Principles of Within Electrode Current Steering[1]

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1 Background

tDCS is a neuromodulation technique that involves noninvasive delivery of weak direct current (1–2 mA) to the brain. Conventionally, tDCS employs rectangular saline-soaked sponge pads (25–35 cm^2) placed on the scalp, with an internal electrode connected to the current source. Impedance measurement across the current source output may fail to recognize nonuniform conditions at the skin interface such an uneven content or saturation. tDCS is well tolerated with minor adverse effects limited to transient skin irritation [1]. Nonetheless, technology that enhances the sophistication of electrode design would further enhance tolerability and promote broad (e.g., home) use.

In order to enhance the reliability and tolerability of tDCS, we describe a novel method called WECS. This concept is distinct from (across electrode) current steering, as developed for implanted devices such as deep brain stimulation (DBS), where current is steered between electrodes that are each in contact with tissue, with the goal of changing desired brain regions that are activated [2]. WECS adjusts current between electrodes not in contact with tissue but rather embedded in an electrolyte on the body surface. The goal here is *not* to alter brain current flow, but rather compensate for nonideal conditions at the surface. This technology leverages our technique for independently isolating electrode impedance and overpotential during multichannel stimulation [3].

With a novel approach, the objective of this first paper was to demonstrate the principles of WECS using an exemplary electrode design typical for tDCS (four rivet-electrode sponge) and extremes of current steering (from uniform in all rivets to a single rivet). Through FEM simulation of this illustrative case, we validate the underlying assumptions of WECS: steering current within electrodes but without altering current distribution in brain target. Having presented this novel idea through an exemplary case, this report supports future studies in optimization of electrode design, automation of algorithms to control current (including using impedance measurement), and ultimately validation under experimental conditions.

2 Methods

Principles. WECS applies to noninvasive electrical stimulation with two or more electrodes (metal-rivets) embedded in an electrolyte (saline or gel)) on the skin [4]. Each electrode is independently powered by a current source. Success in implementation of WECS depends on geometry and material of each component of the assembly and an algorithm for current steering between electrodes. Here our goal is only to demonstrate the principle of such application through a case design. Using a multiscale model including a realistic electrode and head geometry (Fig. 1(*a*)), we showed how current flow in the brain (target) is independent of current steering at the electrode.

Electrode Design. To illustrate implementation of WECS, we use a modified tDCS saline-saturated sponge ($7 \times 5 \times 3$ cm, $\sigma = 1.4$ S/m). The top face of the sponge is perforated with cylindrical Ag/AgCl electrodes ($d_{\text{out}} = 1.5$ cm, $d_{\text{in}} = 0.61$ cm, $\text{extrusion}_{\text{outer}} = 1$ cm, and $\text{extrusion}_{\text{inner}} = 0.50$ cm $\sigma = 5.99 \times 10^7$ S/m), which align with the top surface and protrude through half the sponge thickness (Fig. 1(*a*)). The electrodes are exposed on all surfaces and connect the lead (not shown) via male receptacles at the top. In principle, changing the diameter and distance between the electrodes, the distance between the electrodes and skin, or electrolyte conductivity will discriminate how current from the electrode reaches the skin [5], but here our goal is to illustrate WECS principles in one fixed exemplary geometry. This electrode assembly is placed on the scalp (Fig. 1(*a*)), in our example over the motor region (M1). A return electrode is placed at over the contralateral orbit and is not of concern here.

Current Steering. The electrode assembly receives a fixed total current of 1 mA (with -1 mA collected by the return electrode). The current is actively divided across the electrodes within the electrode assembly. Thus, under an “even” current split, 0.25 mA is delivered to each electrode. Under a “partially uneven” current split 0.5, 0.25, 0.25, and 0 mA current is delivered and under a “fully uneven” split 1.0 mA is delivered to one electrode and 0 mA current to the remaining electrodes.

Computational Methods. WECS was modeled using a previously develop tDCS FEM workflow [6]. A multidomain geometric mesh was generated of a head using a combination of 3D imaging data and computer aided design electrodes (Simpleware, Exeter, UK). The mesh was imported into a FEM solver (COMSOL, Burlington, MA), where conductivities [5] were assigned to each tissue/material domain. Boundary conditions were applied (cathode ground, inward current density on rivets, insulated on other external surfaces), and the Laplace equation solved for Voltage (and in turn electric field and current density).

3 Results

To illustrate the principles of WECS, we considered a simplified electrode assembly with electrodes inside a saline saturated sponge, placed on the scalp (Fig. 1(*a*)), under two extremes of electrode current distribution conditions (even and fully uneven) and one intermediary electrode current distribution (partial uneven) (Fig. 1(*b*)). Streamline plots (Fig. 1(*c*)) of within sponge current flow demonstrate the distribution of current flow in each case from the electrodes to the skin surface. As expected, we found symmetry when steering current from fully uneven to even current application, but in each case current spreads across the electrode–assembly. At the electrode–assembly interface with the skin, the current density distribution varied only incrementally across conditions (e.g., less than would be expected with even minor changes in electrode assembly or skin properties [5]) with no significant difference in peak current density (~2 A/m^2; typically predicted around edges). Thus, with this electrode assembly design even if three of four electrodes failed, current steering to

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the one functional electrode would not significantly increase current density in the skin; hence, not effecting tolerability.

