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What does the ratio of injected current to electrode area tell us about current density in the brain during tDCS?

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ABSTRACT

Objective: To examine the relationship between the ratio of injected current to electrode area (*I*/*A*) and the current density at a fixed target point in the brain under the electrode during transcranial direct current stimulation (tDCS).

Methods: Numerical methods were used to calculate the current density distribution in a standard spherical head model as well as in a homogeneous cylindrical conductor.

Results: The calculations using the cylindrical model showed that, for the same *I*/*A* ratio, the current density at a fixed depth under the electrode was lower for the smaller of the two electrodes. Using the spherical model, the current density at a fixed target point in the brain under the electrode was found to be a non-linear function of the *I*/*A* ratio. For smaller electrodes, more current than predicted by the *I*/*A* ratio was required to achieve a predetermined current density in the brain.

Conclusions: A non-linear relationship exists between the injected current, the electrode area and the current density at a fixed target point in the brain, which can be described in terms of a montage-specific *I*–*A* curve.

Significance: *I*–*A* curves calculated using realistic head models or obtained experimentally should be used when adjusting the current for different electrode sizes or when comparing the effect of different current–electrode area combinations.

1. Introduction

The application of a weak DC current through electrodes on the scalp, commonly referred to as transcranial direct current stimulation or tDCS, has been shown to be able to modulate cortical excitability in an effective and reproducible manner (Priori et al., 1998; Nitsche and Paulus, 2000; Nitsche et al., 2005). All safety studies carried out so far indicate that the application of a current with an intensity of 1 mA for periods up to 20 min using electrodes whose area is about 25–35 cm^2 has no significant adverse effects (Nitsche et al., 2003; Iyer et al., 2005; Poreisz et al., 2007). Because it is considered safe and it is well tolerated, easy to apply and inexpensive, tDCS has already been used in a large number of studies. An overview of recent tDCS experiments and methodological issues is presented in Nitsche et al., (2008).

An assumption that is often made in tDCS studies is that the ratio of the injected current to the electrode area (*I*/*A*) determines the magnitude of the stimulation effect. This assumption is implicitly made when the *I*/*A* ratio is used to specify and compare stimulation intensities, as it is currently done. In a recent study, Nitsche et al. (2007) clearly demonstrated that a reduction in electrode area can increase the focality of tDCS whereas an increase in electrode area can render that electrode functionally ineffective. In this case too, the underlying assumption was that by keeping the *I*/*A* ratio constant while varying current intensity and electrode area, the effect in the brain was the same.

Given the widespread use of this assumption and its implications in terms of protocol design, interpretation of experimental results and safety, we sought to determine its validity on physical grounds. We assumed that the current density at the target location in the brain is a fundamental factor in determining

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stimulation efficacy. Other factors such as neuron orientation relative to the applied electric field, neuronal electrophysiological properties, neural network properties, etc. also play a critical role in determining the outcome of stimulation. Thus, knowing the current density distribution in the brain is a necessary, but not sufficient, condition to predict tDCS efficacy. In this paper, we address only aspects related to the current density distribution.

2. Methods

The current density is a vector function, $\vec{J}(x,y,z)$ defined at every point in a conductive medium, whose direction is that of the current flow at the point under consideration and whose magnitude is given by the current divided by the area perpendicular to the flow, as this area tends to zero. The current density is obtained from the electric field, $\vec{E}$, by means of the relation $\vec{J} = \sigma\vec{E}$ where σ is the electric conductivity of the tissue. In turn, the electric field is determined by the spatial rate of change (gradient) of the electric potential, φ, i.e. $\vec{E} = -\nabla\phi$. Finally, the potential inside the conductive medium is obtained by solving the continuity equation, $\nabla \cdot (\sigma\nabla\phi) = 0$, subject to the appropriate boundary conditions.

Following the approach outlined above, we calculated the current density distribution in two different volume conductors for various electrode configurations, using a finite element package (Comsol 3.3 with AC/DC module, http://www.comsol.com) to solve the continuity equation numerically. Electrodes were modeled as square sponges, 1 cm thick and with an electrical conductivity taken to be equal to that of the scalp, $\sigma = 0.332$ S/m. The only exception was the 100 cm^2 electrode, whose dimensions were 16.9×5.9 cm^2. The upper surfaces of the two electrodes were set to uniform electric potentials, and the potential difference was chosen so that the total injected current was equal to the desired value, e.g., 1 mA. The method is described in more detail in Miranda et al., (2006).

In both models the target point was located 12 mm below the electrode–conductor interface, under the electrode's center. This distance corresponds to the scalp–brain distance in the spherical model.

