Heat Transfer Modeling for Pulse Laser – Assisted Removal of Arrhytmogenic Sources

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Abstract. *One of the possible applications of medical lasers is in treatment of heart arrhythmia. Pulse lasers can become an alternative to conventional treatment or its supplement. Its precision and targeted removal of arrhythmogenic sources without damaging the surrounding tissue is a major advantage. Using nanosecond pulses with this technology achieves the necessary photoablation while preventing heat stress, commonly seen when using continuous-wave lasers. In the case of a pulse laser there is no heat stress in the surrounding healthy tissue because any surplus is transferred away by blood perfusion. A theoretical mathematical model has been created to describe heat transfer in tissues throughout the procedure. The model was created with the COMSOL Multiphysics software. All the necessary parameters were either calculated or experimentally determined in the laboratories of FBME CTU and it's where the model had been experimentally verified as well.*

Keywords: Heart Arrhythmia, Absorption Coefficient, Ablation Depth, Bioheat Transfer Modeling

1. Introduction

Catheter ablation aimed at removal of arrhythmogenic sources with a laser is one of the alternatives to pharmacological treatment of heart arrhythmia. Continuous-wave lasers are currently in use for that very purpose. Their advantage is in precise removal of the pathological tissue but their use can lead to overheating in the tissue. Rising temperatures in the tissue can cause irreversible damage, the scale of which depends on the temperatures reached and on the duration of exposure to these temperatures. Current research is looking into the possibility of using pulse lasers which, with appropriate repeating frequency, would prevent any undesirable overheating. A pulse laser with adequate energy density can effectively remove any pathological tissue by photoablation and any excess heat is transferred into its surroundings. The aim of our work is to create a functioning theoretical model to predict heat transfer in in tissues surrounding the laser-treated area.

2. Subject and Methods

The theoretical model was created using the COMSOL Multiphysics 4.4 software, with the pre-defined module „Bioheat Transfer“ (Fig. 1), with tissue parameters for optical and thermophysical quantities of heart muscle either calculated or predetermined experimentally. Laser beam parameters (pulse length, repetition frequency, energy density) can be adjusted for each specific application.

During our experiments the tissue (porcine heart) was exposed to laser beams with varying energy densities (700 – 2500 $mJ.cm^{-2}$) and varying repetition frequencies (5 – 25 Hz). For that a KrF excimer laser (248 nm) was used. The resulting ablation craters were examined with two goals in mind – to determine the ablation depth and to describe the crater‘s shape and development over time.

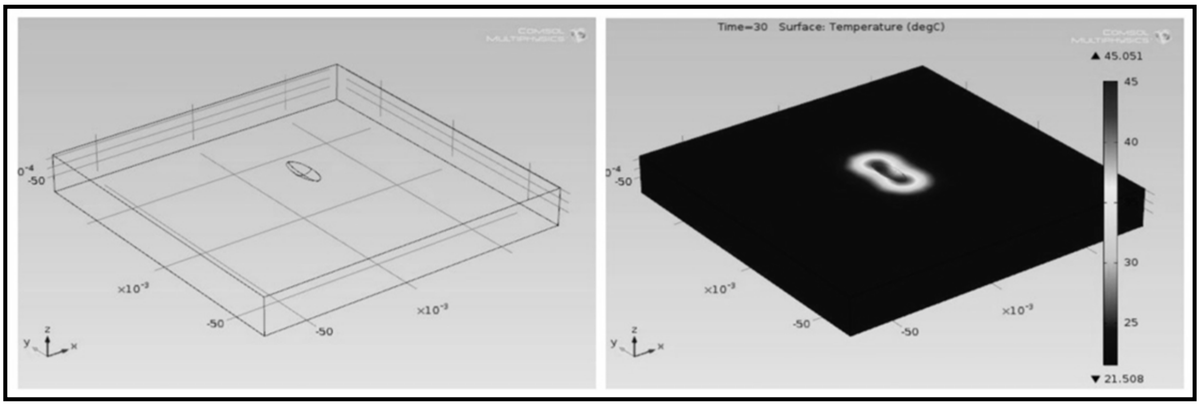

Fig. 1. Heat transfer model created in the COMSOL software. Geometry of the sample with an ablation crater on the left and graphical output with measured temperatures

Crater´s depths measured using various methods (direct measurement, focusing method, scanning). CT scan of its profile proved to be the most optimal and the results from other methods were used only as a reference. The scans were obtained using the XR 4.0, PHYWE RTG unit set at 35 kV and 1 mA on the anode with potassium iodide used as a contrast dye. Fig. 2 displays five craters with a pin of known length (27.05 mm) to help determine their depths. MATLAB was used to ascertain the precise crater depth. Experimentally established crater depths (14.0 ± 1.5) µm for heart muscle tissue were compared to published values [7], [8]. The value we established matches the published values.

