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Cortical Dipole Imaging of Movement-related Potentials in Humans by Means of Parametric Inverse Filter

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Abstract: **The present study aims to identify the anatomic substrate locations of neural generators behind self-paced fast repetitive finger movement, by cortical dipole imaging from scalp-recorded movement-related potentials. The parametric projection filter, which allows inverse estimation with the presence of information on the noise, was applied to movement-related potentials in order to estimate the cortical dipole layer distributions from the scalp potentials. The proposed method demonstrated that the contralateral premotor cortex was preponderantly activated in relation to movement performance. The present results therefore suggest that premotor cortex is involved in the precise control of sequential timed movement based on the motor field (MF) of the movement related potentials.**
Keywords: **High resolution EEG, cortical dipole imaging, inverse problem, parametric projection filter, noise covariance, movement-related potential**

I. Introduction

It is of importance to obtain spatio-temporal 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 image and 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, constrained least square method, and Tikhonov regularization method, have been proposed for solving the ill-conditioned inverse problem. The noise existing in scalp EEG measurements maybe non-uniformly distributed because of the variation in the electrode impedance and experimental environment. Several methods have been developed to handle the non-uniform noise. 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]. 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 expanded the PPF inverse spatial filter to the time-varying filter in order to handle the spatio-temporally varying nature of brain electrical activity [7]. In the proposed approach, the information on the noise structure, as defined by the covariance matrix, is estimated from the spatial information of noise ensemble. We have applied this approach to perform the inverse regularization in equivalent dipole layer source imaging [4] and cortical potential imaging [6], and tested the proposed method in effectively rejecting time-variant artifact such as eyes blink artifact under the background noise [7].

On the other hand, 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 [8] and positron emission tomography studies [9], 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 [10].

In the present study, the performance of the proposed time-variant PPF has been evaluated by human experiments. Especially, the proposed method is applied for movement-related potential (MRP) of fast repetitive movement protocols. We utilize cortical dipole source imaging to locate the possible generators of scalp-measured movement-related potentials related to repetitive finger movements in human. Particularly, we focus our interests in the analysis of motor field (MF) because of the complicated nature of its anatomic substrate.

II. Method

A. 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 are used [11]. 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:

$$g_k = A f_k + n_k \qquad (1)$$

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

$$f_{0k} = B_k g_k \qquad (2)$$

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

B. Inverse Techniques

When the statistical information 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 parametric Wiener filter (PWF) is derived by

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

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]. However, it is difficult to obtain the signal covariance, R_k. Moreover, even if the signal covariance is obtained, the filter may not provide satisfactory performance for non-periodic abnormal signals, which is obviously different from the expectation of signals.

To overcome this problem, the parametric projection filter (PPF) has been introduced to solve the inverse problem [4], [6], [7]. The PPF is derived by

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

The PPF considers just the covariance matrix of the noise distribution, Q_k, that is, $R_k = I$ in (3). The parametric projection filter (PPF), which allows estimating solutions in presence of information on noise covariance structure, has been introduced to solve the inverse problem. The determination of the value of parameter γ_k is left to the subjective judgment of the user. We have applied the parametric projection filter to the inverse problem described by (2). In a clinical and experimental setting, the noise covariance may be estimated from data that is known to be source free. The restoration filters (4) have a free parameter that determines the restorative ability. We have developed a new criterion for determining the optimum parameter using iterative estimation for restoration without knowing the original source distribution. The noise covariance and the regularization parameter of the PPF were supposed to be time-variant because the signal and noise are time-variant in EEG measurements.

D. Subject and Experimental Design

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. 10-15 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.

E. Data Acquisition

Using a 96-channel EEG system (NeuroScan Lab, TX), electrical potentials were recorded from 94 scalp sensors. A/D sampling rate was 250Hz. 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 off-line. 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 200ms before to 300ms 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.

