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Visualization of the electric field evoked by transcranial electric stimulation during a craniotomy using the finite element method

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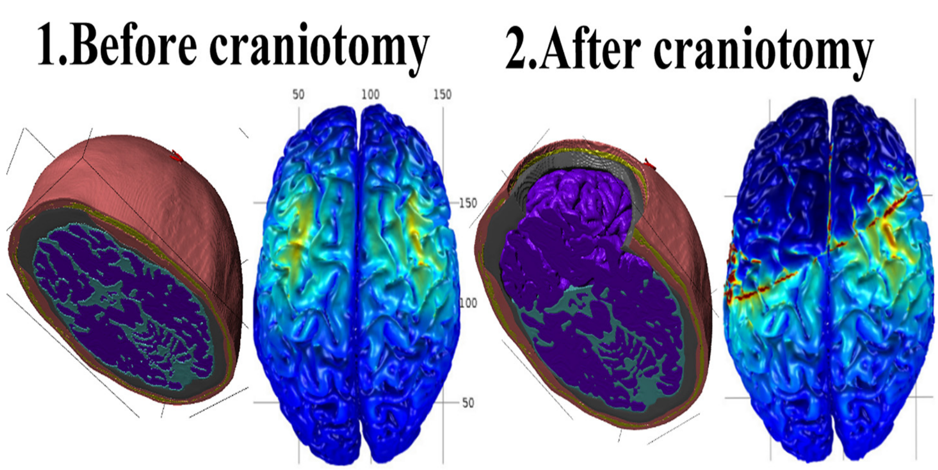
HIGHLIGHTS

- Influences of craniotomy in intra-operative tMEP monitoring were numerically estimated.
- The electric field in the brain radiates out from the cortex just below the electrodes.
- Intensity of the electric field in the brain is most affected by thickness of the CSF layer.
- When the CSF layer is thick, CSF decrease has a major impact in the electric field.
- Bone deletion has larger effect in a case that skull has direct contact with the brain.

GRAPHICAL ABSTRACT



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ABSTRACT

Background: Transcranial MEP (tMEP) monitoring is more readily performed than cortical MEP (cMEP), however, tMEP is considered as less accurate than cMEP. The craniotomy procedure and changes in CSF levels must affect current spread. These changes can impair the accuracy. The aim of this study was to investigate the influence of skull deformation and cerebrospinal fluid (CSF) decrease on tMEP monitoring during frontotemporal craniotomy.

Methods: We used the finite element method to visualize the electric field in the brain, which was generated by transcranial electric stimulation, using realistic 3-dimensional head models developed from T1-weighted images. Surfaces of 5 layers of the head were separated as accurately as possible. We created 3 brain types and 5 craniotomy models.

Results: The electric field in the brain radiates out from the cortex just below the electrodes. When the CSF layer is thick, a decrease in CSF volume and depression of CSF surface level during the craniotomy has a major impact on the electric field. When the CSF layer is thin and the distance between the skull and brain is short, the craniotomy has a larger effect on the electric field than the CSF decrease.

Comparison with existing method: So far no report in the literature the electric field during intraoperative tMEP using a 3-dimensional realistic head model.

Conclusion: Our main finding was that the intensity of the electric field in the brain is most affected by changes in the thickness and volume of the CSF layer.

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1. Introduction

The intraoperative monitoring of motor evoked potentials (MEPs) by transcranial electric stimulation has become popular in neurosurgery for monitoring intracranial aneurysms, tumors, and other intracranial lesions for motor function preservation (Szelényi et al., 2003, 2006, 2010; Zhou and Kelly, 2001). Transcranial MEP (tMEP) monitoring is more readily performed than cortical MEP (cMEP) because tMEP does not require the motor cortex to be exposed. tMEP monitoring is routinely used at our institution during neurosurgery procedures that carry a risk of motor dysfunction, e.g., aneurysm clipping surgery and brain tumor removal. However, some authors have reported that tMEP is less accurate than cMEP, especially in brain tumor surgeries (Lee et al., 2014; Motoyama et al., 2011; Tanaka et al., 2011). Shifts in the tMEP stimulation threshold during craniotomy due to skull deformation and decreases in cerebrospinal fluid (CSF) are well known. In our limited experience, the threshold decreases slightly after the craniotomy if the anesthetic depth and other conditions are equal, but increases following a decrease in CSF during long surgical procedures. Therefore, the craniotomy procedure and changes in CSF levels must affect current spread during transcranial electric stimulation. These changes can impair the accuracy of tMEP monitoring. In addition, there are individual differences in the threshold for eliciting tMEPs. These differences seem to be influenced by the size of the brain, scalp thickness, subcutaneous fat thickness, and the skull thickness. The size of brain is inversely proportional to age. However, the electric field produced by transcranial stimulation and its underlying mechanisms during craniotomy have not been studied previously.

The electric field induced in the brain by transcranial stimulation cannot be studied easily from in vivo or in vitro studies. Therefore, we performed visualization of the electric field in the brain during tMEP monitoring using realistic finite element models generated from standard brain MRI images. Many authors have reported the usefulness of this method for evaluating the electric field in the brain during therapeutic transcranial direct current stimulation (tDCS) (Miranda et al., 2013), and Holdefer et al. have reported a 2-dimensional study of tMEP (Holdefer et al., 2006). However, no one has yet described the electric field during intraoperative tMEP monitoring using a 3-dimensional realistic head model.

