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# Cortical Potential Imaging of Somatosensory Evoked Potential Induced by Mechanical Stimulation*

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*Abstract*— **The objective evaluation of somatic sensations is expected without a patient's subjective opinions to reduce social problems such as those related to lawsuits for nerve injuries or malingering. In this study, the somatosensory evoked potential (SEP) using the mechanical stimulations of the tactile sensation was measured and analyzed in spatiotemporal domains. The cortical potential mapping projected onto the realistic-shaped model was estimated to improve the spatial resolution of the SEP maps by application of cortical dipole layer imaging. The experimentally obtained results suggest that the spatiotemporal distributions of the SEPs reflect the differences for positions, strengths, and patterns of somatosensory stimulations.**

## I. Introduction

In clinical situations, lawsuits for nerve injuries have come to pose serious problems. Evaluation of somatic sensations must depend on a patient's subjective opinions to judge medical treatment, especially when no external injury exists. When pain cannot be evaluated objectively, it is difficult to perceive malingering. Moreover, for disabled people or infants who have difficulty communicating with others, the judgment of a tactile sensation or pain is left to medical workers. For these reasons, it is hoped that some criterion of somatic sensation would be established. Several studies of tactile sensations with various stimuli are progressing, using large-scale medical measuring instruments such as magnetic resonance imaging (MRI), positron-emission tomography (PET), and magnetoencephalography (MEG) [1]-[4]. Simplified diagnostic instruments to assess sensory functions are anticipated for use in actual examinations such as those for dental treatment. We examined methods to evaluate somatic sensation objectively using electroencephalography (EEG).

EEG is an effective method to resolve brain functions in daily life because of its low cost, easy installation, and few restrictions on the measurement environment. However, EEGs present the problem that the spatial resolution is limited due to the low conductivity of the skull. Therefore, it has remained difficult to estimate electrical activity within a brain directly from the scalp potential distribution. To solve this problem, various techniques have been investigated to improve the spatial resolution of EEG [5]–[13]. For review, see [14]. Cortical dipole imaging is one spatial enhancement technique [11]-[13], [15]. This is a method to estimate the dipole distribution on the equivalent layer installed on the virtual surface within a brain from the scalp potential distribution. The cortical dipole imaging can carry out without the knowledge of the number or orientation of the signal sources. This is a merit for the analysis of brain electrical activities as compared with the dipole tracing of several signal sources. Moreover, the cortical potential map was estimated from the dipole layer distribution by applying the transfer matrix from the dipole layer to the cortical surface potential [16], [17]. According to this method, the electrical activity taking place within a brain can be expressed equivalently without any restriction on the number of sources. By applying this cortical potential imaging, it is expected that the spatial resolution of brain electrical activity would be improved compared with the scalp potential imaging. Moreover, the electrical activity would be localized on the realistically-shaped cortical surface to specify the activated location of the brain.

In previous somatosensory evoked potential (SEP) experiments, electrical stimuli have been used because of the ease of carrying out control in experiments related to conventional somatic sensation. However, the electric stimulus is artificial. It differs from the mechanical stimulus that the subject actually receives. Onishi et al. analyzed the brain activity by mechanical tactile stimulus using MEG [4]. They obtained results indicating that the response of on-stimulus coincides with that of an off-stimulus that differed from electrical stimulus.

In this study, the SEP data evoked by the mechanical stimulus for the tactile sense that was given to the hands and the feet of subjects was measured using EEG. Furthermore, although the latency of the peaks in SEPs was analyzed in the time domain, high-resolution brain electrical activity was mapped and examined in the spatial domain. The cortical potential mapping on the realistic-shaped model was estimated from the scalp potentials via the equivalent dipole distribution. We objectively examined evaluation of the difference of stimulus positions and the influence from the intensity and the pattern of stimulus.

