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Objective Evaluation of Somatic Sensation for Mechanical Stimuli by Means of Cortical Dipole Layer Imaging

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Abstract— **In clinical situations, 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 and 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 spatial resolution of SEP maps was improved 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 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 a more effective method to resolve brain functions in daily life than either MRI or PET because of its low cost, easy installation, and few restrictions on the measurement environment. However, EEGs present the problem that the spatial resolution is low due to the low conductivity of the skull. Therefore, it has remained difficult to estimate electrical activity within a brain directly from the potential distribution on the scalp surface. To solve this problem, various techniques have been investigated to improve the spatial resolution of EEG [5]–[8]. For review, see [8]. Cortical dipole imaging is one spatial enhancement technique [5]–[7]. 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. 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 dipole imaging, it is expected that the spatial resolution of brain electrical activity would be improved, especially for the evaluation of somatic sensation.

Moreover, 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 somatosensory evoked potential (SEP) 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 by application of cortical dipole imaging to the scalp potentials. 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.

A tactile stimulator using a piezoelectric actuator (KGS Corp.) is presented in Fig. 1. This actuator, used as a Braille display, consists of eight cylindrical pins of 1.3 mm diameter. Each pin is arranged with 2×4 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

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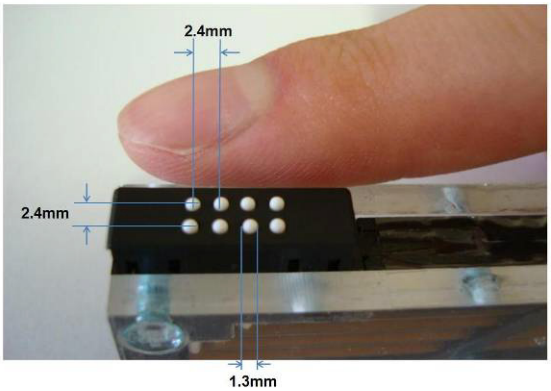

Fig. 1. Tactile stimulator using piezoelectric actuator.

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. Figure 1 shows that the hand or the foot was put lightly on the stimulus device. The stimulus intensity was set to 1.5 V, 5.0 V, or 8.5 V. Here, the voltage of 1.5 V was a value that every subject was able to recognize with tactile sense. The voltage of 8.0 V was insufficient to cause pain even if repeated stimuli were applied to the subject. Three patterns of constant interval, random stimulus duration, and random blank duration were used as the stimulus patterns. In constant interval stimulus, the stimulus duration and the blank duration were fixed to 1 s. However, in random stimulus, the stimulus duration was random from 1 to 5 s. In contrast, in random blank, the blank duration was random from 1 to 5 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. Moreover, to obtain a transfer function in cortical dipole imaging and to display the EEG mapping, the coordinates of the electrode arrangement were measured using a three-dimensional position digitizer (3SPACE Fastrak; Polhemus).

B. Cortical Dipole Imaging

To analyze the spatiotemporal behavior of the SEPs with high precision, the spatial resolution has been improved using cortical dipole imaging. For this study, the head volume conductor was approximated by an inhomogeneous three concentric sphere model [5]. Dipoles are distributed uniformly over a sphere inside of the brain. 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. The transfer matrix from the dipole layer to the scalp potential is obtained by considering the geometry of the model and the physical relations among the quantities involved. The dipole layer distribution is reconstructed from the recorded scalp potential by solving an inverse problem.

The scalp potential distribution measured by scalp surface electrodes is derived by the vector of the equivalent dipole sources distributed over the dipole layer by application of the transfer matrix from the equivalent dipole sources to the scalp potential signals and the additive noise. It is important to infer the origins from the recorded EEG and to map the sources that generate the scalp EEG. Consequently, the dipole source distribution is estimated by the spatial inverse filter. 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 [9] was used as the spatial inverse filter. The regularization parameter was determined using the L-curve method [10]: if the norm of the solution is shown on the vertical axis and the residual norm of observed signal is shown on the horizontal axis, then the line changing the parameter draws an L-shaped curve. In the L-curve, we determined the optimum gamma at which the curvature is maximal.

