From DTI to CTI: The role of anisotropic conductivity of the white matter tissue – an EEG FEM simulation study

D. Güllmar[1,2], J. R. Reichenbach[1], A. Anwander[3], C. H. Wolters[4], J. Haueisen[2,5]

[1]Institute of Diagnostics and Interventional Radiology, Friedrich-Schiller-University, Jena, Germany, [2]Biomagnetic Center, Friedrich-Schiller-University, Jena, Germany, [3]Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany, [4]Institute for Biomagnetism and Biosignalanalysis, Westfalian Wilhelms-University Muenster, Münster, Germany, [5]Institute for Biomedical Technique and Computer Science, Technical University Ilmenau, Ilmenau, Germany

Introduction

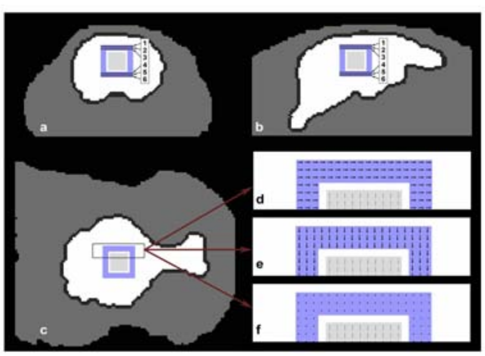
The conductivity in living tissues is known to be anisotropic (in particular in white matter structures). This, however, is usually neglected in EEG source reconstruction studies. FEM modeling enables to take into account anisotropic conductivity, and Diffusion Tensor Imaging (DTI) provides the tool to derive this property *in vivo* assuming that the Diffusion and the Conductivity tensor share the same eigenvectors. A previous study [1] has shown that the influence of anisotropic conductivity on the EEG forward computation is complex. Thus, we decided to test the influence of taking into account anisotropic structure with artificially modeled anisotropies.

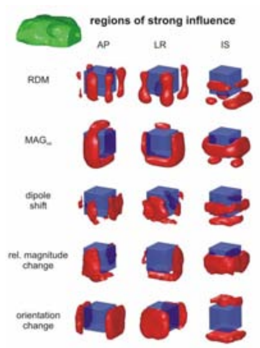
Materials and Methods

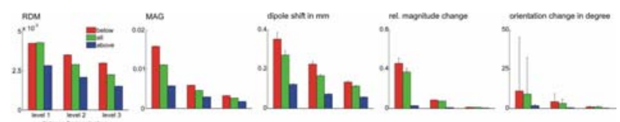
In our investigation we applied a high resolution finite element method (FEM) model with cubic elements (633.172 elements, element length = 0.6 mm) of a rabbit head. Four different tissue types were considered (skin σ=0.33 S/m, skull σ=0.0042 S/m, gray matter σ=0.337 S/m, white matter as an artificial volume block with an isotropic conductivity of 0.14 S/m). We quantified the influence of anisotropy by comparing simulated EEG maps using two different types of volume conductors: 1. inhomogeneous model with isotropic conductivity 2. inhomogeneous model with a volume block of anisotropic conductivity, which represents the white matter tissue. The white matter block in model 2 was set up with anisotropic conductivity with left-right orientation and a ratio of 1:10, so that the conductivity in left-right direction was amounted to 0.65 S/m and to 0.065 S/m perpendicular and orthogonal to this direction. A total of 4104 single dipoles were placed around the white matter in anterior-posterior (AP), left-right (LR) and inferior-superior (IS) direction. The electrical potential was simulated using 100 electrodes placed on the top of the rabbit head. The forward simulation as well as the inverse solution was solved by using the Inverse Toolbox of the Simbio Project [2] including a very fast FEM solver [3,4]. The data derived by the forward simulation using model 1 and 2 were compared by calculating MAG and RDM maps for the electrical potential and magnetic field of every single dipole. To investigate the influence of anisotropy on source localization we applied the simulated data derived by using model 2 as reference data and performed source localization of a focal dipole using model 1.

