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The Computational Study of Subdural Cortical Stimulation: A Quantitative Analysis of Voltage and Current Stimulation

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Abstract— **We investigated the effect of electrode type and stimulation condition (voltage stimulation and current stimulation) in bi-polar subdural cortical stimulation (SCS). For this study, we developed a 3D realistic head model using MRI data with 1 mm^3 spatial resolution and simulated the model using the finite element method (FEM). For each study, we used three types of electrodes — disc, ring, and covered-disc — and three efficiency measures — effective depth of penetration, effective volume, and amount of CSF leakage current — to compare the effectiveness of the stimulation between two stimulation conditions. With voltage stimulation, there was no difference in effectiveness between the disc and ring electrodes. However, the amount of CSF leakage current for the covered-disc type was lower than that for the others. The effective depth of penetration and volume for the ring and disc type electrodes were higher than those for the covered-disc type. The current stimulation using the covered-disc electrode penetrated deeper than the other types of electrodes, and the CSF leakage current was still low. The result for voltage and current stimulation was quite different, as the substrate design manipulated the impedance and output current. In the current simulation, if the electrode was covered with the substrate, more current flowed to the cortex. On the other hand, with voltage stimulation, this substrate design makes the impedance between electrodes high, and the total current is reduced.**

I. Introduction

Electrical neuromodulation of the brain has been widely used to treat the neurological disorders including Parkinsonism, dystonia, intractable central pain, and depression, etc. Several modalities of stimulation have been developed to deliver the electrical current on the brain noninvasively and invasively. Unlike deep brain stimulation which has been extensively studied, cortical stimulation method have been recently gaining attention for its role of brain function investigation and potential therapeutic trial for neurological disorders which do not respond to conservative management. Among the cortical stimulation methods, tDCS, TMS, and HD-tDCS have been extensively investigated using computational models, however, there is a paucity of reports which studied the subdural cortical stimulation with implanted electrodes probably due to difficulty in model generation. In our recent work [1], we created a three-dimensional partial brain model following the work of Wongsarnpigoon *et al.* [2] and compared the effectiveness of epidural cortical stimulation (ECS) and SCS on the motor cortex. However, our study was not satisfactory to delineate the effect of cortical stimulation due to limitation of model. In this study, we investigated the effect of stimulations with various electrode types and stimulation conditions (voltage stimulation and current stimulation) using a realistic head model from MRI. Three efficiency measures were computed in order to quantify the effect of the stimulations: effective depth, effective volume, and the CSF leakage current. To handle more clinical situations, we attached electrodes around the hand area in the precentral motor cortex where the electrical current is injected.

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II. Methods

A. Modeling SCS

MRI data were segmented using Freesurfer and FSL to obtain a 3D computational, realistic human brain model [3, 4, 5]; Freesurfer was used for cortical segmentation and FSL was used for the skull and scalp layers. In addition, we used morphological image processing to remove the intersection between each layer and attached electrodes on the gray matter layer using our MATLAB (MathWorks, MA) script. Our model consists of white matter, gray matter, cerebrospinal fluid, skull, scalp, and electrodes with substrate (Figure 1). The number of tetrahedral elements was about 4.3 million and the electrical conductivity of the tissue was assigned the following isotropic values: white matter, 0.126; gray matter, 0.276; cerebrospinal fluid, 1.65; skull, 0.01; scalp, 0.465; electrode, 9.4×10^6; substrate, 0.1×10^{-9} (unit : S/m) [1, 6].

B. Electrode configurations

In this study, we used three types of electrodes: disc, ring, and covered-disc. The dimensions of the electrodes and substrate as well as the shape of the electrode are displayed in Figure 2. The disc and ring electrodes are the shapes generally used in many studies [2, 7]. However, an grid electrode with many contacts are commonly used in the clinical situation, and these electrode contacts are insulated with silicone membrane except bottom side which face the brain. Therefore, we suggest a new type of electrode, “covered-disc”, to consider more realistic configuration. This electrode has the most current flow through gray matter, thus, it is a more practical electrode configuration than a disc or ring type.

