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Partial Principal Component Elimination Method and Extended Temporal Decorrelation Method for the Exclusion of Spontaneous Neuromagnetic Fields in the Multichannel SQUID Magnetoencephalography

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Abstract

We employed a method eliminating a temporally partial principal component (PC) of multichannel-recorded neuromagnetic fields for excluding spatially correlated noises from event-evoked signals. The noises in magnetoencephalography (MEG) are considered to be mainly spontaneous neuromagnetic fields which are spatially correlated. In conventional MEG experiments, the amplitude of the spontaneous neuromagnetic field is much lager than that of the evoked signal and the synchronized characteristics of the correlated rhythmic noise makes it possible for us to extract the correlation noises from the evoked signal by means of the general PC analysis. However, the whole-time PC of the fields still contains a little projection component of the evoked signal and the elimination of the PC results in the distortion of the evoked signal. Especially, the distortion will not be negligible when the amplitude of the evoked signal is relatively large or when the evoked signals have a spatially-asymmetrical distribution which does not cancel out the corresponding elements of the covariance matrix. In the period of prestimulus, there are only the spontaneous fields and we can find the pure noise PC that is not including the evoked signal. Besides that, we propose a method, called the extended temporal decorrelation method (ETDM), to suppress the distortion of the noise PC from remanent evoked signal components. In this study, we applied the partial principal component elimination method (PPCE) and ETDM to simulated signals and the auditory evoked signals that had been obtained with our homemade 37-channel magnetometer-based SQUID system. We demonstrate here that PPCE and ETDM reduce the number of epochs required in averaging to about half of that required in conventional averaging.

Keywords : Alpha rhythm, brain noise, correlated noise, magnetoencephalography (MEG), spontaneous field, superconducting quantum interference device (SQUID)

I. Introduction

The high sensitivity of the superconducting quantum interference device (SQUID) sensor has enabled us to detect very weak cerebral magnetic fields generated by ionic currents flowing inside cortical neurons. By means of multichannel-based measurement of the neuromagnetic fields, we can find the locations of the current sources and we call the technique magnetoencephalography (MEG). The MEG is a useful noninvasive technique for

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investigating human brain functions. Especially, analyses of responses evoked by certain stimuli give us information on cortical locations related to specific functions in the processing of given stimuli. However, a number of repeated measurements (epochs) and an averaging process are required to detect evoked fields because the amplitude of the evoked fields is relatively smaller than that of the spontaneously generated neuromagnetic fields, e.g., alpha-rhythm, which are not related to the evoked signal under study. Therefore, we should develop a technique to distinguish the evoked fields from the spontaneous fields with a higher signal to noise ratio (SNR) by a smaller number of epochs in averaging. A reduction in the number of epochs in averaging can shorten the experimental time and results in relieving experimental subjects of physical restrictions such as fixation of their heads.

Generally, the spontaneous fields have strong spatial correlation across the recording multichannel sensors [1]. The spatial correlation can be extracted as a principal component (PC) and we can exclude the spontaneous field from raw data by principal component elimination method (PCEM) [2]. However, the noise PC obtained by PCEM still contains some projection components of the evoked signals and the subtraction of the noise PC results in distortion of the evoked signals. Especially, the distortion will not be negligible when the amplitude of the evoked signal is relatively large or when the evoked signals have a spatially asymmetrical distribution that does not cancel out the corresponding elements of the covariance matrix, i.e. in the case that the evoked signal source is not located at the center of the multichannel sensor system. Practically, the location of a signal source under study hardly coincides with the center of sensor system and the process of PCEM will induce a significant shift-error in estimating the position of a signal source.

In this paper, we propose two methods to overcome the problems mentioned previously. The first is partial principal component elimination method, which reduces the influence of evoked signal on the noise PC by using the PC in the period of prestimulus. The second is extended temporal decorrelation method, which corrects the shift error in the conventional PCEM. Here, we describe the principle and details of our methods, and demonstrate the problems in PCEM and the efficiency of our methods by utilizing simulated signals and noises, and present results of reduction in spontaneous fields measured by our homemade 37-channel SQUID magnetometer system in the auditory evoked signal experiment.

