Noise Covariance Incorporated MEG-MUSIC Algorithm: A Method for Multiple-Dipole Estimation Tolerant of the Influence of Background Brain Activity

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***Abstract*—This paper proposes a method of localizing multiple current dipoles from spatio-temporal biomagnetic data. The method is based on the multiple signal classification (MUSIC) algorithm and is tolerant of the influence of background brain activity. In this method, the noise covariance matrix is estimated using a portion of the data that contains noise, but does not contain any signal information. Then, a modified noise subspace projector is formed using the generalized eigenvectors of the noise and measured-data covariance matrices. The MUSIC localizer is calculated using this noise subspace projector and the noise covariance matrix. The results from a computer simulation have verified the effectiveness of the method. The method was then applied to source estimation for auditory-evoked fields elicited by syllable speech sounds. The results strongly suggest the method's effectiveness in removing the influence of background activity.**

***Index Terms*—Array signal processing, biomagnetics, biomedical electromagnetic imaging, biomedical signal processing, fuctional brain imaging, inverse problems.**

I. Introduction

Although the single equivalent current dipole (ECD) is a widely accepted source model in biomagnetism [1], its usefulness is considerably limited when one proceeds to the measurement of higher-order brain functions or when attempts to reconstruct the entire current pathway in a human heart. The obvious extension of single ECD modeling to accommodate more complex biocurrent distributions is multiple dipole modeling. However, if we apply multidipole modeling to the data at each single time point, the estimation accuracy is generally limited by the ill-posed nature of the inverse problem and, thus, multidipole modeling with more than three dipoles is seldom applied in practice.

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The spatio-temporal modeling pioneered by Scherg *et al.* [2], [3] reduces the limitations caused by this ill posedness and enables a more accurate estimation to be attained. In this modeling, the dipole locations are assumed to be unchanged during measurement. By introducing this constraint, the dipole locations can be estimated using a spatio-temporal data set. Because the biomagnetic data can be acquired with a sampling interval of less than one millisecond, a few hundred to several thousand data points can be contained in a single spatio-temporal data set. Obviously, the use of a complete spatio-temporal data set greatly improves the accuracy of the estimation, compared with estimation using the data at each time point separately.

Even when using spatio-temporal modeling, though, estimating multiple dipole parameters generally requires a highly multidimensional nonlinear optimization search in which no existing technique can guarantee that the true solution will be attained within the practical limits of computational time. Thus, the success of multiple dipole parameter estimation greatly depends on how close the initial values are set to the true values of the dipole parameters in this search. One clever way to avoid this highly multidimensional search is to use the multiple signal classification (MUSIC) algorithm, which provides suboptimal estimates for multiple dipole locations by using only a three-dimensional (3-D) search, regardless of the number of sources. This algorithm was proposed by Schmidt [4], [5] in the field of antenna-array processing and introduced to the magnetoencephalographic (MEG) inverse problem by Mosher *et al.* [6].

The measurement of the biomagnetic field from a human brain often suffers from a very low signal-to-noise ratio (SNR). Often, the noise that most seriously affects the localization accuracy arises from spontaneous brain activity that is not related to the neural activity under study. Therefore, such spontaneous brain activity is usually referred to as brain noise. It has been reported that the use of a covariance matrix for such brain noise can significantly reduce its influence in source localization [7], [8]. This paper proposes a MUSIC-type algorithm that incorporates a noise covariance matrix of background brain activity. The algorithm can provide multiple-dipole estimation almost free of the influence of background activity.

In this paper, Section II describes the proposed method. Sections III and IV present results from computer simulation and from the method's application to auditory evoked field measurements; both sets of results strongly suggest that the proposed algorithm is effective. Throughout this paper, plain italics indicate scalars, lower-case boldface italics indicate vectors, and upper-case boldface italics indicate matrices. The superscript T indicates the matrix transpose. The eigenvalues are numbered in decreasing order.

II. Method

A. Definitions and Problem Formulation

Let us define the magnetic field measured by the mth detector coil at time t_k as $b_m(t_k)$, and a vector $\boldsymbol{b}(t_k) = [b_1(t_k), b_2(t_k), \cdots, b_M(t_k)]^T$ as a set of measured data at t_k where $k = 1, 2, \cdots, K$. M is the total number of detector coils, and K is the total number of time points. The spatio-temporal data matrix $\boldsymbol{B}$ is defined as $\boldsymbol{B} = [\boldsymbol{b}(t_1), \boldsymbol{b}(t_2), \cdots, \boldsymbol{b}(t_k)]$. We assume that a total P current-dipole sources generate a biomagnetic field. A spherical homogeneous conductor [9] is assumed, and two tangential components, the ϕ and θ components, of the source moment are considered. For simplicity, we assume in this paper that all dipole sources have fixed orientations during measurement, and the dipole orientation is defined as its normal vector $\boldsymbol{\eta}_p = (\eta_p^\phi, \eta_p^\theta)^T$, where $\|\boldsymbol{\eta}_p\| = 1$. We also define a $2P \times P$ matrix that expresses the orientations of whole P dipole sources as $\boldsymbol{\Psi}$, such that

$$\boldsymbol{\Psi} = \begin{bmatrix} \boldsymbol{\eta}_1 & 0 & \cdots & 0 \\ 0 & \boldsymbol{\eta}_2 & \cdot & \vdots \\ \vdots & \cdot & \ddots & 0 \\ 0 & \cdots & 0 & \boldsymbol{\eta}_p \end{bmatrix}. \quad (1)$$

The magnitude of the pth dipole-source moment is defined as $s_p(t_k)$. The source magnitude vector at t_k is defined as $\boldsymbol{s}(t_k) = [s_1(t_k), s_2(t_k), \cdots, s_P(t_k)]^T$. The source temporal behavior $\boldsymbol{S}$ is defined as $\boldsymbol{S} = [\boldsymbol{s}(t_1), \boldsymbol{s}(t_2), \cdots, \boldsymbol{s}(t_k)]$.

