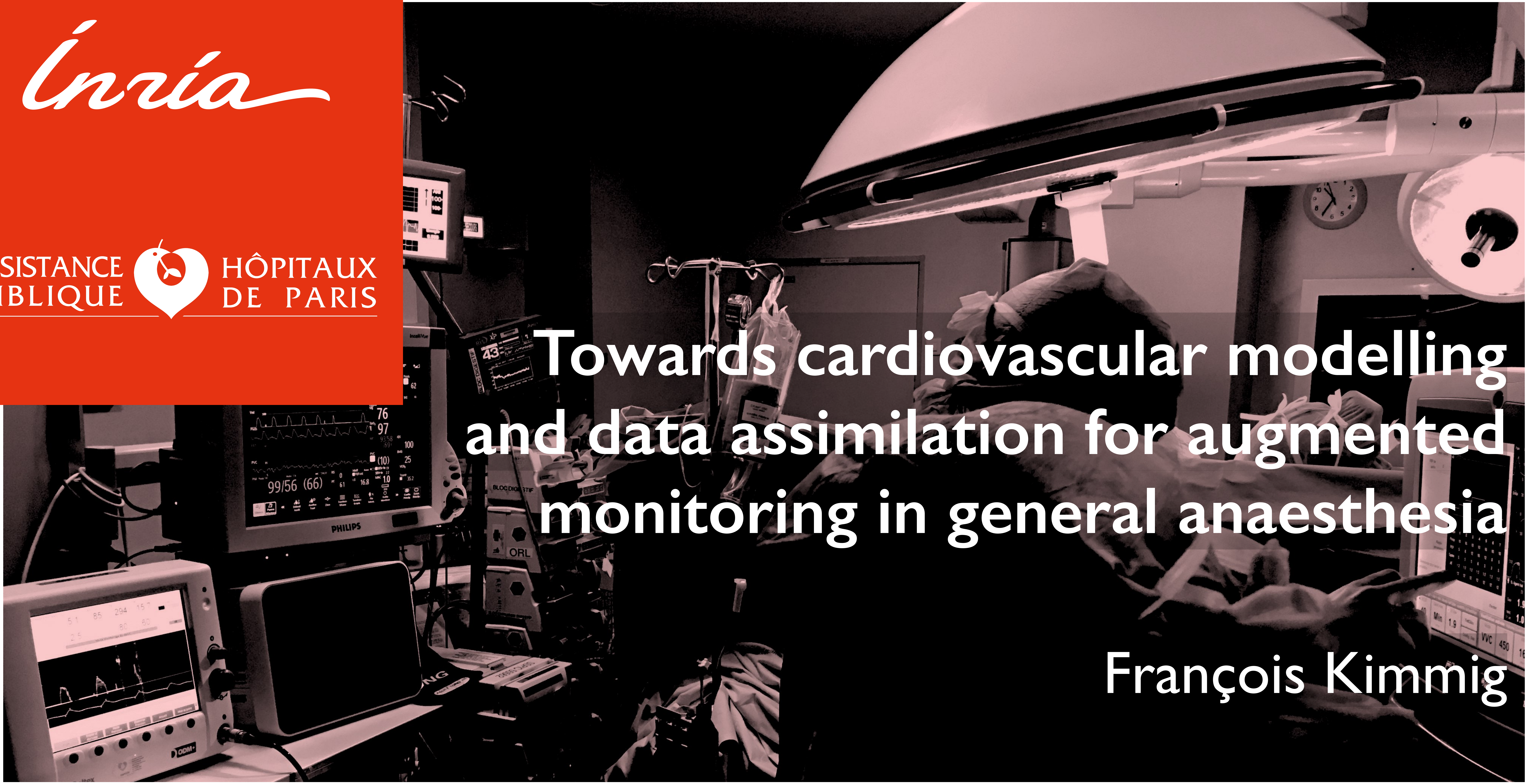
Inria

ASSISTANCE PUBLIQUE HÔPITAUX DE PARIS



# Towards cardiovascular modelling and data assimilation for augmented monitoring in general anaesthesia

François Kimmig

# The team: a joint-venture between Inria and APHP (Parisian hospitals)

François Kimmig

Inria Research Engineer

Dominique Chapelle

Senior Inria researcher

Fabrice Vallée

Senior Anaesthetist

Philippe Moireau

Senior Inria researcher

ASSISTANCE PUBLIQUE HÔPITAUX DE PARIS

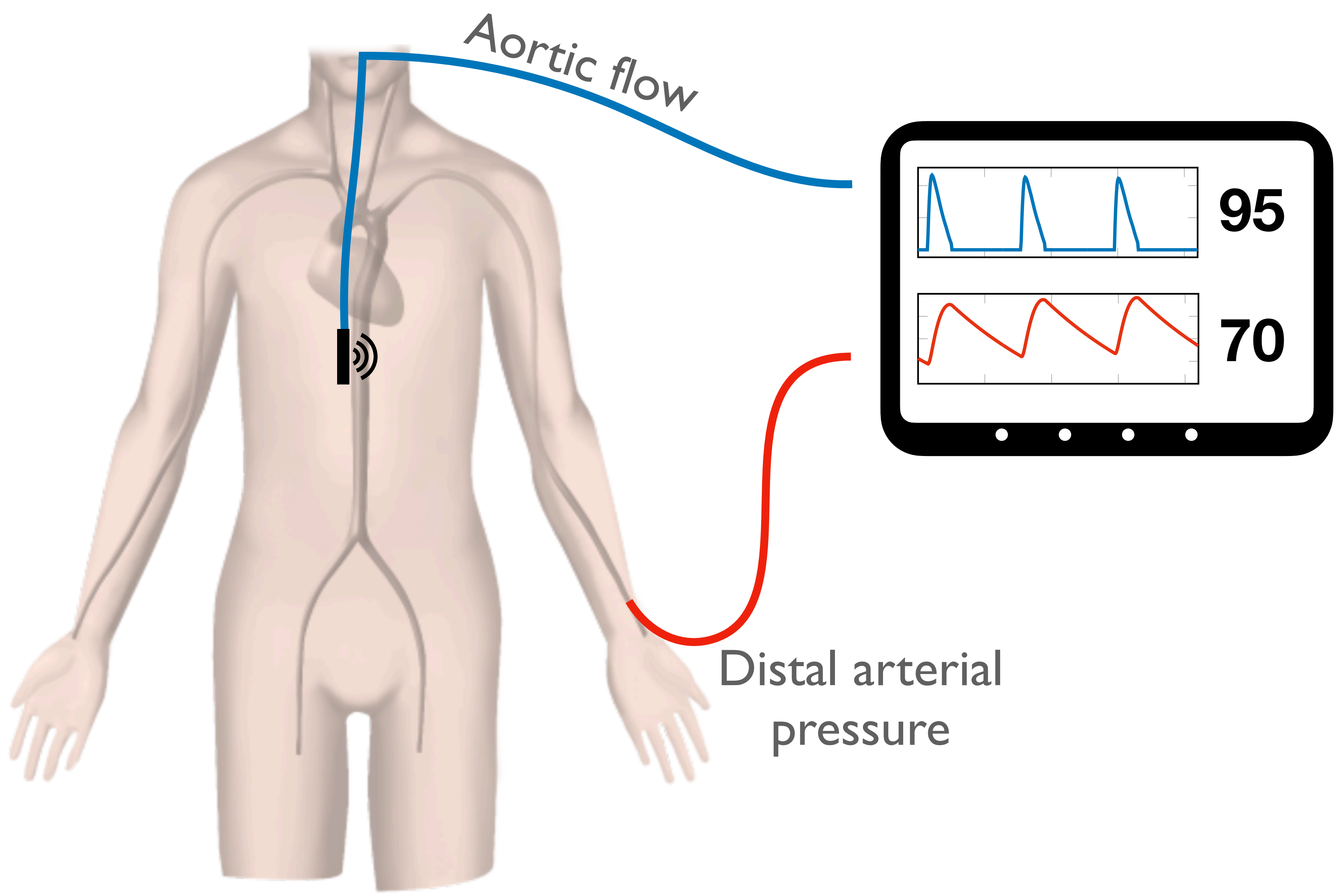
# General anaesthesia

# General anaesthesia

- Maintains the vital functions of the body
- Ensures the safety of the patient

# Anaesthetists do not have access to the information they need most

- **What they have today for hemodynamics monitoring**



- No information on the heart itself
- Insufficient context
- Difficult to distinguish between between different causes of hemodynamics instabilities