II. Principle and method

Principal Component Elimination Method

The magnetic fields measured by a P-channel SQUID magnetometer system in each epoch (total sampling number N) are expressed by a matrix $\boldsymbol{B}$, which consists of the components of (channel number P) × (sampled time number N). For $\mathbf{A} = (1/\sqrt{N-1})\mathbf{B}^{\mathrm{T}}$, $\mathbf{A}^{\mathrm{T}}\mathbf{A}$ is the $P \times P$ matrix called the covariance matrix. The singular value decomposition (SVD) of $\mathbf{A}$ is

$$\mathbf{A} = \mathbf{U}\mathbf{D}\mathbf{V}^{\mathrm{T}}, \qquad (1)$$

where the $P \times P$ orthogonal matrix $\mathbf{V}$ contains the eigenvectors $\mathbf{v}_p$ as columns and $\mathbf{D}$ is the diagonal matrix of the corresponding singular values σ_p, which are the deviations of the data along the principal axes. The largest singular value σ_1 and its corresponding right singular vector $\mathbf{v}_1$ describe the spontaneous noise because the variance of the noise is much larger than that of the evoked signal and the noise has a strong correlation across the channels. Therefore, we can regard the first PC, $\mathbf{v}_1^{\mathrm{T}}\mathbf{B}$, as a shape of spontaneous noise and subtracting the first PC from the original data results in eliminating the spontaneous field. The procedure can be expressed by

$$\mathbf{B}_{evoked} = \mathbf{B} - \mathbf{v}_1\mathbf{v}_1^{\mathrm{T}}\mathbf{B}. \qquad (2)$$

Extended Temporal Decorrelation Method

PCEM uses only the differences in data variances of each signal source. If the evoked field and the spontaneous field have similar variances, they cannot be separated by PC analysis. Even in the case that there are considerable differences in variances, PCs always contain some projection components of independent sources. In order to complete the separation of signal sources in the optical imaging data, a concept of extended spatial decorrelation (ESD) was reported [3]. In ESD, they assumed that the individual source signals are mutually uncorrelated, even if they are shifted relative to each other by small amount. Using the assumption, they separated image data into independent spatial signal sources. We utilize their assumption for the complete temporal separation of the spontaneous field signal from other signal sources such as the evoked signal and subtract the spontaneous field signal from raw data to obtain the pure evoked fields. We refer to this method as extended temporal decorrelation method (ETDM).

To perform ETDM, we should remove all information about the variances in all the PCs, i.e., normalizing PCs to unit variance. The normalized PCs are given by

$$\mathbf{x}_p = \sigma_p^{-1} \mathbf{v}_p^{\mathrm{T}} \mathbf{B}. \qquad (3)$$

Let **Y** denote the matrix that contains the independent source components as rows. Then we should find a weighting matrix **W** such that the rows of

$$\mathbf{Y} = \mathbf{W}\mathbf{X} = \mathbf{W}\mathbf{D}^{-1}\mathbf{V}^{\mathbf{T}}\mathbf{B} \qquad (4)$$

have zero cross correlation function. The optimal weighting matrix based on making the time-shifted correlation function zero is given by the solution of

$$\frac{1}{2}(\mathbf{G}_{\Delta T} + \mathbf{G}_{-\Delta T})\mathbf{W}^{-1} = \mathbf{\Lambda}\mathbf{W}^{-1}, \qquad (5)$$

where $G_{k\,p,\Delta T} = \left\langle x_{k,n} x_{p,n+\Delta T} \right\rangle_n$ is the shifted covariance matrix of the normalized PCs [4], $\mathbf{\Lambda}$ and $\mathbf{W}^{-1}$ are the eigenvalue matrix and the orthogonal eigenvector matrix, respectively. Now we can regard the first independent source, $\sigma_1 \mathbf{Y}_1$, as a pure shape of spontaneous field and subtracting that from the original data results in eliminating the spontaneous field. The result of EDTM can be expressed by

$$\hat{\mathbf{B}}_{evoked} = \mathbf{B} - \mathbf{v}_1 \sigma_1 \mathbf{Y}_1. \qquad (6)$$

Partial Principal Component Elimination Method

Even if the spontaneous field component can be extracted exactly by ETDM and it contains no other component, the components of other sources generating the baseline error still remain in the $\mathbf{v}_1$ of the Eq. (6). To eliminate the evoked signal components in $\mathbf{v}_1$, we perform the PC analysis for only the prestimulus period and find $\hat{\mathbf{v}}_1$ containing no information on the evoked signal, i.e. partial principal component elimination method (PPCE).

