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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  $\mu s$ ) 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.

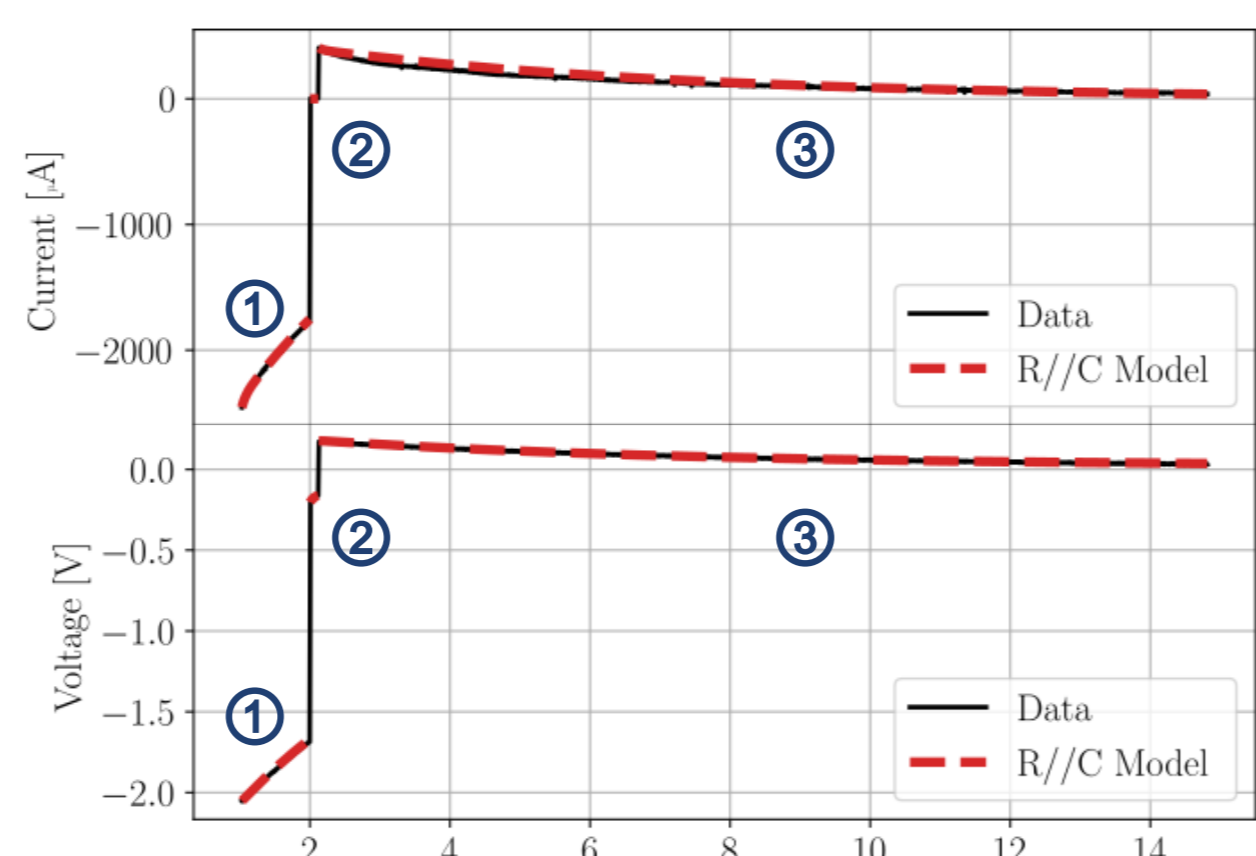
### > Pacemaker coupled to a purely resistive medium

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

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

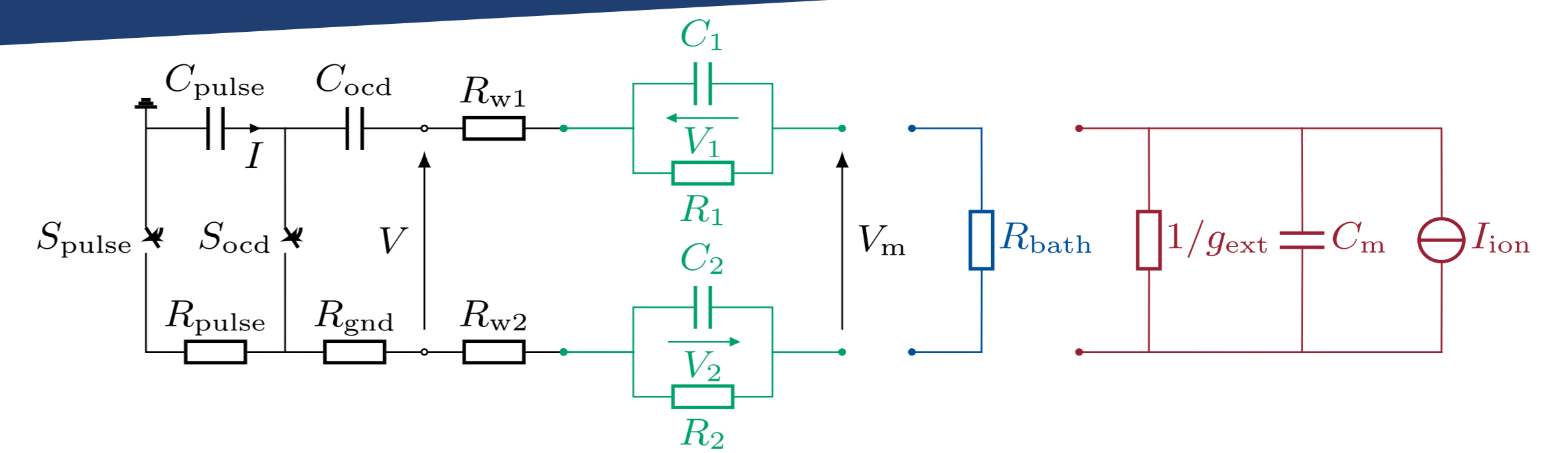
$$\frac{dV_2}{dt} + \frac{V_2}{\tau_2} = \frac{I}{C_2}$$

