Conductivity imaging of the rat brain using diffusion tensor MRI

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Introduction

The imaging of conductivity distributions in the brain gives variable information on physiological and pathological parameters which are not obtained by anatomical imaging. Tissue characterization is conveyed through conductivity because conductivity depends on cell shapes and intra/extracellular fluid compositions. Electrical impedance tomography (EIT), in which surface potentials are measured during applications of currents via surface electrodes, has been applied to obtain conductivity distributions in living bodies. However, conductivity distributions of the brain are difficult to obtain because most of the currents do not penetrate the skull due to the low conductivity of the skull. In this study, we introduce a method of conductivity imaging based on diffusion tensor MRI.

Methods

The effective conductivity σ of tissue can be calculated using the equation [1]

$$\sigma = 2v_{ext}\sigma_{ext}/(3-v_{ext}) \tag{1}$$

where v_{ext} is the fractional volume of extracellular space, σ_{ext} is the conductivity of the extracellular fluid. The relationship between the conductivity σ_{ext} and the diffusion coefficient D_{ext} of the extracellular fluid is obtained from the Stokes-Einstein equation and the balance between the electrostatic force and viscous drag as

$$\sigma_{ext} = \frac{j}{E} = \frac{q^2 N}{6\pi r_i \eta} = \frac{r_w q^2 N}{r_i kT} D_{ext} \tag{2}$$

where r_w and r_i are the Stokes radius of water molecules and ions, q is the charge of the ions, N is the density of the ions, k is the Boltzmann constant, and T is the temperature. Based on the assumption that the composition of extracellular fluid is equal to that of saline solution (0.15 mol/l NaCl), the constants in equation (2) are $r_w/r_i = 0.76$, $q = 1.6\times10^{-19}$ C, $N = 2.0\times10^{25}$ m^{-3}, and $kT = 4.1\times10^{-21}$ J. Diffusion studies using high b values in the brain indicate that the diffusional signal decay is described in terms of a biexponential function

$$\frac{S(b)}{S(0)} = f_{fast}\exp(-bD_{fast}) + f_{slow}\exp(-bD_{slow}) \tag{3}$$

where D_{fast} and D_{slow} are called the fast component and the slow component of ADC, respectively. Though interpretation of the origins of the two components has not yet been established, the fast component and the slow component have been attributed to extracellular fluid and intracellular fluid, respectively [2]. We assume that the diffusion coefficient and the fractional volume of extracellular fluid are equal to the fast component of the ADC and the fraction of the fast component. Based on the models described above, tissue conductivity is obtained from the fast component of the ADC and the fraction of the fast component as

$$\sigma = \frac{2f_{fast}\times9.5\times10^{7}\times D_{fast}}{3-f_{fast}} \tag{4}$$

Images of the rat brain were obtained using a 4.7 T MRI system. MPGs were applied with 4 arrayed b factors of b = 0, 1200, 2400, 3600 s/mm^2, in six directions. A linearized version of function (3) was used to calculate the components of ADC [3].

Results and Discussion

Figures (a)(b) show signal attenuations of diffusion-weighted images. The signals were averaged in the regions of interest (ROIs) located in the cortex and the corpus callosum. The ROIs had a dimension of 2×2×2 mm^3. Linear relations were not observed between the logarithm of the signal intensity and the b factor. The corpus callosum exhibited slightly higher anisotropy in the signal attenuation compared to the cortex. The averaged values of D_{fast} between the six directions in the cortex and the corpus callosum were 5.7×10^{-4} mm^2/s and 6.3×10^{-4} mm^2/s, respectively, and the averaged values of f_{fast} were 0.55 and 0.58, respectively.

Figures (c)-(h) show conductivity images for each MPG direction. The white-matter tissues had higher conductivity values and higher anisotropy compared to the gray-matter tissues. The conductivity images exhibited high intensity in the white-matter tissues when MPG was applied in the same direction as the orientation of neuronal fibers. Figure (i)(j) show the mean conductivity (MC) image and the fractional anisotropy (FA) image. The MC was high in the corpus callosum and the ventricle, while the FA was high in the corpus callosum, the internal capsule, and the trigeminal nerve. In the ROIs located in the cortex and the corpus callosum, the MCs were 2.5×10^{-2} S/m and 2.9×10^{-2} S/m, respectively, and the FAs were 0.46 and 0.50, respectively.

Measurement of conductivity distribution in the brain is important for investigations of brain function and various analyses in biomedical engineering. In this paper, conductivity distribution in the brain was visualized using diffusion-weighted images with high b values. Since the migrating ions encounter high resistance from cell membranes, tissue conductivity highly depends on the shape of cells, which results in inhomogeneity and anisotropy of tissue conductivity. However, it has been difficult to investigate the inhomogeneity and anisotropy in detail by methods based on the application of electric current from surface electrodes. Thus, most of the analyses of electric currents in the brain have been performed on the assumption that the brain is a homogeneous and isotropic conductor. The results in this study indicate that the white matter has higher values of conductivity and higher anisotropy in conductivity compared to the gray matter. This finding suggests that, as reported in numerous papers, neuronal fibers in the white matter orient to a specific direction. The conductivity tensor images obtained in this study enable us to have a more accurate estimation of electric currents in the brain.

References

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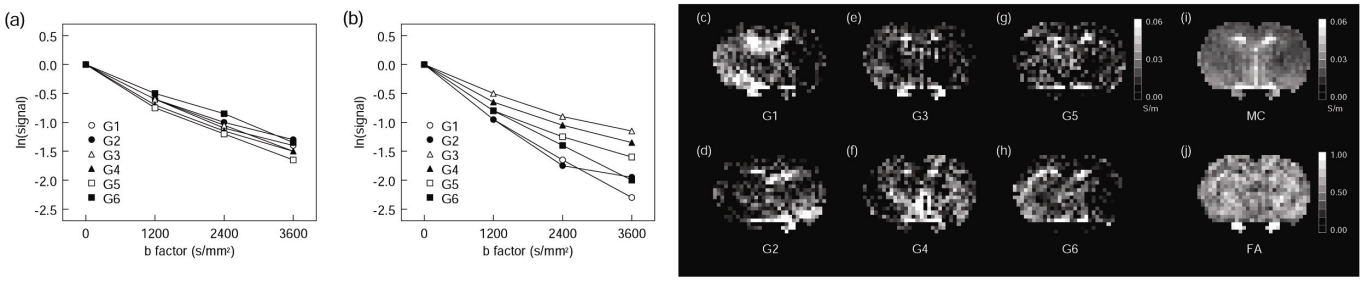

Figure: Signal attenuations in diffusion-weighted image in (a) the cortex and (b) the corpus callosum. (c)-(h) Images of the conductivity in the six MPG directions. (i) The mean conductivity (MC) image and (j) the fractional anisotropy (FA) image. Motion probing gradients (MPGs) were applied in the following directions: $\mathbf{G}_1 = (G/\sqrt{2})(-1\ 0\ 1)^T$, $\mathbf{G}_2 = (G/\sqrt{2})(1\ 0\ 1)^T$, $\mathbf{G}_3 = (G/\sqrt{2})(0\ 1\ 1)^T$, $\mathbf{G}_4 = (G/\sqrt{2})(0\ -1\ 1)^T$, $\mathbf{G}_5 = (G/\sqrt{2})(-1\ 1\ 0)^T$, $\mathbf{G}_6 = (G/\sqrt{2})(1\ 1\ 0)^T$.