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Electrode assembly design for transcranial Direct Current Stimulation: A FEM modeling study*

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Abstract— **Despite accelerating progress in transcranial Direct Current Stimulation clinical and cognitive research, there remains remarkably little consistency in the control of electrode design and preparation. Electrode assembly design determines skin sensation and failure at the electrode can lead to skin burns. Though tDCS is generally well tolerated, the desire for rigor in electrode design is motivated by applications in increasingly diverse environments and populations. Generally the tDCS electrode assembly consists of a flat rubber or metal electrode and a saline/water saturated sponge. Here we show using FEM simulations, that each of these factors should be controlled to regulate current flow density across the skin: 1) sponge thickness 2) solution salinity 3) electrode size, 4) electrode placement in the sponge (including surface or pocket configuration) 5) control of excess fluid at the skin surface 6) use of rivets. Two general patterns of current distribution emerge as a result of integrated design: edge concentration or center concentration. Poor control over any of these electrode assembly parameters will result in unpredictable current density at the skin during tDCS.**

I. Introduction

Transcranial Direct Current Stimulation (tDCS) is actively investigated to treat a wide range of neuropsychiatric disorders, to facilitate (stroke) rehabilitation, and as a research tool to modify cognitive processes. tDCS involves passage of low-intensity (typically 1-2 mA) direct current across the brain using surface electrodes. tDCS is considered well tolerated with common side-effects including transient sensation (e.g. tickling) at the skin. The degree of sensation during tDCS is associated with electrode design [1], and is important for both tolerability, influence on cognitive tasks, and sham reliability [2]. Those isolated cases where skin burns were reported, poor electrode design or preparation was implicated [3][4]. Despite the role of tDCS electrodes in sensation during stimulation, and in preventing burns, electrodes used across studies are surprisingly ad-hoc.

Typically, some form of sponge, saturated in saline or water (tap or distilled), is placed on the skin. Details of the sponge preparation are often not published. The electrode may be either placed on the distal surface of the sponge (e.g. a metal grid), be inside a sponge ‘pocket’ (e.g. rubber electrodes), or even be alligator clips attached to a sponge edge. As noted, the composition and shape of the electrode itself varies widely. Electrodes are typically re-used with unspecified monitoring or condition. And a range of further modifications, including use of gel or pre-treatment of skin, are applied – often without specifications in publications. On the one hand, it is generally held that except for electrode size, the design of the electrode does not influence current flow at the level of the brain [5][6], and tDCS remains well tolerated when applied with experience. On the other hand, it remains unclear what factors of electrode design influence sensation and may increase propensity for burns. As tDCS is investigated in increasingly diverse environments, with increasing dosage/regularity, and to diverse (susceptible) populations [7][8], the ambiguity surrounding tDCS electrode design remains of concern.

The design of electrode for stimulation across the skin has been an area of exhaustive experimental research and modeling [9][10][[11]. Stimulation with prolonged DC (monophasic) current requires special consideration due to electrochemical products [12][13], though many of the long-term stability issues associated with implanted electrodes do not apply [14]. Yet, the particular approaches adopted by tDCS researchers have not been considered in detail. While it is not prudent to directly extrapolate from studies using distinct electrode design (e.g. dry electrodes) or waveforms (e.g. AC), prior studies have suggested how important it is to control details of electrode design and preparation. As a first step to apply increased rigor to tDCS electrodes, in this study we modeled skin current density using a range of electrode designs relevant to tDCS. Namely, we explored parameters that vary (or are not controlled) across clinical tDCS studies including sponge thickness, single vs pocket sponge design, sponge salinity, electrode size, as well as designs using rivets. Our results show that, even within existing clinical variability, the combination of electrode parameters used profoundly influences current density peak and profile at the skin. Control of these parameters thus seems warranted.

II. Methods

A. Head model

As our goal was only to consider the role of abstracted electrode assembly design, we modeled the underlying tissue as four concentric blocks. Each representative tissue had a characteristic thickness that was uniform on all sides (in m): Scalp: 0.0325; Skull: 0.0275; Cerebrospinal Fluid (CSF): 0.015; Brain: 0.425. The representative tissues sections were given isotropic electrical conductivities (in S/m): Scalp: 0.332; Skull: 0.0083; CSF: 1.79; Brain: 0.332 [15].

B. Standard electrode model

In order to examine the effects of modifying different electrode parameters, a “standard” model was created and used as a basis for comparison of all other models. The standard model was based on Soterix Medical EASYpad

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sponge electrodes with dimensions 5 x 7 x 0.5 (cm). The sponges were assigned isotropic electrical conductivities of 1 S/m. The rubber electrode had dimensions of 2 x 3 x 0.1 (cm), and was placed between two sponges as part of the pocket sponge design (see fig 1a). The rubber electrode was assigned an isotropic electrical conductivity of 0.1 S/m. One of the rubber electrodes was treated as a current source, while a return electrode was placed on the opposite side of the tissue. The two largest boundaries of the current source rubber electrode were each assigned an inward current flow with a normal current density of 0.833 A/m². The total inward current flow was therefore 1 mA.

