A Computational Model of Open-irrigated Electrode for Endocardial RF Catheter Ablation

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Abstract

Radiofrequency catheter ablation (RFCA) is an important curative treatment for cardiac arrhythmias. However, during RFCA thrombus formation can occur when the electrode-tissue interface temperature exceeds 80ºC. Open-irrigated electrodes reduce the risk of such side-effect. No computational model of an open-irrigated electrode in endocardial RFCA accounting for both the saline irrigation flow and the blood motion in the cardiac chamber has been proposed yet. Our aim was to introduce the first computer model including both effects. The model has been validated against existing experimental results. Computational results showed that the surface lesion width and blood temperature are affected by the irrigation flow rate. Smaller surface lesion widths and blood temperatures are obtained with higher irrigation flow rate, while the lesion depth is not affected by changing the irrigation flow rate. Larger lesions are obtained when electrode is placed horizontally. Overall, the computational findings are in close agreement with previous experimental results.

1. Introduction

Radiofrequency catheter ablation (RFCA) is a safety procedure to remove cardiac arrhythmias. During RFCA, thrombus can be formed when the electrode-tissue interface temperature reaches around 80ºC [1]. In order to prevent this phenomenon, open-irrigated electrodes have been developed [2-6]. They have holes distributed around the electrode tip through which saline is continuously flushing into the blood-tissue interface [2].

Computer modeling allows to study different issues involved in RFCA in a fast and cheap way, as opposed to ex vivo/in vitro and in vivo setup. To date, all previous models for endocardial RFCA mimicked the effect of the saline irrigation by fixing a constant temperature in the electrode tip [5] and the effect of the circulating blood by considering a convective boundary condition at the blood-tissue interface that does not allow to obtain a realistic distribution of blood temperature in the cardiac chamber [7,8]. Our objective was to set up the first computer model for open-irrigated electrode in endocardial RFCA which take into account simultaneously the saline irrigation and the blood motion. The thermal performance of the model was validated by comparing the computer results with previous experimental studies.

2. Material and methods

2.1. Computational modeling

Figure 1 shows the geometry and dimensions of the three-dimensional computational model, where the XZ-plane is the symmetry plane. The model consists of a fragment of cardiac tissue, a volume of blood (cardiac chamber) and an open-irrigated electrode initially in perpendicular position with respect to the cardiac tissue which includes a sensor embedded within its tip for monitoring the electrode temperature [2]. The cardiac chamber dimensions X = 80 mm and Y = 40 mm (Z = Y) were estimated by means of a convergence test in order to avoid boundary effects.

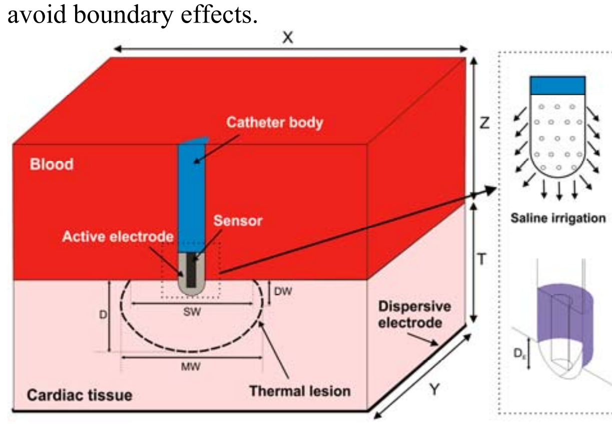

Figure1. Geometry of the computational model built.

We considered an open-irrigated electrode (8Fr diameter and 3.5 mm length) with 56 holes distributed around its tip. The small holes allow the saline solution to continuously flush into the cardiac chamber. The flowing saline mixes with the circulating blood and hence the saline does not form a film around the electrode. Since the blood and the saline feature comparable densities, the mixing can be considered to be homogeneous, and consequently the effect of saline flow can be modeled as an inlet boundary condition into the blood region, specifically a condition set at the zone where the holes are located (see violet surface in Figure 1). We assume that a saline film is not forming at the electrode-tissue interface since the tissue presses the holes in this zone and blocks the saline irrigation flow out. As a consequence, a boundary condition associated with the saline irrigation need not being included at the semispherical part of the electrode tip inserted in the tissue.