The result of ETDM+PPCE is given by

$$\tilde{\mathbf{B}}_{evoked} = \mathbf{B} - \hat{\mathbf{v}}_1 \sigma_1 \mathbf{Y}_1. \qquad (7)$$

III. Simulation and Measurement

Simulation of an Auditory Evoked Field Experiment

Our homemade SQUID magnetometer system has 37-channel sensors on a hemispherical surface. We use the Cartesian coordinate system with the origin is at the center coil in our simulation. The locations and the directions of 37 sensors are shown in Fig. 1.

We obtained the evoked field projection B_{Eit} at the i-th coil at time t by the following equation based on the Biot-Savart law,

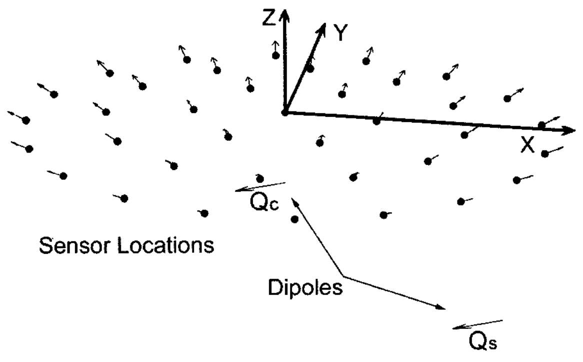


Fig. 1. The Cartesian coordinate system used in the simulation and the directions and the positions of 37 sensors. The $\mathbf{Q}_c$ and the $\mathbf{Q}_s$ are two positions of the simulated dipole.

$$B_{Eit} = \frac{\mu_0 \mathbf{Q}_t \times \mathbf{r}_i \cdot \mathbf{s}_i}{4\pi|\mathbf{r}_i|^3}, \quad (8)$$

where μ_0, $\mathbf{Q}_t$, $\mathbf{r}_i$, and $\mathbf{s}_i$ are the permeability of free space, the dipole moment at time *t*, the distance between the *i*-th sensor and the dipole, and the direction of the *i*-th sensor, respectively. We simulated experiments for two different positions of dipole, i.e. the center position, $\mathbf{Q}_c$, (0 mm, 0 mm, -65 mm) and the shifted position, $\mathbf{Q}_s$, (70 mm, -70 mm, -105 mm). The magnitude of the dipole moment at the occurrence of the evoked signal timing was changed according to a sinusoidal function of the first half period. In our case, we regarded the first 0.3 s as the prestimulus period and the occurrence of the evoked signal timing was at time $t = 0.4$ s (N100m). The direction and the maximum magnitude of both the dipole moments are ($\cos 220°, \sin 220°$, 0) and $|\vec{Q}_{\max}| = 4 \times 10^{-8}\ A \cdot m^2$, respectively. For the simple presentation, we used a simple sinusoidal function as the spontaneous field for all the channels. The frequency was 10 Hz and the amplitude was set to be the same as the maximum magnitude of the detected evoked signal. We superposed this sinusoidal noise upon the simulated evoked signals.

