Impedance MRI and MR neuroimaging

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Abstract

Mapping of electromagnetic fields and electric properties of the brain is helpful in understanding the fundamentals of brain function. This paper introduces recent progress in magnetic resonance imaging (MRI) techniques to obtain the electric properties of the biological tissues and weak magnetic fields arising from neuronal electrical activities. There are two approaches for impedance MRI: Application of external electric currents to the sample and observation of the resulting changes in images provide a straightforward way to estimate the electric properties of the sample. Inferring the tissue conductivity from the water diffusion coefficient provides a less invasive method to estimate the tissue conductivity. Considering that MRI is inherently sensitive to magnetic fields generated in the samples, detection of magnetic fields arising from neuronal electrical activities using MRI is an attractive approach for dramatically improving the temporal resolution of functional MRI. Evaluating the sensitivity of MRI to weak magnetic fields is crucial in realizing this detection. Some papers report that the neuronal magnetic fields are detectable using MRI.

1. Introduction

Functional MRI is based on a fluctuation of blood oxygenation and blood flow occurring after the neuronal electrical activity. The delay in hemodynamic response gives the fundamental limitation to the temporal resolution of MRI. MRI has an intrinsic sensitivity to magnetic fields generated in the sample. The detection of weak magnetic fields arising from neuronal electrical activities enables us to observe the propagating activities with a temporal resolution of milliseconds and a spatial resolution of millimeters. The magnitudes of neuronal magnetic fields, however, are extremely weak, and magnetic field distributions in close proximity to the activated areas are not clear. Thus, the sensitivity of MRI to neuronal magnetic fields has to be carefully assessed.

The conductivities of the brain tissues affect the macroscopic distribution of neuronal electric current. Mapping the conductivity of the brain would show us the underlying electrical feature superimposed on the anatomical information. In addition, electrical properties of the tissues considerably affect the distribution of radio-frequency (RF) magnetic fields in the object. Recent development of ultrahigh field MRI results in higher specific absorption rates (SAR). Mapping of the tissue electrical properties would be an essential technique for safety estimate.

This paper reviews the recent progress of impedance MRI and MR neuroimaging.

2. Impedance MRI

Several groups in the world are developing numerical models of the human body for the purpose of analyzing electromagnetic field distribution [1]. The models are segmented into more than 50 tissues with spatial resolutions of 2 mm or smaller. Use of these models is beneficial for evaluating a typical field distribution. Mapping of electric properties of the tissues using MRI enables us to build numerical models for individual subject. Changes in electric properties or structure due to diseases are also incorporated in the field analyses.

There are two approaches for impedance MRI; injection of current to the sample and estimation of conductivity based on water diffusion. The injected current gives rise to magnetic fields in the sample. The field causes a phase-shift in the Larmor precession of sample magnetization. A set of images obtained with and without the current gives the internal distribution of currents. Some iterative process on the equation of current leads to an estimate of the conductivity distribution [2,3].

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Combination of some basic equation of ion transfer results in a proportionality between tissue conductivity and water diffusion in the tissue. The distribution of water diffusion coefficient can be obtained using diffusion MRI. Based on the model that low-frequency currents flow only in extracellular spaces, the result of diffusion MRI is corrected. This approach shows us not only the value of conductivity but also anisotropy of conductivity [4-6]. Conductivity images of the rat brain and the human brain have been reported.

3. Influence of dielectric properties of samples

The dielectric properties of the sample significantly affect the distributions of RF magnetic fields. Permittivity of the sample determines the wavelength of RF magnetic field. In the recently developed ultrahigh-field MRI with resonant frequencies of 400 MHz or higher, the wavelength of RF field is comparable to or shorter than the size of the human head. The nodes and antinodes of the standing RF wave exhibit inhomogeneities of RF field and signal intensity. This phenomenon is called the "dielectric resonance."

Skin effects in the sample occurs depending on the conductivity and the magnetic resonance frequency. Conductivity values of biological tissues range approximately from 0.1 to 2 S/m. These values give skin depths comparable to the size of human body. The above two effects result in complicated signal inhomogeneities in MRI [7]. Electric field distribution also exhibits significant inhomogeneities. One of the major technical challenges in ultrahigh field MRI is the locally high SAR in the brain.

The above dependences of the signal distributions on the dielectric properties inspire us to inversely estimate the dielectric properties from the acquired images [8]. Our group proposed a method to estimate the permittivity and conductivity by means of spatially differentiating the RF field distribution in the sample [9].

