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Influence of interior cerebrospinal fluid compartments on EEG source analysis

B. Lanfer[1,2], I. Paul-Jordanov[2], M. Scherg[2], C. H. Wolters[1]
[1]Institute for Biomagnetism and Biosignalanalysis, Westfälische Wilhelms-Universität Münster, Germany, benjamin.lanfer@uni-muenster.de
[2]BESA GmbH, Gräfelfing, Germany

Abstract

It is known that incorporating cerebrospinal fluid (CSF) into realistic volume conductor models adds precision for source analysis. However, modeling interior CSF compartments like ventricles or deep sulci creates a complex source space with many deep cavities. Such a fragmented source space can cause problems for dipole fitting and other inverse methods. A solution could be to use a simplified head model, where only the superficial CSF layer between the brain surface and the inner skull boundary is included, while interior CSF compartments are ignored. The present paper aims at investigating if simplified CSF models are sufficiently accurate for forward and inverse solutions.

A simulation study using realistic volume conductor models was performed. First, a detailed and anatomically plausible reference model was created. Then, two test models were derived. Test model A ignored CSF completely, while test model B only ignored CSF in deep sulci and the ventricles. Forward computation errors were assessed by directly comparing the potentials computed in the reference and test models. Inverse errors were investigated by performing source reconstruction of single sources in the test models to reconstruct the potentials simulated in the reference model.

Large topography (relative difference measure (RDM) > 0.1) and localization errors (> 4mm) were found for superficial sources and sources close to internal CSF compartments for model A. In model B, RDM errors > 0.1 were found for only few sources close to the ventricles and close to sulci of larger extent. Localization errors in model B were below 2 mm for nearly all reference sources.

The results suggest that ignoring CSF when creating a head model leads to substantial localization errors. Ignoring only internal CSF-filled compartments, while modeling superficial CSF layers allows source localization with relatively high precision. Thus, avoiding a fragmented source space by not modeling internal CSF compartments is acceptable.

1 Introduction

Advanced numerical methods, for example, the boundary element method (BEM) [1], [2], the finite difference method (FDM) [3] and the finite element method (FEM) [2], [4–6], allow solving the EEG forward problem in individual, realistic volume conductor models. Using these realistic models strongly benefits EEG source analysis (see, e.g., [7]).

In practice, a minimum of three tissues (scalp, skull and brain) are differentiated when realistically modeling the head. Additionally incorporating the CSF adds further precision for EEG source analysis (see, e.g., [5]). CSF occurs, for example, in the ventricular system, which is lying deep inside the head. Further CSF filled spaces can be found between the brain surface and the inner skull, as well as in the sulci.

As in source analysis sources are only allowed to be located in the brain, but not inside the CSF, incorporating interior CSF compartments (e.g., the ventricular system) into the volume conductor has an impact on the space of allowed source positions. A source space for the volume conductor model incorporating inner CSF compartments has large holes and a much more complex geometry as compared to the source space for a simpler three compartment model.

A fragmented source space can cause problems for inverse methods. In the dipole fit approach, for example, the non-linear optimization of the dipole position might get "stuck" due to holes and concavities in the source space, and the globally best fitting source position might not be found. In addition, for a complex source space boundary effects for inverse methods incorporating spatial regularization might increase.

These problems can be alleviated by using either a head model, where CSF is ignored completely, or by using a model, where the superficial CSF between the cortex and the inner skull surface is included, but CSF in deep sulci and the ventricular system is ignored. These simplifications will introduce errors in the forward simulation and source reconstruction. Whether the errors of the simplified CSF models are acceptable will be investigated in this computer simulation study.

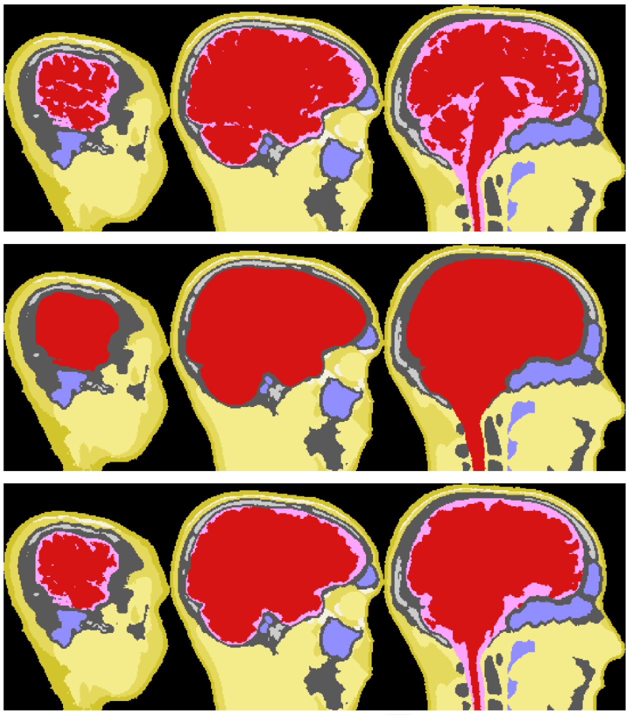
In the present study reference data is simulated in a reference volume conductor model. Potentials computed in test models where CSF is partially or completely ignored are directly compared to the reference data to study the influence on the forward solution. Influences on the solution of the inverse problem are also investigated by reconstructing the reference data while solving the forward solution in the test models with partially or completely ignored CSF.

