Abstract

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Title

Calculation of electric field distributions induced by TMS: comparison of FEM and spherical models

Introduction

The underlying biophysical and physiological effects of transcranial magnetic stimulation (TMS) are still not completely understood. Up to now, our knowledge about the shape and extent of the induced electromagnetic field distributions stems mainly from calculations assuming simplified (e.g. spherical) geometries of the conductivity profile of the head. However, given the complex gyral folding pattern of the human brain, the important question arises how much the result from these models deviates from the real field distributions. Here, we created a detailed model of the head based on structural magnetic resonance scans and calculated the electric field distributions induced by figure-8 coils using the finite element method (FEM). We then directly compared the results obtained with the detailed model with those predicted by a simplified spherical head model.

Methods

A high-resolution mesh for the FEM calculations was created by extracting 5 tissue layers from several co-registered and averaged T1-weighted MR images (MDEFT and ADNI sequences, 1 mm iso-voxel) of a human head using BrainVoyager QX (Brain Innovation, The Netherlands): white matter (WM), gray matter (GM), cerebrospinal fluid (CSF; including the ventricles), skull and skin (Fig. 1a). The extraction of the CSF-skull boundary and the bone in the lower regions of the head was performed in a semi-automated fashion, i.e., some parts of the borders were reconstructed manually from the structural scans. Careful visual inspection of the resulting surface meshes confirmed that they fitted the anatomy of the head as indicated by the scans. The surfaces were optimized and prepared for volume meshing using ReMESH 2.0 (Attene, 2006) and FreeCAD 0.8 (Riegel and Mayer). A tetrahedral volume mesh was then created from the surfaces using Gmsh 2.4 (Geuzaine and Remacle, 2009) with the sizes of the tetrahedra determined by the surface mesh resolution. The volume mesh contains 3.7 million tetrahedra with a higher resolution at the inner 3 layers (WM, GM, CSF; average volume of 0.63 mm^3 per tetrahedron).

To calculate the field distribution induced by TMS, we implemented the spherical head model described by Sarvas (1987) as well as the FEM described by Wang and Eisenberg (1994) using MATLAB (The Mathworks Inc., Natick, MA), Getfem++ (Y. Renard and J. Pommier) and C++. Two figure-8 coils (Magstim 70 mm coil, MagVenture MC-B70) were modeled using dipoles (see Thielscher and Kammer 2004). For the spherical head model, the induced electric field was directly calculated using the equation given by Sarvas (1987). For the FEM calculations, first the vector potential at each node of the volume mesh was calculated. The vector potential was then used as input to the FEM. For the FEM, several conductivity configurations were assigned to the tissue layers to cover the range of reported values.

Results

Several coil positions covering frontal, motor and parietal cortex areas were simulated. The FEM calculations took about 1.5 hours per coil position on a standard 2.8 GHz PC. We determined the focality of the induced electric fields by measuring the GM area in which the field strength exceeded a given threshold relative to the maximum within GM. Several thresholds ranging from 50% to 90% of the maximum were tested. In order to determine how well the results from the spherical model coincided with those of the FEM, we calculated the overlap (in %) between the thresholded cortex areas given by the spherical and realistic head models.

Our results indicate that the amount of overlap is generally good (on average > 87%). That is, for equal relative thresholds, the location of the covered area calculated with the FEM was mostly inside the area of the sphere model. Importantly, however, for all conductivity configurations tested with the FEM, the focality was higher for the realistic compared to the spherical head model (see Fig. 1b&c for an example). Our simulations show that this resulted mainly from locally increased field strengths at the gyral crowns. This effect is a result of the well conducting CSF bordering the GM at both sides and was described theoretically by Miranda et al. (2003). It is maximal when the locally induced electric field is oriented perpendicularly to the gyrus. As a consequence, for some coil positions, high electric field strengths were observed at gyral crowns being not directly underneath the coil center (see red arrow in Fig. 1b).

Conclusions

Our results show that the sphere model gives a reasonable approximation for the general location of the stimulated cortex area, even though the exact positions of the maxima vary between the spherical and FEM head models. Interestingly, the FEM calculations suggest that the electric field induced by TMS may be more focal than generally assumed. We plan to confirm this observation in future simulation studies using FEM models that take the anisotropy of WM into account, based on diffusion tensor imaging data (De Lucia et al., 2007).