## Our objective

**Augment the available information on the patient by extracting from new physiological waveform and new biomarkers from the patient data**

# Attempt to perform augmented monitoring in anesthesia

- **Analysis of the pressure waveform**
  - Do not consider the heart, only the arteries
  - All the analysis based on a single physiological signal

📖 Romano et al. *Crit. Care Med.* 2002

📖 Wesseling et al. *J. Appl. Physiol.* 1993

- **Hypotension Prediction Index**
  - Based on black-box statistical approaches
  - Good prediction success rate of hypotension but no explanation value → not a tool to do medicine

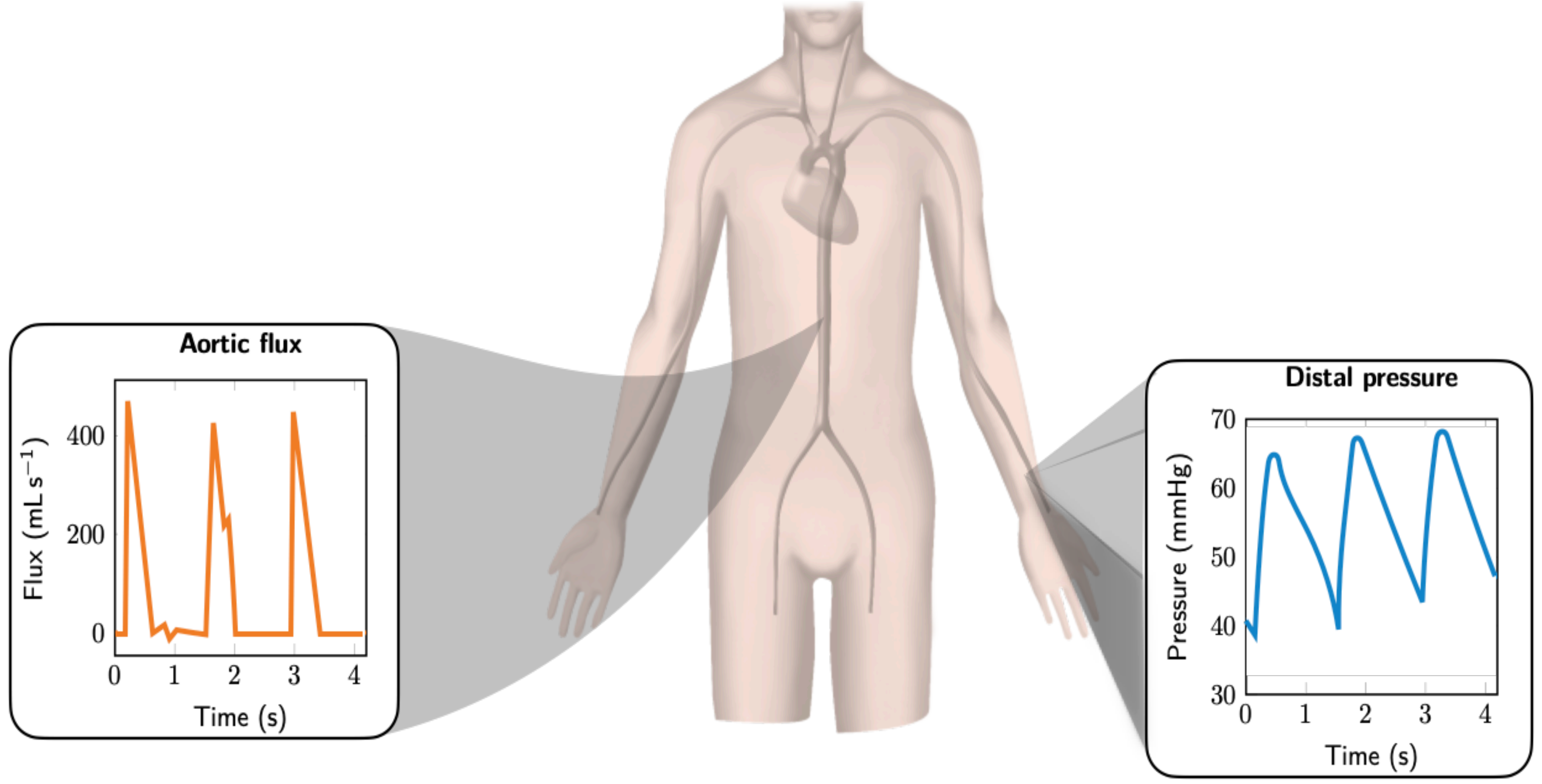
📖 Davies et al. Anesth. & Analg., 2020

📖 Hatib et al. *Anesthesiology*, 2018

# Our original strategy to tackle this problem

- **Use biophysical models as an *a priori* on the system with which data are merged through data assimilation**