2 Methods

2.1 Study setup

A reference volume conductor model was constructed from multiple MR images of the same subject. The model is detailed and anatomically plausible and we regard the data simulated herein as our reference data.
Two test models are derived from the reference model. In test model (TM) A CSF is completely ignored. In TM B CSF only in the ventricular system and in deep and narrow sulci is ignored, while the superficial CSF in the space between the gray matter and the inner bone surface is incorporated into the model.
In our simulation study we investigated the influence of neglecting the CSF on the forward solution and on source reconstruction. The influence on the forward solution was assessed by first computing the potentials in the test models for a set of probe sources distributed throughout the brain. These were then directly compared to the reference data. To investigate the influence on the solution of the inverse problem the reference data was reconstructed while solving the associated forward problem in the test models.
Potentials were simulated for 81 electrodes distributed across the surface of the head following the international 10-10-system. Forward simulations were performed for probe sources oriented in x-, y- and z-directions and placed on a regular 4 mm cubic grid covering the entire brain compartment of the reference model. For our investigations on the inverse solution probe sources on a coarser 10 mm grid were regarded. At each source position we placed inverse probe sources with 10 different orientations regularly sampling one hemisphere.
Source reconstruction of the reference data was performed using the robust goal function scan method on a fine 1 mm regular grid.

2.2 Construction of head models



Soft tissue	0.17 S/m	Scalp	0.43 S/m
Compact bone	0.005 S/m	Fat	0.04 S/m
Cancellous bone	0.021 S/m	Muscle	0.11 S/m
Internal air	0.0001 S/m	CSF	1.79 S/m
Brain (GM, WM)	0.33 S/m		

Figure 1 Sagittal slices of reference model (top row), TM A (middle row) and TM B (bottom row).

The reference volume conductor model as shown in Figure 1 (top row) was created from two T1- and a T2-weighted MR image of the same subject. Segmentation of the model into 9 different tissues was done in a semi-automatic way employing - amongst other techniques - simple thresholding, morphological operations, and automatic classification methods.
A geometry-adapted hexahedral finite element (FE) mesh with a resolution of 1x1x1 mm and approximately 3.6 million FE nodes was

then constructed from the labeled image using the software *vgrid [8]*. The conductivity values for the different tissue types (see Figure 1) were taken from [4].

TM A, in which CSF is ignored completely (Figure 1 (middle row)), was derived from the reference model by re-labeling all voxels belonging to CSF as brain. In TM B only those CSF voxels were re-labeled as brain, which were situated in deep and narrow sulci or in the ventricles (Figure 1 (bottom row)). To determine these voxels a brain mask was generated from the voxels marked as brain in the reference model. This brain mask was then dilated by a large radius (15 mm) and holes inside of the mask corresponding to internal CSF spaces were filled. The mask was then eroded again by the same radius as used for the dilation. Finally, all those CSF voxels in TM B were re-labeled as brain that have been marked in the brain mask.

2.4 Error measures

Differences between the reference potentials at the electrodes, ϕ^{ref}, and the potentials computed in the test models, ϕ^{test}, are measured using the *relative difference measure* (RDM) and the *magnitude error* (MAG) [4]. Here , denotes the norm.

$$\mathrm{RDM} = \left\| \frac{\phi^{ref}}{\|\phi^{ref}\|} - \frac{\phi^{test}}{\|\phi^{test}\|} \right\| \qquad \mathrm{MAG} = \frac{\|\phi^{test}\|}{\|\phi^{ref}\|}$$

The optimal value for the RDM is 0 and the optimal value for the MAG is 1.

Source reconstruction errors are measured by measuring the Euclidean distance between the reference source position and the reconstructed source position. Furthermore, we compute vectors pointing from the reference to the reconstructed source positions. By averaging these mislocalization vectors for all sources at the same position but with different orientations we obtain a mislocalization tendency for each reference source position.

3 Results

Maps of the RDM and MAG errors for sources in a sagittal plane are shown in Figure 2 (top and middle row). For superficial sources and sources close to the interior CSF spaces we observe large RDM errors (> 0.1) in TM A. In TM B RDM errors are in general smaller (see also Figure 3) and only fewer sources close to deep sulci and the interior CSF spaces are affected.

