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The Verification Possibility of Thermal Effect During Cortical Stimulation

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Abstract

Intraoperative electrical stimulation mapping is used to localization and control of eloquent cortex and tracts condition during surgery intervention, however standard protocol is ineffective in pediatric patients. Therefore, the novel paradigm with higher amplitudes of stimulating currents must be applied. A 3D numerical model verified thermal effects of the stimulation to brain tissues. Numerical results of temperature distribution were compared to measurements.

1. INTRODUCTION

Epilepsy is the fourth most common neurological disorder, where pediatric patients are the most endangered group for which the prevalence reaches 1%. In addition, 10-20% of the total number of pediatric patients suffers from a pharmaco-resistive form of epilepsy [2]. A suitable treatment alternative that may be considered is surgical resection of the epileptogenic tissue, resulting in up to 87% of patients being completely free of epileptic seizures [3]. During the surgical procedure, an intraoperative so-called Electrical Stimulation Mapping (ESM) is performed to define vital brain structures [4]. However when performing the ESM in pediatric patients, it is necessary to increase amplitude of the stimulation current pulse [5]. Unique stimulation paradigm designed for pediatric patients is currently being tested in Motol University Hospital in Prague. To achieve a response a sequence of 15 rectangular pulses (lasting 400 μs each) with repetition rate of 500 Hz and intensity up to 100 mA is used.

Biological tissues show electrical losses thus part of the power applied during the ESM is dissipated and converted into heat. A local heating is to be expected when stimulating the cerebral cortex but its extent and amplitude is dependent on a number of parameters. Permanent brain damage is observed already at temperatures exceeding 39 °C [6]. From the above mention reason, there is a need to verify if there is any brain tissue damage during the ESM. Because there is not any suitable non-invasive method which can be used for measurement of temperatures in the treated volume of brain, we decided to estimate the extent and amplitude of the heating by means of numerical simulations.

2. DEVELOPMENT OF NUMERICAL MODEL

2.1 SIMULATION SETUP AND GEOMETRY

Simplified 3D layered numerical model was created in COMSOL Multiphysics 5.1 (COMSOL Inc., Palo Alto, CA, USA). Model consisted of saline solution, gray matter (GM), white matter (WM) and ball electrodes as depicted in Fig. 1. Some parameters of the model were set and validated according to data measured in real patients (impedance of ESM electrodes, ambient temperature and brain surface thermography) and data obtained from simple experiment to verify distribution of electric field. Based on results of this experiment it was found that when a current source is used in the numerical model, it is necessary to incorporate corrections in height of saline layer which decrease simulated voltage by 20%.

Dimensions of the layers (width x depth x height in mm) were as follows: GM (30 x 30 x 3)[7], WM (30 x 30 x 15) and saline solution (15 x 15 x 0.1996). The height of saline solution was calculated using relationship describing dependence of impedance on simulated voltage. Electrodes were modeled as sphere with radius 1mm and distance between electrode centers is equal to 4.5 mm. On the top of electrodes, the input leads were created (cylinders with 0.5 mm radius and height of 5 mm). Electrodes were inserted by half of their diameter into GM layer. Electrical stimulation was bipolar with current amplitude up to 100 mA. Visualization of model geometry and pulse train is shown in the Figure 1. The finite element method was used for solving the differential equation. Discretization grid consisted of tetrahedral elements with a number of 1460137 degrees of freedom and the grid was adapted to requirements of geometry. Firstly, initial conditions were set and a temperature distribution (before ESM) was obtained by a steady state simulation. Than a time dependent simulation of heating (30 ms with a 0.01 s step) followed. Finally, time dependent simulation of cooling was computed (20 s with a 0.1 s step).

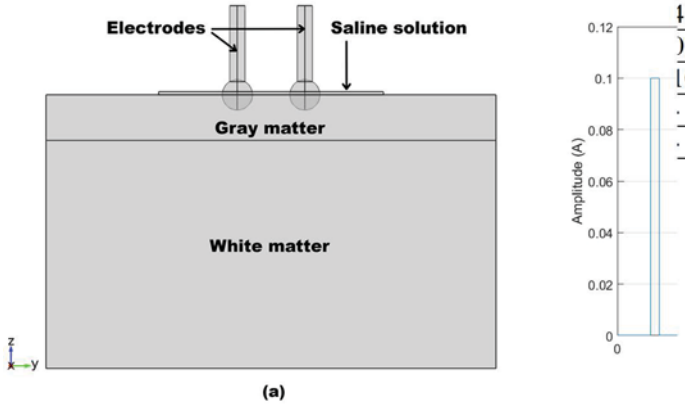

Figure 1: Geometry of simplified geometry, vertical cut x = 0 (a), stimulation impulse (b).