The thermal and electrical properties of the model elements are obtained from [8]. The initial model temperature is 37ºC, except in the electrode tip which is 22ºC, imposed as a consequence of the saline irrigation. The electrical (σ) and thermal conductivity (k) of cardiac tissue are temperature-dependent and are defined by piecewise functions as in [8].

Electrical, thermal and velocity boundary conditions are applied to the model. We consider a constant power ablation mode of 35 W for 30 s [2], which is the usual ablation mode for open-irrigated electrodes in RFCA. We implemented a proportional-integral control algorithm using MATLAB (MathWorks, Natick, MA, USA) and the applied voltage was modulated to maintain the delivering power within 3% of the target. Therefore, a voltage boundary condition is applied at the active electrode surface. On all the outer surfaces of the model, except the bottom surface, a null electrical flux is imposed. The voltage on the bottom surface is set to 0 V to model the dispersive electrode. For the thermal boundary conditions, a null thermal flux is used on the symmetry plane and a constant temperature of 37ºC is fixed on the outer model surfaces. For the velocity boundary conditions, an inlet velocity boundary condition is applied on the left surface of the fluid volume to impose a blood flow velocity of 0.1 m s^{-1} [2]. An outlet boundary condition of zero pressure is fixed on the right surface of the fluid volume. The saline irrigation flow is taken into account by an inlet velocity condition into the blood region. A no slip condition is applied on the upper surfaces of the fluid volume, at the symmetry plane and at the tissue-blood and electrode-blood interfaces.

The model is based on a coupled electric-thermal-flow problem, which is solved numerically using the Finite Element Method (FEM) with COMSOL Multiphysics software (COMSOL, Burlington, MA, USA). The governing equation for the thermal problem is the *Bioheat Equation*, modified by the enthalpy method [8] that includes the phase change to model tissue vaporization:

$$\frac{\partial(\rho h)}{\partial t} = \nabla \cdot (k \nabla T) + q - Q_p + Q_m - \rho c \boldsymbol{u} \cdot \nabla T \qquad (1)$$

where ρ is density (kg m^{-3}), h enthalpy, t time (s), k thermal conductivity (W m^{-1} K^{-1}), T temperature (ºC), q the heat source caused by RF power (W m^{-3}), Q_p the heat loss caused by blood perfusion (W m^{-3}) and Q_m the metabolic heat generation (W m^{-3}). Q_p was not considered since it has been demonstrated that the blood flow away from the coronary arteries does not have significant influence on the temperature distribution during RFCA. Likewise, Q_m was not considered because it is negligible in comparison to the other terms [9]. The last term in the Equation (1) corresponds to the advection term [8], which represents the heat loss due to blood flow and $\boldsymbol{u}$ the velocity field (m/s). This is described by *the incompressible Navier-Stokes Equations* [7,8].

At RF frequencies (≈500 kHz) and over the distance of interest, the biological medium can be considered almost totally resistive, and a quasi-static approach can therefore be used to solve the electrical problem [9].

2.5. Computational simulations

We assess the accuracy of the computational model by comparing the lesion dimensions with available data from experiments [2]. The thermal lesions are identified by the 50ºC isotherm contour, which is usually considered to reasonably represent the isotherm of irreversible myocardial injury in hyperthermic ablation. The thermal lesions are determined by their characteristic dimensions (see Figure 1) [2]: maximum depth (D), maximum width (MW), depth at the maximum width (DW), and surface width (SW). We assessed the lesion volume (LV) using the formula described in [2,4].

Once we checked that the computational model predicts reasonably well the experimental lesions, we studied the variations in both the lesion dimensions created in the tissue and the maximum blood temperature attained in the cardiac chamber (T_{max_blood}) for different saline irrigation flow rates [6], considering perpendicular and parallel electrode positions respect to the tissue surface.

