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Feasibility of Direct Current stimulation through hair using a dry electrode: potential for transcranial Direct Current Stimulation (tDCS) application*

Yishai Valter, Syed Shahabuddin, Neil McDonald, Brooke Roberts, Walid Soussou, Chris Thomas, Abhishek Datta

Abstract— **Conventional transcranial direct current stimulation (tDCS) protocols typically deliver 2 mA for 20-30 minutes. The most common administration uses a wet electrode approach which dries out in ~60 minutes at room temperature. This restricts its application to limited duration electrode-scalp contact use cases unless additional conductive media (saline, gel, or paste) is re-applied. This problem is further compounded by the subject's hair which not only presents administration challenges (interferes with electrode attachment and adhesion) but also acts as a conduit of current flow into the scalp resulting in current hotspots. This non-uniform current injection results in increased skin sensation. The aim of this study was to determine suitability of a commercially available hydrogel for DC delivery through hair. Experiments involved both non-clinical testing on an agar block and clinical testing on subjects' forearms. Electrodes were positioned on the posterior side of the forearm that has hair for the clinical testing. Typical dose as used in tDCS was delivered and pain scores were collected. Results indicate suitable current delivery performance and all subjects tolerated delivery with pain scores ranging between 0-6. Our study paves the way for future testing on the scalp for tDCS application.**

Clinical Relevance—**This study demonstrates the possibility of delivering tDCS through hair via dry electrodes. Specific use cases that cannot use a traditional wet electrode approach stand to benefit from the results of our work.**

I. Introduction

Transcranial direct current stimulation (tDCS) involves the application of low-intensity weak direct current via scalp based electrodes (25-35 cm^2) [1]. As with any electrical stimulation modality, a conductive medium is typically applied between the electrode and the tissue (skin) to aid in the flow of current into the tissue and to prevent skin irritation. Specifically, the conductive medium serves to lower skin impedance and to ensure uniform coupling to the subject. The conductive medium also acts as a facilitator of necessary oxidation and reduction reactions to ensure effective transition of electrons to ions for enabling current flow through tissue [2].

However, the use of a wet conductive medium complicates tDCS procedures. It necessitates an extra step of skin preparation, leaves an unwanted residue, dries out within ~60 minutes in most cases and risks leakage that would expand the contact area and require re-application. It also risks electrode slippage which is highly undesirable when considering that precise electrode placement may be critical for the efficacy and reproducibility of some tDCS applications. These issues prevent widespread adoption of tDCS and hinder its development into a home-friendly technology. Here, we investigated delivery of tDCS dose with a "dry" hydrogel electrode. A dry electrode does not use any saline, gel or paste between the electrode and the skin that can leak or leave a residue. Khadka and colleagues used a multi-layer dry hydrogel composite to successfully apply stimulation to the forehead [3]. However, as most common tDCS electrode placements involve at least one scalp location with hair follicles, the aforementioned solution is of limited practical utility for typical use. Hair presents a substantial impediment to any dry application due to adhesion and associated coupling concern. Furthermore, irrespective of application (wet or dry), hair plays a defining role in current flow distribution into tissue, as current is drawn towards openings such as hair follicles and sweat ducts [4]. This leads to preferential current flow through certain skin sections leading to non-uniform current injection and ultimately manifests as increased skin sensation. A conductive medium helps mitigate non-uniform current distribution leading to more tolerable application. Towards the goal of developing a true dry tDCS solution, we investigated stimulation on the posterior forearm which Jönsson and colleagues report to have a mean hair follicle density (HFD) of 37.4 ± 10.0 per cm^2 [5]. While hair shaft length and diameter have been found to be affected by gender [6], HFD is not [7]. We considered a commercially available hydrogel given its well established performance for TENS and EMS applications [8] and associated favorable characteristics (long-lasting and repeated adhesiveness) It is known that DC stimulation presents unique challenge. We first simulated direct current application on a phantom using an agar gel and measured electrode potential and cell resistance [2]. We also quantified the ability of the material to maintain contact resistance over an extended period (4 hours). During actual tissue stimulation, it is desirable to not only maintain electrode potential to as low a value as possible to reduce injury risk [9] but to also ensure that rated maximum allowed voltage limits presented by the tDCS device are not exceeded [2]. We

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Y. Valter is with Soterix Medical, Inc. New York, NY 10001 USA (Phone: 888-990-8327 E-mail: yvalter@soterixmedical.com).

S. Shahabuddin and C. Thomas are with Soterix Medical, Inc. New York, NY 10001 USA.

N. McDonald, B. Roberts, and W. Soussou, are with Research & Development, Quantum Applied Science and Research (QUASAR),San Diego, CA 92127, USA

A. Datta is with Soterix Medical, Inc. New York 10001 USA, (E-mail: adatta@soterixmedical.com) and with City College of New York, NY 10031 USA (E-mail:adatta@ccny.cuny.edu).

subsequently performed subjective sensation tests on 8 healthy subjects for a typical tDCS dose. We obtained pain scores per the VAS pain rating scale.