C. Electrode parameter modifications

Once the standard model was established, parameters were varied from the standard model to see their effect on the distribution of current density. The 0.5x sponge thickness model and the 2x sponge thickness model have all the same specifications as the standard model, except the sponge dimensions were changed to 5 x 7 x 0.25 (cm) and 5 x 7 x 1 (cm) respectively (Fig 1c). Similarly the 0.5x sponge conductivity and the 2x sponge conductivity models are the same as the standard model except the conductivities of the sponges are changed to 0.5 S/m and 2 S/m respectively (Fig 1d). The 0.5x scalp conductivity and 2x scalp conductivity models have scalp conductivities of 0.166 S/m and 0.664 S/m respectively (Fig 1e). In the 0.5x rubber electrode area and 2x rubber electrode area models, the dimensions of the rubber electrodes were 2 x 1.5 x 0.1 (cm) and 4 x 3 x 0.1 (cm) respectively (Fig 1f). In the no top sponge models, the electrode consists of a rubber electrode on top of a single sponge rather than a pocket electrode assembly. In this case, the top boundary of the rubber electrode was no longer used as a current source (Fig 1g). In the layer of saline models a layer of saline is placed between the electrode and scalp. The saline layer had dimensions 5 x 7 x 0.2 (cm) and an electrical conductivity of 1.4 S/m (Fig 1h). Models were also made with various combinations of these parameter modifications (Fig 1i)

D. Rivet models

Rivets were added to both the standard model and the 0.5x sponge conductivity model to see the effect of rivets when current is concentrated mostly at the edges (standard model) and when it is distributed more evenly with current in the center (0.5x sponge conductivity). The rivets were modeled after conventional Soterix Medical EASYpad sponge electrodes using cylinders: two cylinders (radius 0.6 cm and height of 0.25 cm) and a narrower cylinder (radius: 0.25 cm; height: 0.5 cm) that connects them (fig 2a). The rivets were given an isotropic electrical conductivity of 10^{-20} S/m. To examine the effect of rivet size, large rivets models were created with the radii of the two wide cylinders increased to 1 cm (fig 2d). During tDCS, pressure is often applied to the electrodes, which may cause rivets to protrude into the scalp. We modeled this with each rivet extending 0.05 cm into the scalp layer (fig 2e). To examine the possibility that some fluid may separate the sponge and scalp during tDCS, we modeled a layer of saline under the sponge (fig 2f).

Each model was created in COMSOL Multiphysics 3.3. All internal boundaries were made continuous, except the rubber electrode boundaries. The current source rubber electrode had inward current flow boundary conditions, while the return rubber electrode had ground boundary conditions. All external boundaries were regarded as insulated. Total inward current flow was maintained at 1mA for all models. Each model was solved for normal current density which was then plotted at the scalp surface in A/m² as a subdomain plot.

III. Results

To assess the effect of a given parameter, we examined how the current density is distributed qualitatively (edge concentrated or center concentrated) as well as the peak current density at the scalp surface.

A. Increases in edge concentration

A variety of parameter modifications, when made independently, led to more concentration of current density at the sponge edges. These changes include increasing sponge thickness (fig 1c), increasing sponge conductivity (fig 1d), decreasing scalp conductivity (fig 1e), and increasing the surface area of the rubber electrode (fig 1f). In each of these cases, the increased concentration of current density at the sponge edges also corresponded to higher peak current densities.

B. Increases in center concentration

Not surprisingly, the opposite parameter changes, when applied independently, led to increased concentration of current density in the center of the sponge. Thus, decreasing sponge thickness (fig 1c), decreasing sponge conductivity (fig 1d), increasing scalp conductivity (fig 1e), and decreasing the surface area of the rubber electrode all led to more current density localized in the center of the sponge and a lower peak current density. Removing the top sponge from the electrode assembly also led to more current density concentration in the center of the sponge.

C. Multiple parameter modifications

While it is useful to examine each parameter individually to see how they would change current distribution, these parameters may also be modified in combination. When multiple parameter modifications were made in the same model, the resulting current distribution varied. In some cases, the effect seemed to be the sum of the individual effects of the parameter changes. For example, increasing sponge thickness alone, increases current density concentration at the sponges edges. Decreasing sponge conductivity alone, increases current density concentration in the center of the sponge. When applied at the same time these two parameter changes seem to cancel each other out and little change in current density distribution is observed (fig 1i).