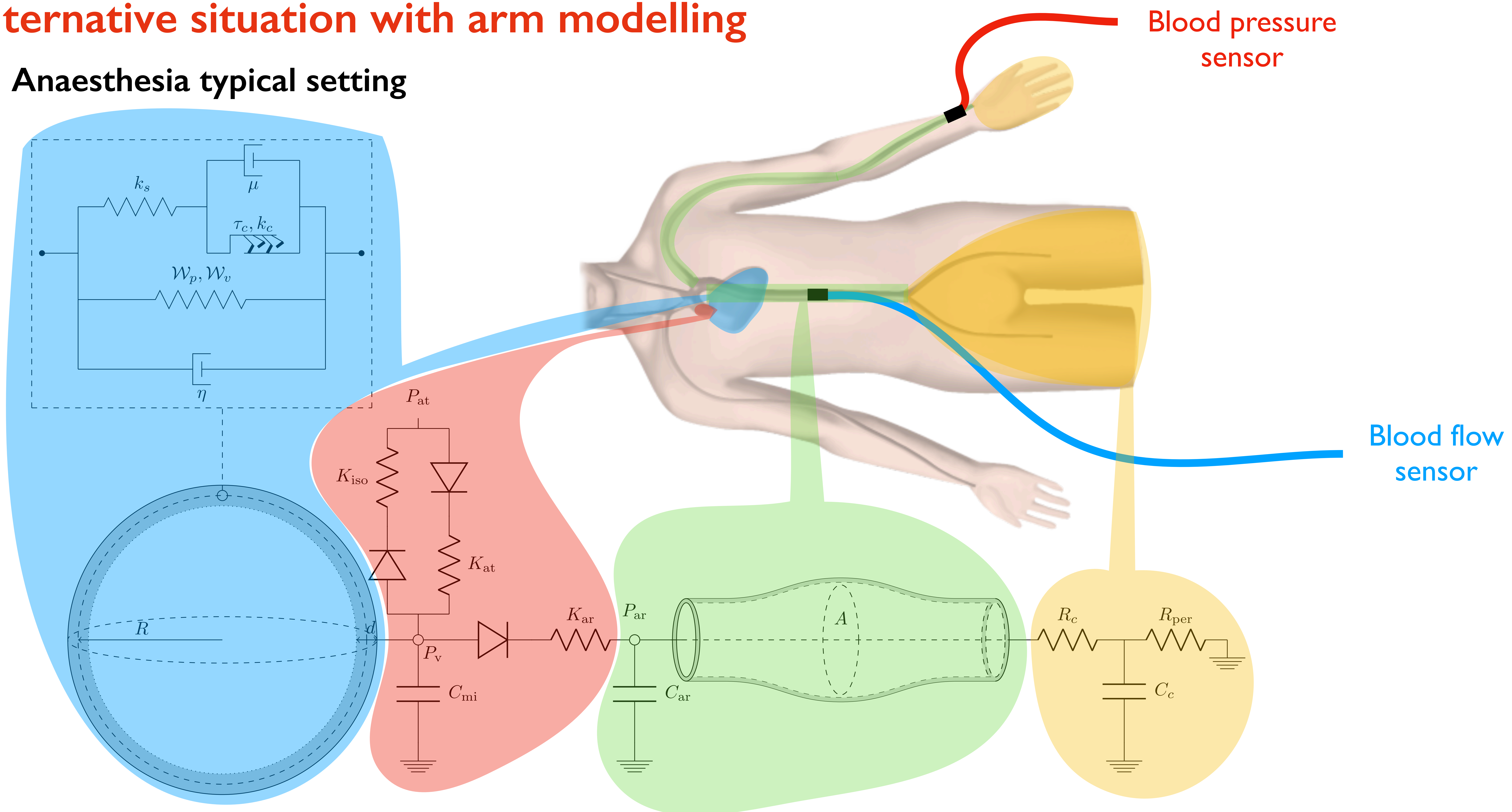
$$
\begin{aligned}
&\mathcal{P}_a(\underline{y}^*) + \mathcal{P}_i(\underline{y}^*) = \mathcal{P}_e(\underline{y}^*), \quad \forall \underline{y}^* \in \mathcal{V},\\
&\underline{\underline{\Sigma}} = \frac{\partial W_e}{\partial \underline{\underline{e}}} + \frac{\partial W_v}{\partial \dot{\underline{\underline{e}}}} + \sigma_{1\mathrm{D}} \underline{\tau}_1 \otimes \underline{\tau}_1 - p \underline{\underline{C}}^{-1},\\
&\sigma_{1\mathrm{D}} = E_s \frac{e_{1\mathrm{D}} - e_c}{(1+2e_c)^2},\\
&(\tau_c + \mu \dot{e}_c) = E_s \frac{(e_{1\mathrm{D}} - e_c)(1 + 2e_{1\mathrm{D}})}{(1+2e_c)^3},\\
&\dot{k}_c = -(|\bar{u}|_+ + w\,|\bar{u}|_- + \alpha\,|\dot{e}_c|)\,k_c + n_0 k_0\,|\bar{u}|_+,\\
&\dot{\tau}_c = -(|\bar{u}|_+ + w\,|\bar{u}|_- + \alpha\,|\dot{e}_c|)\,\tau_c + n_0 \sigma_0\,|\bar{u}|_+ + k_c \dot{e}_c,\\
&-\dot{V} = Q = q(P_v, P_{ar}, P_{at}),\\
&C_p \dot{P}_{ar} + (P_{ar} - P_d)/R_p = Q,\\
&C_d \dot{P}_d + (P_d - P_{ar})/R_p = (P_{vs} - P_d)/R_d.
\end{aligned}
$$



- **The individual bricks come from the literature, the originality lies in the simultaneous usage of these specific bricks and the purpose**

