A Neural Behavior Estimation by the Generalized Correlative Analysis (Invited)

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***Abstract*-The recent developments of SQUID flux meters make it possible to measure the magnetic field caused by the neural activity in a human brain. The field distribution measured on the human head surface provides highly important information of the human brain activities. The problem of obtaining the current signal flow in the brain reduces to the inverse problem, the governing equation of which is written in an integral form. We propose a generalized correlative analysis method based on the Cauchy-Schwarz relation in order to solve the system equation derived from the governing equation. As a result, we have succeeded in estimating current signal flows in the human brain.**

I. INTRODUCTION

One of the most interesting and important investigations on biological systems is to clarify the neural behavior of the human brain. Studies based on the analysis of blood flow distribution in the brain and electroencephalogram (EEG) have clarified the role of each part of the brain, such as somatosensory area for eyes, motor area for hands, memory and so forth. On the other hand, the recent developments of high sensitive superconducting quantum interference device (SQUID) [1] enable us to measure a flux density ranging in tesla from 10^{-14} to 10^{-10}. The magnetic field measured on a human head surface by a SQUID flux meter is called a magnetoencephalogram (MEG) [2]. Many studies have been done based on the MEG [3-5] and are expected to obtain new information for the functional and operational roles of the brain in addition to the conventional medical diagnosis.

With the development of modern digital computers, forward problems of obtaining electromagnetic fields from their source distributions have been solved by general purpose software packages using, for example, the finite element method (FEM) [7,8]. In contrast, the inverse problem of obtaining the electromagnetic source distribution from its field or potential distribution is now studied actively with numerical methods [9,10]. Most of the inverse problems are mathematically reduced to solving integral equations [11]. The MEG analysis leads to the inverse problem in which the magnetostatic governing equation is also written in an integral form. Most of the conventional MEG analyses are reduced to searching for a single current dipole using least squares or statistical methods such as the variance and the correlative coefficient [4-6]. However, in these methods, it is difficult to obtain plural current dipoles.

In this paper, we propose one of the promising approaches for MEG analysis. The authors have succeeded in solving some inverse problems for the current dipole searching in the human eye's magnetic field, for two dimensional shape identification of metallic materials and for magnetocardiogram (MCG) analysis, using the sampled pattern matching (SPM) method based on the Cauchy-Schwarz relation [12,13]. We derive a generalized correlative analysis method from the SPM method. The MEG analyzed in this paper is obtained from reference [4] where a healthy man's right ankle is electrically stimulated. The generalized correlative analysis method successfully provides the distribution of the plural current dipoles corresponding to current signals in the human brain.

II. GENERALIZED CORRELATIVE ANALYSIS

System Equation for MEG Analysis

MEG analysis is basically reduced to a magnetostatic field problem with the open boundary condition because the permeability in the human brain may be approximately assumed to be the permeability of vacuum, μ_0.

The Helmholtz theorem states that any magnetic field intensity vector **H** consists of the rotation of a vector potential **A** and the gradient of a magnetic scalar potential ϕ [14]:

$$\mathbf{H} = (1/\mu_0)\nabla\times\mathbf{A} - \nabla\phi. \quad (1)$$

By taking the rotation of (1), we have

$$\nabla\times\mathbf{H} = \nabla\times\{(1/\mu_0)\nabla\times\mathbf{A} - \nabla\phi\}$$
$$= (1/\mu_0)\nabla\times\nabla\times\mathbf{A}, \quad (2)$$

because $\nabla\times\nabla\phi = 0$ for any scalar function ϕ. For homogeneous materials, the vector potential **A** in (2) is given by

$$\mathbf{A} = \mu_0 \int G\,\nabla\times\mathbf{H}\,dv, \quad (3)$$

where G denotes the Green function. The Green function for three dimensional static fields is

$$G = \frac{1}{4\pi r}, \quad (4)$$

where r is the distance between the source point where **H** is evaluated and the field point at which **A** is given. The current density **J** is related to the magnetic field **H** by

$$\nabla\times\mathbf{H} = \mathbf{J}, \quad (5)$$

where **J** is the current density at the same position as **H**. Therefore, (3) is modified into

$$(1/\mu_0)\mathbf{A} = \int G\,\mathbf{J}\,dv, \quad (6)$$

where the current density **J** satisfies

$$\nabla\cdot\mathbf{J} = 0, \quad (7)$$

because

$$\nabla\cdot\nabla\times\mathbf{H} = 0, \quad (8)$$

for any vector function **H**.

