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Mathematical modeling of radiofrequency ablation during open-heart surgery

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Abstract: In this article a three-dimensional mathematical model of radiofrequency ablation during open-heart surgery is presented. It was developed to study temperature field distribution into myocardial tissue. This model uses an anatomically correct 3D model for the left atrium, obtained by magnetic resonance imaging (MRI) processing of a patient; takes into account thermoelectric characteristic differences depending on the area of electric current application; considers cooling by the air flow. An ex-vivo experiment on the pig's heart was performed where the depth of myocardium tissue damage was measured for the model validation. It was shown that the deviation of the model data from the experiment is within the limits of instrumental measurement error. The developed model is proposed to be used for heart ablation procedures planning, or new equipment development.

Key words: arrhythmia, coagulation, heart, modeling, radiofrequency ablation, resistive heating

1. Introduction

Radiofrequency ablation (RFA) is a procedure witch creates thermal destruction of diseased tissues by the use of radiofrequency current energy. In medical practice, it is the most widely used for various types of tumor treatment [1, 2], as well as cardiac arrhythmias treatment [3, 4].

Radiofrequency ablation of the heart is by far the most effective and safe method for arrhythmias radical treatment [5]. In the case of open-heart RFA, a doctor can see the contact zone of a radiofrequency electrode with the myocardium tissue, but it is not possible to control depth of

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tissue damage. In addition, complications caused by overheating, such as electrode carbonization and micro explosions, which can lead to a heart wall rupture [6] are possible. The mathematical model of RFA allows real-time visualization of thermal field distribution throughout the entire depth of the heart tissue, as well as optimal electrical influence parameter selection in order to protect the tissue from overheating.

The implementation of a resistive heating principle in a mathematical model is described in the works on RFA modeling of cancer tumors [7–9], and in the treatment of arrhythmias [10–12]. Most existing models do not take into account the anatomical features of the patient's heart geometry, the difference of thermo-electrical characteristics of the heart depending on its anatomical zone, as well as cooling from the ambient air. All that features are taken into account in the presented model.

2. Materials and methods

To create a mathematical model of RFA COMSOL Multiphysics 5.4 software has been used. It is finite element analysis, solver and simulation software for various physics and engineering applications, especially coupled phenomena, or multiphysical tasks [10]. To describe the mechanism of resistive heating the combination of Heat Transfer in Solids with boundary condition Biological Tissue and Electrical Current modules were used. The general equation of heat transfer in biological tissue is [10–12]:

$$\rho c \left(\frac{\partial T}{\partial t} \right) = \nabla k \nabla T + q + Q_m - Q_p \,, \tag{1}$$

where: ρ is the density, c is the specific heat, k is the thermal conductivity, q is the amount of heat from the heating source, Q_p is the cooling by blood perfusion, Q_m is the amount of heat released due to metabolism.

During heart radiofrequency ablation resistive heating is the heating source which occurs as a result of radiofrequency current passing through biological tissue with low electrical conductivity. During the interaction with electrical field E in biological tissue occur two types of electrical current: conduction (due to the drift of free electrons and ions and polarization of atoms and molecules) and displacement (due to the interaction related to bound charges) currents. Based on electrical characteristics most biological tissues can be classed as tissue with high water content (skin, muscle, visceral organs) and with low water content (bones, fat). In tissue with high water content conduction currents are the main source when frequency is lower than 400 MHz [13]. Since it is known that current frequency for RFA procedure is in the range of 300–1000 kHz and myocardial tissue is a tissue with high water content, displacement currents are negligible. That is why the heating source can be described as [11]:

$$q = E \cdot J, \tag{2}$$

where: J is the current density, and E is the electric field intensity.

To find values of these two vectors Laplace's equation can be used [12]:

$$\nabla \cdot \sigma \nabla V = 0, \tag{3}$$

where: σ is the electrical conductivity and V is the voltage. By knowing voltage and electrical conductivity current density, electric field intensity can be computed from:

$$E = -\nabla V, \tag{4}$$

$$J = \sigma \cdot E. \tag{5}$$

The radiofrequency ablation during open-heart surgery is carried out on the inner surface of the left atrium. In this area, the thickness of the heart wall is about 2–4 mm. To create one point of thermal destruction through the entire heart wall thickness the duration of radiofrequency electric current application has to be 15–30 s. For such a short period of time, the amount of heat released as a result of metabolism is not significant therefore it can be ignored in mathematical model.