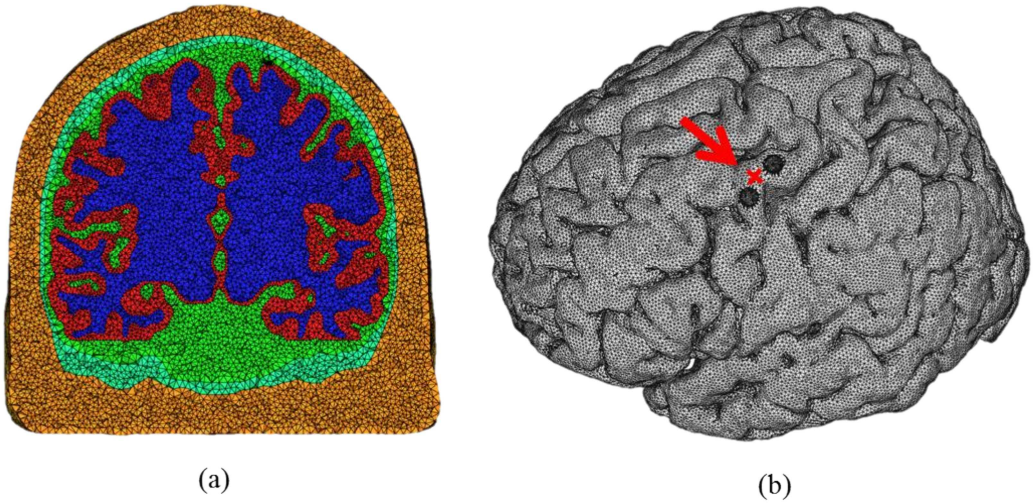

Figure 1. The cross-section of brain model (a), and electrode position on gray matter (b). The red cross is target area that is defined as hand area in the motor cortex.

C. Threshold determination

To quantify the effect of current distribution among various stimulations, we need to set a current density threshold for the motor cortex. The current density threshold of the motor cortex is the minimum current density needed to evoke excitation of a nerve in the motor cortex due to passive stimulation. Based on the literature, the effective current density threshold of the motor cortex was considered to be $2.5 A/m^2$ at frequency 50Hz [8]. However, there is a risk of provoking seizures in response to a surgical procedure or from superthreshold stimulation [9]. Therefore, instead of using 100% of the current density threshold of the motor cortex, we used 50% of the current density threshold ($1.25 A/m^2$).

D. Efficiency measures

We defined two efficiency measures — effective depth of penetration and effective volume — in a previous study [1]. The effective depth of penetration is the diameter of the region having current density above the threshold. This diameter is measured from the electrode along the line perpendicular to the electrode surface. Effective volume is the volume of the region with current density exceeding the threshold. In this study, we define one more efficiency measure: CSF leakage current, which is the amount of current that flows out to cerebrospinal fluid. CSF leakage current can be computed by the following equation:

$$\iiint_{\Omega} J_{norm} dV, \qquad (1)$$

where Ω is the cerebrospinal fluid domain and J_{norm} is the magnitude of the current density. CSF leakage current depends on the total cerebrospinal fluid volume of the model and the total cerebrospinal fluid volume of our models are fixed, so we used this measure to compare among our models. If CSF leakage current is high, much of the current flows to cerebrospinal fluid but not the cortex, which is not efficient. Therefore, cerebrospinal fluid leakage current should be reduced in order to have an effective stimulation.

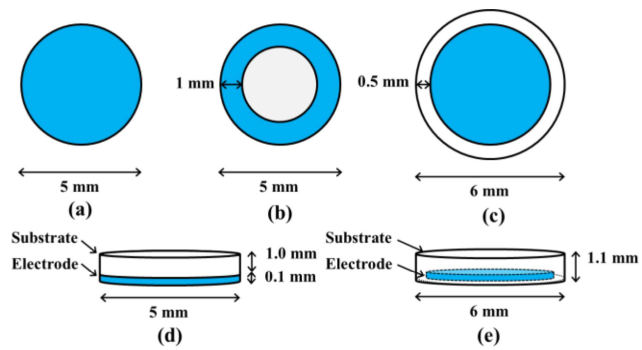

Figure 2. Three types of electrodes such as (a) disc, (b) ring, and (c) covered-disc. The blue one is electrode and white is substrate. (d) is the geometry of disc and ring electrode with substrate. (e) is the geometry of covered-disc electrode with substrate and electrode is covered with substrate without the bottom side of electrode.

III. Experiments and Results

A. Numerical simulations

We considered three types of electrodes and two types of stimulation. FEM analysis was implemented in COMSOL Multiphysics (Version 4.2a; Burligton, MA). The biconjugate gradient stabilized method along with incomplete Cholesky preconditioning was used to solve the FEM model.