In (1), if we assume that the magnetic field is only composed of the current density **J** of (6), then (1) without the term $\nabla\phi$ becomes

$$\mathbf{H} = (1/\mu_0)\nabla\times\mathbf{A}$$
$$= \nabla\times\int G\,\mathbf{J}\,dv, \quad (9)$$

where the current density **J** satisfies the condition of its spatial continuity. Equation (9) is the governing equation of the inverse problem for the MEG analysis with homogeneous open boundary condition.

In order to solve the integral equation (9) numerically, let us discretize a target volume in the brain into the subdivisions ΔV_j, j=1,···,m, as shown in Fig. 1. Denoting n as the number of magnetic field measurement points on the head surface, the magnetic field intensity at the sampled point i becomes

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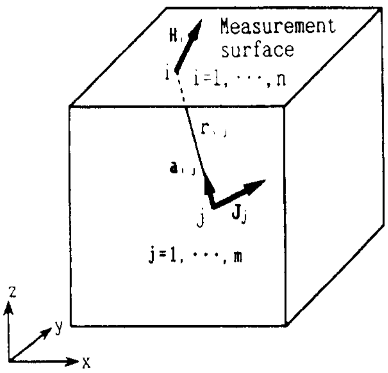

Fig. 1. Model for analysis.

$$H_i = \sum_{j=1}^{m} \frac{J_j \times a_{ij} \Delta V_j}{4\pi r_{ij}^2}, \; i=1, \cdots, n, \tag{10}$$

where r_{ij} and a_{ij} are the distance between the field point i and the source point j; and unit space vector in the direction of r_{ij}, respectively (see Fig. 1). The discretized form of (9) has been derived by assuming that the current density J_j takes a constant value in the subdivision ΔV_j, viz.,

$$\nabla \times \left(\frac{J_j}{4\pi r}\right) = J_j \times \frac{a_{ij}}{4\pi r_{ij}^2}. \tag{11}$$

Using unit space vector e_j in the direction of J_j, (10) is rewritten in the form:

$$H_i = \sum_{j=1}^{m} |J_j \Delta V_j| \frac{e_j \times a_{ij}}{4\pi r_{ij}^2}, \; i=1, \cdots, n. \tag{12}$$

Equation (12) corresponds in essence to the Biot-Savart law. The current dipole ($J_j \Delta V_j$) Am is equivalent to the current element obtained by the product of current and its path length.

The system equation (12) for the MEG analysis is expressed by

$$U = \sum_{j=1}^{m} \alpha_j d_j, \tag{13}$$

where the vectors U and d_j are n dimensional column vectors. From (12), U, d_j and α_j are respectively given by

$$U = [H_1, H_2, \cdots, H_n]^T, \tag{14}$$

$$d_j = \frac{1}{4\pi}\left[\frac{e_j \times a_{1j}}{r_{1j}^2}, \frac{e_j \times a_{2j}}{r_{2j}^2}, \cdots, \frac{e_j \times a_{nj}}{r_{nj}^2}\right]^T, \tag{15}$$

$$\alpha_j = |J_j \Delta V_j|. \tag{16}$$

In (13), the number of equations, n, is generally fewer than the number of the unknowns, m:

$$n < m, \tag{17}$$

because the magnetic field is measured on a surface whereas the field source searching region is a volume as seen in Fig. 1. Therefore, the system matrix composed of the column vectors d_j, j=1, ···, m, is not a square matrix but a rectangular matrix so that the inverse matrix cannot be obtained. This point is the mathematical difficulty of the inverse problem.

Sampled Pattern Matching Method

In order to overcome the difficulty in solving the system equation (13), we have previously proposed the SPM method [12,13]. In this paper, we suggest a modified SPM method leading to a generalized correlative analysis method.

Let the magnetic field pattern vector U decompose into a space variable component U' and a mean component U_θ:

$$U = U' + U_\theta. \tag{18}$$

The elements of the mean component vector U_θ have the same value obtained by integrating the magnetic field intensity on the measurement surface in Fig. 1 and then dividing the integrated result by the surface area. The column vector d_j, j=1, ···, m, can be regarded as a magnetic field pattern vector on the measurement surface depending on the field source position j and the spatial angle of J_j, so that d_j can be similarly decomposed into

$$d_j = d_j' + d_{j\theta}, \; j=1, \cdots, m, \tag{19}$$

where d_j' and $d_{j\theta}$ are the space variable and mean components, respectively. From (13), (18) and (19), we have

$$U' = \sum_{j=1}^{m} \alpha_j d_j', \tag{20a}$$

$$U_\theta = \sum_{j=1}^{m} \alpha_j d_{j\theta}. \tag{20b}$$

The derived system equation (20a) is solved by the SPM method for MEG analysis because the vectors U_θ and $d_{j\theta}$ have no spatial pattern.

