Forward Problem Solution of EMSI's with BEM Using Realistic Head Models

Akalın Z., Gençer N.G.

Electrical and Electronics Engineering Department, Middle East Technical University, Ankara, Turkey

Introduction

Electrical activities of the human brain due to body functions can be measured with electrodes placed on the scalp (EEG) and with magnetic sensors (MEG) placed near the scalp surface. The representation of electrical activity of the brain using electrical and magnetic measurements is called electro-magnetic source imaging (EMSI). The electrical activities are usually modeled by electrical dipoles and the purpose of EMSI is to obtain information about the spatio-temporal behavior of these dipoles. An essential part of obtaining EMSIs is the solution of the electric and magnetic fields (the forward problem) for a given dipole configuration assuming a head model. The solution of the inverse problem (i.e., given the measured data, finding the location and direction of dipoles) is based on the comparison of the measured and calculated fields. To increase accuracy in EMSIs, the human head must be modeled accurately. The purpose of this study is twofold: 1) to obtain an accurate head model, 2) to solve the forward problem of EMSI for this model.

In the earliest studies of EMSI, head models with simple geometries having analytical solutions for a dipole inside the conductor model were used. The simplest head model is the homogeneous sphere. In order to represent layers like skull, scalp and cerebrospinal fluid (CSF), concentric and eccentric spheres models were used.

The localization results have shown that the use of simple head models can lead to significant errors in the source parameters. Using a simple spherical volume conductor model, it is shown that inhomogeneities close to sources can significantly affect the measured MEG and EEG . When there are simultaneously active multiple sources, the accuracy of the head shape becomes even more important. For these reasons realistic head models are used . Since it is not possible to obtain analytical solutions for realistic models, numerical techniques are employed. The most important ones of these methods are the Finite Element Method (FEM) and the Boundary Element Method (BEM). In FEM the volume data is represented with volume elements. Therefore a large number of elements are used for good representations of the head. In BEM, the tissue interfaces are represented with surface elements. Therefore fewer elements are used compared to FEM.

In this study, the segmentation and mesh generation algorithms are explained. The BEM formulation which employs triangular, quadratic, isoparametric elements is used to solve the forward problem of EMSI with realistic meshes.

Method

A. Boundary Element Method

In BEM, the human head is subdivided into compartments with constant material properties. In bioelectric studies, material property is the electrical conductivity of tissues and it is assumed isotropic in BEM formulations. BEM transforms the differential equation that represents the electric potential due to an impressed current source in a conductive body into an integral equation over the boundary surfaces which separate regions with different conductivities. The surface integrals are calculated numerically by dividing the surface into elements. In the literature, different kinds of elements and methods are used to evaluate the surface integrals . This study uses the isoparametric elements proposed by Gençer and Tanzer . Using isoparametric elements in the formulations enables us to express both the global coordinates and potentials on an element using the same interpolation (shape) functions. Each integration on a surface element is written as a linear combination of unknown node potentials. If the potential is to be calculated at M nodes, then in matrix notation, it is possible to obtain the following matrix equation:

$$\Phi = \mathbf{g} + \mathbf{C}\Phi \qquad (1)$$

where Φ is an Nx1 vector of node potentials, $\mathbf{C}$ is an NxN matrix whose elements are determined by the geometry and electrical conductivity information, and $\mathbf{g}$ is an Mx1 vector representing the contribution of the primary sources. The details of the BEM formulation can be found in .

B. Segmentation

Segmentation is a process of classifying elements having the same properties in one group. In this work, segmentation of scalp, skull, CSF, eyes, gray matter and white matter are performed from the 3 dimensional multimodel MR images of the head (T1 and proton density (PD) images are used). A hybrid algorithm that uses 'snakes', region growing, morphologic operations, and thresholding is applied . The segmentation begins by removing the background from volume data. For this purpose 'snake' algorithm is used over PD images. After removing the background, skull and sinus regions are extracted from the PD image using thresholding. A raw image of the brain is obtained from T1 images using thresholding and region growing. To locate the eyes an eye template is obtained from a T1 slice where the eyes are most significant. Using this template and a user defined threshold, eyes are segmented at each slice and extracted using morphological operations. The remaining structures are isolated and segmented by morphological operations and 3D region growing.

