Optimizing tCS and TMS multi-sensor setups using realistic head models. (English)

Summary: The scope of this thesis was to introduce and analyze a novel simulation pipeline for transcranial current stimulation (tCS), transcranial magnetic stimulation (TMS) or combined tCS and TMS (tCMS) which can be used to predict inter-individually optimized stimulation protocol for patients and their specific disease. Major findings of this thesis include:

1. A guideline for efficient yet accurate volume conductor modeling in tCS, TMS and tCMS was developed and presented. This head model generation pipeline allows to build high realistic, individually shaped, geometry-adapted hexahedral head models in less than one day of working time.

2. By providing analytical forward expressions for the adjoint approach (see [S. Vallaghe et al., “The adjoint method for general EEG and MEG sensor-based lead field equations”, Physics in Medicine and Biology 54, No. 1, 135–147 (2009; doi:10.1088/0031-9155/54/1/009)]) and the partial integration approach (see [P.H. Schimpf et al., “Dipole models for the EEG and MEG”, IEEE Trans. Biomed. Eng. 49, No.5, 409–418 (2002)]), EEG forward computations and tCS simulations were linked in a clear mathematical way. Using this relation, the accuracy and efficiency of commonly-used tetrahedral and hexahedral finite element approaches for brain stimulation techniques were investigated. It was shown that while the accuracy of the most easy to realize approach based on regular hexahedral elements already quite high, it can substantially be improved if a geometry-adaptation of the elements employed in conjunction with an isoparametric FEM approach. While the latter approach does not involve any additional difficulties for the user, it reaches the high accuracies of surface segmentation based tetrahedral FEM, which is considerably more difficult to implement and topologically less flexible in practice.

3. In order to find an optimal solver method for brain stimulation, the accuracy and efficiency of three preconditioner methods were investigated: incomplete Cholesky without fill in (IC(0)) Jacobi and algebraic multigrid (AMG) for the conjugate gradient (CG) method. It was shown that a solver accuracy level of 10^-7 is sufficient to attain realistic numerical solutions with the three preconditioner methods. However, the investigation of the solver clock time revealed that the AMG-CG solver significantly outperforms the Jacobi-CG and IC(0)-CG solvers with regard to computational efficiency.

4. With quantification of the optimized current flow fields in simplified, spherical models and realistically shaped FE head models, a proof of concept that the novel optimization method for tCS, TMS and tCMS is working properly was presented. The optimized current flow field were visually inspected. A quantification revealed that the optimized current flow fields show substantially higher focality and directional agreement with the target vectors in comparison to standard current density vector fields. Finally, an in-depth mathematical analysis of the optimization method was provided. While the numerical and modeling errors are thus clearly under control, the influence of inter-individually varying conductivity profiles on optimal electrode configurations was investigated for an auditory cortex stimulation. The probability density functions of the optimized stimulation protocols at the main electrodes were shown to be most sensitive to the uncertainty in the skull conductivity.

In conclusion, a proof of concept that the simulation pipeline for tCS/TMS and tCMS is working properly is presented and that the calculation of individually optimized stimulation is not only feasible for single patients but also for a larger number of patients in clinical trial studies.
MSC:

92-02 Research exposition (monographs, survey articles) pertaining to biology
92C55 Biomedical imaging and signal processing
92C50 Medical applications (general)
94A08 Image processing (compression, reconstruction, etc.) in information and communication theory

Keywords:

simulation pipeline; transcranial current stimulation; transcranial magnetic stimulation; incomplete Cholesky preconditioner methods; Jacobi and algebraic multigrid preconditioner methods