From (18), (19) and (20a), it is obvious that the Cauchy-Schwarz relation used in the SPM method:

$$\gamma_j = \frac{U'^T \cdot d_j'}{\|U'\| \, \|d_j'\|}, \; j=1, \cdots, m, \tag{21a}$$

is equivalent to a coefficient of correlation between the measured magnetic field pattern U' and the field pattern d_j' due to the current dipole ($J_j \Delta V_j$) located at the point j in Fig. 1. Evaluation of (21a) should be done by taking account of the spatial angle of the current dipole. The correlative analysis is carried out by searching for the field source point k where γ_k takes the maximum value in (21a).

In the SPM method, the following procedure is added to the correlative analysis. After finding the source position k which is called a pilot point in the SPM method, a second pilot point can be found by searching for the maximum of

$$\gamma_{kj} = \frac{U'^T \cdot (d_k' + d_j')}{\|U'\| \, \|d_k' + d_j'\|}, \; j\neq k, j=1, \cdots, m. \tag{21b}$$

Similar procedures are continued up to the peak value of γ in order to obtain the field source distribution pattern consisting of plural field source positions. The result of the procedures provides the solution of a modified form of (20a):

$$U' = \sum_{i=1}^{m} \{\beta_i d_i' + \sum_{j\neq i}^{m} \{\beta_{ij}(d_i' + d_j') + \sum_{k\neq i, k\neq j}^{m} \{\beta_{ijk}(d_i' + d_j' + d_k') + \cdots\}\}\}. \tag{22}$$

The 1st, 2nd and 3rd terms on the right hand side of (22) correspond to one, two and three pairs of the north and south magnetic field patterns on the measurement surface, respectively.

The generalized correlative analysis provides the correlative coefficient distribution γ_j', j=1, ···, m:

$$\gamma_1' \simeq [\gamma_1 + \gamma_{k1} + \cdots] / m', \tag{23a}$$

$$\gamma_2' \simeq [\gamma_2 + \gamma_{k2} + \cdots] / m', \tag{23b}$$

..............................,

$$\gamma_k' \simeq [\gamma_k + 1 + 1 + \cdots] / m', \tag{23c}$$

..............................,

$$\gamma_m' \simeq [\gamma_m + \gamma_{km} + \cdots] / m', \tag{23d}$$

where m' denotes the number of repeated procedures similar to (21a) or (21b) and also corresponds to the number of found pairs of the north-south poles. Equations (23a)-(23d) give an averaged correlative coefficient distribution corresponding to a normalized current dipole distribution. Because (23a)-(23d) can be rewritten by

$$\alpha_1 \frac{\|d_1'\|}{\|U\|} \simeq \frac{1}{m'} \frac{U^T}{\|U\|} \cdot \left(\frac{d_1'}{\|d_1'\|} + \frac{d_k' + d_1'}{\|d_k' + d_1'\|} + \cdots\right), \tag{24a}$$

$$\alpha_2 = \frac{\| \mathbf{d}_2' \|}{\| \mathbf{U} \|} \simeq \frac{1}{m'} \frac{\mathbf{U}^T}{\| \mathbf{U} \|} \cdot \left(\frac{\mathbf{d}_2'}{\| \mathbf{d}_2' \|} + \frac{\mathbf{d}_1' + \mathbf{d}_2'}{\| \mathbf{d}_1' + \mathbf{d}_2' \|} + \cdots \right), \quad (24b)$$

....,

$$\alpha_k = \frac{\| \mathbf{d}_k' \|}{\| \mathbf{U} \|} \simeq \frac{1}{m'} \left(\frac{\mathbf{U}^T}{\| \mathbf{U} \|} \cdot \frac{\mathbf{d}_k'}{\| \mathbf{d}_k' \|} + 1 + 1 + 1 + 1 + \cdots \right), \quad (24c)$$

....,

$$\alpha_m = \frac{\| \mathbf{d}_m' \|}{\| \mathbf{U} \|} \simeq \frac{1}{m'} \frac{\mathbf{U}^T}{\| \mathbf{U} \|} \cdot \left(\frac{\mathbf{d}_m'}{\| \mathbf{d}_m' \|} + \frac{\mathbf{d}_1' + \mathbf{d}_m'}{\| \mathbf{d}_1' + \mathbf{d}_m' \|} + \cdots \right). \quad (24d)$$

Obviously, this method has assumed that the angle between the vectors $\mathbf{d}_i'$ and $\mathbf{d}_j'$, $i \neq j$, is always smaller than $\pi/2$, i.e. $\| \mathbf{d}_i' + \mathbf{d}_j' \| > \| \mathbf{d}_i' \|$ or $\| \mathbf{d}_i' + \mathbf{d}_j' \| > \| \mathbf{d}_j' \|$. Also, (24a)-(24d) give a unique solution pattern, not the exact solutions [12, 13].