## II. Methods

### A. Subjects and Methods

Four healthy male subjects in their 20s participated in the experiments. They sat in a quiet state with eye masks and earplugs to intercept the external stimuli. The experiments were performed after obtaining informed consent from each participant. The meaning and the purpose of this research were fully explained to the subject in advance. The experiment could be stopped by any times by a subject's intention.

A tactile stimulator using a piezoelectric actuator (KGS Corp.), consists of eight cylindrical pins of 1.3 mm diameter. It was used as a Braille display. Each pin is arranged with 2 ×

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4 at intervals of 2.4 mm. Each pin moves up and down 0.7 mm. All pins were interlocked simultaneously for this study. The stimulus intensity was controlled by the voltage: at high voltage, the pins move quickly. Consequently, strong tactile stimulus was applied to the subject. The signals of on-stimulus and off-stimulus were input to the EEG system as the trigger for averaging.

The stimulus part was either a left or right index finger or great toe of the foot. The finger or toe was put lightly on the stimulus device. The stimulus intensity was set that every subject was able to recognize the tactile sense. The intensity was insufficient to cause pain even if repeated stimuli were applied to the subject. The constant interval was used as the stimulus patterns. The stimulus duration and the blank duration were fixed to 1 s. Because the on-stimulus and off-stimulus were one set, 38 sets of each experiment were conducted.

The EEG signals were measured using a multichannel digital electroencephalograph (EEG-1100; Nihon Kohden Corp.) and were digitized with the sampling frequency of 250 Hz. The subject put on an electrode cap (Easy Cap; Falk Minow Services) with 100 Ag–AgCl electrodes, which is the arrangement of the extended international 10–20 method. The eye-blink artifacts were eliminated by monitoring the electrooculogram. Moreover, the coordinates of the electrode arrangement were measured using a three-dimensional position digitizer (3SPACE Fastrak; Polhemus) to obtain a transfer function in cortical dipole imaging.

### *B. Cortical Potential Imaging*

To analyze the spatiotemporal behavior of the SEPs with high precision, the spatial resolution has been improved using the cortical potential imaging. The head volume conductor was approximated by an inhomogeneous three concentric sphere model [11]. The normalized radii of the brain, the skull, and the scalp spheres were taken as 0.87, 0.92, and 1.0, respectively. The normalized conductivity of the scalp and the brain was taken as 1.0, and that of the skull as 0.0125. This model incorporates variation in the conductivity of different tissues such as the scalp, the skull, and the brain. It has been used to provide a reasonable approximation to a head volume conductor for cortical dipole imaging. An equivalent dipole layer within the brain simulates the brain electrical activity. Radial dipoles are distributed uniformly over a sphere inside of the brain.

The scalp potential distribution measured by scalp surface electrodes, $\mathbf{g}$, is derived by the vector of the equivalent dipole sources, $\mathbf{f}$, distributed over the dipole layer by application of the transfer matrix, $\mathbf{A}$, from the equivalent dipole sources to the scalp potential signals and the additive noise, $\mathbf{n}$:

$$\mathbf{g} = \mathbf{A}\,\mathbf{f} + \mathbf{n} \tag{1}$$

The transfer matrix from the dipole layer to the scalp potential is obtained by considering the geometry of the head model, the electrode position, and the physical relations among the quantities involved. The dipole layer distribution is reconstructed from the recorded scalp potential by solving an inverse problem. Consequently, the dipole source distribution $\mathbf{f}_0$ is estimated by the spatial inverse filter, $\mathbf{B}$:

$$\mathbf{f_0} = \mathbf{B}\,\mathbf{g} \tag{2}$$

The number of measurement electrodes is always much smaller than the dimensions of the unknown solution. Therefore, this problem is an underdetermined inverse problem. For this study, a Tikhonov zero-order regularization filter [18] was used as the spatial inverse filter.

$$\mathbf{B} = \mathbf{A}^{\mathbf{T}}\,(\mathbf{A}\,\mathbf{A}^{\mathbf{T}} + \gamma\,\mathbf{I})^{-1} \tag{3}$$

where $\mathbf{A}^{T}$ is the transpose matrix of $\mathbf{A}$, $\mathbf{I}$ is the identity matrix, and $\gamma$ is the regularization parameter. The regularization parameter was determined using the L-curve method [19].

