Comparing Isotropic and Anisotropic Brain Conductivity Modeling: Planning Optimal Depth-Electrode Placement in White Matter for Direct Stimulation Therapy in an Epileptic Circuit

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Abstract

INTRODUCTION: The goal of our work was to calculate a patient-specific brain conductivity map for predicting the extent to which direct stimulation therapy can strategically propagate through pathological white matter. Our laboratory developed isotropic and anisotropic human brain finite element method (FEM) models derived from SPGR magnetic resonance imaging (MRI) and diffusion tensor imaging (DTI), respectively for estimating tissue conductivities during direct stimulation therapy. Specifically, the electrostatic electric field (E-field) and, current density surrounding two modeled depth contacts virtually placed in white matter were modeled for a patient with bilaterally independent intractable temporal lobe epileptic sources. The more sophisticated anisotropic model was developed to challenge our three-compartment isotropic model (Rossi et al, 2010). The isotropic model was used to plan optimal implantation of a 4-contact depth lead connected to an investigational implantable pulse generator (NeuroPace, Inc) recently recommended for approval by the U.S. FDA.

SIMPLEWARE SEGMENTATION & MESHING: The isotropic model considered three brain compartments (white matter, grey matter and cerebrospinal fluid (CSF) with uniform conductivities). Segmentation, CAD integration and volumetric meshing were all performed in the Simpleware Software Suite v5.1 (Exeter, UK). Segmentation of the three brain compartments was performed in ScanIP, where an intensity correction filter was executed to minimize segmentation artifacts (Figure 1). Using the +CAD add-on module, the depth electrode model was positioned longitudinally in epileptic temporal lobe white matter at the grey-white matter interface (Figure 2A). The resultant composite of brain and CAD electrode was used to generate a multi-part volumetric mesh by implementing the +FE-free-meshing algorithm in the +FE module (Figure 2B).

COMSOL MULTIPHYSICS: This meshed dataset was imported into COMSOL and converted to a composite of the grey and white matter, and CSF geometry objects to define the isotropic model. The stimulation intensity was set to a peak-to-peak potential difference of 5 Volts. In the isotropic model, a uniform electrostatic E-field was generated by stimulating between two electrode contacts

(Figure 3). COMSOL processing limitations, constrained the computationally-intensive anisotropic model to single slice 2D representations. The anisotropic model was determined from 8100 contiguous transformed matrices within a brain slice of a high-resolution DTI dataset acquired 30-45 minutes following a complex partial seizure without generalization secondarily. Each 3x3 tensor matrix composing a voxel represented acute and transient water diffusion-related changes occurring after the focal seizure. A custom program was developed in MATLAB v2008b to convert each diffusion tensor matrix in an axial brain slice to a conductivity tensor matrix using a linear transformation of the matrices' eigenvalues. A rectangular geometric entity was created for each voxel and related to the corresponding conductivity tensor using the LiveLink-for-MATLAB module to COMSOL interface.

RESULTS: The anisotropic associated E-field and current densities followed anatomical boundaries not apparent in the isotropic conductivity model. The anisotropic modeled E-field and current density maps are shown in Figures 4B & C.

CONCLUSION: Further development of this proof-of-concept anisotropy-driven conductivity planning workflow will facilitate strategic placement of a minimal number of depth-electrode contacts for stabilizing an extensive pathological epileptic network with non-uniform conductivities.

