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Computational Study of Subdural and Epidural Cortical Stimulation of the Motor Cortex

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Abstract—**Cortical stimulation (CS) has gained wide attention for its use in augmenting neurological recovery in various conditions. Noninvasive cortical stimulations using transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS) are less invasive when delivering the electrical current to the patient's brain, but have several limitations. Direct cortical stimulation (DCS) using an implantable stimulation system consisting of epidurally or subdurally placed electrodes and pulse generators, provides cortical stimulation and concurrent rehabilitative training in a stable fashion without limiting a patient's activities. The effectiveness of these two types of DCS - epidural cortical stimulation (ECS) and subdural cortical stimulation (SCS) - has not been compared. In this work, a computer simulation study was conducted to predict the current density distributions (CDD) through cortical stimulations using subdurally or epidurally placed electrodes. The simulation study is based on the human motor cortex model with a three-dimensional finite element model (FEM). The change in CDD depending on the shape of the electrode (disc or ring) is discussed. The output current induced by SCS was about four times larger than that of ECS when voltage stimulations with the same magnitude were regulated. Thus, SCS showed substantially better penetration of the current into gray or white matter. Further, the ring electrode performed comparably or slightly inferior to the disc electrode in both cortical stimulations.**

I. INTRODUCTION

Cortical stimulation is an emerging therapy that augments neurological recovery and aids rehabilitative training. Typically, there are two categories of cortical stimulation: invasive and non-invasive. Non-invasive cortical stimulation, such as transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS), have inspired neuroscientists to predict the potential applications of cortical stimulation to improve neurological conditions. Further, they are less invasive in delivering the electrical current to the patient's brain, as the electrical current is passed through intact skin and skull to the cortex without invasive surgery. However, these noninvasive cortical stimulation methods are known to have some limitations, including short-lasting effects of stimulation and uneasiness of concurrent rehabilitative training. Therefore, invasive cortical stimulation systems consisting of epidurally or subdurally placed electrodes and implantable pulse generators provide cortical stimulation as well as concurrent rehabilitative training in a stable fashion.

The main difference between epidural cortical stimulation (ECS) and subdural cortical stimulation (SCS) is that electrodes are placed epidurally (right above the dura mater) or subdurally (right beneath the dura mater). Compared to SCS, ECS is less invasive and safer in induced seizures [1]. However, SCS has more focality and less loss of current, yielding more efficiency. ECS is strongly influenced by the thickness or conductivity of dura mater [2]. To date, there has not been a study based on comparing ECS and SCS. Thus, we developed 3D computational models for the use of ECS and SCS on the precentral gyrus. For each model, two types of electrode, a disc and a ring type electrode, were used. Through the finite element method (FEM), these models were computed and the current density distributions (CDD) by electrode type were presented to compare ECS and SCS. We remark that Datta *et al* [3] reported the tDCS computational study using FEM on the whole brain for various electrode configurations.

II. METHODS

A. *Modeling ECS and SCS*

To compare ECS and SCS, we developed 3D computational models representing the precentral gyrus (Figure 1). Our models consist of white matter, gray matter, cerebrospinal fluid (CSF), dura mater, and skull, and also have a stimulation electrode(s) including substrate (Figure 2). The scalp is not included in our models because it has no substantial influence on the current density distribution of ECS and SCS. The conductivity and model dimension are determined from the literature, as shown in Table 1 and Table 2. In our study, each electrode(s) is placed above the precentral gyrus in the motor cortex. In the ECS model, the electrode(s) is placed between the dura mater and skull, while the electrode(s) is placed right beneath the dura mater in the SCS model (Figure 1). Two types of electrodes (disc or ring, Figure 2) are considered in this work.

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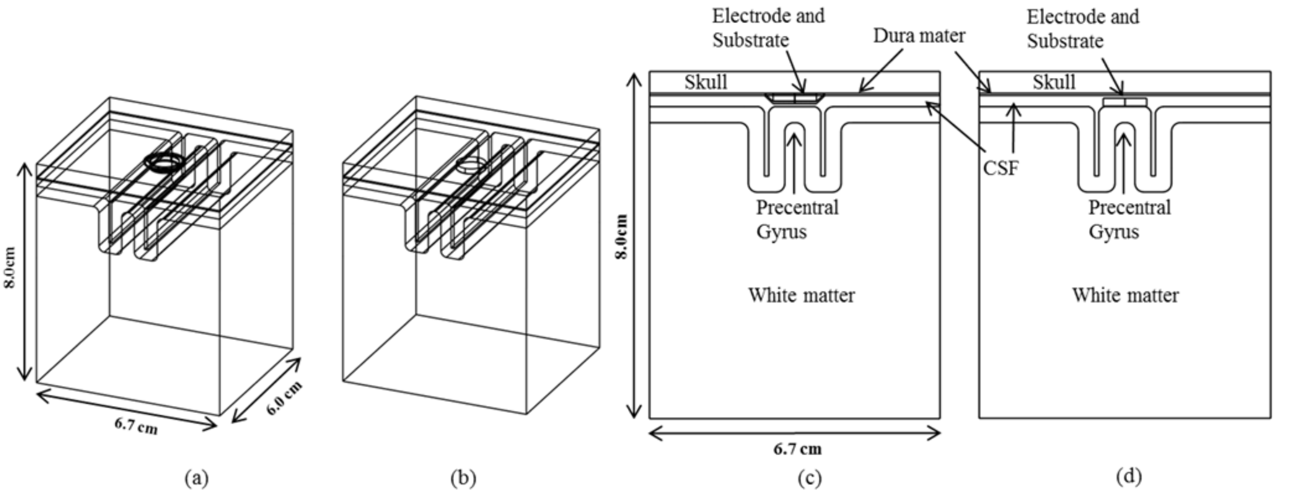

