Waveform Analysis of SEF to Three Different Finger Stimulations based on 3-D Magnetic Measurement

Bong-Soo Kim and Yoshinori Uchikawa
School of Science and Engineering, Tokyo Denki Univ., Ishizaka, Hatoyama, Hiki-gun, Saitama 350-0214, Japan

We carried out measurement of somatosensory evoked fields (SEFs) by applying an electric stimulus to different right fingers (the thumb, fourth finger, and little finger), using three-dimensional second-order gradiometers connected to 39-channel SQUIDs, which can detect magnetic components perpendicular to the scalp (Br) and tangential to the scalp (Bθ, Bφ) simultaneously. A singular value decomposition method was applied to the SEF data for preprocessing. To discriminate the activities of multiple nerves (the median nerve and ulnar nerve) in the fourth finger, time-frequency analysis (wavelet transform) was applied to each set of SEF data. The dominant distribution of power spectrum to the thumb (median nerve) stimulation was different from the distribution of the little finger (ulnar nerve) stimulation (thumb: 16-18 Hz, little finger: 13-15 Hz). However, the fourth finger showed the distribution that combined the results of the thumb and little finger. Furthermore, coherence between each set of SEF data showed a high value in that frequency range. Source localization was also examined by the SEF data with different frequency ranges. We conclude that the proposed method is useful for detecting the frequency component of the SEF data obtained by stimulation of different fingers and for discriminating multiple sources of SEF data in the fourth finger.

Key words: time-frequency analysis, wavelet transform, magnetoencephalogram, and coherence

1. Introduction

Measurement of the magnetic field perpendicular to the scalp has been widely used for research on brain functions. Magnetoencephalogram (MEG) has become a useful tool to investigate brain activity since it has the theoretical advantages of obtaining magnetic field with less skull effects. Somatosensory evoked field (SEF) evoked by median nerve stimulation have shown the generators to locate in the hand area of the human cortex, which fits well with the result reported by Penfield[1],2]. There are problems of separating multiple sources when many distinct areas of cortex are active[3]. Secondary somatosensory (SII) activity is a well-known example of that problem. The SII activity has a smaller intensity and appears in a shorter period. Activation of the SII is also overlapped in time with primary somatosensory (SI) activity[4,5]. We have proposed an algorithm to discriminate the SII from the SI activity[6]. These reports had focused on the spatial distribution or signal source estimation for separating multiple sources.

The nerve activity to elicit evoked magnetic field is different to human hand (median nerve: the thumb and second to fourth finger, ulnar nerve: fourth and little finger). Therefore, evoked field with human fourth finger is consisted by two different nerve activities[7]. It is desired a certain method to separate multiple source activities in the somatosensory evoked field data, such as above two examples. There are only a few reports about separating the multiple sources of the SEF to the fourth finger stimulation[8]. The SEF was measured by stimulation to the five fingers, respectively. The research discussed not discrimination of multiple sources but only a location of each signal source at typical latency.

In this study, we carried out the SEF measurement with stimulus to three different fingers (the thumb, fourth finger, and little finger), respectively. In order to discriminate the multiple sources (fourth finger) in the human cortex overlapping in time, we focus on frequency component of fourth finger. First, Time-frequency analysis (wavelet transform, WT) was applied to discuss the frequency component of each SEF data. Second, difference of frequency component in the SEF to the fourth finger stimulation was discriminated by coherence method. Finally, source estimation was done by the SEF data having different frequency ranges (13-15Hz and 16-18Hz).

2. Method

2.1 Experiment

Fig.1 shows coordinate system and locations of measuring positions on a subject's head. C3 in Fig.1 correspond to ten-twenty electrode system and gray circles are measuring points. Four normal subjects (4 males, aged 21-24 years) participated to the SEF measurement. Informed consent to participate in the study was obtained from all subjects prior to the study. The SEF evoked by the electric stimulus to three different fingers (the thumb, fourth finger and little finger of right hand) were measured with a 3-D magnetic measurement system in a magnetically shielded room[9]. Duration of electric pulse was 0.4ms and intensity of the electric pulse was 3 to 6mA. Inter-stimulus interval (ISI) was 2000±100ms and the SEF data was sampled every 2 kHz. Digital filtering was performed with 1-80Hz BPF and notch filter. Sampled SEF data was averaged with 200 times. The SVD method was applied to the SEF data for
C3

1 a is a factor for normalization. Frequency and $\Pi C$ shown as follows $^{12}$) then the coherence between two time-series data can be respectively.

$$ (W_f)(b,a) = \int_\mathbb{R} \phi_a \left( \frac{x-b}{a} \right) f(x) dx $$

where a is scale parameter and b is shift parameter of the WT. Morlet wavelet is used for wavelet function, $\phi(\alpha) \sqrt{\alpha}$ is a factor for normalization. Frequency resolution of the WT in this study is 0.5 Hz.

In order to discuss the relationship of frequency component between the SEF data to the fourth finger and that of other fingers, coherence method was applied. Time-series of different SEF data are $B_i$ and $B_j$ and then the coherence between two time-series data can be shown as follows $^{20}$

$$ \gamma^2(f) = \frac{P_{ij}(f)}{P_i(f) P_j(f)} $$

where, $P_i$ and $P_j$ are power spectrum of $B_i$ and $B_j$, respectively. $P_{ij}$ shows cross power spectrum of $B_i$ and $B_j$. Coherence values are statistical values between 0 and 1.

