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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 intrinsic 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.

> 0D model for a pacemaker

● **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.

● **Switch.** short transition phase (\sim hundreds of μs) during which switches are open.

● **Output Capacitor Discharge (OCD).** C_{pulse} is isolated and C_{ocd} discharges. This step lasts for 13 ms, and counteracts the electrode polarization that occurred during the pulse.

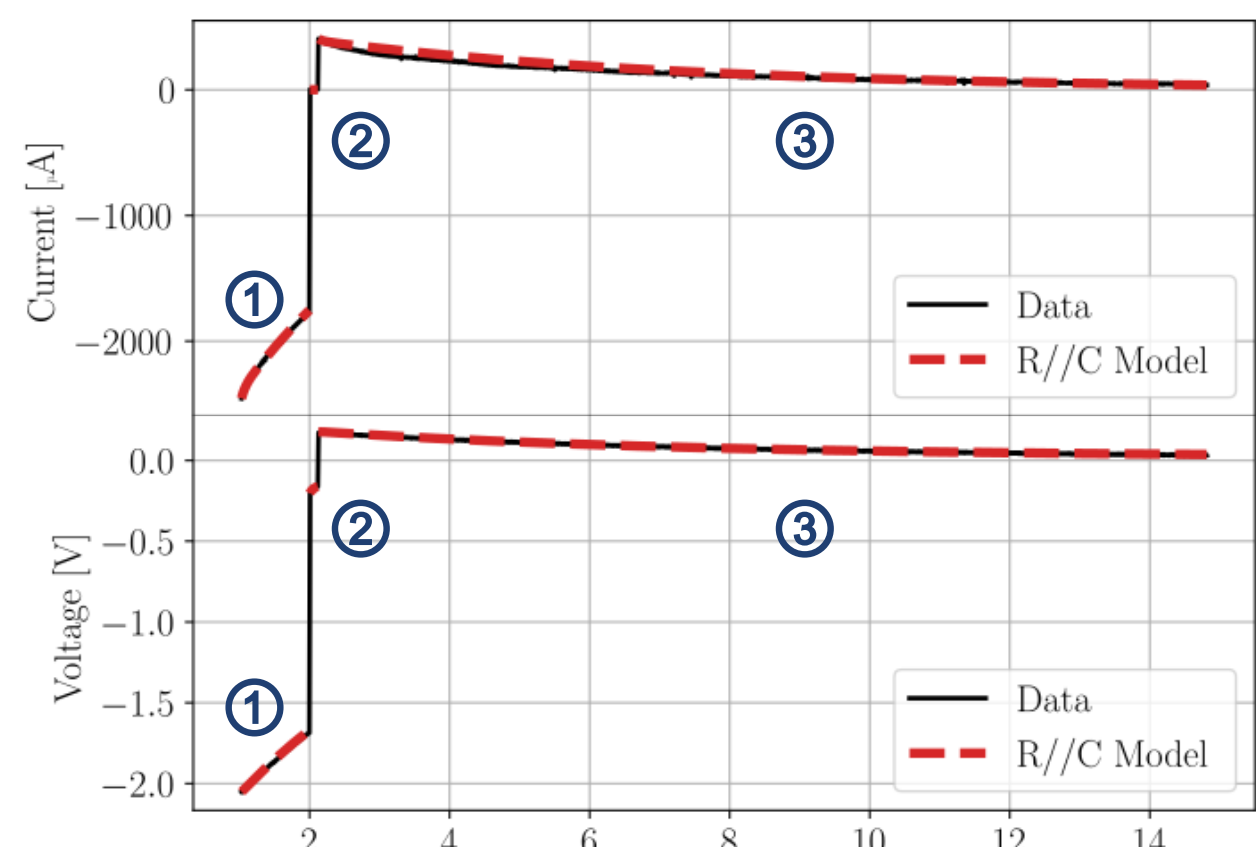
> Pacemaker coupled to a purely resistive medium

$$\frac{dI}{dt} + \frac{1}{\tau} I = \frac{1}{R_{tot}} \left(\frac{V_1}{\tau_1} + \frac{V_2}{\tau_2} \right)$$