► **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 ( $C_1, \tau_1$ ) and ( $C_2, \tau_2$ ).



▲ **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 $g_{ext}$

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

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

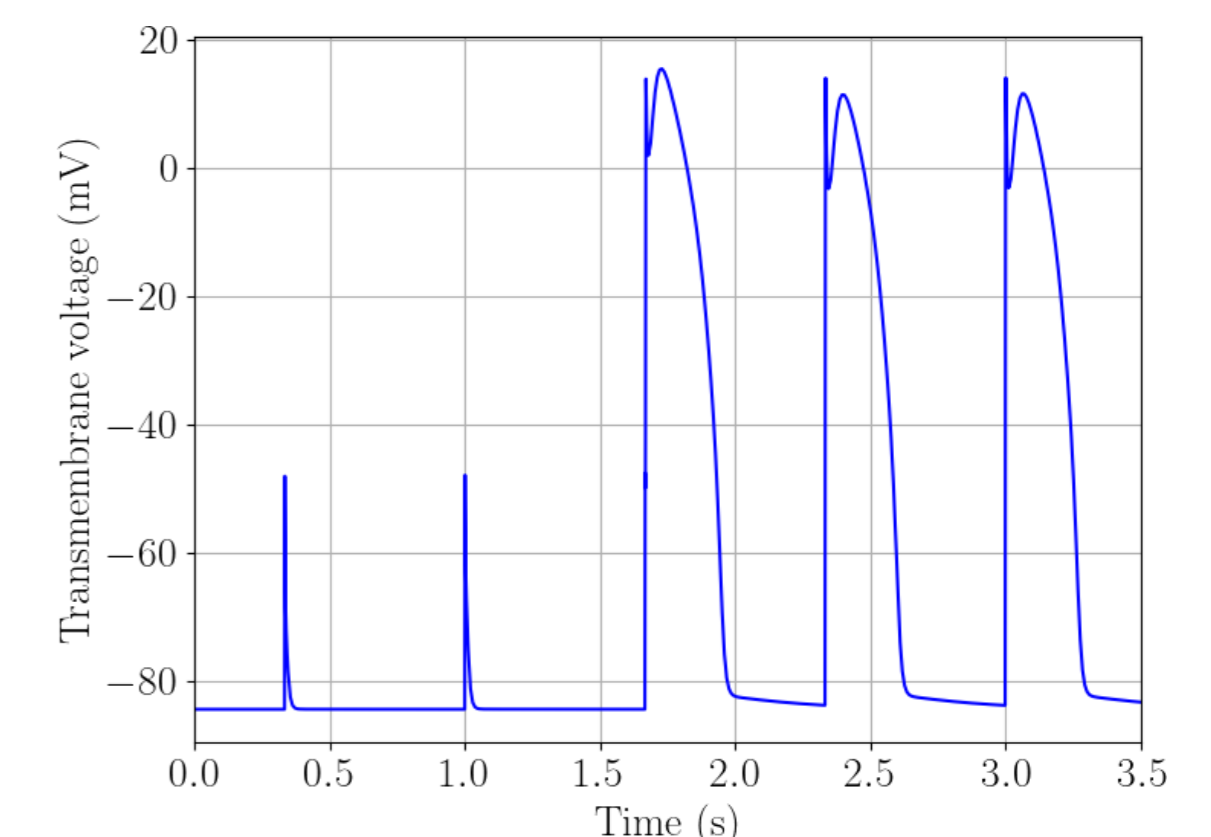
$$\frac{dV_2}{dt} + \frac{V_2}{\tau_2} = \frac{I}{C_2}$$

