# Towards Coupling a 3D Heart Model with a 0D Closed-Loop Circulation in OpenFOAM

1st Irish Fluid Dynamics Meeting

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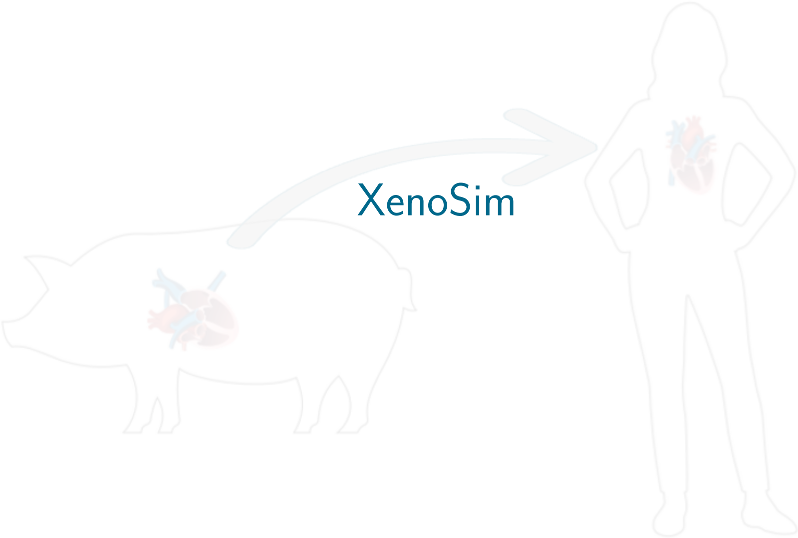

# XenoSim

# Background & Motivation

## Big Picture

- Donor heart shortage continues to limit cardiac transplantation.
- Xenotransplantation is a promising alternative, but haemodynamic performance remains poorly understood.
- Porcine-to-human implantation introduces distinct haemodynamic and electromechanical challenges.

## Key Drivers

- Fundamental pig–human differences in anatomy, compliance, and vascular impedance.
- Limited in-vivo haemodynamic access motivates high-fidelity *in-silico* modelling.
- Need for predictive tools to assess pig-heart performance under human circulatory loading.

XENOsim

European Research Council
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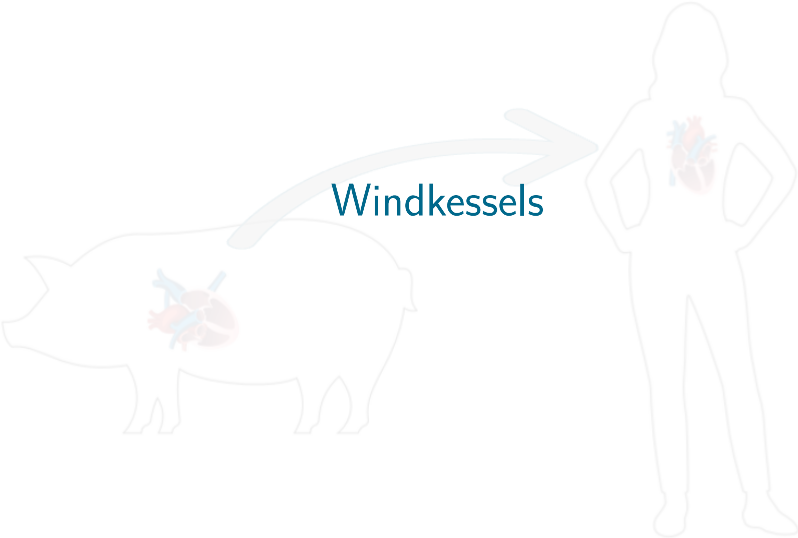
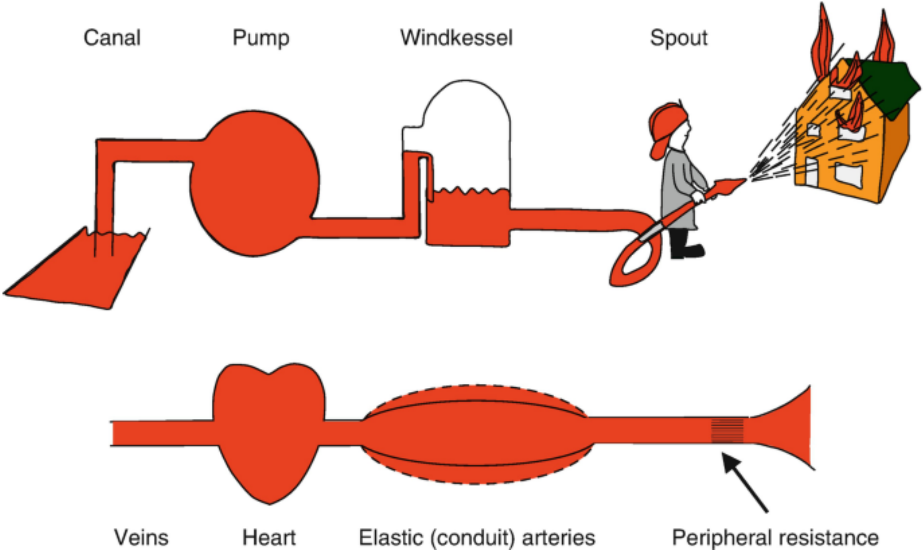
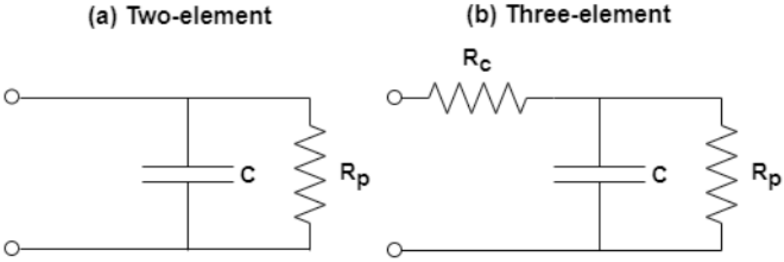


