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Influence of Local and Remote White Matter Conductivity Anisotropy for a Thalamic Source on EEG/MEG Field and Return Current Computation

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Abstract—**Inverse methods are used to reconstruct current sources in the human brain by means of Electroencephalography (EEG) and Magnetoencephalography (MEG) measurements of event related fields or epileptic seizures. There exists a persistent uncertainty regarding the influence of anisotropy of the white matter compartment on neural source reconstruction. In this paper, we study the sensitivity to anisotropy of the EEG/MEG forward problem for a thalamic source in a high resolution finite element volume conductor. The influence of anisotropy on computed fields will be presented by both high resolution visualization of fields and return current flow and topography and magnitude error measures. We pay particular attention to the influence of local conductivity changes in the neighborhood of the source. The combination of simulation and visualization provides deep insight into the effect of white matter conductivity anisotropy.**

We found that for both EEG and MEG formulations, the local presence of electrical anisotropy in the tissue surrounding the source substantially compromised the forward field computation, and correspondingly, the inverse source reconstruction. The degree of error resulting from the uncompensated presence of tissue anisotropy depended strongly on the proximity of the anisotropy to the source; remote anisotropy had a much weaker influence than anisotropic tissue that included the source.

Keywords— **anisotropy, EEG/MEG source reconstruction, finite element method, local conductivity changes, return currents, thalamus, visualization**

I. INTRODUCTION

A critical component of the inverse neural source reconstruction is the numerical approximation method used to reach an accurate solution of the associated forward problem, i.e., the simulation of fields for known dipolar sources in the brain. The forward problem requires a geometric model of the volume conductor (the head and brain), often in the form of spherical shell, Boundary Element (BE) [1] or Finite Element (FE) models. Only the FE method is able to treat both realistic geometries and inhomogeneous and anisotropic material parameters [2,3,4,5].

Past studies have shown that the inclusion of anisotropy is important for an accurate reconstruction of neural sources [2,5,6,7]. Furthermore, recent developments for the FE method in EEG/MEG inverse problems [8,9] dramatically reduce the complexity of the computations, so that the main disadvantage of FE modeling no longer exists. In spherical models of the head, the influence of compartmental conductivity anisotropy (radial versus tangential) on forward and inverse problems in EEG and MEG were studied by [6,7]. However, the white matter compartment is poorly represented by such a model. There have been relatively few studies of the influence of white matter anisotropy on forward EEG and MEG simulation [2,5]. In [10], a strong influence of local conductivity changes around the source to EEG and MEG was reported.

In this paper, we study the effect of white matter anisotropy for the forward EEG and MEG computation for a thalamic source. We especially examine the effects of anisotropy near the source. For deep sources that are surrounded by large anisotropic white matter fiber bundles, such as the pyramidal tract and the corpus callosum, we provide insight into the sensitivity towards anisotropy by means of visualization and interpretation of computed fields and return current flow and the examination of the Relative Difference Measure (RDM) and MAGnification factor (MAG) error measures [1].

II. METHODS

The first step in constructing a realistic volume conductor model is to segment the different tissues within the head. Modeling of the low conducting human skull is of special importance for EEG/MEG source reconstruction. As such, we used a pair of T1-weighted and PD-weighted Magnetic Resonance Images (MRI). We aligned both image datasets with a voxel-similarity based affine

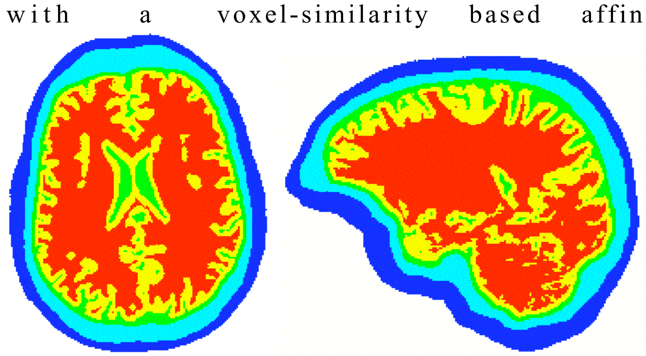

Fig. 1. Segmented five tissue head model: skin (blue), skull (light blue), CSF (green), gray matter (yellow) and white matter (red).