With other combinations however, entirely unexpected effects were seen. For example, increasing sponge thickness alone, increases current density concentration at the sponge edges. Removing the top sponge however, increases current

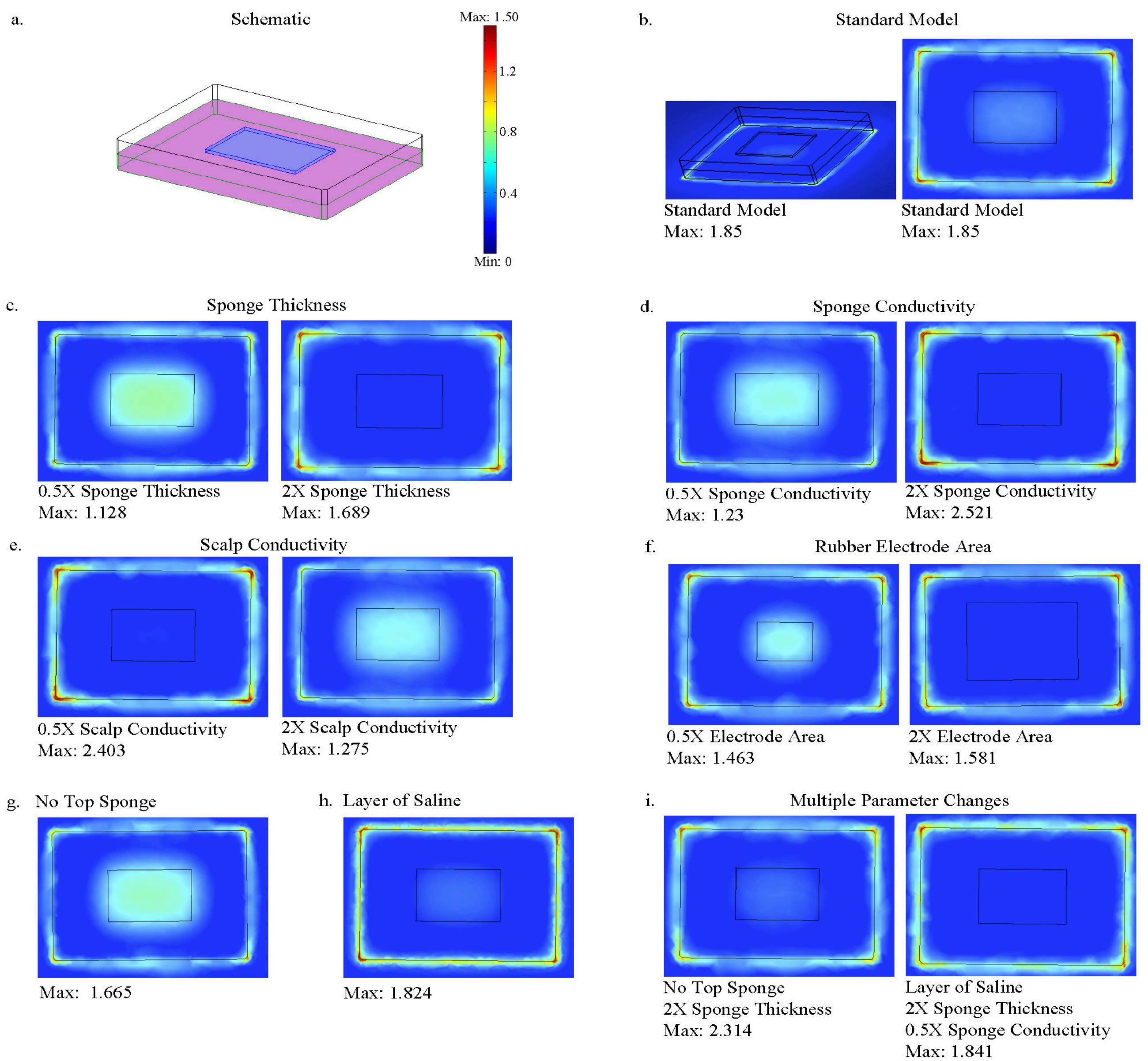

Fig 1.The effect of various parameter modifications on the distribution of current density at the sponge-scalp interface. (a) Schematic of the electrode configuration displaying the contact sponge (pink), the rubber electrode (blue), and the top sponge (transparent wire frame). (b-i) Plots of current density (in A/m²) at the sponge scalp interface. The parameter of interest is indicated above the plot in each figure, while the modification to that parameter is indicated below the plot. All plots are on the same scale with a maximum of 1.5 A/m². Any current current densities greater than 1.5 A/m² were treated as 1.5 A/m². The maximum or peak current density is indicated below each plot in A/m².

density concentration in the center of the sponge. When applied at the same time, the lack of a top sponge does not increase current concentration at the center. Rather, even more current is concentrated at the edges and a higher peak current density is observed than if sponge thickness alone were increased (fig 1i).