# Windkessels

# The Core Idea



# Electrical Analogy and Governing Equations




## WK2 (RC)

$$Q(t) = Q_C(t) + Q_R(t)$$

$$Q(t) = \frac{P(t)}{R_p} + C\frac{dP(t)}{dt}$$

$$\frac{dP(t)}{dt} = \frac{1}{C}\left(Q(t) - \frac{P(t)}{R_p}\right)$$

## WK3 (RCR)

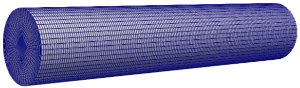
$$P(t) = R_c Q(t) + P_{WK2}(t)$$

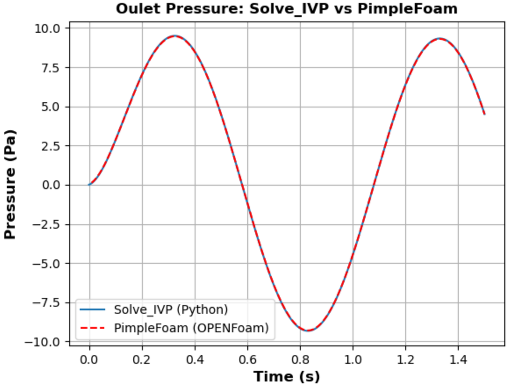
$$\frac{dP_{WK2}(t)}{dt} = \frac{dP(t)}{dt} - R_c\frac{dQ(t)}{dt}$$

$$\frac{dP_{WK2}(t)}{dt} = \frac{1}{C}\left(Q(t) - \frac{P_{WK2}(t)}{R_p}\right)$$

$$\frac{dP(t)}{dt} = \frac{Q(t)}{C}\left(1 + \frac{R_c}{R_p}\right) + R_c\frac{dQ(t)}{dt} - \frac{P(t)}{CR_p}$$

# Verification of WK3 Boundary Condition in OpenFOAM






## Numerical Setup

- **Geometry:** Straight rigid cylindrical pipe ($L = 5.0$ m, $R = 0.5$ m)
- **Inflow:** Prescribed sinusoidal volumetric flow