$$\frac{dV_1}{dt} + \frac{V_1}{\tau_1} = \frac{I}{C_1}$$

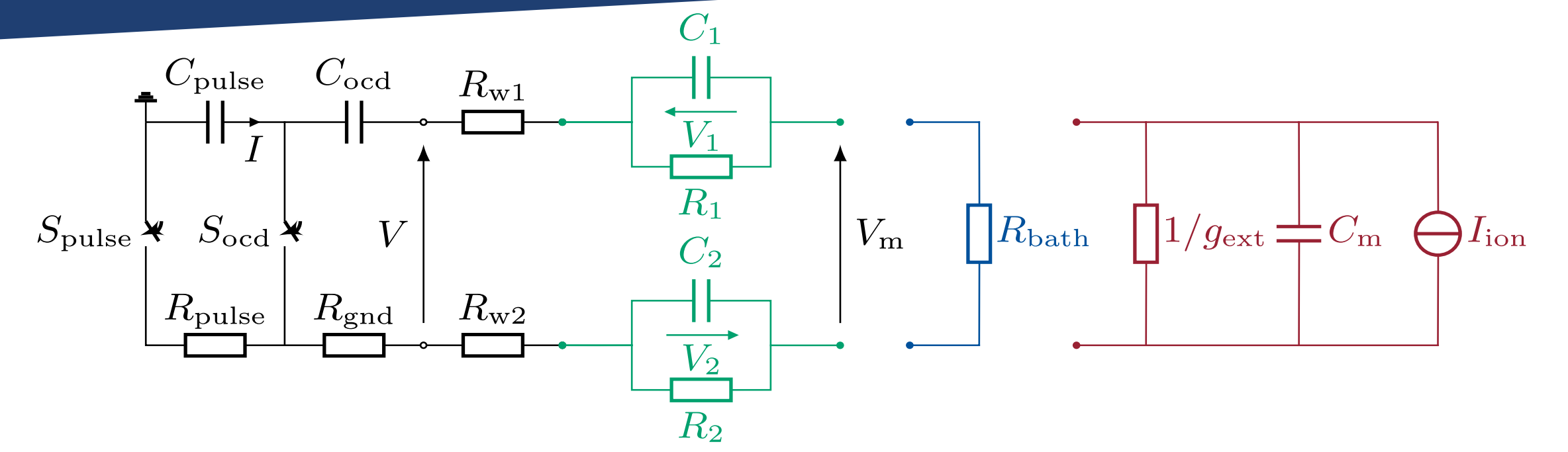
$$\frac{dV_2}{dt} + \frac{V_2}{\tau_2} = \frac{I}{C_2}$$

► **Current** (top) and **voltage** (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 RC circuit with parameters (C_1, τ_1) and (C_2, τ_2).



▲ **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_{ion}, g) with an extracellular conductance g_{ext}

$$\frac{dI}{dt} + \frac{1}{\tau} I = \frac{1}{R_{tot}} \left(\frac{V_1}{\tau_1} + \frac{V_2}{\tau_2} + \frac{I_{ion}(h, V_m)}{C_m} + \frac{V_m}{\tau_m} \right)$$

$$\frac{dV_1}{dt} + \frac{V_1}{\tau_1} = \frac{I}{C_1}$$

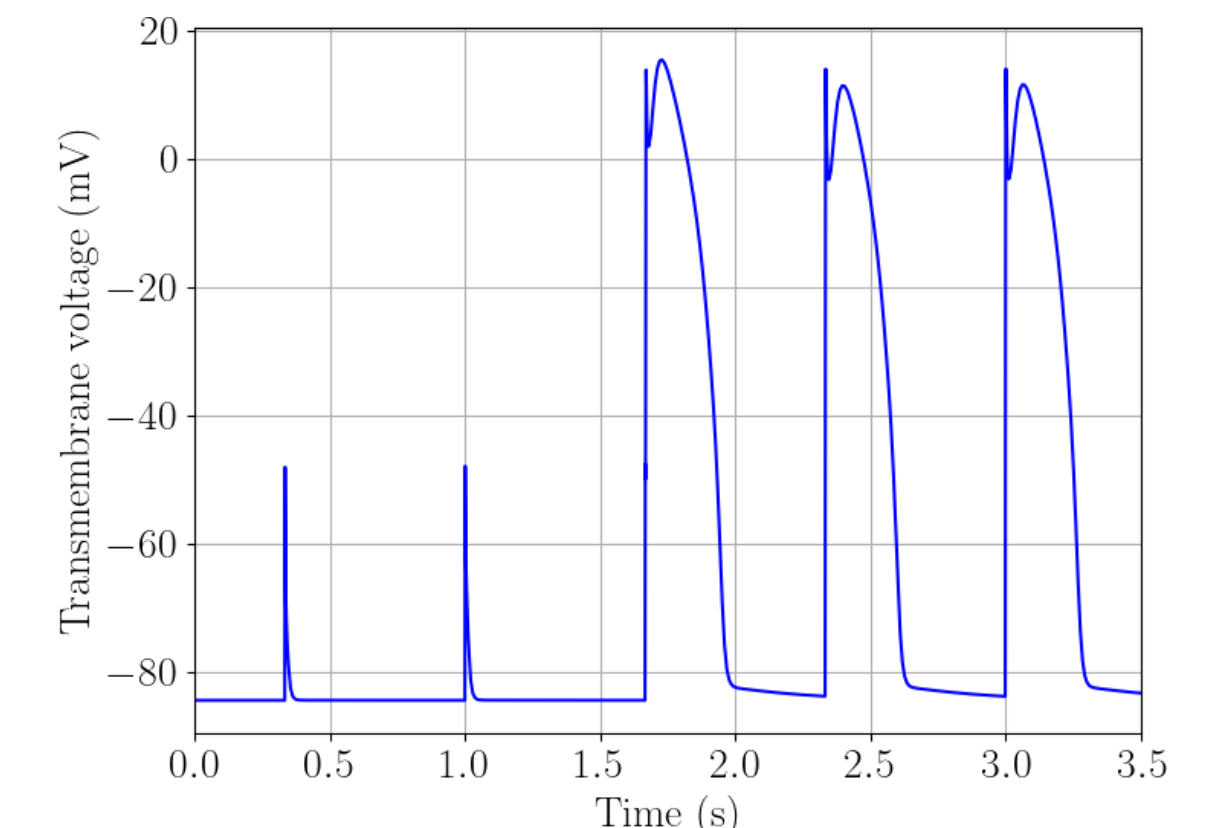
$$\frac{dV_2}{dt} + \frac{V_2}{\tau_2} = \frac{I}{C_2}$$

$$\frac{dV_m}{dt} + \frac{I_{ion}(h, V_m)}{C_m} + \frac{V_m}{\tau_m} = \frac{I}{SC_m}$$

$$\frac{dh}{dt} + g(h, V_m) = 0$$

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}).