The lead field vectors for the ϕ and θ components of the pth source are defined as $\boldsymbol{l}_{p,1}^\phi = (l_{p,1}^\phi, l_{p,2}^\phi, \cdots, l_{p,M}^\phi)^T$ and $\boldsymbol{l}_{p,1}^\phi = (l_{p,1}^\theta, l_{p,2}^\theta, \cdots, l_{p,M}^\theta)^T$. We define the lead field matrix for the pth source as $\boldsymbol{L}_p = [\boldsymbol{l}_p^\phi, \boldsymbol{l}_p^\theta]$, and the lead field vector for the pth source is defined as $\boldsymbol{l}_p = \boldsymbol{L}_p\boldsymbol{\eta}_p$. The lead field matrix for the entire set of P dipole sources is defined as $\boldsymbol{L} = [\boldsymbol{L}_1, \boldsymbol{L}_2, \cdots, \boldsymbol{L}_P]$. Then, the relationship between the measurement vector $\boldsymbol{b}(t_k)$ and the source intensity vector $\boldsymbol{s}(t_k)$ is expressed as $\boldsymbol{b}(t_k) = (\boldsymbol{L\Psi})\boldsymbol{s}(t_k) + \boldsymbol{n}(t_k)$, where $\boldsymbol{n}(t_k)$ is the additive noise. The relationship between $\boldsymbol{B}$ and $\boldsymbol{S}$ is expressed as

$$\boldsymbol{B} = (\boldsymbol{L\Psi})\boldsymbol{S} + \boldsymbol{N} \quad (2)$$

where $\boldsymbol{N}$ is the noise matrix defined by $\boldsymbol{N} = [\boldsymbol{n}(t_1), \boldsymbol{n}(t_2), \cdots, \boldsymbol{n}(t_k)]$.

The conventional way of estimating the locations of the dipole sources is, based on the maximum-likelihood principle, to minimize the following least squares cost function

$$\mathcal{F} = \|\boldsymbol{B} - \hat{\boldsymbol{L}}(\hat{\boldsymbol{\Psi}}\hat{\boldsymbol{S}})\|^2 = \|[\boldsymbol{I} - \hat{\boldsymbol{L}}(\hat{\boldsymbol{L}}^T\hat{\boldsymbol{L}})^{-1}\hat{\boldsymbol{L}}^T]B\|^2. \quad (3)$$

Here, $\boldsymbol{I}$ is the unit matrix, and the estimates of $\boldsymbol{L}$, $\boldsymbol{\Psi}$, and $\boldsymbol{S}$ are denoted as $\hat{\boldsymbol{L}}$, $\hat{\boldsymbol{\Psi}}$, and $\hat{\boldsymbol{S}}$, respectively. This minimization, however, requires a $3P$ dimensional search where P is again the number of sources. Generally, for such a highly multidimensional search, there is no guarantee of obtaining the correct solution unless we can set the initial estimate very close to the true solution.

The MUSIC algorithm [5], [6], [10] has been introduced to avoid this highly multidimensional search. A distinct advantage of this algorithm is that, regardless of the number of dipole sources, it can give a suboptimal estimate of the source locations by using only a 3-D search in the solution space. The MUSIC algorithm, first, implements the eigen decomposition of the measured-data covariance matrix $\boldsymbol{R}_{BB}$, which is obtained by using $\boldsymbol{R}_{BB} \approx \boldsymbol{BB}^T$. We denote the eigenvectors of $\boldsymbol{R}_{BB}$ as $\{\boldsymbol{e}_j\}$, where $j = 1, 2, \cdots, M$. Unless some of the source activities are perfectly correlated with each other, $\boldsymbol{R}_{BB}$ has P eigenvalues arising from the signal sources and $M - P$ eigenvalues arising from the noise. Let us define the matrices $\boldsymbol{E}_S$ and $\boldsymbol{E}_N$ as $\boldsymbol{E}_S = [\boldsymbol{e}_1, \cdots, \boldsymbol{e}_P]$ and $\boldsymbol{E}_N = [\boldsymbol{e}_{P+1}, \cdots, \boldsymbol{e}_M]$. The span of the columns of $\boldsymbol{E}_S$ is called the signal subspace and that of $\boldsymbol{E}_N$ is called the noise subspace. To estimate the locations of the dipole sources, the MUSIC algorithm uses the fact that the lead field vector at each source location is orthogonal to the noise subspace. The source locations are estimated by checking the orthogonality between the lead field vector and the noise subspace projector $\boldsymbol{E}_N\boldsymbol{E}_N^T$.

In practice, some kind of measure to evaluate the orthogonality is needed to implement the MUSIC algorithm; this orthogonality measure is often called the MUSIC localizer. For such a localizer, we can use [6]

$$J(\boldsymbol{x}) = \frac{1}{\lambda_{\min}[\overline{\boldsymbol{L}}(\boldsymbol{x})^T\boldsymbol{E}_N\boldsymbol{E}_N^T\overline{\boldsymbol{L}}(\boldsymbol{x}), \overline{\boldsymbol{L}}(\boldsymbol{x})^T\overline{\boldsymbol{L}}(\boldsymbol{x})]} \quad (4)$$

where $\lambda_{\min}(\cdot, \cdot)$ indicates the generalized minimum eigenvalue of the matrix pair given in parenthesis. In this equation, $\overline{\boldsymbol{L}}(\boldsymbol{x})$ is an $M \times 2$ matrix and is expressed as $\overline{\boldsymbol{L}}(\boldsymbol{x}) = [\boldsymbol{l}_\phi(\boldsymbol{x}), \boldsymbol{l}_\theta(\boldsymbol{x})]$, where $\boldsymbol{l}_\phi(\boldsymbol{x})$ and $\boldsymbol{l}_\theta(\boldsymbol{x})$ are the lead field vectors for the ϕ and θ components of a source at $\boldsymbol{x}$. The MUSIC localizer is calculated in a volume where sources can exist, and the locations where the localizer reaches a peak are chosen as the source locations. Note that the localizer shown in (4) is derived under the assumption that the source orientations are fixed during the measurements. It is, however, proven in [6] that this localizer is also effective for dipole sources whose orientations vary during measurement.

