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Effects of tissue dielectric properties on the electric field induced in tDCS: a sensitivity analysis

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Abstract— **Numerical modeling studies remain the only viable way to accurately predict the electric field (E-field) distribution in transcranial direct current stimulation (tDCS). Despite the existence of multiple studies of this kind, a wide range of different values and properties for the electrical conductivities of the tissues represented is employed. This makes it difficult to predict whether the changes observed between models are due to differences in the geometries of the volume conductors or to the different electrical properties of the tissues. In this study we used the finite element method to calculate the E-field distribution in several spherical head models whose tissues were represented with different isotropic and anisotropic conductivity profiles. Results show that the distribution of the E-field is especially sensitive to the conductivity of the skull, skin and GM. These results might help comparing numerical modeling studies that employ different conductivity values.**

I. Introduction

In recent years several studies have pointed out a wealth of putative applications of transcranial direct current stimulation (tDCS). These include several neuropsychiatric disorders, recovery from stroke and pain relief ([1]). This interest has spurred the appearance of several papers describing the electric field (E-field) distribution in tDCS (e.g., [2]-[4]). Most of these papers make use of numerical modeling (finite element method, FEM) to determine the E-field distribution in spherical or realistic models of the head. One important parameter of these models is the set of dielectric properties used to represent the different tissues. Given that measurements of the electrical conductivity of brain tissues at very low frequencies are scarce, and that a high variability exists among them, different studies use different values. Conductivity values for the skin, for instance, vary between 0.33 S/m ([4]) and 0.465 S/m ([3]). Skull's conductivity also varies significantly among studies. The works that involve measurements of the conductivity report results ranging between 1/80 ([5]) and 1/15 ([6]) of the skin's conductivity. Numerical modeling studies employ a similar range of values: between 1/40 ([3], [4]) and 1/80 of the skin's conductivity ([2]). Values used to model the cerebrospinal fluid (CSF) are mostly consistent among studies: 1.79 S/m (following the value reported by [7]). Regarding the gray matter (GM), a value of 0.32 S/m has been employed in some modeling studies ([4]). However other studies, involving experimental measurements, suggest different studies, some lower (0.17 S/m, [6]) and some higher (0.4 S/m, [8]). Finally regarding the white matter (WM) an effective isotropic value of 0.15 S/m seems to be suggested by most measurements ([6]), and is also employed in numerical modeling studies ([4]). Another source of variability between studies is the fact that, while most studies do not take into account tissue anisotropy, some recent studies do ([9]). Two tissues which are usually considered to be highly anisotropic are the skull and the WM.

In this work we determine the effects of different tissue conductivity values on the E-field distribution induced by tDCS on a spherical head model.

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II. Methods

A. Head model and electrode design and placement

In this study we modeled the head as five concentric spheres, each sphere representing a different tissue. The radii of the spheres representing the scalp, skull, CSF, GM and WM were, respectively: 9.2 cm, 8.6 cm, 8.1 cm, 7.9 cm and 7.6 cm.

Two rectangular 35 cm^2 electrodes were represented in the model, as shown in **Fig. 1**. A perfect electrical contact was assumed between the electrodes and the scalp.

B. Electrical properties of the different head tissues

In this work we created several different models, with different values assigned to the conductivity of each tissue. The values used in the models where only isotropic conductivities were assigned are summarized in **Table I**.