3. Results

3.2. Effect of the irrigation flow rate

Figure 2a shows the effect of changing the irrigation flow rate on the lesion dimensions after 30 s of RFCA with power-control mode for both electrode positions. For the sake of completeness, we include also the case of 0 mL min^{-1}, which represents a non-irrigated electrode. The fact of changing the irrigation flow rate not shows an impact on D and DW. Comparing non-irrigated and irrigated electrode, D is slightly larger with non-irrigated electrode in all cases: D was 6.4 mm and 6.1 mm in perpendicular position and 7.1 mm and 6.8 mm in parallel position for non-irrigated and irrigated electrode, respectively. In contrast, MW and SW are smaller when irrigation flow rate is increased, regardless of the electrode position. The reduction of SW is particularly pronounced when the irrigation flow rate is increased, especially in perpendicular position: SW is reduced from 8.6 mm for a non-irrigated electrode to 6.7 mm for an electrode with 5 mL min^{-1}; and increasing the flow rate, SW is progressively reduced to 5.2 mm for 10 mL min^{-1} and to 3.7 mm for 20 mL min^{-1}.

Figure 2b shows the lesion volume (LV) and the temperature distributions in the cardiac tissue and blood. LV is also reduced with the increase of the irrigation flow rate for both electrode positions: for instance, LV decreases from 248.9 mm^3 to 207.8 mm^3 in perpendicular position when the irrigation flow is incremented from 0 to 20 mL min^{-1}. T_{max_blood} also decreases as the irrigation flow rate is increased for both electrode positions. The only situation where a critical value of T_{max_blood} above 80ºC was registered, hinting the possible formation of a thrombus at the electrode surface, occurs for the non-irrigated electrode (80ºC and 85ºC, in perpendicular and parallel position, respectively). On the contrary, T_{max_blood} always stays below 63ºC for the open-irrigated electrode. We observe a strong correlation between SW and T_{max_blood} for each electrode position: the coefficient of determination R^2 is 0.97 and 0.99 for the irrigated electrode in perpendicular and parallel position, respectively.

3.2. Effect of the electrode position

Both MW and SW are larger with the electrode in parallel position (Figure 2a): with a flow of 5 mL min^{-1}, MW and SW are incremented by 1.4 mm and 2.3 mm, respectively, when the electrode is in parallel position. In contrast, depth is not importantly affected by the electrode position since its variation is just 0.7 mm. LV is also bigger with the electrode in parallel position (see Figure 2b): 212.5 mm^3 and 295.7 mm^3 in perpendicular and parallel position respectively, with a flow rate of 5 mL min^{-1}.

The T_{max_blood} is also affected by the electrode position. The value of T_{max_blood} is higher with the electrode in perpendicular position for lower irrigation flow rates, and the other way around for higher flow rates: for flow rates of 5 and 10 mL min^{-1}, the T_{max_blood} in perpendicular position is higher by 5ºC and 1ºC respectively; while for flow rates of 15 and 20 mL min^{-1}, the T_{max_blood} in parallel position is higher by 2ºC.

3. Discussion

We introduce the first complete computational model for an open-irrigated electrode to be used in RFCA. The innovation was to include the interaction between blood motion and saline irrigation, which allowed to model realistically not only the geometry of the thermal lesion, but also the maximum temperature reached in the surrounding blood, which is known to have an impact on thrombus formation. The model's viability was firstly assessed against data from some existing experimental results [2] and we then conducted computer simulations under different conditions of irrigation flow rate and electrode positioning (parallel/perpendicular) in order to compare the results to those obtained from other experimental studies in which these issues were assessed, and thus further validate the computer model.

Regarding the effect of the irrigation flow rate, our results replicated the performance observed in experiments [6,7], i.e. that 1) high flow rates result in lower temperatures at the blood-tissue interface and smaller lesion diameters, 2) lesion depth is not affected by the different irrigation flow rates, and 3) Standard RF applications with open-irrigated electrodes do not reach an interface temperature of 80ºC preventing thrombus formation.

