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Estimation of Cortical Dipole Sources by Equivalent Dipole Layer Imaging and Independent Component Analysis

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***Abstract*—We explored suitable estimation method for equivalent dipole sources in the brain. In a previous study, we solved an inverse problem that estimated an equivalent dipole-layer distribution from the scalp electroencephalogram by a spatio-temporal inverse filters constructed with parametric projection filter. In the present study, we estimated equivalent dipole sources from dipole layer distributions. Moreover, to identify the number, position, and moment of equivalent dipole sources, we separated each dipole layer distribution using independent component analysis (ICA). The performance of the proposed estimation method was evaluated by computer simulation and human experimental studies in an inhomogeneous three-concentric sphere head model. The present simulation results indicated that the equivalent dipole sources was accurately estimated by ICA and dipole imaging. We also applied the proposed method to human visual evoked potential.**

I. Introduction

To analyze functional brain information processing and to identify the position of focus in brain, noninvasive visualization methods of electrical activity are expected. Brain electrical activities have been represented by either few dipole sources or dipole source distribution. Dipole sources have been estimated directly from the scalp electroencephalogram (EEG) [1]-[3]. However, the exact number of dipoles should be determined previously in these methods. Furthermore, the dipole fitting methods took a lot of times to estimate the sources.

On the other hand, equivalent dipole imaging was proposed to estimate cortical dipole layer (DL) distribution accounted for scalp potential (SP) [4]-[13]. We have developed an inverse procedure for cortical dipole source imaging, using the parametric projection filter (PPF), which allows estimation of inverse solutions in the presence of noise information [14]-[15]. The information on noise structure, as defined by the covariance matrix, is assumed to be known. The DL imaging has an advantage that the high resolution brain electrical activity can be estimated without *ad hoc* assumption on the number of source dipoles. The equivalent DL can be set at arbitrary depth inside of the brain. However, when sources adjoin each other, distributions made from each source will overlap complexly. Moreover, it is difficult to estimate the depth of dipole sources.

Thus, in the present study, we consider to estimate the location and moment of the equivalent dipole sources from the DL imaging. Since each DL with different depth has information on the dipole sources, we use multilayer dipole distributions for source estimation. Moreover, for multiple sources, overlapped distributions caused by each sources are separated by independent component analysis (ICA).

II. Method

A. Estimation Procedure

The estimation procedure of dipole source is composed of dipole source separation and dipole sources estimation as shown in Fig. 1. In the process of dipole sources separation, first, time-series DL distributions overlapped by multiple dipole sources are estimated from electroencephalogram (EEG) by means of spatio-temporal inverse filter. Second, time-series DL distributions are separated into each distribution caused by one dipole source using ICA. Third, separated EEG data are obtained by multiplying a transfer matrix from DL distribution to SP. Finally, in the process of dipole sources estimation, each equivalent dipole sources is estimated from separated EEG data by way of DL distributions.

B. Principle of Dipole Layer Imaging

Let the head be simulated by an inhomogeneous three-concentric-sphere model. This model takes the variation in conductivity of different tissues, such as the scalp, the skull, and the brain, into consideration, and has been used to provide a reasonable approximation to head volume conductor for cortical imaging. In this model, an equivalent DL where dipoles are constructed to generate the measured SP as precisely as possible was established inside of the brain. The transfer matrix from the DL to the scalp is obtained by considering the geometry of the model. The DL distribution is reconstructed from the recorded SP by solving an inverse problem of the transfer matrix from the DL to the SP.

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

$$g = A f + n \qquad (1)$$

where f is the vector of the equivalent source distribution of a DL, n is the vector of the additive zero-mean noise, and g is the vector of SPs. A represents the transfer matrix from the equivalent dipole source to the SP signals. It is important to

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infer the origins from the recorded EEG, and to map the sources that generate the observed EEG on the scalp. The inverse process shall be defined by

$$f_0 = B\,g \qquad (2)$$

where B is the restoration filter and f_0 is the estimated source distribution of the DL. As the measurement electrode number is always much smaller than the dimension of the unknown vector f, this problem is an underdetermined non-unique inverse problem. In order to evaluate the estimated DL distribution, the "true" or original DL distribution should be calculated from the assumed dipole sources. The actual DL distribution was calculated by solving a forward solution from the dipole source to the DL. To solve the inverse problem, we use the parametric projection filter (PPF) as the restoration filter [14]-[16]. The PPF is derived by

$$B = A^*\,(A\,A^* + \gamma Q\,)^{-1} \qquad (3)$$

The PPF considers the covariance matrix of the noise distribution Q derived from the expectation over the noise $\{n\}$ ensemble, $E[n\ \ n^*]$. γ is the time variant regularization parameter. A^* is the transpose matrix of A.