anatomical structure. 3D views of the models of ECS (a) and SCS (b). The cross-section was extruded to generate the 3D model. In the close-up of the cross section of the models of ECS (c) and SCS (d), each electrode and substrate were located between the dura mater and skull and at the center of the precentral gyrus.

B. Computation of simulation

In general, cortical stimulation involves injecting some amount of electrical current or voltage through electrode(s) into the head or brain. In physics, Maxwell's equation can explain such electrical behavior within the head or brain and we can get the following Laplace equation defined in the model Ω:

$$\nabla \cdot (\sigma \nabla V) = 0 \text{ in } \Omega \tag{1}$$

We assume that the electric flux through skull is negligibly small, so the Neumann boundary condition is applied at the upper boundary on skull:

$$n \cdot J = 0 \text{ on } \partial\Omega_{\text{upper}}, \tag{2}$$

where n is the normal vector to the boundary. The Dirichlet boundary condition applied at the remaining outer boundaries in the model and the upper boundary on electrode (s) surface ψ:

$$V = 0 \text{ on } \partial\Omega_{\text{other}}, \tag{3}$$

$$V = V_0 \text{ on } \partial\psi_{\text{upper}}, \tag{4}$$

where V_0 is considered as an input value. In order to solve this elliptic boundary value problem, the finite element method was introduced. For this, a fine mesh is necessary for computing FEM. We generated meshes (about 500,000 tetrahedron elements) in an adaptive way so that the mesh is coarse around simple structures while a finer mesh is used around complicated structures.

C. Estimation of total output current

In the precentral gyrus model, we considered voltage stimulation, so regulated voltage can be a source of current, as described in (1-4). However, we are interested in investigating the current distribution over the model when some amount of voltage is injected through the electrode(s).

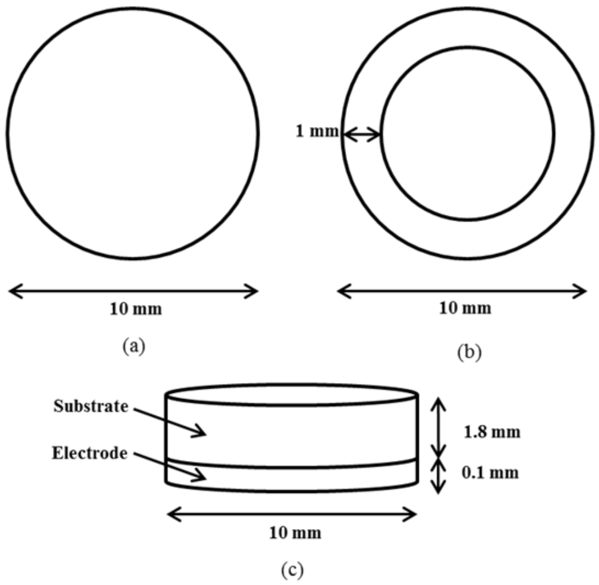

Figure 2. Two types of electrodes such as disc type (a) and ring type (b), and geometry of electrode with substrate (c).

$$\begin{aligned} 0 &= \int_{\Omega} \nabla \cdot (\sigma \nabla V) d\mathbf{r} = \int_{\partial\Omega} (\sigma \nabla V) \cdot n\, dS \\ &= \int_{\partial\Omega_{Upper}} (\sigma \nabla V) \cdot n\, dS + \int_{\partial\Omega_{Other}} (\sigma \nabla V) \cdot n\, dS - \int_{\partial\Psi_{Upper}} (\sigma \nabla V) \cdot n\, dS \end{aligned}$$

Here, n is outward normal vector on the boundary. Because the electrode surface normal vector, n, is directed inward, the third term on the right side changes in sign. After the boundary conditions (2-4) are considered, we get the following:

$$I_{\text{output}} := \int_{\partial\Psi_{Upper}} \sigma \frac{dV}{dn} dS = \int_{\partial\Omega_{Other}} \sigma \frac{dV}{dn} dS. \tag{5}$$

Total output current I_{output} is a current induced by voltage input on the electrode(s) and is formulated in (5).