B. Noise Covariance Incorporated MUSIC

External noise fields cause spatially correlated noise in biomagnetic measurements, and the incorporation of noise correlation is known to reduce the influence of such noise fields [7], [8]. In the MUSIC algorithm, this incorporation can be done in the following manner.

Let us define the covariance matrix of the dipole-source activities as $\boldsymbol{R}_{SS}$ and the noise covariance matrix as $\boldsymbol{R}_{NN}$. Using (2), we get

$$\begin{aligned}\boldsymbol{R}_{BB} &\approx \boldsymbol{B}\boldsymbol{B}^T \\ &= (\boldsymbol{L}\boldsymbol{\Psi})(\boldsymbol{S}\boldsymbol{S}^T)(\boldsymbol{L}\boldsymbol{\Psi})^T + \boldsymbol{N}\boldsymbol{N}^T \\ &\approx (\boldsymbol{L}\boldsymbol{\Psi})(\boldsymbol{R}_{SS})(\boldsymbol{L}\boldsymbol{\Psi})^T + \boldsymbol{R}_{NN}\end{aligned} \tag{5}$$

for correlated noise. We assume that the noise and the signal magnetic field are uncorrelated. Let us denote $\tilde{\boldsymbol{e}}_j$ as an eigenvector obtained by solving the generalized eigenvalue problem

$$\boldsymbol{R}_{BB}\tilde{\boldsymbol{e}}_j = \tilde{\lambda}_j \boldsymbol{R}_{NN}\tilde{\boldsymbol{e}}_j. \tag{6}$$

Using $\tilde{\boldsymbol{e}}_j$, it is easy to show that

$$\begin{aligned}(\boldsymbol{R}_{BB} - \boldsymbol{R}_{NN})\tilde{\boldsymbol{e}}_j &= (\boldsymbol{L}\boldsymbol{\Psi})\boldsymbol{R}_{SS}(\boldsymbol{L}\boldsymbol{\Psi})^T\tilde{\boldsymbol{e}}_j \\ &= 0 \quad \text{for } j = P+1, \cdots, M.\end{aligned} \tag{7}$$

Since both $(\boldsymbol{L}\boldsymbol{\Psi})$ and $\boldsymbol{R}_{SS}$ are full rank matrices, the above equation results in

$$(\boldsymbol{L}\boldsymbol{\Psi})^T\tilde{\boldsymbol{e}}_j = 0 \quad \text{for } j = P+1, \cdots, M. \tag{8}$$

Equation (8) indicates that the locations of the dipole sources are found by checking the orthogonality between the modified noise subspace projector $\tilde{\boldsymbol{E}}_N\tilde{\boldsymbol{E}}_N^T$ and the lead field vector. Here, $\tilde{\boldsymbol{E}}_N$ is defined as $\tilde{\boldsymbol{E}}_N = [\tilde{\boldsymbol{e}}_{P+1}, \cdots, \tilde{\boldsymbol{e}}_M]$. The eigenvectors are normalized in such a way that $\tilde{\boldsymbol{e}}_i^T\boldsymbol{R}_{NN}\tilde{\boldsymbol{e}}_j = \delta_{ij}$. Here, δ_{ij} is Kronecker's delta; $\delta_{ij} = 1$ when $i = j$, and $\delta_{ij} = 0$ when $i \neq j$. Therefore, the localizer for correlated noise is given by

$$J(\boldsymbol{x}) = \frac{1}{\lambda_{\min}[\overline{\boldsymbol{L}}(\boldsymbol{x})^T\tilde{\boldsymbol{E}}_N\tilde{\boldsymbol{E}}_N^T\overline{\boldsymbol{L}}(\boldsymbol{x}), \overline{\boldsymbol{L}}(\boldsymbol{x})^T\boldsymbol{R}_{NN}^{-1}\overline{\boldsymbol{L}}(\boldsymbol{x})]}. \tag{9}$$

This paper proposes using the above localizer to reduce the influence of background brain activities in the MUSIC localization procedure. An accurate estimate of the noise covariance matrix, however, is needed to use the localizer. For this purpose, one should find a portion of the data that contains only noise fields and does not contain any signal information. For evoked neuromagnetic experiments, such a portion can be found in a data portion taken before a stimulus is applied. When the prestimulus data portion is sufficiently long and the interstimulus interval is sufficiently large, an accurate estimate of the covariance matrix can be obtained.

III. Computer Simulation

We performed computer simulations to test the effectiveness of the proposed method. A 37-channel magnetometer whose coil alignment was the same as that of the Magnes biomagnetic measurement system (Biomagnetic Technologies, Inc., San Diego, CA) was assumed. The z direction was defined as the direction perpendicular to the detector coil at the center of the coil alignment, and z is equal to zero at this coil position. The values of the spatial coordinates (x, y, z) are expressed in centimeters. Two signal dipole sources are assumed to exist: the first dipole source at (3.7, 1.0, −4.6) and the second dipole source at (−2.1, 1.0, −7.3). The source of the background activity was assumed to exist at (4.5, −1.3, −11.3). The source and detector configuration for this simulation is shown schematically in Fig. 1.