In some of the models, the skull and WM were modeled as anisotropic. In these compartments the conductivity was represented as a matrix. The conductivity matrix was obtained with the expression: $\sigma = S\sigma_{SPHERICAL}S^{-1}$, where $\sigma_{SPHERICAL}$ is the conductivity matrix in the space of spherical coordinates ($\sigma_{SPHERICAL} = diag(\sigma_R, \sigma_T, \sigma_T)$, where σ_R is the conductivity in the radial direction and σ_T is the one in the tangential direction), and S is a 3×3 matrix where each column is the versor of the spherical coordinate space associated with the radial (first column) and tangential directions (second and third columns). The values σ_R and σ_T were obtained from the values used in the isotropic models (σ_{iso}) by application of the following volume constraint ([10]): $\frac{4}{3}\pi\sigma_{iso}^{\ 3} = \frac{4}{3}\pi\sigma_R\sigma_T^{\ 2}$. Furthermore, it was necessary to specify a relation between the conductivity

values in the radial and tangential directions: $\sigma_T^{SKULL}=10\sigma_R^{SKULL}$ and $\sigma_R^{WM}=10\sigma_T^{WM}$ ([10]).

C. Electric field calculation

The E-field induced in tDCS ($\vec{E}$) can be calculated by solving Laplace's equation for the electrostatic scalar potential (ϕ) and by taking its derivative ($\vec{E}=-\vec{\nabla}\phi$). The solution to Laplace's equation was obtained by employing the FEM, as implemented by Comsol 3.5a (www.comsol.com). This program contains a package that allows solving Laplace's equation (AC/DC module, conductive media DC package).

Modeling of the geometry and selection of appropriate values for the tissue conductivities was performed as described in the previous sections. The electrodes were modeled with an isotropic conductivity of 2 S/m ([2]), and the potential difference between the two outer surfaces of the electrodes was adjusted so that the injected current was of 1 mA. All other outer boundaries were modeled with an insulating current boundary condition, whereas in the inner boundaries continuity of the radial component of the current density was imposed.

The finite element mesh of all models comprised about 120000 tetrahedral second order Laplace elements. The resulting set of equations was solved by the combined use of an iterative solver (GMRES) and a preconditioner (Incomplete LU). All models took about 2 minutes to solve in a computer with a quad-core Core i7 2630QM CPU and 8 GB of RAM.

TABLE I. CONDUCTIVITY VALUES ASSIGNED FOR THE TISSUES IN THE DIFFERENT MODELS

Isotropy	Tissue	Conductivity values
Isotropic tissues	Skin	$\sigma_{Min}=0.33$ S/m $\sigma_{Max}=0.465$ S/m
	Skull	$\sigma_{Min}=\sigma_{Skin}/80$ $\sigma_{Max}=\sigma_{Skin}/15$
	CSF	$\sigma=1.79$ S/m
	GM	$\sigma_{Min}=0.17$ S/m $\sigma_{Max1}=0.32$ S/m $\sigma_{Max2}=0.4$ S/m
	WM	$\sigma=0.15$ S/m
Anisotropic tissues	Skull	$\sigma_{Iso}=\sigma_{Skin}/15$, $\sigma_{Skin}=0.465$ S/m $\sigma_T=0.067$ S/m $\sigma_R=0.0067$ S/m
	WM	$\sigma_{Iso}=0.15$ S/m $\sigma_T=0.07$ S/m $\sigma_R=0.7$ S/m

D. Data analysis

For each model the E-field distribution was analyzed on both the GM-CSF and WM-GM interfaces, but always on the GM side of the aforementioned interfaces. The maxima of the E-field radial component (E_R), tangential component (E_T) and norm (E_{Norm}) were obtained for each interface. Furthermore the E-field's focality was also assessed by calculating the area pertaining to each interface where the E-field obeyed the following condition:

$$E_{T/R/Norm} \geq 0.5 E_{T/R/Norm\ Max}, \quad (1)$$

where $E_{T/R/Norm\ Max}$ is the maximum value of the tangential / radial or norm of the E-field on the analyzed interface.