$$Q(t) = A\sin(\omega t), \qquad A = 1,\ \omega = 2\pi \text{ rad/s}$$

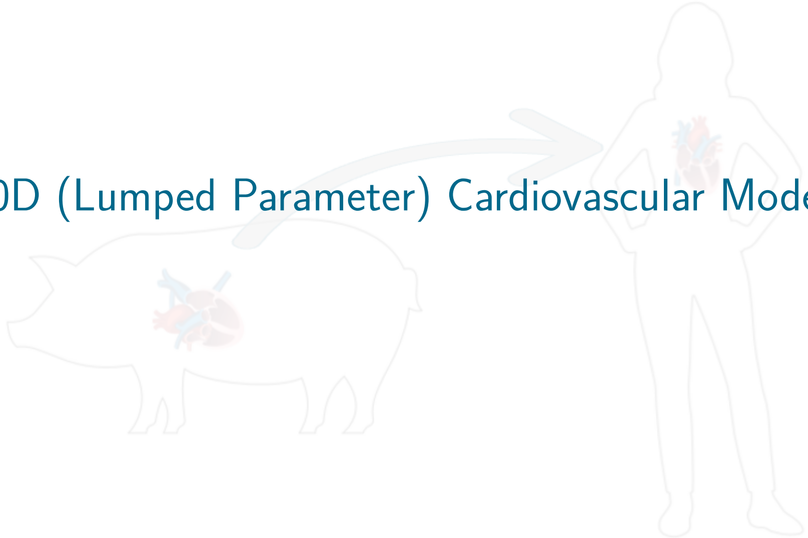
- **Outlet BC:** Three-element Windkessel (WK3) with parameters $R_c = 1$, $R_p = 10$, $C = 0.01$
- **Governing ODE:**

$$\frac{dP_{WK2}(t)}{dt} = \frac{1}{C}\left(Q(t) - \frac{P_{WK2}(t)}{R_p}\right)$$

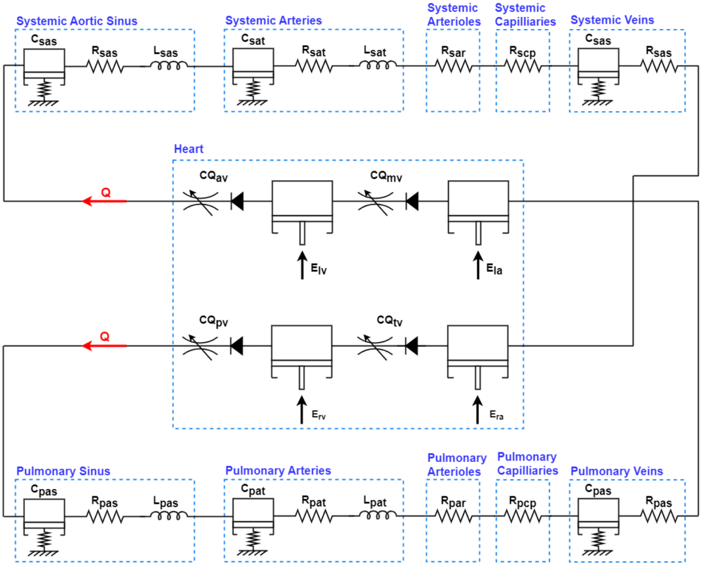
$$P(t) = R_c Q(t) + P_{WK2}(t)$$

- **Verification approach:**
  - ODE integrated numerically using `solve_ivp` (RK45)
  - Outlet pressure from pimpleFoam solver

# 0D (Lumped Parameter) Cardiovascular Modelling



# Completely Lumped System



# Completely Lumped System - Pressure, Flows and Volumes

## Lumped-Parameter Element Relations

**Resistance (Poiseuille):** $\Delta P = RQ$

**Compliance:** $Q = C\,\dfrac{d(\Delta P)}{dt}$

**Inertance:** $\Delta P = L\,\dfrac{dQ}{dt}$

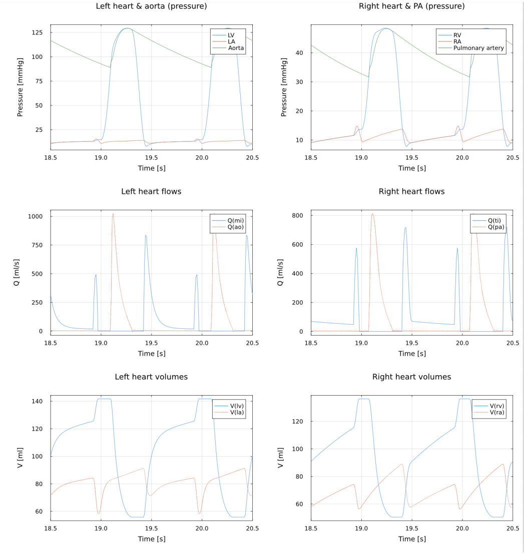
## Kirchhoff Laws (Haemodynamic Form)