II. METHODS

1) Electrode material properties and geometry We used 6 stacked sheets of square (1x1 inch) cutouts of the hydrogel as our dry electrode for all experimentation (**Figure 1)**. The chosen material is manufactured for various biomedical and industrial purposes. In particular, it is produced for low frequency stimulation and is most noted for long-lasting adhesion and strong adhesion after repeated use. Some of its relevant properties are as follows: specific resistance = 2 kOhms/cm, pH= 3-7, gel thickness=0.75 +-0.15 mm, adhesion (90 degrees) = 200-700 g/20 mm, residual monomer ratio =100 ppm. The material is reported to not cause irritation even after 24 hour placement on human skin.

2) Total cell resistance and Electrode potential For studies measuring total cell resistance and electrode potential (total potential over the entire assembly of electrodes), dry electrodes were mounted on a flat block of agar (pH of 6.0) made with 150 mM (physiological) NaCl [2,10]. For the electrode potential experiments, 2 mA DC current was delivered through an agar gel between an active and return electrode comprised of the same hydrogel material. The potential was then the voltage drop across the electrode combination and agar gel. Current was delivered using a conventional tDCS device (Soterix Medical, New York, NY, USA) through two Ag/AgCl ring electrodes placed on each hydrogel block (**Figure 2A right**). Voltage was recorded via two probes placed ~13 cm. apart and fully inserted into each hydrogel. The readings were recorded every 5 minutes over an 80 minute time period using an RMS digital multimeter (FLUKE 177; FLUKE Corporation, Everett, WA, USA). For the total cell resistance measurement, fresh hydrogel electrodes were used. No current was delivered using an external device as the goal was to determine static impedance. Two probes were inserted into each hydrogel to measure total cell resistance. Distance between the probes was 13 cms. Resistance was recorded every 30 minutes over 20 hours.

3) Subject sensation and tolerance settings. The study was conducted in accordance with the protocols and procedures approved by the Western Institutional Review Board. We recruited 8 healthy subjects (males (m) = 6, females (f) =2, 19–32 years). Sensation tests were performed using the hydrogel material on subject forearms. A fresh patch of hydrogel electrode was used for each test. For sensation studies, the rationale was to determine the effect of the "active" anode or cathode electrode- independently of each other. Therefore, two High-Definition (HD) electrodes (Soterix Medical, NY, USA) were used as "return" electrodes and a third active HD electrode was used to drive electrical current through the hydrogel electrode patch. The usage of multiple return electrodes allowed us to ensure that subjective pain scores primarily reflected sensation induced as a result of the active electrode. This strategy has been used in our previous study and by others. The HD electrodes are composed of sintered Ag/AgCl material and are routinely used for HD applications. A minimal amount of conductive gel (HG-GEL) was applied to the top surface of the hydrogel electrode to facilitate contact with the HD electrode. Importantly, no medium was applied between the hydrogel electrode and the forearm. The return electrodes were positioned on opposite sides of the active electrode at a distance of ~5 cm. Each return electrode was applied with an excess of 400 ± 10 mm^3 volume of conductive gel. Electrode holders were used to position the HD electrodes over the forearm and to standardize gel volume used. The experiments were conducted on the posterior forearm with the active electrode positioned approximately midway between the distal and the proximal sections. The subject was seated with the stimulated arm extended and resting on the table. The subjects were free to move their other arm as they wished. There were no steps taken to otherwise prepare the skin prior to stimulation. Even though abrasion affects skin properties, skin abrasion was avoided for two reasons: (1) to test the effect of electrical stimulation on unconditioned skin and (2) experimental ambiguity regarding the precise degree of abrasiveness. Regions of skin with visible irritation or cuts prior to stimulation were avoided. Dry electrodes were applied to the subjects' forearms for 2 minutes before stimulation began to determine if any pain is caused by the dry electrode without current. Stimulation was applied for 20 minutes with subjects scoring pain every 2 minutes from immediately before stimulation began (t= 2), every 2 minutes during stimulation (t = 4 to 22) and 2 minutes after stimulation ended (t= 24). The VAS rating scale was used for pain assessment which can be summarized as: 0: no pain; 1-3: mild pain; 4-6: moderate pain; 7-10: severe pain. Each subject could withdraw from the stimulation at any point during the experiment, regardless of the current pain score or nature of perception. Subject sensation testing was performed twice on each subject. One stimulation session was performed on one forearm followed by a stimulation session on the other forearm. One forearm received cathodal