III. EXAMPLES

Before we practically apply the generalized correlative analysis to MEG analysis, we examine the validity of the method by applying it to typical test examples.

In the first test example as shown in Fig. 2, a straight current flows from the top to bottom corners in a cubic problem region. The currently available SQUID flux meter is capable of measuring only the magnetic fields normal to the brain surface. Therefore, we only consider the z components of the magnetic field vector $\mathbf{H}_i$, $i = 1, \cdots, n$ in Fig. 1. This means that the current density $\mathbf{J}$ can be evaluated only by its x and y components in the cube because of (5). In other words, the z component current density can be represented in a stepwise form as shown in Fig. 2(a). Figure 2(b) shows the magnetic field pattern of the z component obtained from the field source distribution pattern in Fig. 2(a). The number of the measurement points is n = 6×6 = 36 on the top surface of the cube. The conventional single dipole model using least squares [4-6] gives a most dominant single current dipole position as shown in Fig. 2(c). However, generalized correlative analysis provides multiple current dipole distributions as shown in Fig. 2(d)-(f) in which over 90% of the results obtained by (24a)-(24d) are shown in order to get a higher contrast. To verify the uniqueness of the solution patterns obtained by generalized correlative analysis on the different system conditions, the number of the unknowns, m in the system equation (20a) has been changed. The number m includes not only the subdivisions in space but also the angle divisions of current dipoles at the same position. The target volume has been discretized uniformly in space and the number of angle division on the x-y plane is 72. The number of total unknowns in Figs. 2(d)-2(f) is m = 395352, m = 64152 and m = 12600, respectively. From Figs. 2(d)-2(f), it is observed that the solution patterns are unique. Moreover, the solution pattern obtained by a fine mesh tends to reach the exact current flow distribution as shown in Fig. 2(a). Comparing Fig. 2(d) with Fig. 2(c) obtained using the same spatial subdivision, it is obvious that the generalized correlative analysis is far superior to the conventional single dipole model using least squares. The number of pilot points found for different

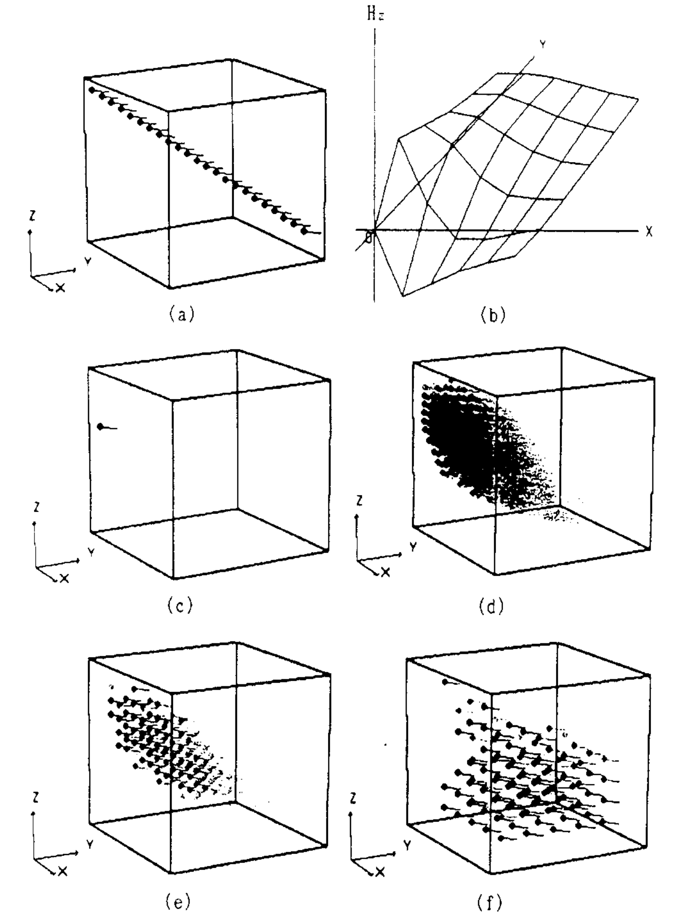

Fig. 2. Current flowing diagonally in the cube. (a) Exact current. (b) The magnetic field pattern normal to the top surface. (c) Current dipole obtained by the conventional single dipole model. (d)-(f) Current dipole distribution obtained by generalized correlative analysis for m=395352, 64152 and 12600.