The aim of this study was to investigate the influence of skull deformation and cerebrospinal fluid (CSF) decrease on tMEP monitoring during frontotemporal craniotomy that is the most popular procedure in neurosurgery.

2. Methods

2.1. Realistic 3D head model creation

The realistic 3D head models created in this study were developed from International Consortium for Brain Mapping (ICBM) T1-weighted images obtained from *BrainWeb* (http://brainweb.bic.mni.mcgill.ca/). The image processing and segmentation of 1 mm × 1 mm × 1 mm and 2 mm × 2 mm × 2 mm resolution images were performed using ScanIP and $^{+}$ScanFE (version 6.0, ©Simpleware Ltd, Exeter, United Kingdom). The brain, CSF, skull, subcutaneous fat, and skin layer all were obtained from the T1-weighted images.

We had planned to use a "whole-brain model" that included the entire brain as well as levels of the foramen magnum using 1 mm × 1 mm × 1 mm resolution images throughout the study, but our computer memory (32 GB RAM) was insufficient to perform the finite element method calculation. Therefore, we developed the "supratentorial model", which included the telencephalon,

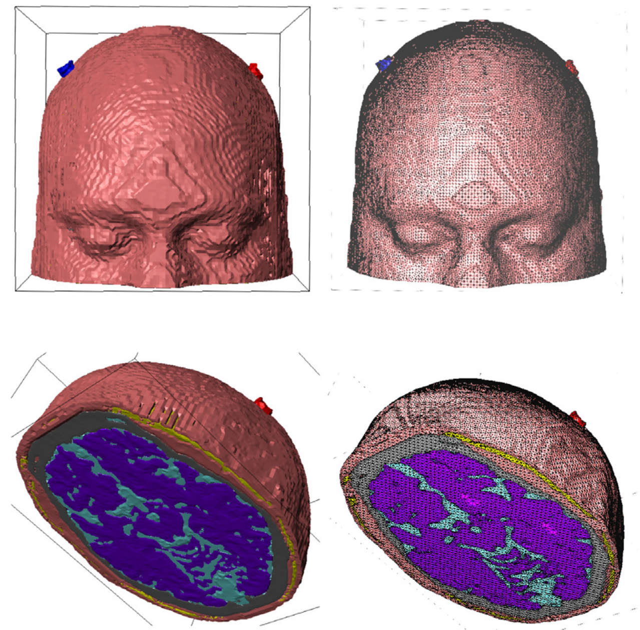

Fig. 1. The "whole-brain model" (top row) and "supratentorial model" (bottom row) in 2 mm × 2 mm × 2 mm resolution images. The 3D model (left) and created mesh (right) of each model are shown.

at a 1 mm × 1 mm × 1 mm resolution to downsize the elements of the models. The "supratentorial model" was created from the "whole-brain model" using the crop tool in ScanIP to truncate the head at the level of the nasion. However, head truncation seemed to artificially increase the electric field in the brain; therefore, we modeled both a "whole-brain model" and a "supratentorial model" using 2 mm × 2 mm × 2 mm resolution images. These two 2 mm × 2 mm × 2 mm resolution models were created to prove that the effect of the truncation level in the "supratentorial model" was negligible (Fig. 1). This "whole-brain model" 2 mm × 2 mm × 2 mm resolution also was used to estimate the electric field around the foramen magnum. These finite element (FE) models meshed into more than 2.5×10^6 tetrahedral elements (i.e., more than 2.5×10^6 degrees of freedom) for the 2 mm × 2 mm × 2 mm resolution supratentorial brain models, 5.9×10^6 tetrahedral elements for the 2 mm × 2 mm × 2 mm resolution whole-brain models, and 1.5×10^7 tetrahedral elements for the 1 mm × 1 mm × 1 mm resolution supratentorial brain models.

Next we created 4 models of craniotomy from the "supratentorial model" 1 mm × 1 mm × 1 mm and 2 mm × 2 mm × 2 mm resolution images: "skin-flap deleted model", "craniotomy model", and two "CSF-decreased models" using the 3D processing tool in Scan IP (Fig. 2). We simulated a frontotemporal craniotomy with a large question-mark skin incision because this procedure is the most popular and commonly used craniotomy procedure in brain surgery. The "skin-flap deleted model" was created based on the "supratentorial model" by removing a skin-flap over the area of the frontotemporal craniotomy. The bone then was removed to create the "craniotomy model." The "CSF-decreased model 2" was designed with the motor cortex emerging from the surface of the CSF layer. In contrast, the motor cortex remained under the CSF layer and only an anterior part of the frontal lobe emerged from the CSF in the "CSF-decreased model 1". These CSF-decreased models were created from the "craniotomy model" by removing part of the CSF layer.

Three brain types were created to estimate the effect of brain size in each craniotomy model. The "normal brain type" was obtained from the *ICBM* T1-weighted images using the