Cooling by perfusion of blood flow in small heart wall capillaries is generally ignored since its effect is almost negligible for cardiac ablation [11], but to increase the accuracy of the mathematical model it can be described with equation [11]:

$$Q_p = \omega_b c_b (T - T_b), \tag{6}$$

where: ω_b is the blood perfusion per unit volume (kg/(m^3· s)), c_b is the specific heat of blood, T_b is the blood temperature. It is assumed that ω_b is uniform throughout the myocardium tissue.

RFA during open-heart surgery is carried out at artificial blood circulation, which is why it is sometimes called ablation on a dry heart. As a result, when modeling this procedure, there is no need to take into account cooling of the heart wall by blood flow, however, it is appropriate to simulate cooling from the environment. In our model, this cooling is realized by modeling the low-velocity air flow around the geometry of the left atrium. If mark convection cooling from air flow Q_a, then the final form of the heat transfer in the biological tissue equation for mathematical modeling of the open-heart ablation will be:

$$\rho c \left(\frac{\partial T}{\partial t} \right) = \nabla k \nabla T + \sigma |E|^2 - \omega_b c_b (T - T_b) - Q_a \,. \tag{7}$$

To describe the thermo-electrical characteristics from e.g. (7), we used parameters presented in M.M. Sychik's work [14]. She proved that various anatomical zones of the heart have different thermo-electrical characteristics. Since open-heart RFA is carried out in the left atrium the parameters of the zone "Left atrium, the mouth of the pulmonary veins" are selected for mathematical modeling. Thermo-electrical characteristics of all materials of the model are presented in Table 1. It should be noted that the model takes into account electrical conductivity dependence on myocardial tissue temperature increase with a temperature coefficient of 2%/°C.

Table 1. Thermo-electrical parameters of model materials

Material	**Density, ρ (kg/m^3)**	**Electrical conductivity, σ (S/m)**	**Thermal conductivity, k (W/(m·K))**	**Specific heat, c (J/(kg·K))**
Left atrium	1200	0.225	0.531	3600
Electrode	6450	10^8	18	840
Air	1.225	0	0.028	1006
Blood	1000	0.667	0.543	4180

3. Model geometry

One of the main differences of the proposed mathematical model of heart ablation is correct 3D anatomical geometry usage. The RFA procedure will be effective only if thermal damage is carried out to the entire depth of the heart wall which size significantly depends on the zone where ablation takes place. Usually ablation during open heart surgery takes place in the left atrium. Heart wall thickness in this zone varies between 2–4 mm. By the use of an anatomically correct 3D model of the left atrium it's possible, by simple change of the active electrode position, to study the parameters of the effective RF influence for any atrium area.

To develop our mathematical model a 3D model of the left atrium that was created by processing patient's magnetic resonance imaging (MRI) was used. Thus, we got correct geometry which includes all anatomical features of the patient, however it contains high polygonal density. Such models are difficult to process in software products for mathematical modeling. Since our goal was to develop a model that could be effectively used both when planning the ablation procedure and directly in real time, manual retopology in 3d's Max software was performed. Thus, all the anatomical features of the patient's left atrium and the proper thickness of its wall have been preserved, and the number of geometry polygons has been reduced from 184.278 to 4.425 as shown in Fig. 1.