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

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

### 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**:

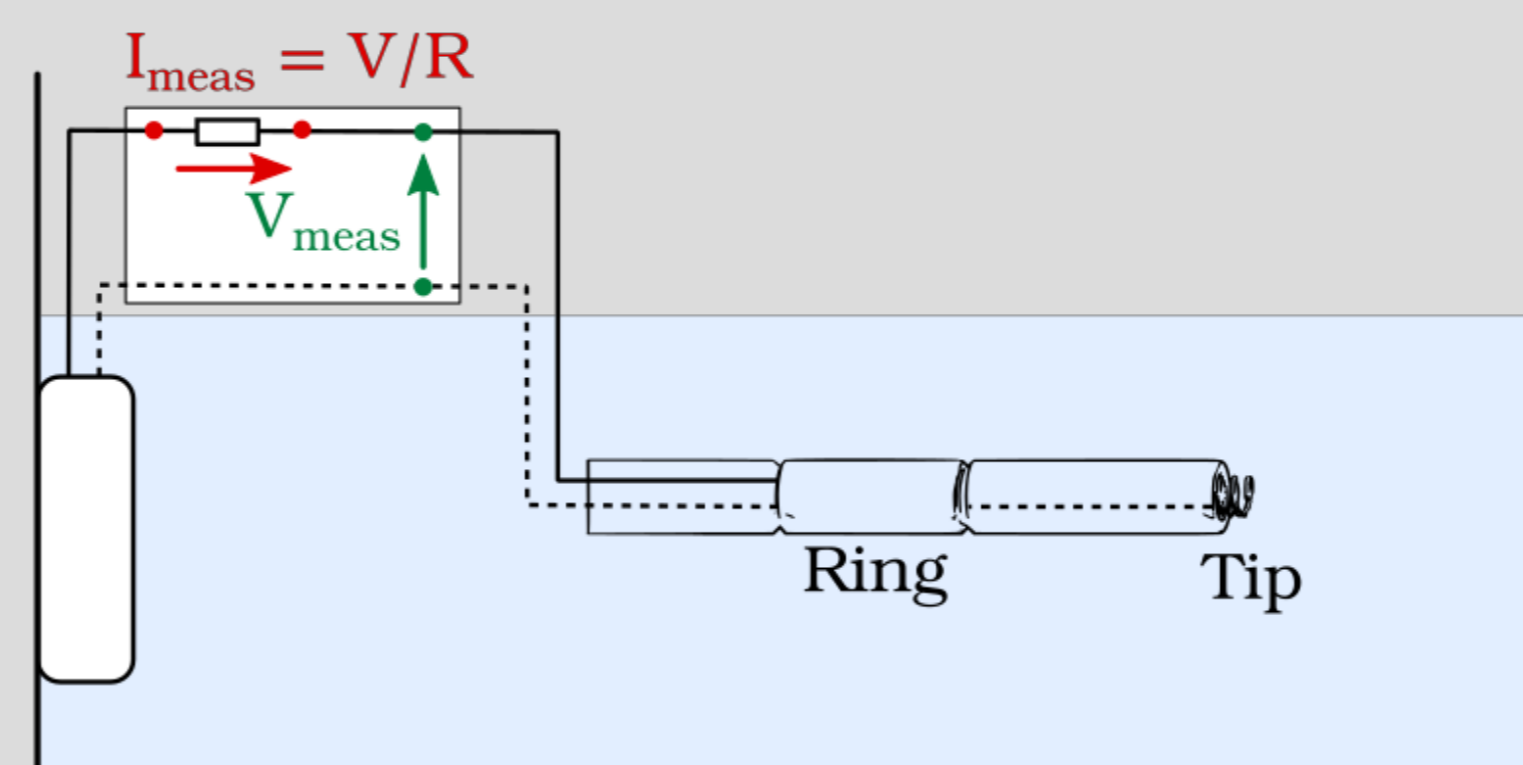
• We measure the current  $I$  and the voltage  $V$  delivered by a pacemaker lead directly in a **saline passive solution** without cardiac tissue.

