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# MODELING CARDIAC STIMULATION BY A PACEMAKER, WITH ACCURATE TISSUE-ELECTRODE INTERFACE

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An implantable pacemaker aims to restore a cardiac beat when the intrisic conduction system fails. It sends energy to the heart in the form of a voltage pulse and it is programmed to deliver enough energy to trigger a cardiac depolarization (which is called capture). We present a 0D model of a cardiac pacemaker with a cardiac tissue. We take into account electrochemical phenomena observed during pacing, like electrode polarization. To validate it, we compare numerical results with ex-vivo experimental data of stimulation threshold detection.

### > **OD** model for a pacemaker

**O** Pulse. A tank capacitor  $C_{pulse}$  acts as source of current. In the meantime, a second capacitor  $C_{ocd}$  is charged. The duration (d) and the amplitude ( $V_{stim}$ ) of the pulse is decided by the clinician.

**2** Switch. short transition phase (~ hundreds of µs) during which switches are open.

**B** Output Capacitor Discharge (OCD). C<sub>pulse</sub> is isolated and C<sub>ocd</sub> discharges. This step lasts for 13 ms, and counteracts the electrode polarization that occured during the pulse.

### > Pacemaker coupled to a purely resistive medium

Current (top) and voltage



**Equivalent circuit** of a **pacemaker** (black, left) coupled to either a **resistive medium** (blue, middle), or a **single cell model** (red, right) via connecting dots and contacts (green, middle).

### **>** Pacemaker coupled to a rescaled Beeler-Reuter [3] ionic model (I<sub>ion</sub>, g) with an extracellular conductance g<sub>ext</sub>

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			^



(bottom) delivered by a pacemaker lead in a saline **solution** (black solid line). Red dashed lines are the **calibration** for 2 V and 1 ms.

#### **Parameters:**

• device:  $R_{tot}$ ,  $\tau = R_{tot}C_{tot}$  depend on the phase (1, 2 or 3). • contacts: modeled by a parallel R C circuit with parameters ( $C_1$ ,  $\tau_1$ ) and ( $C_2$ ,  $\tau_2$ ).

# > Calibration: ringer tests

To evaluate the accuracy of the R//C model for the electrode polarization: • We measure the current I and the voltage V delivered by a pacemaker lead directly in a saline passive solution without cardiac tissue.

• We use a MicroPort Vega lead to obtain datasets of (Imeas, Vmeas) for different stimulation amplitudes and durations.

• Method. Weighted least square on Imeas and Vmeas. • **Resolution.** SciPy implementation of the L-BFGS-B algorithm

 $\rightarrow$  Identifying properties of contacts (C<sub>1</sub>,  $\tau_1$ ) and (C<sub>2</sub>  $\tau_2$ ).





**Parameters:** + Scaling parameters: S,  $\tau_m = SC_m / g_{ext}$ .



▲ Transmembrane voltage computed for a single set of parameters ( $V_{stim}$ , d, S,  $g_{ext}$ ).







**A** Fitted currents and voltages when calibrating parameters  $\theta = (R_1, R_2, R_3)$  $\tau_1, \tau_2$ ): comparison between a single experimental dataset (gray solid line),  $\theta$  calibrated on this dataset (blue dotted line) and  $\theta$  calibrated on the 9 datasets together (red solid line).

## **Computer model compared to experimental data**



▲ Lapicque curve obtained after detection of a 50% capture ratio. Blue points are for 0% capture, and red points for 100% capture.



### > Lapicque curve

In order to save battery, the energy delivered by the pacemaker must be just above the cut-off threshold between capture and non-capture.

• Lapicque curve: threshold of stimulation in the voltage-duration plane [2]. • Computed from ratio of successful captures in the 0D model with a 2D dichotomy.

$$A(d) = A_{\rm rh} \left( 1 + \frac{t_{\rm ch}}{d} \right)$$

- **> Animal and computer experiments** 
  - Two wedge preparation of sheep hearts in a saline solution [5].
  - Testing a range of pulse durations and stimulus amplitudes to localize the stimulation threshold.
- Scaling parameter **S** has a great influence (determines the amount of current seen per  $cm^2$  of membrane).

### • Little influence of the parameter gext

• Study the **influence of bio-electrodes parameters** (contact with tissue, not only a bath).

# > Next

### > 3D model of tissue slab surrounded by blood

\* Take the geometry into account (electrode distances, front wave propagation, ...) \* Compare experimental data with our 3D solution.





▲ **Right ventricle endocardial** view of the tissue wedge preparation with the pacemaker electrode implanted in the septum (arrow). Other implantations sites were located in the apex (×) and at the base of the ventricle (+).

Example of activation map obtained from optical mapping.

▲ Comparison of Lapicque curves (solid lines) computed with different values of S (top) and  $R_1$  (bottom). The **shaded regions** indicate where the **experimental capture threshold** is located, for different stimulation sites on the tissue wedge. abla



Equi-potential electrodes coupled with the device [4].

• Transparent boundary conditions on the box.

• Bidomain in the tissue  $(u_i, u_e)$ . With bath loading in the blood (u<sub>e</sub>).

### > Additional ex-vivo data to adjust the model

 $\bullet$  Activation by optical mapping  $\rightarrow$  conductivity distribution. \* Voltage measured by the lead.

\* Geometries, fibers orientation and collagen distribution from 9.4T MRI.

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