

An Improved Multiresolution Technique to Reconstruct Magnetoencephalography(MEG) Source Distribution

Chang-Hwan Im, Kwang-Ok An, Hyun-Kyo Jung, Yong-Ho Lee, and Hyuk-Chan Kwon

Abstract: In this paper, an improved technique for multiresolutive reconstruction of magnetoencephalography (MEG) source distribution is proposed. Using the proposed technique, focal solution with higher energy density can be reconstructed. Moreover, the proposed approach is very easy to implement compared to conventional ones. The usefulness of the proposed technique is verified by the application to a real brain model.

Keywords: Inverse problem, magnetoencephalography (meg), multiresolutive technique, sensitivity analysis.

1. INTRODUCTON

Magnetoencephalography (MEG) source localization is a kind of inverse problem, which reconstructs brain electrical activities using magnetic field measurements outside the head. It is difficult to reconstruct focal and accurate source distribution due to the fact that many variables should be reconstructed with the limited number of measured data available. There have been different approaches to reconstruct the brain neural sources. The most general approach is a dipolar method, which assumes that the distribution of the brain activity is concentrated at one point and the parameters of the 'one-point' dipole are found without any information on the brain anatomical data [1, 2]. However, when using the dipolar method, the localized dipole may not always be located on the real cortical surface as shown in Fig. 1(b). In addition, it has a critical disadvantage that the number of dipoles, i.e., the number of active areas, cannot be estimated a priori. To solve the above problems, the cortically distributed source approach has been widely studied [3]. The cortically distributed source model assumes that all dipoles are located perpendicularly to the cortical surface, which is usually extracted from MRI data, and only their magnitudes are reconstructed. However, the conventional minimum

norm least square (MNLS) approach provides very smooth-looking intensity patterns but fails to recover focal brain activities as shown in Fig. 1(c). To solve the problem, developments of special techniques to focalize the solution are needed.

Recently, multiresolutive reconstruction techniques have been proposed to reduce the search space around emerging active areas [4, 5]. Although they showed improved characteristics in reducing computational cost and finding focal solutions, there are still some problems, especially on implementation. To implement the conventional methods, multigrid-type surface mesh should be used. This is hard to generate on a highly curved cortical surface. Moreover, ellipsoids used to restrict search spaces are not appropriate for the curved cortical surface.

In this paper, an improved concept for the multiresolutive reconstruction is proposed. The proposed technique is very easy to implement due to the fact that it is not node-based but region-based and it uses hexahedra instead of ellipsoids to restrict the search spaces. Interesting regions with higher energy density are split into smaller hexahedra, whereas the others are not considered any more (set to 0). Actually, the use of adaptive mesh refinement techniques for the inverse problem is not a new one, even in the bi-magnetic inverse problems [4-6]. However, the adap-

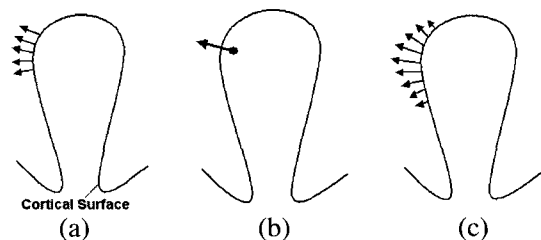


Fig. 1. Original activation and comparison of results from different methods: (a) original activation, (b) dipolar fit, (c) distributed source model.

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Chang-Hwan Im, Kwang-Ok An, and Hyun-Kyo Jung are with the School of Electrical Engineering and Computer Science (ENG420-040) in Seoul National University, Sillim-dong, Kwanak-gu, Seoul, 151-744, Korea (e-mail: ichism@elecmech.snu.ac.kr).

Yong-Ho Lee and Hyuk-Chan Kwon are with the Korea Research Institute of Standards and Science (KRISS), Daejeon, Korea.

even in the biomagnetic inverse problems [4-6]. However, the adaptive region refinement technique applied to the cortically distributed source model is a completely new work. The main scheme used for the reconstruction is the sensitivity analysis with the conjugate gradient (CG) updating scheme [7]. By applying the process repeatedly, focal brain activations can be found.

2. PROPOSED MULTIREGIONAL METHOD

2.1. Cortically distributed source model

Brain neural activity is represented by continuous current flow, which is usually modelled as the distribution of discrete current dipole moments. The aim of the source reconstruction is to estimate the distribution on a brain cortex. The current dipole moments are located perpendicularly to the cortical surface. Because the directions of the dipoles are already determined, their magnitudes at each cortical surface mesh are variables to be reconstructed.