Reference

Marvin A Rossi, Glenn Stebbins, et al. Predicting white matter targets for direct neurostimulation therapy. Epilepsy Res, 91,176-186 (2010).
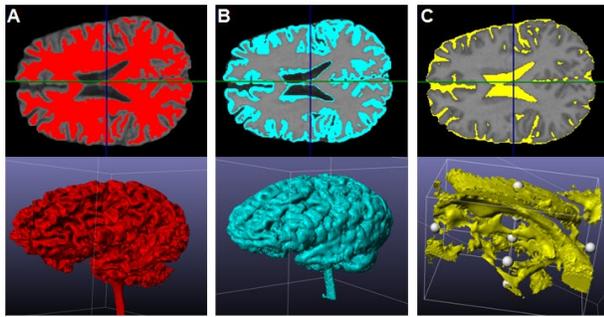
Figures used in the abstract

Figure 1: Segmentation of the subject's high-resolution SGPR MRI dataset (124 contiguous slices, voxel resolution: 0.859 mm3) was performed in Simpleware to create a FEM mesh prior to importing into COMSOL Multiphysics v4.3b for calculating the biophysics of stimulation. (A) White matter, (B) grey matter, and (C) CSF compartments are shown.
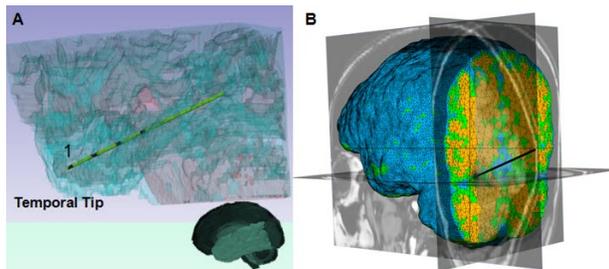

Figure 2: (A) A CAD rendering of the depth electrode model consisted of four conductive cylinders (1.27mm diameter x 0.2mm height) separated by insulators (10mm between cylinder midpoints). Using the Simpleware +CAD module, this electrode model was positioned longitudinally (from occipital to frontal) in epileptic temporal lobe white matter within 4-5mm of the grey-white matter interface. (B) A variable mesh density was employed, with a maximum edge length of 0.25mm lying within a 40mm radius surrounding each electrode contact. The variable mesh transitioned linearly outward to a maximum edge length of 5mm.
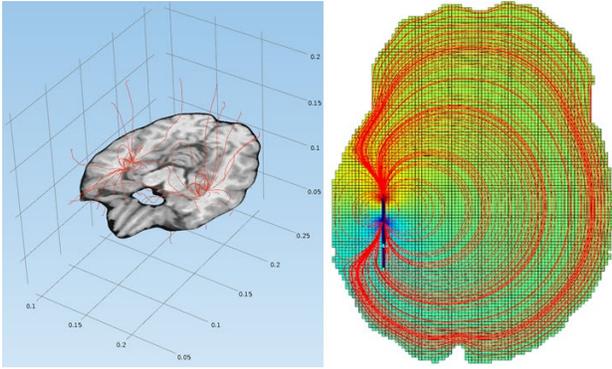
Figure 3: The 3D and 2D isotropic models representing the uniform E-field are shown. The platinum/iridium electrode contact conductivity was set to 15x106 S/m. White matter was represented as a homogeneous and isotropic tissue medium where, conductivity=0.15 S/m. Adjacent isotropic grey matter conductivity was set to 0.06 S/m, and CSF = 1.79 S/m.
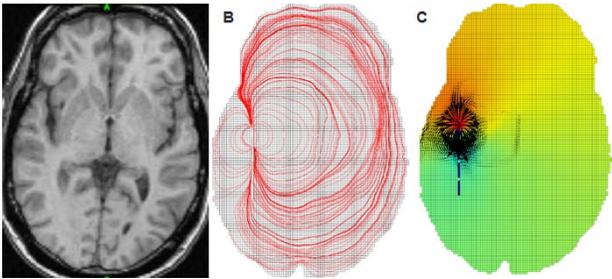

Figure 4: A 2D anisotropic conductivity model of the E-field (B) and current density maps (C) are shown. The anisotropic associated E-field and current densities followed anatomical boundaries not apparent in the isotropic conductivity model. DTI voxel resolution: 1.95 x 1.95 x 3 mm3. The anisotropic model was processed on a Xeon 3.0 GHz dual eight-core Windows 7 workstation with 192GB RAM.