Figs. 2a and 2b show the generated evoked signals for the dipole $\mathbf{Q}_c$ and $\mathbf{Q}_s$, respectively. For both the cases, we present the results of PCEM (Figs. 2c and 2d), the results of PPCE (Figs. 2e and 2f), and the results of ETDM+PPCE (Figs 2g and 2h). For the symmetric field distribution ($\mathbf{Q}_c$), the noise PC was correctly found by PCEM because the contribution of the evoked positive fields cancels out the contribution of the evoked negative fields in the covariance matrix. However, the finite amplitudes of evoked signals affect on the v_1 of Eq. (2), which results in a baseline error of Fig. 2c. Fig. 2e shows it can be corrected by PPCE. When the fields have the asymmetric distribution ($\mathbf{Q}_s$), we observe a shift error. Figs 2d and 2f show positive evoked fields even though all the original evoked field are negative. Moreover, the baseline error appears as an aspect of spontaneous field (Fig. 2d). We can correct it by ETDM+PPCE (Fig. 2h).

Auditory Evoked Field Measurement

The 37-channel magnetometer system was applied to measure auditory evoked fields. As a nonmagnetic auditory stimulus, a capacitive earphone was used and the signal lines were twisted in pair.

Figs. 3a, 3b, and 3c show superposed 37 channel traces of the auditory-evoked responses and the spatial mappings of N100m peak for the conventional averaging, PCEM, and PPCE+ETDM, respectively. The mappings show dipolar features. Auditory stimuli of a 1-kHz tone burst, 170-ms duration, and about 70-dB normal hearing level were applied to the right ear of a normal human subject in a random interval, and field measurements were done over the left temporal lobe. Sampling rate was 500 Hz. The traces and the maps were obtained applying each method to 100 epochs of data, and through a digital 40-Hz low pass filter.

The N100m peak, field component generated about 0.1 s after the stimulus onset at the time 0.3 s, was obtained. This peak corresponds to the primary response of the auditory cortex to the sound stimulus.

The traces graphs shows the improvement in SNR and in the baseline-drift correction for both the results of PCEM and PPCE+ETDM. In this case, because the amplitude of evoked signal is much smaller than that of the overall noises, the baseline error was not significant. Therefore, PCEM gave a SNR similar to that of PPCE+ETDM. However, we can observe the slight shift (toward down-right direction) of the spatial fields distribution of PCEM (Fig. 3b) in comparison with Figs. 3a and 3c. This shift will also get larger if the signal source is more deviated from the center of sensors.

Reduction in the number of epochs in averaging

As we mentioned before, a reduction in the number of epochs in averaging is important for a practical experiment. In this section, we compare the SNR of PPCE+ETDM with that of the conventional averaging.

SNR is defined by two ways in our analysis. The first is the prestimulus region SNR (PSNR) defined by the ratio of the RMS values of signals (fields during 40 ms at the time of the peak occurrence) and noises (fields during 300 ms before the stimulus onset). The second is the evoked region SNR (ESNR) defined by the ratio of the former signal to RMS

