A new protocol for the rapid generation of accurate anatomically realistic Finite Element Meshes of the head from T1 MRI scans

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Reconstruction of images in Electrical Impedance Tomography (EIT) of brain function in the adult head benefits from the use of accurate numerical models, which may utilize meshes created by the Finite Element Method (FEM). Previously, these have been produced by manual segmentation and parametric representation of surfaces which were later meshed, but this was time consuming and required CAD specialist expertise; as a result a single standard mesh was used for all subjects and this may have introduced errors. We demonstrate a new mesh generation procedure, which employed the freely available BrainSuite segmentation and Cubit meshing software. By this procedure, anatomically accurate finite element meshes of the head can be produced from T1 MRI scans in less than an hour. Acceptable images of test objects in the human head could be obtained with image reconstruction with the new meshes using experimental tank and simulated data. For uniform mesh density, the optimum element size was 7 mm, or 7mm for scalp, 5mm for skull and CSF and a bias factor 1.4 for brain for variable sizing. This appears to provide a practicable and rapid new method which could be used to provide individual subject FEM meshes without special expertise for EIT imaging in the head or elsewhere in the body if accurate individual meshes are required.

Introduction

Electrical impedance image reconstruction usually employs a forward model, which is commonly formulated using Finite Element Method (FEM). This numerical approach requires an accurate volume mesh. Images are generated by calculating conductance change in each element. Improved image quality can be obtained by the use of anatomically accurate meshes. Due to the large inhomogeneities in the different tissues of the human head, i.e. brain, CSF, skull and scalp, an accurate geometrical representation is essential. However, this may pose difficulty for both segmentation and meshing as the surfaces are irregular. In a previous study from our group, production of a FEM mesh of the head took several days by a skilled operator and so a single prototype mesh was employed to reconstruct images for all subjects. [1]. The difference between the prototype and individual subjects’ anatomy is likely to introduce significant errors. Finite Element meshing techniques have been extensively used in industry [2], and offer robust means for discretizing a domain while maintaining. Several quantitative measures may be used to assess mesh quality [3].

In previous published work, the human head was modelled as a single homogenous or concentric sphere, which was meshed into tetrahedra. Attempts to create bespoke meshes were based on manual segmentation from textbook-standard heads [4], or MRI images [1]; some studies employed adaptive mesh refinement strategy [5]. However, we are not aware of any published method for the rapid, practicable production of Finite Element meshes for use in EIT.

In order to produce meshes from MRIs, a combination of segmentation and meshing needs to be applied. Segmentation is a process of identification of individual regions of interest in an image. In three dimensions, this allows the generation of bounding surfaces that define different regions or structures. In the mesh generation process, each domain is divided into predefined volume elements according to a meshing algorithm which is normally set to optimise a predefined mesh quality measure.
The purpose of this work was to produce a protocol for the generation of Finite Element meshes for head EIT from T1 MRI scans. This protocol was intended to be quick to apply and produce meshes that are of equivalent mesh quality to meshes produced using published methods.

Outline of meshing procedure

1) Segmentation. BrainSuite is a public domain software intended for use to segment a MRI. It uses a combination of an edge-preserving filter and a Marr-Hildreth filter to isolate the brain followed by a series of threshold detection instances to determine scalp, outer and inner skull surfaces [6]. These surfaces can be exported from this program and imported individually into the CUBIT meshing software [3].

2) Meshing. CUBIT is licensed software available from Sandia National Laboratories, USA. Surfaces are used to define volume models. Low sensitivity areas were removed by cutting the head longitudinally at the level of the base of the nose. In order to use CUBIT’s advancing front algorithm and allow for meshes of variable density, the volume was divided sagittally and the TETMESH meshing strategy was applied. This solid mesh was exported as a genesis file to unite the resulting two halves. This process was repeated for all layers excluding the brain. The brain was meshed using a CUBIT command that applies a fine mesh to the outer surface, which gets coarser internally. This allows a greater level of detail to be applied to thin structures, such as the skull and cerebrospinal fluid (CSF). With all surfaces meshed into volumes, the genesis files were re-imported into CUBIT. The meshes were removed to allow subtraction of volumes to form tissue layers, which were subsequently meshed and exported as I-DEAS files for use in MATLAB based processing. Before the meshes could be compiled and saved, the elements were renumbered from a starting number of one.

The proposed meshing procedure was assessed by producing example meshes from rat and human MRI scans. A mesh for a human shaped latex tank was also generated, using surfaces from a manual segmentation from a CT image. This tank mesh was used to optimise settings for the size of the elements in different tissue layers, by reconstructing images from experimental data using different settings.

Methods

Description of method

All MATLAB functions and CUBIT GUI instructions and screenshots are available on request.

1. MRIcro (www.mircro.com) was used to rescale T1 MRI scan by a factor of 0.5

2. Segmentation was performed using BrainSuite 2.0 (BrainSuite.usc.edu) and default settings.

3. File conversion was performed using MATLAB (The Math Works) with a combination of readdfs and write_stl_2 functions.

4. CUBIT was opened and set facet_modify on entered into the command window. The scalp ‘.stl’ surface was imported with a feature angle of 0. The volume was cut transversely beneath the nose. All volumes inferior to the cut were deleted. The volume was then divided sagittally in a similar manner. Identical surfaces were identified and merged. The volume was then meshed using the TETMESH scheme with a constant interval size of 7. The mesh produced was compiled into a single block, and exported as a genesis file. The skull and CSF were meshed using a constant interval size of 5, with the transverse cuts being sequentially 1mm superior to the previous imported volume. The brain surface was imported and cut transversally 3mm superior to the cut applied to the scalp. The volume was divided sagittally and surfaces merged. However, the volume was meshed with a constant size of 5 applied to the midline curve, and the shared central surface was meshed using the bias sizing function with a factor of 1.4.

