CONDUCTIVITY TENSOR MR IMAGING

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INTRODUCTION

The estimation of conductivity distributions in the brain is essential for various biomedical engineering analyses such as obtaining current distributions in electric stimulation and magnetic stimulation, calculating the absorption of electromagnetic waves from mobile phones, and current source estimations in electroencephalography (EEG) and magnetoencephalography (MEG). In addition, tissue characterization is conveyed through conductivity, which depends on cell geometry and intracellular fluid and 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 [1]. However, EIT has relatively low spatial resolution when using a limited number of surface electrodes. Moreover, 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 [2]. Some new methods use magnetic resonance imaging (MRI) to obtain conductivity distributions. Conductivity-weighted magnetic resonance images are obtained during applications of external AC magnetic fields, which induce conductivity-dependent eddy currents in a sample [3,4].

Since the conductivity of biological tissues has anisotropy due to asymmetric cellular structures, conductivity is generally expressed by tensor. However, it is difficult to investigate distributions of conductivity anisotropy by conventional methods because of the immense complexity in measurement. In this study, we introduce a new method of conductivity tensor imaging using diffusion MRI to obtain conductivity distributions of the rat brain and the human brain.

MATERIALS AND METHODS

The method of conductivity imaging was based on the proportionality between the self-diffusion coefficient of water and conductivity [5-7]. Conductivity distributions in the rat brain and the human brain were estimated using this method. Images of the rat brain were obtained using a 4.7 T MRI system, with the stimulated echo acquisition mode (STEAM) sequence and a spin-echo imaging sequence. Five animals were used in each measurement. Motion probing gradients (MPGs) were applied in 6 directions. Numbers of b factor steps in the STEAM and spin-echo measurements were 61 and 4, respectively. The diffusion coefficient and the fractional volume of extracellular space were estimated from the relationship

between the signal intensity and the b factor. The estimation was based on the model that the fast component of diffusion originated from the extracellular space. The effective conductivity of tissues was estimated using an equation for the balance of electrostatic force and viscous resistance on an ion, the Stokes-Einstein equation, and the Cole's model of conduction in porous media. Regions-of-interest (ROIs) were located on the cortex and the corpus callosum.

Measurements of humans were carried out using a 1.5 T MRI system. Images of 5 healthy volunteers were obtained using an echo-planar imaging (EPI) sequence. MPGs were applied with 25 arrayed b factors.

RESULTS

Conductivity tensor images of the rat brain were obtained from the diffusion-weighted images. The signal attenuation in the corpus callocum exhibited high anisotropy due to alignment of neuronal fibers. The mean conductivities (MCs) in the cortex and the corpus callosum were $(6.14 \pm 0.46)\times10^{-2}$ S m^{-1} and $(7.31 \pm 0.70)\times10^{-2}$ S m^{-1}, respectively. The fractional anisotropies (FAs) in the cortex and the corpus callosum were 0.25 ± 0.07 and 0.33 ± 0.03, respectively. Regions with high conductivity anisotropy were found in the white matter.

