MEASUREMENT OF ELECTRIC CURRENT DENSITY WITH MAGNETIC RESONANCE IMAGING

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Introduction

Results of a Magnetic Resonance Imaging (MRI) study to image uniform and non-uniform electric current density are presented in this abstract. Current density in a volume conductor, containing magnetic resonance active nuclei, can be imaged using MRI [1,2]. A standard spin echo pulse sequence is used, simultaneously with a bipolar current pulse. The flux density, parallel to the main imaging field, generated by the current pulse is encoded in the phase of the complex MR image. The spatial distribution of magnetic flux density can therefore be extracted from the phase image. Current density is calculated from the magnetic flux density.

Experimental Set-up

This study is performed on an Oxford 2.0 Tesla magnet interfaced to a custom built MR spectrometer. Cylindrical phantoms with different internal geometry filled with 9g/lt NaCl, 1g/lt $CuSO_4 \cdot 5H_2O$ solution in water, are used in the experiments. Two 19mm diameter copper disc electrodes are placed at both ends of cylindrical phantoms. The electrodes are soldered to silver coated BNC connectors to maintain the electrical connection to shielded cables which are used to deliver current pulses. The imaging sequence is a standard spin echo MRI sequence with an addition of a bipolar current pulse, following the slice selective 90^o pulse. The polarity of the current pulse is reversed in synchrony with the application of the 180^o pulse so that the phase shift produced is not cancelled out by the 180^o pulse. The pulse repetition time is 1 second and the echo time is 105 milliseconds. The duration of the bipolar current pulse is 63.5 milliseconds. Amplitude of the current pulses range between 0 to 30mA.

Measurement of externally applied current density by magnetic resonance

Assuming a noise free data and neglecting the geometric distortions, a standard complex MR image can be expressed as

$$M_c = M(x,y)\exp[j\gamma B_0(x,y)t] \qquad (1)$$

where, M(x,y) is the continuous real transverse magnetization, γ is the gyro-magnetic constant, $\vec{B}_o$ is the magnetic flux density of the main imaging field and t is the time.

Static electric current applied to a conductor generates a constant magnetic field with flux density $\vec{B}$. If the current carrying conductor contains MR active nuclei, the component of the magnetic flux density parallel to the main magnetic field accumulates a phase term in the spin echo signal. The complex image is given by,

$$M_c = M(x,y)\exp\{j\gamma[B_0(x,y)t + B_j(x,y)T_c]\} \qquad (2)$$

Where, $\vec{B}_j$ is the component of $\vec{B}$ parallel to the main imaging field $\vec{B}_o$ and T_c is the duration of the bipolar current pulse. Any phase inhomogeneities need to be eliminated to make the phase image represent only the phase initiated by the current flow. In order to achieve this, the phase image acquired with a current pulse is normalized by the phase image acquired without a current pulse ,

$$\frac{\exp\{j\gamma[B_0(x,y)t + B_j(x,y)T_c]\}}{\exp[j\gamma B_0(x,y)t]} \qquad (3).$$

Phase wraps are removed from the normalized phase image by phase unwrapping. The phase component caused by the magnetic field $\vec{B}_j$ is

$$\Phi_{jn} = \gamma B_j(x,y)T_c \qquad (4).$$

The magnetic flux density $\vec{B}_j$ can be calculated using equation (4).

Current density is related to the magnetic flux density by $\vec{J} = \mu_0^{-1}(\nabla \times \vec{B})$. In order to calculate the current density in one direction, the components of the flux density in two orthogonal directions in the plane perpendicular to the direction of the current density are needed. To determine components of the current density in three orthogonal directions, components of the magnetic flux density in all three directions are required. This is achieved by repeating the sequence three times and each time aligning one of the three orthogonal axis of the object with the main imaging field.