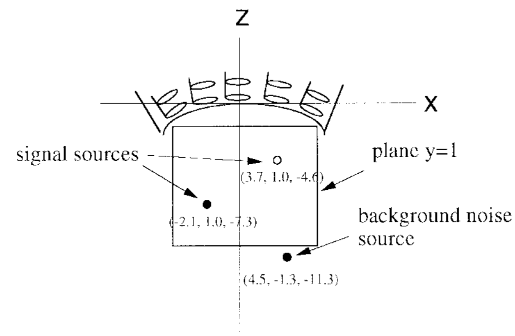


Fig. 1. Source and detector configuration assumed in computer simulation.

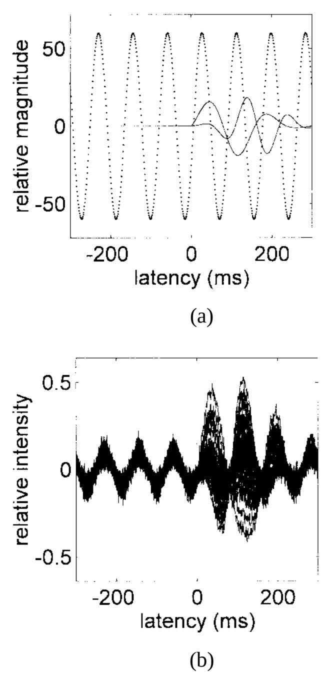


Fig. 2. (a) Waveforms assumed for calculating the ϕ components of two signal sources (solid lines) and one background noise source (dotted line) in the computer simulation. (b) Simulated 37-channel recordings calculated in the computer simulation. The portion between 0 and 300 ms is used for the MUSIC multidipole analysis, and that between −300 and 0 ms is used to calculate the noise covariance matrix.

To generate the simulated biomagnetic field, the ϕ components of the signal sources were modeled using exponentially damped sinusoidal functions, and the ϕ component of the background activity was modeled using a sinusoidal function. The θ components for both types of sources were set at zero for simplicity. The waveforms of the ϕ components are shown in Fig. 2(a). The simulated biomagnetic field was calculated by using these waveforms at 1-ms intervals. Uncorrelated Gaussian noise was added to make the final signal-to-noise ratio equal to 3.6. The SNR was defined by the ratio of the Frobenius norm of the signal-magnetic-field spatio-temporal matrix to that of the noise matrix. The simulated 37-channel recordings are shown in Fig. 2(b).

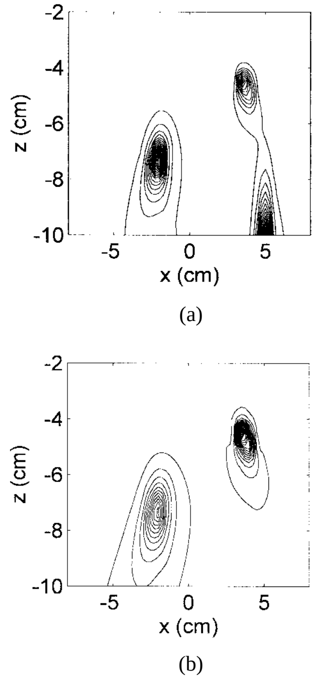


Fig. 3. Results of calculating MUSIC localizers on the plane $y = 1$ with the simulated 37-channel recordings in the computer simulation. (a) The conventional MUSIC localizer given in (4) was used and (b) the localizer proposed in (9) was used. Each contour shows the relative value of the localizer, and each area where the localizer reaches a peak is considered to be the location of one dipole.

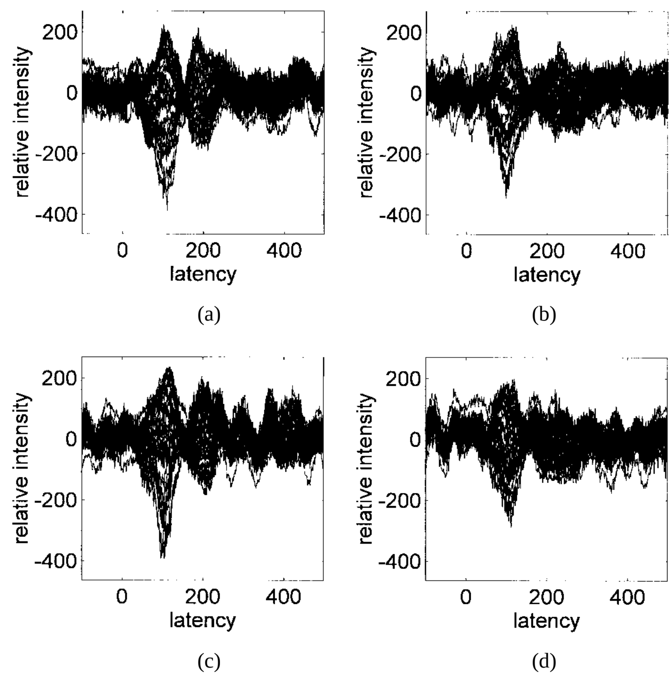


Fig. 4. Overlapped display of 37-channel recordings of auditory evoked responses elicited by the four syllables: (a) /bae/, (b) /dae/, (c) /pae/, and (d) /tae/.

