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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Goal

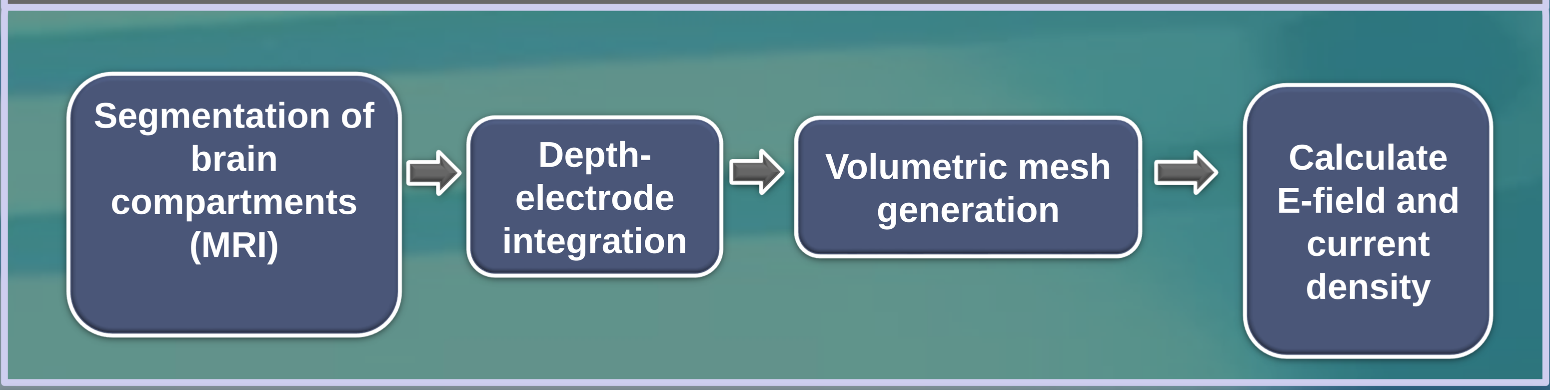
Calculate a patient-specific brain conductivity map for predicting the extent to which investigational direct stimulation therapy (NeuroPace, Inc) can propagate through pathological white matter.

Methods

- Develop isotropic and anisotropic human brain finite element method (FEM) models from SPGR magnetic resonance imaging (MRI) and diffusion tensor imaging (DTI) for estimating tissue conductivities during direct stimulation therapy.
- Calculate electrostatic electric field (E-field) and current density surrounding depth contact electrode leads, virtually placed in white matter.

Isotropic Model

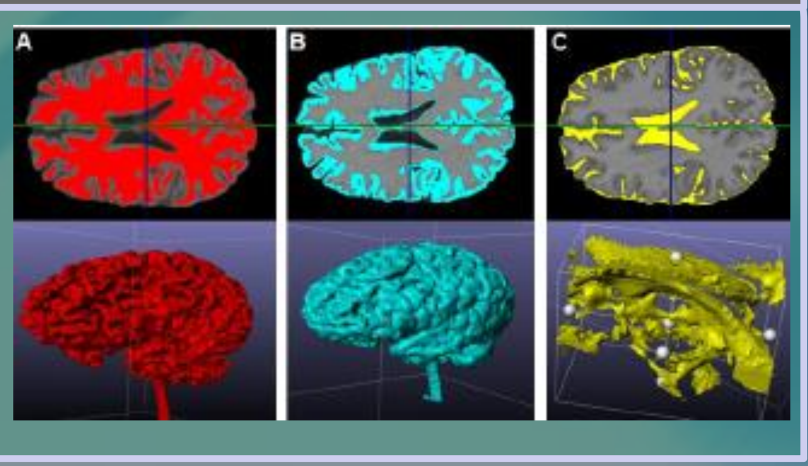
Workflow



Segmentation of Brain Compartments

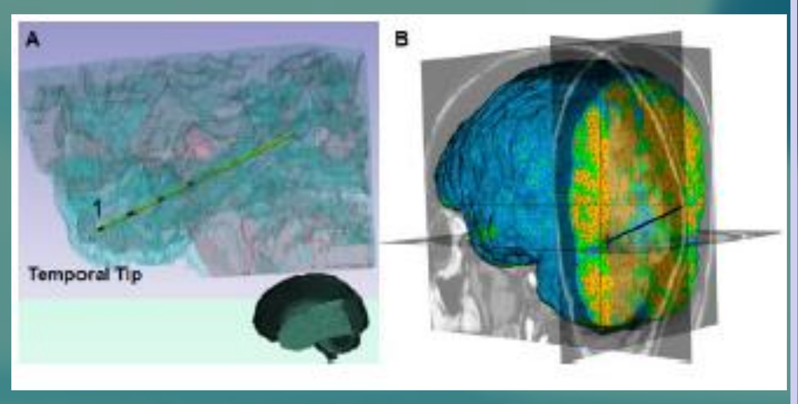
Three brain compartments, using SPGR MRI, were considered:

