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From experimental data to 3D realistic simulations: a pacemaker example

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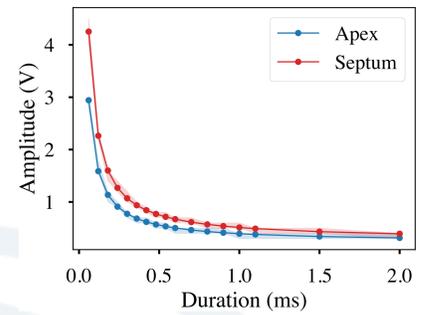
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Introduction & context

An implantable pacemaker aims to restore a cardiac beat when the intrinsic conduction system fails. It sends energy to the heart in the form of a voltage pulse during a fixed duration and it is programmed to deliver enough energy to trigger a cardiac depolarization.

We present results of a 3D model of a cardiac pacemaker with a tissue surrounded by blood. We take into account electrochemical phenomena observed during pacing, like electrode polarization, which is crucial to make realistic simulations. We explain how we use experimental data to feed our model with valid inputs. To validate the model, we will compare numerical results with ex-vivo experimental data of stimulation threshold detection and voltage measurements.

Fig. 1. Experimental threshold Lopicque curves on healthy tissue for two implantation sites (apex and septum).



Exploiting experimental data

We need to determine some input values for our model in order to obtain realistic outputs. We use optical mapping measurements to optimize 2 parameters in the Beeler-Reuter ionic model. We also need to extract the volume fraction of healthy tissue, from MRI images, on a multi-cellular level.

Fig. 3. Sheep ventricle preparation for optical mapping and pacing experiments. Endocardial view of the right ventricle with apex on the right and septum at the center of the image.

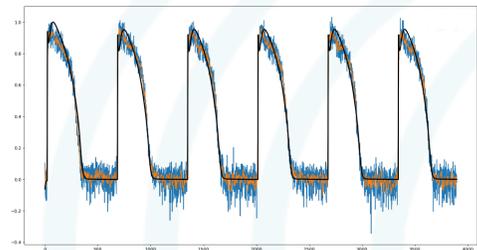
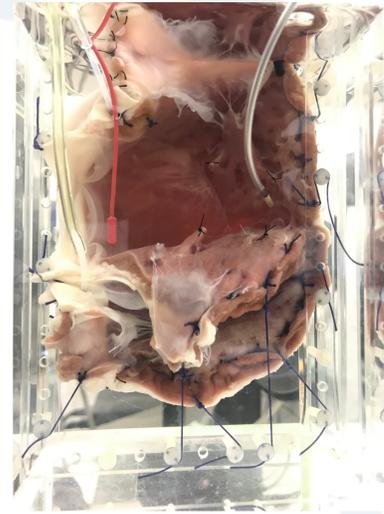


Fig. 2. Example of optical mapping signal. Blue: raw signal; orange: smoothed signal; black: computed action potential with the Beeler-Reuter ionic model and optimized parameters.

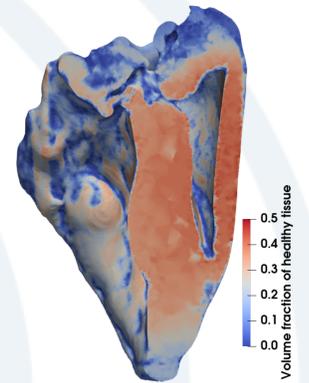


Fig. 4. Volume fraction of healthy tissue from the pilot experiment.

0D models & bath experiments

As surrogate models to 3D ones, several 0D models were first designed. These models include a pacemaker equivalent circuit and 2 contact models, one for each electrode. The propagation media is replaced by a passive one, in order to calibrate the contact parameters (c_+ , c_- , g_+ and g_-). The calibration is performed on experimental voltage and current, measured when delivering current into a passive saline solution, Fig. 5.

In the following 0D models we add rescaled membrane models such as Beeler-Reuter [1]. The calibration shows great influence of the scaling parameters. The models also allow to study the influence of bio-electrodes parameters (contact with tissue, not only a bath) and to perform a simplified threshold search and compare it to animal experiments.

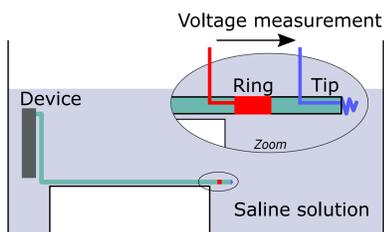


Fig. 5. Sketch of the bench test used to calibrate the electrode contact models.

Conclusion

Combining the information obtained from experimental data and real characteristics of the pacemaker (electrical circuit and geometry), we computed the propagation of the electrical activity generated by the pacemaker. 3D results are preliminary but promising.

