Cortical Dipole Imaging of Movement-related Potentials by Means of Parametric Inverse Filters Incorporating with Signal and Noise Covariance

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Summary

Objective: The objective of this study is to explore suitable spatial filters for inverse estimation of cortical equivalent dipole layer imaging from the scalp electroencephalogram. We utilize cortical dipole source imaging to locate the possible generators of scalp-measured movement-related potentials (MRPs) in human.

Methods: The effects of incorporating signal and noise covariance into inverse procedures were examined by computer simulations and experimental study. The parametric projection filter (PPF) and parametric Weiner filter (PWF) were applied to an inhomogeneous three-sphere head model under various noise conditions.

Results: The present simulation results suggest that the PWF incorporating signal information provides better cortical dipole layer imaging results than the PPF and Tikhonov regularization under the condition of moderate and high correlation between signal and noise distributions. On the other hand, the PPF has better performance than other inverse filters under the condition of low correlation between signal and noise distributions. The proposed methods were applied to self-paced MRPs in order to identify the anatomic substrate locations of neural generators. The dipole layer distributions estimated by means of PPF are well-localized as compared with blurred scalp potential maps and dipole layer distribution estimated by Tikhonov regularization. The proposed methods demonstrated that the contralateral premotor cortex was preponderantly activated in relation to movement performance.

Conclusions: In cortical dipole source imaging, the PWF has better performance especially when the correlation between the signal and noise is high. The proposed inverse method was applicable to human experiments of MRPs if the signal and noise covariances were obtained.

Keywords

High-resolution EEG, cortical dipole imaging, inverse problem, parametric Weiner filter, signal and noise covariance, movement-related potential

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1. Introduction

It is of importance to obtain spatiotemporal information regarding brain electrical activity from noninvasive electromagnetic measurements. Because of inherit high temporal resolution of electroencephalogram (EEG) measurements, high resolution EEG imaging, which aims at improving the spatial resolution of the EEG modalities, has received considerable attention in the past decades. Such EEG imaging modalities would facilitate noninvasive localization of foci of epileptic discharges in the brain, and the characterization of rapidly changing patterns of brain activation. A number of efforts have been made in the development of high-resolution EEG techniques, which attempt to map spatially distributed brain electrical activity with substantially improved spatial resolution without ad hoc assumption on the number of source dipoles (for review, see [1]). Among them of interest is the spatial enhancement approach, which attempts to deconvolve the low-pass spatial filtering effect of volume conduction of the head [1, 2]. Cortical dipole layer imaging technique, which attempts to estimate the cortical dipole distribution from the scalp potentials, is one of the spatial enhancement techniques. In this approach, an equivalent dipole source layer is used to model brain electrical activity and has been shown to provide enhanced performance in imaging brain electrical sources as compared with the smeared scalp EEG [3-5].

The inverse problem of EEG is ill-posed and in general a regularization procedure is needed in order to obtain stable inverse solutions. Many regularization strategies, such as the generalized inverse with truncated singular value decomposition, minimum norm method, and Tikhonov regularization method, have been proposed for solving the ill-conditioned inverse problem [6]. Several methods have been developed to handle the non-uniformly distributed noise [7-9]. We have previously developed the parametric projection filter (PPF)-based cortical dipole layer imaging technique, which allows estimating cortical dipole layer inverse solutions in the presence of noise covariance [4]. We have applied this approach to perform the inverse regularization in equivalent dipole layer source imaging [4] and cortical potential imaging [10]. Our previous results indicate that the results of the PPF provide better approximation to the original dipole layer distribution than that of traditional inverse techniques in the case of low correlation between signal and noise distributions. Moreover, we have tested the proposed method in effectively rejecting time-variant artifact such as eyes blink artifact under the background noise [11].

Weiner reconstruction frameworks based on both signal and noise covariance matrices have been also investigated [3, 12-14]. We have studied the restorative abilities of the parametric Weiner filter (PWF) as compared with the PPF in simulation for an ideal homogeneous 3D head model [15].

In the present study, the performance of the proposed PPF and PWF has been evaluated by computer simulation under various noise conditions for inhomogeneous volume conductor spherical head model [16]. Moreover, the proposed method is applied for movement-related potentials (MRP) of fast repetitive finger movement protocols [17-20]. We utilize cortical dipole source imaging to locate the possible generators of scalp-measured MRPs in human.

2. Method

2.1 Principles of Cortical Dipole Imaging

In the present cortical dipole imaging study, the head volume conductor is approximated by the inhomogeneous three-concentric sphere model and a closed dipole layer of 1280 dipoles is used [16]. This head model takes the variation in conductivity of different tissues, such as the scalp, the skull and the brain, into consideration.