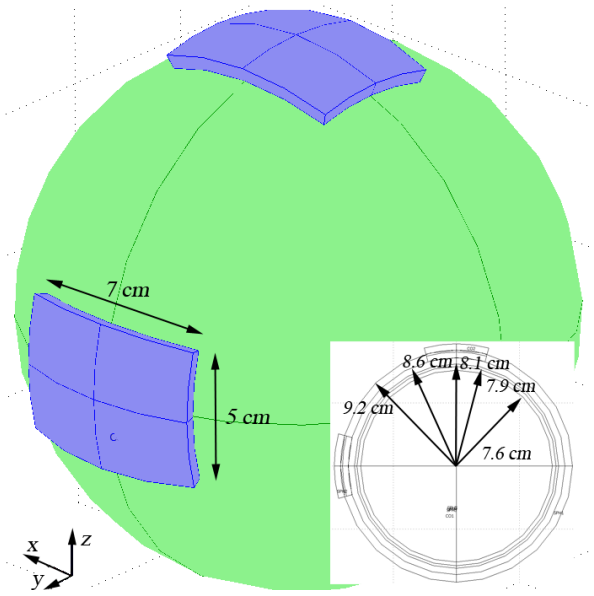

Figure 1. Concentric sphere head model (the radius of each is sphere is shown in the inset). Two rectangular 35cm^2 electrodes are used to inject a current of 1 mA through the tissue.

III. RESULTS

The different models studied in this work showed some remarkably different E-field distributions. This was observed for all components of the field and in all the interfaces considered. The differences for both the isotropic models and for the anisotropic ones are discussed hereinafter.

A. Isotropic models

Decreasing the conductivity of the skin from 0.465 S/m to 0.33 S/m (without changing the conductivities of the other tissues) increased the maximum values of all field components, on both interfaces. The maxima increased to 112% - 116% of the values obtained in the model with a conductivity of 0.465 S/m. The E-field distribution remained almost unaltered by the change in the skin's conductivity. A slight improvement on the focality was, however, observed: the areas calculated with (1) in the model with σ_{Skin}=0.33 S/m decreased to values between 67% and 96 % of the values obtained in the model with σ_{Skin}=0.465 S/m.

Changing the skull's conductivity from $\sigma_{Skin}/15$ to $\sigma_{Skin}/80$ (without changing the conductivities of the other tissues) lead to an expected decrease of the E-field's values. The decrease is observable for all field components and on all the studied surfaces. The maximum values of E_R and E_T decreased to about 50% and 59% of their original value, respectively. The decrease is about the same, irrespective of the interface considered. The E-field distribution is also significantly affected by the decrease in the skull's conductivity (compare **Fig. 2a** with **Fig. 2b**), which leads to

significant changes in the field's focality. This is especially noticeable for E_R, whose focality decreased in the model with lower skull's conductivity: the area given by (1) increased to about 136% (WM-GM) and 139% (GM-CSF) of the values obtained in the model with higher conductivity.

Regarding the conductivity of the GM, decreasing its value from 0.32 S/m to 0.17 S/m increased the contribution of E_R to the E-field's norm. This can be explained by the fact that this change in conductivity increases the maximum value of E_T to 103% (WM-GM) and 105% (GM-CSF), whereas E_R increases to 192% and 176% in the same interfaces. It is interesting to note that the distribution of E_R and E_T is not affected significantly with this change, but the distribution of E_{Norm} is significantly different (compare **Fig. 2a** with **Fig. 2c**). Focality of all the field's components, however, remains almost unchanged. As expected, increasing the conductivity from 0.32 S/m to 0.4 S/m produced the opposite effects: the contribution of E_R to the field's norm was decreased due to a high decrease of E_R (maximum decreased to 82 % in the GM-CSF and 79 % in the WM-GM) and a small decrease of E_T (maximum decreased to 97 % in the GM-CSF and 94 % in the WM-GM). As before, no large changes in focality were observed.