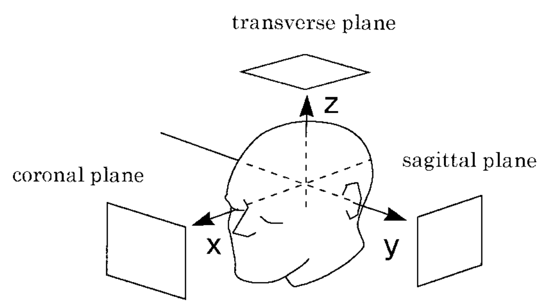


Fig. 5. The x, y, and z coordinates used to express the localization results shown in Figs. 6–8. The midpoint between the left and right preauricular points is defined as the coordinate origin. The axis directed away from the origin toward the left preauricular point is defined as the $+y$ axis, and that from the origin to the nasion is the $+x$ axis. The $+z$ axis is defined as the axis that is perpendicular to both these axes and directed from the origin to the vertex.

The data portion from 0 to 300 ms was used for the MUSIC localization experiments. First, the conventional MUSIC localizer shown in (4) was applied to this data portion, and the results of calculating the localizer on the $y = 1.0$ plane are shown in Fig. 3(a). These contours show the relative value of the localizer, and each area where the localizer reaches a peak is considered to be the location of one dipole source. Here, the localizer detects two signal sources, but also detects a false source caused by the influence of background activity. Next, the proposed localizer in (9) was applied to the same portion of the data. The noise covariance matrix was calculated using the data from -300 to 0 ms. The results are shown in Fig. 3(b). Comparing Fig. 3(a) with Fig. 3(b), one can see that the influence of the background activity is almost completely eliminated. The results in Fig. 3 clearly demonstrate the effectiveness of the proposed MUSIC localizer.

IV. Application to Auditory-Evoked Field

The proposed method was applied to source localization for the N1m component of auditory-evoked responses elicited by speech sounds. The biomagnetic fields were measured using a 37-channel Magnes magnetometer installed at the Biomagnetic Imaging Laboratory, University of California, San Francisco, CA. All measurements were done in a magnetically shielded room.

The subject was a male volunteer with no audiological abnormalities. The auditory stimuli used in the experiments were four kinds of syllables /dae/, /bae/, /pae/, and /tae/. The subject was asked to discriminate the voiced syllables /dae/ and /bae/ from the voiceless syllables /pae/ and /tae/. The subject pressed one response button when perceiving a /dae/ or /bae/ and pressed another button when perceiving a /pae/ or /tae/. Stimuli were presented to the subject's right ear, and the magnetometer was placed above the subject's left hemisphere. The subject used his left hand to press the response buttons.

The four syllables were presented in a pseudo random order at variable interstimulus intervals ranging from 1 s to 1.5 s. The stimulus duration was 300 ms and the total data acquisition time was 600 ms, including a 100-ms prestimulus interval. The data sampling frequency was 1041.7 Hz and a bandpass on-line filter with a bandwidth between 1 Hz and 400 Hz was applied. The 100 epochs were averaged and no off-line digital filter was applied. The averaged 37-channel recordings for the four kinds of auditory stimuli are shown in Fig. 4. In the prestimulus data portions of these recordings (from -100

