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Finite Element Simulations of Transcranial Direct Current Stimulation after Decompressive Craniectomy

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Abstract: Decompressive craniectomy is used to treat the patients with brain swelling and the patient's skull is partly removed. Finite element simulation of transcranial direct current stimulation is a mathematical analysis method based on three-dimensional head model analysis of transcranial direct current stimulation current distribution. The impact factors to the including the influence of different electrode shapes, different electrode areas are explored to transcranial direct current stimulation after decompressive craniectomy. when anode area is 10 cm^2 and cathode areas vary from 2 cm^2 to 30 cm^2, the electric field strength of the cathode is hardly affected by the anode area. when cathode area is 10 cm^2 and anode areas vary from 2 cm^2 to 30 cm^2, the smaller the anode area is, the larger the electric field intensity of the cathode is. The stimulation of the circular electrode is better than the square electrode stimulation. The smaller the electrode area, the larger the change of the electric field near the internal electric field electrode. In practice, this study has certain reference value for the choice of tDCS.

1. Introduction

Transcranial Direct Current stimulation (tDCS) is a technology that the direct current(DC) is injected into the brain tissue through the electrode on the subject's head epidermis, which could change the charge distribution on the surface of the membrane, affect the release of neurotransmitters, improve the excitability of neurons, and ultimately regulate brain function in stimulating subjects[1]. Compared with the traditional rehabilitation therapies, tDCS is a noninvasive emerging technique which uses weak current to regulate neuronal activity in the cerebral cortex. Studies have shown that tDCS could be used for aphasia[2-5], motor dysfunction[6-9], cognitive dysfunction[10-13], depression[14-16], disorders of consciousness17-19 and other brain damages caused by disfunction. C Poreisz et al.[10] suggest that tDCS minor adverse effects in healthy humans and patients with varying neurological disorders according to the present tDCS safety guidelines. TDCS result in modifications of perceptual and cognitive and behavioral functions in the different cortical areas, moreover, it can induce beneficial effects in brain disorders[20-22]. GS Shekhawat et al.[23]found tDCS could be helpful for the sound therapy based tinnitus treatments.

Based on the multi-layer three-dimensional finite element model of the real human head and mature finite element methods, the finite element simulation and numerical analysis are applied in the study of tDCS [24-32]. Poor focus of tDCS is a problem to be solved, current stimulation should gather as much as possible in the lesion brain area rather than the non-disease area under ideal conditions. Peterchev[33] et al. have shown that a lot of parameters could influence electrical stimulation, including the stimulation electrode or coil configuration parameters: shape, size, position, and electrical properties, as well as the electrode or coil current waveform parameters and so on. Changes of brain electrical anisotropy and other indicators after brain injury will affect the distribution of current in the brain tissue34. Those changes including scalp surface area, degree of convexity, electrical impedance of skull, intracranial edema and other indicators after bone flap decompression may affect tDCS electric field distribution. By analyzing the vector distribution of the electric field or the current density in the model, it is possible to deduce the distribution of the electric field or current in the head when directly stimulating the human head in practice. Finite element analysis of tDCS in patients after decompressive craniectomy has not been found yet. Taking the patients with complete decompression of craniofacial left crab flap as an example, finite element method is used to simulate the focusing and distribution characteristics of tDCS. After decompressive craniectomy, the shape of the electrod, the location and stimulation parameters (current value, etc.) of tDCS could influence the electric field or current distribution which provide some guidance for practical experiments or applications.

2. Finite Element Simulation and Numerical Analysis of TDCS after Decompressive Craniectomy

2.1. Theoretical Analysis

As long as there is biological activity of living organisms, the body will be accompanied by a series of bioelectric phenomena. Maxwell's equations are the basic point for the analysis and study of bio-electro-magnetism. The differential equations of Maxwell's equation are expressed as follows

$$\nabla \cdot \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \tag{1}$$

$$\nabla \cdot \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{2}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{3}$$

$$\nabla \cdot \mathbf{D} = \nabla \varepsilon \mathbf{E} = -\nabla \varepsilon \nabla \mathbf{V} = \rho \tag{4}$$

where **H** is Magnetic field strength vector (A/m), **E** is the field strength vector (V/m), **B** is magnetic induction vector (T), **D** is the electric displacement vector (C/m^2), **J** is the current density vector (A/m^2), **V** is the potential vector (V), ρ is the charge density (C/m^3).