> Calibration: ringer tests

To evaluate the **accuracy of the R/C model** for the **electrode polarization**:

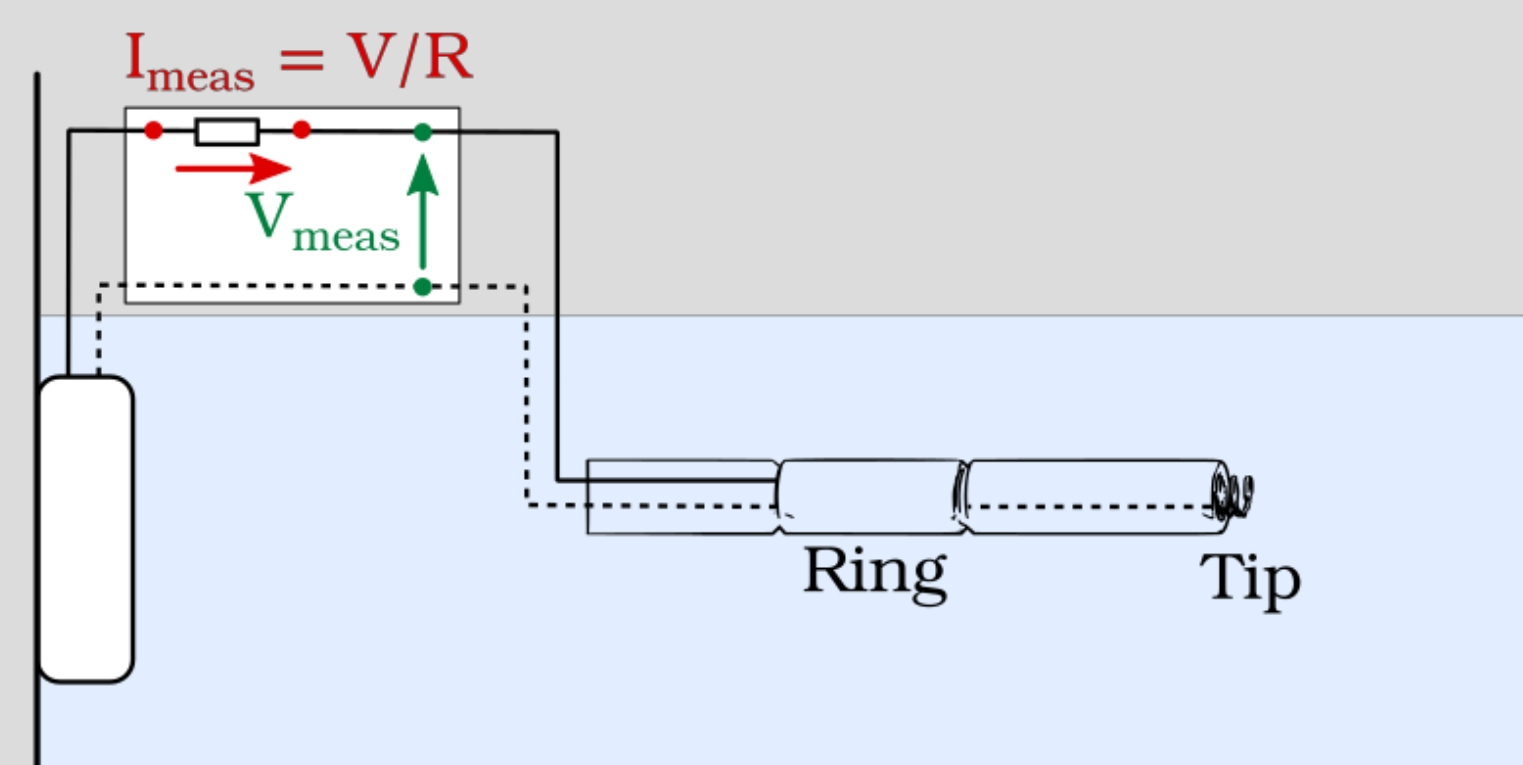
• We measure the current I and the voltage V delivered by a pacemaker lead directly in a **saline passive solution** without cardiac tissue.

• We use a MicroPort Vega lead to **obtain datasets of (I_{meas}, V_{meas})** for **different stimulation amplitudes and durations**.