B. Anisotropic models

Specifying an anisotropic conductivity for the skull lead to results similar to those observed when the conductivity of the skull was reduced to its lowest value in the isotropic models. Therefore, almost the same decrease of the maxima of the different components of the E-field was observed (less than 1% variation). Focality of the different components of the E-field also changed accordingly: in the anisotropic skull model, the focality of E_R was the most strongly affected, with areas obeying (1) increasing to about 142% (WM-GM) and 153% (GM-CSF). The E-field distribution obtained in this model is, therefore, very similar to the one obtained in the model with isotropic low skull conductivity (compare **Fig. 2b** and **Fig. 3a**).

In comparison with the isotropic model, the model with anisotropic WM displayed very similar values for the radial component of the E-field in both the GM-CSF and WM-GM interfaces. The maximum values of the tangential component of the E-field, however, increases to about 103% (GM-CSF) and 106% (WM-GM) of the values obtained in the isotropic models. The areas calculated by (1) also showed little variation, decreasing only slightly to values between 92 % and 99 % of those obtained in the isotropic models. The overall field distribution is similar to that obtained in the isotropic models (compare **Fig. 2a** and **Fig. 3b**).

The fully anisotropic model combines both aforementioned effects. Therefore, regarding the maximum values of the components of the E-field, they decreased to values similar to those obtained in the model with the anisotropic skull. The maximum values obtained for E_T (and E_{Norm}), however, were slightly higher in this model, due to the slight boost effect that the anisotropic WM introduces: maximum values of about 105% of the ones obtained in the anisotropic skull model. Regarding focality, again the radial component was the one that suffered the highest change. In this model, the area evaluated from (1) increased to 130% (WM-GM) and 135% (GM-CSF) of the values reported for the isotropic model. Notice that this increase is slightly lower than that reported for the model with only the skull modeled as anisotropic. Finally, the overall field distribution is similar to that obtained in the model with anisotropic skull and isotropic WM (compare **Fig. 3a** and **Fig. 3c**).

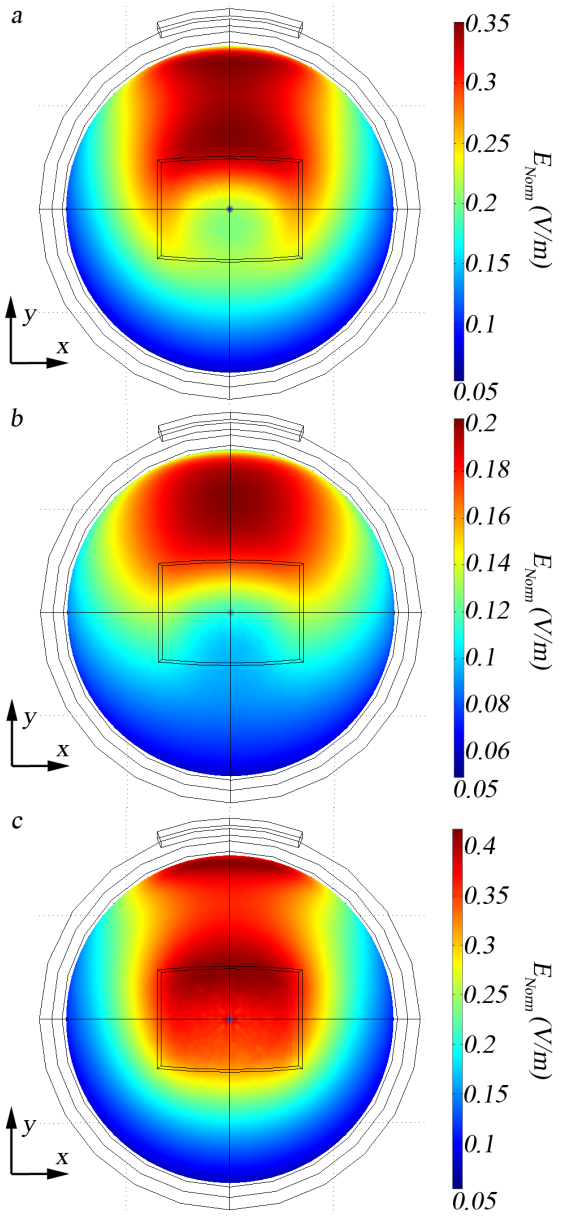

Figure 2. Electric field's norm distribution in the GM-CSF interface (GM side) for different isotropic models: (a) σ_{Skin}=0.465 S/m, σ_{Skull}=σ_{Skin}/15, σ_{GM}=0.33 S/m; (b) Same as (a) but with σ_{Skull}=σ_{Skin}/80; (c) Same as (a) but with σ_{GM}=0.17 S/m.