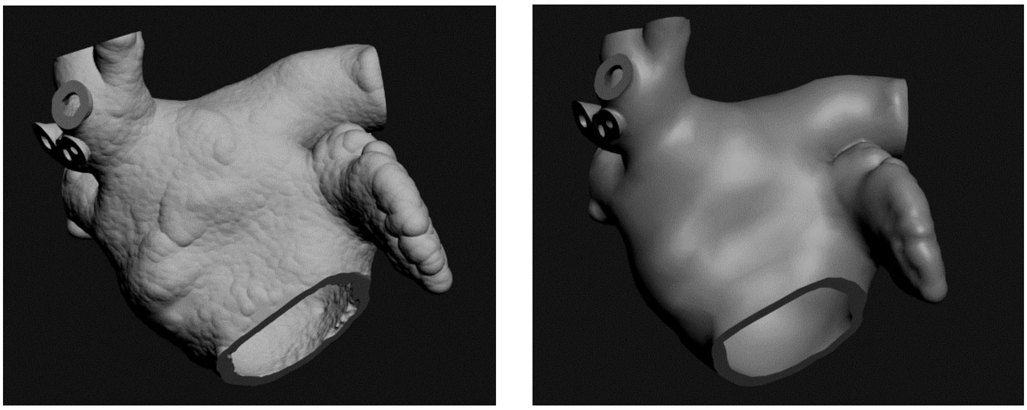
(a) (b)

Fig. 1. Geometry of left atrium: a highly detailed model created by MRI image processing (a), simplified by manual retopology model (b)

The geometry of the mathematical model also includes a monopolar electrode with a spherical tip which diameter is 4 mm and ambient air. They were built in the COMSOL Multiphysics 5.4 graphic editor by basic shapes. The final geometry of the RFA mathematical model is shown in Fig. 2. All the thermo-electrical characteristics of the mathematical model elements are shown in Table 1. This table also includes data for the material of blood. Although a separate geometric element is not used in the mathematic model, these parameters are needed to simulate convection cooling from small capillaries of the geometry element – the left atrium. The volumetric blood flow velocity is taken uniformly throughout the tissue and equals 0.00106 kg/m^3·s.

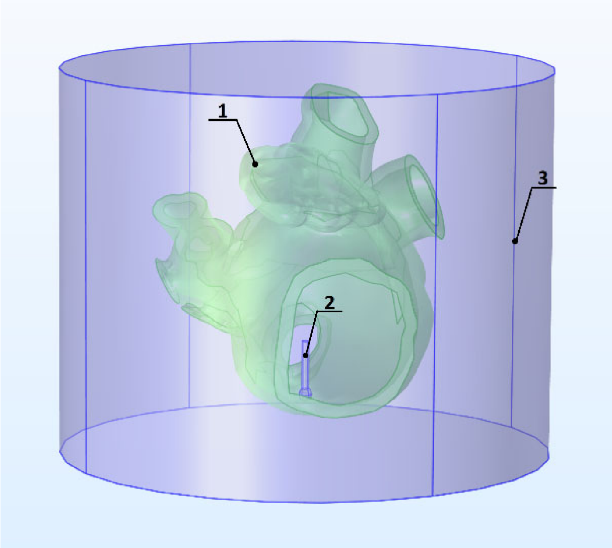

Fig. 2. Mathematical model geometry: left atrium (1), radiofrequency electrode (2), air (3)

4. Results

Let's simulate heart radiofrequency ablation procedure for a voltage of electric current 30 V and its frequency of 500 kHz. Modeling results will be analyzed for 60 s ablation procedure duration. In this case a monopolar spherical tip electrode with a diameter of 4 mm is used for modeling. The passive electrode is simulated by the use of boundary condition "Ground" that was applied to the outer surface of the heart. Initial myocardium tissue and blood temperature is set to 36.6°C, electrode and ambient air temperature −20°C. It is considered that air flow is laminar and velocity is set to 0.3 m/s. Modeling results are shown in Figs. 3 and 4.

