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腦部活動之電生理訊號源模型建立、估算、與分析 (1/2)

Bioelectric Source Modeling, Estimation, and Analysis of Brain Activities

計畫編號：NSC94 – 2213 – E – 009 – 098 –

執行期限：94 年 8 月 1 日至 95 年 7 月 31 日

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中文摘要

傳統以腦電波儀為基礎之腦機介面（EEG-based Brain-Computer Interface）研究是在受試者的頭皮貼上 EEG 電極，然後利用在電極上所量測到的頭皮電位波形來進行訊號分類並轉換成控制命令，以操控電腦或機器執行該受試者的意念所相對應的任務。由於在電極上所量測的電位，是由腦部所有活化區域所誘發的電生理訊號傳導至該電極位置的整體效應，因此與控制意念或特定事件不相關的腦部活動將會干擾訊號量測與分析。為了增加腦機介面系統的準確性、穩定度、與效能，我們在本計畫中開發腦部活動之電生理訊號源模型建立、估算、與分析技術，以計算與控制意念或特定事件相關之腦部神經元活動時序訊號，腦機介面系統即可利用這個腦部活動訊號來進行特徵擷取與訊號分類。基於前階段的研究成果，我們已可以利用重疊球體模型進一步建構出最大對比之光束構成法 (Maximum Contrast Beamformning Method)來逆向推算活化源位置，並且以階層式的搜尋方法，加速逆向活化源的計算。可以準確的估計出活化源的位置，對於之後生理訊號的分析，有相當大的幫助。

關鍵詞：腦電波儀、活化源模型、重疊球體模型、腦機介面、光束構成法

Abstract

EEG has been widely applied in functional brain studies due to its high temporal resolution and low cost. In this work, we focus on the development of an accurate and efficient EEG forward model as well as the inverse solution for neuronal source estimation from the EEG measurements. Our forward model gains its accuracy by fitting an overlapping sphere for each EEG sensor. The computation of the overlapping sphere requires only the multi-shell geometry, instead of boundary element method, thus the proposed forward model is easy to compute. Based on the proposed forward model, the beamforming technique is applied to calculate the distributed sources in the brain space. Hierarchical search in the solution space is applied to save the amount of computation. According to our

experiments using phantom data and visual-evoked potential data, the proposed forward model and inverse solution can efficiently and accurately estimate the source of brain activation.

A. Previous works

Inverse solution can be separated as fitting method and scanning method. Fitting method including focal source and distributed source solves inverse problem by fitting the measured surface potential to the predicted surface potential from the EEG forward model. Scanning method is to scan the whole brain space and reveal locations having significant neuronal activation.

1) Fitting method:

a) Focal source: Assume brain source consists of only a single dipole. Least-square estimation can be used to solve the inverse problem. If there are multiple dipoles, we can first use the independent component analysis to decompose the EEG measured data into several components induced by different dipoles, then apply least-square estimation for each component to solve the inverse problem.

b) Distributed source*:* If we have no prior knowledge of how many sources in the brain, distributed source estimation method can be used. LORETA (LOw REsolution brain electromagnetic TomograAphy) [1] is a widely-used method to solve the distributed source inverse problem. It find a smooth area of possible brain activation because the neighboring grid points have similar activation.

2) Scanning method: Now we introduce a inverse method, called beamforming, which scans the whole brain space to reveal possible source locations. The main idea of beamforming is to design a special kind of spatial filter that can linearly combine the recorded EEG data from every sensor to reconstruct the source activation:

$$y = \mathbf{w}^T(\mathbf{r}_0; \mathbf{q}_0)\mathbf{x}, \tag{1}$$

where y is the reconstructed moment of the dipole with location r_0 and orientation $\frac{q_0}{\| q_0 \|}$ and $w(r_0; q_0)$ is an N × 1 vector denoting the spatial filter. In [2], Van Veen et al. proposed a linearly constraint minimum variance spatial filter and the solution of $w(r_0; q_0)$ is:

$$\mathbf{w} = \frac{(\mathbf{C} + \alpha\mathbf{I})^{-1}\mathbf{l}}{\mathbf{l}^T(\mathbf{C} + \alpha\mathbf{I})^{-1}\mathbf{l}}, \tag{2}$$

where l is the leadfield, α represent the regularization parameter, and C is the covariance matrix of measured data. We drop $(r_0; q_0)$ for w and l for simplicity and clarity. Notice that the induced surface potential is inversely cubic-proportional to the source depth [3]. Therefore, if the spatial filter is computed for a deeper position, the reconstructed neural activation will be larger. Therefore, we calculate the f statistic of the activation power:

$$f = \frac{\mathbf{w}^T\mathbf{C}_\mathbf{a}\mathbf{w}}{\mathbf{w}^T\mathbf{C}_\mathbf{c}\mathbf{w}}, \tag{3}$$

where Ca and Cc denote the covariance matrices estimated from the measured data in the active and control states respectively.