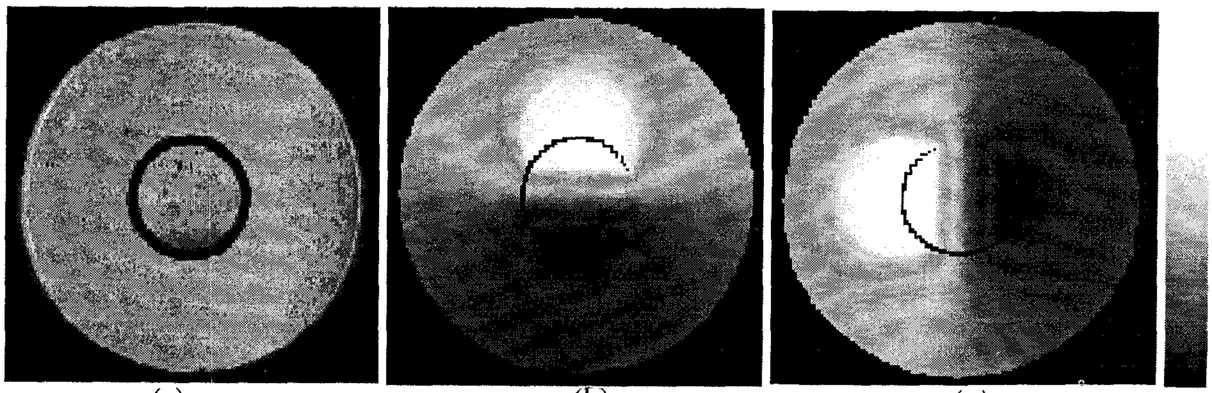
(a) (b) (c)

Figure-1 **(a)** Magnitude image of an xy-plane cross-section of the concentric cylindrical phantom. Component of the magnetic flux density, initiated by a current flow along the z-axis of the inner tube, **(b)** in x-direction and **(c)** in y-direction.

In Figure-1 (a), an MR image of a phantom is given. This phantom consists of two concentric cylinders. Both cylinders are filled with the same saline solution and the internal and external cylinder are electrically isolated. Current is applied, along the z-axis to the inner cylinder. Images in Figure-1 belong to an xy-plane slice, midway along the z-axis. Figure-1 (b) and (c) are the images of $\vec{B}_x$ and $\vec{B}_y$ measured using MRI. To determine the component of the current density in the z-direction (J_z) in the xy-plane, flux density components $\vec{B}_x$ and $\vec{B}_y$ should be differentiated along y and x directions respectively and scaled by $1/\mu_o$

$$\vec{J}_z = \left[\frac{\partial \vec{B}_y}{\partial x} - \frac{\partial \vec{B}_x}{\partial y}\right]\frac{1}{\mu_o}. \tag{5}$$

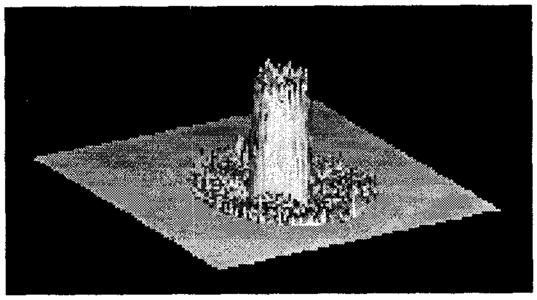

Figure-2 Current density distribution in the xy-plane of the phantom, measured by MRCDI.

These directional derivatives are calculated by convolution with a 3x3 template. The other components of the current density can be calculated similarly based on relations

$$\vec{J}_y = \left[\frac{\partial \vec{B}_x}{\partial z} - \frac{\partial \vec{B}_z}{\partial x}\right]\frac{1}{\mu_o} \text{ and } \vec{J}_x = \left[\frac{\partial \vec{B}_z}{\partial y} - \frac{\partial \vec{B}_y}{\partial z}\right]\frac{1}{\mu_o}.$$

Results and Conclusion

Images of non-uniform and uniform current density are produced using MRI. On a phantom with homogeneous conductivity, current density at the electrode-electrolyte interface is imaged. Current densities as low as $1 \mathrm{mA/m^2}$ can be measured. Current density imaging has potential biomedical applications in better understanding externally applied electric fields to the body (e.g. defibrillation current fields) and measurement of lead-sensitivity maps for bio-potential recording. Since biological tissues have different electrical properties, it may be possible to obtain anatomical and functional information from current density images. Spatial distribution of electrical conductivity and current density are directly related. Determination of current density accurately may also lead to precise high resolution conductivity images.

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References:

[1] G.C. Scott, M.L.G. Joy, R.L. Armstrong and R.M. Henkelman, "Measurement of nonuniform current density by magnetic resonance," IEEE Trans. on Medical Imaging, V.10, 3, pp.362-74, 1991.

[2] G.C. Scott, M.L.G. Joy, R.L. Armstrong and R.M. Henkelman, "Sensitivity of magnetic-resonance current-density imaging," J. Magnetic Resonance, 97,, pp.235-54, 1992.