Moreover, if the anatomical data of the brain can be obtained, the brain electrical activity should be projected on the realistic-shaped cortical surface. The cortical potential map, $\mathbf{h}_0$, was estimated from the scalp potential map via the dipole distribution, $\mathbf{f}_0$:

$$\mathbf{h_0} = \mathbf{C}\,\mathbf{f_0} \tag{4}$$

where $\mathbf{C}$ is the transfer matrix from the dipole layer distribution to the cortical potentials. We employed the realistically-shaped cortical surface data modeled by Okamoto [20]. This model is considering the averaged geometry of Japanese human head. It will be more precise if we could obtain the head model from same subject. Actually, $\mathbf{h}_0$ can be directly calculated from $\mathbf{g}$ by applying $\mathbf{CB}$.

## III. Results

### *A. Simulation*

Before applying to the SEP experimental data, the visualization ability of the cortical potential imaging was conformed in computer simulation. The scalp potential was observed with 128 electrodes. The dipole distribution was represented by 1280 radial dipoles with various depths. The cortical potentials were estimated from the dipole distribution. The scalp potential was blurred with the low conductivity of the skull. The cortical dipole distribution with the depth of 0.7 was estimated from the scalp potential by applying the spatial inverse filter based on Tikhonov regularization. Moreover, the cortical potential mapping was calculated from the dipole distribution using the transfer matrix from the dipole layer to the cortical surface potential. Because the cortical potential was plotted based on the realistic cortical surface, we could obtain the anatomical information of localized area.

The relative error and the correlation coefficient between actual and estimated cortical potentials when changing the radius of dipole layer were plotted in Fig. 1. One negative radial dipole source was located at left hemisphere with the eccentricity of 0.6 to simulate the somatosensory activity. When the relative error was small, the correlation coefficient became large. In the case of the dipole source with the eccentricity of 0.6, if the depth of the dipole layer was set to 0.65-0.75, the relative error decreased while the correlation coefficient increased. That is, the accuracy of the cortical potential would be improved when the spherical dipole layer was set to cover the dipole source.

### *B. Somatosensory Evoked Potential*

We recorded 35 single responses to obtain averaged SEP data using the triggers of on-stimuli and off-stimuli. A fifth-order Butterworth filter was used for the band pass filter with the frequency band between 1.6 Hz and 35 Hz. Cortical

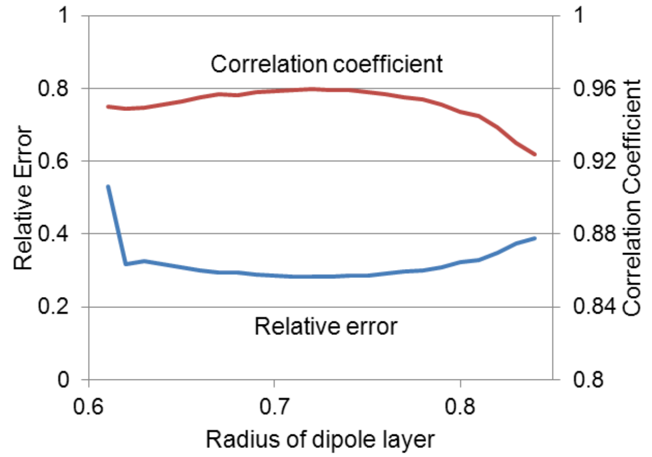


Fig. 1. Relative error and correlation coefficient between actual and estimated cortical potentials when varying the radius of dipole layer. The dipole source was located at the eccentricity of 0.6. In this case, the radius of 0.73 was optimum for the dipole layer.

