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Comparing different electrode configurations using the 10-10 international system in tDCS: a finite element model analysis

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***Abstract*—For the past few years, the potential of transcranial direct current stimulation (tDCS) for the treatment of several pathologies has been investigated. Knowledge of the current density distribution is an important factor in optimizing such applications of tDCS. We use the finite element method to compare three different models in tDCS, where the stimulation electrodes (EEG electrodes) are placed in the 10-10 international system coordinates. We studied the focality and the distribution of the current density in depth and at the surface of the brain for three different electrode configurations. We show that the use of EEG electrodes increases the focality of tDCS, especially when one cathode and several anodes are used. Additionally, these electrodes need less injected current, can be placed at scalp positions whose relationship with the underlying cerebral cortex are known and allow the use of tDCS and EEG recording concomitantly.**

I. Introduction

Transcranial direct current stimulation (tDCS) is a non invasive, painless, safe and portable technique that has been shown to modulate cortical excitability ([1-3]). Its application is simple and economic: a weak DC current (less than 2 mA) is injected between the surface electrodes that are connected to a stimulation device. These advantages combined with the fact that tDCS has shown promising results as a potential therapy in stroke ([4]), Parkinson's disease ([5]), depression ([6]) and epilepsy ([7-8]) reinforce its applicability within the clinical practice. However, the spatial distribution of the current density inside the head and the adequate electrode configuration for specific tDCS applications are not fully understood.

Most of the studies in tCDS use two rectangular electrodes with an area of 35 cm^2. This configuration has several drawbacks in terms of focality ([9]) and control of the impedances at the electrode-scalp interface ([10]). In this work we propose the use of EEG electrodes for tDCS. This kind of electrodes is already used in clinical settings and can be placed in an EEG cap. Moreover, electrode positions can easily be identified in the 10-10 International System and the electrode-skin impedances can be easily monitored. Importantly, the electrodes need less current compared to the larger electrodes, and allow the application of tDCS with the EEG recording concomitantly, which is of great importance in terms of safety, particularly because it allows the monitoring of the interictal activity in epilepsy patients. Some studies have already used smaller electrodes ([11-12]).

We used the finite element method to calculate the distribution of the current density produced in the brain by three different electrode configurations, in which the stimulation electrodes were placed on the surface of a spherical head model according to the 10-10 International System.

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II. METHODS

A. Spherical head model

The 3D spherical head model of Rush and Driscoll ([13]) was adapted in order to implement a four-layer spherical head model. The latter contains four homogeneous and isotropic layers representing the scalp, skull, cerebrospinal (CSF) and brain. The radii and the electric conductivity values were the following r_{brain} = 7.9 cm, r_{CSF} = 8.1 cm ([14-15]), r_{skull} = 8.6 cm and r_{scalp} = 9.2 cm ([16]); σ_{brain} = 0.332 S/m ([17], σ_{CSF} = 1.79 S/m ([18]), σ_{skull} = 0.0083 S/m ([16-17]) and σ_{scalp} = 0.332 S/m ([17]). The model was created using a commercially finite element software package (Comsol 3.4, www.comsol.com). The spherical head model was centered on the origin of an orthonormal reference frame where the x-axes passes through the left and right pre-auricular points and the y-axes passes through the nasion. The positions of the 10-10 International System electrodes are represented in the model by circles (see Fig. 1).

B. Electrode model

We modeled EEG ring electrodes supplied by EasyCap www.easycap.de/easycap/e/products/products.htm). These consist in an Ag/AgCl sintered ring (11.8 mm O.D., 5.0 mm I.D., 2.0 mm high) that is snapped into an adaptor (2.45 mm high) on the EEG cap. Only the lower surface of the ring, closer to the scalp, is conductive. Thus, the electrode was modeled as two cylinders of gel. The first, 2.45 mm high, filled the space between the scalp and the electrode ring. The second, 2.0 mm high, occupied the center of the electrode ring (see Fig. 1). The gel surface in contact with the conductive electrode surface was set to be at a uniform electric potential. The electrical conductivity of the gel (http://www.electro-cap.com) was measured to be 10 S/m.