C. Analysis Method

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. The processed data were mapped on the scalp surface based on the measured electrode coordinates. Cortical dipole 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 [5]–[7]. For the experiments on stimulus intensities and stimulus patterns, the averaged amplitude of the remarkable peak over the localized spatial and time domains was calculated to evaluate quantitatively. Four subjects underwent the experiments twice. Differences in the conditions of stimulus intensities and stimulus patterns were evaluated statistically.

III. Results

An example of SEP waveforms after on-stimuli and off-stimuli is presented in Fig. 2. The right hand was stimulated with 5 V. The stimulus point was set to 0 ms. The peaks commonly appearing in all subjects were expressed as P1, P2, ..., and P5 in ascending order of the latency.

The dipole distributions were estimated from the scalp potential at each peak of Fig. 2. The localized area cannot be found from the scalp potential mappings because of the low spatial resolution. However, the spatial resolution of the signal has been improved by application of cortical dipole imaging.

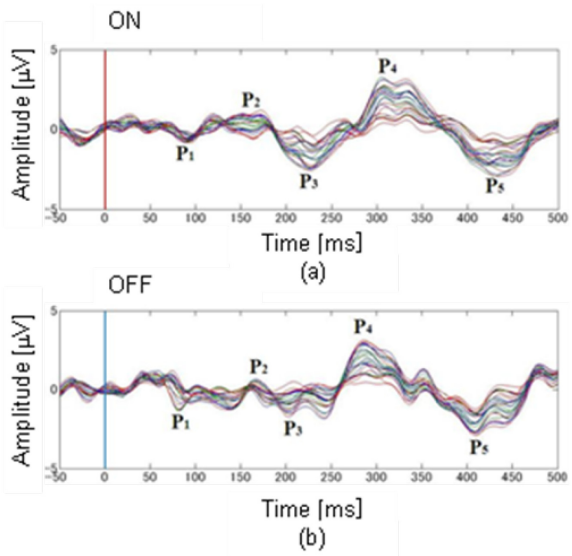

Fig. 2. SEP waveforms when stimulating on right hand with 5 V: (a) after on-stimulus and (b) after off-stimulus.

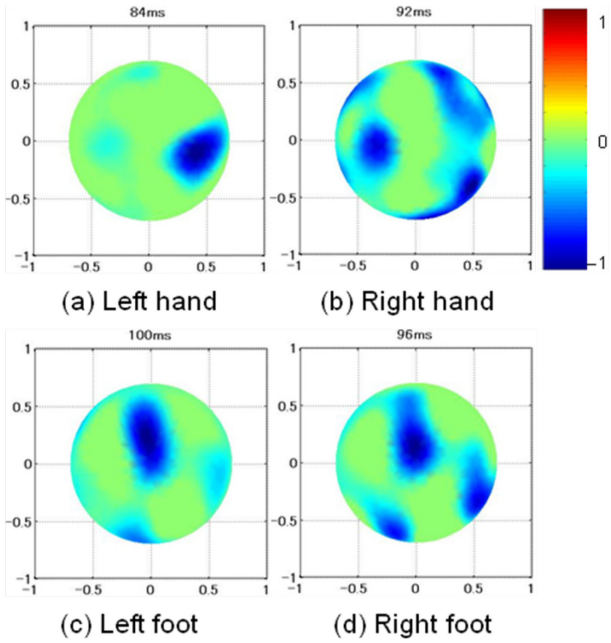

Fig. 3. Dipole distributions at P1 when varying the stimulus position.

It became easy to specify the activated part within the 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. When the tactile stimulus was applied to the index finger of the right hand, the negative peak of P1 was observed in the primary somatosensory area of the left brain. Moreover, the peaks at P2–P5 were observed at the parietal and frontal region, which is not related with the position or the intensity of the stimuli.

Next, we obtained the dipole distributions when changing the stimulus position. The results for the negative peak P1 are depicted in Fig. 3. The positive values of the dipole distribution were masked by zero. Only the negative values were displayed to emphasize the negative potential. 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 P1 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.

Moreover, the dipole distributions were estimated when changing the stimulus intensity. The mean amplitudes of the dipole distribution at P1 over eight experiments with four subjects are portrayed in Fig. 4 for different stimulus intensities. The mean amplitude became significantly large, so that the stimulus was strong. Compared with the mean amplitude of the 5.0 V stimulus, the mean amplitude changed about 70% in the 1.5 V stimulus and about 120% in the 8.5 V stimulus.