Results

The relative difference measure (RDM) between the potentials with and without taking into account anisotropic structure was less than 0.01. The values of the magnitude changes (MAG) ranged from 0.94 to 1.04. The reconstructed dipoles using the isotropic model with potentials derived by employing the anisotropic model were compared by means of dipole shift and change of dipole magnitude. These measures were also found to be low compared to the used grid size of 0.6 mm. Despite this weak influence of the anisotropy, we found RDM and dipole shift to be linearly dependent on the distance between dipole and anisotropy, whereas MAG, magnitude and orientation changes seem to be non-linearly correlated to this distance (cf. right figure). Furthermore, the dipoles located below the anisotropic block are more strongly influenced than dipoles located above the block. In a qualitative analysis, which was realized by employing 3D models (cf. middle figure) we found the strongest influence of anisotropy on RDM at the edges of the cube for dipoles with AP and LR orientation, which differs from the result obtained for the IS orientation. The MAG values are most strongly influenced if the dipole is oriented parallel to the surface of the anisotropic cube. We obtained very similar results for the relative magnitude change. Thus, the MAG values of the forward computations predict quite well the results of the dipole magnitude changes in the inverse computations. On the contrary, the correlation between dipole shift and RDM was found to be rather low, indicating that RDM is not well predicting the dipole shifts. One reason for this might be due to the rather small values obtained for the dipole shift. The change in dipole orientation was influenced most strongly for dipoles oriented perpendicular to the surface of the anisotropic cube.







Figures: *left* - Schematic view of the positioning of the artificial anisotropic cube (light gray) employing the segmented rabbit model. Subfigures (d-f) show a zoomed view of the coronal slice in subfigure c demonstrating the positioning and orientation of the dipoles as well as the conductivity tensors in the anisotropic cube used for the forward analysis. *Middle* – Matrix of 3D models to visualize regions of strong influence. The anisotropic cube is shown in transparent blue, and regions of values above the 0.8 percentile for RDM, MAG, dipole shift, magnitude change and orientation change are visualized by red surfaces. *Right* - Analysis of the influence of the distance on RDM, MAG, dipole shift, relative magnitude change and orientation change. The diagrams show the mean value with variance obtained by assuming a Rayleigh distribution (planes above – see left figure 1-3, planes below – see left figure 4-6).

Discussion

The influence of anisotropy on source estimation was found to be complex, even with this simple artificial setup. Nevertheless, we found that all investigated measures (RDM, MAG, shift, magnitude and orientation change) were more strongly influenced the closer the dipoles were placed to the anisotropy. Consequently, we expect a stronger influence on all quantities if the dipoles were located inside the anisotropic tissue. The relation between the orientation of the dipole and the orientation of the anisotropy seems to have little influence on the estimated dipole orientation and magnitude. In other words, the influence of anisotropy seems not to be dependent on the dipole orientation relative to the anisotropy orientation, but only on the dipole orientation relative to the cube as such. For example, the dipole's orientation is more influenced if the dipoles point perpendicular to the cube; in contrast the magnitude change is more influenced for dipoles placed parallel to the anisotropic structure. All these findings will be tested in a study of a human brain model using conductivity tensor eigenvectors derived by Diffusion Tensor Imaging.

References

[1] Güllmar, D. et al. Proc. Intl. Soc. Mag. Reson. Med. 13 (2005, Miami, FL, USA), p. 1304.
[2] Simbio, Information Society Technologies (IST) Programme, Framework V Project IST-1999-10378, http://www.simbio.de
[3] NeuroFEM, Finite Element Software for fast computation of the forward solution in EEG/MEG source localization. http://www.neurofem.com
[4] C.H. Wolters, L. Grasedyck, W. Hackbusch, Inverse problems 2004 Aug; 20(4): 1099-1116.