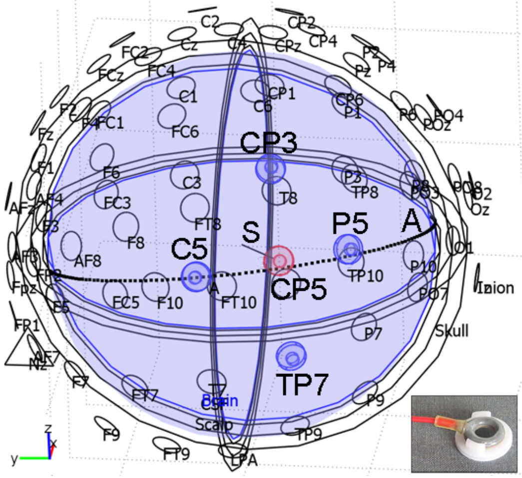

Fig. 1. Representation of the electrode montage M3, where the cathode is placed on the left hemisphere at CP5 (red electrode) and the four anodes are placed around the cathode at C5, TP7, P5 and CP3 (blue electrodes). The radial line (S) in the brain under CP5 and the arc (A) on the surface of the brain and that passes under C5, CP5 and P5 are also shown. The 10-10 system electrodes and the anatomic landmarks are also represented. A ring electrode placed on its adaptor is shown in the inset.

The coordinates of the 10-10 International System electrodes were obtained using the program Source V (www.neuroscan.com/source.cfm) and projected onto the spherical model. The stimulation electrodes used in the three models were placed as follows: M1) two EEG electrodes placed at the FPz and CP5 as shown in Fig. 2a, M2) four EEG electrodes placed at FP1, FPz, FP2 and CP5 as shown in Fig. 2b, and M3) five EEG electrodes placed at C5, TP7, P5, CP3 and CP5 as shown in Fig. 1.

The potential difference between the two electrodes was adjusted so that at a point P on the brain surface and located radially under the cathode (CP5), the magnitude of the current density was the same for all the models: 0.073 A/m^2. We estimated that this is the current density in the brain using a standard configuration of 1 mA into 35 cm^2 electrodes ([19]), which has been shown to modify the excitability in the human brain ([9]). By doing this, we ensured the same current density for each model at point P.

C. Effect on current density of varying number and position of electrodes

In all models the unique cathode was placed in the CP5 position. This choice was motivated by the case of a patient with an epileptogenic focus localized under this electrode position. Since cathodal stimulation has been shown to decrease cortical excitability, this setup may be relevant for this patient. For montage M1, the unique anode was placed at FPz. For montage M2, the three anodes were placed in the frontal cortex where there was no epileptogenic activity (FP1, FPz and FP2). This montage is similar to the one traditionally used to stimulate the motor cortex ([1]). For the third montage, M3, the four anodes were placed around the cathode in C5, TP7, P5 and CP3 positions.

In this study three different montages were compared in terms of the distribution of the current density along the radial line (S) and the arc (A) shown in Fig. 1. The focality of the models was quantified through the calculation of the area (A_{50}) and the volume (V_{50}) of the brain where the current density was within 50% of its maximum power at the brain surfaced ([20]).

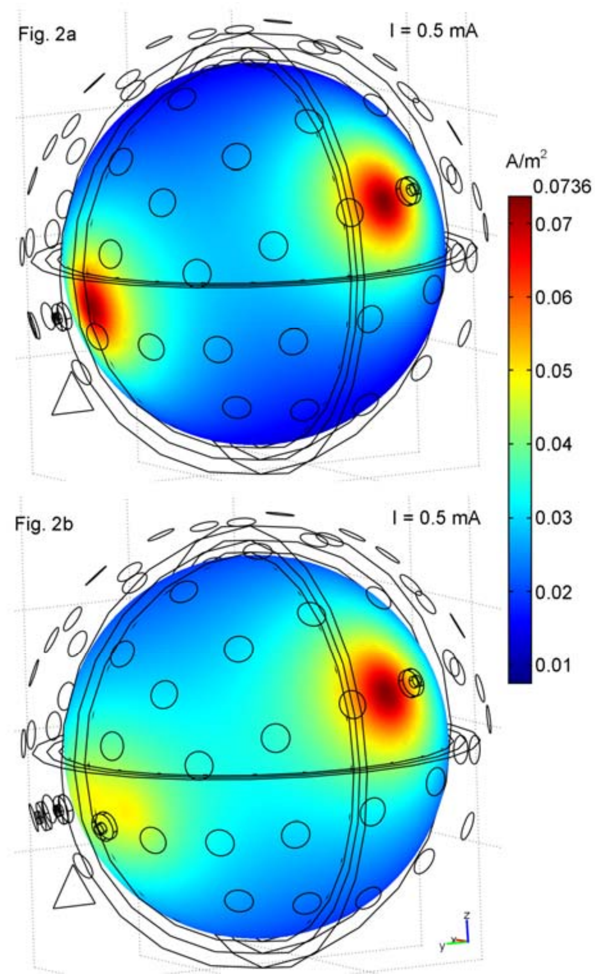

Fig. 2. The distribution of the magnitude of the current density at the surface of the brain for M1 (Fig. 2a) and M2 (Fig. 2b). For both configurations an injected current of 0.5 mA is needed to achieve a current density of 0.073 A/m^2 in the brain under the center of the cathode.