B. Voltage stimulations using three types of electrodes

In the voltage simulation, we compared the effect of stimulations for three types of electrodes across various input voltages (0.5, 1, 1.5, 2V) by computing efficiency measures. CSF leakage current was proportional to the input voltage. The results from the disc and ring electrodes were comparable, with a little more current from the ring electrode leaked to cerebrospinal fluid than that from the disc electrode (Figure 3). However, the covered-disc electrode had a relatively lower CSF leakage current than the others, which means that the covered-disc has lower current flowing to cerebrospinal fluid and is more efficient than the others. When we used another efficiency measure, effective volume, the result seemed to differ. Similar to CSF leakage current, the effective volume was almost the same for the disc and ring electrodes, but the covered-disc electrode had a lower effective volume than the others, up to a maximum of 4.5 times lower (Figure 4). We observed similar behavior for the effective depth of penetration. As shown in Figure 5, the disc and ring electrodes had almost the same level in the effective depth of penetration, but the effective depth for the covered-disc electrode was lower, up to a maximum of two times lower. Therefore, the current from the disc and ring electrodes more deeply penetrated as compared with the covered-disc electrode. However, we found that the disc and ring electrodes consumed more needless current as compared with the covered-disc electrode.

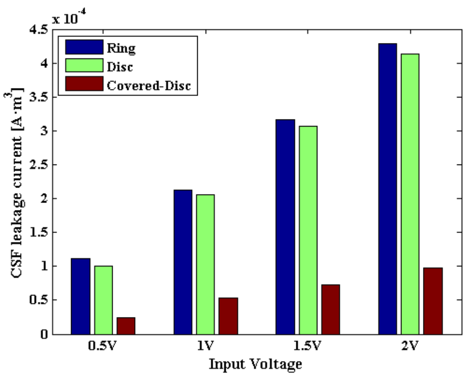

Figure 3. The CSF leakage current in the voltage stimulation

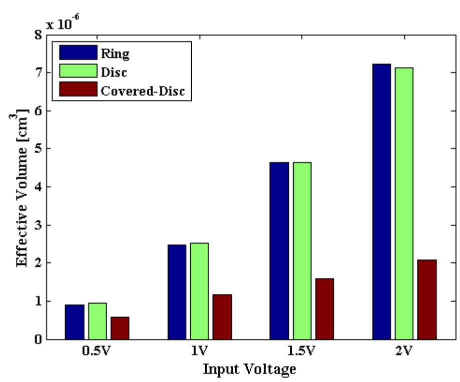

Figure 4. The effective volume of motor cortex (white matter+gray matter) in the voltage stimulation

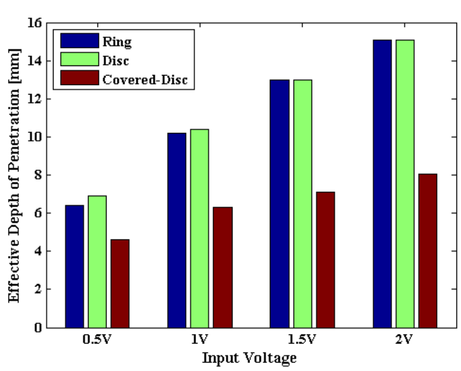

Figure 5. The effective depth representing extent of current penetration in the voltage stimulation

C. Current stimulations using three types of electrodes

In the current stimulation, we compared three types of electrodes across various input currents (1, 2, 3, 4, 5mA) using efficiency measures. The CSF leakage current of the covered-disc model was less than that found with the other electrodes (Figure 6). However, in examining effective volume, the covered-disc electrode took more area to stimulate, with a maximum of 182% for the 1mA stimulation (Figure 7). In regards to the effective depth of penetration, the current for the covered-disc model penetrated deeper as compared with the other cases, with a maximum of 162% for the 1mA stimulation (Figure 8). The amount of current was fixed in this stimulation, so the other measures (effective volume and effective depth of penetration) should be high when the CSF leakage current is low. In addition, the covered-disc model covered the surface of the electrode without the bottom side, which has contact with the gray matter. Therefore, we can get much higher current penetration effects from the covered-disc electrode than other electrodes types.

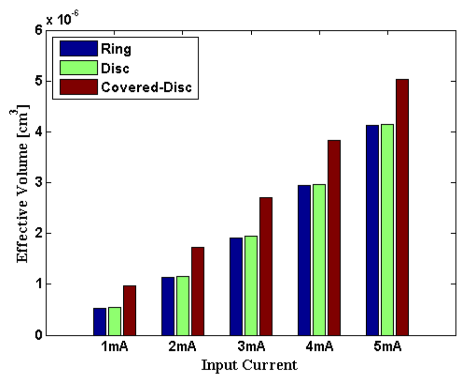

Figure 7. The effective volume of motor cortex (white matter+gray matter) in the current stimulation

