In Silico Assessment of a Multipore Electrode Design for High Power Short Duration Ablation

Argyrios Petras¹, Massimiliano Leoni¹, Zoraida Moreno Weidmann², Jose M Guerra², Luca Gerardo-Giorda¹,³

¹ Johann Radon Institute for Computational and Applied Mathematics (RICAM), Austrian Academy of Sciences, Linz, Austria
² Department of Cardiology, Hospital de la Santa Creu i Sant Pau, IIB Sant Pau, Universitat Autònoma de Barcelona, CIBER CV, Barcelona, Spain
³ Institute for Mathematical Methods in Medicine and Data-Based Modelling, Johannes Kepler University, Linz, Austria

Abstract

High Power Short Duration (HPSD) ablation is an emerging approach to the radiofrequency catheter ablation for the treatment of cardiac arrhythmias. New catheter technologies have been introduced accommodating HPSD protocols, featuring multiple pores distributed around the electrode tip among others. Our previous in-silico assessment considered 6-pores electrodes, which were proven to not provide adequate cooling of the blood during the ablation. In this work, we explore the impact of a better electrode cooling system on the HPSD procedure using our previously validated computational model. A new electrode design is considered that consists of 66 irrigation pores based on state-of-the-art catheters used for HPSD. Ablations of 90W applied power for a duration of 4s for different contact forces show improved cooling of the electrode, without any steam pop complications. Yet, multiple pores around the electrode tip are not sufficient for effective blood cooling at low flows.

1. Introduction

Radiofrequency ablation using open-irrigated catheters is a commonly used treatment for cardiac arrhythmias. Recently, high-power short-duration ablation protocols have been introduced to increase the efficiency and reduce the duration of the procedure. These protocols use applied powers between 70-90W for 4-8s to eliminate the arrhythmogenic tissue. Typical state-of-the-art catheters that support these ablation protocols use an enhanced cooling system with multiple irrigation pores at the electrode tip. A previous study from our group indicated that catheters with 6 irrigation pores appear to be more prone to charring formation, reaching systematically temperatures higher than 80°C in the blood [1]. This complication has been observed regardless of the shape of the electrode tip, hinting the need for better tip cooling systems.

In this study, we assess the effect of the presence of multiple irrigation pores at the electrode tip using our in-silico framework [2] on a simulated human atrial tissue.

2. Methods

2.1. Geometry

The simulation geometry is based on the in-vitro experimental setup [3] and consists of the blood chamber 80x80x54mm, the atrial tissue 80x80x6mm and a board that models the external factors of the system 80x80x20mm. The electrode, inspired from state-of-the-art catheters, has a diameter of 2.5mm and a length of 3.5mm. It consists of 66 irrigation pores of 0.116mm diameter spread around the electrode tip as shown in Fig. 1. Six cylinders of diameter 0.28mm are placed within the tip, mimicking 3 thermocouples and 3 mini electrodes. The design of the entire geometry and the electrode is shown in Fig. 1.

The mechanical interaction of the electrode with the tissue is described by the axisymmetric Boussinesq equation for a cylindrical profile with rounded corners [4], and the resulting deformation is applied to the tissue geometry.

2.2. Mathematical model

The interaction of the blood and the irrigated saline is described by the incompressible Navier-Stokes equations in the blood-saline subdomain. The electrical potential is governed by a quasi-static equation augmented with a con-
temperature is considered at all external sides of the computational box. No thermal flux conditions are imposed lateral to the catheter body and at the top surfaces of the electrode, the thermocouples and the minielectrodes.

2.4. Model parameters

The model parameters are considered as in [1, 5]. Both the microelectrodes (ME) and the thermocouples (TC) are considered to be coated by a resistive material such as glass fiber, and thus are homogenized and modeled with the parameters of the thermistor as in [2]. Table 1 summarizes the values of the density \( \rho \) in \( kg/m^3 \), the specific heat \( c_1 \) in \( J/(kgK) \), the electrical conductivity \( \sigma_0 \) in \( S/m \) and the thermal conductivity \( k_0 \) in \( W/(mK) \) for the different subdomains of the model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Blood</th>
<th>Tissue</th>
<th>Board</th>
<th>Electrode</th>
<th>TC &amp; ME</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho )</td>
<td>1050</td>
<td>1081</td>
<td>1076</td>
<td>21500</td>
<td>32</td>
</tr>
<tr>
<td>( c_0 )</td>
<td>3617</td>
<td>3686</td>
<td>3017</td>
<td>132</td>
<td>835</td>
</tr>
<tr>
<td>( \sigma_0 )</td>
<td>0.748</td>
<td>0.281</td>
<td>( \sigma_b )</td>
<td>4.6 \times 10^6</td>
<td>( 10^{-5} )</td>
</tr>
<tr>
<td>( k_0 )</td>
<td>0.52</td>
<td>0.56</td>
<td>0.518</td>
<td>71</td>
<td>0.038</td>
</tr>
</tbody>
</table>