**Flow conservation at a node (KCL):**

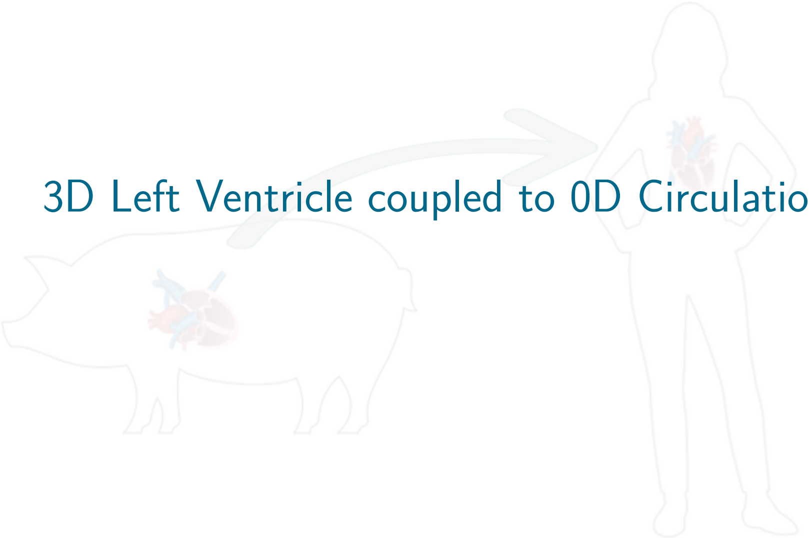
$$\sum Q = 0$$

**Pressure balance around a loop (KVL):**

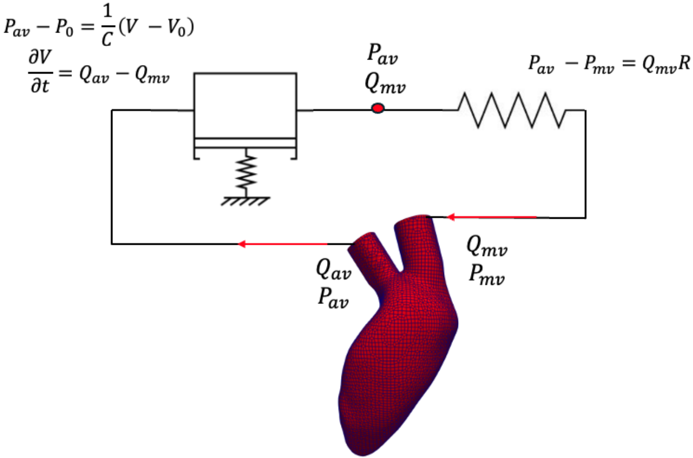
$$\sum \Delta P = 0$$



# 3D Left Ventricle coupled to 0D Circulation



# Incorporating a 3D Left Ventricle in OpenFOAM




## OpenFOAM BCs

- Prescribe $P_{av}$ and $Q_{mv}$ at the OpenFOAM boundaries
- Compute $Q_{av}$ and $P_{mv}$ from the 3D model and use them to update the LPM
- $\frac{\partial P_{av}}{\partial t} = \frac{1}{C}(Q_{av} - Q_{mv})$ (setting $P_0 = V_0 = 0$)
- $\frac{\partial P_{av}}{\partial t} = \frac{1}{C}(Q_{av} - \frac{1}{R}(P_{av} - P_{mv}))$
- $Q_{mv} = \frac{1}{R}(P_{av} - P_{mv})$

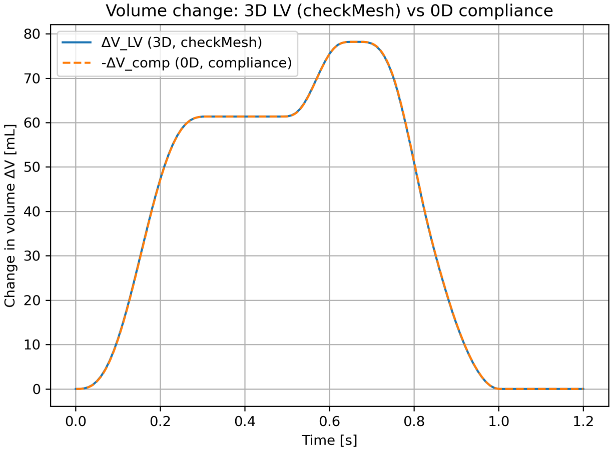
# Discretisation and Verifying Closed Loop