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

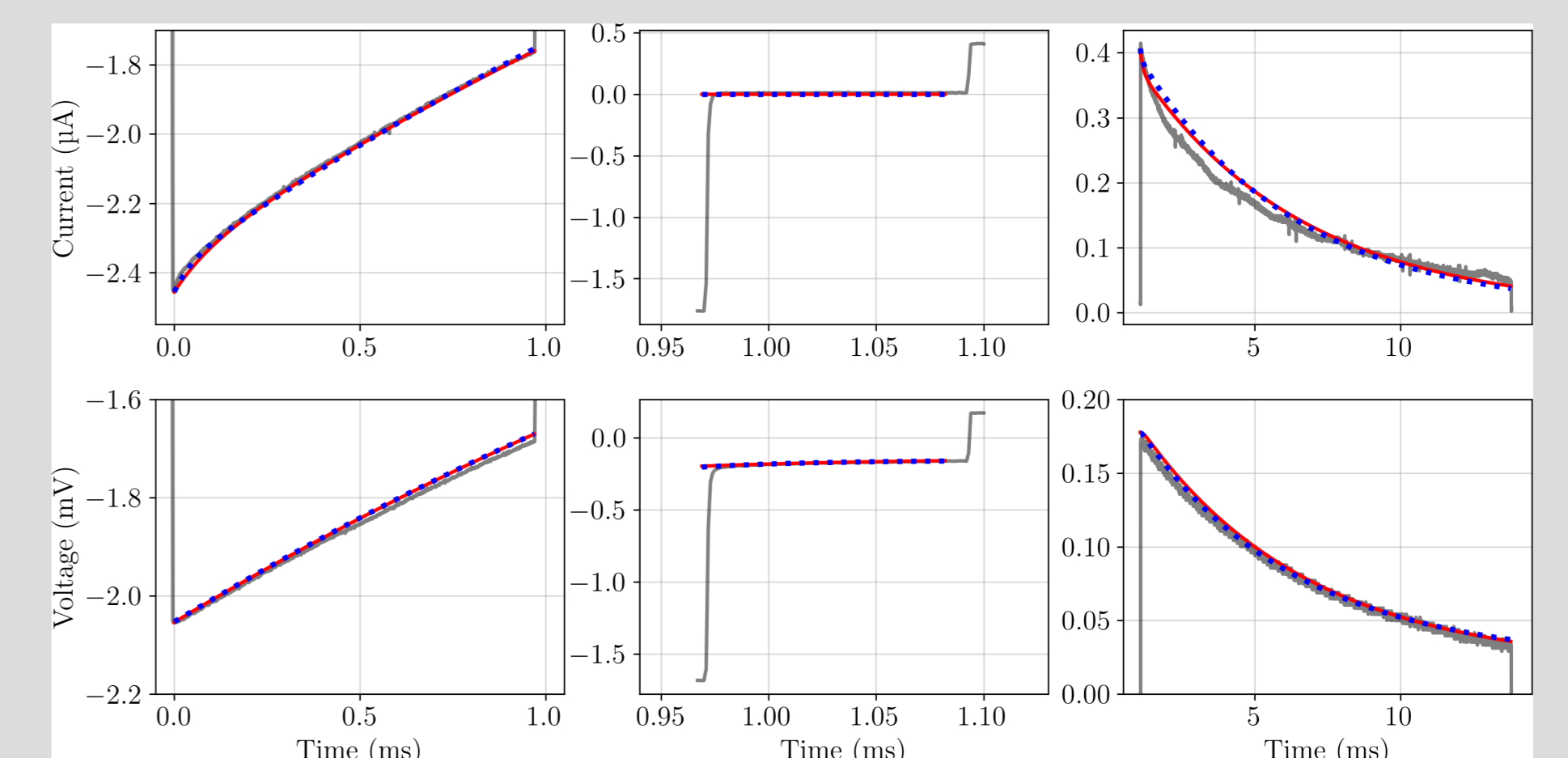
• **Method.** Weighted least square on  $I_{meas}$  and  $V_{meas}$ .

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

→ **Identifying** properties of contacts ( $C_1, \tau_1$ ) and ( $C_2, \tau_2$ ).