In this work, we have an interest in the current flowing down the electrode(s). Even if there is a small current flowing above the electrode(s), it may be negligible since there is a significantly low conductivity of the substrate on the electrode(s), and thus it is not of interest in the current study. Therefore, we roughly estimated the total output current as the sum of all currents flowing out of the boundary of the model below the electrode(s). By such reasoning, the total output current in ECS is the sum of currents flowing through the boundaries of the dura mater, CSF, gray matter, and white matter. Further, the total output current in SCS is the sum of currents flowing out of the boundaries of CSF, gray matter, and white matter. The dura mater is not considered here because the electrodes in SCS are located below the dura mater.

D. *Determine a threshold*

We wanted to quantify the current density distribution by estimating effective depth and effective volume in the model. The effective current density threshold is the minimum current density needed to evoke excitation of a nerve in the motor cortex due to passive stimulation. Based on the literature [4], the effective current density threshold was considered to be 2.5A/m^2.

III. EXPERIMENTS AND RESULTS

A. *Configuration of the simulations*

Numerical experiments were conducted on a PC (Intel i7 Quadcore CPU at 2.8 GHZ, 64 bit OS and 16 GB RAM). Two types of electrodes were simulated in both ECS and SCS in order to compare them. Due to a slight geometrical difference between the models, the total number of elements in the models differs, but this difference does not affect the comparison analysis of these models.

The model was implemented in COMSOL Multiphysics (Version 4.1a; Burlington, MA), and the biconjugate gradient stabilized method along with incomplete Cholesky preconditioning was used to solve FEM model. About 2 minutes on a PC was taken per model computation.

B. *The effective volume*

In our simulations, we explored the extent of current density distribution for each CS over various input voltages (1 V, 1.5 V, 2 V, 2.5 V, 3 V). We remark that high input voltages like 3 V are not realistic, but we used them to observe the extent of current density distribution. To quantify this extent, we defined an effective volume as a volume of the region having current density over the effective threshold (2.5 A/m^2). To compare ECS and SCS, effective volumes were estimated for the brain cortex consisting of gray matter and white matter. Figure 3 and Figure 4 show that SCS has effective volumes that are about 6 times larger on average than those of ECS. We found (not shown here) that the difference between effective volumes in the gray and white matter increases as the injection current increases. Evidently, SCS penetrated deeper into the brain than ECS on regulated voltage stimulation.

C. *The effective depth of penetration*

As another way to quantify the extent of current density distribution, the effective depth of penetration is defined as the diameter of the region having current density over the effective threshold. This diameter is measured from the electrode along the line perpendicular to the electrode surface. As expected, SCS yields relatively deeper penetration, with penetration about 3.4 times greater on average than ECS (Figure 5). After 1.5 V, SCS reached the bottom of the model (7cm in depth). So the effective depth on SCS is not changed although the effective volume gets larger.

TABLE I
CONDUCTIVITIES OF TISSUES AND ELECTRODE USED IN THE MODEL [3]

Compartment	Conductivity (S/m)
Substrate conductivity	0.1×10^{-9}
Electrode conductivity	9.4×10^{6}
Skull	0.00625
Dura mater	0.065
CSF	1.7
Gray matter	0.2
White matter (parallel to fibers)	1.1
White matter (perpendicular to fibers)	0.13

TABLE II
DIMENSION OF TISSUES AND ELECTRODE USED IN THE MODEL [3]

Property	Dimension (mm)
Skull thickness	5
Dura mater	0.5
CSF	2.6
Gray matter thickness	3.7
Precentral gyrus width	12
Central sulcus width	1
Precentral sulcus width	1
Central sulcus depth	16
Precentral sulcus depth	16
Electrode thickness	0.1
Substrate thickness	1.8

D. *Total currents entering CSF and white or gray matter*

To assess how much current enters the CSF, gray matter, and white matter, we estimated the total output currents I_{output} induced by voltage sources. In Table 2, we tabulated the total output current as well as the total currents entering CSF, gray matter, and white matter, respectively. SCS produced total output currents about four times larger than those of ECS when the regulated voltage was 1 V. In ECS, only 1 or 2% of the total output current flowed out through the dura mater, while about 45% flowed out through CSF and the remaining 53% of current entered the brain cortex. SCS has a similar behavior with the exception of the dura mater.

E. *Comparison of the two electrode types*

In both CSs, the overall difference between the disc and ring electrodes was relatively small. We found that the difference based on the type of cortical stimulation (location of electrode) was significantly larger than the difference based on electrode type. In short, the electrode types are comparable in both CSs.

