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Effect of electrode profile and conductivity on current density and cutaneous sensation during transcranial DC stimulation

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Abstract—**Non-invasive brain stimulation (NIBS) such as transcranial direct current stimulation (tDCS) involves passing low currents through the brain and is a promising tool for inducing cortical excitability. However tDCS presents challenges in terms of discomfort due to painful cutaneous sensation and reduced efficacy in stimulating deeper cortical structures. This warrants design optimization of the stimulation electrode that interfaces with the tissue and injects the electrical current. In this study we investigated the effect of electrode profile and conductivity on current density at depths below the center of the electrode as well as along the electrode-skin interface. We also investigated cutaneous sensation during tDCS with electrodes having different conductivities.**

We found from Finite Element Analysis that lower conductivity as well as concave-top sponge electrode can reduce edge-effects. Furthermore, concave-top sponge electrode in conjunction with lower electrode conductivity can improve current density at shallow depths below the center of the electrode. Two-way ANOVA revealed a significant effect of electrode conductivity (p=0.0000) and hair/bald condition (p=0.0029) as well as their synergistic effect (p=0.0000) on the cutaneous sensation. Moreover, a lower conductivity sponge electrode reduced prickle sensation at the edges during tDCS.

I. Introduction

NON-INVASIVE brain stimulation (NIBS) such as transcranial direct current stimulation (tDCS) is a promising tool for inducing cortical excitability and facilitating motor learning. It has been shown that NIBS can facilitate neuroplastic mechanisms [1,2] and multiple parameters like stimulation strength, duration, timing, and electrode position may affect the efficacy of NIBS in modulating cortical excitability [3-4]. Prior work on investigating these effects using computational techniques have shown that a non-linear relationship exists between the injected current at the electrode, the electrode area and the current density at a fixed target point in the brain [5]. However the effect of the electrode profile and electrode conductivity remained to be investigated.

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Nitsche et al. [3] have shown that a reduction in electrode area can increase the focality of tDCS and an increase in the electrode area can make it ineffective. The current density at a target location inside the brain is affected by the electrode area [5] besides other factors. In this simulation study using a simple cylindrical model [5], we focused on the effect of electrode profile and electrode conductivity while keeping other factors same.

II. Methods

A. Finite Element Analysis

We considered a cylinder made out of homogenous conductive material having the conductivity of scalp (σ=0.332 S/m), following Miranda et al [5]. The 1cm thick square sponge electrodes having different conductivities (σ_1=0.332S/m, σ_2=0.083S/m, σ_3=1.328S/m) were placed at the center of the top and bottom of the cylinder. Two electrode areas (A_1=36cm^2, A_2=9cm^2) and two surface profiles (flat-top, concave-top [6]) were investigated. The concavity was selected for our electrode sizes based on prior work [6]. The top surface of the electrode was set at a uniform electrode potential such that the average current density at the electrode-scalp interface was 0.0286A/cm^2 [5].

We were interested in current density (J) distribution within the sponge electrodes as well as within the cylinder which is given by,

$$\nabla \bullet J = 0$$
$$J = \sigma E \quad (1)$$
$$E = -\nabla V$$
$$\therefore \nabla \bullet (\sigma \nabla V) = 0 \quad (2)$$

Where E is the electric field intensity, V is the electric potential, and σ is the conductivity of the medium.

For constant σ, equation (2) is a Laplace equation and Finite Element (FE) method was used to solve it with FE software (QuickField, Tera Analysis, USA). The FE modeling was conducted following Miranda et al. [5] and only the upper half was studied since the lower half was its mirror reflection. Model was adaptively discretized with finer mesh near the electrodes and coarse mesh close to the boundaries. The mesh elements having first-order basis functions were refined until the solution reached a steady value within a 0.1% tolerance.