These values were adjusted through a process of trial and error by observing the effect of adjusting each value over reconstructed experimental data, using a mesh from a head shaped latex tank. The data were collected using a sponge suspended inside the cranium of a human skull that had been immersed in 0.2% saline inside the tank.
Finally, the genesis volumes were re-imported into CUBIT and subtracted from one another to produce tissue layers. These were exported as universal files (unv format) to be imported to MATLAB using the ideas_importer function. The separate layers of the mesh were united using the mesh_unite function.

Example mesh production

An MRI of a Sprague-Dawley rat head was meshed to produce a three layer mesh containing scalp, skull and brain, totalling 95,000 elements. The human head was meshed in four layers: scalp, skull, CSF and brain with 98,000 elements. The latex tank was meshed with three layers corresponding to saline outside the skull, skull and saline inside the skull. This required 84,000 elements after the maxilla and zygomatic arches had been removed from the skull (Figure 1).

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Number of elements</th>
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<tbody>
<tr>
<td>A - Rat</td>
<td>95,000</td>
</tr>
<tr>
<td>B - Human</td>
<td>98,000</td>
</tr>
<tr>
<td>C - Tank</td>
<td>84,000</td>
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</table>

Figure 1 Example meshes produced using the protocol, A: three layer rat head mesh, B: four layer human head mesh, C: three layer tank mesh.

Optimisation and validation using saline tank data

1) EIT images of a sponge in a latex saline filled tank containing a human skull were reconstructed with a linear time difference algorithm and mesh element sizes of 5, 6, 7, 8 & 9mm (figure 2). 2) The validity of the meshing protocol was empirically verified by reconstructing simulated data. Boundary voltages were calculated using the SuperSolver [7] code suite over a mesh created previously with I-DEAS for three different perturbations. The images were reconstructed using the I-DEAS mesh and a CUBIT mesh with a constant interval size of 7 throughout (Figure 3). 3) The effect of variable mesh density was assessed by reconstructing images with meshes of the saline filled tank with: a constant interval size of 7mm, a skull layer of constant interval 5mm, and three meshes with a skull layer of constant interval 5 with brain element variability (bias factor) increasing centrally by 1.2, 1.4 and 1.6 (Figure 4).

<table>
<thead>
<tr>
<th>CS6</th>
<th>CS7</th>
<th>CS9</th>
<th>Actual position</th>
</tr>
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<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Figure 2 Reconstruction of experimental data in three example meshes, with a constant interval size of 6 (CS6), 7 (CS7) and 8 (CS9). Right - the position of the perturbation and level of illustrated slice.

<table>
<thead>
<tr>
<th>New mesh</th>
<th>Standard mesh</th>
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<tbody>
<tr>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
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</table>
Figure 3. Reconstruction of simulated data for the saline filled head tank. Data were produced using an I-DEAS mesh and reconstructed using the CUBIT mesh with 7 mm element size.

CS7 | CS7 s5 | Bias 1.4 | Bias 1.6
---|---|---|---

Figure 4 Reconstruction of experimental data using meshes of variable density. A mesh with constant size of 7 (CS7), with a refined skull of constant size 5 (CS7 s5) and with refined skull and biased brains of factors 1.2, 1.4 and 1.6 were used in reconstruction. The mesh with a brain biased with a factor of 1.2 contained too many elements for the algorithm to reconstruct.

Results and Discussion

This procedure for mesh generation allows production of visually realistic meshes which also enabled recovery of reasonably correctly localized perturbations. The meshes seem to possess similar quality and utility as the previously published procedure with manual segmentation with the industry standard I-DEAS software [1]. Reasonable recommended settings for meshing a human head are a constant interval size of 7 when meshing the scalp, 5 for the skull and CSF and a bias factor 1.4 for meshing the brain.

When meshing a human head with this procedure, a significant number of badly shaped tetrahedra were identified (Fig. 5). A bad tetrahedral is one with a scaled Jacobian of less than 0.2, and is a measure of how uniform and isotrophic each element is [3]. The majority of these bad elements were located at the base of the model, where the cut had occurred. This was reduced with variable density meshing with a bias setting of 1.4.

Work in progress is to assess if this confers a significant improvement in image quality for imaging abnormalities in the adult head, using simulated data and MRIs in normal subjects. In addition, we plan further quantitative analysis of the modeling errors in order to support a definite claim for the validity of this procedure.

In summary, this robust and quick procedure provides a way for producing meshes of good quality that could be used in EIT image reconstruction. Although this work was specifically tailored for the adult head, where anatomic intricacy suggests that its use is most likely to confer improvements in image quality, this method could easily be adapted for use elsewhere in the body.

Figure 5 Percentage of poor quality tetrahedrals in each model. Blue bar is tank meshed with a constant interval size of 7, blue and white is tank meshed with a brain bias of 1.4. Red bar is for human head meshed with a constant size of 7 and red and white is human head meshed with bias of 1.4.

References