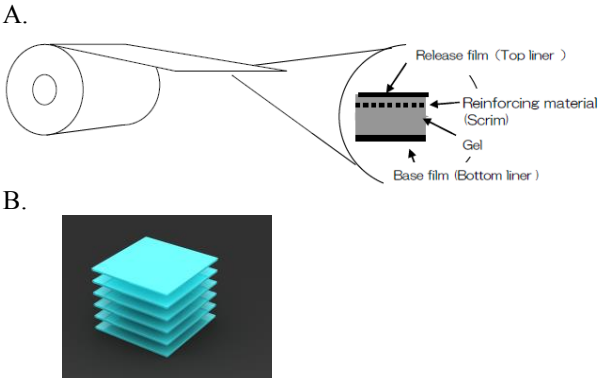

Figure 1: A Hydrogel composition **B.** Six stacked sheets of the hydrogel material were used for all experimentation. This number was arbitrarily chosen.

stimulation and the other forearm received anodal stimulation (Figure 3). Images were taken before and after stimulation to evaluate erythema. All measurements (total cell resistance and electrode potential) and pain ratings were collected at room temperature (18-22°C) and relative humidity (30-60%) confirmed via a Temperature Humidity meter.

III. Results

Using the set-up as explained in the Methods section above and depicted in **Figure 2A left**, total resistance values were recorded over 20 hours. We observed a steady drop in resistance from 612 kohms (t=0) to 382 kohms (t=9 hours) reflecting a drop of ~38%. Thereafter, resistance values saturated and did not change in any noteworthy fashion. A final value of ~348 kohms was noted at the end of the