C. Independent Component Analysis (ICA)

When multiple dipole sources are complexly distributed in brain, it is difficult to estimate each dipole source from overlapped SP. In that case, we separate time-series DL distributions by ICA. ICA is an analysis method that extracts independent sources from the observed signal based on statistical independence of the original signal. Figure 2 shows an analysis model of ICA. In this model, independent sources s are mixed each other by a mixing matrix M. The observed signal g is described by

$$g = M\,s \qquad (4)$$

First, number of sources is decided by principal component analysis (PCA). The principal component z is expressed by

$$z = V\,g \qquad (5)$$

where V is the whitening matrix. Next, independent signals are estimated by the appropriate restoring matrix W. Finally, the original signal is estimated by

$$y = W\,z \qquad (6)$$

ICA algorithm estimates the independence of the original signal and the optimization based on the estimation, searches an optimum-restoring matrix.

D. Dipole Sources Estimation

A dipole expressed by the position and moment represents a neural electric current source. Figure 3 shows the dipole source estimation method by means of DL imaging. Peak points that exceed a certain threshold are extracted from estimated DL distributions with various radii. These peak points are approximated by lines. We suppose that dipole source exists on this line. Various SP are calculated by changing the depth and moment of candidate dipole sources. The optimum dipole source is decided by minimizing a relative error between the estimated SP and observed SP. In this study, we estimate DL distributions with various radii from EEG separated ICA in order to find optimum dipole sources.

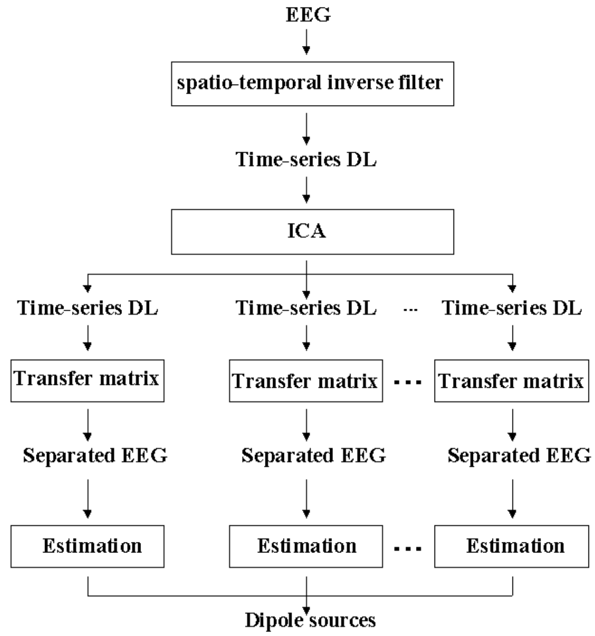

Fig. 1. Estimation method of equivalent dipole sources.

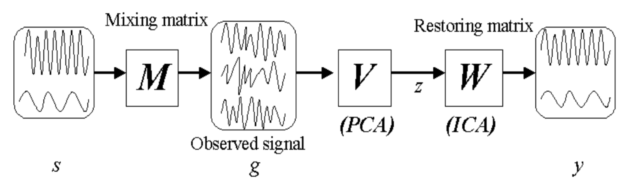

Fig. 2. Analysis model of Independent component analysis (ICA). Number of sources is decided by principal component analysis (PCA). A restoring matrix W estimates independent components.

E. Simulation Protocol

The proposed method was applied for an inhomogeneous concentric three-sphere volume conductor head model. In the head model, the radii of the brain, r_1, the skull, r_2, and the scalp, R, spheres were taken as 0.87, 0.92, and 1.0, respectively. The normalized conductivity of the scalp and the brain was taken as σ_0=1.0, conductivity of the skull as σ_s=0.0125. The potentials on the scalp surface, generated by dipole sources inside the brain, can be calculated by solving the forward problem.

Two radial dipole sources were supposed to exist in the head model. The eccentricity of both sources is 0.7 with the angle of $\pi/3$. Strength of two dipoles changed as 10Hz and 40Hz sin wave. Furthermore, 10% Gaussian white noise was added as background noise. The simulated EEG was acquired at a sampling rate of 250Hz and the length of analysis section is 0.5sec. The simulated EEG was separated by ICA. Furthermore, the dipole sources were estimated by the method described in Fig. 3. Finally, they were compared with true dipole sources.