The SEP waveforms with random stimulus were evaluated in comparison with the constant stimulus. If the stimulus duration was random, the P4 amplitude decreased. If the blank duration was random, then the P4 amplitude increased. The mean amplitudes of the dipole distribution around P4 over 8 experiments were presented in Fig. 5 for stimuli with constant and random intervals. As compared with the constant interval stimulus, the amplitude of P4 decreased to about 35% for the random stimulus. However, the amplitude increased to about 160% of the constant interval stimulus for the random blank. Even if the amplitudes mutually differed, the activation parts in the dipole distribution were the same as the constant interval stimulus.

IV. Consideration

To evaluate the human reaction to somatic sensation objectively, we devoted attention to the latency and mapping of the SEP. The spatial resolution of the EEG data is low under the influence of the low conductivity of the skull. Therefore, the cortical dipole imaging was applied to realize high-resolution imaging. It was confirmed that the signal was localized by cortical dipole imaging compared with the scalp potential mapping. According to these visualization techniques, we were able to obtain not only information in the time domain such as the SEP duration, but also information in the spatial domain including the activation position. The spatial resolution would be improved using the signal and noise covariance incorporated inverse filter based on independent component analysis [11].

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. These results were identical to those obtained from an earlier study using MEG; it is not apparent in the case of the electrical stimulus [4]. It is

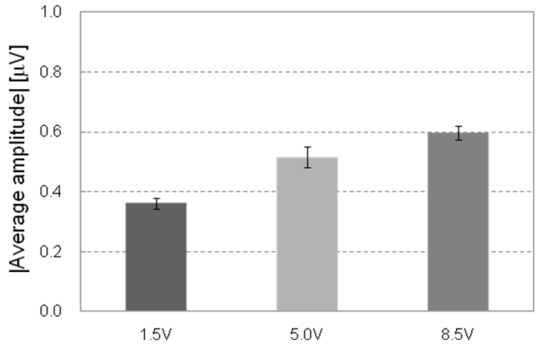

Fig. 4. Averaged amplitudes of P1 when varying the strength of the stimulus.

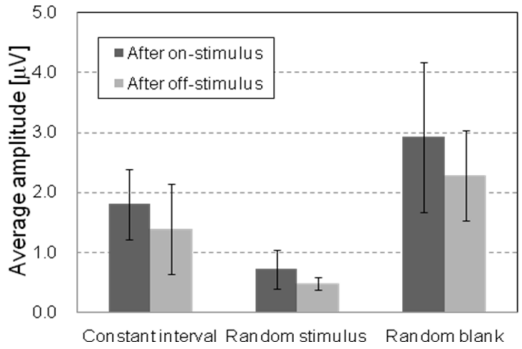

Fig. 5. Averaged amplitudes of P4 when varying the stimulus pattern.

considered that the form 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 (P1). Subsequently, the reversal of potential was repeated at around the parietal and frontal lobes: P2, P3, P4, and P5. 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 P1 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 dipole distribution for the peak P1. Using high-resolution cortical dipole imaging, the stimulus on other body parts might be distinguished 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.

The strength of a stimulus is distinguishable by observing the dipole distribution for P1. However, for some subjects, the dipole distribution did not change even if the stimulus intensity was changed. That is true because of the influence from the individual difference of the sensitivity. The threshold of the sensation is different in each subject. Therefore, it is necessary to assess the threshold for the experiments by changing the stimulus intensity.

The difference of the stimulus pattern might be distinguished from the amplitude of the peak P4 at about 300 ms after the stimulus. The positive peak P4 was considered as the event-related potential P300, which is related to cognitive tasks such as caution or consciousness. The amplitude of P300 decreases when the subject is indifferent to the target stimulus. It increases so that the appearance frequency of the target stimulus becomes low. Regarding random stimulation, the stimulus duration was longer than the duration of the blank. The reaction to the stimulus became blunted. Therefore, the amplitude of P4 might have decreased. However, for the random blank, the blank duration was long, and the subject was anticipating the coming stimulus. The reaction to the stimulus became sharpened. Therefore, it is thought that the amplitude of P4 increased.

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