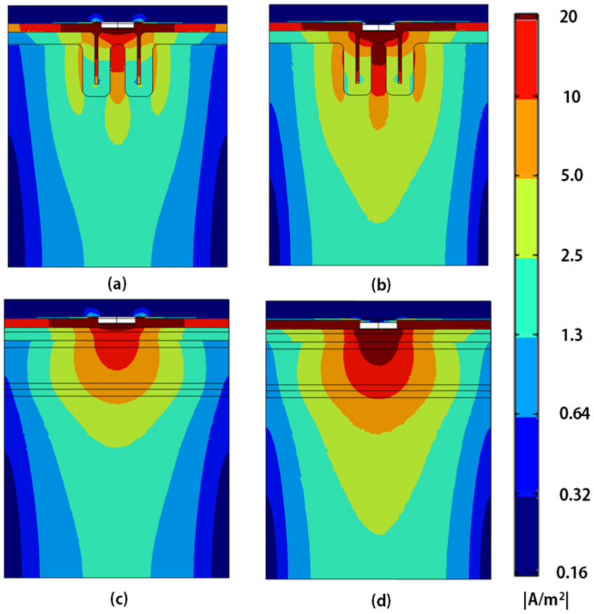

Figure 3. The current density distributions generated by +1V using a disc electrode on ECS and SCS were plotted on cross-sections of the model made perpendicular to the extrusion direction and through the middle of the electrode on ECS (a) and SCS (b), and parallel to the extrusion direction and perpendicular to the surface of electrode on ECS (c) and SCS (d).

TABLE III
TOTAL OUTPUT CURRENTS INDUCED BY VOLTAGE INPUT (1V) AND CURRENTS ENTERING CSF, GM, AND WM LAYERS ARE TABULATED FOR DISC AND RING TYPE ELECTRODES.

		I_{output} (mA)	I_{CSF}	I_{GM}	I_{WM}
Disc	ECS	4.35 (100%)	4.33 (99.5%)	2.36 (54.3%)	1.92 (44.1%)
	SCS	17.66 (100%)	- -	9.76 (55.3%)	7.99 (45.2%)
Ring	ECS	4.31 (100%)	4.26 (98.9%)	2.33 (53.6%)	1.89 (43.4%)
	SCS	17.48 (100%)	- -	9.62 (55.0%)	7.88 (45.1%)

IV. DISCUSSION

To compare ECS and SCS, we conducted a simulation to see how the current densities of ECS and SCS are distributed in various conditions. We found that SCS is more effective in terms of the current amount entering the brain cortex and the extents of current than ECS. However, SCS requires implanting an electrode beneath the dura mater, while with ECS the electrode is placed above the dura mater. At the cost of placing an electrode beneath the dura mater, more promising effects may be obtainable with SCS.

We tested two types of electrodes in this work. Overall, the difference between the two was very small, although the disc type of electrode seemed more effective than the ring type. The ring type can be an alternative choice to the disc electrode without significantly reducing effectiveness, and has another advantage in that there is room in the middle of the electrode, which can be used for a pH sensor or a sensor for monitoring neural responses to stimuli. We used electrodes of 10 mm in diameter in this work. Electrode types over various disc diameter and thickness of ring can be considered to find the optimally effective electrode shape. Such an investigation is in progress.

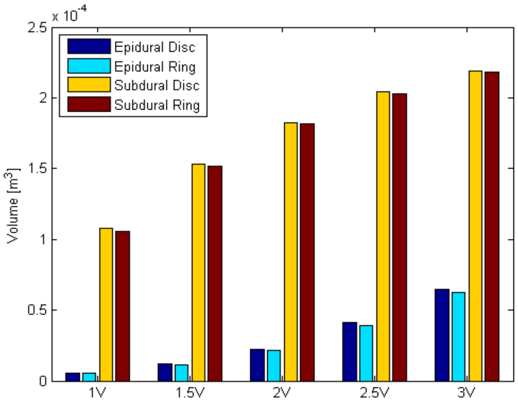

Figure 4. The effective volume in the cortex (gray matter + white matter).

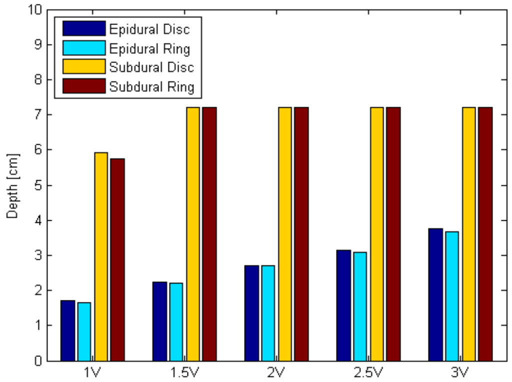

Figure 5. The effective depth representing extent of current penetration.

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