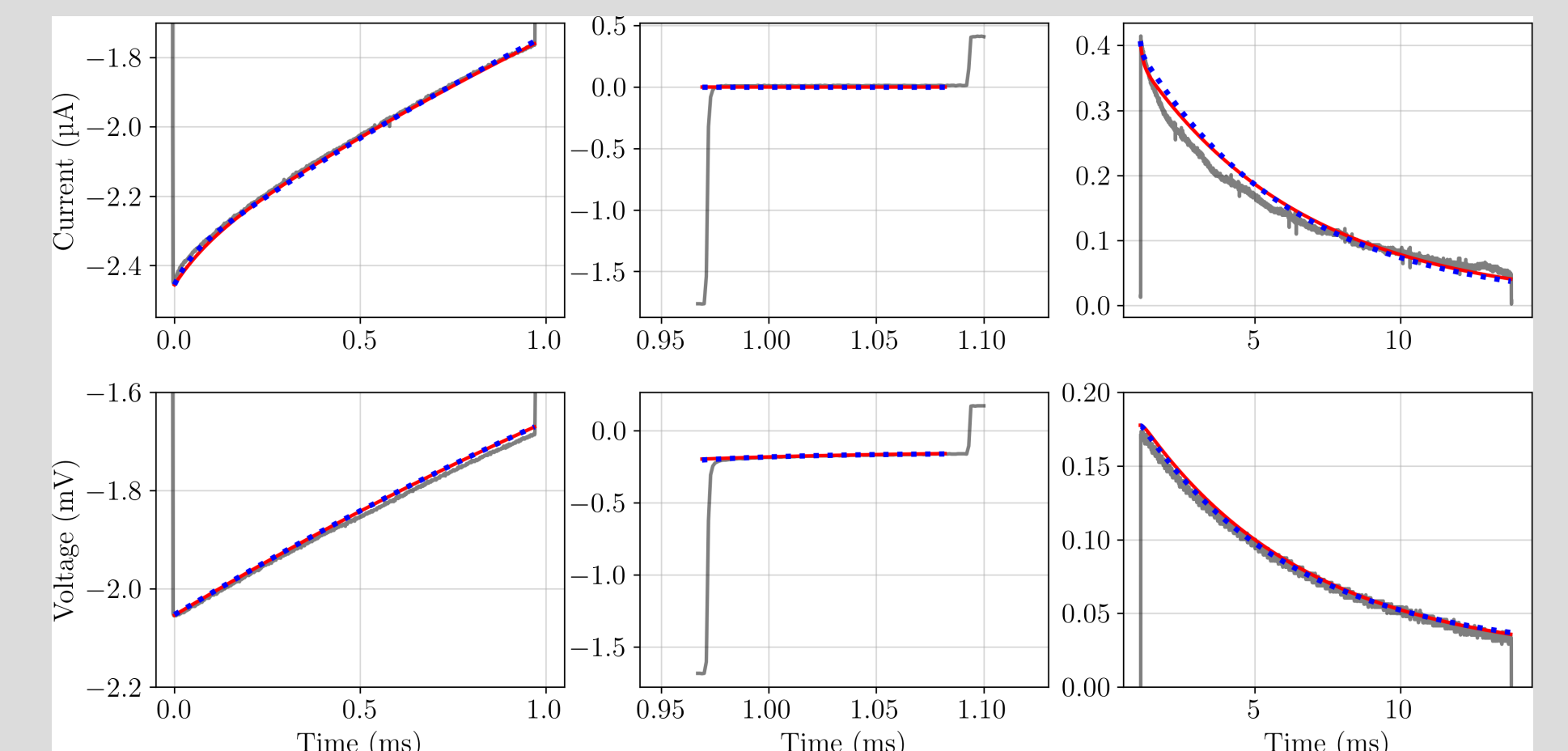
• **Method.** Weighted least square on I_{meas} and V_{meas} .

• **Resolution.** SciPy implementation of the L-BFGS-B algorithm

→ **Identifying** properties of contacts (C_1, τ_1) and (C_2, τ_2).