In the Maxwell's equations, the relationship of field could be expressed as

$$\mathbf{D} = \varepsilon \mathbf{E} \tag{5}$$

$$\mathbf{B} = \mu \mathbf{H} \tag{6}$$

$$\mathbf{J} = \sigma \mathbf{E} \tag{7}$$

where ε is the relative permittivity, μ is the tissue permeability, σ is the tissue conductivity.

Transcranial micro-current stimulation therapy is usually stimulated with a constant intensity current and the electric field created by a constant current is defined as a constant electric field in an electric field theory. The Maxwell's equations for a constant electric field can be expressed as

$$\nabla \times \mathbf{H} = \mathbf{J} \tag{8}$$

$$\nabla \times \mathbf{E} = 0 \tag{9}$$

Scatter the Eq. (8) on both sides, with the theory that the divergence of the curl of any vector is always equal to zero. we can obtain

$$\nabla \cdot \nabla \times \mathbf{H} = \nabla \cdot \mathbf{J} = 0 \tag{10}$$

The internal current propagation also conforms to Gauss's law. The total amount of current can be expressed as the sum of the source current and the conduction current and the equation can be written as

$$\mathbf{J} = \sigma \mathbf{E} + \mathbf{J}_e \tag{11}$$

where J is the total current density (A/m2), σE is the conduction current density vector (A/m2), Je is the source current density vector (A/m2).

By submitting Eq. (11) into Eq. (10), we can obtain

$$\nabla \cdot \nabla \times \mathbf{H} = \nabla \cdot \mathbf{J} = \nabla \cdot (\sigma \mathbf{E} + \mathbf{J}_e) = \nabla \cdot \sigma \mathbf{E} + \nabla \cdot \mathbf{J}_e = 0 \tag{12}$$

At the meantime, scalar potential φ is introduced, the relationship between E and φ can be expressed as

$$\mathbf{E} = -\nabla \varphi \qquad (13)$$

By submitting Eq. (13) into Eq. (12), we can obtain

$$\nabla \cdot \sigma \nabla \varphi = \nabla \cdot \mathbf{J}_e \qquad (14)$$

The certain voltage and the electric field strength can be attain as the current is input to the field. but for the current source region, $\mathbf{J}_e = 0$, the potential function of the equation can be expressed as

$$\nabla \cdot \sigma \nabla \varphi = 0 \qquad (15)$$

In isotropic homogeneous dielectric, the current in the media follow the law of conservation of charge, that is, the current continuity equation could be expressed as

$$\nabla \cdot \mathbf{J} = -\frac{\partial \rho}{\partial t} \qquad (16)$$

where t is time.

Adjacent subfields with the current continuity equation can be expressed as

$$\mathbf{n} \cdot (\mathbf{J}_i - \mathbf{J}_{i+1}) = 0 \qquad (17)$$

where n is the vector perpendicular to the tissue.

Combinate with the previous equations, the distribution of the electric field, the distribution of the electric field intensity and the current density can be obtained.

2.2. Electric Field Analysis with Different Stimulations

According to the anatomical structure of the human head and practical application needs, human head could be simplified and selected from the inside to the scalp, skull, cerebrospinal fluid and brain. The Mimics software was used to import CT images of patients to generate three-dimensional geometric models of scalp, skull, cerebrospinal fluid and brain. Geomagic Studio is used to fit the NURBS surface and get the solid geometry entities, and finally Finite Element Method is used to simulate the stimulating. The skull has a 40 cm^2 hole on the left to approximately model the condition that patient went through craniocerebral trauma who underwent decompressive craniectomy. In the finite element model, each layer of scalp, skull, cerebrospinal fluid and brain is considered as a material with isotropic homogeneous dielectric and relative parameters, and those are shown as follows in Table 1.

Table 1: The size and conductivity of each layer of tissue.

organization name	electrical conductivity(S/m)	relative permittivity
scalp	0.13004	5.2239
skull	0.50624	11.066
cerebrospinal fluid	4.0054	65.39
brain	1.5106	35.541

In the location of the electrode in contact with the scalp electric field distribution is more complicated, so in the split, the software automatically set the grid of the region most intensive, the other areas are relatively sparse. The steady state solution is selected and the relative error is set 0.001. The individual differences of the human body and external influences are ignored. The current is applied to the electrode pads in contact with the skin when stimulated. Electrode is set to be symmetrical on both sides of epidermis model, the shape of the contact part between the electrode and the model is a spherical cap. There is no current outflow in the scalp which was electrically isolated characteristics. Electrode anode current direction inwards applying different stimulation currents and the cathode end is grounded in which the potential is zero, as shown in Figure 1. Some certain conditions are considered to compare the electric field distribution including the influence of different electrode shapes, different electrode areas. The electrode shape includes: the square and the circlular. The electrode areas include: 2cm2, 5 cm2, 10 cm2, 20 cm2, 30 cm2. Current intensity is considered from 0.1mA to 2 mA.