# Alternative situation with arm modelling

- **Anaesthesia typical setting**



Blood pressure sensor

Blood flow sensor

Heart ventricule

Valves

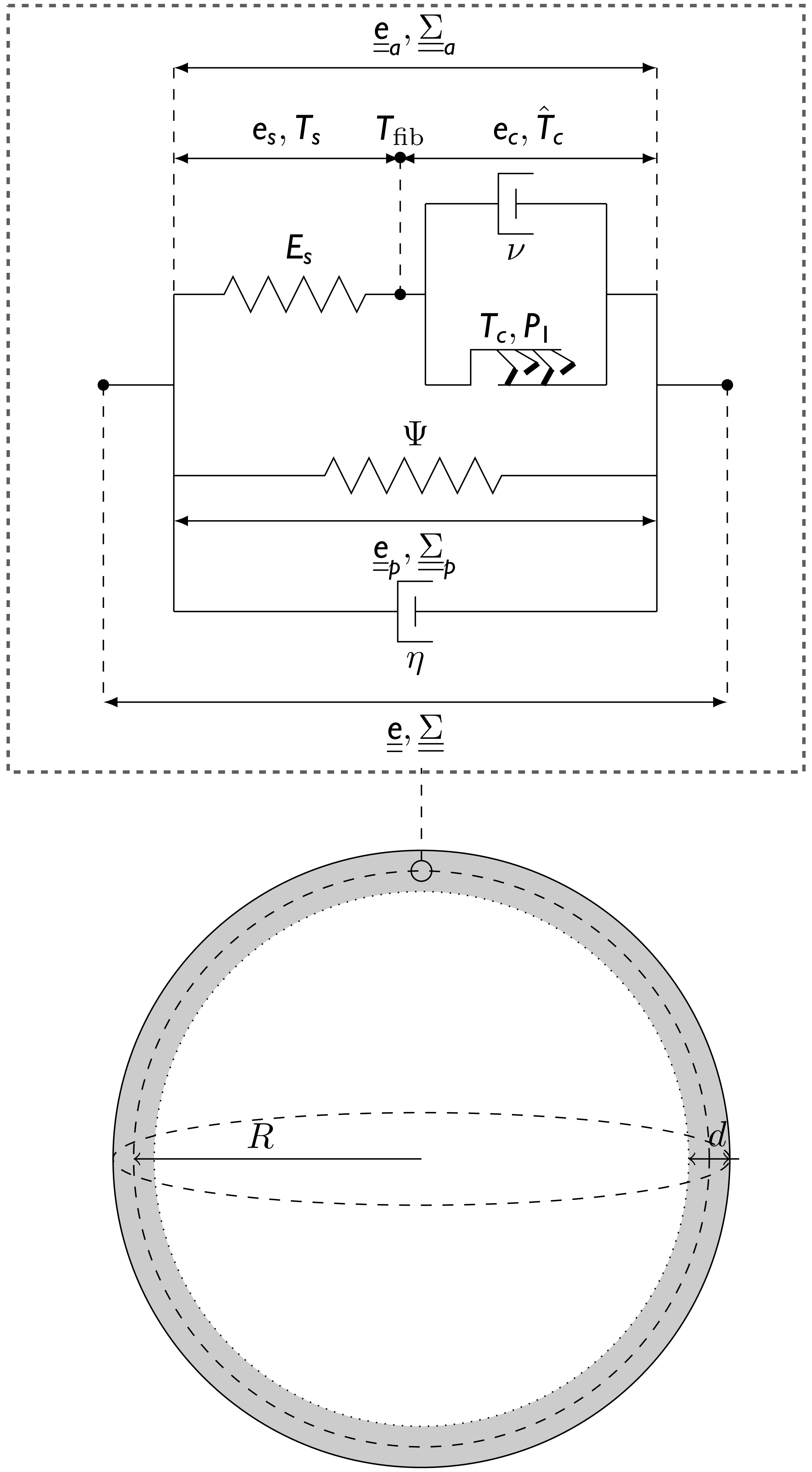
Aorta - 1D circulation

Distal arterial circulation - 0D circulation

# Model equations

Caruel, Moireau, Chapelle, et al., BMMB, 2013

- **Heart tissue model**



### Equations derived from the principle of virtual power

$$\forall \underline{w} \in \mathcal{V}(\Omega_0), \quad \int_{\Omega_0} \rho \underline{\ddot{y}} \cdot \underline{w}\, \mathrm{d}\Omega + \int_{\Omega_0} \underline{\underline{\Sigma}} : d_y \underline{\underline{e}} \cdot \underline{w}\, \mathrm{d}\Omega = -\int_{\Gamma_{endo}} P_v \underline{\nu} \cdot \underline{\underline{F}}^{-1} \cdot \underline{w} J \mathrm{d}S$$

### Tissue rheology

- 3D parallel law $\underline{\underline{e}} = \underline{\underline{e}}_a + \underline{\underline{e}}_p$ strain (Green-Lagrange tensor) $\underline{\underline{\Sigma}} = \underline{\underline{\Sigma}}_p + \underline{\underline{\Sigma}}_a$ 2PK stress
- 1D series law $e_{\text{fib}} = e_s + e_c$ extension $T_{\text{fib}} = T_c + T_s$ 1PK stress

### A shell assumption is applied

- ODE on the displacement $y$

$$\begin{cases} \rho_0 V_0 \ddot{y} + \dfrac{V_0}{R_0} k_s \left( \dfrac{y}{R_0} - x_c/\ell \right) + \dfrac{\partial \mathcal{W}_p}{\partial y}(y) + \mathcal{W}_v(y, \dot{y}) = P_v \dfrac{\partial V(y)}{\partial y}, \\ \mu\, \dot{x}_c/\ell - k_s \left( \dfrac{y}{R_0} - x_c/\ell \right) = -\boxed{T_c,} \end{cases}$$