The observation system of brain electrical activity on the scalp shall be defined by the following equation:

$$g_k = Af_k + n_k \tag{1}$$

where f_k is the vector of the equivalent source distribution of a dipole layer, n_k is the vector of the additive noise and g_k is the vector of scalp-recorded potentials. Subscript k indicates the time instant. A represents the transfer matrix from the equivalent source to the scalp potentials. The inverse process shall be defined by

$$f_{0k} = B_k g_k \tag{2}$$

where B_k is the restoration filter and f_{0k} is the estimated source distribution of the dipole layer.

2.2 Inverse Techniques

When the statistical informations of signal and noise are presented, the Wiener filter can be applied to the inverse problem [3, 12]. Suppose R_k and Q_k the signal and the noise covariance, which can be derived from the expectation over the signal $\{f_k\}$ and noise $\{n_k\}$ ensemble, $E[f_k f_k{}^*]$ and $E[n_k n_k{}^*]$, respectively. $f_k{}^*$ and $n_k{}^*$ are the transpose of f_k and n_k, respectively. The PWF is derived by

$$B_k = R_k A^* (A R_k A^* + \gamma_k Q_k)^{-1} \tag{3}$$

with γ_k a small positive number known as the regularization parameter, and A^* is the transpose matrix of A. If $R_k = Q_k = I$ (the identity matrix), then Equation 3 is reduced to the zero-order Tikhonov regularization method. The PWF has been applied to brain source imaging [3, 12]. If it is difficult to obtain the signal covariance, R_k, the PPF has been introduced to solve the inverse problem [4, 10, 11]. The PPF is derived by

$$B_k = A^* (A A^* + \gamma_k Q_k)^{-1}. \tag{4}$$

The PPF considers just the covariance matrix of the noise distribution, Q_k, that is, $R_k = I$ in Equation 3. The restoration filters (Eqs. (3) and (4)) have a free parameter γ_k that determines the restorative ability. The determination of the value of parameter is left to the subjective judgment of the user. We have developed a new criterion that estimates the optimum parameter using iterative calculation for restoration [4]. The criterion estimates the parameter that minimizes the approximated error between the original and estimated source signals without knowing the original source distribution. In a clinical and experimental setting, the noise covariance, Q_k, may be estimated from data that is known to be source-free. The signal covariance, R_k, is calculated using observed scalp potentials, the transfer function, and estimated noise covariance [3]. Since the signal and noise are time-variant in EEG measurements, the signal and noise covariance, and the regularization parameter were supposed to be time-variant.

2.3 Simulation

We have applied Tikhonov regularization, PPF, and PWF to the inverse problem of the cortical dipole layer imaging in inhomogeneous head model. Two radial dipoles, located at the center position, were used as the