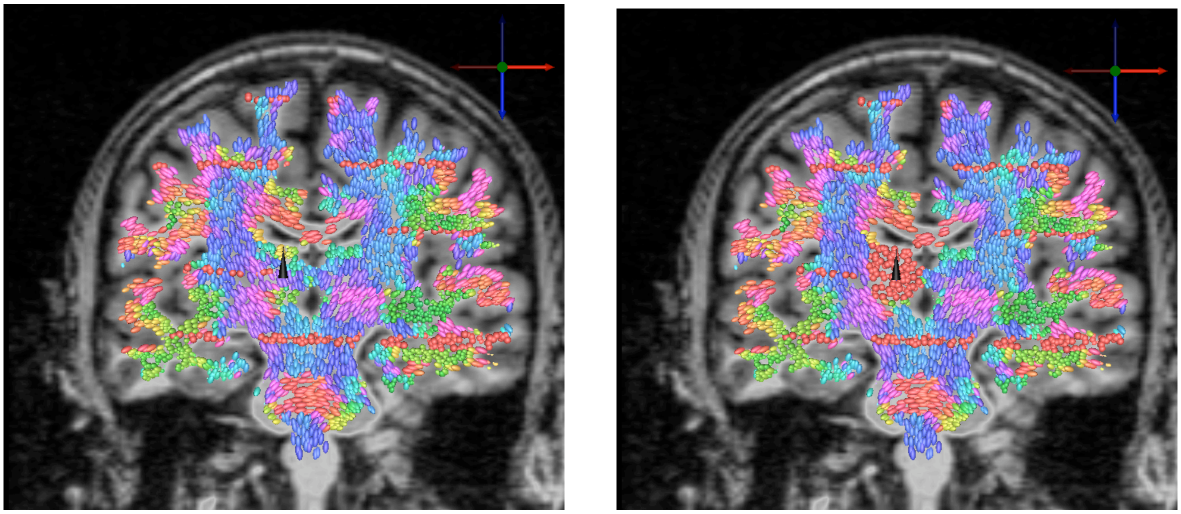

Fig. 2. Coronal slice of the models *aniso_thalaniso* (left) and *aniso_thaliso* (right) with left thalamic dipole source. The conductivity tensors of finite elements in the white matter are displayed on the underlying T1-MRI using 1:2 anisotropy.

registration without pre-segmentation using a cost-function based on mutual information [5]. Our nearly automatic segmentation process consisted of a 3D implementation of an Adaptive Fuzzy C-Means classification method which compensates for image intensity inhomogeneities, followed by a deformable model algorithm to smooth the inner and outer skull surfaces [5]. We segmented five head compartments; skin, skull, cerebrospinal fluid (CSF), gray and white matter. Because the fractional anisotropy within the thalamus is a factor three times higher than the fractional anisotropy of neocortical gray matter, we assigned both thalami to the white matter compartment for the following simulation study. The segmented five tissue headmodel is shown in Fig.1.

In the second step, we generated a FE model using a surface-based tetrahedral tessellation of the segmented compartments, resulting in 147,287 nodes and 892,115 elements. The following isotropic conductivities were assigned to skin (0.33 S/m), skull (0.0042 S/m), CSF (1.79 S/m), brain gray (0.33 S/m) and white matter (0.14 S/m). Anisotropic conductivity ratios of approximately 1:9 (normal to parallel to fibers) have been measured for brain white matter [11]. Following the proposition of [12], we assumed that the conductivity tensors share the eigenvectors with the water diffusion tensors, measured by means of Diffusion Tensor MRI (DT-MRI). Using multiple sessions, we measured whole-head DT-MRI. The MRI slices were axially oriented and 5mm thick with an inplane resolution of 2mm x 2mm. We computed the eigenvalues for the white mater conductivity tensors using two constraints, a volume constraint that retains the geometric mean, i.e., the volume, of the eigenvalues [5], and Wang's constraint [13], where the product of the longitudinal and one transversal eigenvalue is kept constant and equal to the square of the isotropic value. The resulting tensor-valued conductivity slices were not exactly parallel and we filled the gaps with the isotropic white matter conductivity.