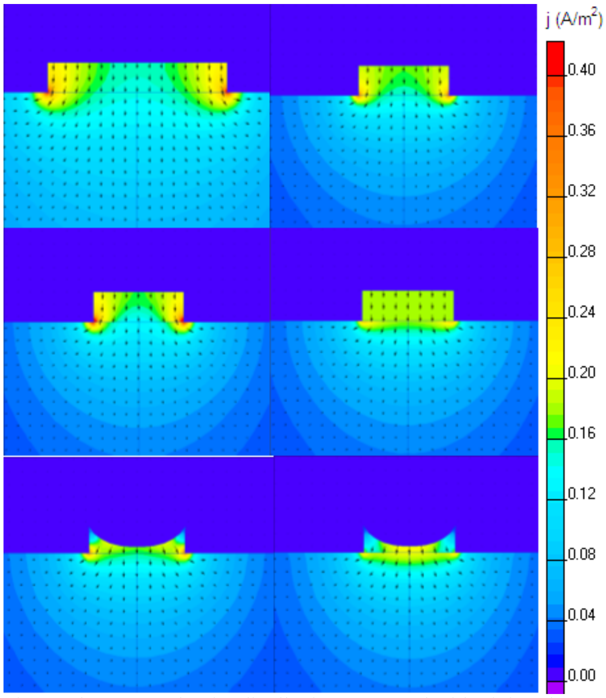

Fig. 1. The current density distribution computed with Finite Element analysis. The top row shows the effect of change in the area from A_1=36cm^2 (left panel) to A_2=9cm^2 (right panel) while keeping the electrode conductivity σ_1=0.332S/m and electrode profile (flat-top) same. The second row shows the effect of change in electrode conductivity from σ_1=0.332S/m (left panel) to σ_2=0.083S/m (right panel) while keeping the electrode area (A_2=9cm^2) and electrode profile (flat-top) same. The third row shows the effect of change in electrode conductivity from σ_1=0.332S/m (left panel) to σ_2=0.083S/m (right panel) while keeping the electrode area (A_2=9cm^2) and electrode profile (concave-top) same.

In the first set of calculations, the effect of change in area (A_1=36cm^2 and A_2=9cm^2) was considered for flat-top electrode while keeping the electrode conductivity σ_1=0.332S/m same. In the second set of calculations, the effect of electrode conductivity (σ_1=0.332S/m, σ_2=0.083S/m, σ_3=1.328S/m) was considered on the smaller flat-top electrode (A_2=9cm^2). In the third set of calculations, the effect of electrode profile (flat-top vs. concave-top) was studied while keeping the area (A_2=9cm^2) and electrode conductivity (σ_1=0.332S/m) same. In the fourth set of calculations, the effect of decreasing the conductivity from σ_1=0.332S/m to σ_2=0.083S/m was studied for the smaller electrode (A_2=9cm^2) with concave-top.

B. Cutaneous sensation tests for electrode conductivity

Ten healthy subjects (all male, 21-38 years old) volunteered for this study. Out of ten healthy subjects, five were bald at the vertex. All subjects signed an informed consent according to the recommendations of the declaration of Helsinki for investigations with human subjects.

This part of the study was based on prior work done by Minhas et al [7]. The electrical conductivity of the 6cmx6cmx1cm sponge electrode (sponge soaked in saline solution) was varied by changing the molarity of the electrolyte. The excess electrolyte was dripped off under gravity from the sponge before application. The conductivity of the sponge electrode was measured with a conductance cell [8]. The anodal stimulation was provided at the vertex of the head with 6cmx6cmx1cm sponge electrode while the 6cmx6cmx1cm reference electrode was placed above the right orbit. The sponge electrodes were gently held in place with a modified hair-net skull-cap. The cutaneous sensation was evaluated based on the perception of the start and end of tDCS while the current intensity was changed. The constant current stimulator (PCM Equipments, India) was hidden from the view of the subject when the investigator increased the current intensity from 0mA to 2mA in steps of 0.1mA while asking the subject at each step if he could feel the start of the tDCS. Then the current intensity was decreased from 2mA to 0mA in steps of 0.1mA while asking the subject at each step if he could feel the end of the tDCS. This was repeated three times with 30mins of rest in-between the tests. In a separate test, the subjects were asked to describe the cutaneous sensation at 2mA current intensity while the tDCS was continued for 10 minutes.