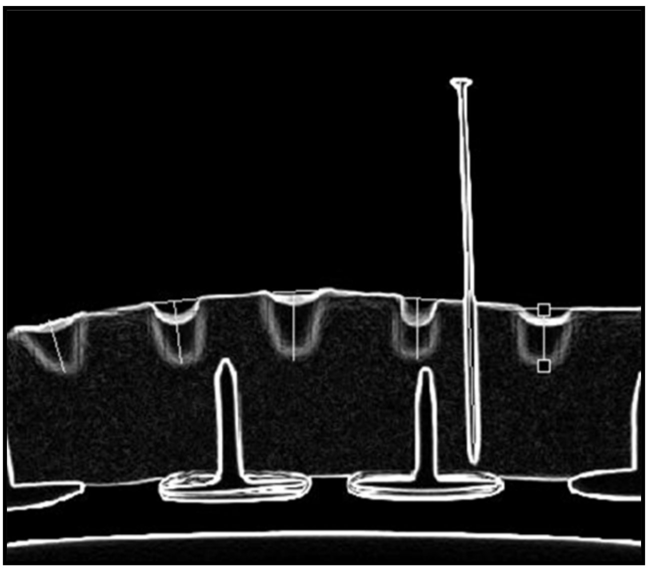

Fig. 2. A CT image of the craters' profile (500 pulses, 1240 mJ.cm^{-2})

Another one of the parameters necessary for the simulation model is the absorption coefficient of heart muscle tissue. Through spectrophotometric analysis, using the Shimadzu UV-VIS-NIR 3600, the transmittance values of bovine myocardium were measured in a wide wavelength range from 185 to 3300 nm. 50 µm thick samples were used, which is enough to neglect local non-homogeneous segments of the tissue, while maintaining precision of the measurement. The absorption coefficient was calculated from the obtained transmittance values for the wavelength range examined (Fig. 3).