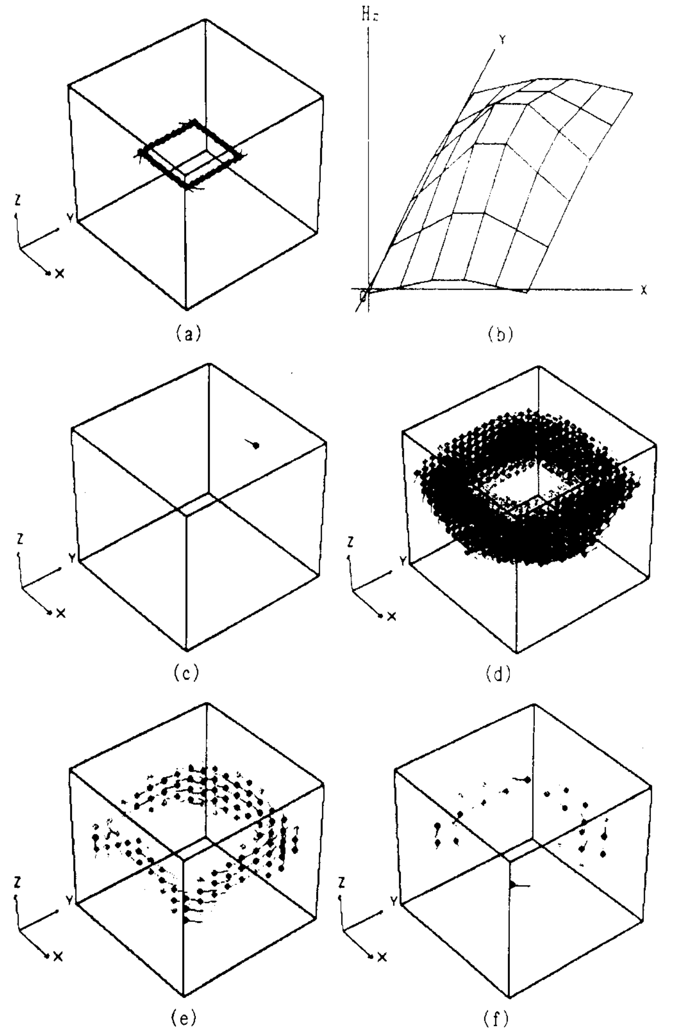

Fig. 3. Current flowing in a loop shape in parallel to the x-y plane. (a) Exact current. (b) The magnetic field pattern normal to the top surface. (c) Current dipole obtained by the conventional single dipole model. (d)-(f) Current dipole distribution obtained by generalized correlative analysis for m=395352, 64152 and 12600.

Table 1. Coefficients of correlation for the examples.

Figure	2(c)	2(d)	2(e)	2(f)	3(c)	3(d)	3(e)	3(f)
Number of found pilot points.	1	3	3	5	1	10	5	4
γ	0.98	0.99	0.99	0.99	0.78	0.99	0.95	0.97
γ_{total}	--	0.88	0.88	0.88	--	0.98	0.97	0.93

subdivisions is listed in Table 1 where γ and γ_{total} denote the correlative coefficients due to the pilot points and due to the entire current dipoles in the target volume, respectively.

In the loop shaped current shown in Fig. 3(a), the superiority of the generalized correlative analysis is very clearly demonstrated compared with the previous one. The magnetic field pattern composed of the z component shown in Fig. 3(b) is caused by the field source distribution shown in Fig. 3(a). Applying the conventional single dipole model to the field pattern of Fig. 3(b) gives a most dominant single current dipole as shown in Fig. 3(c). It is obviously impossible to reproduce the loop shape current distribution by the conventional single dipole model. However, the generalized correlative analysis can provide the loop shaped current dipole distributions as shown in Figs. 3(d)-3(f) where the number of the unknowns in Figs. 3(d)-3(f) is respectively equivalent to that in Figs. 2(d)-2(f). Figures 3(d)-3(f) show over 90% of the results obtained by (24a)-(24d). The uniqueness of the solution patterns is again confirmed from Figs. 3(d)-3(f). The correlative coefficients are listed in Table 1. Comparing γ given by the single current dipole in Fig. 3(c) with others given by the plural current dipoles in Figs. 3(d)-3(f), it is obvious that the field source distributions obtained by generalized correlative analysis yield the more accurate results compared with the single dipole model.