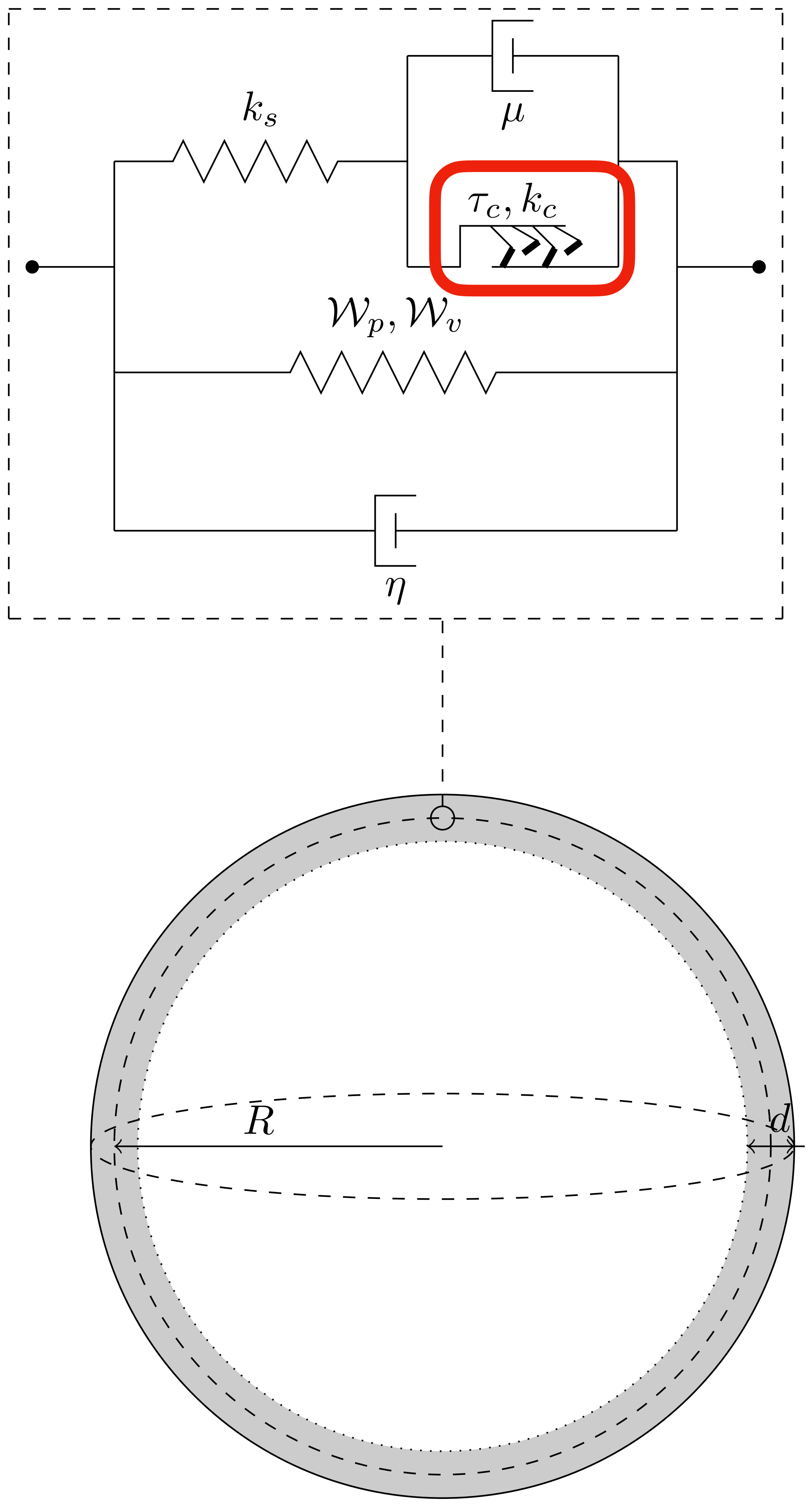
**Active contraction force**

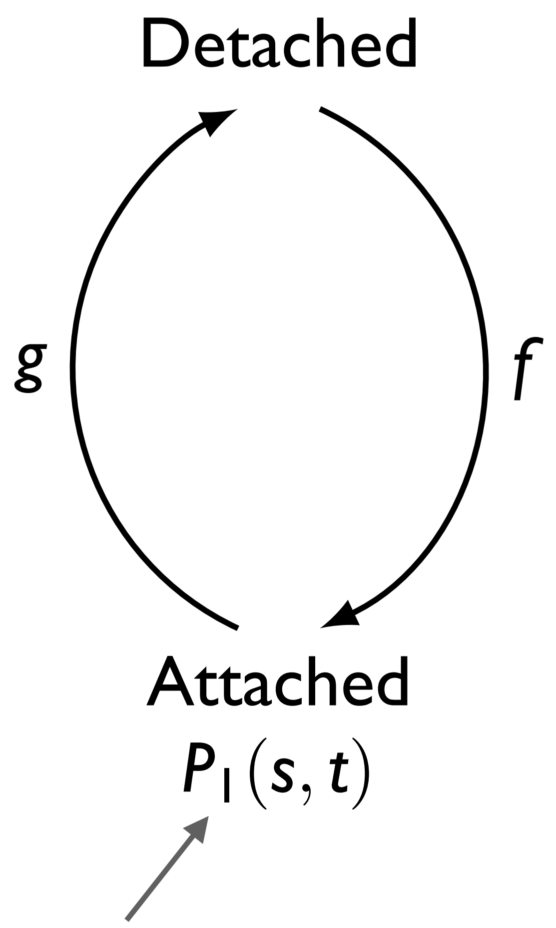
# Model equations

Huxley, Progr Biophys Chem, 1957

Kimmig, Caruel, BMMB, 2020

- **Heart tissue model**



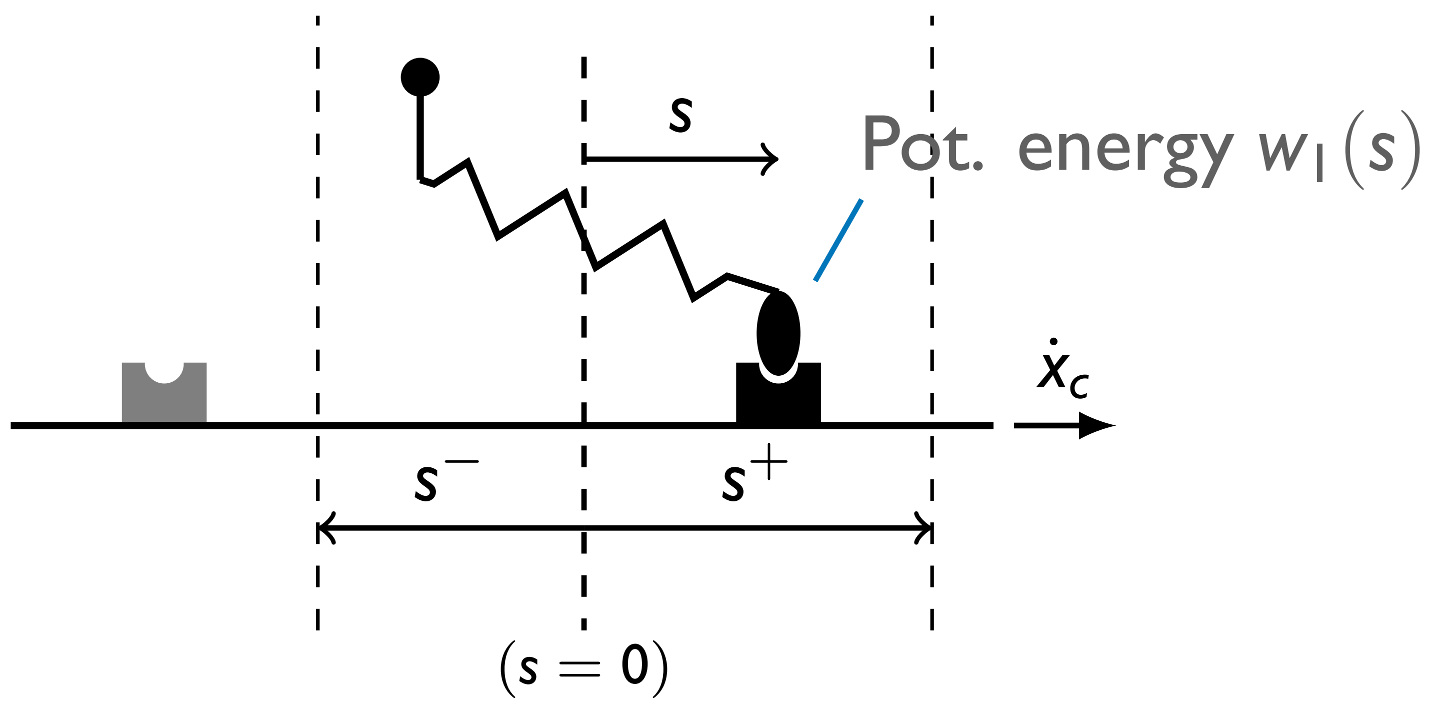

Detached

$g$

$f$

Attached

$P_1(s,t)$



Ratio of attached heads among heads located at distance $s$ of the nearest actin site

$$\frac{\partial P_1}{\partial t}(s,t) = f(s)(1 - P_1(s,t)) - g(s)P_1(s,t) - \dot{x}_c \frac{\partial P_1}{\partial s}(s,t)$$

- **Simplification assumption on the transition rates and the potential energy**
  - System of 2 coupled ODEs where the active force $T_c$ is directly a variable, which depends on the electrical activation $\nu$

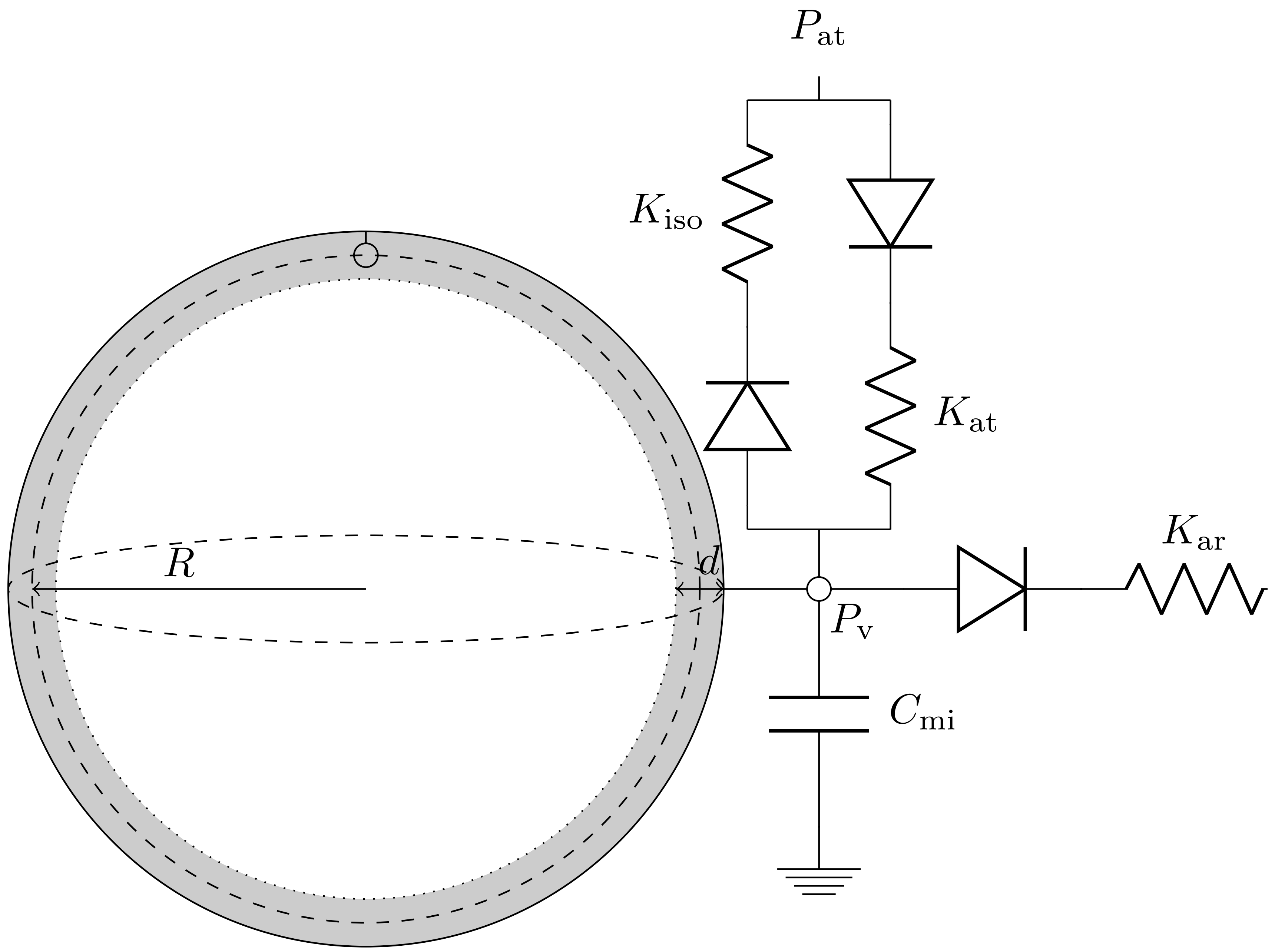
$$\boxed{\begin{cases} \dot{K}_c(t) = -(|\nu| + \alpha \dot{x}_c) K_c(t) + n_0(x_c) K_0 |\nu|_+ \\ \dot{T}_c(t) = -(|\nu| + \alpha \dot{x}_c) T_c(t) + n_0(x_c) \boxed{T_0} |\nu|_+ + \dot{x}_c K_c(t) \end{cases}}$$