Spatial distribution of each SEF data was also examined. Single source estimation was performed using the moving dipole inverse solution $^{13}$ with a spherical homogeneous conductor model as a human head. The cost function $f$ and Goodness-of-fit ($G$) are defined as

$$ f = \frac{\sum_{k=1}^n (B_{mk} - B_{c_k})^2}{\sum_{k=1}^n (B_{mk})} \quad (3) $$

$$ G = \sqrt{1 - f} \times 100 \ [%] \quad (4) $$

where $B_{mk}$ is the measured magnetic field at $k$-th position, $B_{c_k}$ is the calculated field.

### 3. Results

The WT analysis was applied to the each SEF data to discuss the frequency component. Fig.2 is a typical result of the WT with each SEF data to three different finger stimulations (subject A). Waveforms of upper panels in Fig.2 show typical SEF waveforms of Br component. Middle ((a)-(c) in Fig.2) and lower panels ((d)-(f) in Fig.2) show the results of the WT analysis of Br and $B_\theta$ components, respectively. Since the $B_\theta$ component, the other tangential component, did not show dominant power spectrum as a result of the WT analysis, that component was omitted in Fig.2. Average of the power spectrum was calculated using the results of the WT method in all measurement points. Normalization of averaged power spectrum in Fig.2 (a) to (f) was done with the extreme of the power spectrum, respectively. Intensity of the normalized power spectrum was represented by three different colors in Fig.2 (black: 0.9 to 1.0, dark gray: 0.6 to 0.9, gray: 0.3 to 0.6).
0.6 and white: less than 0.33), respectively. In the result of the SEF to the thumb stimulation (Fig.2 (a)), Power spectrum above 0.9 (black area) appeared at 15-20 Hz in 50-150ms. Power spectrum above 0.9 (black part) in Fig.2 (b), which showed the result of the SEF to the little finger stimulus, appeared at 10-15Hz in 50-200ms. On the other hand, power spectrum of fourth finger stimulus showed mixed pattern with the thumb and the little finger in Fig.2 (c). The B0 component (Fig.2 (c)) showed that dominant power spectrum was located to 10-20 Hz. Tangential component showed extreme just above the signal. From the dominant power spectrum was located to 10-20 Hz. Distribution of the power spectrum in Fig.2 (a) was smaller than that of the thumb. This frequency range also reflected the ulnar nerve (the little finger) activity. Fig.3 (c) shows the correlation between the thumb and the fourth finger (Fig.2 (b)) and Fig.3 (c). The correlation showed lower value (below ±0.3) in around 11.5 to 14.5Hz. This frequency range reflected the ulnar nerve (the little finger) activity, since the little finger was subtracted from the fourth finger in Fig.3 (b). The correlation showed higher value (>0.65) in around 15.5 to 18.5Hz. It also showed that this frequency range reflected the median nerve (the thumb finger) activity. Fig.3 (e) also shows the correlation between the little finger (Fig.2 (b)) and Fig.3 (c). The correlation showed higher negative value (> -0.85) in around 13.5Hz, since the power spectrum of the fourth finger was smaller than that of the thumb. This frequency range also reflected the ulnar nerve (the little finger) activity.

4. Discussion

The FFT method is widely used for analyzing frequency component of measured data. Frequency analysis by the FFT is effective for a periodic steady signal (e.g. alpha rhythm). Since magnetic response of the human cortex evoked by electrical stimulus was appeared short interval (< 0.85) in around 13.5Hz, since the power spectrum of the fourth finger... From the result of the FFT,
The coherence between the thumb and the fourth finger showed high value in 17-18Hz in Fig.4 (b) (17Hz: \( \chi^2 = 0.55 \), 18Hz: \( \chi^2 = 0.61 \)). The student t-test for a statistical analysis was applied to the coherence of the fourth finger and those of other fingers. It found that the frequency component of the SEF evoked by the median nerve (thumb) stimulation differed from that of the ulnar nerve (little finger). Furthermore, the fourth finger, existing two nerve activities, had both frequency components.

Spatial distribution of each SEF data was also examined. Digital filter (FIR filter) was applied to limit frequency band of the SEF to the fourth finger stimulation. A band pass filter processing, having different pass band (13-15 and 16-18Hz, -3dB points), was performed to the SEF. Low pass band (13-15Hz) corresponded to the little finger (ulnar nerve) and high pass band (16-18Hz) corresponded to the thumb (median nerve). Signal source estimation was done with the band pass filtered SEF data to the fourth finger stimulation and typical SEF data (1-80Hz BPF for the SEF data to the thumb and the little finger stimulations). Table 1 and Fig.5 show the results of the source estimation of the SEF data to three finger stimulations. The three latencies (52, 55, and 58ms) around the peak in Fig.2 were used for the source estimation. The GOF was calculated by equation (4) and Table 1 shows average of the GOF (mean\( \pm \)S.D.) at the

![Image](image_url)

**Fig.4** Result of coherence (Br component, black bar of (a) and (b) is the coherence between the thumb and little finger, gray bar of (a) is little and fourth finger, and gray bar of (b) is thumb and fourth finger, *: significance of difference (student t-test) is P < 0.05).
This study was supported in part by a grant from the 21st Century COE (Center of Excellence) program of ministry of Education, Culture, Sports, Science, and Technology in Japan, and Research Institute for Science and Technology of Tokyo Denki University (Q05S-02).

Acknowledgements This study was supported in part by a grant from the 21st Century COE (Center of Excellence) program of ministry of Education, Culture, Sports, Science, and Technology in Japan, and Research Institute for Science and Technology of Tokyo Denki University (Q05S-02).

References