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Heat transfer due to electroconvulsive therapy: Influence of anisotropic thermal and electrical skull conductivity

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ABSTRACT

Background and objectives: This paper focuses on electroconvulsive therapy (ECT) and head models to investigate temperature profiles arising when anisotropic thermal and electrical conductivities are considered in the skull layer. The aim was to numerically investigate the threshold for which this therapy operates safely to the brain, from the thermal point of view.

Methods: A six-layer spherical head model consisting of scalp, fat, skull, cerebro-spinal fluid, grey matter and white matter was developed. Later on, a realistic human head model was also implemented. These models were built up using the packages from COMSOL Inc. and Simpleware Ltd. In these models, three of the most common electrode montages used in ECT were applied. Anisotropic conductivities were derived using volume constraint and included in both spherical and realistic head models. The bio-heat transferring problem governed by Laplace equation was solved numerically.

Results: The results show that both the tensor eigenvalues of electrical conductivity and the electrode montage affect the maximum temperature, but thermal anisotropy does not have a significant influence. Temperature increases occur mainly in the scalp and fat, and no harm is caused to the brain by the current applied during ECT.

Conclusions: The work assures the thermal safety of ECT and also provides a numerical method to investigate other non-invasive therapies.

1. Introduction

Electroconvulsive therapy (ECT) is a non-invasive treatment that applies an electric voltage or current on the scalp through electrodes [1], and this electric field (E-field) reaches into deep brain regions [2]. It is an intervention used to treat psychiatric conditions, such as depression, schizophrenia, bipolar maniac states, catatonia and schizoaffective disorders [3]. The stimulation is generated in cycles with pulse currents that vary from 500 mA to 900 mA, frequencies between 20 Hz and 120 Hz for a period of up to 8 seconds [3].

The waveforms used in ECT nowadays are brief and ultra-brief pulses. Finite pulse duration is responsible for neuronal depolarization and seizure induction. For brief pulses, for example, the optimal current duration in the order of 0.1–0.2

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ms may be responsible for producing central neuronal depolarization [3]. The most common electrode configurations are bifrontal (BF), bilateral frontotemporal (BL) and right unilateral (RUL) [1–3]. Electrode placement and stimulus intensity influence cognitive side effects and efficacy [3].

The human body is sensitive to changes in temperature. Even a small increase of approximately 1°C can affect the function of a single neuron and neuronal networks [4,5]. Temperatures higher than 40 °C, can produce cell damage and tissue ablation [5]. Different tissues have different thermal damage thresholds. Details are provided in Yarmolenko et al. [6]. To compensate for any extra heating and to maintain the temperature at an acceptable level, the organism uses metabolic processes.

Some studies considering heat effect during electrical stimulation in the head can be found in the literature. Swartz [7] reported that skin was the only possible site for an electrical burn during ECT. When considering deep brain stimulation (DBS), Elwassif et al. [5] developed a voltage controlled one layer white matter (WM) model, and showed that temperature in the brain increases when the values of electrical conductivity increase, and the temperature decreases when thermal conductivity values rise. When working with transcranial direct current stimulation, Datta et al. [4] reported that the current limits used nowadays are safe to the brain from the thermal point of view. Electrical and thermal physics are also simultaneously considered in brain implant studies [8].

The skull consists of spongiosa (soft bone layer) enclosed by compacta (two hard bone layers). That macroscopic structure is what effectively generates the anisotropy in the skull, as the spongiosa has a much higher conductivity than the compacta [9]. According to Rush and Driscoll [10], the skull can be defined as having an electric conductivity ratio of up to 1:10 radially to tangentially to the skull surface.

Studies of the human head considering skull electrical anisotropy (σ) can be found in the literature [11–13]. Studies considering thermal anisotropy (k) are found in the study of human and animal eyes [14,15]. To the best of our knowledge, until now there have been no studies that have considered thermal anisotropy of the human head under transcranial electrical stimulation; and that have analysed the behaviour of temperature while taking into account electrical anisotropy.

The goal of this study was, first, to analyse the effect of heat transfer on the brain region due to ECT stimulation. Second, with the intention to develop a more realistic head model, we mathematically applied anisotropic thermal and electrical conductivities within the skull layer and examined these influences. The forward solutions were computed for both isotropic and anisotropic versions of a realistic (RHM) and a spherical (SHM) head model using the finite element method (FEM), and we evaluated the results by showing the temperature (T) behaviour within the tissues represented by the model.

2. Methods

2.1. Model details

2.1.1. Spherical geometry

A spherical head model (Fig. 1a–c) with six layers was built using the COMSOL *Multiphysics* 5.1 (COMSOL Inc.) package. Each layer represents one different tissue. These are scalp, fat, skull, CSF (cerebro-spinal fluid), GM (grey matter) and WM. The most external layer was assigned 18.4 cm diameter, as the average size of the adult human head. The layer thicknesses were 5.6 mm for scalp, 3.75 mm for fat, 7.08 mm for skull, 3 mm for CSF, 3 mm for GM and 69.57 mm for WM [16].

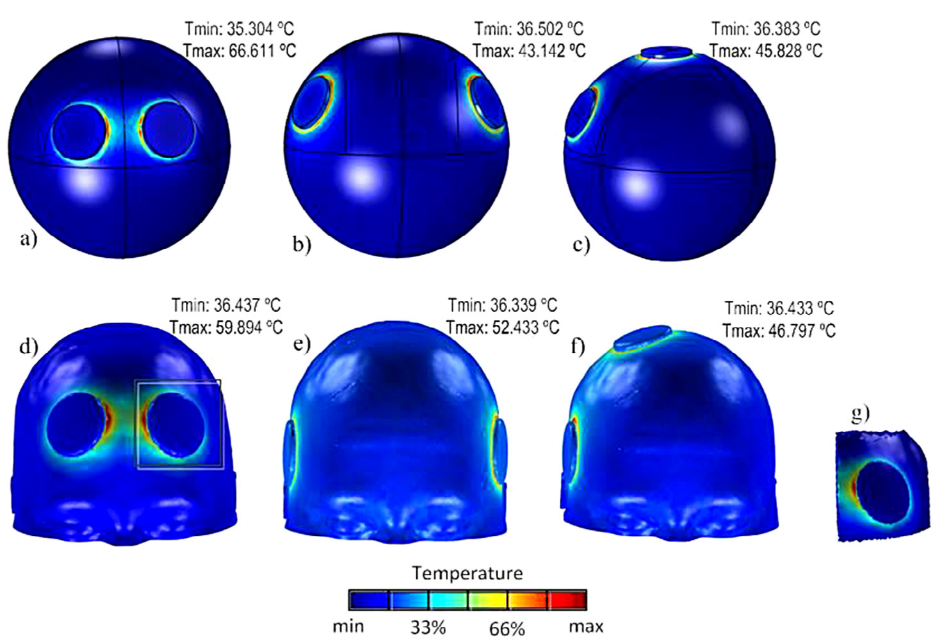

Fig. 1 – Models showing the electrode montage (a) BF, (b) BL and (c) RUL SHM; and (d) BF, (e) BL and (f) RUL RHM. The black box in image (d) represents the (g) region of interest (ROI). The colour map represents temperature. (Color version of figure is available online.)