III. RESULTS

A. Finite Element Analysis

The magnitude of the current density is shown in Figure 1 (same color bar for all the figures). The top row of Figure 1 shows the effect of change in the area from A_1=36cm^2 (left panel) to A_2=9cm^2 (right panel) while keeping the electrode conductivity σ_1=0.332S/m and electrode profile (flat-top) same. The second row of Figure 1 shows the effect of change in electrode conductivity from σ_1=0.332S/m (left panel) to σ_2=0.083S/m (right panel) while keeping the electrode area (A_2=9cm^2) and electrode profile (flat-top) same. The third row of Figure 1 shows the effect of change in electrode conductivity from σ_1=0.332S/m (left panel) to σ_2=0.083S/m (right panel) while keeping the electrode area (A_2=9cm^2) and electrode profile (concave-top) same. The first row of the Figure 1 shows that the current density at a fixed depth below the center of the electrode is less for smaller electrode even when the average current density at the electrode-skin interface is same, as shown by Miranda et al also [5]. The second and third rows of the Figure 1 show that the edge-effects were reduced and the charge density at the electrode-skin interface became more uniform with – 1. Concave-top (third row, first panel) than flat-top (second row, first panel) for the same electrode conductivity (σ_1=0.332S/m) and electrode area (A_2=9cm^2), 2. Decrease in electrode conductivity from σ_1=0.332S/m (left panel) to σ_2=0.083S/m (right panel) with same electrode area (A_2=9cm^2) and same electrode profile.

TABLE I
NORMALIZED CURRENT DENSITY FOR VARIOUS ELECTRODE PARAMETERS

Parameters (electrode profile, electrode area, electrode conductivity)	Normalized current density along cylinder axis		Normalized current density along electrode-skin interface	
	Depth 1.2 cm	Depth 3cm	Center	Edge
Flat-top, 36cm^2, ~0.3S/m	0.3818	0.2821	0.4498	1.3816
Flat-top, 36cm^2, ~0.1S/m	0.4067	0.2875	0.5033	1.0421
Flat-top, 36cm^2, ~1.3S/m	0.3653	0.2821	0.4087	1.7823
Flat-top, 9cm^2, ~0.3S/m	0.3064	0.1718	0.4607	1.0948
Flat-top, 9cm^2, ~0.1S/m	0.3173	0.1722	0.5130	0.8708
Flat-top, 9cm^2, ~1.3S/m	0.3009	0.1757	0.4139	1.3011
Ernst-top, 9cm^2, ~0.3S/m	0.3119	0.1708	0.5002	1.0114
Ernst-top, 9cm^2, ~0.1S/m	**0.3356**	0.1729	**0.6399**	**0.7358**
Ernst-top, 9cm^2, ~1.3S/m	0.3085	0.1788	0.4269	1.3304

Figure 2 shows the magnitude of normalized current density (all normalized by 0.029mA/cm^2) along the electrode-skin interface and at depths below the center of the electrode, for change in electrode area, electrode conductivity, and electrode profile. Figure 2a shows the effect of change in electrode conductivity (square-marker=0.332S/m, circle-marker=0.083S/m, point-marker=1.328S/m) and electrode area (black=36cm^2, red=9cm^2) along the electrode-skin interface for the same electrode profile (flat-top) while Figure 2b shows the same effect at depths below the center of the electrode. The decrease in electrode conductivity reduces the current density at the edges (edge-effect) and slightly increases the current density at the center as shown in Figure 2a and tabulated in Table I. Figure 2b shows that larger electrode lends to higher current density at depths below the center of the electrode as found by Miranda et al. also [5]. Moreover, lower electrode conductivity may slightly improve the current density at shallow depths as tabulated in Table I. Figure 2c shows the effect of change in electrode conductivity (square-marker=0.332S/m, circle-marker=0.083S/m, point-marker=1.328S/m) and electrode profile (black=concave-top, red=flat-top) along the electrode-skin interface for the same electrode area (9cm^2) while Figure 2d shows the same effect at depths below the center of the electrode.

