Anisotropic Conductivity Tensor Imaging using a Combination of MREIT and DTI

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Target audience

This study may provide a direct method to visualize the electrical anisotropic conductivity tensor map. It might be helpful to the people who are interested in the imaging of anisotropic characteristics of biological tissue.

Purpose

The purpose of this study is to show the potential of MREIT tissue anisotropic electrical property imaging combining with the water-diffusion tensor map through the imaging experiments and numerical simulations of anisotropic conductivity phantom.

Methods

The pulsed gradient spin echo (PGSE) excites the spin system by applying time-constant magnetic field gradients before and after the π-pulse and acquires the *k*-space data. Due to the diphase magnetization diffused, the intensity of magnitude reflects the amount of diffusion occurred during the diffusion gradient pulses. In MREIT, both positive and negative currents of the same amplitude and duration are injected to measure the one component of magnetic flux density $\mathbf{B} = (B_x, B_y, B_z)$. From the measured B_z of $\mathbf{B}$, the projected current density $\mathbf{J}^P$ can be recovered, which is the best approximation of $\mathbf{J}$ induced by the injected current.[1]

The effective water diffusion tensor $D_\sigma = S_D\, \widetilde{D}\, S_D^T$ and the effective conductivity tensor $\sigma_D = S_D\, \widetilde{\sigma}\, S_D^T$ satisfies the following linear relationship[2]

$$\widetilde{\sigma} = \frac{\sigma_e}{d_e}\, \widetilde{D} \tag{1}$$

where S_D is the three orthogonal eigenvectors, $\widetilde{D} = diag(d_1, d_2, d_3)$ and $\widetilde{\sigma} = diag(\sigma_1, \sigma_2, \sigma_3)$ are the diagonal matrices for the diffusion and conductivity tensors, respectively, σ_e is the extracellular conductivity and $d_e$is the extracellular diffusion coefficient. The recovered current density by the externally injected current can be represented as

$$\mathbf{J}^{i,P} = -\sigma_D \nabla u^i = -\frac{\sigma_e}{d_e} D_\sigma \nabla u^i, \quad i = 1,2 \tag{2}$$

where u^i is the voltage potential corresponding to the independent injection current $g^i, i = 1,2$. The current density satisfy the following relation

$$\nabla \times \left(D_\sigma{}^{-1}\mathbf{J}^{i,P}\right) = -\frac{\nabla\eta}{\eta} \times \left(\eta \nabla u^i\right) = \nabla \log\eta \times \left(D_\sigma{}^{-1}\mathbf{J}^{i,P}\right), \text{ where } \eta = \frac{\sigma_e}{d_e} \tag{3}$$

Using the above relation between the known quantities D_σ and $\mathbf{J}^{i,P}$, we can derive the direct algorithm to reconstruct the scaling factor η which is the extracellular conductivity and diffusivity ratio. To verify the proposed method, we constructed a cylindrical conductivity phantom and attached four carbon-hydrogel electrodes (HUREV Co. Ltd, Korea) at the middle of the phantom. We filled it with 1 S/m saline solution and placed one cylindrical isotropic object (TX-151) of 2 S/m conductivity. We also put three pieces of anisotropic biological tissues (chicken breast) with the dimension of 35×35×35 mm^3. Figure 1 shows the phantom configuration and its location inside the bore of the 3 T MRI scanner. We acquired the diffusion-weighted data using a single-shot spin-echo EPI to measure the diffusion tensor D_σ. For MREIT data, we sequentially injected 10 mA currents by two different injection currents using multi-echo pulse sequence.

Results and Discussion

From the measured diffusion-weighted data applied in 15 directions and the echo signal intensity without the sensitizing gradient, we recovered the six diffusion coefficient values for the diffusion tensor. From the three chicken breast regions with muscle fibers oriented in the x-, y- and xy-directions as shown in Figure 1(a), the diffusion tensor map shows the different diffusion anisotropy effects at each ROI. For the cylindrical gel region, the water molecule diffusions show the isotropic diffusion, which is the same as that of the background saline. Using the measured $B_z^i, i = 1,2$, we recovered the projected current densities $\mathbf{J}^{1,P}$ and $\mathbf{J}^{2,P}$. We solved the system using (3) and reconstructed the scaling factor η with the projected current densities $\mathbf{J}^{1,P}$ and $\mathbf{J}^{2,P}$ and the recovered diffusion tensor D_σ. Figure 2(a) shows the reconstructed scaling factor η obtained from both the DTI and MREIT imaging experiment. Figure 2(b) shows the reconstructed conductivity tensors in the regions of the biological tissues without any referred extracellular and diffusivity values.

Conclusion

We proposed a novel method to reconstruct the anisotropic conductivity tensor image inside an electrically conducting object by combining the DTI and MREIT techniques.

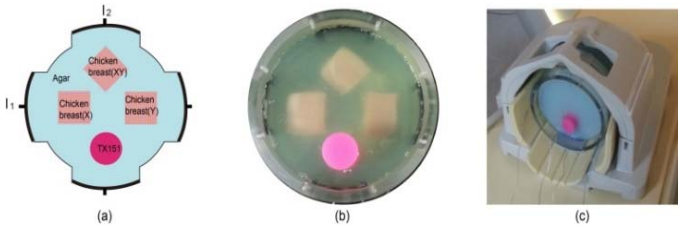

Fig. 1. (a) Phantom design and (b) its top view. (c) Experimental setting inside a 3T MRI scanner.

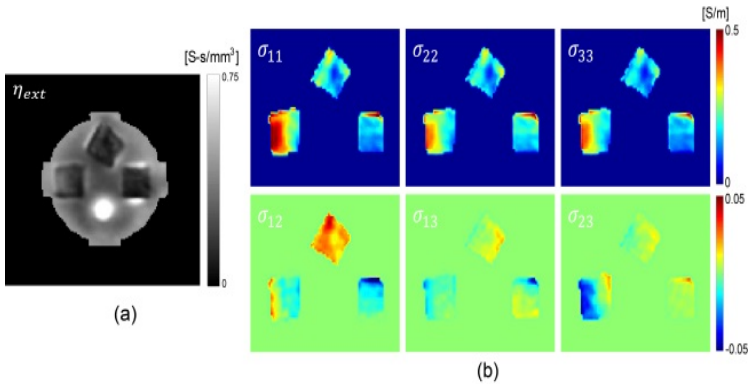

Fig. 2. (a) Reconstructed scaling factor η obtained from both the DTI and MREIT imaging experiment. (b) Reconstructed conductivity tensor of the anisotropic tissue regions.

References

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