**Contractility**

# Model equations

Manganotti, Moireau, et al. submitted

- **Cavity model with valves**



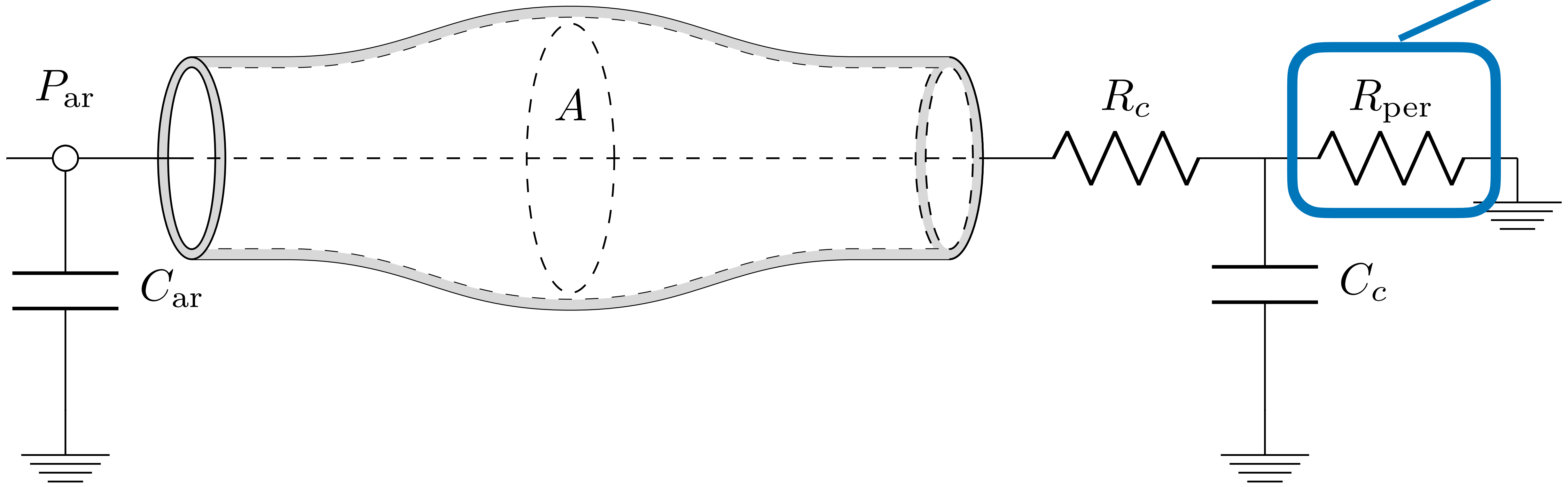
**Equation derived from the conservation of flux**

$$C_{mi}\dot{P}_v - Q_v + \frac{|P_v - P_{ar}|_+}{K_{ar}} + \frac{|P_v - P_{at}|_+}{K_{iso}} - \frac{|P_{at} - P_v|_+}{K_{at}} = 0$$

# Model equations

Manganotti, Moireau, et al. submitted

- **Arteries models**
  - Mix of 1D and 0D arterial models



**Distal resistance**

# Model automatic calibration

Moireau & Chapelle, ESAIM, 2011

- **Reduced model, governed by a finite set of differential equations**

Model operator

State variables

$$\begin{cases} \dot{y}_{|\theta}(t) = A(y, \theta, t), t \in [0, T] \\ y_{|\theta}(0) = y_\diamond \end{cases}$$

Unknown parameters

- The model needs to be personalised for any given patient, i.e. we want to **estimate the patient-specific $\theta$**

Data Observation operator

- We want to solve $$\min_\theta \left\{ J_T(\theta) = \frac{1}{2} \|\theta - \theta_\diamond\|^2_{P_0^{-1}} + \frac{1}{2} \int_0^T \left\| z - C(y_{|\theta}(t)) \right\|^2_{W^{-1}} \mathrm{d}t \right\}$$

Regularisation with a priori estimate

Link between data and model

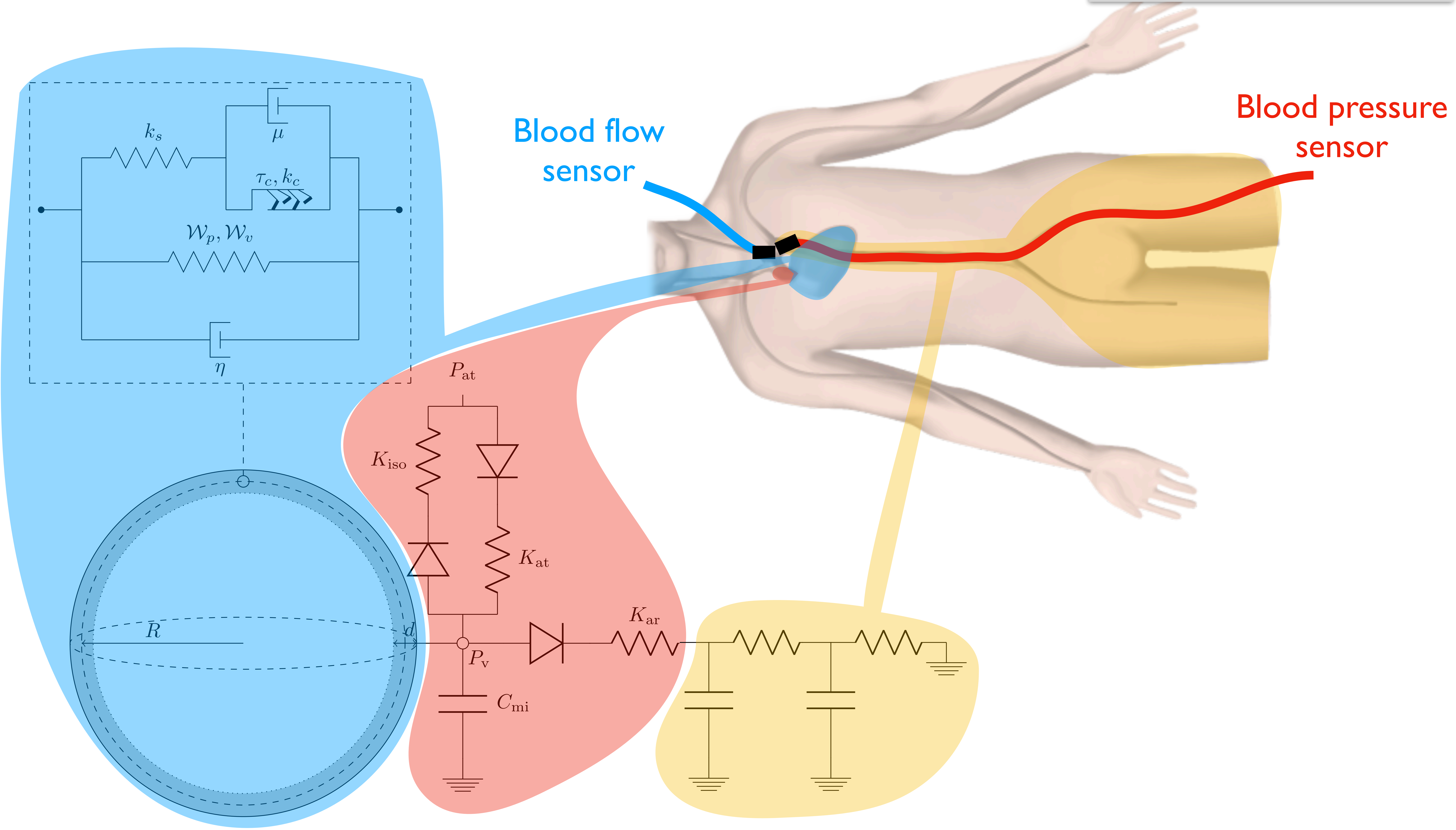
- Sequential update of the estimation of $\theta$ when $T$ is varying ⇨ Kalman filter extended for non-linear problems