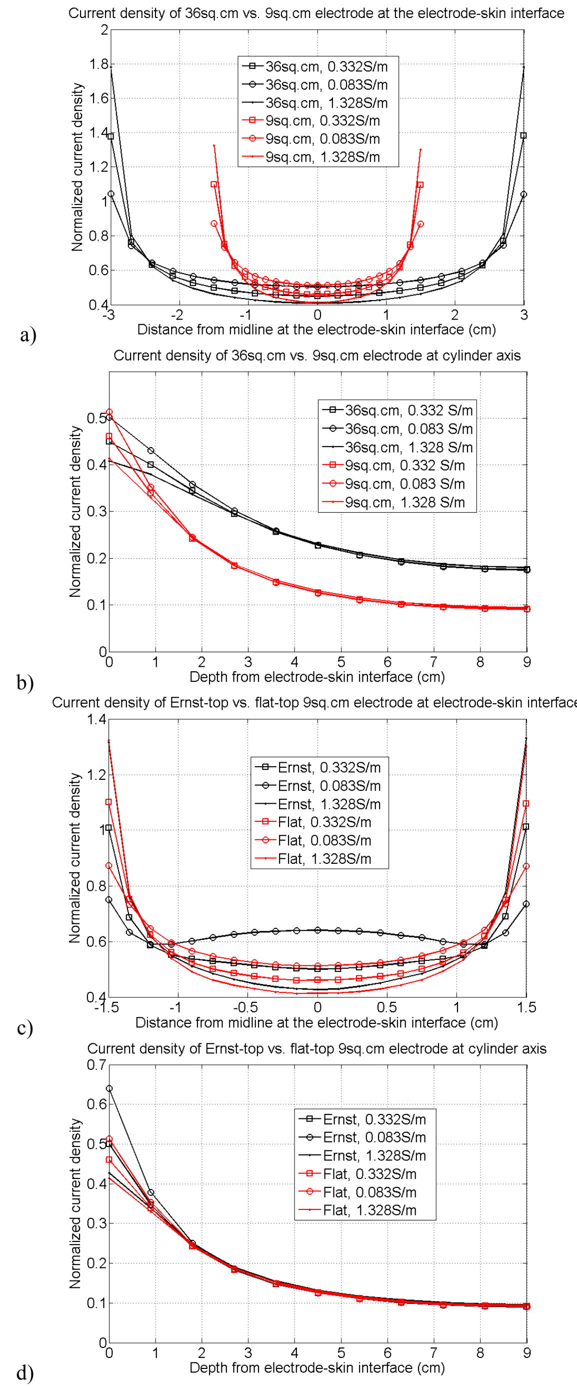

Fig. 2. Normalized (by 0.029mA/sq.cm) current density distribution plots show the effect of the electrode profile and conductivity. a) & b): effect of change in electrode conductivity (square-marker=0.332S/m, circle-marker=0.083S/m, point-marker=1.328S/m) and electrode area (black=36cm^2, red=9cm^2) along the electrode-skin interface (a) and at depths below the center of the electrode (b), for the same electrode profile (flat-top). c) & d): effect of change in electrode conductivity (square-marker=0.332S/m, circle-marker=0.083S/m, point-marker=1.328S/m) and electrode profile (black=concave-top, red=flat-top) along the electrode-skin interface (c) and at depths below the center of the electrode (d) for the same

The concave-top electrode profile reduces the current density at the edges (edge-effect) and a decrease in electrode conductivity further reduces the edge-effect while increasing the current density at the center and at shallow depth, as shown in Figure 2c, 2d and in Table I (highlighted in bold).

B. Cutaneous sensation

Two-way (electrode conductivity, hair/bald) ANOVA ('anova2' in Matlab, The MathWorks, Inc., USA) revealed a significant effect of electrode conductivity (p=0.0000) and hair/bald condition (p=0.0029) as well as their synergistic action (p=0.0000) on the current intensity for cutaneous sensation of the start and end of stimulation. The data is tabulated in Table II and the ANOVA results are shown in Figure 3.

Qualitative assessment of cutaneous sensation at 2mA revealed a burning sensation at the center and prickle sensation at the edges of both the electrodes (anode and cathode). The subjects with hair complained more of the burning sensation than bald subjects. The burning sensation was present for all electrode conductivities at the start of tDCS but reduced with time during tDCS application. The prickle sensation substantially reduced with lowering of the electrode conductivity.

TABLE II

CURRENT INTENSITY AT THE CUTANEOUS SENSATION OF START AND END OF STIMULATION FOR VARIOUS ELECTRODE PARAMETERS

Parameters (electrode profile, electrode area, electrode conductivity)	Bald subjects		Hair subjects	
	Start (mA)	End (mA)	Start (mA)	End (mA)
Flat-top, 36cm^2, ~0.3S/m	0.68±0.18	0.73±0.07	0.49±0.21	0.52±0.12
Flat-top, 36cm^2, ~0.1S/m	0.94±0.07	1.02±0.13	0.67±0.14	0.73±0.11
Flat-top, 36cm^2, ~1.3S/m	0.46±0.05	0.65±0.04	0.42±0.18	0.45±0.14