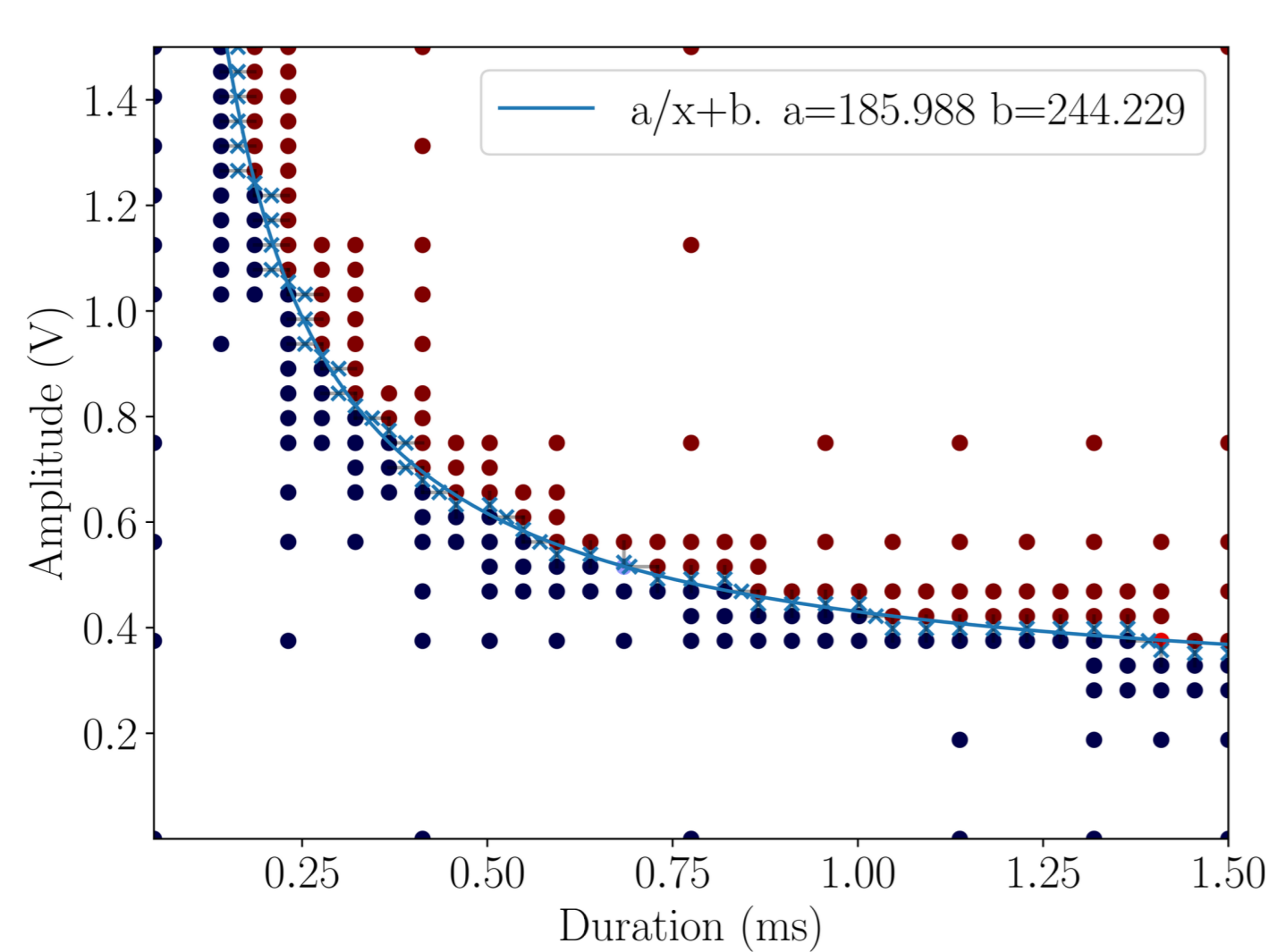


▲ **Sketch** of the bench test used to calibrate the electrode contact model.