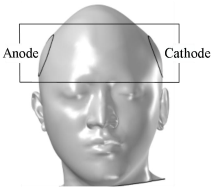

Figure 1: Electrical stimulation of the head model.

3. Results and Discussions

3.1. Stimulation Effect Analysis on the Electrode Areas

The excitation current intensity is 2 mA. The cathode area is 10 cm^2 and the anode areas are respectively 2cm^2, 5 cm^2, 10 cm^2, 20 cm^2, 30 cm^2. Electrode shape is selected with the circular as shown in Figure 2 and electrode shape is selected with the square as shown in Figure 3. Simultaneously, the anode area is 10 cm^2 and the cathode areas are respectively 2cm^2, 5 cm^2, 10 cm^2, 20 cm^2, 30 cm^2. Electrode shape is selected with the circular as shown in Figure 4 and electrode shape is selected with the square as shown in Figure 5. As can be seen from Figure 2 and Figure 3, when anode area is 10 cm^2 and cathode areas vary from 2 cm^2 to 30 cm^2, the electric field strength of the cathode is hardly affected by the anode area. As can be seen from Figure 4 and Figure 5, when cathode area is 10 cm^2 and anode areas vary from 2 cm^2 to 30 cm^2, the smaller the anode area is, the larger the electric field intensity of the cathode is.

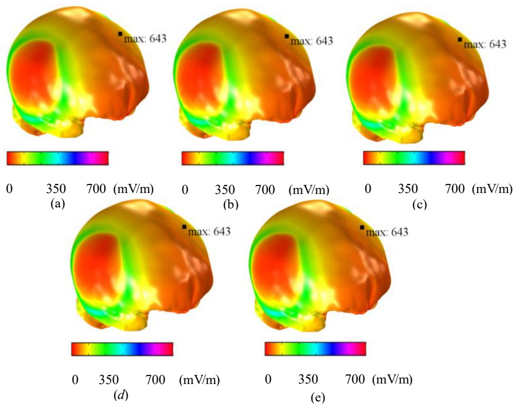

Figure 2: The electrode shape is circular. (a) The electric field distributions with cathode area of $2cm^2$; (b) The electric field distributions with cathode area of $5cm^2$; (c) The electric field distributions with cathode area of $10cm^2$; (d) The electric field distributions with cathode area of 20 cm^2; (e) The electric field distributions with cathode area of $30cm^2$.

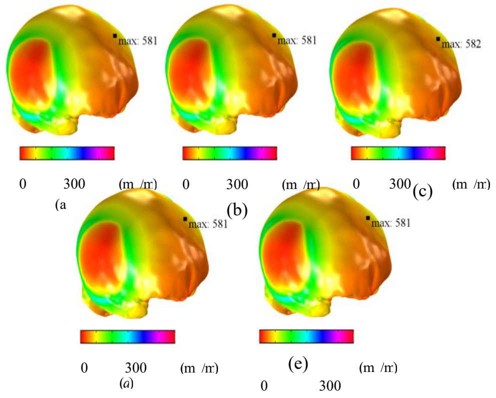

Figure 3: The electrode shape is square. (a) The electric field distributions with cathode area of $2cm^2$; (b) The electric field distributions with cathode area of $5cm^2$; (c) The electric field distributions with cathode area of $10cm^2$; (d) The electric field distributions with cathode area of $20cm^2$; (e) The electric field distributions with cathode area of $30cm^2$.

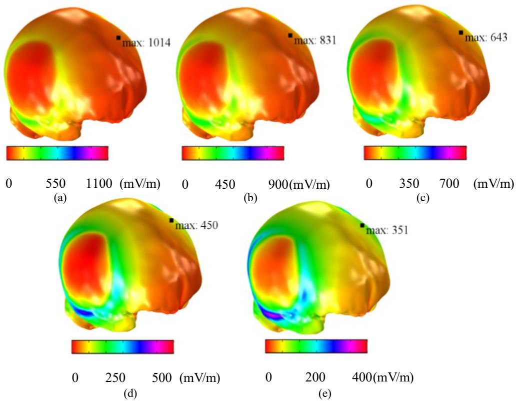

Figure 4: The electrode shape is circular. (a) The electric field distributions with anode area of $2cm^2$; (b) The electric field distributions with anode area of $5cm^2$; (c) The electric field distributions with anode area of $10cm^2$; (d) The electric field distributions with anode area of $20cm^2$; (e) The electric field distributions with anode area of $30cm^2$.