III. RESULTS

A. Comparison of the three electrode montages: in depth

The variation of the current density with depth along a radial line in the brain (S) passing through the center of the cathode, for configurations M1, M2 and M3, is shown in Fig. 3. The results show that the same current density at the surface of the brain, 0.073 A/m^2, is attained with less injected current for the M1 and M2 configurations (0.5 mA) than for the M3 configuration (0.8 mA). Additionally, the current density in M3 decays more rapidly with depth as compared to M1 and M2 montages. At a point 1 cm below the inner surface of the skull, the magnitude of the current density for M1 and M2 is approximately 64.5% of the maximum value obtained in the brain whereas for M3 this value is only 44.9 %.

We also calculated the tangential and the radial components of the current density along line S for the three electrodes configurations studied. For M1, M2 and M3 the radial component was always much larger than the tangential one. For instance, at a point 1 cm below the inner surface of the skull, the tangential component for montages M1 and M2 was 16% of the maximum value obtained in the brain whereas for M3, this value was 3.4%. For both M1 and M2, the radial component at the same point was 64% whereas for M3, it was 44%. Thus, the ratio of the tangential and radial components was 25% for M1 and M2 and 7.7% for M3.

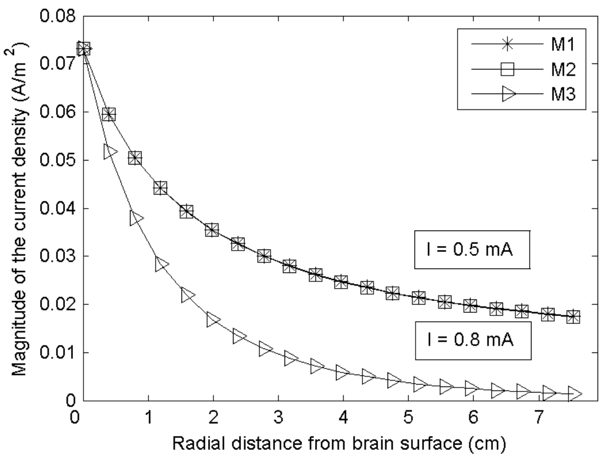

Fig. 3. Comparison of the magnitude of the current density in the brain along a radial line (S) passing through the center of the cathode, CP5, for the three electrode configurations.

B. Comparison of the three electrode montages on the surface of the brain along arc A

For the three electrode montages, the magnitude of the current density and its tangential and radial components were calculated along arc (A). The arc length is four times the angular distance from C5 to P5. The results obtained for M1 and M2 have approximately the same trend but are different from the ones obtained for M3 (see Fig. 4).

The magnitude of the current density for M1, M2 and M3 peaks under the cathode (see Fig. 4a). For M1 and M2 it decreases more slowly with distance from the cathode but then increases as the arc approaches the anode(s), to the left of the graph. In M3 it decreases rapidly under the cathode and becomes almost zero at the extremities of the arc.

The tangential component of the current density for the three montages is shown in Fig. 4b. Its distribution is almost indistinguishable for M1 and M2 except close to the anode(s), where the tangential component is higher when just one anode is used. For the three electrode montages a minimum exists below the cathode. For M1 and M2 this component increases with distance from this electrode, reaches a peak and then remains fairly high. In M3, two peaks are seen below C5 and P5, and then the tangential component decreases to almost zero as the distance from these electrodes increases.