B. Proposed inverse solution

In Equation (2), we need to know the source orientation $\frac{q_0}{\| q_0 \|}$ before we calculate the spatial filter w. Here we adopt the method proposed in [4] to analytically calculate the optimal source orientation in a closed-form manner. In the following we describe the proposed inverse solution.

1) Maximum contrast beamforming: Substitute $l = G\frac{q_0}{\| q_0 \|} \cong Gj$ into Equation (2) to obtain:

$$\mathbf{w} = \frac{(\mathbf{C}+\alpha\mathbf{I})^{-1}\mathbf{G}\mathbf{j}}{\mathbf{j}^T\mathbf{G}^T(\mathbf{C}+\alpha\mathbf{I})^{-1}\mathbf{G}\mathbf{j}} \doteq \frac{\mathbf{A}\mathbf{j}}{\mathbf{j}^T\mathbf{B}\mathbf{j}}, \tag{4}$$

where we define matrices A = $(C + \alpha I)^{-1}G$ and B = $G^T (C+ \alpha I)^{-1}G$. Consequently, we can determine the optimalsource orientation [5], [6], [4] by maximizing the power contrast between the active and control states:

$$\hat{\mathbf{j}} = \arg\max_{\mathbf{j}} \frac{\mathbf{w}^T\mathbf{C}_\mathbf{a}\mathbf{w}}{\mathbf{w}^T\mathbf{C}_\mathbf{c}\mathbf{w}} = \arg\max_{\mathbf{j}} \frac{\mathbf{j}^T\mathbf{A}^T\mathbf{C}_\mathbf{a}\mathbf{A}\mathbf{j}}{\mathbf{j}^T\mathbf{A}^T\mathbf{C}_\mathbf{c}\mathbf{A}\mathbf{j}}$$
$$\doteq \arg\max_{\mathbf{j}} \frac{\mathbf{j}^T\mathbf{P}\mathbf{j}}{\mathbf{j}^T\mathbf{Q}\mathbf{j}}, \tag{5}$$

where we define matrices P = A^TCaA and Q = A^TCcA. The solution of Equation (5) is the eigenvector with respect to the maximum eigenvalue of matrix $Q^{-1}P$ [7]. In short, maximum contrast beamforming can determine the optimal source orientation, based on the maximum contrast criterion, and the resulted spatial filter w for each source location r_0. Then Equation (3) can be used to measure the f statistic for the location r_0.

2) Hierarchical-search beamforming: To compromise between the computational cost and spatial resolution of the probed search space in the brain, we adopt a hierarchical framework to search for the activation region in a coarse-to-fine manner. In the following we list the algorithm of hierarchical-search beamforming:

1) Initialize the ROI (Region of Interest) manually.

2) Spatially sample the ROI with low resolution.

3) Estimate the power statistics of the sampled points using the beamforming technique.

4) Select the points with large power statistics as the new ROI.

5) Resample the new ROI with higher spatial resolution.

