Weighted minimum-norm source estimation of magnetoencephalography utilizing the temporal information of the measured data

Sunao Iwaki[a)] and Shoogo Ueno[b)]
Department of Biomedical Engineering, University of Tokyo. 7-3-1 Hongo, Bunkyo-ku, Tokyo 113, Japan

The weighted minimum-norm estimation (wMNE) is a popular method to obtain the source distribution in the human brain from magneto- and electro- encephalograpic measurements when detailed information about the generator profile is not available. We propose a method to reconstruct current distributions in the human brain based on the wMNE technique with the weighting factors defined by a simplified multiple signal classification (MUSIC) prescanning. In this method, in addition to the conventional depth normalization technique, weighting factors of the wMNE were determined by the cost values previously calculated by a simplified MUSIC scanning which contains the temporal information of the measured data. We performed computer simulations of this method and compared it with the conventional wMNE method. The results show that the proposed method is effective for the reconstruction of the current distributions from noisy data. [S0021-8979(98)38511-4]

I. INTRODUCTION

Sophisticated techniques to provide functional imaging of information processing in the human brain are needed for clinical applications and for tools of investigation of higher brain functions. Many methods have been developed to reconstruct the internal electrical current distributions in the human brain from magneto- and electro-encephalographic (MEG/EEG) measurements.[1] Among those, the minimum-norm estimation (MNE)[2,3] is a popular technique to obtain the internal primary current distributions if the detailed information about the generator profile was not available. Because the sensitivity of the sensors decreases as the distance from the source increases, the MNE tends to introduce a bias towards superficial sources.[4] To avoid this problem, the weighted MNE (wMNE) method, which minimizes the weighted norm of the solution (depth normalization), has been widely applied.[4,5] However, because the conventional wMNE method deals with only the instantaneous distribution of MEG/EEG data, reconstructed currents could be seriously distorted when the method is applied to noisy data. To reduce the distortion of the reconstructed current distribution, a method to include temporal information of the MEG/EEG data into the wMNE method using simplified multiple signal classification (MUSIC)[6] prescanning is proposed in this article.

[a)]Electronic mail: iwaki@medes.m.u-tokyo.ac.jp
[b]Electronic mail: ueno@medes.m.u-tokyo.ac.jp

II. METHODS

A. Weighted minimum norm estimation

Here, we define the primary current distribution at time instant t_i as $\mathbf{p}(t_i)=[\mathbf{p}_1(t_i),\mathbf{p}_2(t_i),\ldots,\mathbf{p}_N(t_i)]^T$ and the measured field distribution as $\mathbf{f}(t_i)=[\mathbf{f}_1(t_i),\mathbf{f}_2(t_i),\ldots,\mathbf{f}_M(t_i)]^T$, where N is the number of possible current source locations and M is the number of sensors. The relationship between $\mathbf{f}$ and $\mathbf{p}$ is described as

$$\mathbf{f}=L\mathbf{p}+\mathbf{n}, \tag{1}$$

where L is a gain matrix called the lead field matrix and $\mathbf{n}$ is the additive measurement noise. The conventional wMNE method can be written as follows.[7]

$$\mathbf{p}=L^{-}\mathbf{f}, \tag{2}$$

where L is given by

$$L^{-}=(L^TL+\gamma\mathbf{W}_c)^{-1}L^T, \tag{3}$$

which minimizes the cost $E_c=\|\mathbf{f}-\mathbf{f}_c\|^2+\gamma^2\|\mathbf{W}_c\mathbf{p}\|^2$, ($\mathbf{f}_c$: calculated value of field distribution).[7] The diagonal matrix $\mathbf{W}_c$ contains the weighting factors for depth normalization, and γ is a regularization parameter, which controls the degree of regularization, determined in accordance with the signal-to-noise ratio (SNR). In this article, we use the simplest weighting factors for depth normalization ($\mathbf{W}_c=\mathrm{diag}\{\|L_i\|_2\}$).

B. Weighted minimum norm estimation with MUSIC prescanning

Because the conventional wMNE method deals with only instantaneous distributions of MEG/EEG data, results of current reconstruction could be seriously distorted when

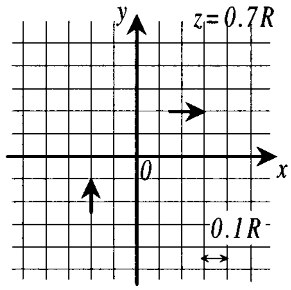

FIG. 1. Assumed source locations for the computer simulations. Two dipolar current sources were located at $(-0.2R,-0.2R,0.7R)$ and $(0.2R,0.2R,0.7R)$.

applied to noisy (low SNR) data. To reduce the distortion of the reconstructed current distributions, we propose a method to include temporal information in the wMNE using simplified MUSIC prescanning.