III. Results

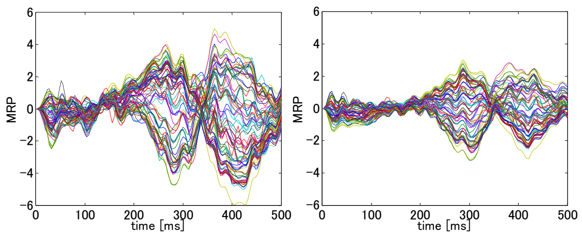
Cortical imaging analysis of the movement-related potentials was conducted during the period of MF. For dipole imaging, the time point with the highest activity in the period of MF waveform was determined to be around 50ms after the peak of EMG. Fig.1 shows 94 averaged waveforms of scalp-recorded potentials for right hand movement and left hand movement. Fig. 2 displays the estimated results of the cortical dipole layer imaging. Note that the estimated dipole layer distributions are well-localized as compared with blurred scalp potential maps. 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. Fig. 2 also indicates that the location of right hand movement activity seems more temporal than the activity in left hand movement.

IV Discussion

The cortical imaging approaches are virtually applicable to any kind 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.

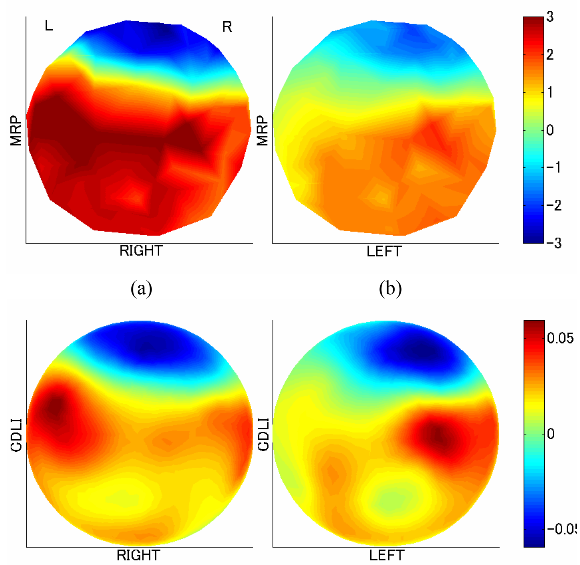
Noise plays an important role in cortical dipole layer imaging, as in any other ill-posed inverse problem. In the present study, we have initially investigated the performance of cortical potential imaging by considering noise covariance through the use of parametric projection filter. The present study 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 [15-16]. Thus, we calculated the noise covariance at the time point of EMG peak, that is between pre and post movement.

Fast repetitive finger movements are associated with distinct phased pattern of cortical activity, which differed from traditional studies of movement-related cortical potentials, which have been focused on the preparation of single movements. Such pattern has been referred as 'steady-state movement-related cortical potential' [15], [17]. However, it was named as motor field (MF) because it has different location and orientation scalp potential pattern with post-MP, but demonstrates the same pattern with MF which has been reported in [17]. The present 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. Also a complicated mechanism is involved into the motor control procedure, and these include sophisticated structure architectures and functional relationships, such as primary motor area and premotor area. Ipsilateral activity also can be seen when the distributed source model is applied.



(a) (b)

Fig. 1. Movement related potentials for (a) right hand movement and (b) left hand movement.



(a) (b)

(c) (d)

Fig. 2. Scalp potential map (top) and Cortical dipole layer imaging (bottom) in the period of MF for right hand movement (left) and left hand movement (right).

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REFERENCES

[1] B. He, "Brain Electric Source Imaging – Scalp Laplacian mapping and cortical imaging," *Crit. Rev. Biomed. Eng.*, vol.27, pp.149-188, 1999.

[2] P. Nunez, R.B. Silibertein, P.J. Cdush, R.S. Wijesinghe, A.F. Westdrop, and R. Srinivasan, "A theoretical and experimental study of high resolution EEG based on surface Laplacian and cortical imaging," *Electroenceph. Clin. Neurophysiol.*, vol.90, pp.40-57, 1994.

[3] A.M. Dale and M.I. Sereno, "Improved localization of cortical activity by combining EEG and MEG with MRI cortical surface reconstruction: a linear approach," *J. Cognitive Neuroscience*, vol.5, pp.162-176, 1993.