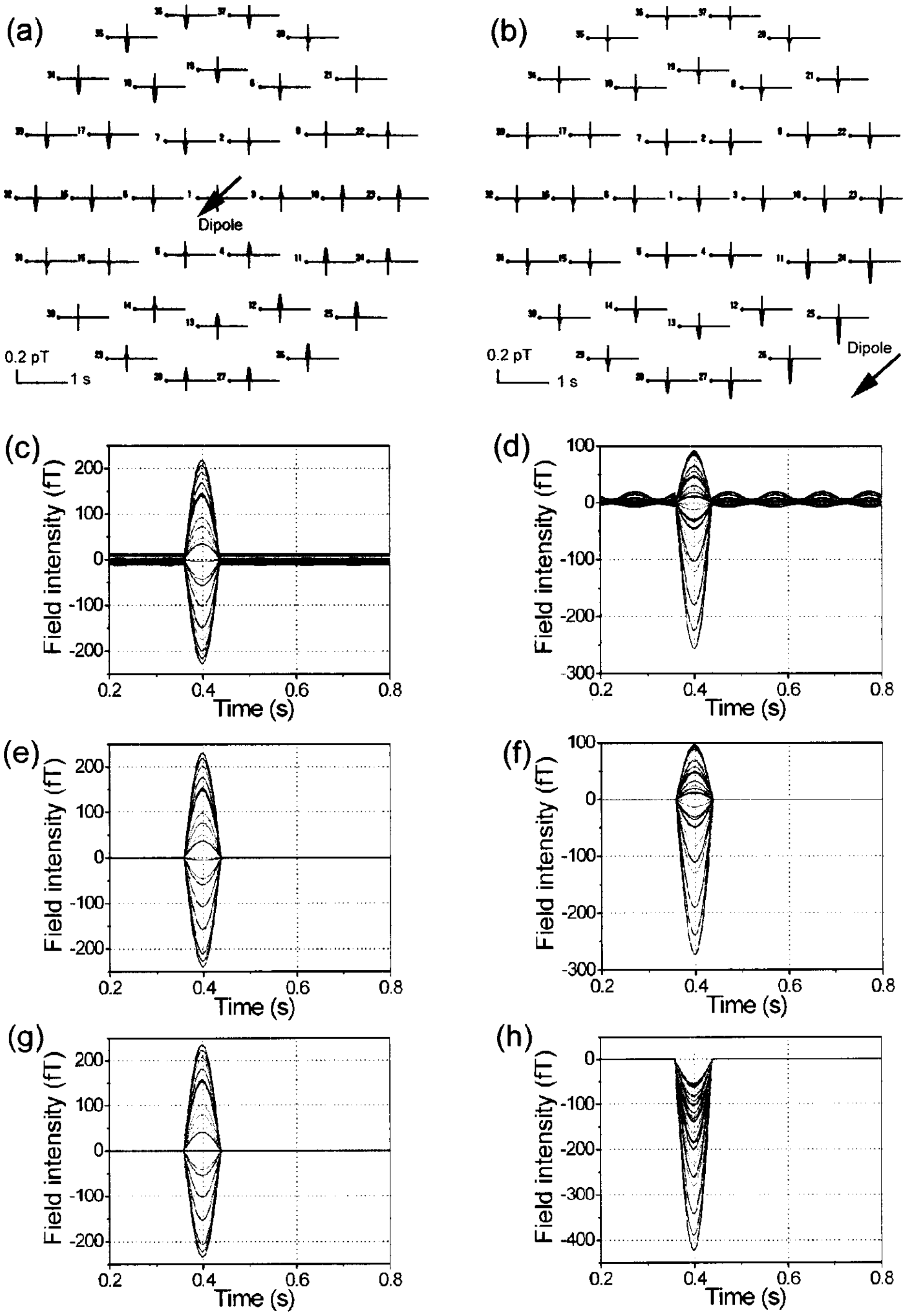
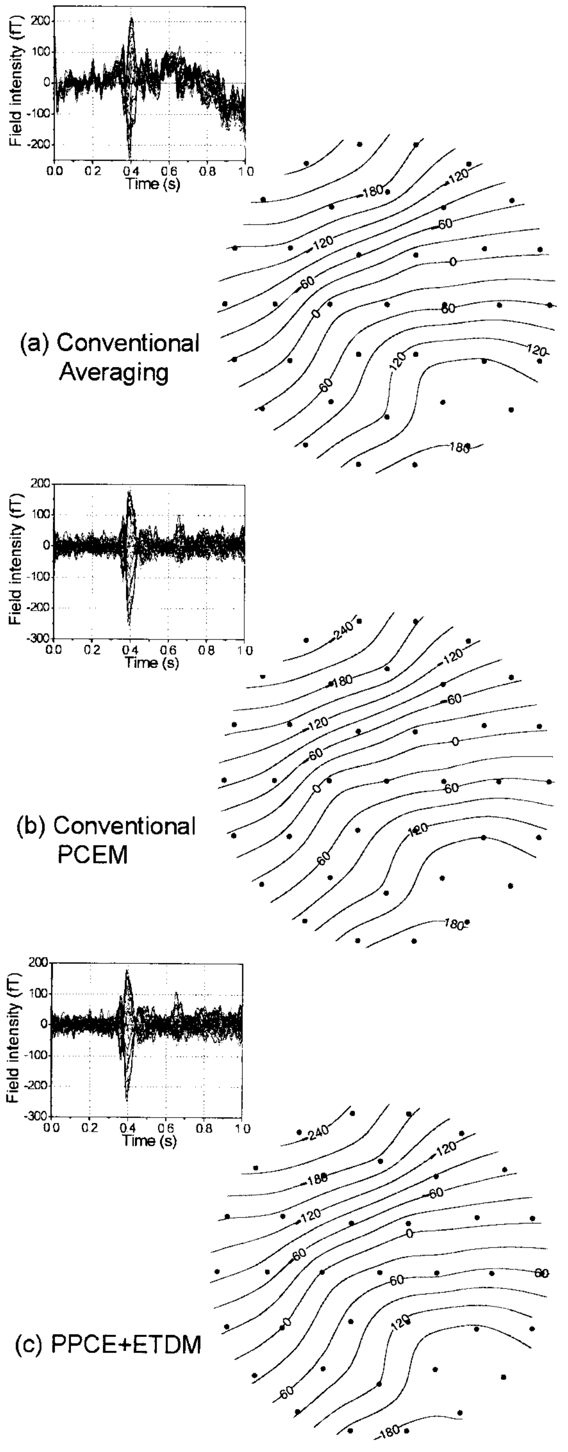


