Artefact elimination in spatiotemporal cortical dipole layer imaging with parametric projection filter

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Abstract. We explore suitable spatiotemporal filters for inverse estimation of an equivalent cortical dipole layer (DL) distribution from the scalp electroencephalogram (EEG) for imaging of brain electric sources. 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. We have expanded the PPF to the time-varying filter in order to handle the spatiotemporally varying nature of brain electrical activity. The present simulation results indicate that the estimation error is reduced substantially by taking the spatiotemporal properties of the noise into consideration, such as eye-blink artefacts, and the proposed time-variant PPF method provides enhanced performance in rejecting time-varying noise. © 2004 Elsevier B.V. All rights reserved.

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1. Introduction

It is important 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 to achieve high resolution EEG imaging. Among them and of interest is the spatial enhancement approach, which attempts to devolve the low-pass spatial filtering effect of volume conduction of the head (for review, see Ref. [1]). The cortical dipole layer (DL) 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 [2–4].

The inverse problem of EEG is ill posed, and in general a regularization procedure is needed in order to obtain stable inverse solutions. 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 [3,5]. 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.

In the present study, we have expanded the PPF inverse spatial filter to the time-varying filter in order to handle the spatiotemporally varying nature of brain electrical activity. Concretely, the noise covariance and the regularization parameter of the PPF are supposed to be time-variant in order to eliminate the influence of the background noise and eye-blink artefact.

2. Methods

2.1. Spatiotemporal dipole layer source imaging

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

\[ g_k = A f_k + n_k \quad (k = 1, \ldots, K) \]

where \( f_k \) is the equivalent source distribution of a dipole layer (DL), \( n_k \) is the additive noise and \( g_k \) is the scalp-recorded potentials. Subscript \( k \) indicates the time instant. \( A \) denotes the transfer matrix from the equivalent source to the scalp potentials.

It is important to estimate the origins from the scalp-recorded EEG, and to image the sources that generate the observed EEG. The inverse process shall be defined by

\[ f_{0k} = B_k g_k \]

where \( B_k \) is the spatiotemporal restoration filter and \( f_{0k} \) is the estimated source distribution of the DL. If the statistical information of the noise or signal are known or estimated for accuracy, the restorative ability of the restoration filter \( B_k \) should be improved by using not only the transfer function but also signal and noise information.

In the present simulation study, the head volume conductor is approximated by the inhomogeneous three concentric sphere model [6]. This head model takes the variation in conductivity of different tissues, such as the scalp, the skull and the brain, into consideration. An equivalent DL is assumed within the brain sphere being concentric to the cortical surface. Radial current dipoles are uniformly distributed over the spherical DL to simulate brain electrical sources accounting for the scalp potentials. The electrical sources inside the DL sphere are equivalently represented by the DL surrounding the sources, regardless of the number or the direction of the dipole sources [2–4]. The transfer function from the DL to the scalp potentials is obtained by considering the geometry of the model and physical relationship between the quantities involved. The strength of the DL is estimated from the noise-contaminated scalp potentials.
2.2. Time-varying parametric projection filter

When the statistical information of noise is presented, the projection filter can be applied to the inverse problem. Suppose $Q_k$, the noise covariance, which can be derived from the expectation over noise $\{n\}$ ensemble, $E[n \ n^*]$. $n^*$ is the transpose of $n$. The parametric projection filter (PPF) [3,5] is derived by

$$B_k = A^* (AA^* + \gamma_k Q_k)^{-1},$$

with $\gamma_k$ a small positive number known as the regularization parameter. The PPF, using the free parameter, can improve the restorative ability from the projection filter, which provides the orthogonal projection of the original signal onto the range of the restoration filter that minimizes the expectation over the noise component in the restored signal. We have applied the time-invariant version of the PPF to the cortical dipole layer source imaging [3] and cortical potential imaging [5]. The time-variant PPF (tPPF) can also be applied to the spatiotemporal inverse problem described by Eq. (2) [7].

We have developed a criterion for determining the optimum parameter. One possibility is to use the following cost function:

$$J(\gamma_k) = E_n \| f_{0k} - B_k (Af_{0k} + n_k) \|^2$$

where $f_{0k}$ is the restored DL distribution using an initial value for $\gamma_k$, which should be relatively large to reduce the effect of additive noise on the coefficients. Furthermore, we use the recursive procedure that renewing the DL distribution $f_{0k}$ provides the optimum approximation of parameter $\gamma_k$.

If there is no spontaneous artefact in the series of EEG measurements, the noise covariance $Q_k$ should be constant and it may be estimated from data that are known to be source free, such as prestimulus data in evoked potentials in a clinical situation [8]. If there are some artefacts, such as eye blink, $Q_k$ should be adaptive to the spatial distribution of the artefacts in order to suppress them. The eye blink covariance is substituted by the voluntary wink data. The eye-blink artefacts may be eliminated by using two types of noise covariance

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![Fig. 1. Cortical DL imaging of two radial dipoles. (a) Actual DL distribution. (b) Scalp potential contaminated with artefact and noise. (c) Estimated result with constant $Q_k$. (d) Estimated result with time-variant $Q_k$.](image-url)
in the tPPF according to the signal conditions with or without artefacts. The time interval of eye blink is estimated by the correlation coefficient between each scalp potential distribution and the eye-blink template measured by voluntary wink data in advance.

3. Results

A DL with 1280 radial dipoles at a radius of 0.8 was used [6]. Fig. 1(a) shows one example of the actual DL distribution of two radial dipoles at several time points. The dipole sources were located at the eccentricity of 0.7 with the angle of $\pi/3$. The strength of each dipole is changed with sinusoid in time (10 and 30 Hz). The scalp potential was contaminated with two kinds of additive noise [Fig.1(b)]. One is the time invariant background noise expressed by Gaussian white noise. The other is the time variant noise of eye-blink artefacts, which appear as spike-like shapes at the upper parts of the eyes. As shown in Fig. 1(d), the DL distribution obtained by the tPPF shows two areas of well-localized activity similar to the actual DL source distribution and the artefacts were eliminated. The RE between the actual and estimated DL distributions was reduced by the tPPF in every time instant. Especially, the RE during the period with the artefact was dramatically reduced.

4. Conclusion

We have developed a time-varying noise covariance incorporated inverse filter for cortical imaging, and showed its applicability in suppressing rapidly changing artefacts. The present simulation results suggest that the estimation error is reduced substantially by taking the spatiotemporal properties of the noise into consideration, such as eye-blink artefacts. Further investigations on other applications of this new method should be addressed in the future.

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