showed up to 6 times higher magnitude than the surrounding areas.

Figure 5 $\nabla \ln(\sigma)$ data generated by CDII processing (equation 1). There is a clear outline of inner boundary of the saline filled voids. The conductivity transition areas are indicated by higher magnitude.

Integrated sigma values showed roughly 50% higher conductivity inside the saline area than the surrounding gel (Figure 6). The outlines of the voids were no longer clear but displayed blurred appearance.

Figure 6 Relative conductivity map obtained through integration. The $\nabla \ln(\sigma)$ shown in Figure 5 was integrated using quality-guided approach. Note the blurred edges of the saline filled voids.

IV. DISCUSSION

The $\nabla \ln(\sigma)$ data clearly indicates CDII’s ability to identify areas of changing conductivity. As expected, areas with homogeneous conductivity exhibited no $\nabla \ln(\sigma)$ signals. There was blooming of high $\nabla \ln(\sigma)$ areas near the boundary of saline filled voids, which could be attributed to the swelling of agar gel. As the agar gel absorbs water, the conductivity of material will increase due to the increasing percentage of saline in the volume (Less densely occupied by agar). The integrated data showed high conductivity regions (saline filled voids) with an accurate relative conductivity values. The blooming observed in $\nabla \ln(\sigma)$ data was also observed in the integrated images as a gradual transition of conductivity from one area to the other.

Unlike other electrical impedance tomography (EIT) approaches, CDII does not suffer from loss of spatial resolution deep within the sample. CDII only requires current density vector information at each point within the sample to calculate conductivity and, therefore, does not depend on information from the neighboring regions. This implementation of CDII, however, assumes isotropic conductivity of the sample and requires two current density vectors $J_1$ and $J_2$ to be non-parallel. The on-going research is focused on expanding CDII technique to overcome these limitations.
V. CONCLUSION

CDII, for the first time, demonstrated an impedance imaging method to non-invasively measure conductivity values within the sample accurately.

V. ACKNOWLEDGEMENT

Authors would like to acknowledge Franz Schuh for machining work and Tim DeMonte for assistance with imaging.

REFERENCES