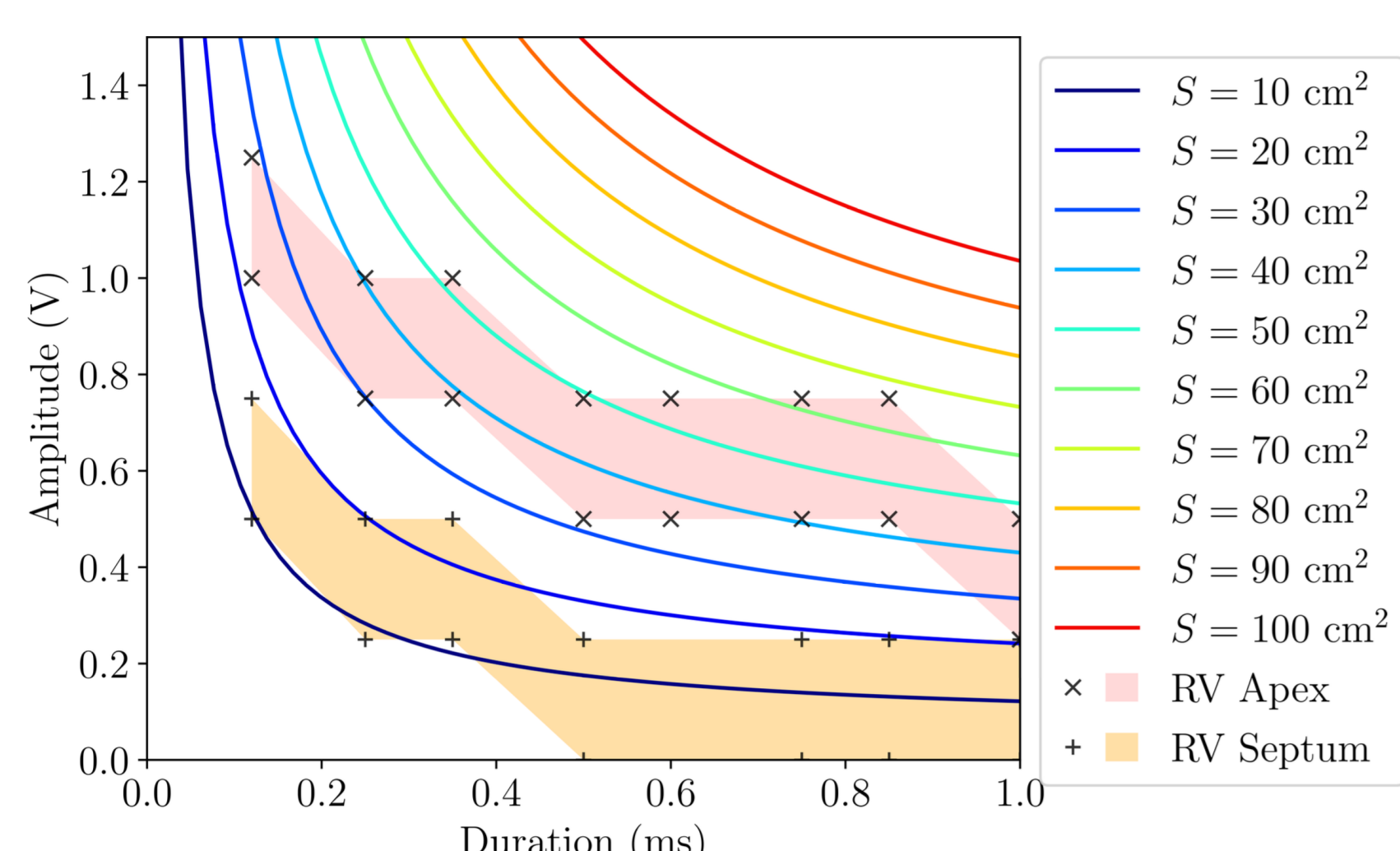


▲ **Fitted currents and voltages** when calibrating parameters  $\theta = (R_1, R_2, \tau_1, \tau_2)$ : comparison between a single experimental dataset (gray solid line),  $\theta$  calibrated on this dataset (blue dotted line) and  $\theta$  calibrated on the 9 datasets together (red solid line).

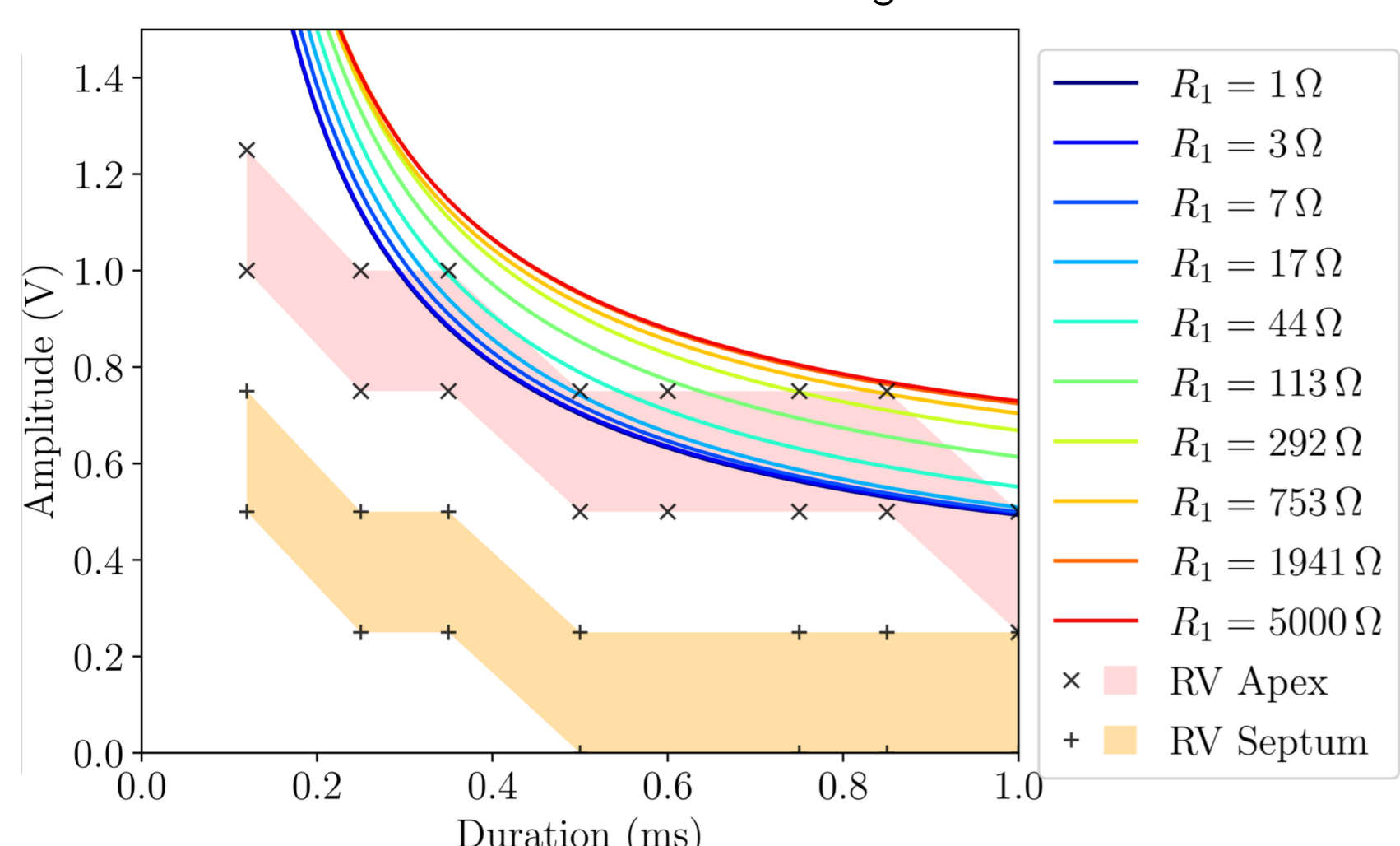
## > Computer model compared to experimental data



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



▲ 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**.