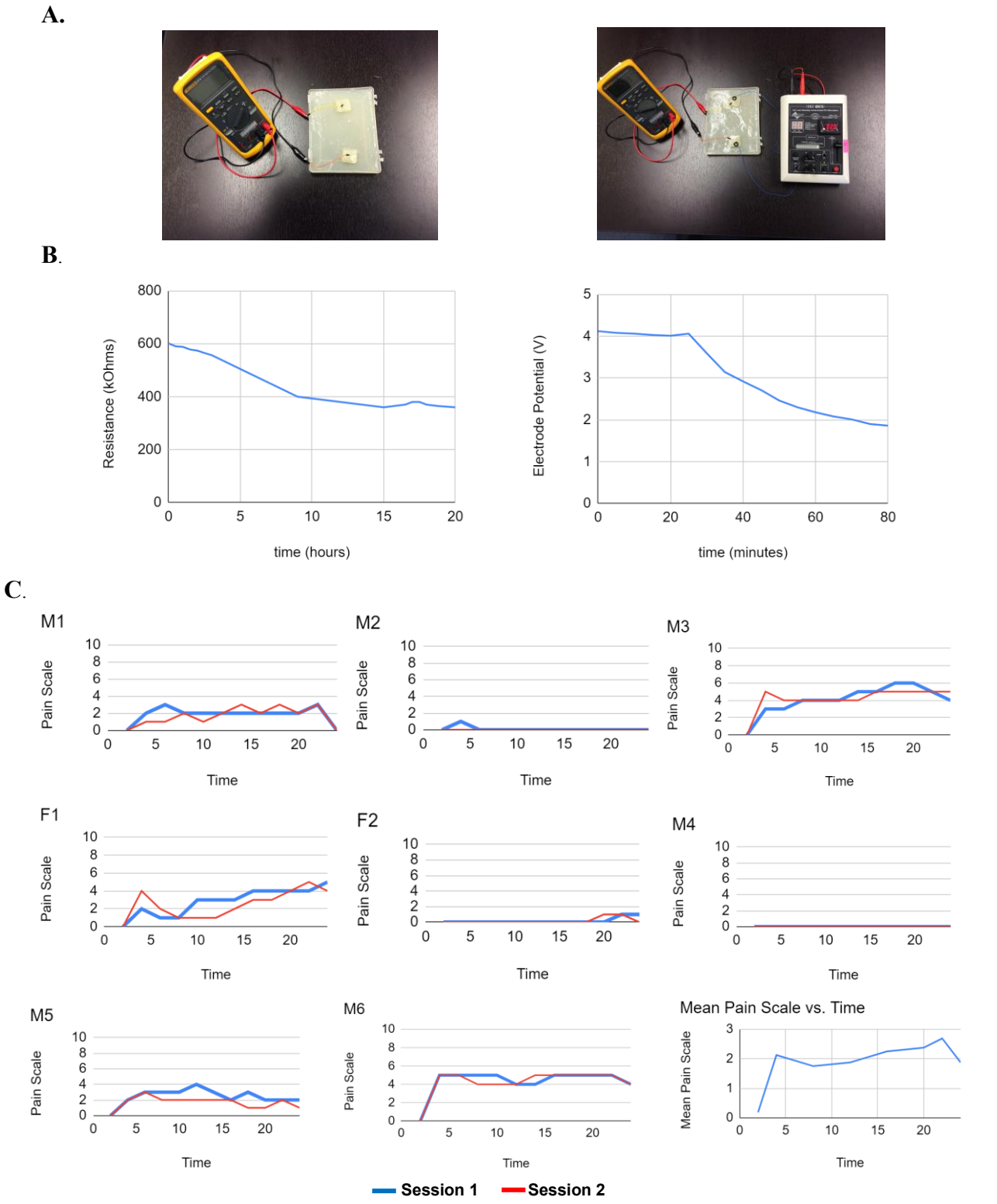

Figure 2. A. Total cell resistance and Electrode potential measurement configuration. **B.** Total cell resistance and Electrode potential recordings over time**. C.** Individual VAS pain ratings (Blue line: Session 1, Red line: Session 2)

recording session (t= 20 hours). With respect to electrode potential recordings, we observed that values remained <5 V indicating that tDCS could be easily applied. With typical cut-off voltage for tDCS devices ranging between 15-120 V, this indicates ample voltage available to source current through the electrode set-up. The electrode potential profile stayed relatively constant for the first 25 minutes and progressively dropped thereafter over time (**Figure 2A right**). We noted a reading of ~1.9 V at the end of the recording session (t = 80 minutes). Additionally, we did not observe any residue build up which would have likely indicated generation of electrochemical byproducts.

The individual pain rating scores indicated that all 8 subjects completed the entire 20 minutes of stimulation at 2 mA intensity. No serious adverse events were reported. The worst pain score reported was a 6 by M3 and for a brief amount of time (~ 1 min). As expected, mild erythema occurred on the stimulation sites across all subjects, but it

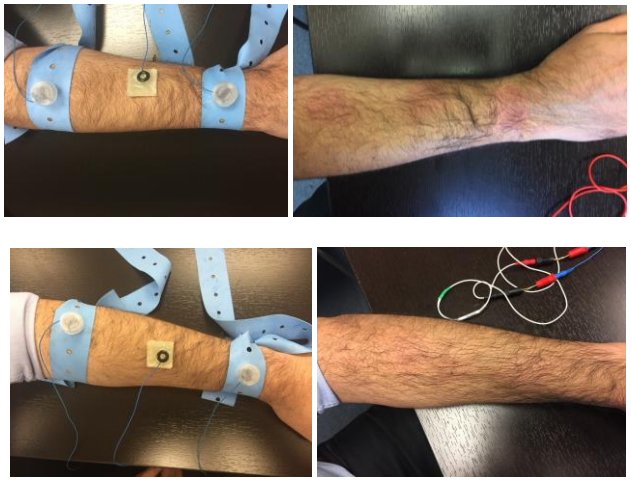

Figure 3: shows exemplary images of forearms *during* stimulation and immediately *after* stimulation. Subject M5 right arm (**top**) and left arm (**bottom**)

it dissipated within an hour of stimulation completion. While cathodal stimulation has been reported to result in higher skin irritation than anodal stimulation [14], we observed no particular difference between the pain ratings reported by the subjects. We also noted a wide mixture of reported pain ratings with 3 subjects (M2, F2, M4) reporting virtually no pain to consistent pain scores (but tolerable) reported through the course of the stimulation session (M3, M6, F1). Nonethelesss, the erythema observed at the end of the session showed no particular correspondence to the pain scores reported in the stimulation session.

IV. Discussion

This study demonstrates that DC application through hair is feasible using a dry electrode approach. Further, there was no noteworthy difference in subject sensation between anodal and cathodal stimulation. It should be noted that the mean forearm HFD is approximately 37/cm^2 [5] while the scalp, where tDCS is usually performed, has a much higher HFD. Giacometti reported 615/cm^2 hair follicles on the scalps of adults between the ages 20-30, 485/cm^2 on adults 30-50 and 305/cm^2 on bald scalps of ages 45-85 [7]. Furthermore, forearm hairs have a shaft diameter of approximately 30 micrometers while scalp hairs are wider with an average shaft diameter of 50 micrometers [11]. Therefore, further research should be performed to explore the use of dry electrodes on areas with higher HFD and wider follicles.

The most evident advantage of a dry electrode is easier and subject-friendly application avoiding the need to wash hair post stimulation sessions. Other advantages include planning longer duration studies that do not allow operator intervention, such as closed-loop studies [12] that involve monitoring subjects over extended duration (entire day) and applying tDCS based on subject state [13]. Other additional advantages relate to safety (no gel leakage) and robustness.

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