Fig. 2. (a) and (b) show the generated evoked signals for the dipole Q_c and Q_s, respectively. For both the cases, we present the results of PCEM, (c) and (d), the results of PPCE, (e) and (f), and the results of ETDM+PPCE (g) and (h). We can observe that there is no baseline error and shift error in (g) and (h).



(a) Conventional Averaging

(b) Conventional PCEM

(c) PPCE+ETDM

Fig. 3. Experimental results for the auditory evoked signal (the traces and the mappings for each method).

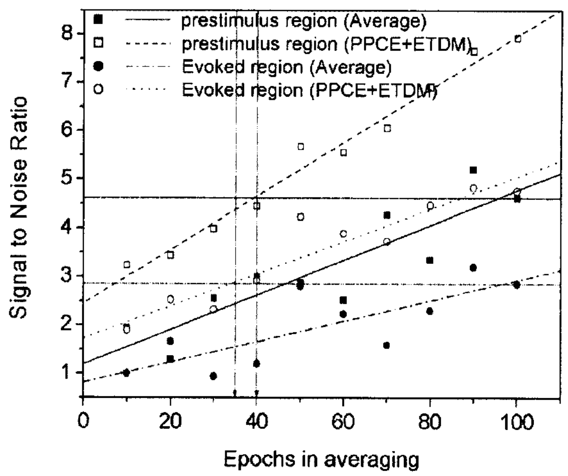


Fig. 4. SNRs of evoked fields obtained by PPCE+ETDM (open objects) and conventional method (filled objects) as a function of the number of epochs in averaging. Figure shows two types of SNR. One is for the prestimulus region and the other is for the evoked region. In both case, PPCE+ ETDM reduces the number of epochs required in averaging to less than half of that required in conventional averaging

noises that consist of fields during 300 ms after the disappearance of the N100m signal.

Changes in SNR as a function of the number of epochs in averaging were examined both for the evoked fields obtained by the conventional method and PPCE+ETDM (Fig. 4). Although SNR increased with increases in the number of epochs for both of the definitions and both of the methods, the increasing rates of SNRs in PPCE+ETDM were higher than those in the conventional averaging method. Here, we can obtain evoked fields that have the same PSNR of the evoked field obtained by conventional averaging over 100 epochs by averaging over only 40 epochs (35 epochs for ESNR). Even though the value of ESNR is less than that of the PSNR, the improvement in ESNR is better than that of PSNR, which is due to the correction of the baseline drift in PPCE+ETDM.

IV. Conclusion

We have proposed two methods, ETDM and PPCE, to correct the failures of PCEM that is used for eliminating spontaneous neuromagnetic field in evoked field experiments. We presented our methods correct successfully the shift error and the baseline error generated in PCEM by the evoked field simulation. We also applied our methods to the reduction in spontaneous fields in the auditory evoked signal experiment that had been measured by our homemade 37-channel SQUID magnetometer. We demonstrate that PPCE and ETDM reduce the number of epochs required in averaging to less than half of that required in conventional averaging.

Acknowledgments

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