A linear temperature dependence is considered for the tissue specific heat, electrical and thermal conductivities as:

\[
\begin{align*}
c(T) &= c_0 \left( 1 - 0.0011(T - T_b) \right), \\
\sigma(T) &= \sigma_0 \left( 1 + 0.015(T - T_b) \right), \\
k(T) &= k_0 \left( 1 + 0.0022(T - T_b) \right),
\end{align*}
\]

where \( T_b = 37^\circ C \) is the body temperature. The electrical conductivity of the external effects board \( \sigma_b \) is tuned to match the initial resistance of the system and power delivered to the tissue. Denoting with \( A \) the ratio of the electrode surface area in contact with the blood over the one with the tissue, and with \( \Sigma \) the corresponding ratio of the electrical conductivity, the power dissipated in the tissue is written as

\[
P_t = \frac{1}{1 + A \Sigma} P,
\]

where \( P \) is the total power given by the ablation protocol [2].

The mechanical properties of the simulated human atrial tissue are considered as in [6], with a Young’s modulus of 40\( kPa \) and Poisson’s ratio of 0.499.

2.5. Lesion estimation

To provide a fair comparison against the simulated lesions with the 6-pore catheters [1], we consider the 50\(^\circ C\)
isotherm contour for the lesion size estimation. The measured quantities in this study include the lesion depth (D) from the undeformed tissue and width (W), as identified therein.

3. Results

The system (1) is numerically solved using the finite element method, implemented in the FEniCSx computing platform (fenicsproject.org). The simulations were run in the in-house HPC cluster of RICAM.

We consider a high power protocol of 90W for a total of 4s. The model simulates a total of 7s: the saline irrigation is set to a standby mode of 2mL/min for 1s, followed by an irrigation of 8mL/min for 2s before the beginning of the ablation [7]. The saline temperature is set to 22°C, similar to [1].

The initial transition phase from standby mode to active irrigation allows for a better cooling of the electrode tip before the beginning of the ablation. Fig. 2 shows the effect on the cooling for different blood flow rates using a contact force of 10g.

Next, we explore the complication rate of this electrode design for different contact forces ranging from 5g to 20g. Table 2 shows the virtual ablation outcome for different blood flow velocities. The flow velocities were chosen to mimic the ones found in epicardium (0m/s), healthy atria (0.1m/s) and cavo-tricuspid annulus (0.5m/s) [1], and are also typical in in-vitro experimental setups [3]. The catheter provides safe ablations for high blood flow velocity of 0.5m/s and any chosen contact force. On the other hand, only for 5g and a low blood flow setting of 0.1m/s we get a safe ablation. The rest of the ablations with low and no blood flow resulted in the overheating of the blood at 80°C, hence a charring complication. No steam pops were observed in the simulated ablations.

Table 2. The list of complications for different contact forces and blood flow velocities. The green S indicates a safe protocol, while the yellow C the risk of charring formation.

<table>
<thead>
<tr>
<th>Force \ Blood flow</th>
<th>0.5 m/s</th>
<th>0.1 m/s</th>
<th>0 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>5g</td>
<td>S</td>
<td>S</td>
<td>C</td>
</tr>
<tr>
<td>10g</td>
<td>S</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>15g</td>
<td>S</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>20g</td>
<td>S</td>
<td>C</td>
<td>C</td>
</tr>
</tbody>
</table>

Finally, using the high blood flow, at which no complications are observed, we explore the resulting lesion size dimensions for contact forces of 5 – 20g. The resulting tissue temperature distribution and the lesion depth and width appear in Fig. 3. The lesion dimensions range between 5.2 – 7mm for the width and 2.6 – 4mm for the depth, as measured from the undeformed tissue. These values are comparable to the ones reported in the literature [8] for a total delivered energy of 360J using high power ablation protocols.
4. Conclusions

The multipore electrode of this study appears to better cool the electrode and the surrounding blood when compared with the 6-pore electrodes. Yet for low and no blood flow and for contact forces larger than 5g charring appears in the wake of the catheter above the electrode. This indicates that the increase in the number of the irrigation pores is not sufficient for the effective cooling for such scenario, hinting that other technologies such as temperature cutoff or variable saline irrigation rates are required.

In terms of lesion size dimensions, the multipore electrode produces lesions comparable to the 6-pore electrodes, and within available experimental data [8].

5. Limitations

The thermocouples and the minielectrodes are modeled as homogenous without accounting for the interior structure or the impact of the electrical field generated from the minielectrode in the ablation outcome. Nonetheless, a temperature variation is observed at the thermocouples following the tissue and blood temperature rise. Additionally, our model considers constant power ablation protocols with a fixed saline irrigation flow rate and a fixed saline temperature. State-of-the-art catheters use temperature control to titrate the applied power and varying saline irrigation flow rates following the feedback from the thermocouples. The saline temperature also varies according to the irrigation rate [9] and can have an impact in the ablation outcome. These aspects are part of our ongoing work.

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References


Address for correspondence:
Argyrios Petras
Altenbergerstrasse 69, 4040 Linz, Austria
argyrios.petras@ricam.oeaw.ac.at