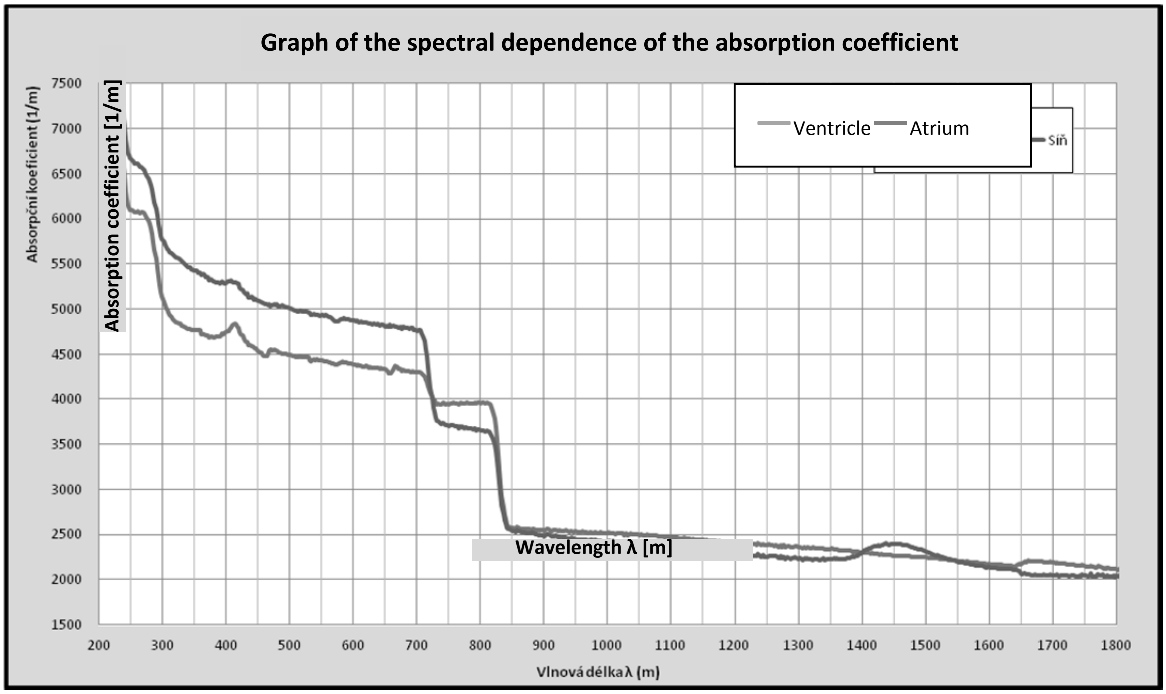

Fig. 3. Spectral dependence of the absorption coefficient for heart muscle in a selected range of wavelengths.

For validating the proposed model a theoretical calculation of the surface heat transfer was compared to an image captured by a thermal camera monitoring the sample surface throughout the exposure (fig. 3). FLUKE TI55/20FT is thermal imaging camera with 320 × 240 resolution, sensitivity of 0.05 ^{o}C and all data recorded at 60 Hz.

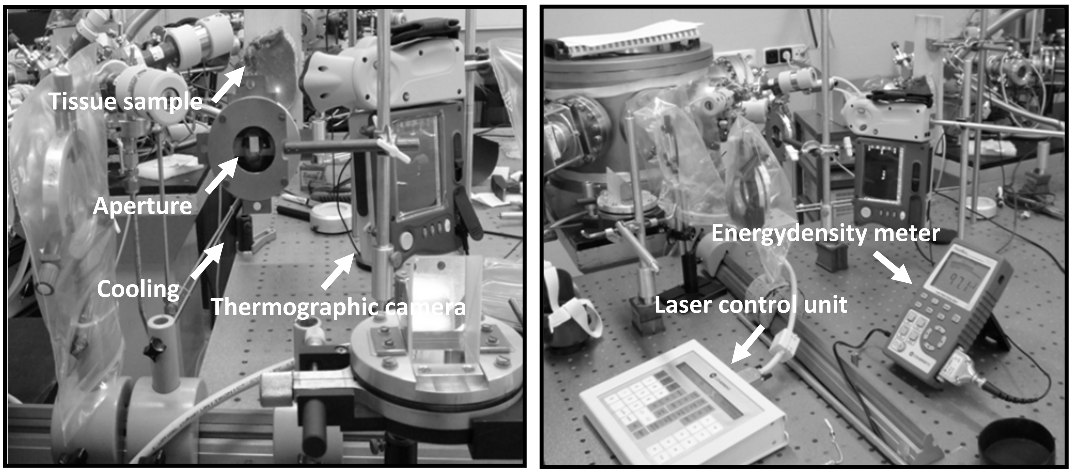

Fig. 4. Surface heat monitoring apparatus.

Neither blood perfusion nor metabolic heat was included in this experiment and for the default sample temperature the real value was used. Convective heat dissipation from the surface of the sample was included.

3. Results

A model of heat transfer in heart muscle tissue during removal of pathological nodes by photoablation was created. Parameters describing the laser-tissue interaction were determined experimentally or calculated from the chemical composition of the tissue. Spectral dependence of absorption coefficient for heart muscle tissue of the atrium as well as the ventricle was measured for wavelengths ranging from 200 nm to 3000 nm and as a result the model is applicable for lasers using various wavelengths when an appropriate absorption coefficient is used. The ablation depth and shape of the crater, created through photoablation, were detailed using CT images. The model was experimentally verified by monitoring the sample's surface heat transfer and its comparison to the calculated theoretical values. It is possible to determine the maximal temperature reached in the tissue and its duration to help assess the risk of irreversibly damaging the tissue. We have created a working model of heat transfer in heart muscle tissue following its exposure to a laser and subsequently verified it experimentally. The model allows us to predict changes in temperature during the process of removing arrhythmogenic sources using a pulse laser. With it, the type of laser and its parameters (energy density, frequency) can be tailored for each individual procedure.

4. Discussion

Using adequately set up pulse lasers is proving to be a perspective alternative method for use in heart arrhythmia treatment. The pulse mode allows for setting a repeating frequency that prevents any excessive heat from spreading into and damaging surrounding healthy tissue, because the heat is transferred from it by conduction and blood perfusion. If a thermal imaging camera monitors the tissue surface during the procedure, the heat transfer can be immediately compared to the theoretically predicted development and then, if necessary, the repetition frequency can be adjusted without terminating the procedure.

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