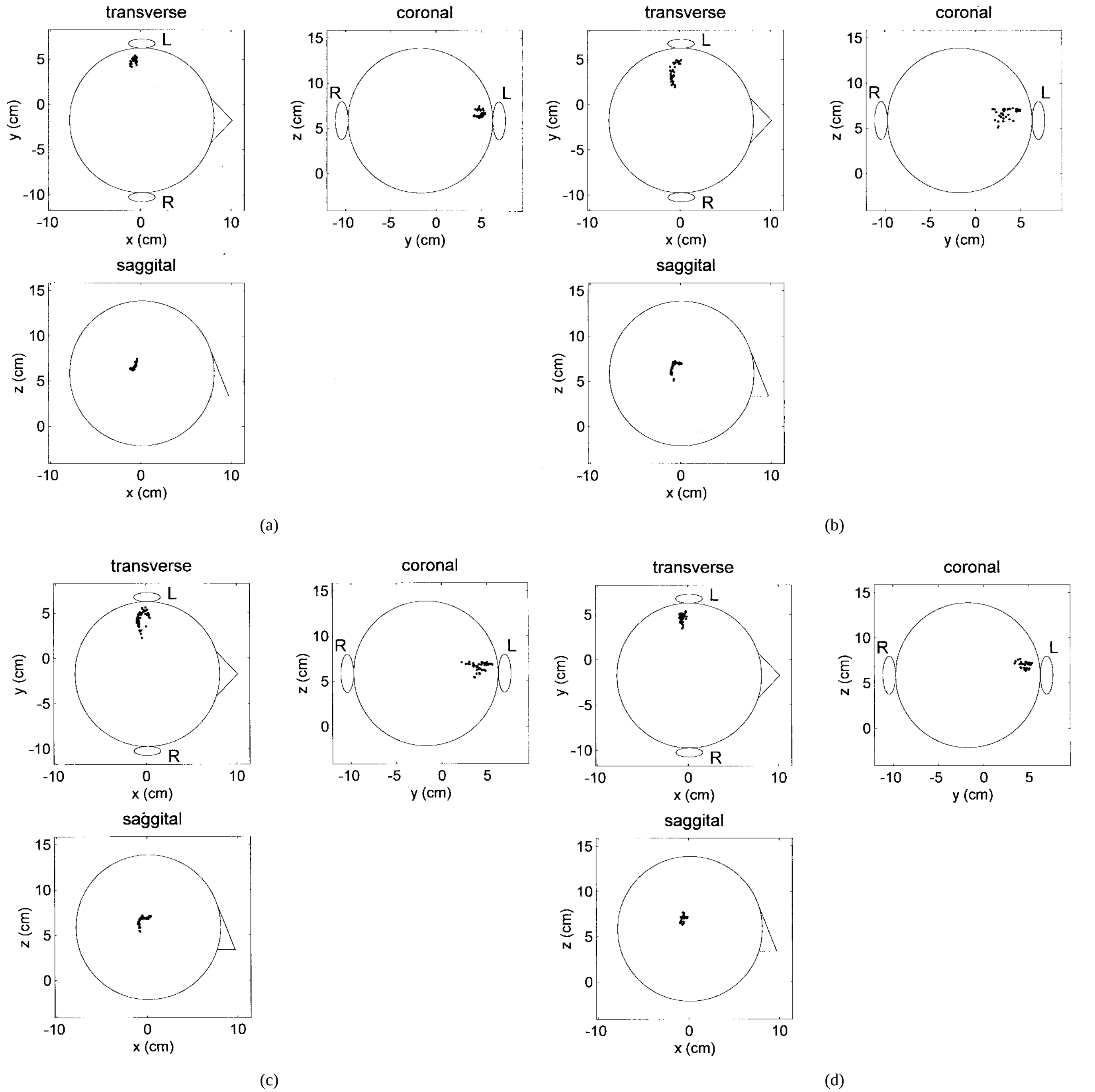


Fig. 6. Single-dipole estimation results for the auditory evoked responses shown in Fig. 4. Results are shown for the evoked responses from (a) /bae/, (b) /dae/, (c) /pae/, and (d) /tae/. The estimated locations whose goodness-of-fit was greater than 0.95 were selected, and their projections onto the transverse, coronal, and sagittal planes were plotted. The circles depicting a human head represent the projections of the sphere used in the forward model onto the transverse, coronal, and sagittal planes. Each dot represents one estimated dipole location. L and R indicate the subject's left and right hemispheres.

to 0 ms), a fairly large amount of background noise can be observed. This may be caused by the overlapping of motor cortex activations elicited by the button-press response to the previous syllable.

The x, y, and z coordinates used to express the estimated results are depicted in Fig. 5. The midpoint between the left and right preauricular points is defined as the coordinate origin. The axis directed away from the origin toward the left preauricular point is defined as the $+y$ axis, and that from the origin to the nasion is the $+x$ axis. The $+z$ axis is defined as the axis that is perpendicular to both these axes and directed from the origin to the vertex. These coordinates are measured in centimeters.

A single dipole analysis was applied to the data portion from 0 ms to 300 ms of the auditory evoked field data. In this analysis, the biomagnetic recordings were digitally filtered with a bandpass filter with a bandwidth ranging from 1 Hz to 20 Hz, and the location of a single dipole was estimated for each time point. From approximately 300 estimated locations, those whose goodness-of-fit was greater