IV. Discussion

Regarding the effects reported for the skin conductivity changes, they can be explained by the shunting effect that this tissue has on the injected current. Higher skin conductivities lead to higher shunting, which decreases the E-

field maximum values (as less current reaches inner tissues) and decreases focality (more current spread).

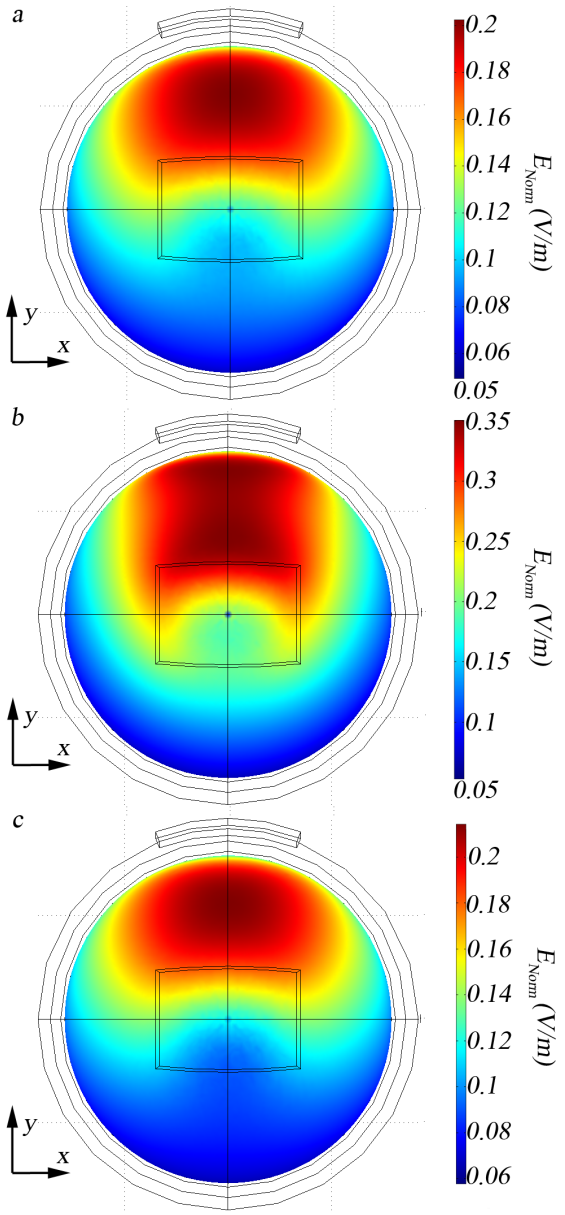

Figure 3. Electric field's norm distribution on the GM-CSF interface (GM side) for different anisotropic models: (a) Anisotropic skull; (b) Anisotropic WM; (c) Anisotropic skull and WM. In all models with anisotropic tissues, σ_{Skin}=0.465 S/m, σ_{CSF}=1.79 S/m and σ_{GM}=0.32 S/m.

The skull is the tissue whose conductivity most influences the E-field distribution. Lower skull conductivities decrease the amount of current reaching the inner tissues, and as such decreases the E-field values. Furthermore current has to spread more before flowing radially across the skull, which significantly decreases the focality of the field in the cortical surface and in the GM side of the WM-GM interface. An anisotropic conductivity profile for the skull resulted in an E-field distribution similar to the one obtained in the isotropic model with lowest conductivity for the skull. This is because the radial conductivity of the anisotropic skull, 0.007 S/m, is similar to the lowest isotropic value used to model the skull, 0.006 S/m.

