Toward direct detection of neuronal magnetic fields using MRI: Local and three-dimensional mapping of somatosensory evoked fields in the rat brain

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Introduction: In this study, we calculated local distribution of neuronal magnetic fields in the rat somatosensory cortex based on multichannel potential recordings, and found that the resulting field magnitude of 2.8×10^{-12} T was comparable to the theoretical sensitivity limit of MRI. Detection of weak magnetic fields arising from neuronal electrical activities using MRI is an attractive but challenging topic in functional MRI. Feasibility of this approach has been evaluated using numerical simulations, phantom experiments, in vitro experiments, and animal and human studies [1-4]. Some of the previous papers have indicated or implied that neuronal activities were detected using MRI. However, these results do not seem sufficiently reproduced by other groups so far. The theoretical and phantom studies have encountered a difficulty in modeling neuronal magnetic fields in close proximity to the group of firing neurons. In animal and human studies, one has been able to statistically analyze the acquired images, but has not been able to compare the measured results with an appropriate physical model. Discussing the feasibility of direct detection of neuronal activities will stand on clear evidence if one obtains the local magnetic field distribution at the activating area. We measured three-dimensional distribution of local electric potentials in the rat somatosensory cortex using a 16-channel microelectrode array. Local distributions of electric current and magnetic field were calculated from the measured potentials.

Materials and Methods: Figure 1(a) shows the 16-channel microelectrode array for the potential recordings. Each needle has a length of 3 mm, a diameter of 100 μm, and an array interval of 300 μm. The needles were insulated with epoxy except for the tip of 50 μm. The animals were anesthetized with isoflurane for surgical operation. The head was fixed on a stereotaxic instrument. A part of cerebrospinal fluid was drained through a suboccipital catheter for suppressing an increase of intracranial pressure. After removal of the scalp, a cranial window of 3×5 mm was formed on the somatosensory cortex corresponding to the left hindpaw (1 - 4 mm left and 1 - 6 mm posterior from the bregma), and the dura matter was removed. The microelectrode array was inserted into the brain through the cranial window, as shown in figure 1(b), with depth steps of 0.5 mm, 0.8 mm, 1.1 mm, and 1.4 mm. A small hole was formed on the contralateral skull. A single needle electrode was inserted through the hole for giving a reference potential. A pair of needle electrodes was inserted to the left hindpaw for electric stimulation. Stimulations were delivered at 4 pulses per second. The anesthetic was then replaced by mixture of urethane (700 mg/kg) and α-chloralose. Somatosensory evoked potentials were measured through the microelectrode array, and were recorded using a multichannel amplifier (MED-64, Alpha MED Scientific). The signals were filtered with cut-off frequencies of 100 Hz and 2.5 kHz, and were sampled at 20 kHz. Three-dimensional distributions of electric current density were calculated as derivation of measured potentials multiplied by the electric conductivity (σ = 0.51 S/m) for 64 sampling points with a spatial resolution of 300 μm. The local magnetic field distributions were then calculated using Ampere's law. The area of calculation was divided into 8000 sub-grids for avoiding a physically meaningless divergence of magnetic field intensity.

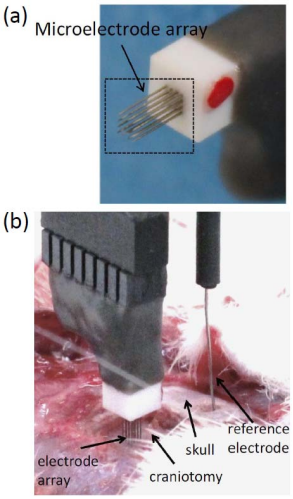

Figure 1: (a) 16-channel microelectrode array. (b) Insertion of the electrode to the rat brain.