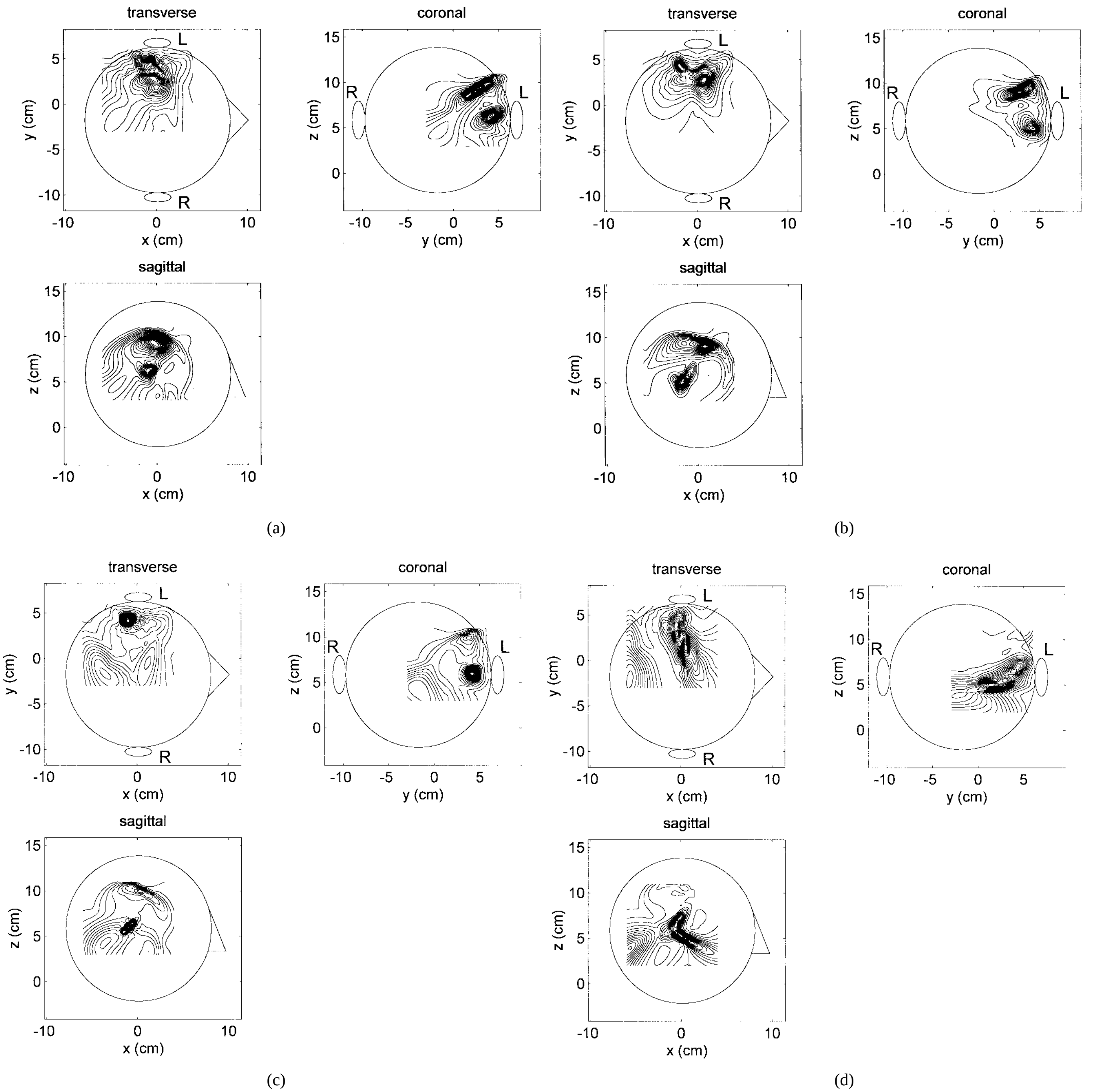


Fig. 7. The results of calculating the conventional localizer in (4) in a 3-D volume. The projections onto the transverse, coronal, and sagittal planes are shown. Results are shown for the evoked responses to (a) /bae/, (b) /dae/, (c) /pae/, and (d) /tae/.

than 0.95 were selected and the projections of these locations onto the transverse, coronal, and sagittal planes are plotted in Fig. 6.

Fig. 6 (a)–(c) and (e), respectively, shows the results for the syllables /dae/, /bae/, /pae/, and /tae/. Each dot represents one estimated location of a single dipole. The circles depicting a human head represent the projections of the sphere used to calculate forward solutions. All of the results show clusters of dipole locations near the primary auditory cortex area. This is in good agreement with previous analysis on the speech-sound elicited neuromagnetic fields, in which a single dipole source was localized near the primary auditory cortex [11], [12]. The dipole clusters are concentrated in the results for /bae/ and /tae/, but are fairly widely distributed for /dae/ and /pae/, probably because of the influence of background activity.

The results of applying the MUSIC algorithm with the conventional localizer given in (4) are shown in Fig. 7. Here, using the data shown in Fig. 4, the MUSIC localizer was calculated with an interval of 0.5 cm within a volume defined as $-4 \leq x \leq 6$, $-3 \leq y \leq 6$, and $3 \leq z \leq 11$. All of these results show complex source configurations probably due to the background brain activity. The MUSIC algorithm with the localizer proposed in (9) was next applied. The results are shown in Fig. 8. These results indicate that a single source

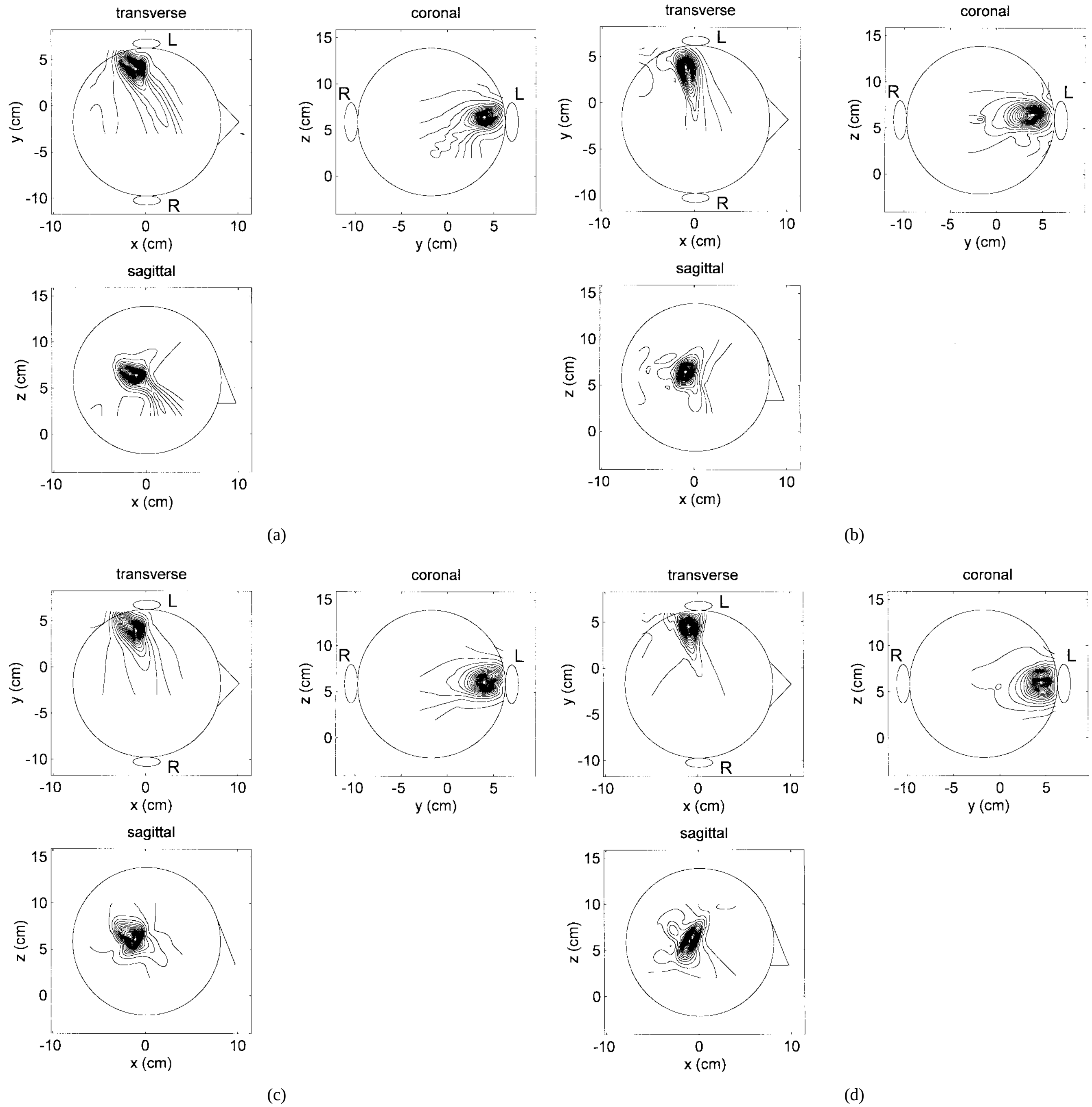
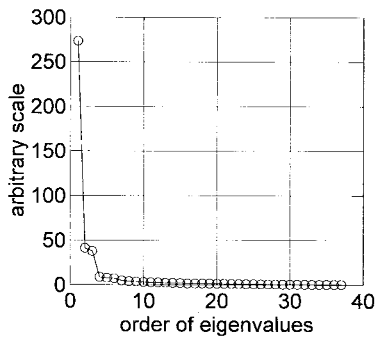