In the first model, one square electrode was placed centrally on the upper base of a homogeneous cylindrical conductor ($\sigma = 0.332$ S/m) and an identical electrode was placed symmetrically on the lower base. The current density distribution is shown in a plane that passes through the center of the electrode and contains the axis of the cylinder. Only the upper half of the distribution is shown, as the lower half is the reflection of the upper half. The purpose of these calculations was to investigate the effect of electrode size on the current density distribution, without the confounding effects of tissue geometry and heterogeneity.

In the second model, two electrodes were placed on a standard 3-layer spherical head model with $r_{\text{scalp}} = 9.2$ cm, $r_{\text{skull}} = 8.5$ cm, $r_{\text{brain}} = 8.0$ cm (Rush and Driscoll, 1969) and slightly different conductivities, $\sigma_{\text{scalp}} = \sigma_{\text{brain}} = 0.332$ S/m, $\sigma_{\text{brain}}/\sigma_{\text{skull}} = 40$ (Goncalves et al., 2003). One electrode was placed over the motor cortex and the other over the contralateral eyebrow. For convenience, the first electrode will be referred to as the "stimulation" electrode and the second one as the "reference" electrode, even though such terms do not necessarily reflect their effective roles (Nitsche et al., 2007). Either electrode can be the anode or the cathode; this choice affects only the direction of the current in the head, not its magnitude. Three different sets of calculations were performed to investigate the effect of electrode size on the current density distribution in the brain, taking into account tissue heterogeneity.

In the first set of calculations, the area of the reference electrode was fixed at 35 cm^2 while the area of the stimulation electrode and the injected current were varied in such a way as to keep I/A constant at 1/35 mA/cm^2. The magnitude of the current density at the target point below the stimulation electrode is reported.

In the second set of calculations, the area of the stimulation electrode and the injected current were kept constant at 35 cm^2 and 1 mA, respectively, as the area of the reference electrode was varied. The magnitude of the current density at the target point below the reference electrode is reported.

In the third set, the area of the reference electrode was fixed at 35 cm^2 while the area of the stimulation electrode was varied. The injected current was adjusted so as to fix the current density at the target point at a constant value, 0.0087 mA/cm^2, which is equal to its value when the area of both electrodes is equal to 35 cm^2 and the injected current is 1 mA. The intensity of the current injected into the electrode is reported.

3. Results

For the cylindrical conductor, the current density distribution was calculated for a pair of square electrodes with an area of 35 cm^2 each and an injected current of 1 mA (Fig. 1, left) and for a pair of electrodes with an area of 35/4 cm^2 each and an injected current of 1/4 mA (Fig. 1, right). In both cases $I/A = 1/35$ mA/cm^2. The magnitude of the current density at the target point is 0.016 mA/cm^2 under the larger electrode and 0.011 mA/cm^2 under the smaller electrode. The color scale is common to both plots and is maximal at 0.040 mA/cm^2 to facilitate the visual comparison of the current density near the target point. The current density near the electrode edges in contact with the cylinder reached values higher than this, up to 0.086 mA/cm^2, and they are all shown as dark red. When the current injected into an electrode was doubled, then the current density distribution remained the same but its magnitude is doubled everywhere in the conducting volume, independently of electrode size (not shown). Similar plots for the current density distribution in a spherical model of tDCS of the motor cortex can be found in Miranda et al. (2006).

The spherical head model used in this study is shown in Fig. 2, with a 1 cm^2 electrode over the motor cortex and a 35 cm^2 electrode over the right eyebrow. The color plot shows the magnitude

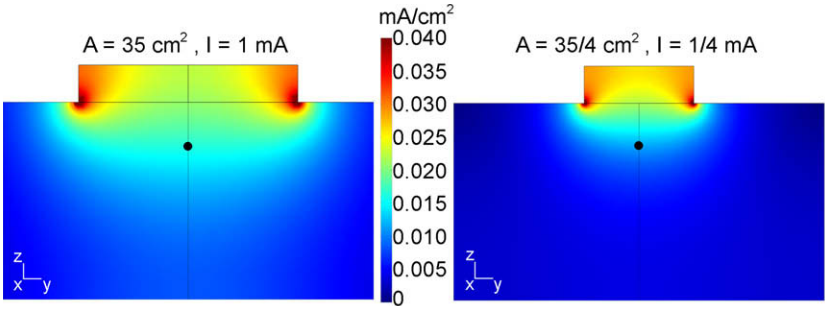

Fig. 1. Effect of decreasing the electrode area on the current density distribution whilst maintaining a constant I/A ratio. At a target point at fixed depth of 12 mm (black dot), the current density is lower for the smaller electrode.