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Numerical Quality of the Scalp Electrical Potentials from 3-D MRI Content-adaptive Finite Element Models of the Whole Head

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Abstract

Realistic finite element (FE) head models are becoming more popular due to realistically volumetric analysis of bioelectromagnetic problems of the brain. Recently, we have developed a MRI content-adaptive FE meshing (cMesh) scheme that allows fast, automatic, and adaptive FE mesh generation. In this work, we have generated cMesh FE head models of the whole head and tested the quality of the scalp electrical potentials against those from a standard FE head model made up with equidistant FEs. The results demonstrate a significant gain in computation time with minor loss in numerical accuracy of the scalp electrical potentials. The cMesh generation scheme and cMesh models should be applicable to various bioelectromagnetic problems.

1. Introduction

Electrical potentials generated by neuronal electrical activity in the brain can be recorded on the scalp using EEG. Then from the measured scalp potentials, neuronal sources can be localized in the brain by solving the inverse problems. To find the locations and strengths of current sources within the brain, electrically conducting volume models of the head are required in both forward and inverse problems. The realistic finite element (FE) head models have recently become popular, since the FE head model allows the realistic representation of the full head volume geometry.

The conventional FE head models usually are made up of the equidistant or regular-sized FEs such as equilateral triangles in 2-D and cubes or tetrahedrons in 3-D, ending with dense and non-adaptive meshes. More recent FE head models of *the whole head* can be found in [1] where the influence of tissue anisotropy on the E/MEG FE forward solutions and the computation of return currents were reported and in [2] where geometry-adapted FE volume models were investigated using node-shift hexahedral meshes.

Critical requirements of the FE head model generation include (i) fast and automatic mesh generation that allows modeling of individual head and (ii) automatic adaptive meshing capability to reduce the overwhelming computational load of FE analysis.

Recently, we have developed a fast, automatic, and adaptive meshing technique to generate content-adaptive FE meshes (cMeshes) to given MRIs [3]. Our adaptive meshing approach provides (i) fast and automatic generation of individual-specific whole head models on the order of *1~2 min* and (ii) significant reduction of the computational loads using less number of nodes and elements, while maintaining the numerical accuracy of FE analysis.

In this work, we have generated the cMesh head models of *the whole head* via our automatic adaptive meshing technique and tested the quality of the computed scalp potentials against those from the standard FE head models with equidistant FEs. The comparison of the scalp electrical potentials and examination of computational costs indicate that there is a significant gain in computation time with minor loss in numerical accuracy of scalp electrical potentials. The results suggest that the cMesh head model generation can be a practical means for realistic FE head modeling towards bioelectromagnetic problems.

2. Methods

2.1. Generation of 3-D full FE head models

Two cMesh models of the whole head (77 MR slices, 1 x 1 x 1mm^3 voxel size) differing in the number of nodes and elements were generated using our cMesh generation technique as follows: 1) structural feature maps are derived from MR images using the structure tensor. 2) content-adaptive FE nodes are sampled based on the spatial density of feature maps. 3) cMeshes are generated using tetrahedral elements in 3-D (see [3] for the details). The fully automatic generation of the cMesh whole head model with 148,852 nodes and 943,072 elements took only 88.4 sec. As for the reference model, the FE head model was generated using equidistant tetrahedral elements with inner-node spacing of 2mm. Since the analytical forward solutions cannot be obtained from an arbitrary geometry, we use the solutions from the reference model as the gold standard. Element-wise isotropic conductivity mapping was used in the five sub-regions: white matter, gray matter, CSF, skull, and scalp. All FE models along with conductivity information were imported into ANSYS [4] for scalp potential computation.

2.2. Computation of scalp electrical potentials

The forward potential solutions due to a same current generator were obtained from each full FE head model via ANSYS. As the solver of the Poisson equation, an iterative solver was used (i.e., the preconditioned conjugate gradient method). Only the scalp potential values were selected to examine numerical quality against those from the reference FE head model. As evaluation measures, linear correlation coefficient (CC) and residual errors (RE) were used along with the forward computation time (CT) as a numerical efficiency measure [3].

3. Results

Figs. 1 (a) and (b) show the sagittal views of the 3-D reference and cMesh head model with isotropic electrical conductivities which are color labeled accordingly. Figs. 1 (c) and (d) show the sagittal cutplanes of 3-D forward potential maps from Fig. 1 (a) and Fig. 1 (b) respectively. In Table 1, the CC values show strong correlation of the scalp electrical potentials between the cMesh models and reference model. The results from cMesh-2 demonstrate CC=0.999 and RE=0.037 indicating there is only minor difference in the scalp electrical potentials and the significant gain in CT of 45% (5.47 to 3.02 min) with significantly reduced nodes and elements.

4. Discussion and Conclusion

We have demonstrated the cMesh head model generation of the whole head on the order of 1~2 min and examined the numerical quality of the scalp electrical potentials by comparing to those of the standard FE head model. The results show that there is a significant reduction in computation time with minor loss in numerical accuracy of the scalp electrical potentials. The subject-specific cMesh modeling of the whole head and its adaptive mesh features should be useful for the FE analysis of bioelectromagnetic problems.

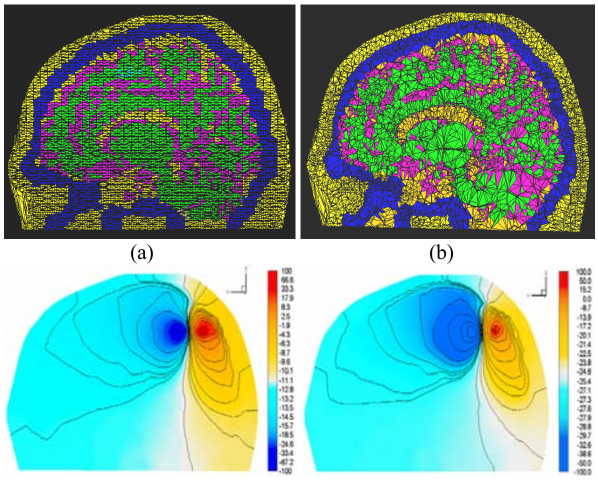

Fig. 1. Sagittal view of (a) the reference FE head model (yellow=scalp, blue=skull, green=white matter, magenta=gray matter, and orange=CSF) and (b) cMesh FE head model. Sagittal cutplane of (c) the 3-D forward potential map from (a) and (d) from cMesh-1

Table 1. Numerical quality of the scalp electrical potentials

FE Model	No. of Nodes	No. of Eles.	CC	RE	CT (min)
Reference	159,513	945,881	1	0	1 (5.47)
cMesh-1	148,852	943,072	0.999	0.031	0.60 (3.28)
cMesh-2	109,625	694,588	0.999	0.037	0.55 (3.02)

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5. References

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