

C4 Numerical modeling of pulsed field ablation in swine ventricular myocardium

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Duration of the experiments: 120 min

Max. number of participants: 6

Location: Laboratory of Biocybernetics

Level: Basic

PREREQUISITES

No specific knowledge is required for this laboratory exercise.

The aim of this laboratory practice is to use numerical modeling to understand how applied voltage, waveform, tissue electrical properties, and ablation catheter and return electrode placement affect electric field distribution and lesion size for pulsed field ablation (PFA) in ventricular myocardium.

THEORETICAL BACKGROUND

Pulsed field ablation (PFA) is a novel non-thermal ablation modality that is being rapidly adopted to treat cardiac arrhythmias [1]. In PFA, high-voltage pulses generate strong electric fields in the target tissue, permeabilizing cell membranes (electroporation) and leading to cell death [2]. While PFA has been highly successful for atrial fibrillation, achieving transmural lesions in the thicker ventricular myocardium remains a challenge.

The goal of PFA is to ablate the target arrhythmogenic tissue by establishing a field strong enough to cause irreversible electroporation. The field strength above which cells die is called the lethal electric field threshold (LET), a useful simplification of the otherwise graded and complex process of cell death [3]. The extent of a PFA lesion therefore depends on the electric field distribution in the target tissue and its LET. The LET is dependent on the tissue type and the pulse protocol/waveform (e.g. monophasic vs. biphasic pulses, pulse duration, number of pulses) [3], [4]. The electric field distribution, in turn, is governed by the applied voltage; the shape, size, and placement of the active (ablation) and return electrodes; and the electrical properties of the tissue [5]. The ablation catheter is placed in contact with the myocardium, while the return electrode can be arranged in several ways: as a dispersive patch on the patient's skin (unipolar), on the same catheter (bipolar) [5], or on a separate catheter, for example in the inferior vena cava (modified unipolar) [6] – each with its own trade-offs.

The electric field distribution in realistic anatomical geometries cannot be calculated analytically. It is computed numerically instead, most often with the finite element method, which divides the model geometry into small elements and solves the governing equations on the resulting mesh [7]. Numerical modeling allows us to compare different electrode configurations, calculate the resulting electric field distributions, and predict lesion volume and depth by evaluating where the electric field exceeds the LET for the specific pulse protocol/waveform [4], [6].

EXPERIMENT

A finite element method numerical modeling program, COMSOL Multiphysics (COMSOL AB, Stockholm, Sweden), will be used to simulate PFA in swine ventricles using a focal ablation catheter and a schematic biventricular heart model in a swine torso, described in [4] and [6]. The heart model includes the myocardial fiber orientation (Figure 1A) and is embedded in a swine torso together with the segmented thoracic tissues and a dispersive patch (Figure 1B).

The electric field distribution is calculated by solving the continuity equation for conservation of charge in a stationary study:

$$\nabla \cdot (\sigma \nabla V) = 0$$

where V is the electric potential and σ is the electrical conductivity. The electric field is then calculated as $E = -\nabla V$. The applied voltage is prescribed at the ablation electrode and 0 V at the return electrode; all other outer boundaries are electrically insulating. The conductivity of the ventricular myocardium is anisotropic, with a higher value along the myocardial fibers than transverse to them, and increases with the local electric field due to electroporation [3].

We will investigate how voltage, lethal electric field threshold (LET), tissue electrical properties, and ablation catheter and return electrode placement affect lesion size and depth for PFA in ventricular myocardium.

The models should be set up and solved to achieve the following objectives:

- Calculate the impedance for the specific PFA setup and parameters.
- Calculate and visualize the electric field distribution in the ventricular myocardium.
- Determine the lesion volume by calculating the volume of ventricular myocardium exposed to an electric field above the chosen LET.
- Determine the lesion depth by calculating the maximum distance perpendicular to the endocardial wall where the electric field is above the LET.