The system configuration used for the simulation was 4-D Neuroimaging Neuromag™ 122-channel whole-head planar-type gradiometer system (http://www.4dneuroimaging.com/external_english/html/n122spec.html) with realistic position of the subject's head in the helmet. Fig. 2 shows the positions of sensors and the brain cortex, extracted from MRI data. Magnetic flux density at each sensor was calculated using J. Sarvas' formula [8], which assumes spherical volume conductor.

To generate cortical patches and construct forward data set, the concept of virtual area was adopted [9]. The virtual area was assigned to each vertex as a third of the area of all triangles meeting at the vertex. This assumption is valid because the total area remains equal to the actual area of the full tessellation. The cortical patch was generated using the following process:

- A point is selected as a seed of an activation patch area.
- Including neighboring vertices around the patch extends the patch area.
- If the total virtual area of the cortical patch exceeds a predetermined surface area, the extension of the activation patch is terminated.

Each patch was made of a set of dipoles with constant current dipole moment density of 1 nAm/mm^2 . The current dipole moment at each vertex was calculated by the product of the current dipole moment density and the virtual area defined above.

2.2. Multiresolution reconstruction technique

The unknowns to be reconstructed are the magnitudes of the current dipole moments at each cortical vertex. The basic assumption of the proposed

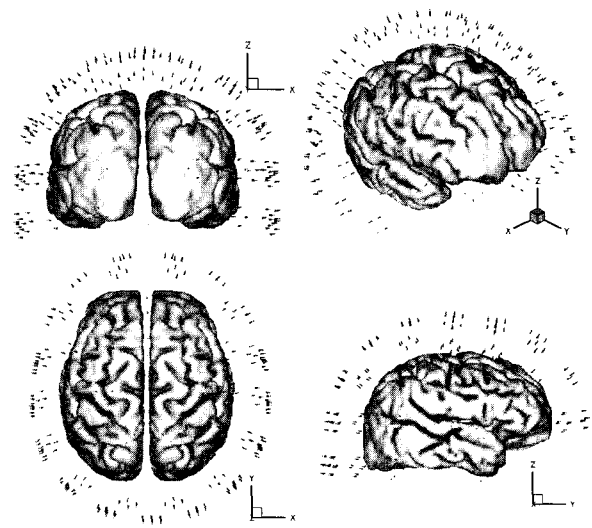


Fig. 2. Positions of SQUID sensors (Neuromag 122 channel system with 4 bad channels). Vectors represent the normal direction of each sensor.

method is that the vertices within a hexahedron have the same moment value. Fig. 3 shows the 2D schematic illustration to explain the proposed method (a hexahedron in 3D \rightarrow a rectangle in 2D). Processes to apply the proposed method are as follows:

Step 1) Generate initial hexahedra. Initial values for each hexahedron are set to zero (0).

Step 2) Calculate sensitivity for each hexahedron. Objective function to be minimized is defined as:

$$F = \sum_{j=1}^{N_s} (B_j - B_{ej})^2, \quad (1)$$

where N_s is the number of sensors, and B_j and B_{ej} represent the calculated and measured magnetic flux density at a sensor j , respectively. The value of sensitivity, dF/dQ_i , for each hexahedron is calculated by

$$\frac{dF}{dQ_i} = 2 \sum_{j=1}^{N_s} (B_j - B_{ej}) \frac{dB_j}{dQ_i}, \quad (2)$$

where Q_i is the moment value of i -th hexahedron, $i=1,2,\dots,N_r$ (the number of hexahedra). The cortical surface vertices that are included in the i -th hexahedron have the same moment value, Q_i . Then, terms in (2) can be easily evaluated analytically.

Step 3) After calculating the sensitivities for all the design variables, they are updated by using the conjugate gradient (CG) updating scheme.

Step 4) Repeat Step 2) – Step 4) until a stopping criterion is satisfied. In this paper, the iteration stops when the total sum of the sensitivities decreases below a predetermined value (1% of the initial value).

Step 5) If reconstructed moment values of some hexahedra are below a predetermined threshold

($0.3 \times$ maximum value was used in this paper), remove them from variables. Remained hexahedra are refined and resultant values from previous resolution are used for their initial values. Repeat *Step 2) – Step 5)* until satisfactory resolution is obtained.