# Preliminary results validating the model

- **Particular measurement setup**

Le Gall, Chabiniok, Hussain, et al., PLoSOne, 2020

Arthur Le Gall

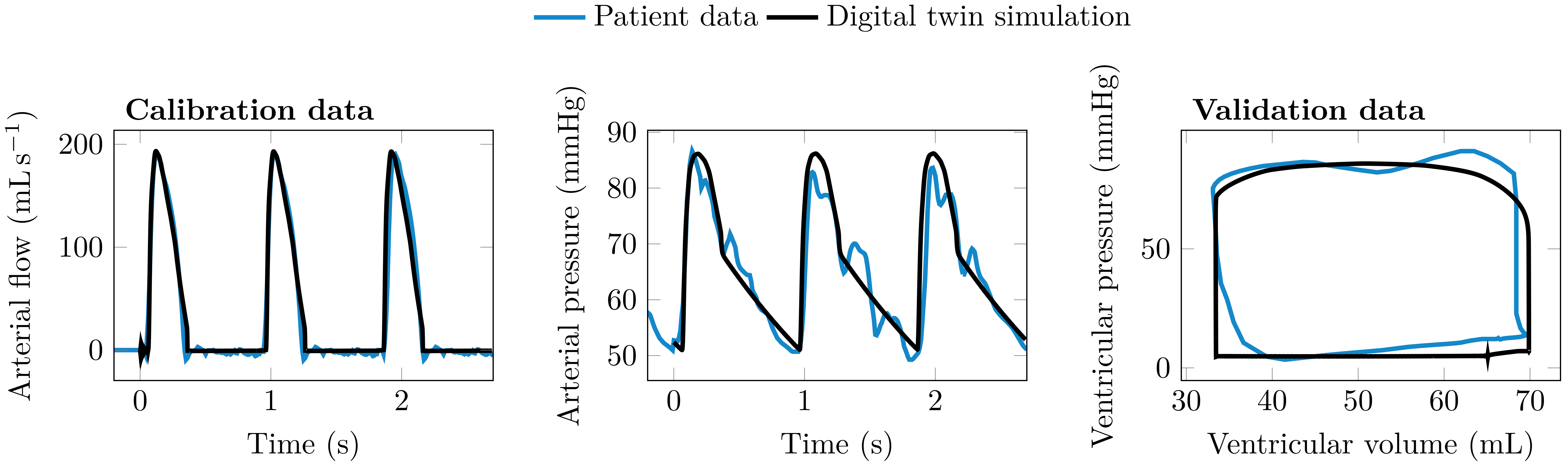


# Preliminary results validating the model

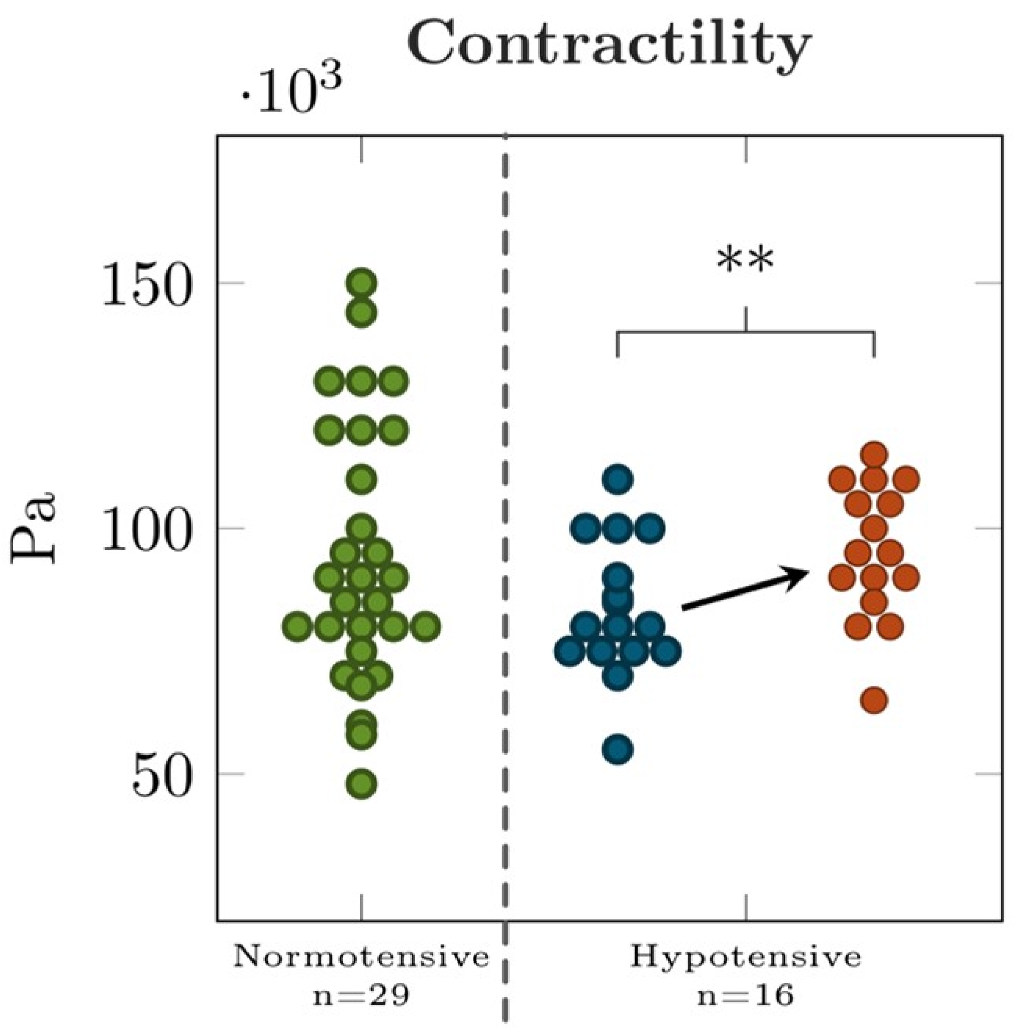
Le Gall, Chabiniok, Hussain, et al., PLoSOne, 2020