[4] J. Hori and B. He, "Equivalent dipole source imaging of brain electric activity by means of parametric projection filter," *Annals of Biomedical Engineering*, vol.29: pp.436-445, 2001.

[5] B. He, D. Yao, and J. Lian, "High Resolution EEG: On the Cortical Equivalent Dipole Layer Imaging," *Clin. Neurophysiol.*, vol.113, pp.227-235, 2002.

[6] J. Hori and B. He, "EEG Cortical potential imaging of brain electrical activity by means of parametric projection filters," *IEICE Trans. Info. & Syst.*, vol.E86-D, no.9, pp.1909-1920, Sep. 2003.

[7] J. Hori, M. Aiba, and B. He, "Spatio-temporal dipole source imaging of brain electrical activity by means of time-varying parametric projection filter," *IEEE Trans. Biomed. Eng.*, vol.51, no.5, pp.768-777, May 2004.

[8] H. Boecker, A. Kleinschmidt, M. Requardt, W. Hanicke, K.D. Merboldt, and J. Frahm, "Functional cooperativity of human cortical motor areas during self-paced simple finger movements. A high-resolution MRI study," *Brain*, vol.117, pp.1231-1239, 1994.

[9] J.A. Sweeney, M.A. Mintun, S. Kwee, M.B. Wiseman, D.L. Brown, D.R. Rosenberg, and J.R. Carl, "Positron emission tomography study of voluntary saccadic eye movements and spatial working memory," *J. Neurophysiol.*, vol.75(1), pp.454-68, Jan. 1996.

[10] Y. Ni, L. Ding, J. Cheng, K. Christine, J. Lian, X. Zhang, N. Grusazuskas, J. Sweeney, and B. He, "EEG source analysis of motor potentials induced by fast repetitive unilateral finger movement," *Proc. 1st IEEE-EMBS Int. Conf. Neural Eng.*, Mar. 2003.

[11] Y. Wang and B. He, "A computer simulation study of cortical imaging from scalp potentials," *IEEE Trans. Biomed. Eng.*, vol.45, pp. 724-735, 1998.

[12] J. W. Philips, R. M. Leahy, and J. C. Mosher, "MEG-based imaging of focal neuronal current sources," *IEEE Trans. Med. Imaging*, vol.16, pp. 338-348, 1997.

[13] R. Grave de Peralta Menendez and S. L. Gonzalez Andino, "Distributed source models: standard solutions and new developments," In: Uhl, C. (ed): *Analysis neurophysiol. brain functioning*, Springer Verlag, pp.176-201, 1998.

[14] K. Sekihara and B. Scholz, "Average-intensity reconstruction and Weiner reconstruction of bioelectric current distribution based on its estimated covariance matrix," *IEEE Trans. Biomed. Eng.*, vol.42, pp.149-157, 1995.

[15] C. Gerloff, N. Uenishi, T. Nagamine, T. Kunieda, M. Hallett, and H. Shibasaki, "Cortical activation during fast repetitive finger movements in humans: steady-state movement-related magnetic fields and their cortical generators," *Electroenceph. Clin. Neurophysiol.*, vol.109, pp.444-453, 1998.

[16] F. Babiloni, C. Babiloni, F. Carducci, F. Cincotti, L. Astolfi, A. Basilisco, P.M. Rossini, L. Ding, Y. Ni, J. Cheng, K. Christine, J. Sweeney, and B. He, "Assessing time-varying cortical functional connectivity with the multimodal integration of high resolution EEG and fMRI data by Directed Transfer Function," *NeuroImage*, vol.24, pp.118-131, 2005.

[17] C. Gerloff, C. Toro, N. Uenishi, L.G. Cohen, L. Leocani, and M. Hallett, "Steady-state movement-related cortical potentials: a new approach to assessing cortical activity associated with fast repetitive finger movements," *Electroencephal. Clin. Neurophysiol.,* vol.102, pp.106-113, 1997.