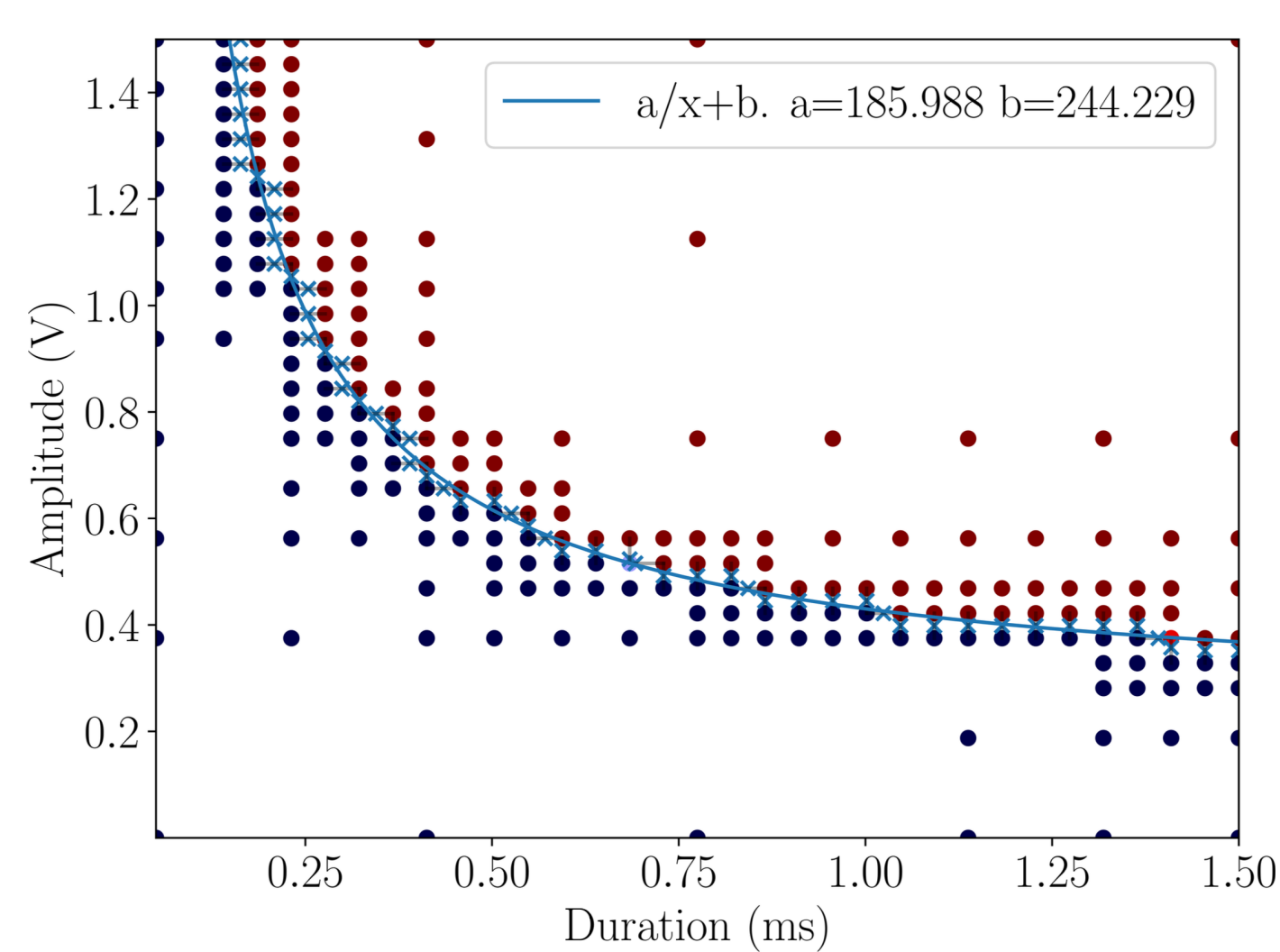


▲ **Sketch** of the bench test used to calibrate the electrode contact model.