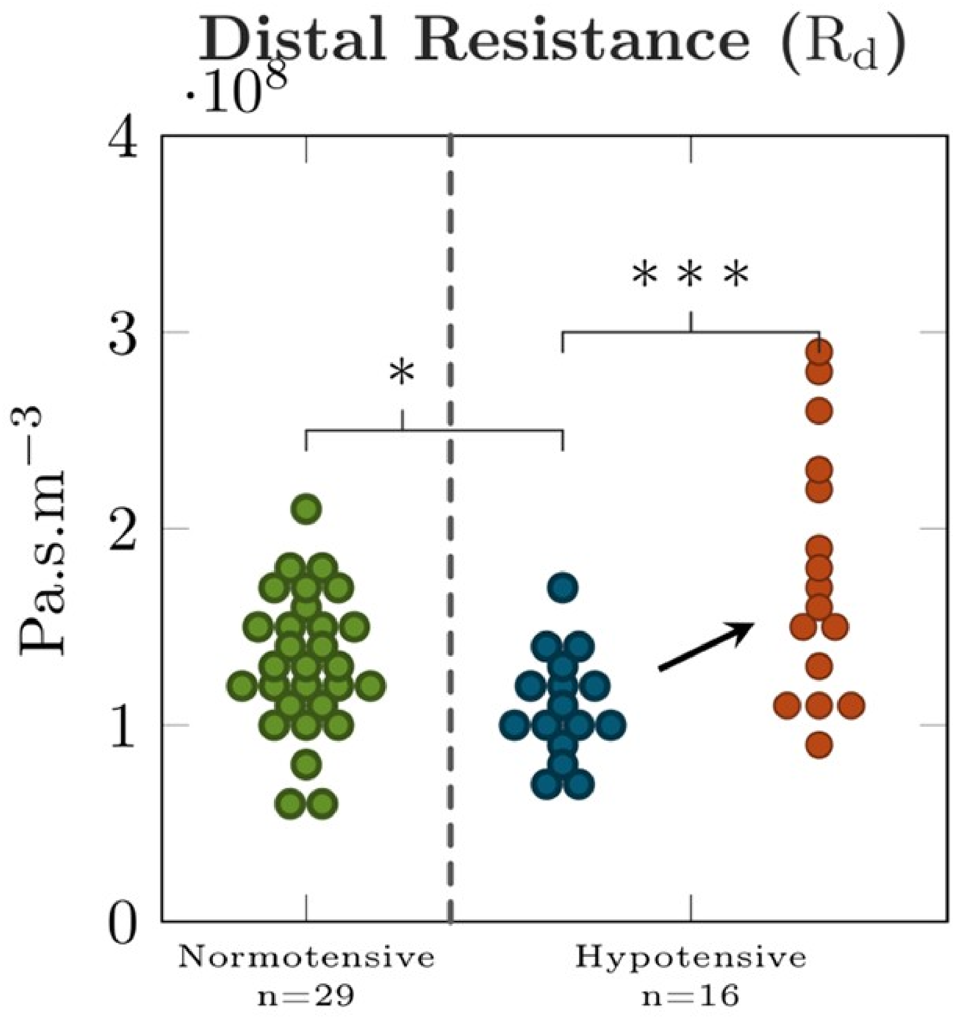
Arthur Le Gall

- **Calibration and validation data**



- **Interpretation of the estimated parameters**

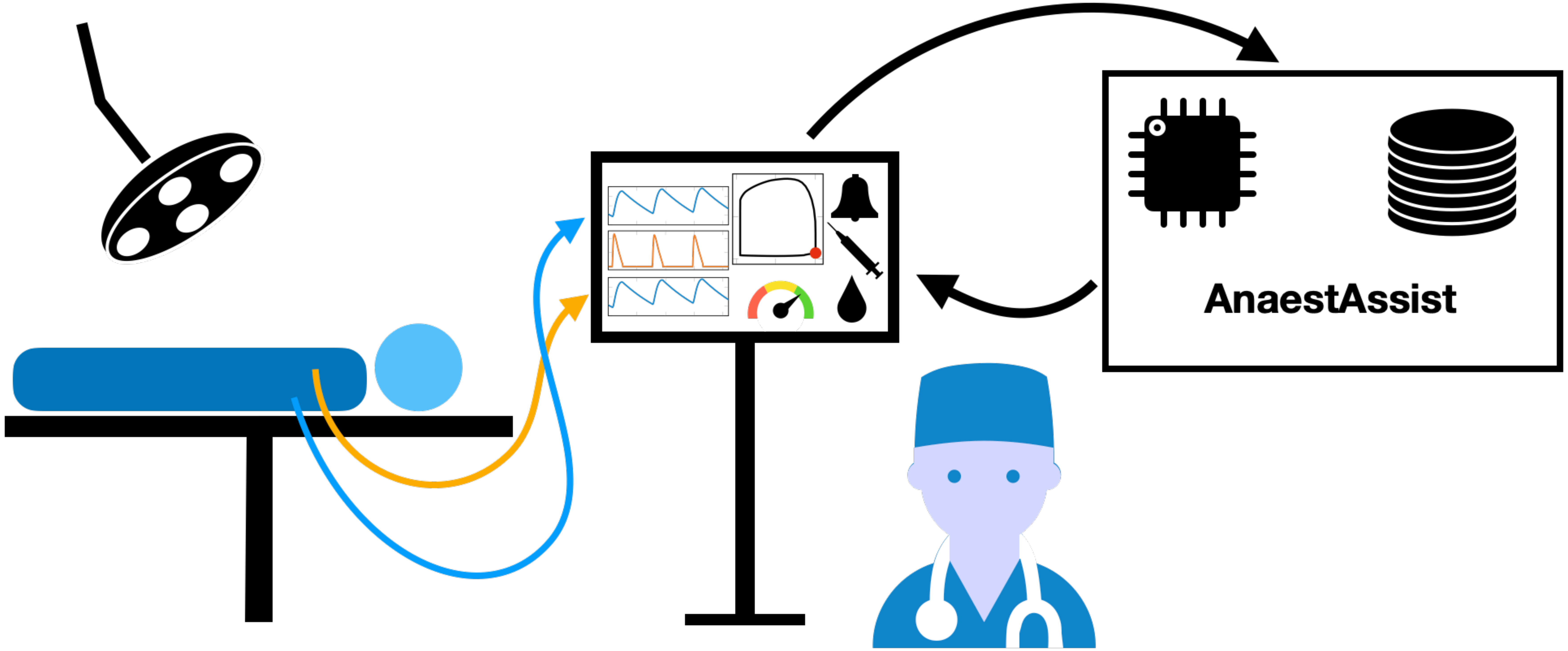




# Envisioned workflow for ORs and ICUs

- **Once the model is calibrated we can simulate augmented information**
  - New information to better follow the state of the patient (contractility, arterial distal resistance, …)

- **Based on augmented information relevant alert and recommandation can be produced**



# Perspectives

- **Need of a more solid clinical validation**
- **Include new modelling element to improve model predictions**
- **Go to the medical application**

Classical monitoring

Augmented monitoring