For the EEG forward computation, we placed 71 electrodes interactively on the head surface according to the international 10/20 system. For the MEG, we modeled each magnetometer flux transformer of the BTI (4-D NeuroImaging, San Diego, USA) 148 channel whole-head system with eight isoparametric quadratic finite row elements.

Using the dipole model of [14], we performed EEG and MEG forward computations for a left thalamic source in the isotropic five-compartment FE model and in the corresponding models with white matter anisotropy (Fig.2). In order to study the influence of local conductivity changes, we considered two different anisotropic models. For the first model *aniso_thalaniso*, we treated the finite elements in the neighborhood of the thalamic source as anisotropic elements (Fig.2, left), while in the second model *aniso_thaliso*, we extracted 1113 neighboring finite elements and modeled them as isotropic (Fig.2, right).

To quantify the error between isotropic and anisotropic field values at the sensors, we used the RDM and MAG error measures [1]. The RDM is a measure for the topography error (Minimal error: RDM=0), while the MAG indicates magnitude differences (Minimal error: MAG=1).

In order to better assess the influence of anisotropy, the return current on the model surface is visualized by means of a Line Integral Convolution (LIC) technique[15] computed directly over the head geometry. This method

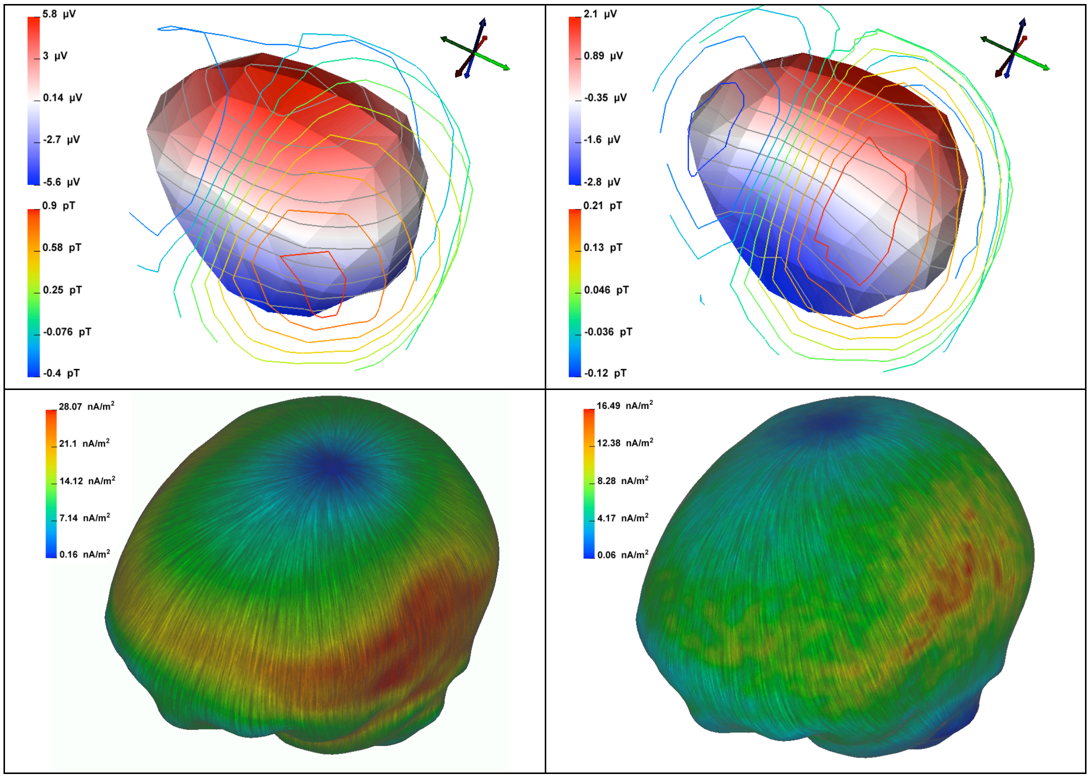

Fig.3: Isofield EEG and MEG distribution (top row) and surface return current (bottom row) for the left thalamic source in the isotropic model (left) and in model *aniso_thalaniso* with 1:10 white matter anisotropy (right).

permits a continuous depiction of the directional information and is combined with a color mapping of the current magnitude that gives insight into the quantitative aspects of the electrical flow.