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

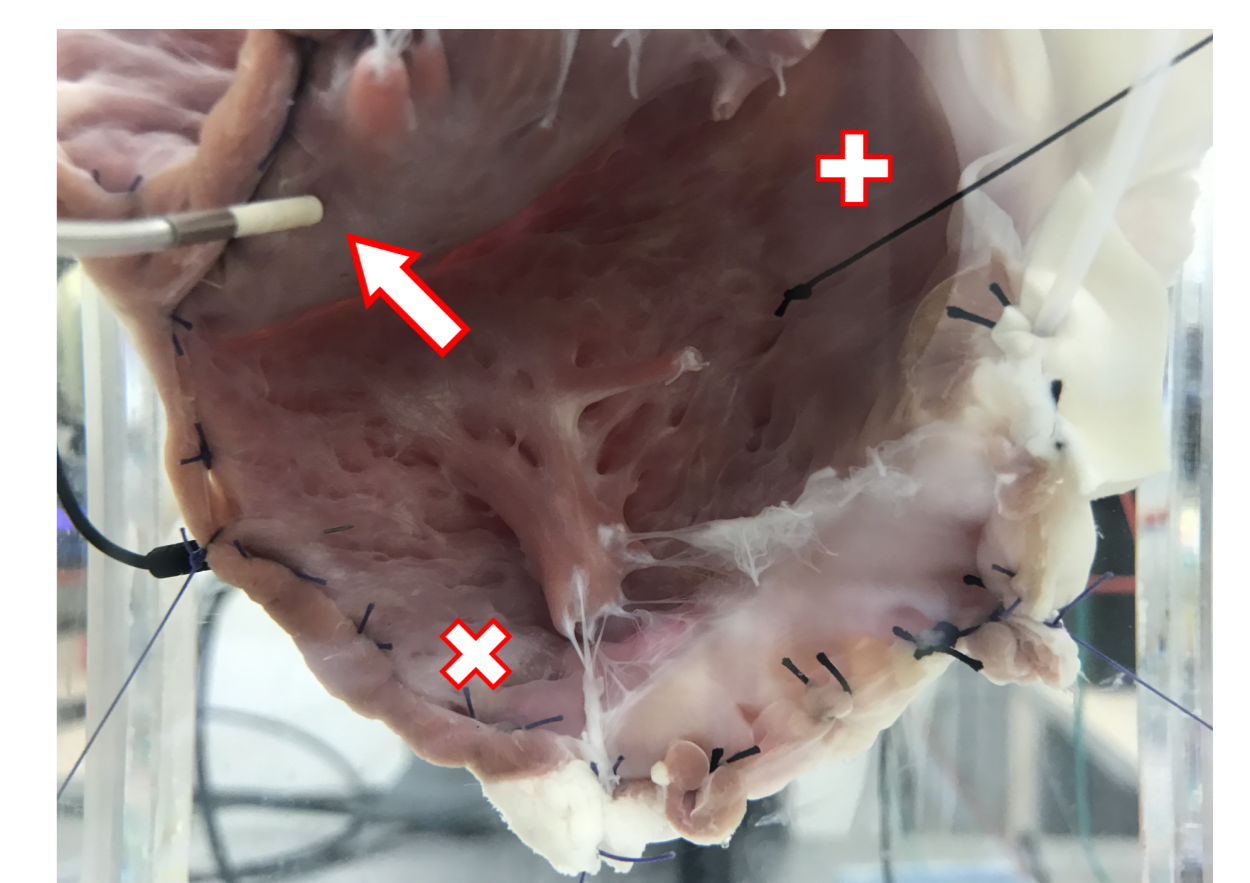
### > Animal and computer experiments

- **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<sub>ext</sub>**

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

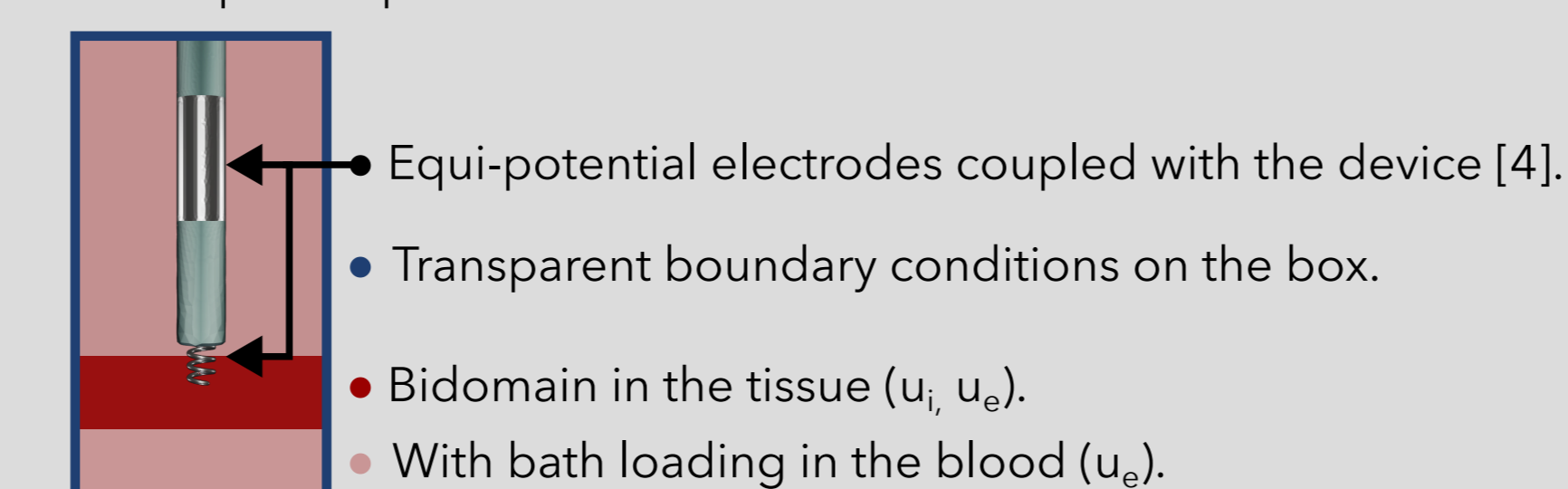


▲ **Right ventricle endocardial** view of the tissue wedge