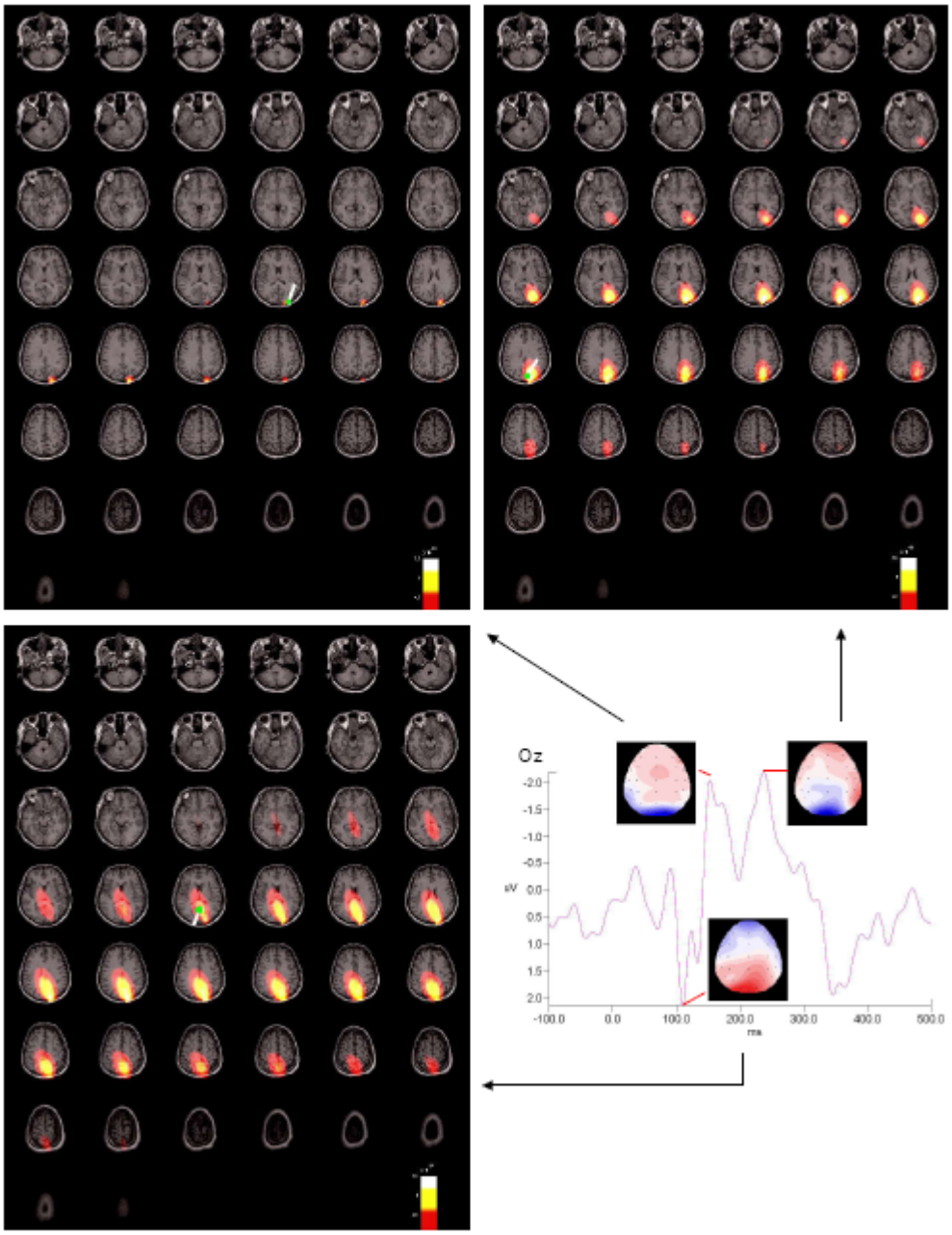
6) Repeat Steps 3–5 until the spatial resolution is high enough.

By specifying a proper ROI we can avoid the estimated source to be outside the human head area. However, we still need to further consider the source located inside the head but outside the sphere model because the spherical forward model assumes that the dipole source is located inside the sphere. For a dipole outside the sphere, we use a “similar” dipole that falls within the boundaries of the sphere

[8], [9], [10] as the representative of the original dipole. Thus, we can calculate for all the dipole sources inside the whole ROI, no matter inside or outside the sphere model.

C. Experiment of visual-evoked potential

We also apply our method to estimate the neuronal activity from the EEG data during a visual task. The subject is a 24-year-old female. During the experiment, a white square appeared on the center of LCD (liquid crystal display) screen once per 0.3 second as the visual stimulus. From the visual ERP obtained by averaging 513 trials, as shown in the right-bottom part of Figure 4, we found a positive peak at 109 ms and two negative peaks at 153 ms and 238 ms respectively, where stimulus on-set time is 0 ms. Functional mapping by using the proposed method (Sun with OS and hierarchicalsearch beamforming), as well as the dipole-fitting results, for each of the three peaks are illustrated in Figure 4. It is obvious that our method successfully reveal the region in the occipital area with strong significance of neuronal activity.



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