Fig. 8. The results of calculating the localizer proposed in (9) in a 3-D volume. The projections onto the transverse, coronal, and sagittal planes are shown. Results are for the evoked response to (a) /bae/, (b) /dae/, (c) /pae/, and (d) /tae/.

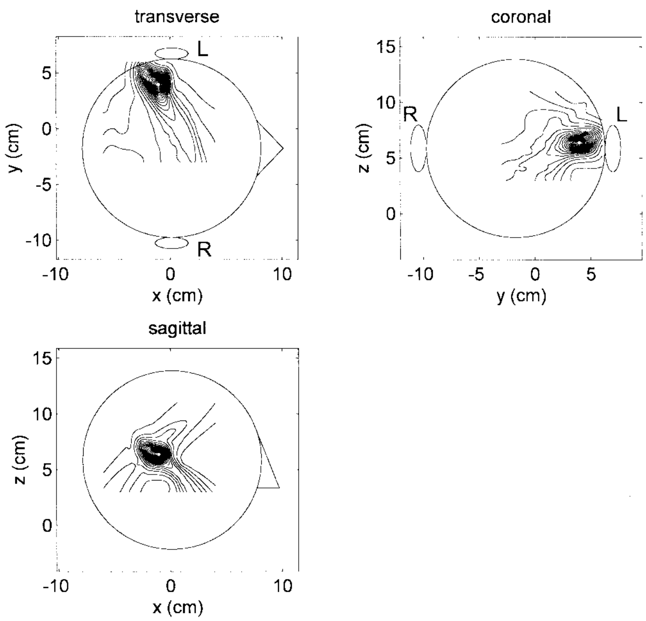
exists in the area near the primary auditory cortex in all four cases. It is easy to see that each peak location in Fig. 8 is very close to the center of one dipole cluster in Fig. 6. Thus, the MUSIC results are in very good agreement with the single dipole estimation results. Although the nature of sources for speech-sound-elicited neuromagnetic fields has not yet been fully understood, several previous investigations suggest a single dipole source located near the primary auditory cortex for such neuromagnetic fields [11]–[13]. Thus, the results obtained using the proposed localizer are more plausible than the results in Fig. 7, which were obtained using the conventional localizer in (4). These results in Fig. 8 strongly suggest the effectiveness of the proposed MUSIC localizer in removing the influence of background activity.

V. Discussions

In the proposed algorithm, the number of sources can, in principle, be obtained by separating nonzero generalized eigenvalues $\tilde{\lambda}_j$ where $j = 1, \cdots, P$ from zero-level generalized eigenvalues $\tilde{\lambda}_j$ where $j = P+1, \cdots, M$. This separation may not be easy when the number of time points used to calculate the covariance matrix is small, or when sources are partially correlated. The eigenvalues for the data set obtained



(a)



(b)

Fig. 9. (a) The plot of the generalized eigenvalues $\tilde{\lambda}_j$ in (6) calculated using the evoked responses to /bae/. (b) The results of applying the proposed localizer to the evoked response to /bae/ when setting the number of sources at seven.

from the stimulus /bae/ are plotted in Fig. 9(a). The MUSIC results for /bae/ shown in Fig. 8 were obtained by setting the number of sources to three, but as can be seen from Fig. 9(a), the determination of the source number to three is somewhat ambiguous. However, in general, the MUSIC algorithm is tolerant of source-number overestimation [14]. This tolerance is demonstrated in Fig. 9(b) where the MUSIC results for /bae/ were calculated by setting the source number to seven. Even though the number of sources was considerably overestimated, no serious distortion resulted. Therefore, if there is any ambiguity in determining the number of sources, the largest possible number should be used.

The success of the proposed algorithm depends on how accurately the noise covariance matrix is estimated. This accuracy is primarily determined by the number of time points used for the estimation. It is, however, not easy to determine the number needed to give an accurate estimate of the covariance matrix, because this number depends on various conditions during data acquisition, such as the amplitude of the noise and the source and detector configurations. Therefore, when applying the proposed method, the data acquisition should be designed to provide as many time points as possible for the noise covariance estimation. Also, the proposed method may not work well when the SNR for the uncorrelated sensor noise is extremely high. This is because the noise covariance matrix becomes almost singular, and the inverse of the covariance matrix cannot be calculated. This fact usually does not affect the practical application of the method to the MEG inverse problem, because in most cases of MEG measurement the SNR of the sensor noise seldom exceeds 50. However, if the method is applied to extremely high SNR data, one should be careful when interpreting the results.

VI. Conclusion

In summary, this paper proposes a multiple dipole estimation method that is tolerant of the influence of background brain activity. This method is based on the MEG-MUSIC algorithm and incorporates information on the noise covariance matrix. A computer simulation verified the effectiveness of the proposed method. The method was also applied to speech-sound-elicited auditory evoked fields, and results strongly suggesting the method's effectiveness were obtained.

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