A. White matter
B. Grey matter
C. Cerebrospinal Fluid



Depth Electrode Placement

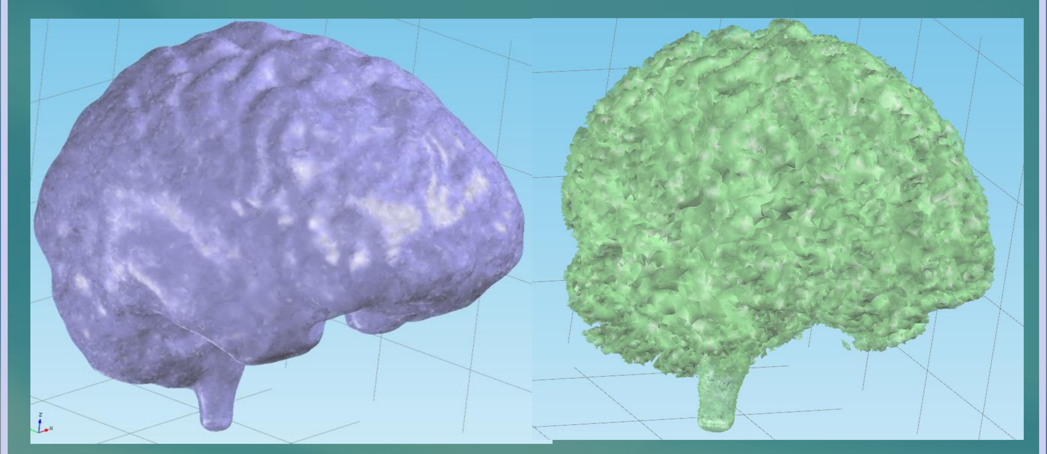
A CAD electrode model (composed of four conductive cylinders separated by insulators) was positioned longitudinally in the temporal lobe White matter at the grey-white matter interface.



Volumetric Mesh Generation

The composite of brain and CAD electrode was used to generate a multi-part volumetric mesh implementing Simpleware's, +FE-free meshing algorithm in the +FE module.

Resulting mesh was imported to COMSOL Multiphysics. V 3.4b.



Calculate Electric Field and Current Density from Stimulation & Compartments

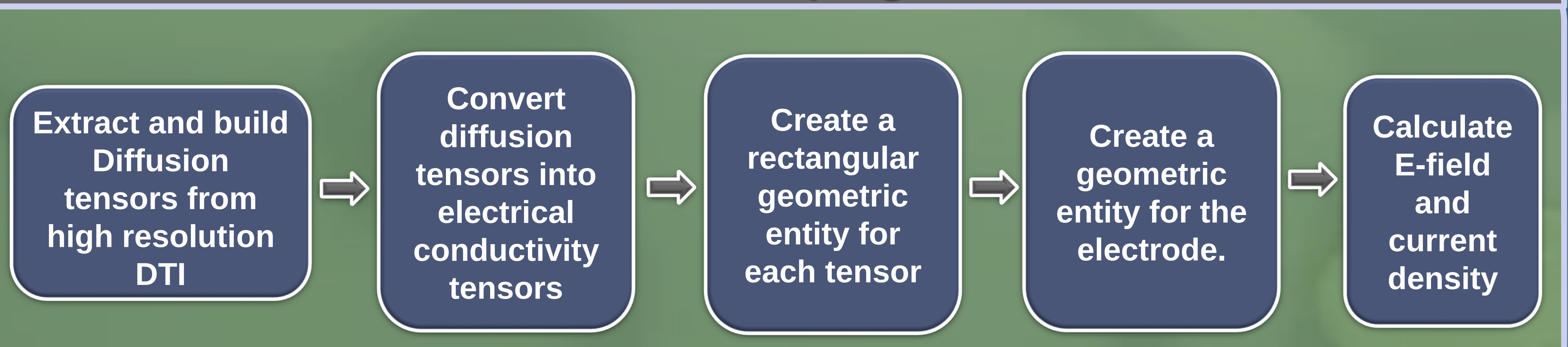
An isotropic electrical conductivity was assigned for each brain compartment:

- White matter=0.15S/m
- Grey matter=0.06S/m
- CSF=1.79S/m

A stimulation intensity was set to a peak-to-peak potential difference of 5V.