IV. CURRENT SIGNAL ESTIMATION IN THE HUMAN BRAIN

From past studies on the human brain functions, it has been well-known that the nerves of a human's ankle are related with a particular region of the brain enclosed by the square solid line in Fig. 4 [3]. Hence the MEG obtained while a healthy human's right ankle has been electrically stimulated by a rectangular pulse of 0.2 ms with the period of 0.5 s, was measured on the head surface shown in Fig. 4(b) by Uchikawa and Kotani [4]. Only the magnetic field normal to the head surface was measured. The head surface is not a flat plane, however the measurement surface has been assumed to be a plane surface in the following MEG analysis.

Generalized correlative analysis is now applied to the MEGs measured at five different times, 40 ms, 80 ms, 90 ms, 100 ms and 120 ms after the pulse was impressed. Figures 5-9 show the MEGs measured at $n = 5\times5 = 25$ points and estimated current dipole distributions where the number of unknowns $m = 1125000$ includes the angle division of 72 in the target volume. To get a much higher contrast, over 95% of the results obtained by (24a)-(24d) are shown in Figs. 5-9 because the number of the found pilot points is much larger than that of the test examples. The number of found pilot points, γ and γ_{total} of

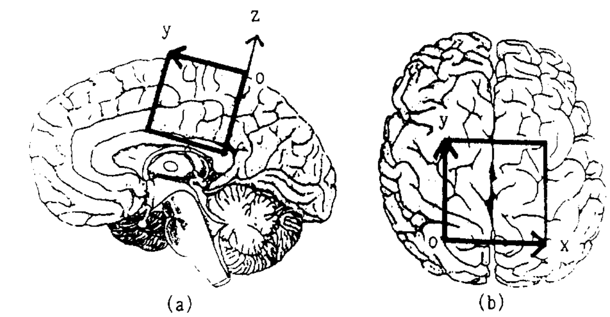

Fig. 4. Target area for searching for current dipoles in the human brain. (a)Profile. (b)Top view.

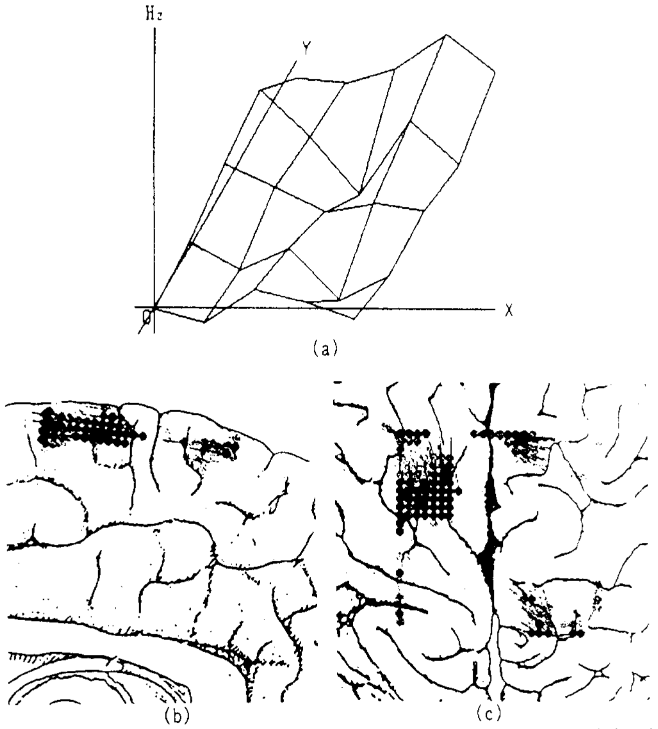

Fig. 5. Estimated current dipole distribution (40ms). (a)MEG. (b)Profile. (c)Top view. Some currents are flowing locally in different directions.