III. Results

The Figs.3 and 4 clearly show the importance of local conductivity changes around the source for both EEG and MEG. In model *aniso_thalaniso* (Fig.3, right column, and Fig.4, in red), with topography differences to the corresponding isotropic model of about 80% for EEG and about 50% for MEG, the 1:10 white matter anisotropy substantially compromises the forward field computation. Furthermore, in addition to this topography error, the anisotropy significantly weakens the fields, which is expressed by a MAG of less than 0.5 for the EEG and even less than 0.3 for the MEG and the strongly reduced amplitude of the surface return currents. We find two return current areas of minimal amplitude (in blue), one on the top and one on the bottom of the model (not shown). As it can be observed, the 1:10 white matter anisotropy in model *aniso_thalaniso* strongly shifts the minimal amplitude return current points in comparison to the isotropic case. In both cases, the amplitude of the return currents is well correlated to the thickness of the skull (compare the color scaling of the return currents with the segmented model in Fig.1). While high return currents are flowing in the thin lateral areas, they are significantly attenuated in the thicker occipital areas and in the areas of the frontal sinuses. The white matter anisotropy diffuses the surface return currents.

In contrast to those results, the effect of the white matter anisotropy in combination with the local isotropy in model *aniso_thaliso* is much weaker, for a ratio of 1:10 the RDM is below 10% and the MAG close to the optimum.

IV. Discussion

It was found that conductivity (anisotropy) changes around the source have a strong influence on the EEG and MEG forward problem, while anisotropy in a certain distance from the source has only a smaller effect. This is in agreement with a study of local (isotropic) conductivity changes in [10]. The sources are embedded in brain gray matter structure, which has a measured anisotropy ratio of about 1:2 (tangentially:perpendicular to the cortical surface) [10] or higher for gray matter structures such as the thalami, as the fractional anisotropy ratio of the DTI data shows. Furthermore, most sources are very close to the white matter compartment. It can therefore be expected that the modeling of the gray and white matter anisotropy is important for an accurate reconstruction of the sources, as also reported by [2,5]. As a final note, the

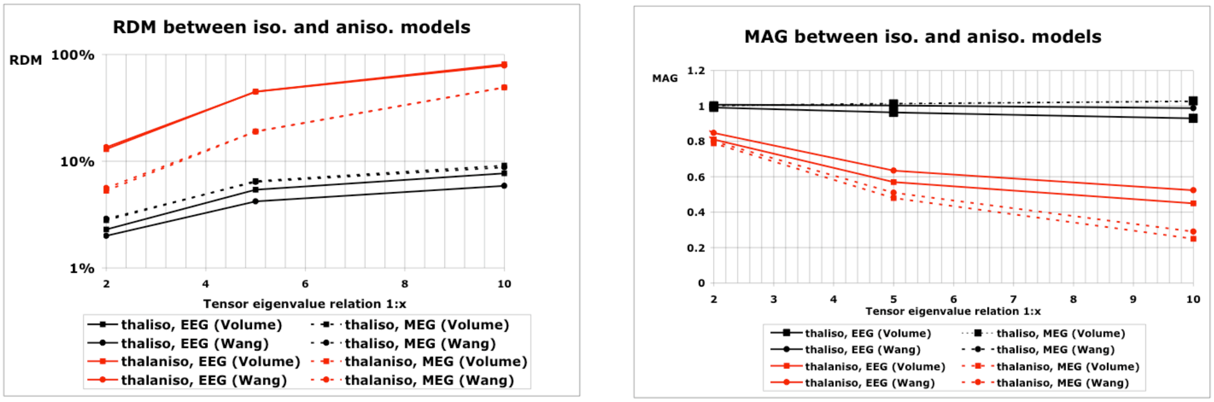

Fig.4: EEG and MEG topography (left, log. Y-axes) and magnitude error (right) for the volume and Wang's constraint for various white matter anisotropy ratios and both models *aniso_thalaniso* (red) and *aniso_thaliso* (black).

source model via an accurate implementation method for the dipole will be of significant importance [5,16].

V. Conclusion

The modeling of gray and white matter anisotropy is important for an accurate EEG/MEG based reconstruction of the neural sources, especially with regard to the orientation and strength components. The more the source is surrounded by anisotropy, the larger is the influence.

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