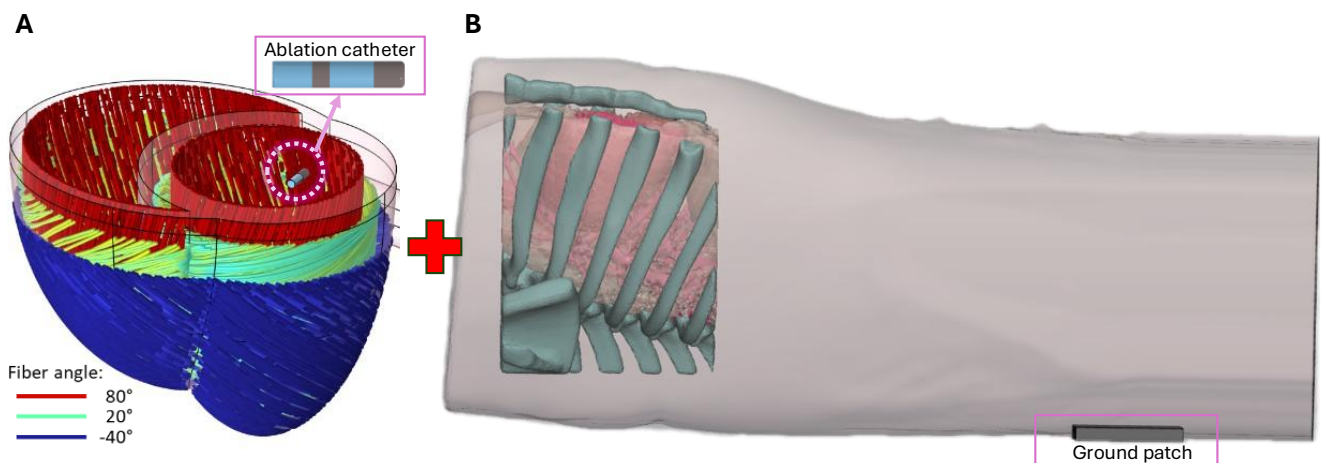


Figure 1: Model geometry for unipolar PFA in swine ventricles with a focal ablation catheter. (A) Schematic biventricular model of the swine heart showing the ablation catheter positioned in the left ventricle (LV) and the myocardial fiber orientation, which varies continuously from endocardium to epicardium and is shown sampled at three depths. (B) Swine torso with the segmented thoracic tissues (ribs, lungs, heart, and blood/vasculature) and the dispersive ground patch in the lumbar region. The biventricular model in (A) is embedded within the torso at the location of the segmented heart.

Protocol:

1. Open the pre-built 3D model of the biventricular heart inside the swine torso following the lecturer's instructions, and familiarize yourself with the model.
2. Assign electrical properties to the tissues, considering the anisotropic and field-dependent electrical conductivity of the ventricular myocardium.

3. Set up and solve the model for the standard unipolar PFA configuration by defining the ablation catheter in the left ventricle (LV) and a skin patch on the lumbar region.
4. Calculate impedance for the unipolar PFA configuration.
5. Visualize the electric field distribution in the ventricular myocardium.
6. Determine lesion size (volume and depth) for different LET values.
7. Change the applied voltage and solve the model. Investigate the effect of different voltages on lesion size.
8. Investigate the effect of different ablation catheter placements on lesion size by moving the ablation catheter to different locations in the LV (e.g. basal–apical, posterior–anterior segments).
9. Change the return electrode placement in the model to a bipolar or modified unipolar configuration and solve it.
10. Visualize the electric field distribution, calculate impedance and lesion size, and compare the results against the standard unipolar configuration.

REFERENCES:

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- [3] Kos B., et al. Determination of lethal electric field threshold for pulsed field ablation in ex vivo perfused porcine and human hearts. *Front Cardiovasc Med*. 10:1160231, 2023.
- [4] Miklavčič D., et al. Biophysics and electrophysiology of pulsed field ablation in normal and infarcted porcine cardiac ventricular tissue. *Sci Rep*. 14:32063, 2024.
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- [7] S. Dokos, *Modelling Organs, Tissues, Cells and Devices*. in Lecture Notes in Bioengineering. Berlin, Heidelberg: Springer Berlin Heidelberg, 2017. doi: 10.1007/978-3-642-54801-7.

EXPECTED RESULTS

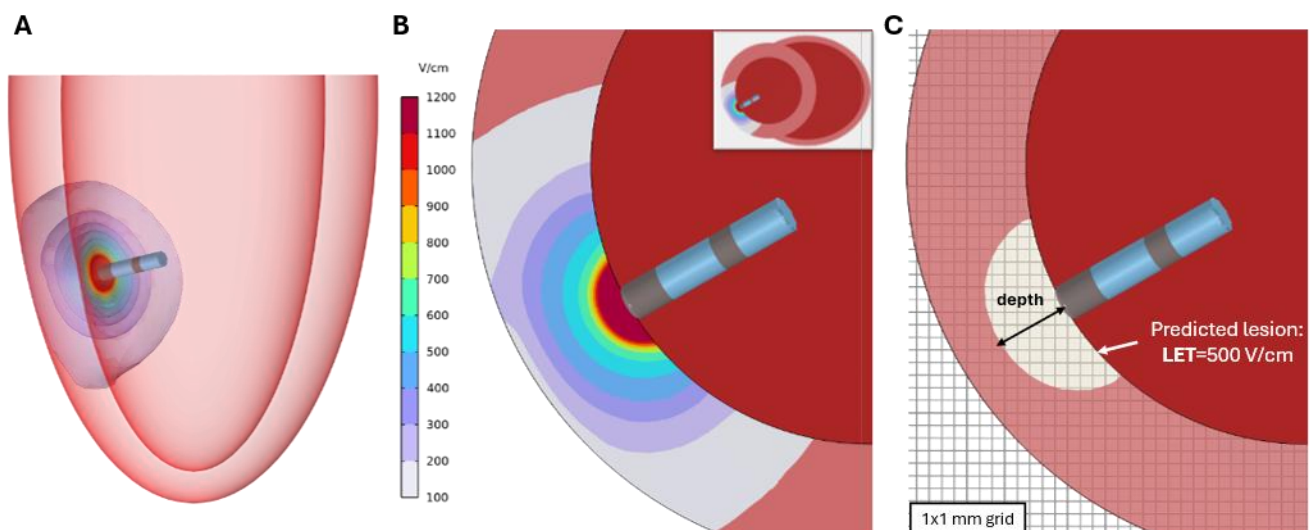


Figure 2: Simulated unipolar PFA in the LV at 2000 V. Electric field distribution in the myocardium: (A) 3D view and (B) 2D short-axis slice, with an inset showing the full cross-section). (C) Predicted lesion on the same slice for LET of 500 V/cm, grid is 1×1 mm.

NOTES & RESULTS