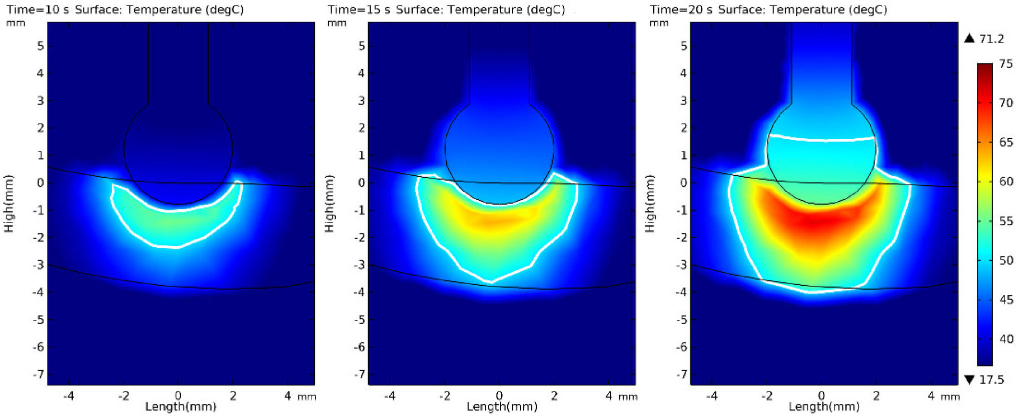

Fig. 3. Diagram of thermal field spreading in time

In Fig. 3, temperature field distribution over time is showed. For analysis simplification a 2D slice in the *xz* plane that passes through the center of the electrode is given. A white contour marks a zone heated to more than 50°C, which corresponds to a zone with irreversible destruction of biological tissue [15]. It can be seen that the ablation procedure with a duration of 10 seconds causes a zone with irreversible damage to the myocardial tissue, however complete transmurality and therefore effective damage was achieved only with a procedure duration of 20 s. In this case, the maximum heating temperature was 71.2°C, which is significantly lower than 100°C at which ruptures of the heart wall may occur due to micro explosions.

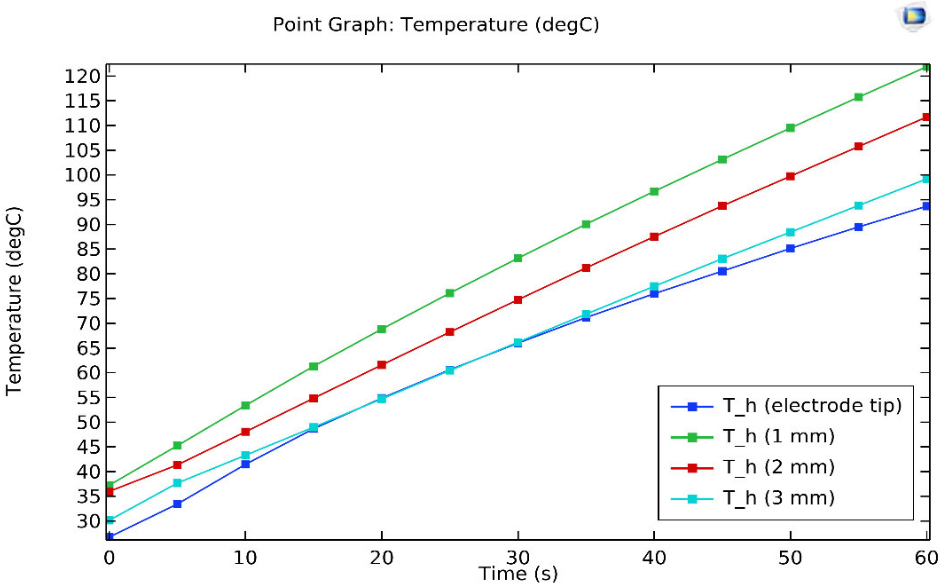

Fig. 4. Myocardial tissue heating graph at a depth of 0–3 mm from the radiofrequency electrode tip

Fig. 4 shows a graph of the myocardial tissue temperature changes in time at a distance of 0–3 mm from the electrode tip. It can be seen that the maximum heating temperature is observed not at the electrode tip, but at a distance of 1 mm from it, which is due to the air flow cooling of the surface of myocardial tissue and the electrode. It is also worth to notice that for the selected voltage, the critical duration of application is 40 s, since then the maximum temperature of heart tissue heating is higher than 100°C, which in real conditions will lead to rapid evaporation of fluid and ruptures of the heart wall.

5. Experimental validation of the mathematical model

To validate the mathematical model, an experiment on pig's heart was performed (see Fig. 5). During open-heart radiofrequency ablation, the convection cooling of blood flow is not significant [11, 16], so it is possible to use the results of an ex-vivo experiment to check the model. As a source of radiofrequency energy a generator BTM-300M1 was used. Its maximum power is 200 W and current frequency is 440 kHz. As an active electrode Erbe monopolar electrodes with a tip diameter of 2 and 4 mm were used. For each of the electrode 6 ablation points were carried out for an ablation duration of 5 and 15 s and an electric current power of 10, 20 and 30 W. The criterion for mathematical model validation was the transmurality of the destruction zone, since it is the main factor determining effectiveness of heart ablation procedure.