C. MESH GENERATION

In order to solve the forward problems, the geometrical information should be converted into a numerical form (mesh). This section presents the applied mesh generation algorithm for the BEM. The algorithm used in mesh generation is shown in Fig. 1. The adaptive skeleton climbing (ASC) algorithm is used to triangulate the volume data at a given threshold . The algorithm places one or more triangles to each boundary voxel and can generate 4 to 25 times fewer triangles than that generated by the marching cubes algorithm.

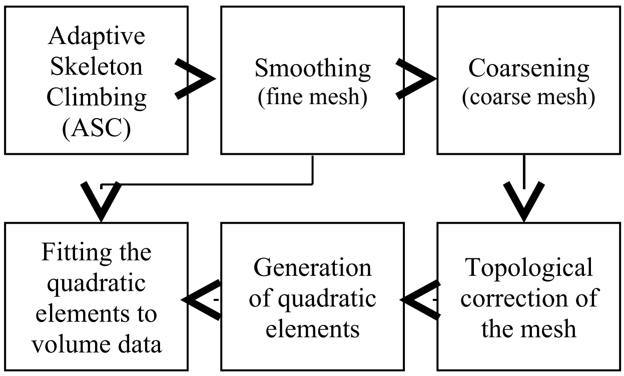

Figure 1 : The algorithm used in mesh generation

Smoothing is a surface signal low-pass filter algorithm . It suppresses the high frequencies caused by noise and the slices of the MR images. The vertices of the polyhedral surface are moved without changing the connectivity of faces. Number of vertices and faces are preserved. In coarsening, an error is calculated at each node with respect to the Delaunay criteria . At every step of coarsening the node pair with lowest errors are connected together and the coarse mesh is obtained. The resulting mesh, after triangulation and coarsening, may contain some undesirable topological artefacts, such as disconnected or multiply connected components and singular nodes. These are corrected after the coarsening step to create a single manifold surface that represents a given boundary.

Using the resulting linear mesh, nodes are added at each mid point of every edge and these points are placed to fit the original fine mesh to create quadratic elements that match the volume data.

In previous BEM studies, the boundaries are represented as closed, non-intersecting surfaces. However, to obtain realistic head models, the eyes should also be included in the model. When the eyes are included, the skull-CSF and the skull-scalp interfaces cannot be taken as closed interfaces. In that case, skull-eye, skull-scalp, skull-CSF, eye-scalp, eye-CSF interfaces occur. In this study the outer and inner surfaces of the skull is obtained using snakes algorithm as closed surfaces from the segmented image data. Meshes are created for inner and outer surfaces of the skull and for the two eyes. An automatic algorithm based on is applied to the intersecting surfaces of outer-skull and Eye1, outer-skull and Eye2, inner-skull and Eye1, inner-skull and Eye2 respectively, to form a mesh of skull and eyes. An illustration of the head is shown in Fig 2.

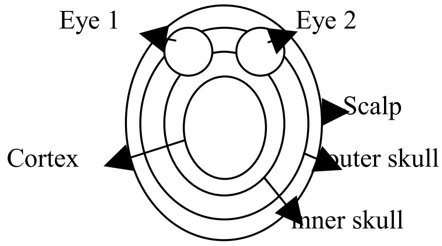

Figure 2 : An illustration of the realistic head geometry.

Algorithm for mesh generation over intersecting surfaces can be summarized as follows :

1. Find the intersections between the given surfaces
2. Determine the chains contained in the set of intersection line segments
3. Remove all the triangular elements near each of the intersection chains
4. Generate intermediate nodes along intersection chains
5. Identify disjointed patches of triangular elements created in the process of surface intersection
6. Construct new objects by selectively picking individual surface parts

Results

In this work segmentation is applied to the axial MR images with 60 slices, 3 mm thickness . The skull and sinus regions are assumed to have the same electrical properties. Consequently, they are segmented as the same tissue type.

A mesh generation algorithm using ASC, smoothing, coarsening is employed. The resulting meshes of cortex, white matter, skull and scalp are presented in Fig. 3. To obtain the skull and eye meshes, an automatic mesh generation algorithm over intersecting surfaces is employed. The resulting mesh of the cortex, skull and eyes is presented in Fig. 4. This mesh is presented with linear elements.

BEM is solved for the mesh in Fig. 4. The mesh contains 4773 nodes and 3409 elements. The solution took 14.75 minutes on a 933MHz Pentium III computer with 1GB RAM. The resulting field patterns matched our expectations.

