Generating High Quality Tetrahedral Meshes of the Human Head and Applications in fNIRS

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Abstract: We report a workflow to efficiently create high-quality tetrahedral meshes of the human brain and head from neuroanatomical scans. We also demonstrate the utility of these accurate brain models for optical brain imaging.

OCIS codes: (170.3660) Light propagation in tissues; (170.5280) Photon migration; (170.7050) Turbid media.

1. Introduction

Triangular and tetrahedral meshes play key roles in the representation, visualization, and analyses of the human brain. Tetrahedral meshes, in particular, are routinely used in trans-cranial magnetic stimulation (TMS) and trans-cranial direct current stimulation (tDCS) to evaluate brain damages and study major brain disorders [1]. These tetrahedral mesh representations are also used in electroencephalography (EEG) in conjunction with the conductivity properties of the brain tissues to monitor brain activites [2]. In addition, physical deformations can be simulated on tetrahedral mesh models of the head to assist neurosurgeon in the study of traumatic brain injuries (TBI) and surgical planning [3]. In fNIRS, tetrahedral mesh models are used to calculate light propagation inside the head using finite-element (FD) [4] and mesh-based Monte Carlo methods [5].

Tetrahedral meshes present important advantages over a voxelated and octree representations namely in the ability to represent curved shapes without terraced boundaries, the applicability in finite element analyses, and the control over the mesh density. Many brain meshing algorithms have been proposed, yet there remains a lack of a workflow that generates anatomically accurate models, is computationally efficient, allows control over the mesh density, and accepts various input types.

Here, we report an easy-to-use and automated MATLAB workflow - “brain2mesh”. It can robustly and rapidly generate multi-layered tetrahedral meshes for the human head from a segmented dataset. A surface-based mesh generation approach based on the meshing toolbox Iso2Mesh is used to ensure the conformity of the tissue boundaries and to allow for fine control of the mesh quality and density. This meshing toolbox can process the outputs of most neuroanatomical analysis tools by handling probabilistic or multi-labeled segmentations, and surface models in some specific cases.

2. Methods

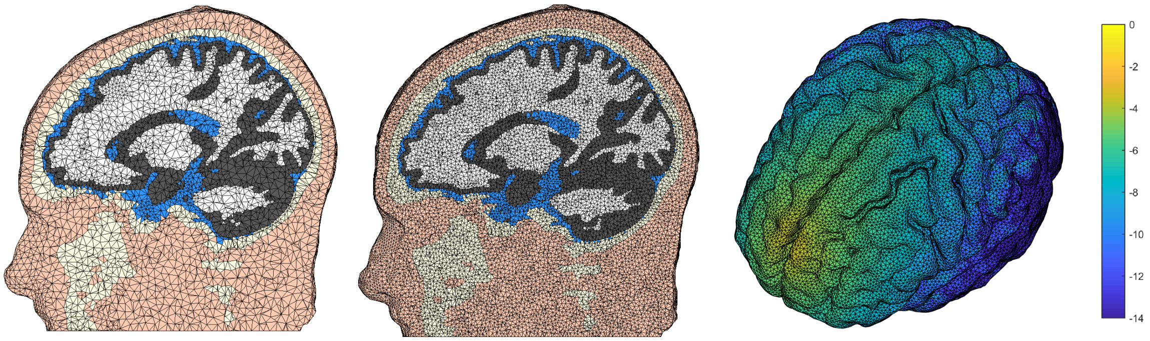
We first pre-process the segmented volumes to ensure a layered tissue model with white matter, grey matter, cerebrospinal fluid, skull, and scalp, ranked from inside to outside layer order. If other tissue types are present, they are mapped to these existing tissue classes. A gap between each of the layers is ensured through the use of dilation and shrinking operators on these segmented volumes. This is important to ensure that, once the surface meshes of the different layers are generated, they do not intersect at the merging step.

From the pre-processed segmented volumes, an ε-sampling algorithm is applied to generate the indvidual surface meshes [6]. The Cork 3D Boolean Library is then called to resolve the surface meshes in a valid configuration, and the resulting combined surface is processed by Tetgen [7] to generate the final tetrahedral mesh. To assign the correct tissue types to the mesh labels, point-in-surface tests are rapidly computed. The final meshing step is to remove the assumptions made at the pre-processing step by correctly relabeling the tetrahedral elements contained within the gaps that were artificially added to ensure separation between tissue layers.

From the generated tetrahedral mesh, the points corresponding to the inion, nasion, and left and right preauricular positions are located to automatically generate a 10-10 system [8]. Using optical properties and the 10-10 locations, the simulation of light propagation can be trivially calculated using Mesh-based Monte Carlo [5].

3. Results

To demonstrate our workflow, we generated a coarse and dense mesh of a 40-44 years-old atlas [9] with generation times of 36.1s for Fig.1(a) and 70.4s for Fig.1(b) on an Intel i7-6700K processor. The resulting tetrahedral mesh does not have any noticeable detail from the assumptions made in the pre-processing steps, and the volumes of each of the



(a) (b) (c)

Fig. 1. (a) A coarse mesh of 599,073 tetrahedral elements, (b) a denser mesh of 2,335,398 tetrahedral elements of a 40-44 years-old [9], and (c) the fluence on the grey matter surface resulting from a steady-state mesh-based Monte Carlo (MMC) simulation at 670 nm from a pencil beam illumination at the Fz position (on a log-scale).

meshed tissue regions was tested to be within 1% of the corresponding segmented volumes. For the simulated example shown in Fig.1(c), the optical properties from [10] are used and the position simulated is the pencil beam shined at the Fz position. The direction vector for the source is determined by the normal to the skin surface and the number of simulated photons was 10^6.

4. Conclusion

In summary, we described an automated meshing workflow that can efficiently generate multi-layered tetrahedral meshes of human head and brain from segmented MRI scans. The main advantages of this workflow are the fast mesh generation times in the order of a few minutes, the fine-grained control over the size and quality of the elements, the compatibility with a large number of neuroimaging tools, the smoothness of the boundary layers, as well as the high fidelity of these layers with respect to the original segmented data. We also show how these head models can be used in a typical fNIRS simulation. Our open-source tool "brain2mesh" is available at:

`http://mcx.space/brain2mesh`

5. Acknowledgement

This research is supported by the National Institutes of Health (NIH) grants# R01-GM114365 and R01-CA204443.

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