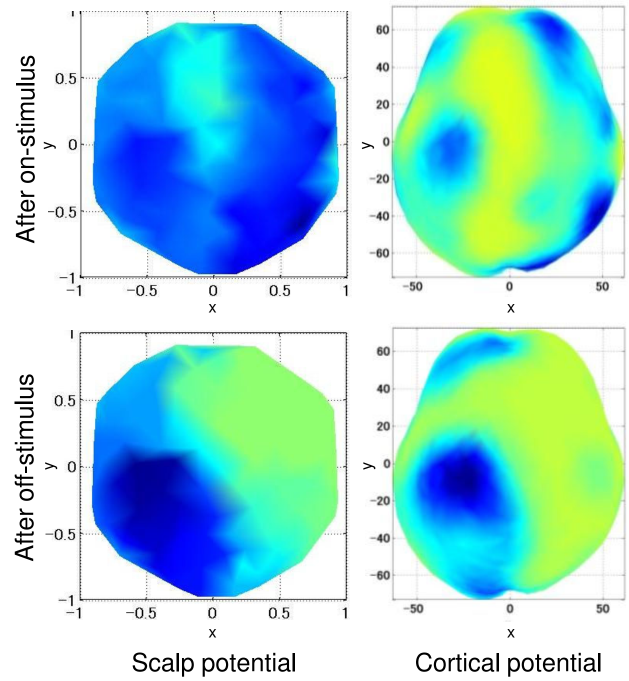


Fig.2. Scalp potential (Left) and cortical potential (Right) distributions at N80 after on-stimulus (Upper) and off-stimulus (Lower) on right hand with 5V. The negative peak was observed in the primary somatosensory area of the left brain in both cortical potential distributions. .

potential imaging was applied to this scalp potential mapping. Based on heuristic results, the number of dipoles was set to 1280 and a radius of the dipole layer was set to 0.70 [12]. Several peaks were commonly appeared in SEP waveforms of all subjects after on-stimuli and off-stimuli. Especially, we paid attention to the first negative peak N80 that appeared about 80ms after the stimuli [4].

The cortical potential mappings were estimated from the scalp potential at the peak N80. Figure 2 shows examples of the measured scalp potential mappings (left) and the estimated cortical potential mappings (right) of a representative subject after on-stimulus (upper) and after off-stimulus (lower). The scalp potential and the cortical potential are normalized by the maximum of the absolute amplitudes. Moreover, in displaying cortical potential mappings, the signal contrary to the polarity of the peak was masked by zero in order to emphasize the information on each peak. That is, the positive values were set to zero at the negative peak of N80. The localized area cannot be found from the scalp potential mappings because of the low spatial resolution. On the other hand, the spatial resolution of the signal has been improved by application of cortical potential mapping. It became easy to specify the activated part within the brain. When the tactile stimulus was applied to the index finger of the right hand, the negative peak of N80 was observed in the primary somatosensory area of the left brain. The results of the SEP signals and mappings in on-stimuli and off-stimuli were almost identical. This phenomenon produced the same results even if the position and the intensity of the stimulus were changed.

Next, we obtained the cortical potential mappings when changing the stimulus position. The results for the negative peak N80 are depicted in Fig. 3. The result is shown after on-stimulus with the intensity of 5 V constant. A negative spot was observed at a primary somatosensory area of the left brain when a stimulus was applied on the right hand. However, the negative spot was observed at a primary somatosensory area of the right brain when stimulus was applied on the left hand, which means that N80 had appeared at the opposite side of the primary somatosensory area against the stimulus side. When stimulating the right or left foot, both peaks were observed at the parietal lobe because the primary somatosensory area of feet was close to the median plane. The results of other subjects were similar to these results.

## IV. Discussion

To evaluate the human response to somatic sensation objectively, we paid attention to the latency and mapping of the SEP. The spatial resolution of the EEG data is insufficient under the influence of the low conductivity of the skull. Therefore, the cortical potential imaging was applied to realize high-resolution imaging. It was confirmed that the activated signal was localized by cortical potential imaging compared with the scalp potential imaging. In this research, we attempted to purely improve the spatial resolution of the SEP using Tikhonov regularization which does not need the statistical information on signal and noise.

