Factors influencing Current flow through the Skin during Transcranial Electrical Stimulation: Role of Waveform, Tissue properties, and Macro-pores

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Introduction

Fundamental questions remain about the mechanisms of transdermal current passage during transcranial electrical stimulation (TES) and approaches to optimize electrodes, waveform, and skin preparation to maximize tolerability. Examples of previously unexplained observations include 1) a higher impedance to DC (transcranial Direct Current Stimulation, tDCS) than to high-frequency stimulation, 2) skin lesions occur rarely at the electrode edges where prior models predict maximum current density, 3) abrasion appears to decrease tolerability in some instances (e.g. tDCS) and enhance it in others (e.g. Electroconvulsive therapy, ECT), 4) repeated stimulation sessions may enhance tolerability or increase irritation, 5) preference for gel or saline properties appears to vary across applications.

Methods

We developed the first high-resolution FEM model of skin comprising sweat pores, epidermis, dermis, sweat glands, subcutis, hair follicles, and blood vessels. Skin tissue conductivity based on cylinders filled with saline (0.1 - 0.4 Ω cm) to mimic sweat pores/ducts was carried out. Pore density was set to be 3/cm². The diameter of the ducts ranges from 10 to 40 μm. We conducted experiments testing varieties of electrode assembly and characterized skin and gel response. Images of forearm post-stimulation was taken for each subject to characterize skin response to gel and electrode assembly.

Figure 1: A high resolution skin model consisting of epidermis, dermis, subcutis, hair follicle, sweat glands, sweat pores, and blood vessels patterned to a 5 cm x 5 cm x 2 cm skin layer assembled with electrode (saline soaked sponge: diameter: 1 mm, height: 0.8 mm). Isotropic electrical conductivity values were assigned as follows (in S/m): epidermis 0.12, dermis 0.23, subcutis 0.08, hair 1410-8; sweat glands 1-4, sponge 1.4, and blood 0.43.

Results

• Images taken post-stimulation clearly locate subjective skin lesion and the type of lesion/abrasion.
• Finite element modeling (FEM) of current density concentration around the sweat pores and other skin tissue components performed using COMSOL. 4.3 shows that sweat ducts form electrical weak points in the epidermis during tDCS, the epidermis present a significant captive barrier. Stimullation was taken for each subject to characterize skin response. We conducted experiments testing varieties of electrode assembly and characterized skin and gel response. Images of forearm post-stimulation was taken for each subject to characterize skin response to gel and electrode assembly.

Forearm Testing

Figures 2A-2D: Skin irritation was most prominently seen around the center of the anode at the electrode-skin interphase. Significantly less irritation was seen at the cathode.

Figures 2E-2H: Depending on individual subject tolerability, superficial scarring was seen to form at varying times during the stimulation period.

Figures 2I-2L: Variability in skin sensitivity and tolerance can be seen as the rate at which the irritation progresses through the stimulation period. A subject may form irradiation early on (2 days after stimulation - Figure K) or be able to progress for the entire 5 day period with moderate irritation (Figure J).

• Under the conditions tested, skin irritation reflects current passage rather than electrochemical burden.

FEM Analysis

Small Pores

Macro Pore

Current Density Distribution in Hair follicles

Current Density Distribution in Sweat glands

Figure 3: A1 & B1 represent current density distribution in the epidermis and dermis when small sweat pores (0.01 mm) are predominant in the skin. A2 & B2 illustrate current density distribution when there is one big sweat pore (0.04 mm) present in addition to existing small pores. C illustrates current density in the hair follicles and D shows current density found in the sweat gland that are connected to the sweat pores. FEM results show that current found its way through sweat pores (ducts) even though the upper most layer of epidermis (Stratum Corneum) is highly resistive and is occupied predominantly by hairs.

Although finite element modeling results showed leading-edge current spikes, significant current density concentration were also seen at the sweat pores. Since sweat ducts/pores are filled with sweat (chiefly a saline solution), current appears to be conducted in the skin though the conductive tubes into the well-conducting dermis and tissues below.

Conclusion

• During tDCS, the epidermis present a significant captive barrier and current is predominately carried by sweat pores such that moisturizing the epidermis but not abrasion will increase tolerability.
• Regions of susceptibility thus might be near larger sweat pores and not at electrode edges.

References