preparation with the pacemaker electrode implanted in the septum (arrow). Other implantations sites were located in the apex (x) and at the base of the ventricle (+).

## > Next

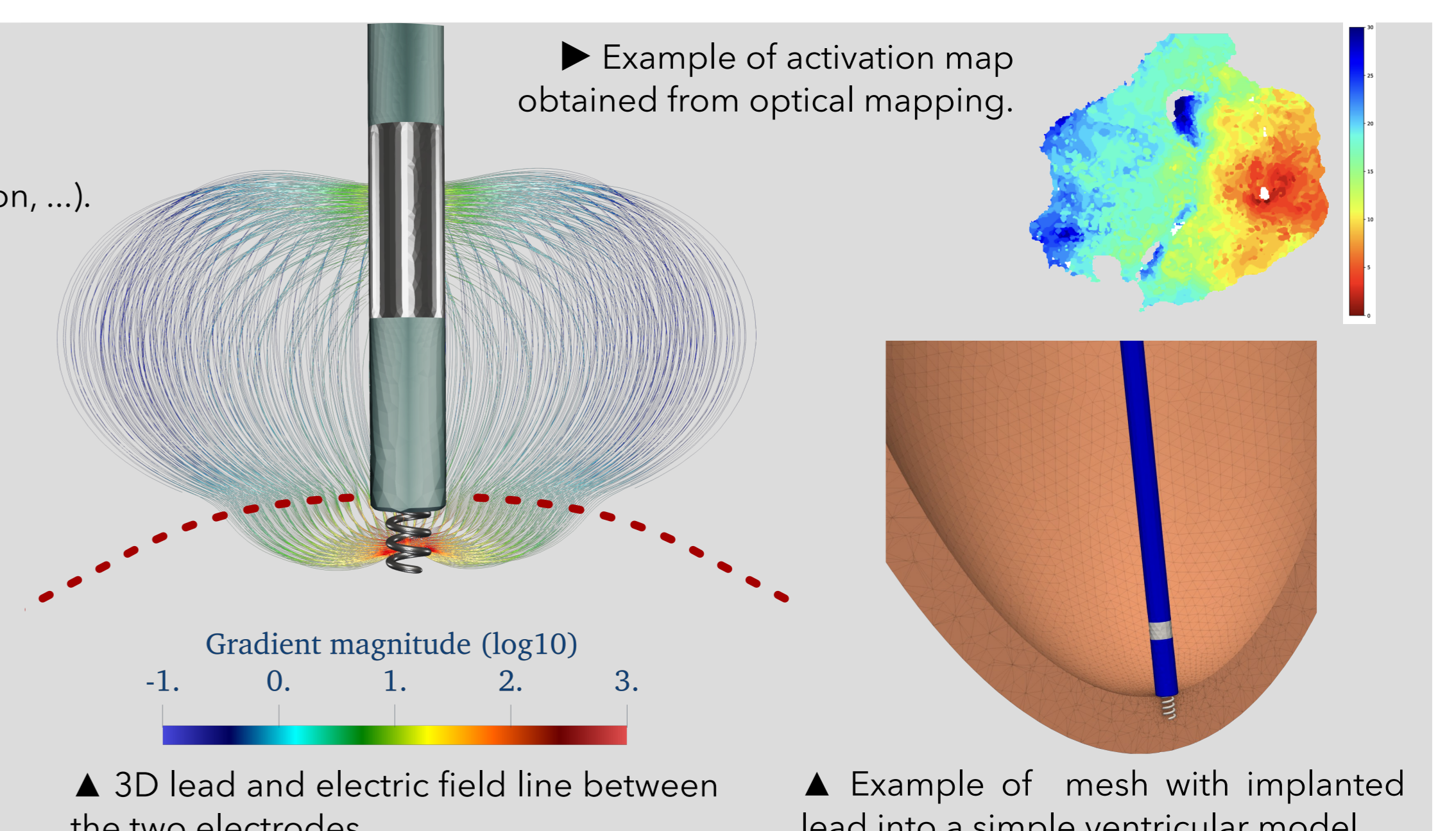
### > 3D model of tissue slab surrounded by blood

- 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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