## Discretisation

$$P_{av}^{[1]} = \frac{P_{av}^{[0]} + \frac{\Delta t}{C}\left(Q_{av}^{[1]} + \frac{P_{mv}^{[1]}}{R}\right)}{1 + \frac{\Delta t}{RC}}, \quad \text{initial } n = 0$$

$$P_{av}^{[n]} = \frac{4\,P_{av}^{[n-1]} - P_{av}^{[n-2]} + \frac{2\Delta t}{C}\left(Q_{av}^{[n]} + \frac{P_{mv}^{[n]}}{R}\right)}{3 + \frac{2\Delta t}{RC}}$$

$$Q_{mv}^{[n]} = \frac{P_{av}^{[n]} - P_{mv}^{[n]}}{R}$$



# Coupling to a CLR Circuit

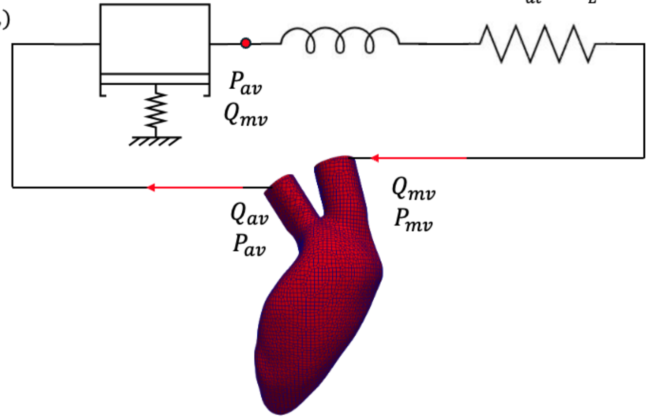
$$P_{av} - P_0 = \frac{1}{C}(V - V_0)$$

$$\frac{dV}{dt} = Q_{av} - Q_{mv}$$

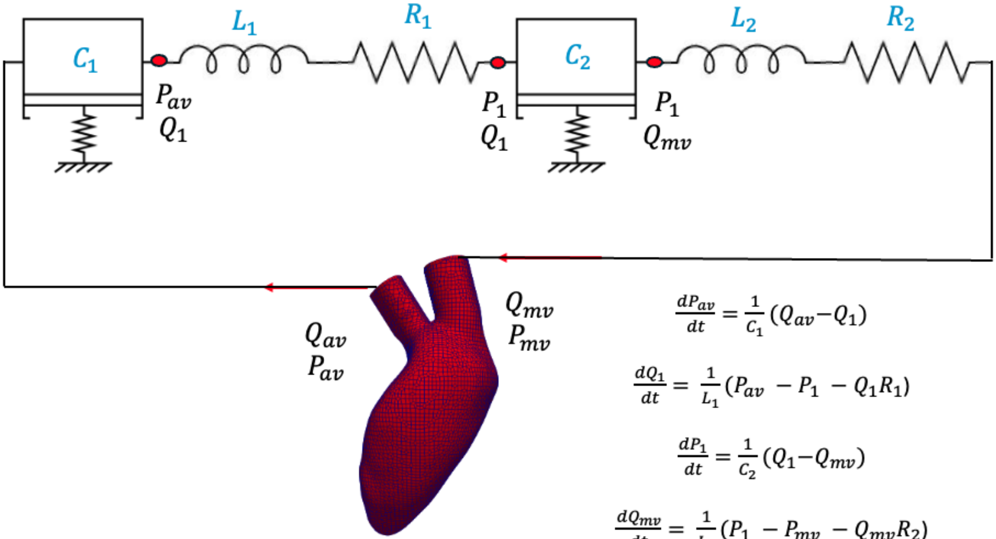
$$\frac{dP_{av}}{dt} = \frac{1}{C}(Q_{av} - Q_{mv})$$