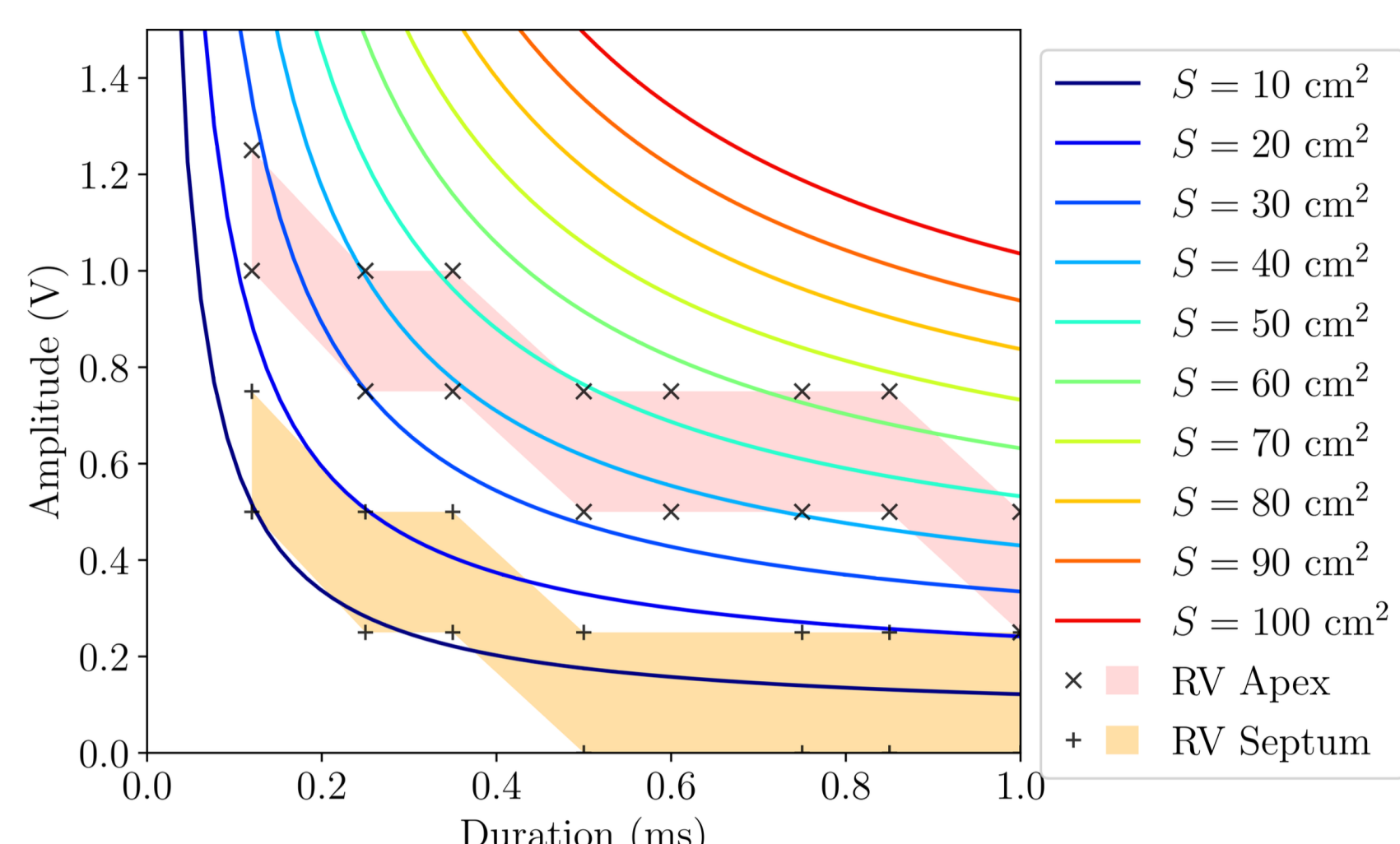


▲ **Fitted currents and voltages** when calibrating parameters $\theta = (R_1, R_2, \tau_1, \tau_2)$: comparison between a single experimental dataset (gray solid line), θ calibrated on this dataset (blue dotted line) and θ calibrated on the 9 datasets together (red solid line).

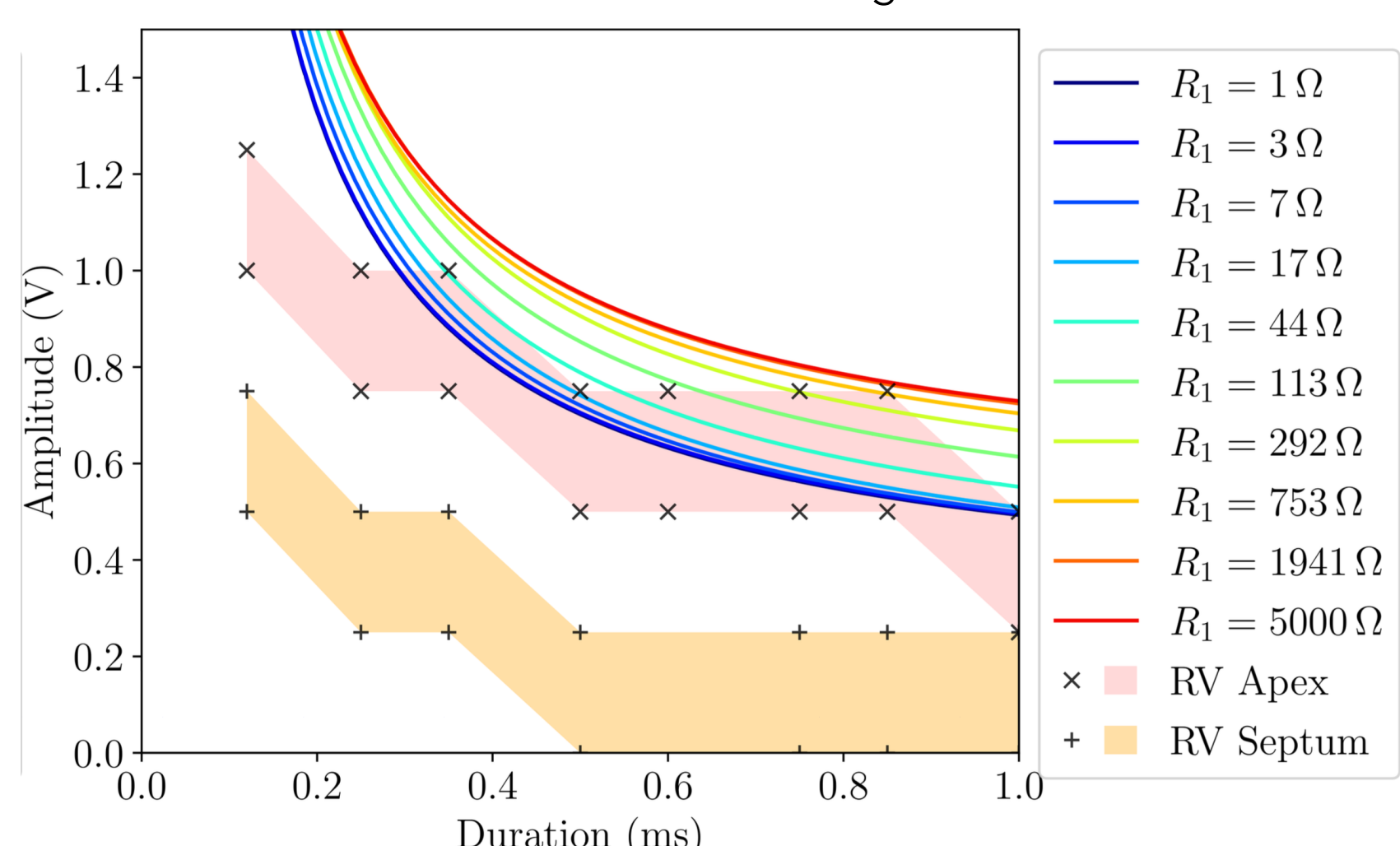
> Computer model compared to experimental data



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



▲ 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. ▼



> 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**.