2.3. Estimation of reconstructed result: a performance test of reconstructing methods.

To compare the reconstructed distribution quantitatively, a measure, denoted as ϵ , is proposed to evaluate how well a method can find focal solution. It is defined as the ratio between original and reconstructed energy stored in activation areas. Generally, the distributed source reconstructed by the MNLS approach shows over-smoothed distribution. In this case, the reconstructed energy density in the original activation area is usually smaller than the original. In other words, higher ϵ means that the method can find more focal solution. In this paper, to verify the performance of the proposed method, ϵ was adopted.

3. CORTICAL PATCH TESTS AND RESULTS

3.1. Constructing forward data set

Neuromagnetic inverse problem is very hard to verify by experiments because exact source distribution of the real human brain cannot be estimated *a priori*. For that reason, artificially constructed forward data set simulated with patch activation is used [9, 10]. Fig. 4 shows the positions of two original virtual neural activations (named activation 1 and 2) used to construct the forward data set. Normal

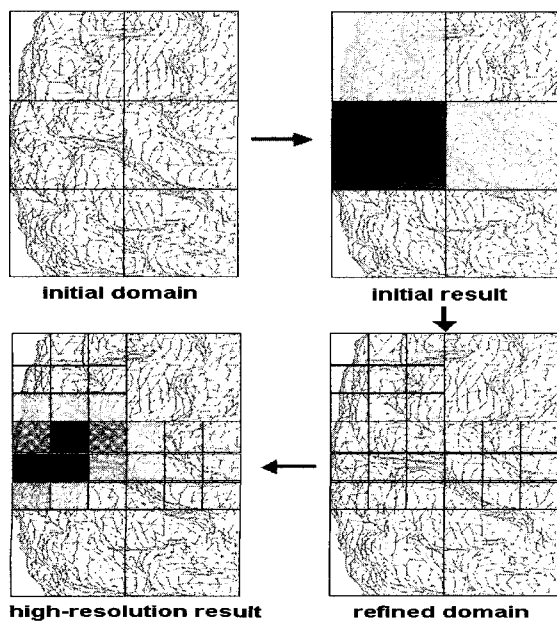


Fig. 3. 2D Schematic illustration to explain the proposed method.

component of magnetic flux density at each sensor was calculated using Sarvas's formula [8]. 20-dB (signal-to-noise ratio with respect to power) white Gaussian noise was added to the data in order to increase reality.

3.2. Results of inverse calculation

384 hexahedra ($8 \times 8 \times 6$), which cover the whole cortical surface, were used for the initial resolution reconstruction. Some hexahedra that have small moment values below a predetermined threshold ($0.3 \times$ maximum value was used in this paper) were removed. Fig. 5 shows the remainder of hexahedra and their values (six hexahedra remained) after the initial reconstruction. Each remaining hexahedron was divided into 48 small hexahedra ($4 \times 4 \times 3$). Hence, the total number of hexahedra used for the second resolution was 288. Fig. 6 shows the reconstructed result from the second resolution.

Fig. 7 and Fig. 8 show the reconstructed source distributions on the cortical surface for the first and second resolution, respectively. For comparison, the magnitude of the source was normalized on the basis of the maximum value. We see from the figures that more focalized distribution was obtained using higher resolution.

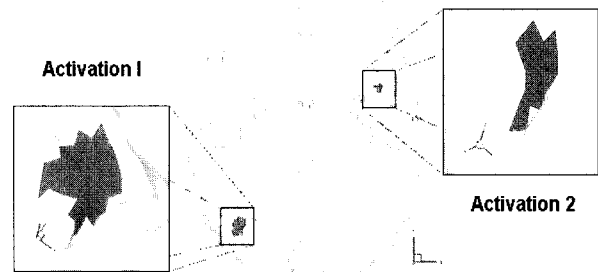


Fig. 4. Positions for two neural activation patches.

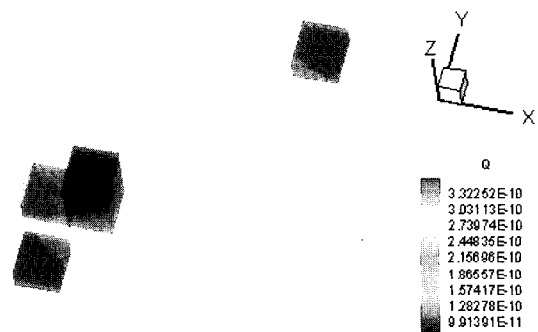


Fig. 5. Remaining hexahedra from the first resolution

For comparison, a conventional approach that uses whole cortical meshes as variables was simulated. Fig. 9 shows the reconstructed source distribution obtained by the conventional ‘whole cortex’ reconstruction based on the MNLS approach. The total number of variables (the number of elements) was 41472, which is much greater than that for the proposed technique. It is seen that the focal characteristic of the reconstructed result is not satisfactory compared to the result shown in Fig. 8.