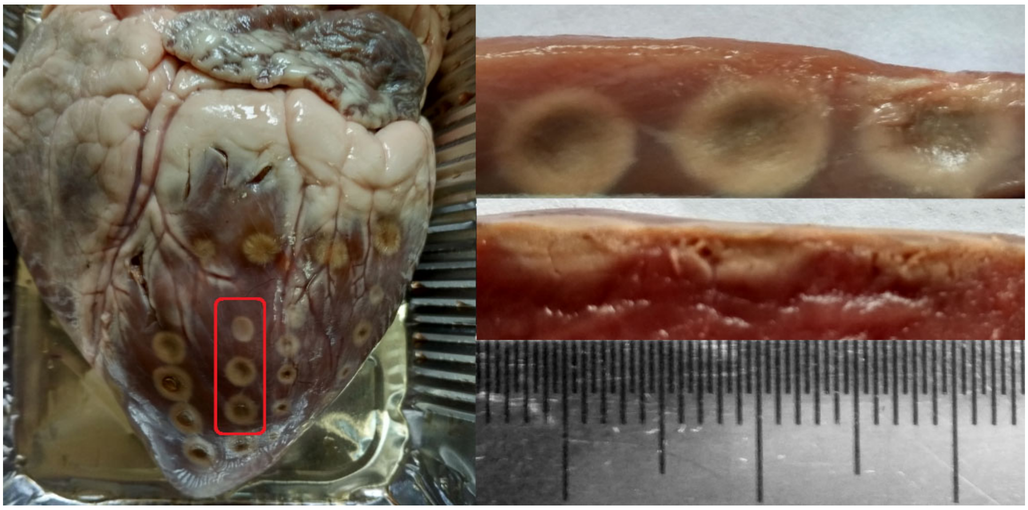

Fig. 5. Ex-vivo experiment on pig's heart

Table 2 shows the results of comparing a mathematical model with experimental research data. The simulation was carried out with the corresponding power and frequency of the electric current settings and application duration, also convection cooling of blood flow was not taken into account. Destruction depth in the experimental data was determined by measuring the size of the zone with a clearly noticeable color change. Measurements were made with a ruler, so

Table 2. Validation of mathematical model based on destruction depth

Electrode tip diameter (mm)	**Type of data**	**Ablation duration (s)**					
		5			**15**		
		Power of radiofrequency current (W)					
		10	**20**	**30**	**10**	**20**	**30**
2	experiment	0	0.5	2.5	0	1	1.2
	model	0	0.9	3	0.6	1.5	1.4
4	experiment	0	0	1	0	2	3
	model	0	0	1.5	0	2	3.3

*Measurement error for every value is ±0.5 mm the measurement error for each value is ±0.5 mm. For the mathematical model the size of the myocardial tissue zone heated to more than 50°C was measured.

From the obtained data it can be seen that the difference between the results of mathematical modeling and the ex-vivo experiment on a pig's heart does not exceed 0.6 mm. Such a deviation is almost equal to the limits of the instrumental measurement error which shows that the developed mathematical model has high accuracy.

6. Conclusion

Heart radiofrequency ablation effectiveness primarily depends on the proper depth of myocardium tissue damage, and on the other hand excessive overheating of the heart wall leads to its destruction due to rapid liquid evaporation. It is possible to control these parameters using the correct mathematical model of the RFA procedure, the development of which is discussed in this article. The process of its creation in COMSOL Multiphysics 5.4 software for finite element modeling is described in stages, including the features of constructing an anatomically correct model geometry, describing its thermo-electrical characteristics and physical modules.

The mathematical model was validated based on the data of an ex-vivo experiment on a pig's heart. The depth of thermal damage was selected as the criterion for verification. It was shown that the deviation of the model data from the experiment is within the limits of the instrumental measurement error, which confirms its reliability.

The presented mathematical model opens up fundamental possibilities for designing radiofrequency ablation tools with real-time modeling of the prognostic depth of electro-thermal effects on myocardium tissue to ensure the safety of the ablation procedure.

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