F. Human Experimentation

Human VEP experiments were carried out to examine the performance of the proposed estimation method. A healthy subject was studied in accordance with a protocol approved by the Institutional Review Board of the University of Illinois at Chicago. Visual stimuli were generated by the STIM system (Neuro Scan Labs, Inc.). 96-channel VEP signals referenced to right earlobe were amplified with a gain of 500 and band-pass filtered from 1 Hz to 200 Hz by Synamps (Neuro Scan Labs, Inc.), and were acquired at a sampling rate of 1kHz by using SCAN 4.1 software (Neuro Scan Labs, Inc.). The electrode locations were measured using Polhemus Fastrack (Polhemus, Inc.) and best fitted on the spherical surface with unit radius. Half visual field pattern reversal check boards (black and white) with reversal interval of 0.5sec served as visual stimuli and 400 reversals were recorded to obtain averaged VEP signals. The display had a total viewing angle of 14.3° by 11.1°, and the check size was set to be 175’ by 135’ expressed in arc minutes.

III. RESULT

A. Simulation Results

Figure 4 shows the results of source separation. Maps of the SP shows overlapped distributions of dipole sources (top). First (middle) and second (bottom) separated SP demonstrate separated distributions by ICA. In this case, the number of independent components was two. Even if there was a big difference in strength between first and second dipole sources, distributions were accurately separated by ICA.

B. VEP Experimental Results

Visual information evoked by left visual field is transmitted to the vision cortex in right back of the head, and VEP appears. From EEG on electrode of right back of head, we confirmed peak components of VEP, P1, N1, P2, and N2, as shown in Figure. 5. By applying PCA, we decided the number of dipole sources as three by the contribution ratio of eigenvalues. Figure 6 shows the separated results of dipole layer distributions. Especially, in separated SP2, the peak of positive potential appeared on right back of brain at P2.

Figure 7 indicates estimated dipole sources at P2 on the realistic-shaped head model. The position of source is already known physiologically and it locates at calcarine sulcus in vision cortex. We confirmed that the results were in good agreement with physiological view.

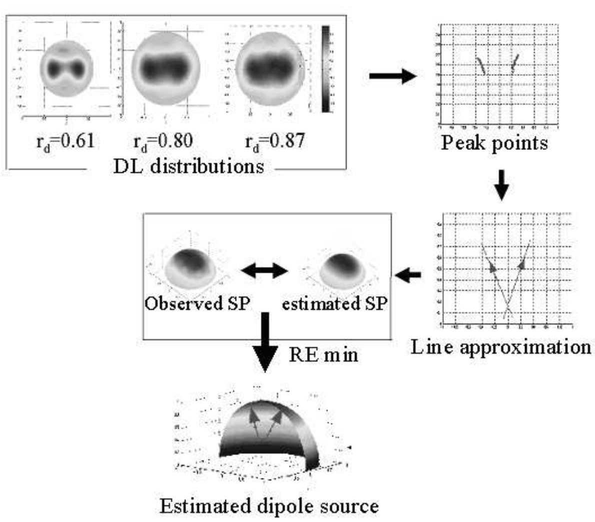

Fig. 3. Dipole source estimation method by means of dipole layer imaging. Peak points were estimated from DL distributions with various radii and were approximated them by line. We suppose that dipole source exists on this line. The optimum dipole source is decided by minimizing a RE (relative error) between the estimated and observed SP.

IV. DISCUSSION

To solve inverse problem, we used the PPF. If the noise covariance could be estimated precisely, the restorative ability may be substantially improved by the PPF. In proposed estimation method, we suppose that equivalent dipole sources in the brain were independent each other. In ICA algorithm, we applied the non-Gaussianity to estimate the independence. We don't think that real EEG by equivalent dipole source depends on gauss distribution. Consequently, to separate EEG, we have to suppose that equivalent dipole sources in the brain are independent each other. We separated DL distribution instead of EEG because the spatial resolution of DL

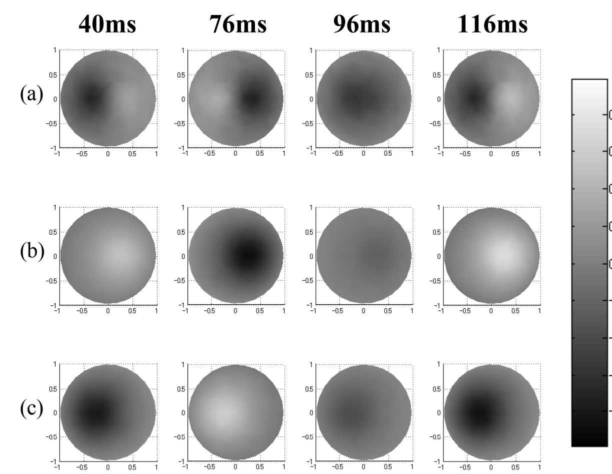

Fig. 4. Result of dipole sources separation (simulation). (a) SP, (b) first, and (c) second separated SPs by ICA.