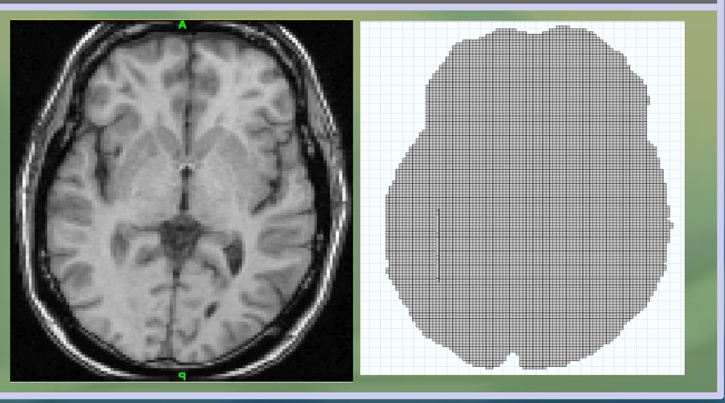
Anisotropic Model

Workflow for Developing a 2D Model



Create a Rectangular Geometric Entity for Each Voxel

A rectangular geometric entity was created for each voxel and related to the corresponding tensor using LiveLink™ for MATLAB.



Extract Diffusion Tensors from High Resolution DTI

A program was developed in MATLAB to extract a 2nd rank water diffusion tensor for each voxel in a DTI .

$$\boldsymbol{D} = \begin{bmatrix} Dxx & Dxy & Dxz \\ Dxy & Dyy & Dyz \\ Dxz & Dyz & Dzz \end{bmatrix}$$

Convert Diffusion Tensors to Conductivity Tensors

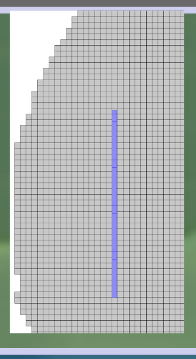
A linear relationship was established between diffusion tensors $\boldsymbol{D}$ and conductivity tensor $\boldsymbol{\sigma}$.

$$\boldsymbol{\sigma} = \left(\frac{\sigma_e}{d_e}\right)\boldsymbol{D}$$

$$\frac{\sigma_e}{d_e} = 0.736\ S(s)/mm^3$$

Geometric Entity for the Electrode

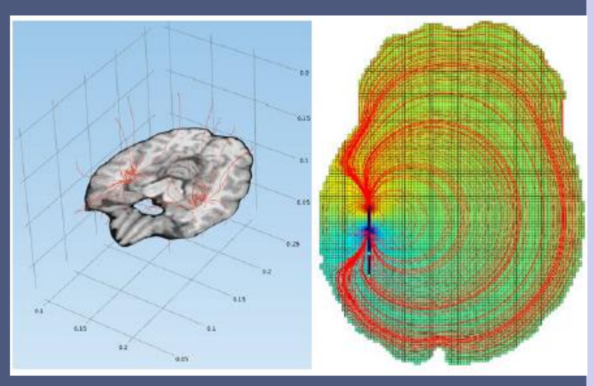
A geometric entity for the electrode was placed in the temporal lobe.
A potential difference was then applied to the electrode.



Results

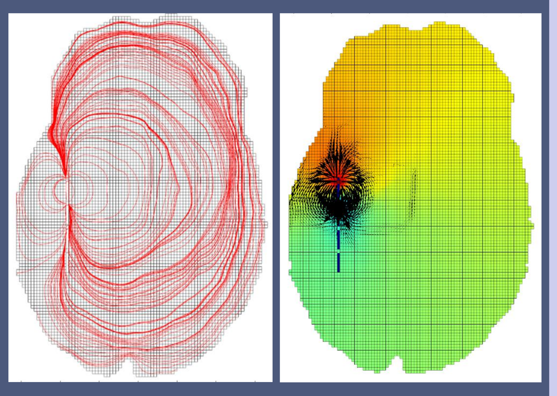
Isotropic Model

A uniform pattern in E-field lines is obtained after applying the potential difference to the electrode contacts.



Anisotropic Model

The anisotropic associated E-field and current densities followed anatomical boundaries not apparent in the isotropic conductivity model..



Conclusions

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 investigational direct neurostimulation therapy.

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