First, to separate signal and noise subspaces of $M\times l$ spatio-temporal measured data matrix $\mathbf{F}=[\mathbf{f}(t_1),\mathbf{f}(t_2),\ldots,\mathbf{f}(t_l)]$ using an eigen-decomposition of the auto-correlation matrix of $\mathbf{F}$. Here, we denote $\mathbf{\Lambda}_s,\mathbf{\Lambda}_n$ as a diagonal matrix containing signal and noise eigenvalues, and $\mathbf{\Phi}_s,\mathbf{\Phi}_n$ as signal and noise eigenvectors, respectively. Then, for each scanning grid j located in the head model, we calculate the cost values c_j,

$$c_j=1/\lambda_{\min}\{\mathbf{U}_{Lj}^T\mathbf{\Phi}_n\mathbf{\Phi}_n^T\mathbf{U}_{Lj}\}, \tag{4}$$

where $\lambda_{\min}\{\bullet\}$ denotes the minimum eigenvalue of $\{\bullet\}$, and $\mathbf{U}_{Lj}$ denotes the principal left eigenvector of L_j. Then c_j becomes 0 at the correct source location when the source is modeled as a single current dipole,[8] and c_j approximates the relative values of time-averaged current intensity if the source can be modeled as a few current dipoles.[9]

We use the cost values c_j to determine the weighting factors of wMNE as follows.

$$\mathbf{W}=\mathbf{W}_c+\mathbf{W}_m=\text{diag}\{\|L_i\|_2\}+\alpha\ \text{diag}\{I-\tilde{c}_j\}, \tag{5}$$

$$L^-=(L^TL+\gamma\mathbf{W})^{-1}L^T, \tag{6}$$

where $\tilde{c}_j$ is a normalized value of c_j, and α is a alteration parameter of weighting factors. This method minimizes the cost $E_m=\|\mathbf{f}-\mathbf{f}_c\|^2+\gamma^2\|(\mathbf{W}_c+\mathbf{W}_m)\mathbf{p}\|^2$ that causes the reconstructed current distribution to be biased towards the regions with the largest c_j values calculated by the simplified MUSIC prescanning. When $\alpha=0$, the proposed method becomes identical to the conventional wMNE method.

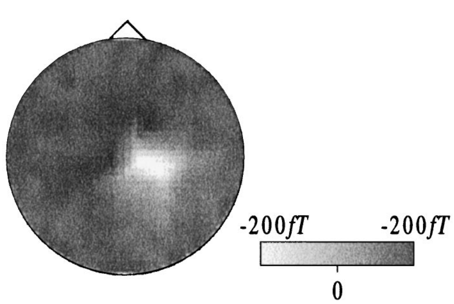

FIG. 2. Example of the spatial distribution of the MEG. The SNR of the simulated data was set to 4 dB.

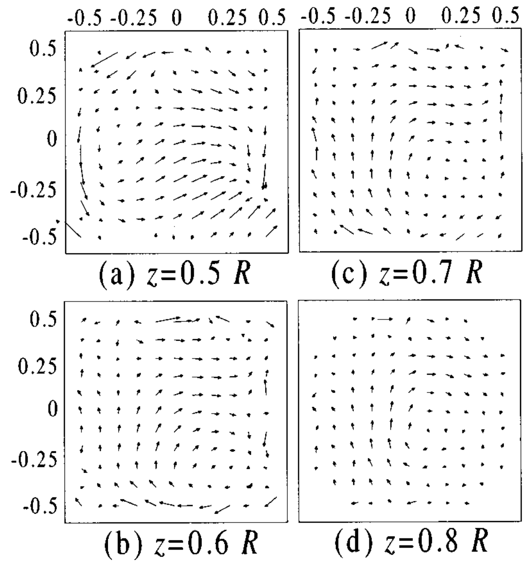

FIG. 3. Results of current reconstruction using the conventional wMNE method. Axial views of the reconstructed current distributions in the x-y plane are displayed with (a) $z=0.5R$, (b) $z=0.6R$, (c) $z=0.7R$, and (d) $z=0.8R$. The SNR of the simulated data was 4 dB, and the regularization parameter γ was set to 0.4.

This method utilizes not only the instantaneous spatial distribution but also the temporal properties of the measured data. It is possible to reconstruct current distribution properly even if the SNR of the measured data were so low that the conventional wMNE method might fail to reconstruct.

III. RESULTS AND DISCUSSION

We performed computer simulations of the proposed method and compared the results with the results from the conventional wMNE method.