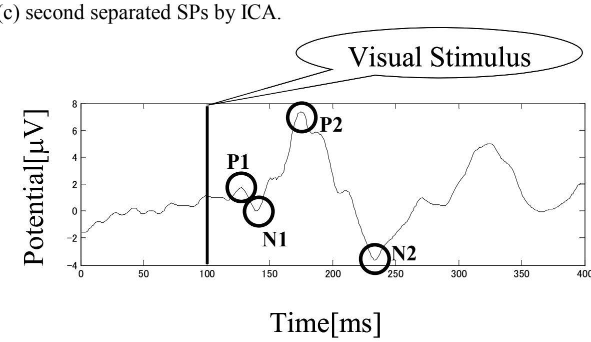

Fig. 5. EEG on electrode of right back of head. There were peak components of VEP, P1, N1, P2, and N2.

distribution was much higher than that of SP. As a result of experiments, the separation's accuracy of time-series DL distribution was better than that of EEG. Moreover, to separate dipole sources clearly, we must estimate DL distribution correctly.

Fig. 4 indicates that if dipole sources are accurately separated by ICA, dipole sources are successfully estimated by our method. Furthermore, estimation error of dipole sources did not depend on the strength of dipole sources, so much. In Fig. 7, although we confirmed agreement with physiological view, we don't know true dipole sources in experiment. So, to examine our inverse method, it is necessary to apply it to other human experimentations and examine the results in near future.

V. Conclusion

We proposed new estimation method of equivalent dipole sources composed of dipole sources imaging, separation, and estimation. In simulation, the dipole sources were accurately estimated by means of dipole layer imaging and ICA. In experiment, estimated results were in good agreement with physiological view.

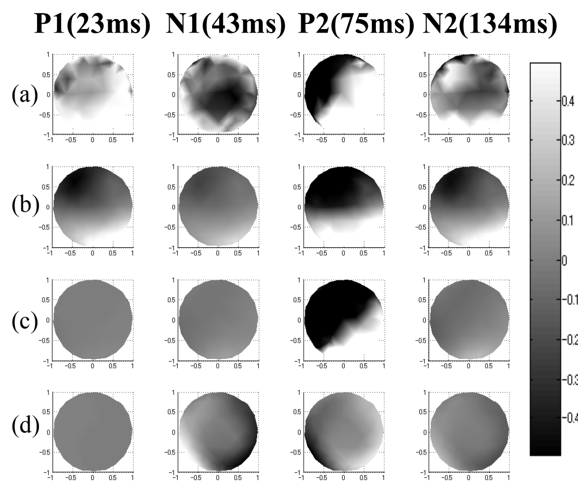

Fig. 6. Results of dipole sources separation (VEP). (a) SP, (b) first, (c) second, and (d) third components separated by ICA.

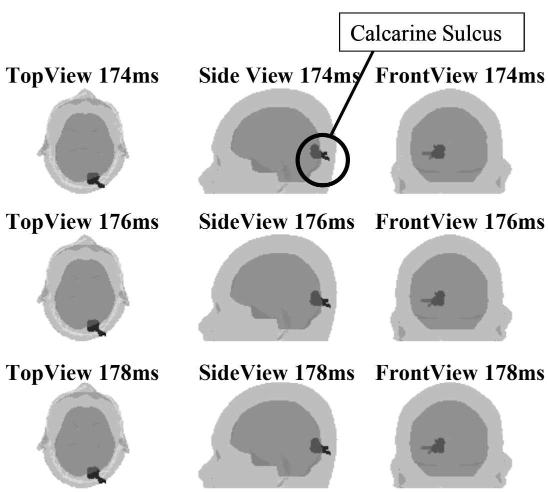

Fig. 7. Estimated dipole source at P2 (peak component of VEP). These figures show estimated dipole sources at 174 ms, 176 ms, and 178 ms.

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