Regarding the electrode position (parallel vs. perpendicular), our model predicts larger lesion sizes when the electrode position is parallel to the tissue. As of today, the question of which electrode position provides larger lesions is still controversial. In fact, while some experimental studies reported larger lesions with the electrode in parallel contact [2,6], others showed smaller lesion sizes with this position [3] and others showed that the electrode position did not affect to the lesion size [4]. It has been suggested that the larger lesions obtained in perpendicular position could be linked with the fact that this positioning would allow for more external irrigation (namely, the holes providing external irrigation are not occluded, as could occur when the tip is parallel to the tissue). However, our computational model appears to support the findings in other studies [2,6] where larger lesions emerge for the parallel position of the catheter, independently of the irrigation flow rate, the applied power and the contact pressure. We think that possibly the discrepancy observed between experimental results about the effect of the electrode positioning could be related to the numerous variables that interplay during an experimental RF application, making the findings difficult to reproduce. In any case, our results support those works that favor the parallel positioning in terms of lesion size.

5. Conclusions

The model shows great potential in designing intervention strategies in terms of electrode positioning and tuning of the flow rate.

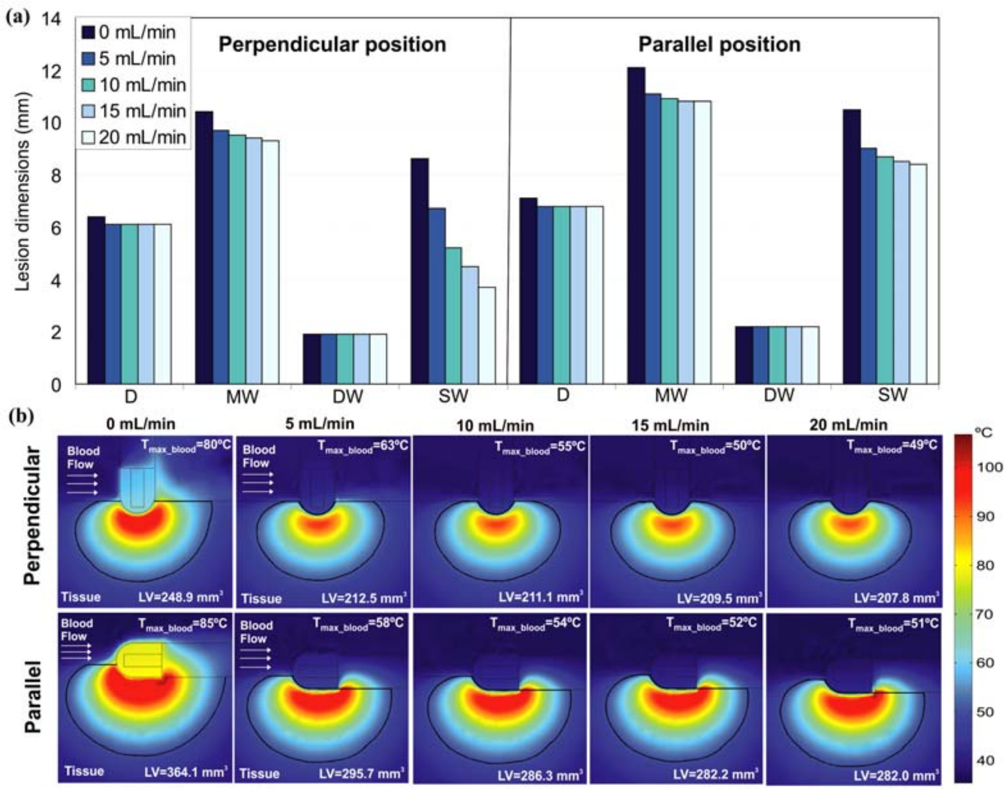

Figure 2. Effect of the irrigation flow rate and electrode position: (a) lesion dimensions and (b) temperature distributions in the cardiac tissue and blood and lesion volume (LV) after 30 s of RFCA. The black line corresponds to 50ºC isotherm.

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