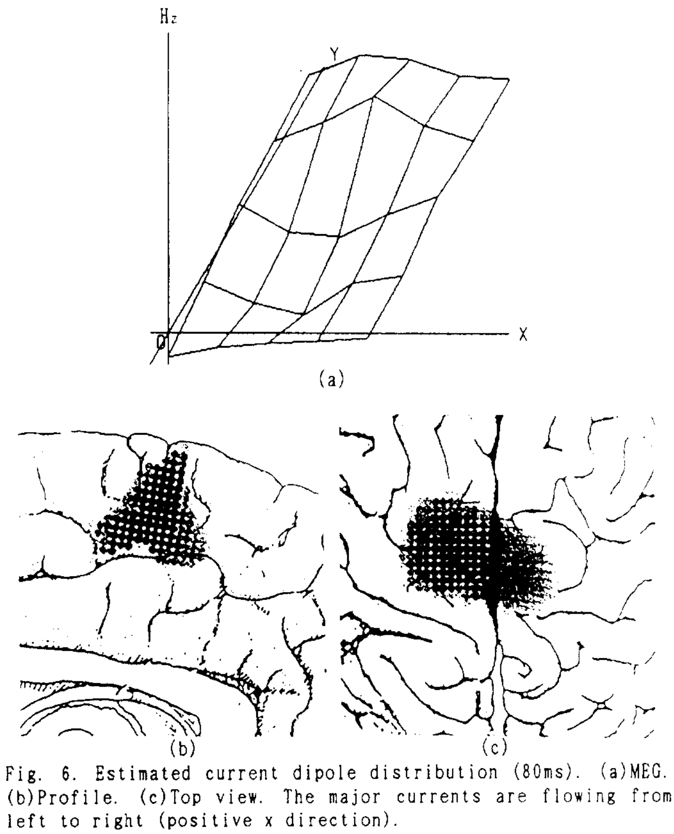

Fig. 6. Estimated current dipole distribution (80ms). (a)MEG. (b)Profile. (c)Top view. The major currents are flowing from left to right (positive x direction).

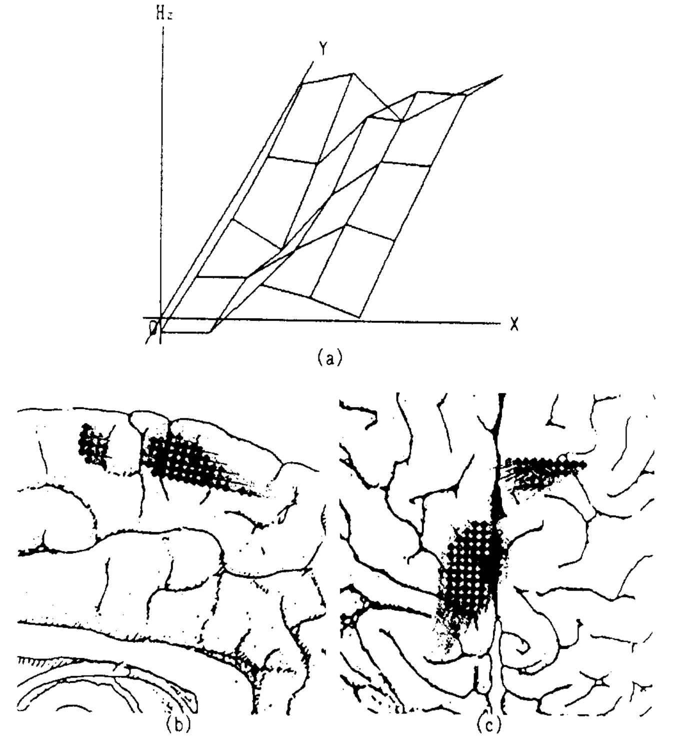

Fig. 7. Estimated current dipole distribution (90ms). (a)MEG. (b)Profile. (c)Top view. The major currents are flowing backward (negative y direction).

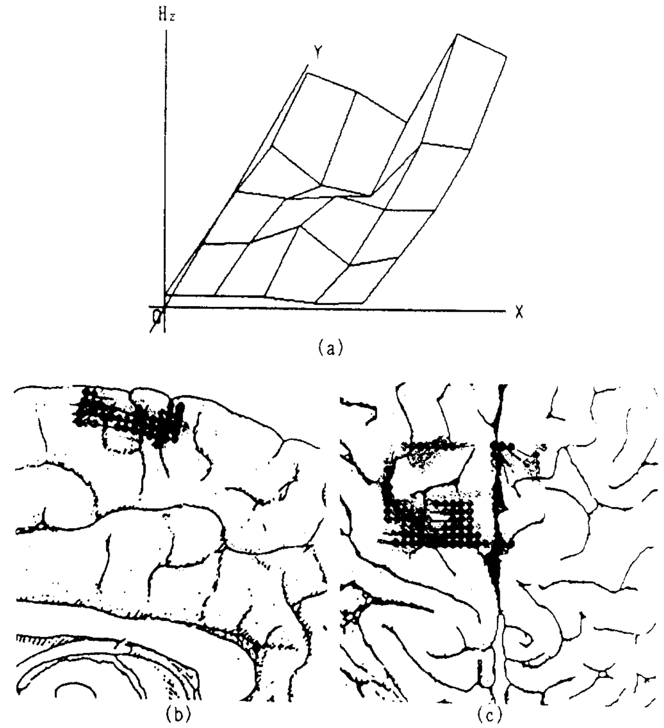

Fig. 9. Estimated current dipole distribution (120ms). (a)MEG. (b)Profile. (c)Top view. The major currents are flowing from right to left (negative x direction) with some other local currents.