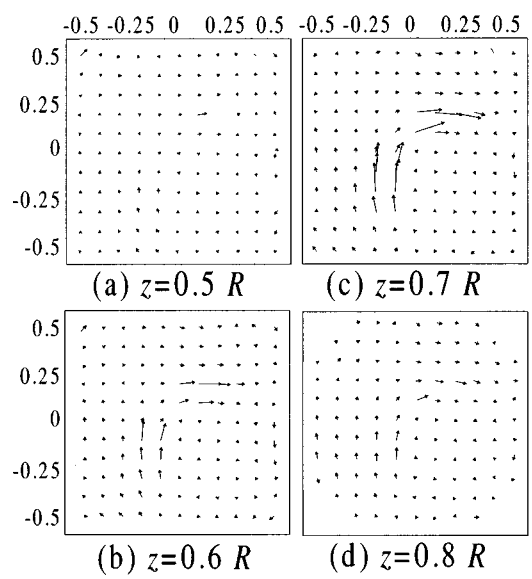

FIG. 4. Results of current reconstruction using the proposed method. Axial views of the reconstructed current distributions in the x-y plane are displayed with (a) $z=0.5R$, (b) $z=0.6R$, (c) $z=0.7R$, and (d) $z=0.8R$. The SNR and γ were the same as for Fig. 3, and the alteration parameter α was set to 0.06.

Figure 1 shows an assumed source configuration for these simulations. Two current dipoles were located in the x-y plane [(a) $(x,y,z)=(-0.2R,-0.2R,0.7R)$, (b) $(x,y,z)=(0.2R,0.2R,0.7R)$, R: radius of the head model]. The y component of the assumed source (a) and the x component of the source (b) were assumed to alter synchronously. Magnetic fields generated by these sources were assumed to be measured at 80 points on the upper hemisphere of the head model, and white noise was added. The SNR of the simulated data was approximately 4 dB, which was relatively low when compared with actual MEG measurements of large evoked responses with an adequate number of signals averaged. However, the SNR was not low when compared with that of spontaneous brain activities without averaging or evoked responses with a limited number of data sets. An example of the instantaneous spatial distribution of simulated data is shown in Fig. 2.

The results of the current reconstruction using the conventional wMNE method and the proposed method are shown in Fig. 3 and Fig. 4, respectively. In each figure, axial views of reconstructed current distributions in the x-y plane are displayed with (a) $z=0.5R$, (b) $z=0.6R$, (c) $z=0.7R$, and (d) $z=0.8R$. In these simulations, the regularization parameter γ and alteration parameter α were set to $\gamma=0.4$, $\alpha=0.06$ empirically. The reconstructed current distribution was severely distorted in the conventional wMNE method under noisy measurement condition as SNR equals to 4 dB. In the proposed method, current distributions corresponding to two assumed sources were clearly reconstructed. These results indicated the effectiveness of the proposed method for the reconstruction of internal current distributions under the noisy measurement condition. In these cases, the increase of the amount of calculation in the proposed method was less than 10% of that required in the conventional wMNE method.

Further consideration must be given to develop algorithms to obtain optimum values of the regularization and alteration parameters.

IV. CONCLUSION

We proposed a method to reconstruct current distributions in the human brain based on the weighted minimum-norm estimation technique with the weighting factors defined by simplified MUSIC prescanning. With this method, in addition to the conventional depth normalization technique, weighting factors of the wMNE were determined by the cost values previously calculated by simplified MUSIC scanning which contains the temporal information of the measured data. We performed computer simulations of this method and compared it with the conventional wMNE method. The results show that the proposed method is effective for the reconstruction of the current distributions from noisy data.

[1] M. S. Hamalainen, R. Hari, R. J. Ilmoniemi, J. Knuutila, and O. V. Lounasmaa, Rev. Mod. Phys. **652**, 413–497 (1993).
[2] R. J. Ilmoniemi, M. S. Hamalainen, and J. Knuutila, *Biomagnetism: Application and Theory*, edited by H. Weinberg, G. Stroink, and T. Katila (Pergamon, New York, 1985), pp. 278–282.
[3] J. Z. Wang, S. J. Williamson, and L. Kaufmann, IEEE Trans. Biomed. Eng. **39**, 665–675 (1992).
[4] B. Jeffs, R. M. Leahy, and M. Singh, IEEE Trans. Biomed. Eng. **34**, 713–723 (1987).
[5] A. A. Ioannides, J. P. R. Bolton, and C. J. S. Clarke, Inverse Probl. **6**, 523–542 (1990).
[6] J. C. Mosher, P. S. Lewis, and R. M. Leahy, IEEE Trans. Biomed. Eng. **39**, 541–557 (1992).
[7] H. C. Andrews and B. R. Hunt, *Digital Image Restoration* (Prentice–Hall, Eaglewood Cliffs, NJ, 1977).
[8] R. O. Schmidt, IEEE Trans. Antennas Propag. **34**, 276–280 (1986).
[9] K. Sekihara and B. Scholz, IEEE Trans. Biomed. Eng. **43**, 281–291 (1996).