$$P_{av} - P_{mv} = L\frac{dQ_{mv}}{dt} + Q_{mv}R$$

$$\frac{dQ_{mv}}{dt} = \frac{1}{L}(P_{av} - P_{mv} - Q_{mv}R)$$



# Coupling to a CLR x2 Circuit



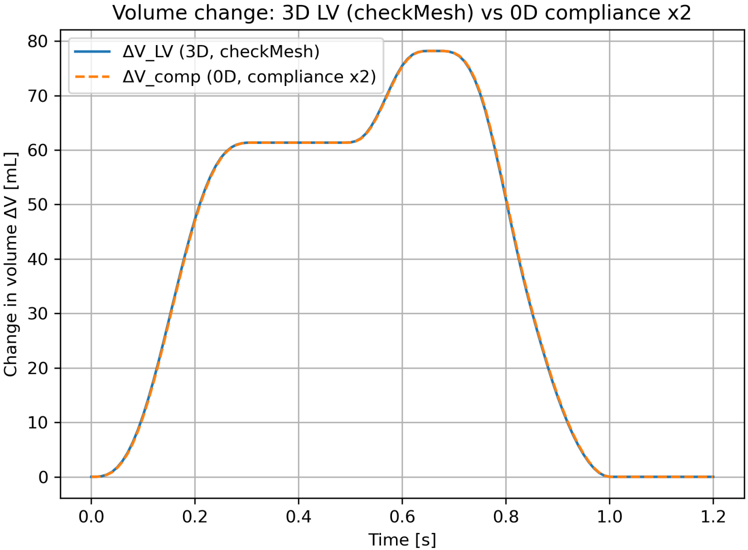

$$\frac{dP_{av}}{dt} = \frac{1}{C_1}(Q_{av} - Q_1)$$

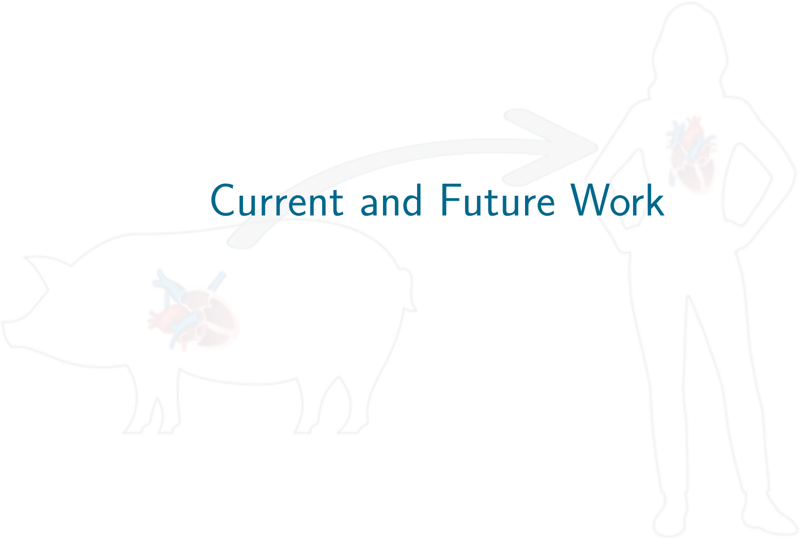
$$\frac{dQ_1}{dt} = \frac{1}{L_1}(P_{av} - P_1 - Q_1 R_1)$$

$$\frac{dP_1}{dt} = \frac{1}{C_2}(Q_1 - Q_{mv})$$

$$\frac{dQ_{mv}}{dt} = \frac{1}{L_2}(P_1 - P_{mv} - Q_{mv} R_2)$$

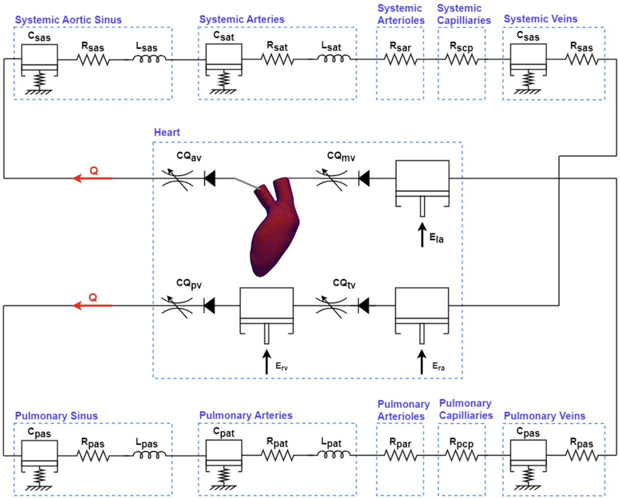
# Volume Conservation with 2 Compliance Chambers





# Current and Future Work

# WIP: Fully Coupled 0D – 3D System




## Progress & Next Steps

- **Future:**
  - Build a full **0D closed-loop circulation** model
  - Add further **3D heart chambers**
  - Incorporate **pig-specific geometry**
  - Develop a **modular OpenFOAM framework** to switch chambers between 0D and 3D

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# Thank you!

Happy to take questions

# References


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