D. *Effect of rivets*

The inclusion of rivets could increase current density localization in the center of the sponge, as some current density entered the scalp at the inner edges of the rivets. If the rivets were small enough, peak current density decreased (fig 2c). However if the rivets were too large, peak current density increased (fig 1d). Perhaps this was due to a decrease in the conductive area of the sponge as the non-conducting rivets begin to account for more area. If the rivets were protruding into the scalp, the peak current density was increased as well (fig 2e). If, however, a thin layer of saline was included underneath the sponge, the rivets have close to no effect on current density distribution (Fig 2f).

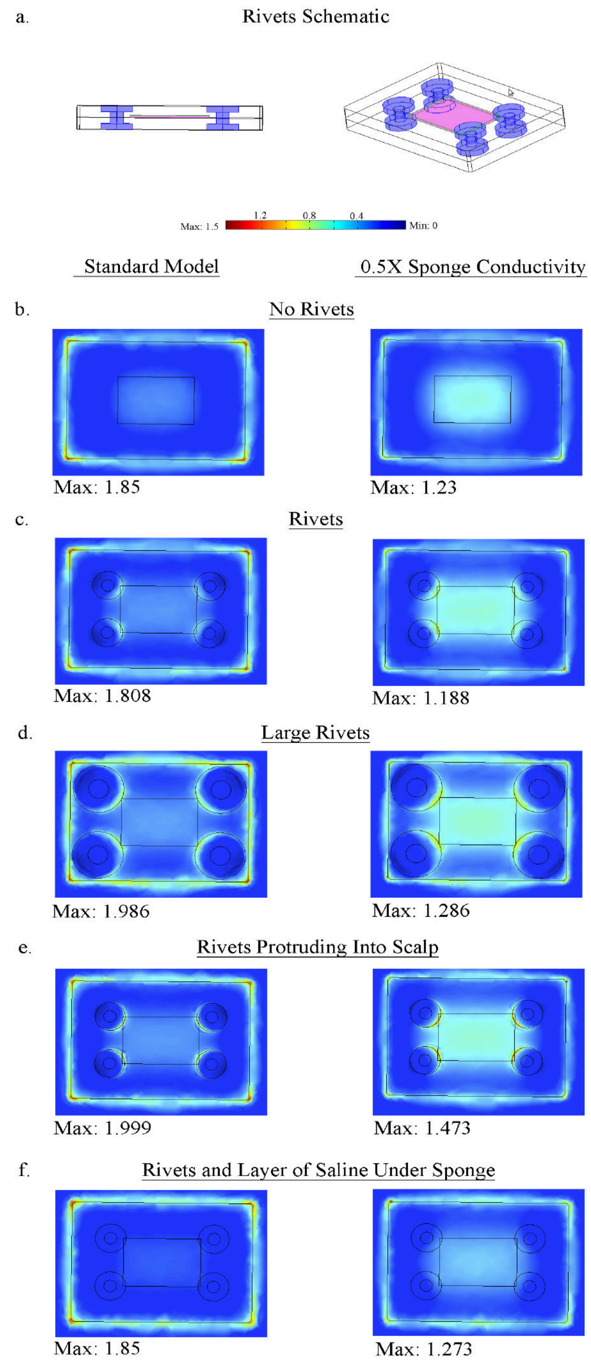

Fig 2. The effect of rivets on current density distribution in the standard and 0.5x sponge conductivity models. (a) Schematic of electrode configuration displaying rivets (blue), rubber electrode (pink), and sponges (transparent wire frame). (b-f) Plots of current density (in A/m²) at the sponge scalp interface. The various rivet configurations are indicated above each plot. Standard models are on the left, while 0.5x sponge conductivity models are on the right for each rivet configuration. All figures are plotted on the same scale with a maximum of 1.5 A/m². Any current densities greater than 1.5 A/m² were plotted as 1.5 A/m². The maximum or peak current density is provided below each plot in A/m².

IV. Discussion

Each of the electrode assembly parameters had an effect on both the qualitative distribution of current density and the peak current density at the scalp surface. However, to allow direct comparisons across electrode shapes, our simplified model does not address: 1) realistic head shapes and anatomy (which may lead asymmetric current distribution at electrode edges, at different stimulation sites); 2) potential difference in skin properties (skin micro-architecture). Therefore in clinical practice these current distributions may be different. Furthermore, the relationship between current distribution and cutaneous sensation or burns during tDCS remains largely undetermined. Therefore, we do not propose an optimal electrode configuration. Rather, we assert that each of these electrode parameters does affect current distribution and must be controlled.

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