Regarding the GM, a smaller conductivity value increases the contribution of the radial component of the E-field to the norm. This can significantly affect the E-field distribution making it more focused under the electrodes (where the radial component of the E-field is greatest). The effects of modeling the WM as anisotropic on the other hand, do not produce significant changes in the E-field distribution.

These results were obtained using a very simple spherical head model. However, they are expected to hold when more realistic volume conductors are used because the underlying physical laws that explain these results remain unchanged. The results are also independent on electrode geometry and positioning. In other configurations, however, the relative contribution to the total E-field of its tangential and radial components will differ. Therefore the figures reported here for the changes in the magnitude of the components of the field and its focality will not remain valid. However the same trend of variation should be observed.

This study shows t he importance of taking into account the conductivities assigned to head tissues when comparing different modeling studies of the induced E-field in tDCS.

REFERENCES

[1] M. A. Nitsche, L. G. Cohen, E. M. Wassermann *et al.*, "Transcranial direct current stimulation: State of the art 2008," *Brain Stim,* vol. 1, no. 3, pp. 206-23, Jul, 2008.

[2] P. C. Miranda, M. Lomarev, and M. Hallett, "Modeling the current distribution during transcranial direct current stimulation," *Clin Neurophysiol,* vol. 117, no. 7, pp. 1623-9, Jul, 2006.

[3] A. Datta, V. Bansal, J. Diaz *et al.*, "Gyri-precise head model of transcranial direct current stimulation: Improved spatial focality using a ring electrode versus conventional rectangular pad," *Brain Stim,* vol. 2, no. 4, pp. 201-207, Oct, 2009.

[4] R. Salvador, A. Mekonnen, G. Ruffini *et al.*, "Modeling the electric field induced in a high resolution realistic head model during transcranial current stimulation," *Conf Proc IEEE Eng Med Biol Soc,* vol. 1, pp. 2073-6, 2010.

[5] S. Rush, and D. A. Driscoll, "Current distribution in the brain from surface electrodes," *Anesth Analg,* vol. 47, no. 6, pp. 717-23, Nov-Dec, 1968.

[6] T. F. Oostendorp, J. Delbeke, and D. F. Stegeman, "The conductivity of the human skull: results of in vivo and in vitro measurements," *IEEE Trans Biomed Eng,* vol. 47, no. 11, pp. 1487-92, Nov, 2000.

[7] S. B. Baumann, D. R. Wozny, S. K. Kelly *et al.*, "The electrical conductivity of human cerebrospinal fluid at body temperature," *Ieee Transactions on Biomedical Engineering,* vol. 44, no. 3, pp. 220-223, Mar, 1997.

[8] N. K. Logothetis, C. Kayser, and A. Oeltermann, "In vivo measurement of cortical impedance spectrum in monkeys: implications for signal propagation," *Neuron,* vol. 55, no. 5, pp. 809-23, Sep 6, 2007.

[9] H. S. Suh, S. H. Kim, W. H. Lee *et al.*, "Realistic Simulation of Transcranial Direct Current Stimulation via 3-D High-resolution Finite Element Analysis: Effect of Tissue Anisotropy," *Embc: 2009 Annual International Conference of the Ieee Engineering in Medicine and Biology Society, Vols 1-20*, pp. 638-641, 2009.

[10] C. H. Wolters, A. Anwander, X. Tricoche *et al.*, "Influence of tissue conductivity anisotropy on EEG/MEG field and return current computation in a realistic head model: A simulation and visualization study using high-resolution finite element modeling," *Neuroimage,* vol. 30, no. 3, pp. 813-826, Apr 15, 2006.