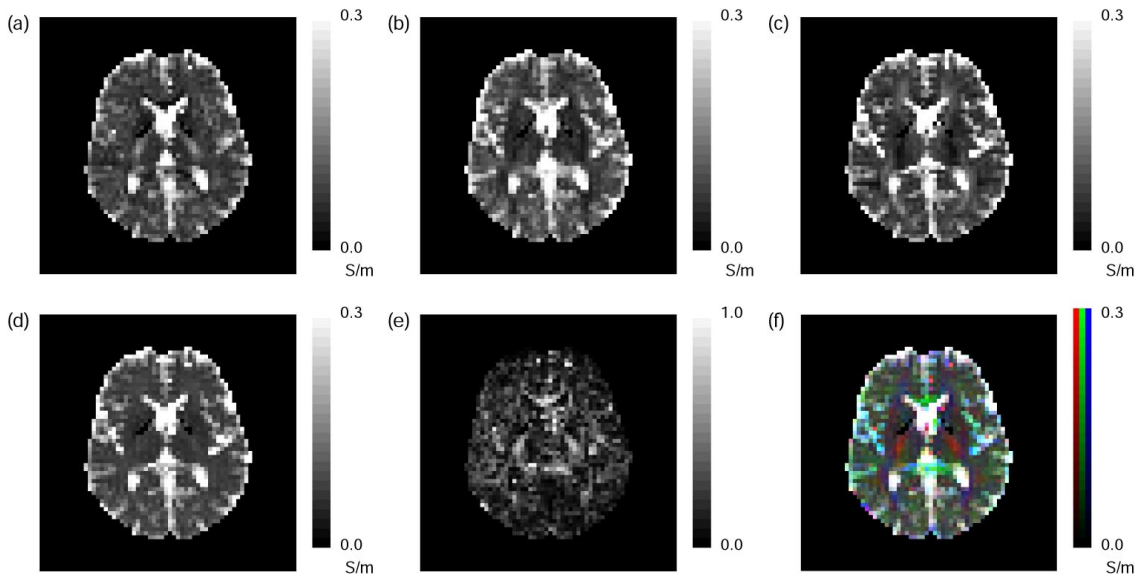

Figure 1: (a)(b)(c) Images of the estimated conductivities in the human brain for the anterior-posterior, right-left, and superior-inferior directions. (d)(e) Images of the mean conductivity (MC) and the anisotropy index (AI). (f) Color map of conductivity. The intensities of red, green, and blue are proportional to the conductivities in the anterior-posterior, right-left, and superior-inferior directions, respectively.

Figures 1(a)(b)(c) show images of conductivities in the human brain. The gray matter did not have a clear dependence of conductivity on the MPG direction. The white matter contained several regions whose conductivities are highly dependent on the MPG direction. The internal capsule exhibited high conductivity when the MPG was applied in the superior-inferior direction. The corpus callosum exhibited high conductivity when the MPG was applied in the right-left direction. Figures 1(d)(e) show images of the MC and the AI. Regions with high AI values were found in the white matter. Figure 1(f) shows a color map of the conductivity. In each pixel of the map, the intensities of red, green, and blue are proportional to the conductivities in the anterior-posterior, right-left, and superior-inferior directions, respectively. The regions with isotropic and high conductivity appear as white color because a mixture of the three colors results in white color. The red, green, and blue regions have highly anisotropic conductivity. In the red regions, for example, the primary axis of the anisotropic conductivity aligns in the anterior-posterior direction. The color map is useful for overview of the localization of the anisotropic conductivity and its primary axis rather than quantitative evaluation of the anisotropic conductivity.

DISCUSSION

In this study, conductivity distribution of the human brain was obtained from MR images. The inhomogeneity and anisotropy of the conductivity in each tissue is not considered in conventional conductivity models which are used in current source estimations of EEG and MEG. However, it has been pointed out that the results of current source estimations depend on the spatial distribution of conductivity in the models. The results in this study clarified the significant inhomogeneity and anisotropy in the white matter. Thus, use of an inhomogeneous and anisotropic conductivity model is desirable especially for estimating current sources at the deep part of the brain.

Conventional methods of impedance tomography have not been applicable to the brain because of the high resistivity of the skull. Development of a conductivity model from cross-sectional images requires complicated processes such as segmentation. Anatomical structures of the conventional conductivity models are usually based on an individual who is different from the subjects of EEG or MEG, or based on a representative or average anatomical structure among a number of humans. In many cases, the conductivity models are approximated using a sphere with three or four layers. These models are not identical to the conductivity distributions of each subject. As a result, current source estimations using these models are affected by differences in conductivity among subjects. Our method enables imaging of conductivity in one hour, and does not require complicated image processing. Imaging of conductivity can be carried out for each subject. When the subject has the experience of having had a surgical operation on the brain, his or her conductivity distribution may be different from that of a healthy volunteer. In such subjects, current source estimations based on conventional conductivity models do not

lead to reasonable results. Imaging of conductivity for each subject is important for clinical applications of EEG and MEG.

Conductivity in biological tissues depends on current frequency because electric charges in tissues are transferred by multiple mechanisms such as the drift of ions, capacitance of membranes, and rotation of polar molecules. Low-frequency currents are mainly conducted via the drift of ions, and conductivity decreases with a decrease in frequency. The conductivity calculated by our method corresponds to the values at DC or very low frequencies because our conductivity model considers only the extracelluar current [5]. Conductivities of biological tissues in the frequency range of 10 Hz – 100 GHz can be obtained using Gabriels' database [8] which summarizes directly measured dielectric properties of tissues. This database gives conductivity values of 0.089 S/m and 0.058 S/m for the gray matter and the white matter, respectively, at a frequency of 100 Hz, and the conductivity values estimated by our method are comparable to these values.

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