To compare the results quantitatively, a measure, which was denoted as ϵ in the previous section, was applied to evaluate how well a method can find focal solution. As stated earlier, higher ϵ means that the method can find more focal solution. Table 1 shows the comparison between various cases. From the table, it is seen that the results from the proposed technique yields more focal solution compared to those from conventional ‘whole cortex searching’ method.

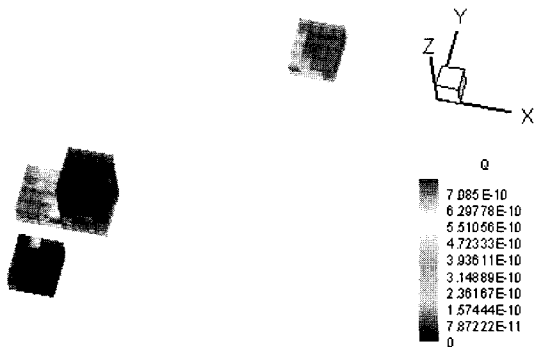


Fig. 6. Results from the second resolution.

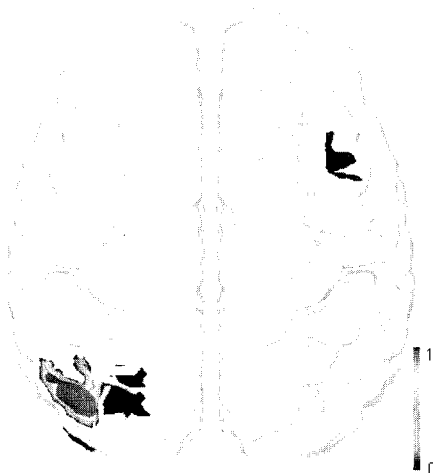


Fig. 7. Reconstructed result from the first resolution. Values over $0.3 \times$ (maximum current density) are presented for the visualization purpose (Fig. 8 and Fig. 9 are the same).

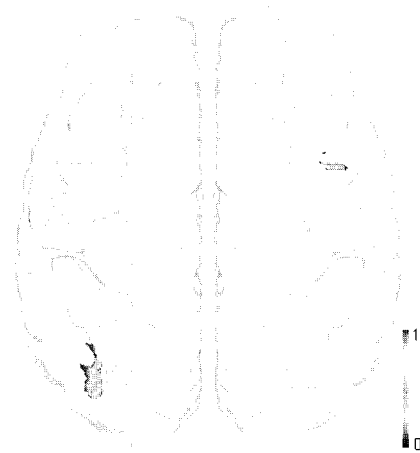


Fig. 8. Reconstructed result from the second resolution.

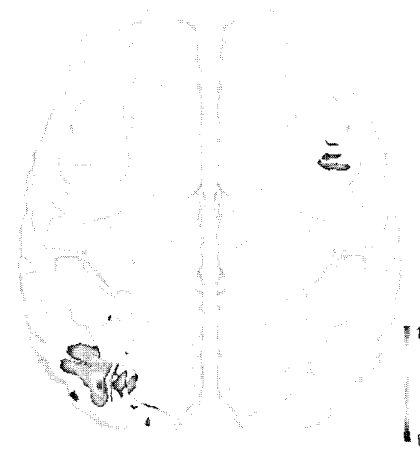


Fig. 9. Source distribution by whole cortex reconstruction. (41472 variables were directly applied.)

Table 1. Comparison of focal characteristics.

| Methods | ϵ (activation 1) | ϵ (activation 2) |
|---------------|---------------------------|---------------------------|
| MNLS | 0.161 | 0.090 |
| Resolution I | 0.279 | 0.082 |
| Resolution II | 0.389 | 0.346 |

4. CONCLUSIONS

In this paper, an improved concept for the multiresolution reconstruction was proposed. This concept is very easy to implement compared to conventional approaches. From the simulation for a real brain model, it was shown that focal brain activations could be found more effectively using the proposed method.

