3D DOT Brain Imaging: An Anatomical Atlas-Based Method

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Introduction

For functional neuroimaging modalities, a capability that is increasingly regarded as essential is the ability to map image findings to the underlying anatomy. In the case of diffuse optical tomography (DOT), complicating the goal of mapping DOT activation findings to brain anatomy is the need for a representative atlas that can support the flexible generation of the imaging operator for any selected optode arrangement. Whereas access to individual structural maps is increasingly common, efforts to generate individualized finite element method (FEM) meshes in support of DOT reconstructions can be cumbersome. To facilitate the accurate generation and mapping of DOT findings, we have established a library of FEM meshes from a selected MRI that has been segmented according to different tissue types. Specification of optode arrangement corresponding to individual or multiple head regions is made either by graphical selection, or through the loading of measures of head-shape and optode position followed by an affine transformation based on measured fiducials. This information is used to configure the corresponding imaging operators obtained from a precalculated database. Experimental evaluation has shown that determination of head shape, optode location, reconstruction of activation maps and mapping to individualatlases can be achieved with high fidelity.

Methods

MR-based FEM model library: A single-subject MRI of the brain, having a 1 mm resolution and obtained form Source Signal Imaging, was used as our atlas in the present study [1]. The image was segmented into five classes including skin, skull, cerebrospinal fluid, gray matter, and white matter. The FEM model library consists of the FEM meshes of brain regions of interest (ROIs) and corresponding forward solutions to the photon diffusion equation for identified tissues. Each ROI mesh is generated from the segmented image atlas by use of EMISE MR Viewer [1], in which there are nearly 3000–3500 nodes, as shown in Fig. 1A. The spatial extent of each mesh file normally covers about 50-70 cm² on the surface of the head and has a depth of up to 5 cm. In order to cover all regions of brain, we have generated 25 overlapping ROI meshes in our library. Fig. 1B shows twelve ROI meshes of the library.

In each ROI mesh there are about 400 boundary nodes on the surface of the head with approximately a 4 mm spatial resolution. We consider the surface nodes as the possible source/detector positions, and numerically solve the FEM discretized photon diffusion equations using Type III boundary conditions [2]:

\[
\begin{bmatrix}
[A] & [B] & [C]
\end{bmatrix}
\begin{bmatrix}
[I]_A \\
[I]_B \\
[I]_C
\end{bmatrix}
= 0
\]

Solutions to these equations [9] and [2a/b/c] provide the retrieved detectors values and weight functions (Jacobian operators), respectively. The pre-calculated results are incorporated into the FEM model database. The complete brain MRI model database represents over 200 GB of data.

To efficiently and conveniently employ the model library, we have developed a Matlab-based interactive FEM model generation tool: FEM Brain Model Generator, as shown in Figure 2. By using the generator, the users can easily generate themselves FEM mesh models matching the experimental source/detector geometries by inputting the coordinates of source/detector positions and brain fiducial points measured by 3D digitizer, or by using the generator GUI to manually specify source and detector positions on the head surface of the image atlas.

3D Digitizing and imaging: Mapping of optode-position information from an individual subject to an FEM library model is accomplished by first digitizing brain fiducial points and source/detector positions and then applying an affine transformation. The fiducials and optode positions can be measured by a commercial 3D digitizer, e.g., Polhemus patriot, as shown in Figure 3A. Figure 3B illustrates that 10-20 system points that are selected as the standard head shape fiducials in our method. The measured coordinates \( P_i \) of 13 fiducial points on individual subject head surface and the known coordinates \( P_0 \) of 13 fiducial points on the images atlas surface are related by an affine transformation matrix \( (M) \) [3]:

\[
P = P_0 M
\]

From the equation above, the affine transformation matrix \( M \) can be solved by a least square method using matrix left division:

\[
M = \frac{1}{P_i - P_0}
\]

Next, the measured optode coordinates \( P_i \) are registered to the image atlas by following an affine transformation:

\[
P_M = P_0 M
\]

where \( P_i \) is the registered optode coordinate matrix.

3D registering and registration: Shown in Figure 5 and Table 1 are experimental results of 3D digitizing and registration for four points on a solid brain phantom. Figure 5A shows the comparison of the spatial contours from the phantom (blue) and the corresponding contours from the image atlas (green). Figures 5B and 5C show the four registered points on the image atlas. Listed in the Table 1 are measures of the precision (CV = 0.1%) and accuracy (2-5 mm error) of this registration for eight consecutive trials.

Sensitivity of 3D Image Mapping to Initial Guess: Table 2 shows AAL mapping results from 10 different runs of 3D DOT simulation of imaging data that explore the sensitivity of mapping accuracy on increasing errors in the initial guess. Considered are four target media whose optical properties increasingly differ from initial guess in \( \mu_r \) only (except target D). Conditions explored: Optode array 24x3x24 covering 4 x 10 cm area, symmetric to midline; ROI: 1.5 cm object, mean depth 2 cm, middle of occipital cortex. Initial Guess: \( \mu_r = 0.06, \mu_t = 10 \) cm²/s. Target Media (background): \( \mu_r, \mu_t \) in: 0.8, 0.1, 0.15, 0.2 cm²/s; ROI: \( \mu_r, \mu_t \) in: 0.15, 0.01, 0.015, 0.02 cm²/s; Background: \( \mu_r, \mu_t \) in: 0.001, 0.005, 0.0005, 0.01 cm²/s.

Table 2: Anatomical labels and percentages per cluster in reconstructed inclusion region for four target media

<table>
<thead>
<tr>
<th>Target Medium (error, %)</th>
<th>Cuneus_L</th>
<th>Calcarine_L</th>
<th>Cuneus_R</th>
<th>(others)</th>
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<td>0</td>
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<tr>
<td></td>
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<td>0</td>
<td>20.0</td>
<td>0</td>
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</tbody>
</table>

Experimental Validation with Programmable Anthropomorphic Head Phantom: Results in Figure 7 show image overlay obtained from frontal cortex study on head phantom containing programmable electrodielectric cell to mimic hemoglobin signal [8]. The 1x1x0.2 (cm³) cell is embedded right frontal to a depth of ~2 cm below the head surface. Positionally error of highest contrast pixel is ~3 mm. Figure 8 shows result of fourier Transform for programmed and recovered function.

Conclusions

In summary, we have developed an anatomical atlas-based method for efficient generation and 3D registration of DOT image findings. As confirmed by numerical simulations and experimental data from solid-state programmable phantoms, our method is computation-efficient and is able to carry out, with high spatial and temporal accuracies, the necessary mappings—of optode-position information from an individual subject to an FEM library model, and of volumetric image information from the model back to the individual.

References


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