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Modeling the current distribution during transcranial direct current stimulation

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Abstract

Objective: To investigate the spatial distribution of the magnitude and direction of the current density in the human head during transcranial direct current stimulation (tDCS).
Methods: The current density distribution was calculated using a numerical method to implement a standard spherical head model into which current was injected by means of large electrodes. The model was positioned in 'MNI space' to facilitate the interpretation of spatial coordinates.
Results: The magnitude and direction of the current density vector are illustrated in selected brain slices for four different electrode montages. Approximately half of the current injected during tDCS is shunted through the scalp, depending on electrode dimension and position. Using stimulating currents of 2.0 mA, the magnitude of the current density in relevant regions of the brain is of the order of 0.1 A/m^2, corresponding to an electric field of 0.22 V/m.
Conclusions: Calculations based on a spherical model of the head can provide useful information about the magnitude and direction of the current density vector in the brain during tDCS, taking into account the geometry and position of the electrodes. Despite the inherent limitations of the spherical head model, the calculated values are comparable to those used in the most recent in vitro studies on modulation of neuronal activity.
Significance: The methodology presented in this paper may be used to assess the current distribution during tDCS using new electrode montages, to help optimize montages that target a specific region of the brain or to preliminarily investigate compliance with safety guidelines.

Keywords: Stimulation; Electric; Direct current; Polarization; Transcranial; Motor cortex

1. Introduction

Long term changes in motor cortex excitability following transcranial direct current stimulation (tDCS) have been recently demonstrated non-invasively in humans (Nitsche and Paulus, 2000, 2001; Priori et al., 1998). During tDCS, a weak electrical current (≤ 1 mA) was applied using two surface electrodes and after tDCS changes in cortical excitability were assessed using transcranial magnetic stimulation (TMS). Since then this phenomenon has been reproduced by several groups of authors, mostly using the same montage of electrodes: one placed over the hand representation in the primary motor cortex and the other above the contralateral eyebrow. Many of these studies aimed at clarifying the mechanisms underlying the physiologic effects of tDCS (Ardolino et al., 2005; Baudewig et al., 2001; Liebetanz et al., 2002; Nitsche et al., 2004). However, much of this renewed interest in tDCS derives from its potential use in therapeutic applications (see (Priori, 2003) for an historical perspective). Recently, tDCS has been used for the experimental treatment of Parkinson's disease (Lomarev, 1996; Lomarev

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et al., 1991, 1993) and for electroanalgesia with pulsed currents (Mignon et al., 1996). In these cases, a frontal-mastoid montage was used, with 1 frontal electrode and two electrodes over the mastoids. Further information on the experiments reported in Russian by Lomarev et al. can be found in Table T1 of the supplementary material, available in the on-line version of this paper. Other potential applications are in assisting recovery after stroke (Fregni et al., 2005a) and in the treatment of depression (Fregni et al., 2005b). In this last case, the proposed montage consists in one anode placed over the left dorso-lateral prefrontal cortex (DLPC) and one cathode placed above the contralateral eyebrow.

Despite the increased use of tDCS and its foreseeable clinical applications, the spatial distribution of the current density within the volume of the human brain for a given electrode montage is largely unknown.

In 1968, Rush and Driscoll (1968) derived an analytical solution for the spatial distribution of the current flowing in the brain, supplied through surface electrodes. The head model consisted of three concentric spheres representing the scalp, skull and brain and current was injected through two point-like electrodes. They found a good agreement between the calculated values and those measured in a realistically shaped experimental setup (human skull suspended in head shaped receptacle filled with saline solution). A more recent calculation is also limited to point-like electrodes (Ferdjallah et al., 1996).

Here, we look at the current distribution in the brain using four different tDCS montages. Electrode size and shape is taken into account in our calculations, given the considerable extent of the electrodes necessarily used in tDCS.

2. Methods

The results reported in this paper were obtained using the finite element (FE) method (Johnson, 1997). This standard numerical technique for solving partial differential equations is used to calculate a solution for the current density distribution (in A/m^2) based on a model of the volume conductor (head) and of the electrodes, in which both their geometry and their physical properties are specified. The three-dimensional distribution is calculated throughout the volume of the model and can be viewed in any slice chosen by the user or on the model's boundaries.

The widely used spherical head model of Rush and Driscoll (1969) was implemented, with the original radii and electrical conductivity values, using a commercial finite element program ($r_{scalp}=9.2$ cm, $r_{skull}=8.5$ cm, $r_{brain}=8.0$ cm and $\sigma_{scalp}=\sigma_{brain}=0.450$ S/m, $\sigma_{skull}=0.006$ S/m; Femlab 3.1 with electromagnetics module, http://www.comsol.com).

The electrodes in these simulations were based on electrodes supplied by Amrex-zetron, Inc. (http://www.amrex-zetron.com), which consist of a metal mesh held over a 1 cm thick sponge by a rubber frame. The sponge is soaked in physiologic saline solution before being applied to the scalp. The area of the sponge in contact with the skin is 5×5 cm^2 for the small electrode and 6.5×15 cm^2 for the large one (Amrex®, part no. 2-A103 and part no. 2A-105, respectively). These electrodes were modeled as rectangular cutouts from a 1 cm thick spherical shell placed over the scalp (see figures). The outer surface of the electrode, in contact with the metal mesh, was taken to be at a uniform electric potential. The electrical conductivity of the electrode will be lower than that of physiologic solution (approx. 2.0 S/m) due to the presence of the sponge; we have arbitrarily taken it to be equal to σ_{scalp}.

The positions of the electrodes on the spherical model were determined from distances measured from Cz along the scalp in the posterior–anterior and medial–lateral directions on an 'average' head. In order to report current density values at anatomically relevant locations in the brain, the spherical model was positioned in MNI-space by visual inspection of its superposition on the ICBM152 template using MRIcro (Brett et al., 2002; Rorden and Brett, 2000). For a reasonable fit around the vertex as well as the motor and premotor areas, the three concentric spheres were centered on a point whose MNI coordinates are (0, −18, 2). The position of these spheres in the midsagittal slice of the ICBM152 template can be viewed in Fig. S1 of the supplementary material. See (Gehring and Willoughby, 2002), on-line supplementary material, for a similar choice: (0, −16, 6). The MNI coordinates of some points of interest were taken to be: vertex or Cz on the scalp (0, −10, 94), center of gravity of the representation of the abductor pollicis brevis in the left primary motor cortex or $M1_{APB}$ (−35, −27, 56) (Denslow et al., 2004), point within the left dorso-lateral prefrontal cortex or DLPC (−35, 24, 59). Conversions between Talairach and MNI coordinates were performed using M. Brett's routines, available at http://www.mrc-cbu.cam.ac.uk/Imaging/Common/mnispace.shtml, and the resulting coordinates rounded to the nearest millimeter.

Results are reported for four electrode montages consisting of one anode and one or two cathodes. The potential difference between the electrodes was adjusted so that the total DC current injected through the anode was always 2.0 mA. When there are two cathodes, 1.0 mA was extracted through each cathode.

3. Results

The first montage considered is the one used for tDCS of the motor cortex, using two small electrodes (5×5 cm^2). The anode was placed with its center radially over the left $M1_{APB}$ and the cathode was placed above the right eyebrow with its center 155 mm anterior and 40 mm lateral to Cz. Fig. 1 shows the current density in the brain and skull in the