Source	SS	df	MS	F	Prob>F
Columns	3.68267	2	1.84133	67.29	0
Rows	0.25055	1	0.25055	9.16	0.0029
Interaction	1.12999	2	0.56499	20.65	0
Error	4.76123	174	0.02736		
Total	9.82444	179			

Fig. 3. ANOVA table showing Source of variability, Sum of Squares (SS) due to each source, their degrees of freedom (df), their Mean Squares (MS), and F statistics. The p-values show electrode conductivity levels - 0.3S/m, 0.1S/m, 1.3S/m (in Columns) and subject type – Bald, Hair (in Rows) and their synergistic effect (Interaction) affect the current intensity for cutaneous sensation of stimulation.

IV. Discussion

Our simple model based on prior work by Miranda et al. [5] showed that a decrease in electrode conductivity can reduce edge-effect at the electrode-skin interface but will need higher stimulation voltage (higher compliance voltage for the stimulator). The conductivity of the sponge electrodes may be changed by changing the molarity of the electrolyte or by changing the porosity of the sponge. Furthermore we showed that concave-top sponge electrode can reduce the edge-effect and in conjunction with lower electrode conductivity can improve the current density at center (center-effect) and at shallow depth. This provides a lower cost solution as compared to using expensive electrode gel with recurring costs. However the concavity and the electrode conductivity need to be further optimized for the individual depth and current density targets (e.g. hand area is about 1.2cm and leg area about 3cm in depth).

The cutaneous sensation study on healthy subjects revealed that lower electrode conductivity reduced prickle sensation at the edges. Subjects complained of burning sensation at the center of the electrode, which was present irrespective of the electrode conductivity changes and was more prevalent in subjects with hair than bald subjects. The burning sensation which reduced with time during tDCS, may be caused due to skin inhomogeneities [9]. We found that application of a thin layer of conductive electrode gel on scalp before placing the sponge electrode substantially reduced the burning sensation for subjects with hair. This may be due to homogenization of the electrical conductivity of the outer layers of epidermis [9]. A more detailed skin model is necessary to explore these postulates.

V. Conclusion

The following conclusions can be drawn from our study:

- Lower conductivity of the sponge electrode can lower edge-effect and reduce prickle sensation at the edges.
- Concave-top sponge electrode can lower edge-effects and in conjunction with lower electrode conductivity can improve current density (center-effect) at shallow depths (~1.2cm) below the center of the electrode.

References

[1] M. Hallett, "Neuroplasticity and rehabilitation," Journal of Rehabilitation Research and Development, vol. 42, no. 4, 2005.

[2] M. A. Nitsche, W. Paulus, "Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation," Journal of Physiology, vol. 527, no. 3, pp. 633-639, 2000.

[3] M. A. Nitsche, S. Doemkes, T. Karaköse, A. Antal, D. Liebetanz, N. Lang, F. Tergau, W. Paulus, "Shaping the effects of transcranial direct current stimulation of the human motor cortex," Journal of Neurophysiology, vol. 97, no. 4, pp. 3109-3117, 2007.

[4] M. A. Nitsche, D. Liebetanz, N. Lang, A. Antal, F. Tergau, W. Paulus, "Safety criteria for transcranial direct current stimulation (tDCS) in humans," Clinical Neurophysiology, vol. 114, pp. 2220–2222, 2003.

[5] P. C. Miranda, P. Faria, M. Hallett, "What does the ratio of injected current to electrode area tell us about current density in the brain during tDCS?," Clin Neurophysiol., vol. 120, no. 6, pp. 1183–1187, June 2009.

[6] G. J. Ernst, "Uniform-field electrodes with minimum width," Optics Communications, vol. 49, no. 4, pp. 275-277, 15 March 1984.

[7] P. Minhas, V. Bansal, J. Patel, J. S. Ho, J. Diaz, A. Datta, M. Bikson, "Electrodes for high-definition transcutaneous DC stimulation for applications in drug delivery and electrotherapy, including tDCS," J Neurosci Methods., vol. 190, no. 2, pp. 188-197, 15 July 2010.

[8] T. Shedlovsky, Conductometry, in A. Weissberger (ed.), "Technique of Organic Chemistry," Interscience Publishers, Inc., New York, 1960.

[9] S. Grimnes, "Pathways of ionic flow through human skin in vivo," Acta Derm Venereol, vol. 64, pp. 93-98, 1984.