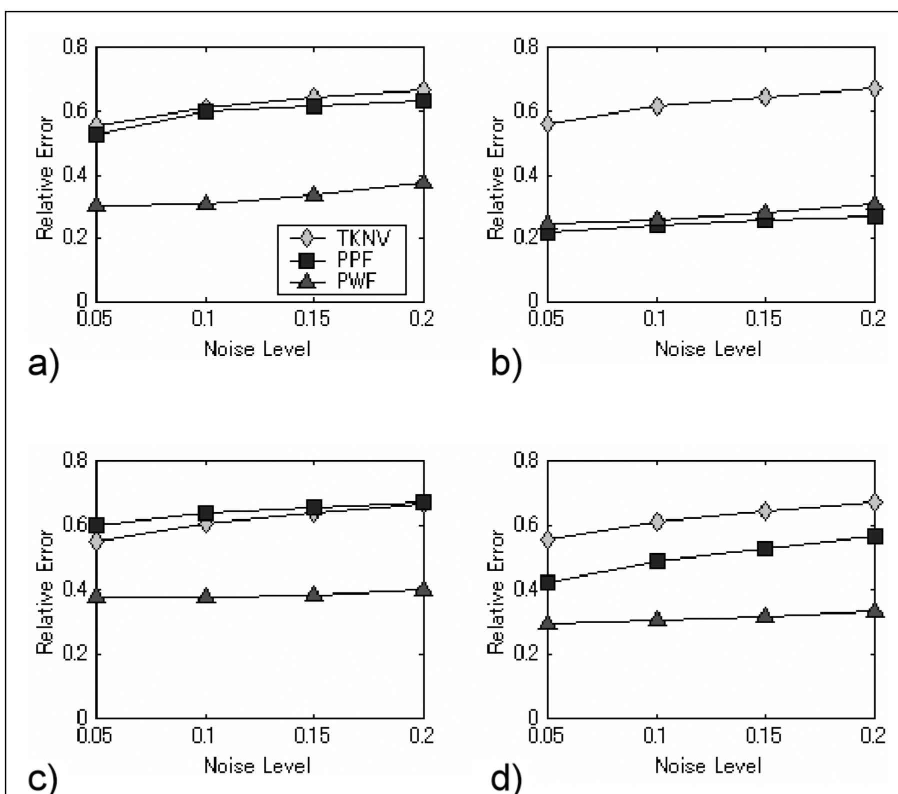

Fig. 1 Simulation results of relative error between actual and estimated cortical dipole layer distributions against the noise level. The scalp potentials were contaminated with a) uniform Gaussian white noise, b) edge-, c) center-, and d) side-concentrated non-uniform noise configurations.

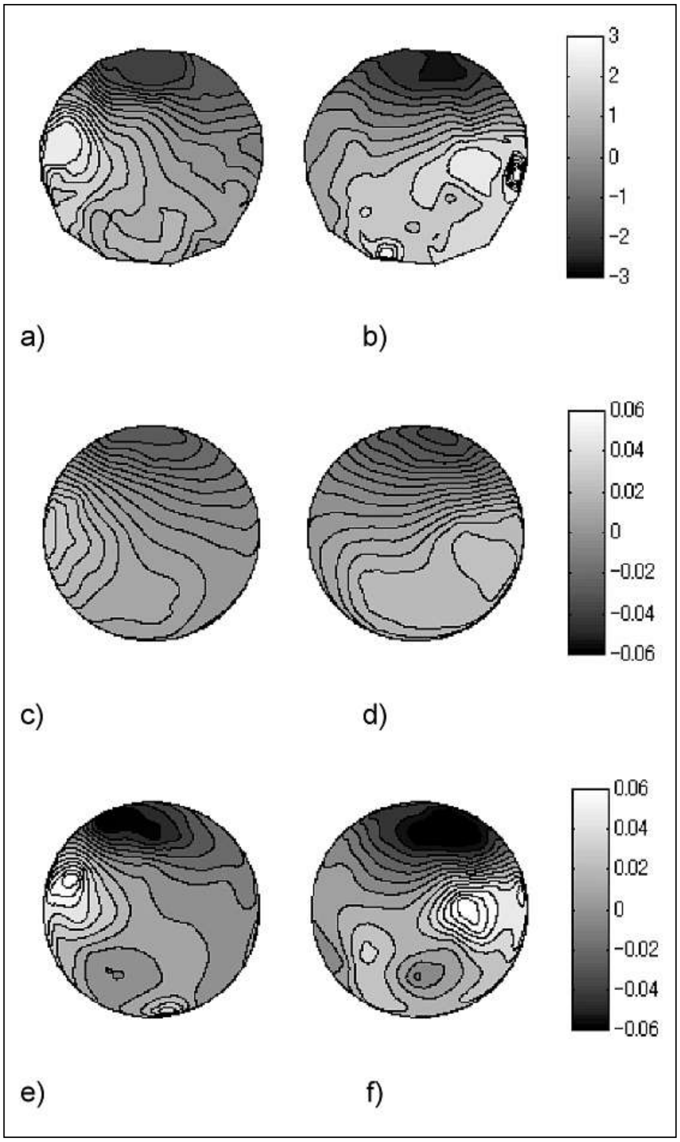

Fig. 2
Scalp potential map (top) and cortical dipole layer imaging estimated by Tikhonov regularization (middle) and parametric projection filter (bottom) in the period of MF for right-hand movement (left) and left-hand movement (right).

sources. The simulations were performed with various noise configurations such as uniform Gaussian white noise and edge-, center-, and one-side-concentrated non-uniform noise.

2.4 Human Experimentation

A right-handed female normal subject with age of 24 years took part in the present study after informed consent was obtained according to the Institutional Review Board. The subject performed fast repetitive finger movements which were cued by visual stimuli. Ten to 15 blocks of 2 Hz thumb oppositions for both hands were recorded, with each 30-second blocks of finger movement and rest. During movement, subject was instructed to avoid eye blinks, swallowing, or any movement other than the required finger movements.

Using a 96-channel EEG system (NeuroScan Lab, TX), electrical potentials were recorded from 94 scalp sensors. A/D sampling rate was 250 Hz. One bipolar EMG was recorded and the peak point of EMG was used as a trigger for the MRP averaging. All data were visually inspected, and trials containing artifacts were rejected. After the EEG recording, the electrode positions were digitized using a 3D localization device with respect to the anatomic landmarks of the head (nasion and two preauricular points).