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

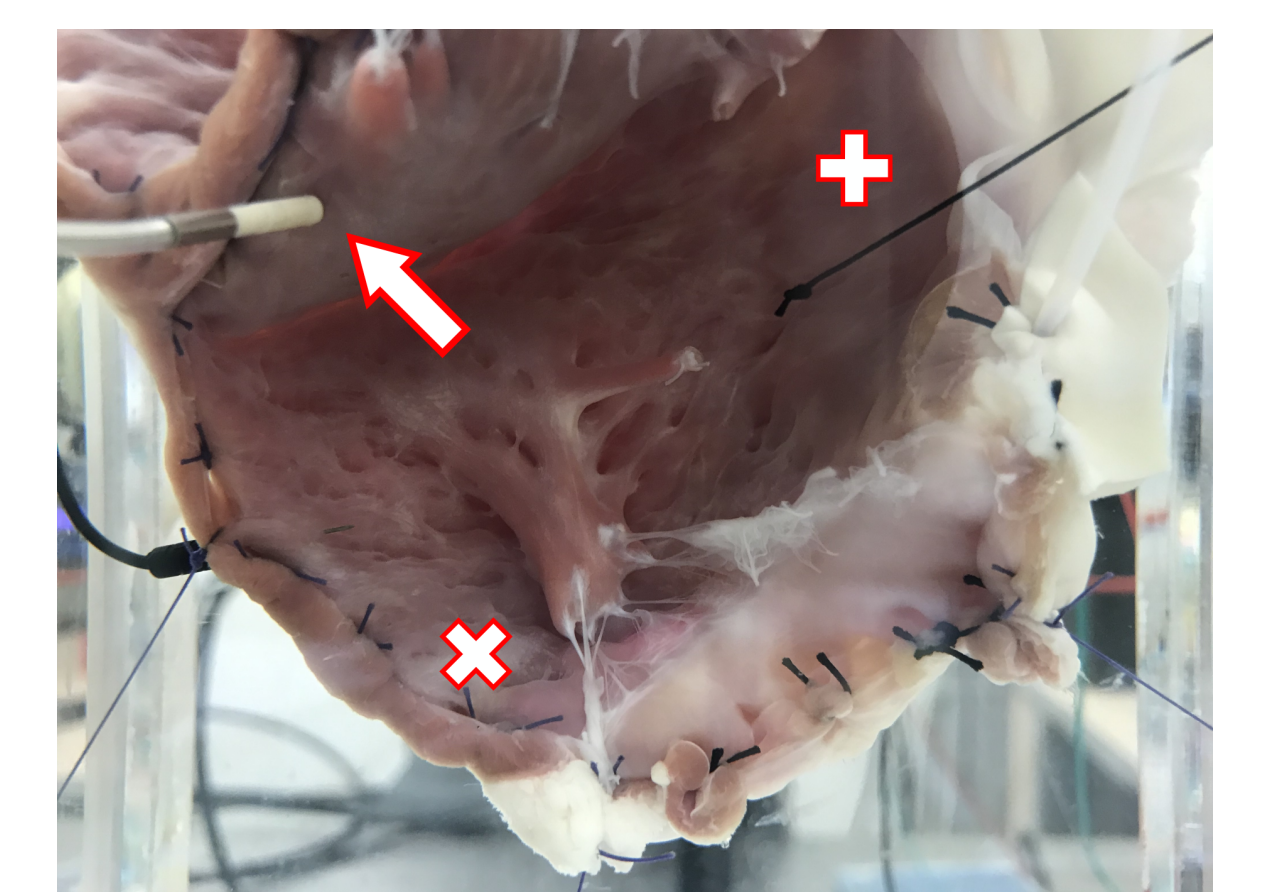
> Animal and computer experiments

- **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 **g_{ext}**

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

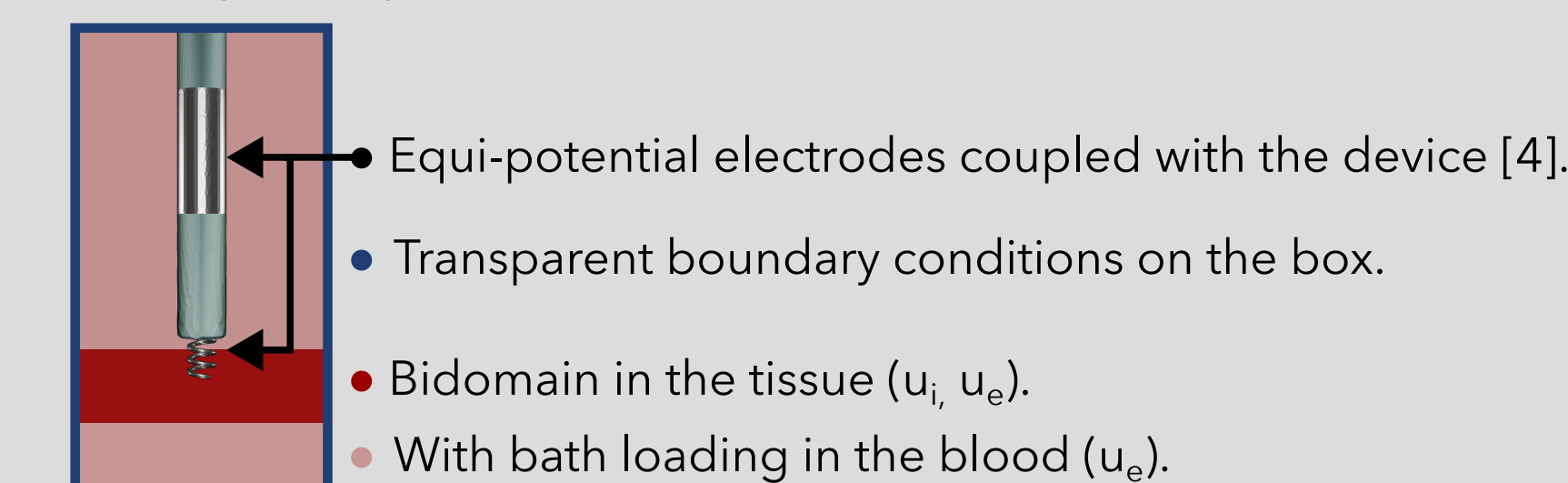


▲ **Right ventricle endocardial** view of the tissue wedge preparation with the pacemaker electrode implanted in the septum (arrow). Other implantation sites were located in the apex (+) and at the base of the ventricle (+).

> Next