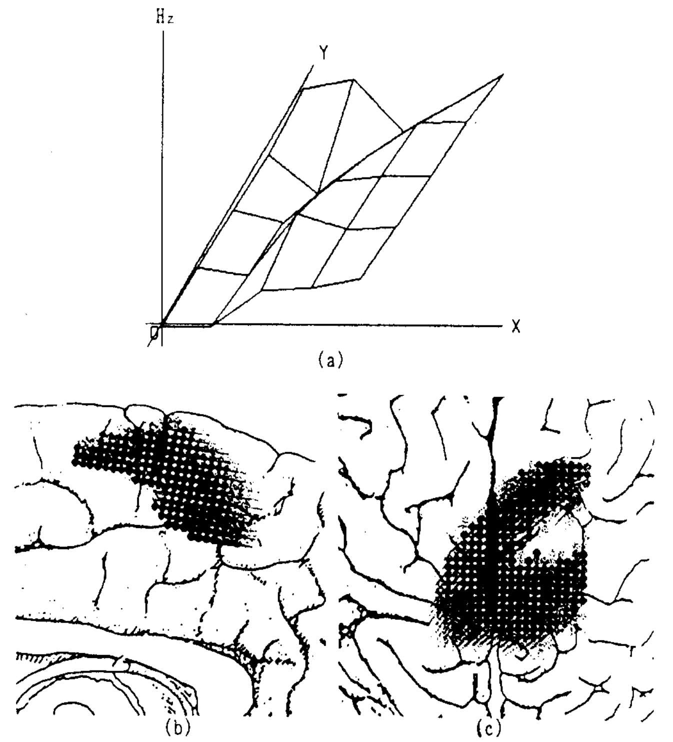

Fig. 8. Estimated current dipole distribution (100ms). (a)MEG. (b)Profile. (c)Top view. The major currents are flowing toward -135 degree referred to the positive x direction. The depth of the currents become maximum.

Table 2. Coefficients of correlation for the MEG analysis.

Figure	5(40ms)	6(80ms)	7(90ms)	8(100ms)	9(120ms)
Number of found pilot points.	21	11	9	12	15
γ	0.97	0.98	0.95	0.93	0.99
γ_{total}	0.85	0.85	0.88	0.86	0.81
γ_{single}*	--	0.86	0.71	0.68	--

* The coefficients of correlation for a single current dipole were obtained from the paper [4].

the results in Figs. 5-9 are listed in Table 2. In addition to the computed correlative coefficients, the coefficients γ obtained by the conventional single dipole model analysis [4] are also listed in Table 2 for reference. From Table 2, it is clarified that the multiple current dipoles result in far accurate magnetic field patterns corresponding to the measured MEGs.

From a sequential flow of the current dipoles shown in Figs. 5-9, the following current signal pattern changes are observed. The major currents start to flow in the positive x direction at 80 ms (see Fig. 6) after some different local currents are observed at 40 ms (see Fig. 5). At 90 ms (see Fig. 7), the currents change their direction toward the negative y direction. At 100 ms (see Fig. 8), the major currents flow toward -135 degree referred to the x axis. Then the depth of the major current flow becomes the maximum, which coincides with the result of [4]. Finally, some local currents occur again at 120 ms (see Fig. 9).

V. CONCLUSION

As shown above, a formulation of the magnetostatic field for MEG analysis has been proposed. This formulation suggests that the governing equation for MEG analysis reduces to an integral equation. Further, we have proposed a generalized correlative analysis method based on the SPM method [12,13] in order to obtain a unique solution pattern.

The comparison between the conventional single dipole model and generalized correlative analyses has demonstrated that the proposed method is far superior to the conventional one. As a result, it has been shown that the generalized correlative analysis makes it possible to search for plural current dipole distributions corresponding to the current signals in the human brain. Thus, we have succeeded in obtaining the sequential current flows in the human brain with high accuracy.

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