The final validation will consist in comparison between activation maps from optical mapping and the ones from the simulation. The main objectives to achieve are the comparison with experimental threshold curves thanks to the 3D simulations and to study the influence of design/contacts/tissue health on these curves.

Pacemaker model & preliminary results

The global problem to solve, Fig. 6, is composed of the device internal circuitry, two chosen electrode models and a propagation model. The partial differential equations part includes the bidomain equations in the tissue and a Poisson equation in the blood, both with homogeneous Neumann boundary conditions at the boundary of the box. The coupling with the pacemaker is achieved thanks to non standard boundary conditions at electrode boundaries.

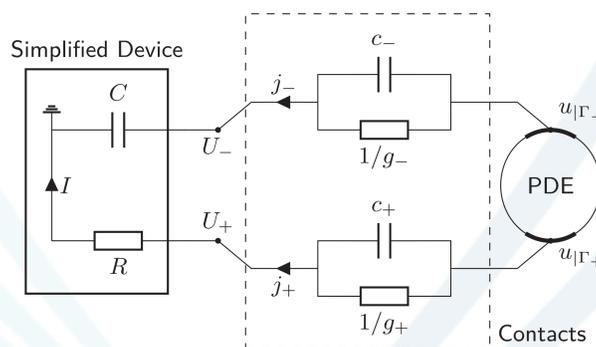


Fig. 6. Schematic electrical circuit to model the pacemaker with the device circuit on the left, contact (electrode) models, and the propagation PDE on the right.

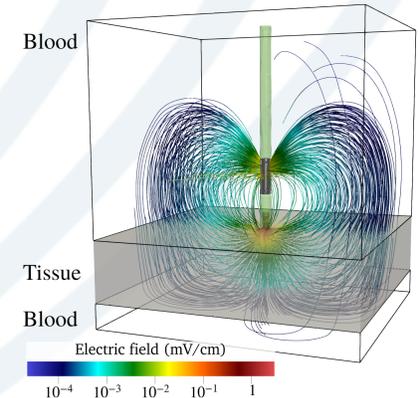


Fig. 7. 3D computation of the electric field generated by the pacemaker in the tissue and blood. The lead geometry, including screw and ring, is as realistic as possible and based on manufacturer's CAD.

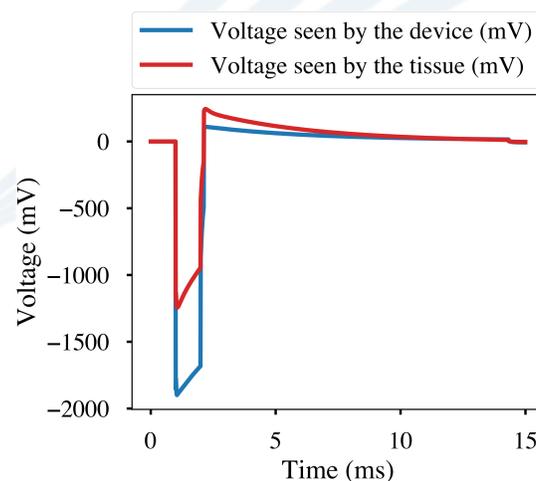


Fig. 8. Additional outputs from the 3D model, including the measured voltage and electrode surface potentials.

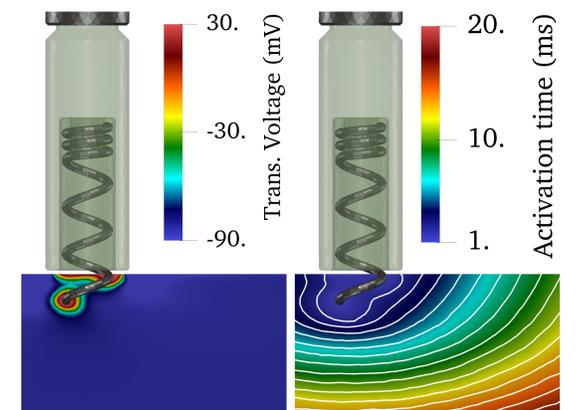


Fig. 9. Zoom on the screw area with electric field and transmembrane voltage at 0.5ms after the beginning of the stimulation (2.5V, 1ms).

[1] Valentin Pannetier et al. "Modeling Cardiac Stimulation by a Pacemaker, with Accurate Tissue-Electrode Interface". In: *Functional Imaging and Modeling of the Heart - 12th International Conference, FIMH 2023, Lyon, France, June 19-22, 2023, Proceedings*. Ed. by Olivier Bernard et al. Vol. 13958. Lecture Notes in Computer Science. Springer, 2023, pp. 194–203. DOI: 10.1007/978-3-031-35302-4_20.