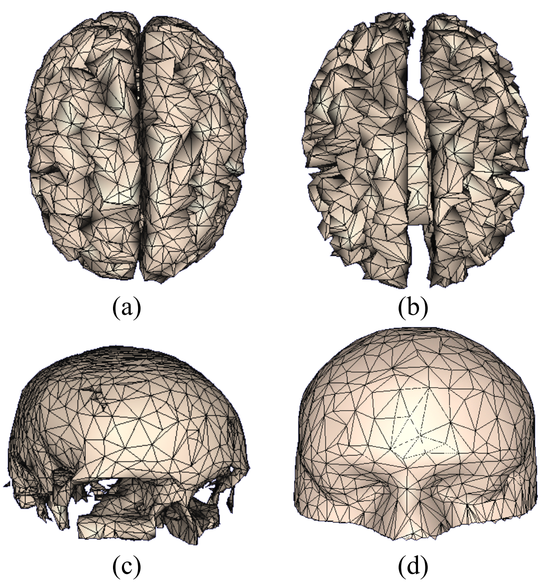

Figure 3 : The meshes generated for (a) cortex with 5000 elements, (b) white matter with 5000 triangles, (c) skull with 5000 triangles and (d) scalp with 2000 triangles

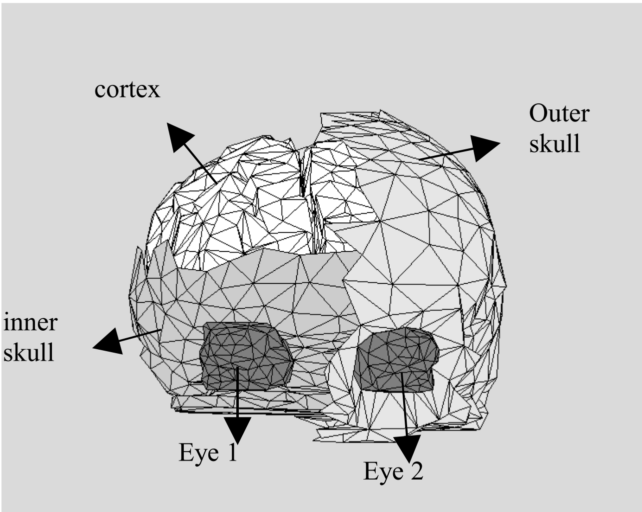

Figure 4 : The mesh obtained after mesh generation over intersecting surfaces algorithm is employed.

Discussion

In this work, a realistic head model representing scalp, skull, cortex and eye tissues is obtained. Using this model, it will be possible to obtain accurate inverse problem solutions. Since the model contains different tissue types, sensitivity of the forward and inverse problems to conductivity can be investigated.

References

[1]N. B. Cuffin, D. Cohen, "Magnetic Fields of a dipole in special volume conductor shapes," *IEEE Trans. Biomed. Eng.*, Vol. 24, No. 4, 372-381, 1977.

[2]S. Ueno, K. Iramina, K. Harada, "Effects of inhomogeneities in cerebral modeling for magneto-encephalography," *IEEE Trans. Magn.*, vol. 23, 3753-3755, 1987.

[3]N. B. Cuffin, "EEG Localization accuracy improvements using realsitically shaped head models," *IEEE Trans. Biomed. Eng.*, vol. 43, no. 3, 299-303, 1996.

[4]N. G. Gençer, I. O. Tanzer, "Forward problem solution of electromagnetic source imaging using a new BEM formulation with high-order elements," *Phys. Med. Biol.*, 44, pp. 2275-2287, 1999.

[5]Z. Akalın, N. G. Gençer, "MR Kafa Görüntülerinin bölütlenmesi", *Biyomedikal Mühendisliği Ulusal Toplantısı Bildiriler Kitabı*, 138, İstanbul, 2000.

[6]T. Poston, T. Wong, P. Heng, "Multiresolution isosurface Extraction with Adaptive Skeleton Climbing", *Eurographics '98*, vol.17, no: 3, 1998.

[7]G. Taubin, "A Signal Processing Approach to Fair Surface Design," *Siggraph'95,* 1995.

[8]M. Garland, P. Heckbert, "Surface Simplification Using Quadratic Error Metrics," *Proc. of Siggraph*, pp. 209-216, 1997.

[9]S. H. Lo, "Automatic mesh generation over intersecting surfaces," *Int. J. for Numer. Methods in Eng.*, vol. 38, 943-954, 1995.

[10] "Brain Web: Simulated Brain Database", internet address: *http://www.bic.mni.mcgill.ca/brainweb*.