REFERENCES

- [1] C. Wolters, "Comparing regularized and non-regularized nonlinear dipole fit methods: A study in a simulated sulcus structure," *Brain Topography*, vol. 12, no. 1, pp. 3-18, 1999.
- [2] M. Fuchs, M. Wagner, H.-A. Wischmann, and A. Theisen, "Source reconstructions from combined MEG and EEG data," *Electroenceph. Clin. Neurophysiol.*, pp. 93-111, 1998.
- [3] A. Dale and M. Sereno, "Improved localization of cortical activity by combining EEG and MEG with MRI cortical surface reconstruction: A linear approach," *J. Cogn. Neurosci.*, pp. 162-176, 1993.
- [4] R. Srebro, "An iterative approach to the solution of the inverse problem," *Electroencephalogr. Clin. Neurophysiol.*, vol. 98, pp. 349-362, 1996.
- [5] L. Gavit, S. Baillet, J.-F. Mangin, J. Pascatore, and L. Garnero, "A multiresolution framework to MEG/EEG Source Imaging," *IEEE Trans. Biomed. Eng.*, vol. 48, no. 10, pp. 1080-1087, October 2001.
- [6] S. Iwaki and S. Ueno, "A high-speed estimation of internal electrical sources in the human brain from the MEG measurements using subspace scanning with multiple scanning resolutions," *IEEE Trans. Magn.*, vol. 33, no. 5, September 1997.
- [7] E. J. Haug, K. K. Choi, and V. Komkov, *Design Sensitivity Analysis of Structural System*, Academic Press, New York N.T., 1986.
- [8] J. Sarvas, "Basic mathematical and electromagnetic concepts of the biomagnetic inverse problem," *Phys. Med. Biol.*, 32(1), pp. 11-22, 1987.
- [9] M. Chupin, S. Baillet, C. Okada, D. Hasboun, and L. Garnero, "On the detection of hippocampal activity with MEG," *Proc. of Conference on Biomagnetism-BIOMAG 2002*, Germany, 2002.
- [10] K. Jerbi, J. C. Mosher, G. Nolte, S. Baillet, L. Garnero, and R. M. Leahy, "From dipoles to multipoles: Parametric solutions to the inverse problem in MEG," *Proc. of Conference on Biomagnetism-BIOMAG 2002*, Germany, 2002.



Chang-Hwan Im was born in Taegu, Korea in 1976. He graduated from the School of Electrical Engineering, Seoul National University in 1999. He received his M.S. from the same university in 2001. He is now working toward his Ph.D. in the School of Electrical Engineering and

Computer Science at Seoul National University. His research interests are bio-electromagnetic applications, numerical analysis and design of electromagnetic devices, microwave passive devices.



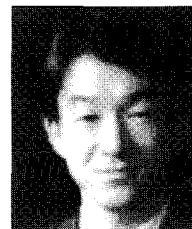
Kwang-Ok An was born in Seoul, Korea, in 1978. She graduated from the School of Electronic Engineering of Inha University in 2001. She received her M.S. degree from the School of Electrical Engineering and Computer Science at Seoul National University in 2003. Her research interests are biomagnetic application

and numerical analysis for electromagnetic devices.



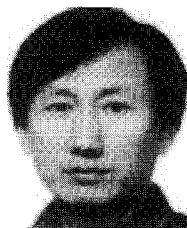
Hyun-Kyo Jung graduated from the School of Electrical Engineering, Seoul National University in 1979. He received his M.S. and Ph.D at the same university in 1981 and 1984, respectively. He worked as faculty at Kangwon National University from 1985 to 1994 and joined Polytechnic University in New York, USA from

1987 to 1989. He has been teaching at the Seoul National University since 1994. From 1999 to 2000, he also served as a visiting professor in UC Berkley, USA. His research interests cover the various fields of the analysis and design of electric machinery and numerical field analysis of electrical system especially with the finite element method.



Yong-Ho Lee received his Ph.D. from the School of Physics, Korea Advanced Institute of Science and Technology (KAIST), in 1989. He worked as a visiting researcher at Twente University, Netherlands, from 1993 to 1994. He has been teaching at Kyunghee University since 1999 and working for the Korea Research

Institute of Standards and Science, Daejeon, Korea, since 1989. His research interests include SQUID Systems and biomagnetic measurement.



Hyuk-Chan Kwon received his M. S. at the School of Nuclear Engineering, Seoul National University, in 1981. He has been working for the Korea Research Institute of Standards and Science, Daejeon, Korea since 1981. His research interests include fabrication of SQUID and biomagnetism technology.