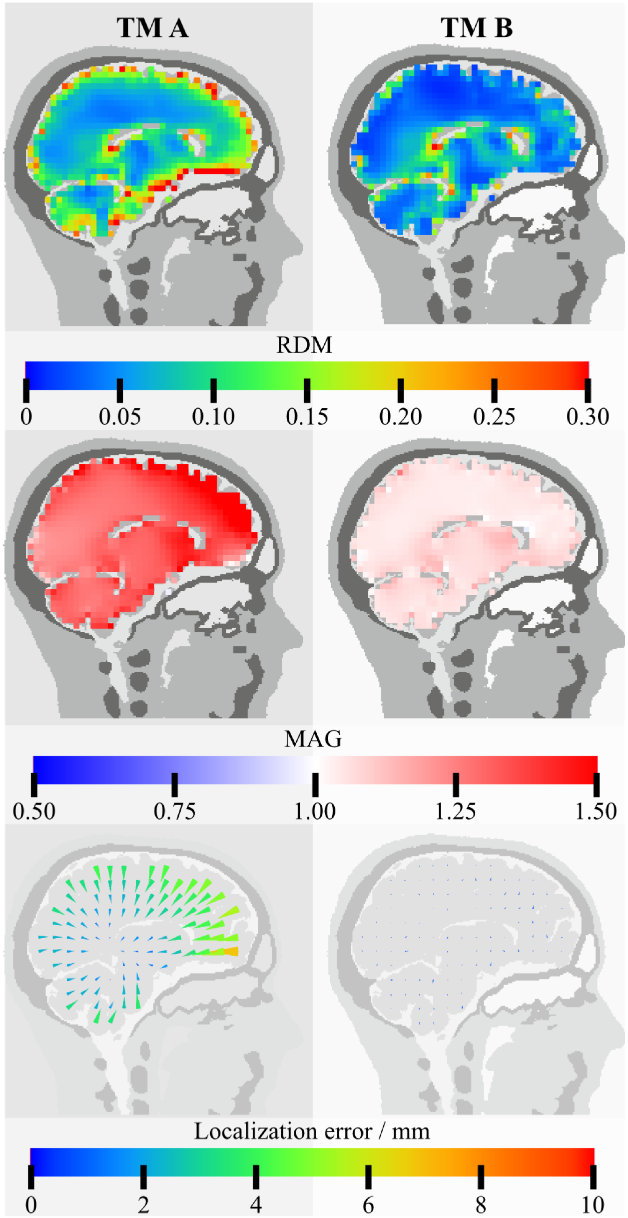


Figure 2 RDM (top) and MAG (middle) error maps, and maps of mislocalization tendencies (bottom) for TM A and TM B.

MAG errors indicate that the potentials in TM A are strongly overestimated for nearly all source positions. This cannot be observed for TM B where MAG errors are mainly close to the optimal MAG value of 1 (Figure 3).

The source reconstruction errors caused by partially or completely ignoring the CSF are presented in Figure 2 (bottom row). The figure

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shows the mislocalization tendencies for TM A and B. For TM A large mislocalization errors (> 4 mm) can be seen especially for frontal sources. Sources tend to be reconstructed at positions deeper in the brain. Observed source reconstruction errors for TM B are negligible for nearly all source positions (< 2 mm) (Figure 3). A clear mislocalization tendency can, thus, not be made out for TM B.

4 Conclusion

In summary, we find large errors for the forward solution and for the source reconstruction when completely ignoring the CSF. Ignoring the internal CSF spaces and CSF in deep sulci caused smaller and more local errors, especially for the source reconstruction, that might be negligible for many applications.

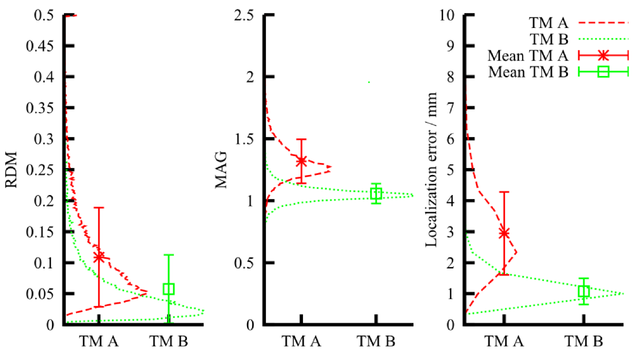

Figure 3 Histograms of RDM, MAG and localization errors.

It should be noted, that we only investigated source reconstruction errors for single source scenarios. Source reconstruction in multiple source scenarios is less stable and errors might be considerably larger.
The influence of completely ignoring CSF on EEG source analysis was also investigated in a previous publication by Ramon et al. [5]. In their work the authors find average localization errors of 2-3 mm depending on the dipole orientation for sources in the area of the motor cortex. In comparison, we find similarly small errors in some regions of the cortex (e.g., the motor cortex or occipital cortices). Yet in other areas, for example, the frontal lobe, larger localization errors of 4 mm and more were observed. This difference might be explained by the amount of CSF in the vicinity of the considered cortex area. In areas close to larger CSF filled spaces errors will be larger, while they will be smaller in areas where there is fewer or no CSF. The errors for TM B observed in this study, especially the negligible single source reconstruction errors, lead to the final conclusion that internal CSF spaces like ventricles or deep sulci can safely be ignored while still allowing a relatively high accuracy for EEG source analysis. Simplified CSF models like TM B can thus be employed to avoid the problems of complex source space geometries.

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