The results shown in Fig. 2 indicate that when the stimulus interval was constant, the SEP data after on-stimuli and off-stimuli showed similar responses. This result was identical to those obtained from an earlier study using MEG; it is not apparent in the case of the electrical stimulus [4]. It is considered that the shape on the skin surface will change with the mechanical stimulus, although the form does not change with the electrical stimulus. Moreover, the SEP waveforms in a time-series were similar even with different positions, intensities, and patterns of the stimuli. First, activation was observed at the somatosensory area at about 80 ms after stimuli (N80). Subsequently, the reversal of potential was

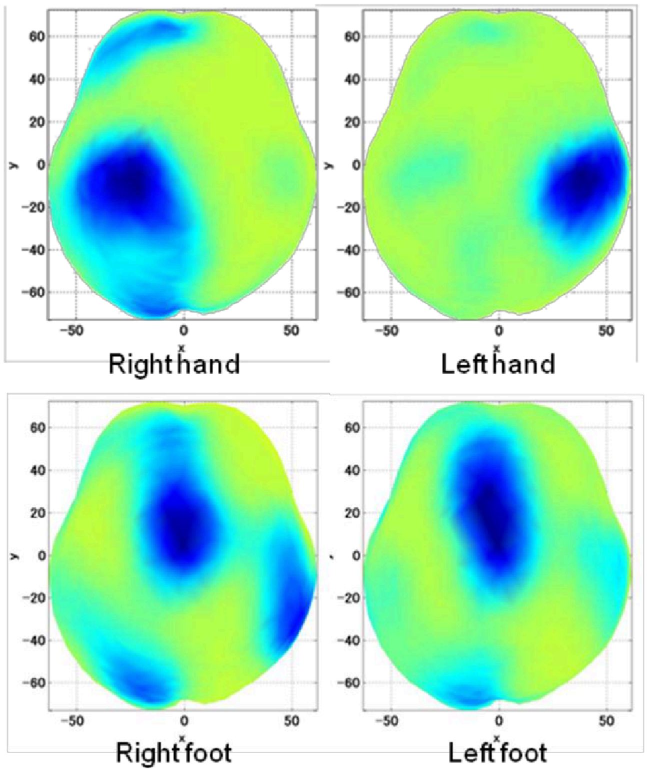


Fig. 3. Cortical potential distributions at N80 when varying the stimulus position. A negative spot was observed at a primary somatosensory area corresponding to the stimulus positions.

repeated at around the parietal and frontal lobes from 100ms to 400ms after stimuli. This phenomenon is thought to show the transmission process of somatosensory information within the brain.

As shown in Fig. 3, by changing the stimulus position, the negative peak N80 appeared at a primary somatosensory area of the opposite side against the stimulus side at about 80 ms after the stimulus. These positions for the hand and the foot were in agreement with Penfield's brain map showing the functional localization of the primary somatosensory area. Therefore, it is considered that the stimulus position is distinguishable from the cortical potential mapping for the peak N80. Using high-resolution cortical potential imaging, the stimulus on other body parts might be identified in addition to those on the hand and the foot. The somatosensory area of the hand was separated from the median plane. Therefore, it was easily discriminable. However, because the somatosensory area of the foot was close to median plane, it was difficult to distinguish the right and left differences. If we obtain the information on the dipole orientation, right and left feet would be distinguishable.

In conclusion, the SEP evoked by the mechanical stimulations of the tactile sensation was measured and analyzed in spatial domains. The cortical potential mapping projected onto the realistically-shaped cortical surface was estimated to improve the spatial resolution of the SEP maps. The experimentally obtained results suggest that the position of the stimulation could be distinguished by observing the position of the negative peak in the primary somatosensory area at about 80ms after the stimulus. Based on these results, the objective evaluation of other feelings, such as painfulness and temperature, is also considered near future.

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