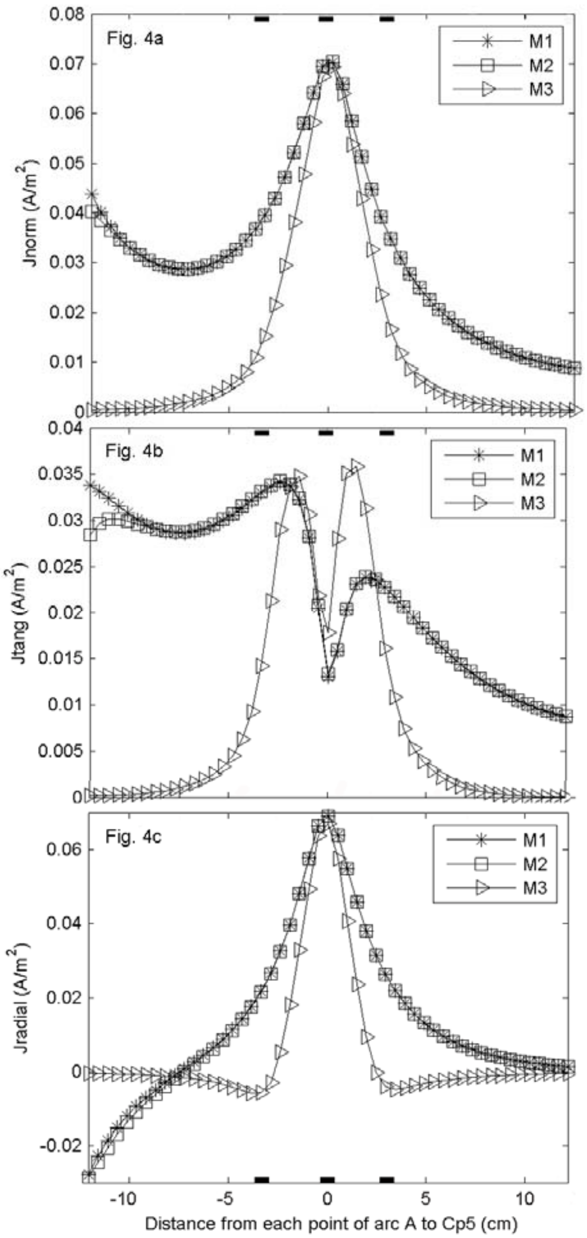

Fig. 4. Comparison of the current density distribution in the brain along an arc (A) that passes through C5, Cp5 and P5. Fig. 4a shows the plot of the magnitude of the current density, Fig. 4b the plot of the tangential component of the current density whereas Fig. 4c presents the radial one. The black rectangles represent the radial projection of the electrodes on the brain surface.

The radial component of the current density for the three montages is shown in Fig. 4c. It is highest under the cathode and decreases with distance from this electrode. For M3, the radial component decreases more rapidly than for M1 and M2 and it becomes negative right below the two anodes C5 and P5. Away from the cathode, the radial component for M3 becomes approximately zero. For M1 and M2, the radial component also tends to zero away from anode(s) (right). Close to the anodes, it decreases and becomes negative (left).

C. Comparison of the three electrode montages: a focality study

The A_{50} areas were 19.9 cm^2 for M1, 10.0 cm^2 for M2 and 5.2 cm^2 for M3. The V_{50} volumes were 7.3 cm^3 for M1, 3.7 cm^3 for M2 and 1.0 cm^3 for M3.

IV. DISCUSSION

This study quantifies the current density distribution in a spherical head model using different electrode montages to stimulate the central parietal region. In these models, EEG electrodes positioned using the 10-10 International System were used for stimulation. These smaller electrodes allow the use of tDCS with lower injected currents and help to increase focality under the region of interest. They also allow the application of tDCS concomitantly with the EEG recording, which is of great importance for safety reasons.

The comparison of configurations M1, M2 and M3 presented in this work suggest that the use of several anodes and one cathode for cathodal DC stimulation helps to increase the focality of cortical stimulation in the sense that it allows a significant reduction of the functional effects of anodic stimulation (see Fig. 2). For instance, the magnitude of the current density at a point on the brain surface under FPz is 40% lower than the one obtained at the same point with M1. This may improve the interpretation of the functional effects of stimulation, which is of special importance in clinical settings, such as the treatment of epilepsy ([9]).

The comparison of M2 and M3 electrode montages shows that on the cortex, M3 is more focal under the cathode than M2, at the expense of more injected current (Fig. 4c). These results show that in M3 the radial component of the magnitude of the current density under the anodes is 10% of the one attained under the cathode. Therefore, M3 affects almost exclusively a small brain area under the cathode. However stimulation of deep regions is better achieved with M2. This electrode configuration is also focal under the cathode, needs less injected current and achieves higher current density values in depth.

Preliminary calculations indicate that the current density at the edge of the electrodes in contact with the scalp may be up to a factor of ten larger for these EEG electrodes than for a 35 cm^2 electrode. It is therefore extremely important that the electrode-scalp impedance be minimized using the usual EEG techniques.

The kind of modeling presented here can help to determine which is the best electrode montage for a particular tDCS application. The possibility of choosing the electrode montage that maximizes the current density in the targeted brain region may be useful to optimize modulation of cortical excitability.

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