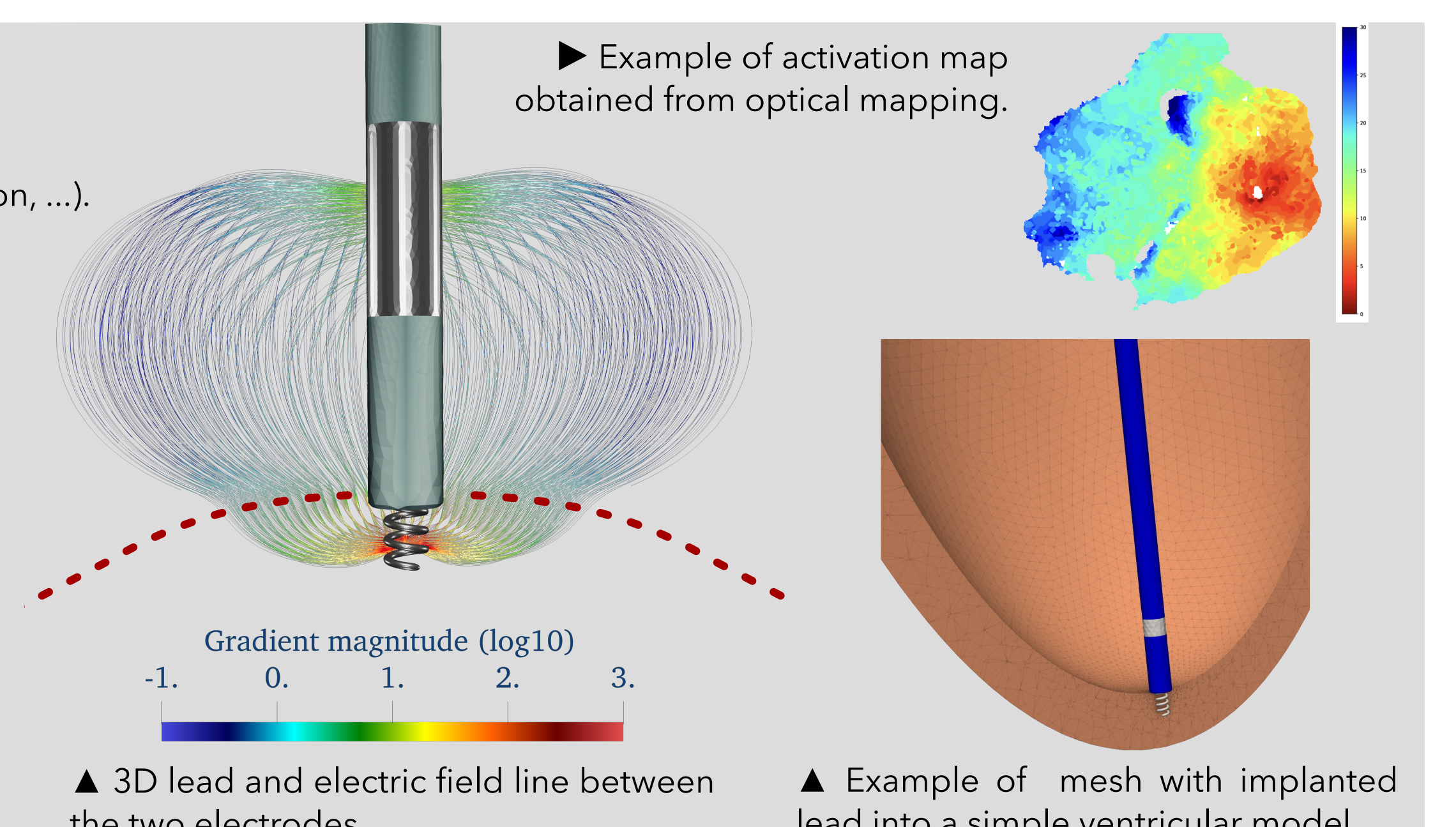
> 3D model of tissue slab surrounded by blood

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



> Additional ex-vivo data to adjust the model

- Activation by optical mapping → conductivity distribution.
- Voltage measured by the lead.
- Geometries, fibers orientation and collagen distribution from 9.4T MRI.



▲ 3D lead and electric field line between the two electrodes.

▲ Example of mesh with implanted lead into a simple ventricular model.

References

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