4. Sensitivity to weak magnetic fields

The magnetic field B generated in the sample gives a phase shift $\varphi = \gamma \cdot B \cdot T_E$ in the Larmor precession, where γ is the gyromagnetic ratio, and T_E is the echo time. The theoretical sensitivity σ_B to the magnetic field is given by $\sigma_B = 1/(\mathrm{SNR} \cdot \gamma \cdot T_E)$, where SNR is the signal-to-noise ratio of the image. This equation indicates that improving the SNR is essentially important for detecting weak magnetic fields. In previous studies, the sensitivity is evaluated through numerical, phantom, and in vivo experiments under a variety of samples and measurement conditions [10-13]. A straightforward approach to improve the SNR is averaging the signals.

Neuronal magnetic fields are detected when the field intensity is higher than the above sensitivity. Previously the neuronal magnetic fields have been measured using SQUID systems. Due to the limitation of the SQUID measurements in which the signal detector coils are located outside the brain, the magnetic field distribution around the activated area has remained to be understood. Our group reported a measurement of three dimensional distribution of somatosensory evoked potentials [14]. The resulting field magnitude of 2.8 pT was comparable to the theoretical sensitivity of MRI for the rat brain. Another study suggested that the neuronal magnetic fields arising in the human brain are detectable using MRI [12].

5. Detection of magnetic fields arising from neuronal electrical activities

Experimental detection of neuronal magnetic fields has been tried for a variety of materials such as cell culture [15], animals [16], and humans. The significance of in vitro experiments is the elimination of hemodynamic effects. Both of the neuronal magnetic fields and blood oxygenation level affects the magnetic resonance signals, causing signal variations. The neuronal field can be clearly distinguished from the blood oxygenation effect through the in vitro experiments. A previous study showed that neuronal cells cultured on a micro electrode array exhibited a detectable magnetic field. Blood in the animal brain can be washed out by means of slicing the brain and perfusing artificial cerebrospinal fluids [13].

Due to the high requirement of the signal to noise ratio, in vivo detection of neuronal magnetic fields is not necessarily easy. Our group reported temporal signal variations observed in the rat brain, suggesting the detection of neuronal magnetic fields, as shown in figure 1. Several groups are trying to catch the neuronal fields in the human brain.

6. Conclusions and future prospects

The imaging of neuronal magnetic fields is an attractive technique for functional brain imaging in the next generation. Improving the SNR is essential for advancing the applications of this method. Emerging techniques such as ultrahigh-field magnet, cryogenic cooling of the RF coil, and parallel imaging will help improving the SNR. Impedance MRI methods give the basis for analyzing current distributions generated in the brain.

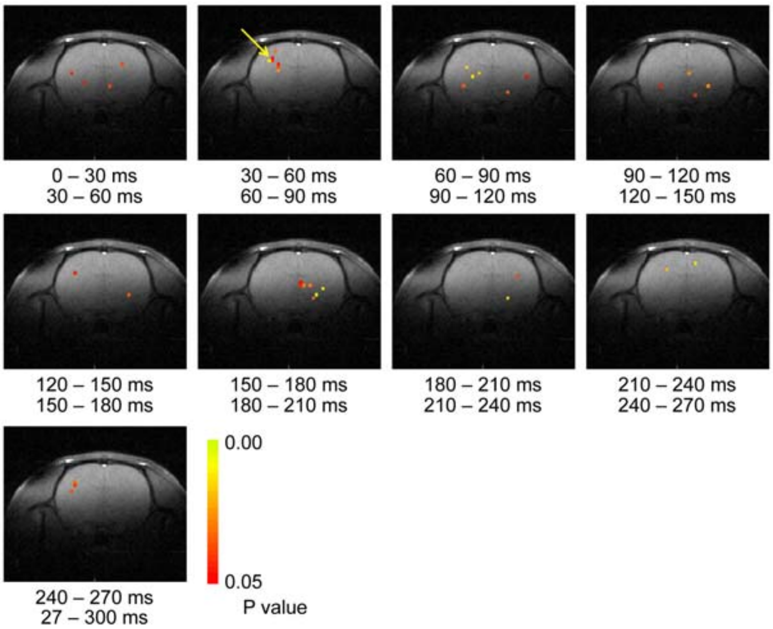

Figure 1: Detection of neuronal magnetic fields arising from the rat brain. The time "0 – 30 ms, 30 – 60 ms" means a comparison between the image excited at 0 ms (acquired at 30 ms) and the image excited at 30 ms (acquired at 60 ms) [16].

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