EMG-locked averaging was done offline. About 450 artifact-free single epochs were averaged according to the following procedure. The EEG data were digitally filtered with a band-pass of 0.3-50 Hz. Each EMG peak point was marked automatically using threshold detection. For averaging, single epoch from 200 ms before to 300 ms after EMG peak point were extracted from the continuous EEG data. The noise covariance of the PPF was estimated by the EEG data at the time point of EMG peak.

3. Results

Figure 1 shows the relative error between actual and estimated dipole layer distributions against the noise level in three inverse techniques. The eccentricity of the dipole sources is 0.7 and the angle of two dipoles is 70 degrees. The radius of dipole layer is set to 0.8. The PPF and PWF have better performance for the edge-concentrated non-uniform noise (low correlation between signal and noise) than Tikhonov regularization (Fig. 1b). On the other hand, in the case of the Gaussian white noise, center-concentrated noise, and one side-concentrated non-uniform noise (moderate and high level of correlation between signal and noise), the results of PWF were better than the Tikhonov regularization and PPF (Figs. 1a, c, d).

Cortical dipole imaging analysis of the MRPs was conducted during the period of the motor field (MF). For dipole imaging, the time point with the highest activity in the period of MF waveform was determined to be around 50 ms after the peak of EMG. Figure 2 displays the estimated results of the cortical dipole layer imaging for right-hand movement and left-hand movement. Note that the dipole layer distributions estimated by means of PPF are well-localized as compared with blurred scalp potential maps and dipole layer distribution estimated by Tikhonov regularization. The localized areas for MF in both hands were located in the premotor cortex, which is consistent with the hand motor representation. Most activities of the source in right-hand movement in the period of the MF covered the precentral sulcus. Figure 2 also indicates that the location of right-hand movement activity seems more temporal than the activity in left-hand movement.

4. Discussion

4.1 Cortical Imaging and Inverse Techniques

The cortical imaging approaches are virtually applicable to any kinds of brain source distribution (both localized and distributed) [1]. This is due to the generalized nature of the equivalent surface source models behind the cortical imaging techniques. These techniques should be useful particularly for localizing and imaging cortical sources.

We have initially investigated the performance of cortical potential imaging by considering noise covariance through the use of PPF. The present study suggests that enhanced performance can be obtained in cortical dipole imaging by considering the noise covariance. The noise covariance may be estimated from data that is known to be source-free, such as prestimulus data in evoked potentials in a clinical situation. In movement-related potentials, prominent features including a pre-movement peak before EMG peak and a post-movement peak after EMG peak have been reported [17, 18]. Thus, we calculated the noise covariance at the time point of EMG peak that is between pre- and post-movement.

If we can obtain both signal covariance matrix and noise covariance, the PWF can be applied to the inverse problem. Actually, it is difficult to estimate the signal covariance exactly from the observed scalp potentials. In our MRP experiments, the results of PWF were worse than PPF because of incomplete signal covariance matrix estimation. Whenever the signal covariance is estimated, the PWF reconstructs the averaged signal over the time.

4.2 Simulation Results

The present simulation results suggest that the PWF incorporating signal information provides better cortical dipole layer imaging results than the PPF and Tikhonov regularization under the condition of high correlation between signal and noise distributions. On the other hand, the PPF has better performance than other inverse filters under the condition of low correlation between signal and noise distributions.

Since the correlations between the eyes blink artifact and the brain electrical activities are low in most cases, we may use the PPF for eyes blink artifact suppression. If we can obtain the signal covariance in time course, the time-variant PWF would be also applicable to the equivalent cortical dipole layer imaging. In order to improve the resolution of restored dipole source imaging, we should choose the PPF and PWF according to the correlation between signal and noise distributions. The time variant PWF will be addressed in future investigation.

4.3 Experimental Results

Tremendous effort has been made to elucidate neural mechanisms that participate in the self-paced movements in humans. The design of single movement experiment requires the subject to perform a self-paced movement for several seconds. However, subjects usually find it difficult to maintain a constant level of motivation for lengthy recording in order to achieve a satisfactory signal to noise ratio. On the other hand, functional magnetic resonance [21] and positron emission tomography studies [22], which have employed fast repetitive movement protocols, have demonstrated that contralateral sensorimotor area, premotor cortex, supplementary motor area, and to a lesser extent the ipsilateral sensorimotor area are also active during human unilateral repetitive voluntary finger movement. To facilitate further application of multi-modal functional imaging approaches, a fast repetitive movement protocol has been used. The present experimental study indicates that contralateral predominant activity of MF would occur after the EMG peak for both hands, which extends previous evidence supporting a hemispheric functional asymmetry of motor control.

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