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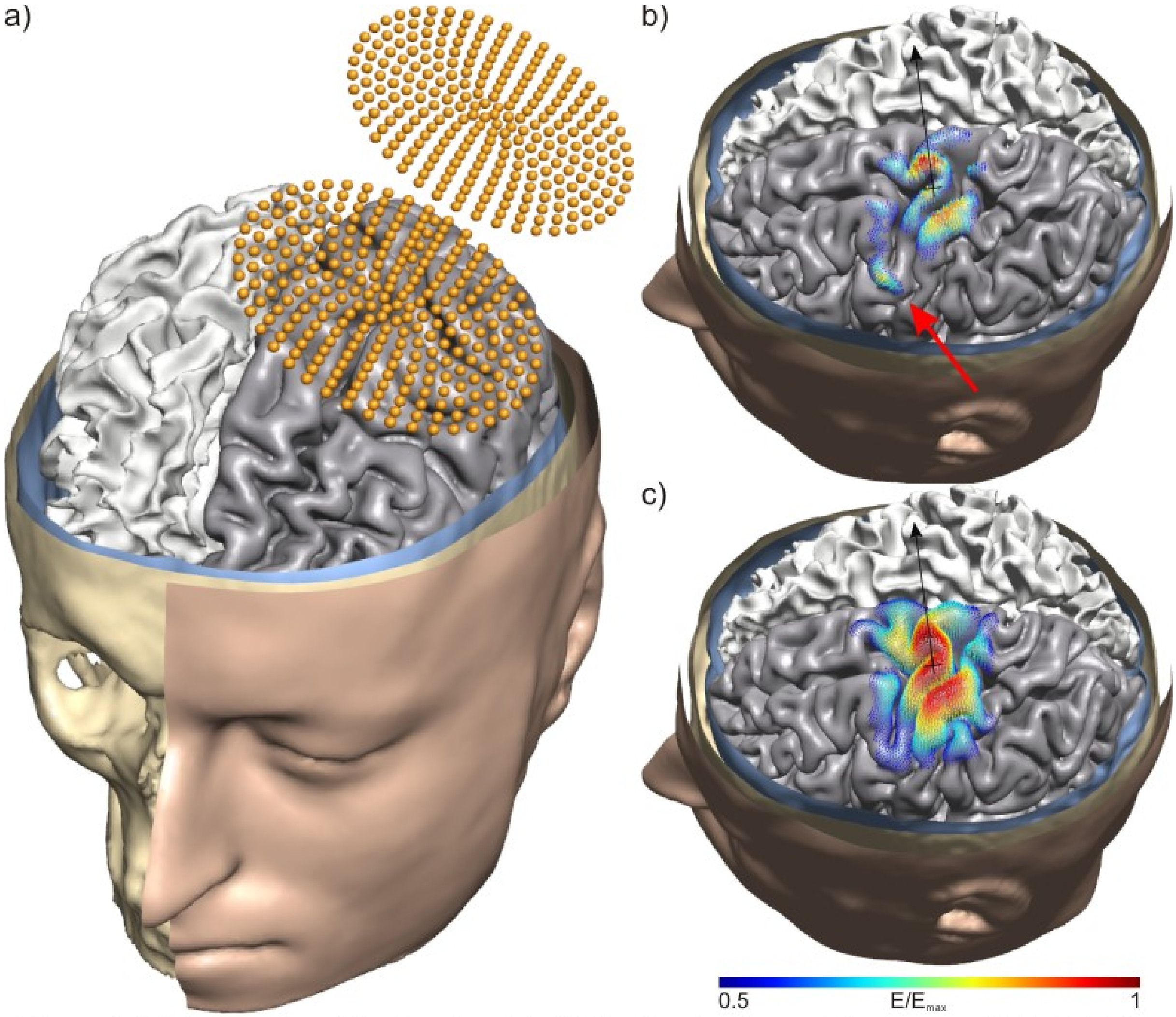

Figure 1 a) Cut-away view of the head model with the 5 surface layers. The orange dots indicate the positions of the dipoles modeling the Magstim figure-8 coil positioned over the left motor cortex. b&c) Electric field distributions calculated with the FEM (b) and the spherical model (c), both thresholded at 50% of their maxima. Coil positions and orientations are marked with black cross and

Caption of Figure 1:

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