Results: Figure 2 shows the local field potentials for the 16 electrode channels inserted at 0.8 mm below the brain surface. The electrical stimulations were applied at 30 ms, and the peak of somatosensory evoked potentials occurred around 50 ms. The latency of evoked potentials ranged from 19.7 ms to 22.4 ms. The peak magnitude of evoked potentials ranged from 4.11 μV to 16.55 μV. The upper right electrode of (1,4) exhibited the highest magnitude and the shortest latency, suggesting that the evoked neuronal activity traveled from upper right channels to lower left channels. The maximum of calculated electric current density was 18 mA/m^2 occurring at 18 ms, and the electric current density gradually decreased. The time and location of the peak current density were similar to those of electric potentials. Three-dimensional distribution of calculated magnetic flux density was plotted in figure 3 for 18 ms after the stimulation. The maximum magnetic flux density within the calculating region was 2.8×10^{-12} T. Figure 4 shows the time course of calculated magnetic flux density on the plane 0.8 mm below the brain surface and for time steps ranging from 17 ms to 20 ms. The peak of magnetic field occurred at 18 ms and at upper left of the measuring plane.

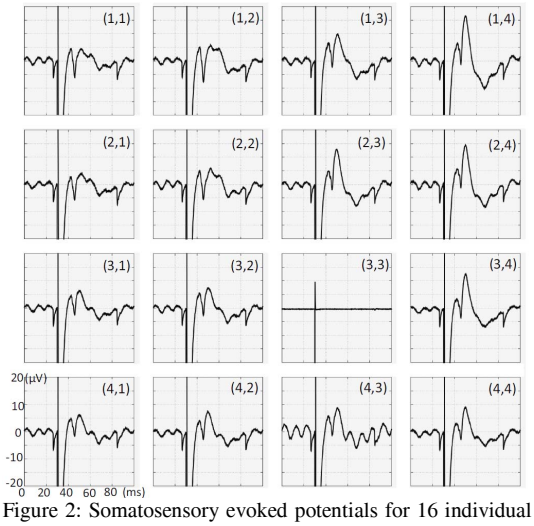

Figure 2: Somatosensory evoked potentials for 16 individual channels.

Discussion: The theoretical limit of sensitivity for detecting weak magnetic fields using gradient-echo phase-angle images is given by [2]

$$\sigma_B = \frac{1}{\mathrm{SNR}\cdot\gamma\cdot\mathrm{TE}} \qquad (1)$$

where SNR is the signal-to-noise ratio in the measuring condition. We estimated the SNR for imaging the rat brain, based on the method of our previous study [2], for the following parameters: B_0 = 4.7 T, TE = 30 ms, NEX = 320, and the equivalent resistance of the rat brain of 80 mΩ in the receiver RF coil. The estimated sensitivity was 2.7×10^{-12} T, which is comparable to the peak amplitude of the evoked magnetic fields. The optimization of imaging parameters will improve the SNR, and other evoked or spontaneous brain activities would exhibit higher peak of neuronal magnetic fields. These improvements lead to realization of directly detecting neuronal magnetic fields. Conventional method of functional MRI has a physiologically-limited temporal resolution. The direct detection of neuronal magnetic fields potentially visualizes the spatiotemporal changes of brain activities, and may become a novel technique to facilitate understanding of brain function.

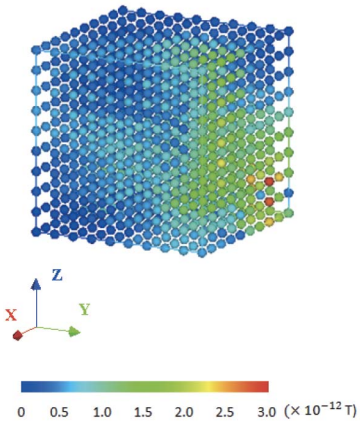

Figure 3: Calculated local magnetic field in the somatosensory cortex.

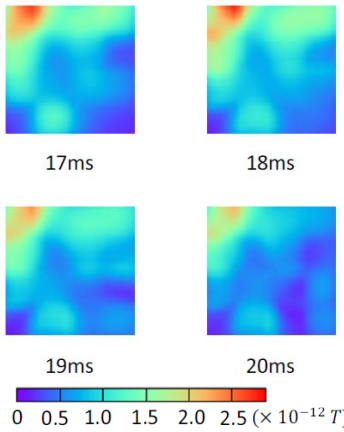

Figure 4: Time course of the calculated local magnetic field.

References: [1] Sekino M et al., *IEEE Trans Magn* 2009;45:4841-4844. [2] Hatada T et al., *J Appl Phys* 2005;97:E109. [3] Petridou N et al., *PNAS* 2006;103:16015-16020. [4] Halpern-Manners NW et al., *PNAS* 2010 ;107 :8519-8524.