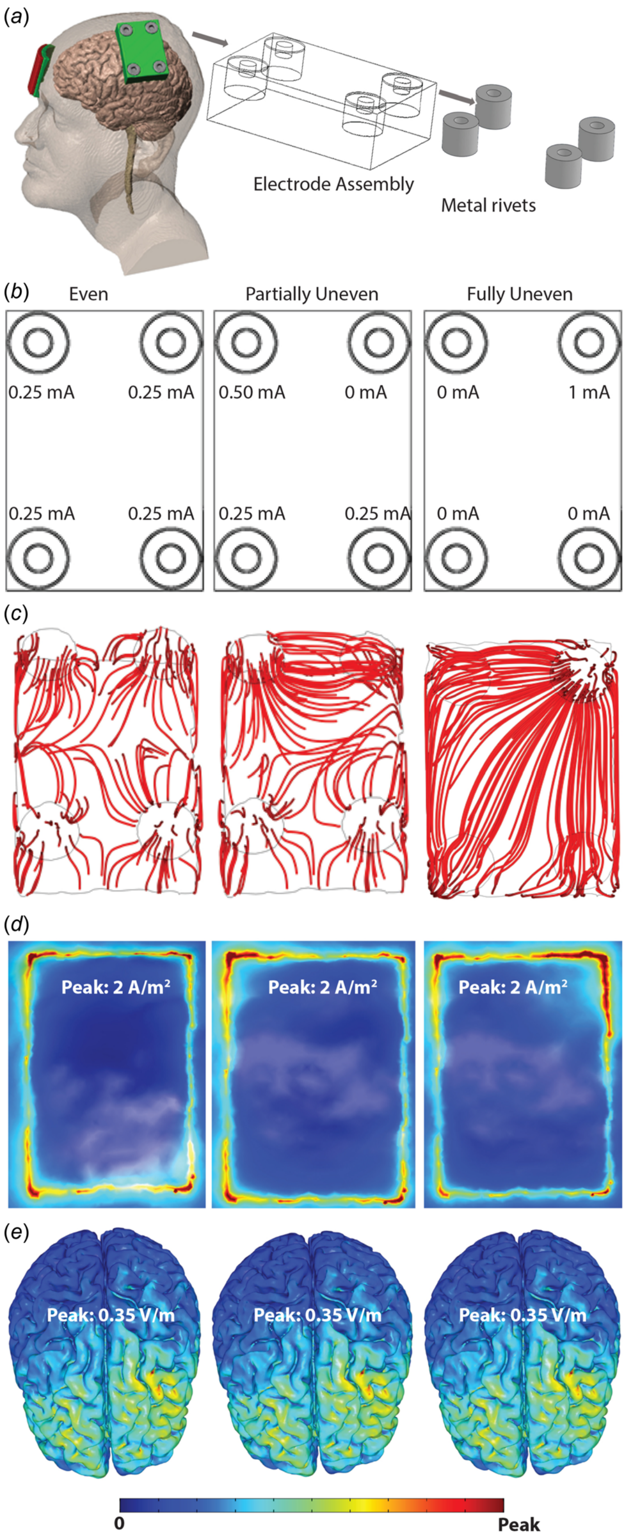

Fig. 1 FEM analysis of electrode assembly to validate the underlying assumption of WECS. (*a*) A montage with electrode assembly. (*b*) Even, partially uneven, and fully uneven current injection mode through metal rivets of an electrode assembly keeping total current constant. (*c*) A streamline current flow from each metal rivets under all three current injection conditions. (*d*) Current density observed at the scalp electrode interface. (*e*) An electric field distribution found in the brain target.

Furthermore, we predicted that the electric field at the brain under all three cases was essentially identical (Fig. 1(*e*)). Therefore, using this electrode–assembly design, current can be steered across electrodes without effecting current distribution in the brain target. We note the goal of WECS in contrast to current steering in DBS is not to alter current flow at the target (neuromodulation).

4 Interpretation

WECS is proposed here as a novel method to increase the tolerability of tDCS without altering underling neuromodulation. Thus, using an exemplary design, we illustrated how current flow in the brain can remain unaltered (Fig. 1(*e*)) even as current is steered between electrodes inside the electrode–assembly. WECS can be generalized to other noninvasive electrical stimulation technique and potentially to invasive techniques where an artificial or natural electrolyte barrier exists between the electrode and the tissue. For invasive techniques, WECS may complement traditional current steering but be used to protect electrode and tissue from injury. Success of this approach depends on the appropriate design of the electrode assembly (Fig. 1(*a*)) and the algorithm used to steer current between electrodes—topics to be considered in future design efforts.

The essential principles in WECS design relate to producing functional equivalency between current arriving at each electrode as far as current entering the brain target. Specifically, regardless of how a total amount of current is distributed between electrodes, brain current flow is unchanged. A further consideration is how current flow at the skin (scalp) is altered. On the one hand, current steering should avoid significant increases in current density at the skin, maintaining as uniform a current density at the skin as practical. On the other hand, when nonideal conditions at the electrode or skin arise, including increasingly nonuniform current flow or electrode failure, current steering may be used to compensate. For example, if a given electrode fails and a high overpotential at the electrode is detected, current may be steered to other electrode to minimize electrochemical hazard [4] or if one region of the sponge becomes dry during use, current may be diverted to the most distant electrodes.

Inherent to the above concept is the ability to detect nonideal conditions and program appropriate corrective measures. The simplest feedback is the voltage at each current source, which using signal processing and "test signals" (superimposed currents not used for neuromodulation) or a "sentinel electrode" (not used for DC) may be used to calculate single electrode impedance [3]. Additional information can be derived by using test signals to isolate the impedance of the sponge/electrolyte between the electrodes, generating a prediction for current density patterns that can be corrected.

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