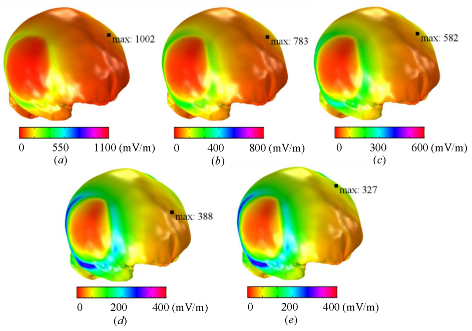

Figure 5: The electrode shape is square. (a) The electric field distributions with anode area of $2cm^2$; (b) The electric field distributions with anode area of $5cm^2$; (c) The electric field distributions with anode area of $10cm^2$; (d) The electric field distributions with anode area of $20cm^2$; (e) The electric field distributions with anode area of $30\ cm^2$.

3.2. Stimulation Effect Analysis on the Electrode Shapes

The excitation current intensity is 1 mA, electrode shape is selected with the circular as shown in Figure 6 and electrode shape is selected with the square as shown in Figure 7. When the electrode shape is circular, the maximum electric fields along the electrode area of $2cm^2$, $5\ cm^2$, $10\ cm^2$, $20\ cm^2$, $30\ cm^2$ are respectively 505 mV/m, 421 mV/m, 322 mV/m, 222 mV/m, 173 mV/m. When the electrode shape is square, the maximum electric fields along the electrode area of $2cm^2$, $5\ cm^2$, $10\ cm^2$, $20\ cm^2$, $30\ cm^2$ are respectively 445mV/m, 381 mV/m, 291 mV/m, 221 mV/m, 169 mV/m. As we can see, although the electrode area of the circular electrode is the same with the electrode area of the square electrode, the electric field of the circular electrode is always bigger than the square electrode. The stimulation of the circular electrode is better than the square electrode stimulation. The smaller the electrode area, the larger the change of the electric field near the internal electric field electrode.

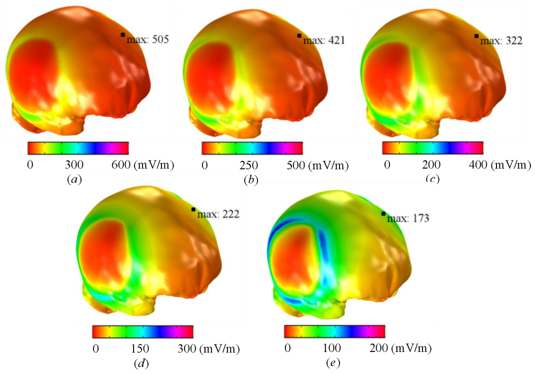

Figure 6: The electrode shape is circular. (a) The electric field distributions with electrode area of 2cm^2; (b) The electric field distributions with electrode area of 5cm^2; (c) The electric field distributions with electrode area of 10cm^2; (d) The electric field distributions with electrode area of 20cm^2; (e) The electric field distributions with electrode area of 30 cm^2.

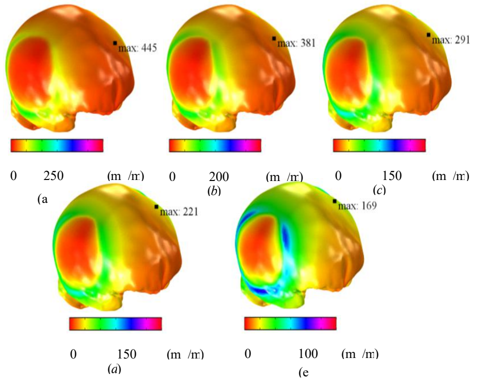

Figure 7: The electrode shape is square. (a) The electric field distributions with electrode area of 2cm^2; (b) The electric field distributions with electrode area of 5cm^2; (c) The electric field distributions with electrode area of 10cm^2; (d) The electric field distributions with electrode area of 20cm^2; (e) The electric field distributions with electrode area of 30cm^2.

4. Conclusions

Finite element simulations of transcranial direct current stimulation after decompressive craniectomy, it provides evidence for the clinical use of tDCS and improves the clinical efficacy of tDCS. The simulation results help compare the focusing effect of different therapeutic parameters of tDCS and optimize the treatment parameters in clinical application, which lays a solid foundation for the accurate rehabilitation medicine treatment and improves the clinical efficacy and comprehensive rehabilitation effect of tDCS. It's very scientific and social.

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