2.2 PHYSICS

The Pennes' bioheat equation [8] was used, coupled with thermal contribution of the electric field Q_j (W·m^{-3}), which depends on voltage distribution in model, obtained by Laplace equation, than:

$$\rho C \frac{\delta T}{\delta t} = \nabla \cdot (k \nabla T) + Q_{bio} + Q_{met} + Q_j, \quad (1)$$

where ρ is density (kg·m^{-3}), C is specific heat (J·kg^{-1}·K^{-1}), k is thermal conductivity (W·m^{-1}·K^{-1}), Q_{met} is metabolic heat (W·m^{-3}) and Q_{bio} is computed as:

$$Q_{bio} = \rho_b C_b \omega_b \cdot (T_a - T), \quad (2)$$

where ρ_b, C_b, ω_b is the blood density, blood specific heat and blood perfusion (s^{-1}). T_a is arterial temperature and T is tissue temperature. For quantification of GM damage the Arrhenius integral model was used, where values of the model parameters were set to A = 7.39·10^{37} s^{-1} and E_a =2.577·10^5 J·mol^{-1} [9].

2.3 PARAMETERS USED IN SIMULATION

Equations describing temperature dependence have been implemented in the model (see Table 1). Ambient temperature was set to 21°C. Heat loses due to radiation were also considered (ε_{GM} = 0.80 [10], ε_{Saline} = 0.98, $\varepsilon_{elec.}$ = 1). Heat transfer coefficients (W·m^{-2}·K^{-1}) were: h_{GM} = 3 [11], $h_{elec.}$ = 16 and external natural convection: horizontal plate, upside for saline. Properties of electrodes were selected from COMSOL material library (stainless steel UNS S17600) with added specific heat capacity, conductivity and relative permittivity. Conductivity of brain was estimated using Cole-Cole model and decomposition of pulse train in the spectrum.

Table 1: Used parameters and initial temperatures (* marks temperature dependent constants).

	Saline solution	Gray matter	White matter	Electrodes	Blood
C)	35	37	37	35	36.7[8]
	1.815*[12]	0.0855*[13]	0.0531	1.37e+6	
	80[14]	5.74e+6[15]	5.29e+6[15]	1	
	4141.056[16]	3696[15]	3583[15]	480	
	).617*[18]	0.55[19], [20]	0.48[15]	18.044	
	000.32[16]	1045[15]	1041[15]	7776.33	
	.	0.0133*[15], [21]	0.00367[15]	-	
	.	16 239*[15], [21]	4497.1[15]	-	

3. RESULTS AND DISCUSSION

The temperature distribution estimated by means of steady-state simulation (after applying the electrodes and sputtering the brain with saline solution) shows a temperature drop in the vicinity of the electrodes up to 34.5 °C. The surface temperature of GM has fallen to 36 °C after the contact with the colder environment. The temperature distribution simulated numerically here shows the highest temperatures in the saline solution layer. The maximum reached temperature was 38.83 °C. The simulated temperatures correspond to the temperature range measured by the IR camera (38.5-39 °C). The temperature distribution on the surface of the model as well as on the surface of the brain of the real patient showed a symmetrical distribution (see Fig. 2).

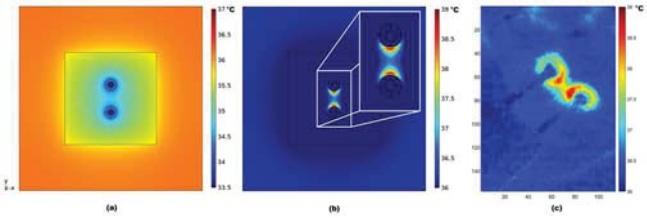

Figure 2: Temperature distribution on the surface of model before stimulation (a), after 30 ms pulse train (b) and surface temperature of stimulated human brain covered by a layer of saline solution measured by IR camera (c).

The maximum temperature increase in GM was observed at the interface of the GM with a layer of saline solution (up to 2.5 °C). WM heating was not observed. The value of Arrhenius integral (GM) ranged from 10^{-8} after one pulse train to about 10^{-7} in the early stages of cooling, indicating that cellular damage was not found in the tissue.

The cooling of the tissue layers had exponential character and at the end of the 20 second simulation the temperature at the level of initial values (0.1% difference) was observed.

In the literature the numerical models of brain tissue heating, verifying the safety for deep brain stimulation (DBS) were found [6]. The model of tissue heating developed by us for ESM safety verification is unique in terms of methodology and simulation settings that utilize real square pulse and temperature-dependent material parameters.

The numerical model taking into account ball electrodes and above mention setting confirmed the safety of the stimulus paradigm used in Motol University Hospital. The highest temperatures appeared in a very small volume (in

the order of 10^{-2} mm^3) near the electrodes in saline solution only. Warming of brain tissue occurred primarily in Layer I of neocortex [22].

4. CONCLUSIONS

The performed numerical simulations demonstrated that temperatures estimated after brain stimulation with single pulse train have not reached the values which would results in a tissue damage. Temperature distribution on the surface of the numerical model shows good agreement with thermographic measurement. The influence of temperature dependent parameters and creation of advanced models using above mentioned knowledge will be the subject of the future research.

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