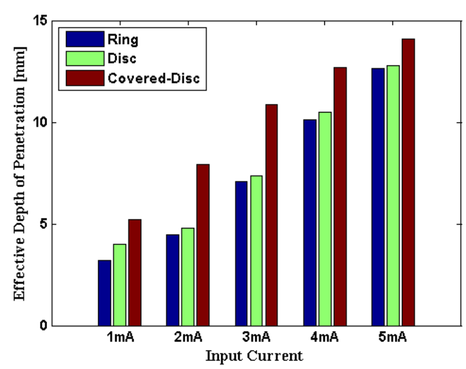

Figure 8. The effective depth representing extent of current penetration in the current stimulation

IV. CONCLUSION

To observe current distribution behavior for voltage and current stimulations in SCS, we conducted numerical simulations using three types of electrodes — disc, ring, and covered-disc — and a realistic brain model. We found that covered-disc is the more realistic simulation. Because the thickness of the electrode was quite thin, the difference among

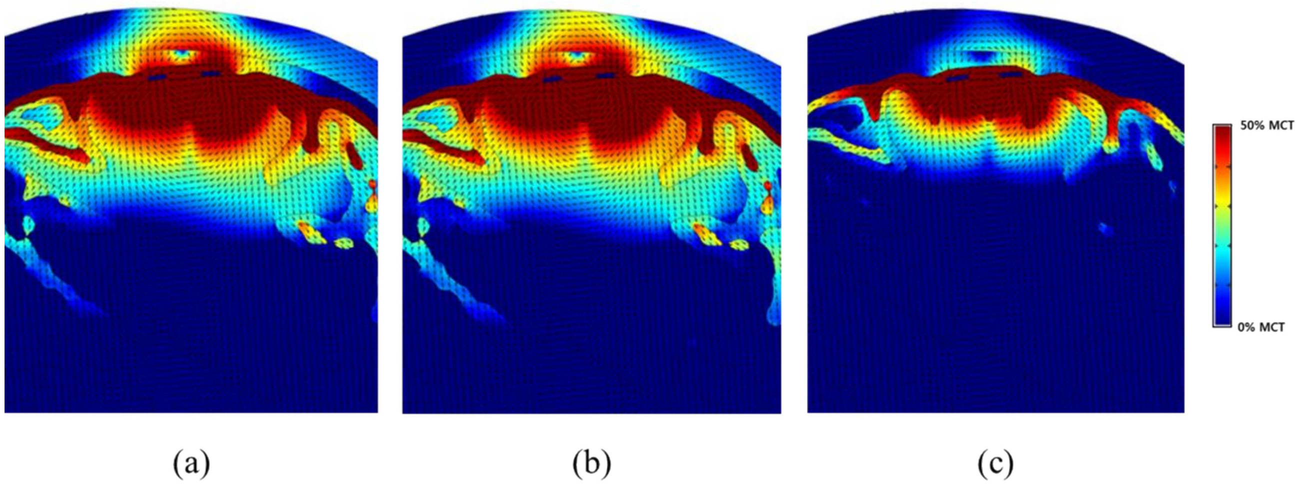

Figure 9. The cross-section of current density distribution around electrodes on voltage stimulation using disc (a), ring (b), and covered-disc (c) at 1V stimulation amplitude.

electrodes seemed to be small, but the current distribution by stimulation was quite different. In the voltage stimulations, the leaking amount of current to cerebrospinal fluid from the covered-disc electrode was low, and the effective volume and penetration were also low. In the current stimulations, the current from the covered-disc approached a deeper region and took more area to stimulate. However, CSF leakage current with the covered-disc electrode was still lower than that found with the other electrodes. Because the electric conductivity of cerebrospinal fluid is considerably higher than that of gray matter, a lot of current flow out to cerebrospinal fluid when electrodes are exposed to cerebrospinal fluid. Therefore, constant current stimulation and covering of electrode, such as a covered-disc electrode, can play a major role in flowing current to the cortex as well as reducing leakage to CSF. In the voltage stimulation, the current from exposed electrodes to cerebrospinal fluid, such as in disc and ring electrodes, penetrated deeper as compared with the current from an unexposed electrode. The impedance between exposed electrodes is lower than that of an unexposed electrode due to the high conductance of cerebrospinal fluid. This means that the output current of an exposed electrode is higher than that of an unexposed electrode, and the exposed electrode seems to be more effective as compared with an unexposed design. The substrate design is also important in SCS stimulation, as in voltage stimulation, the shape of the substrate significantly affected the result; the substrate manipulates the amount of output current and effect of stimulation. On the contrary, although substrate design was not a strong influence in the current stimulation, it should be taken into account in cortical stimulation. In any cases, both electrode type and substrate design are carefully considered in SCS.

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