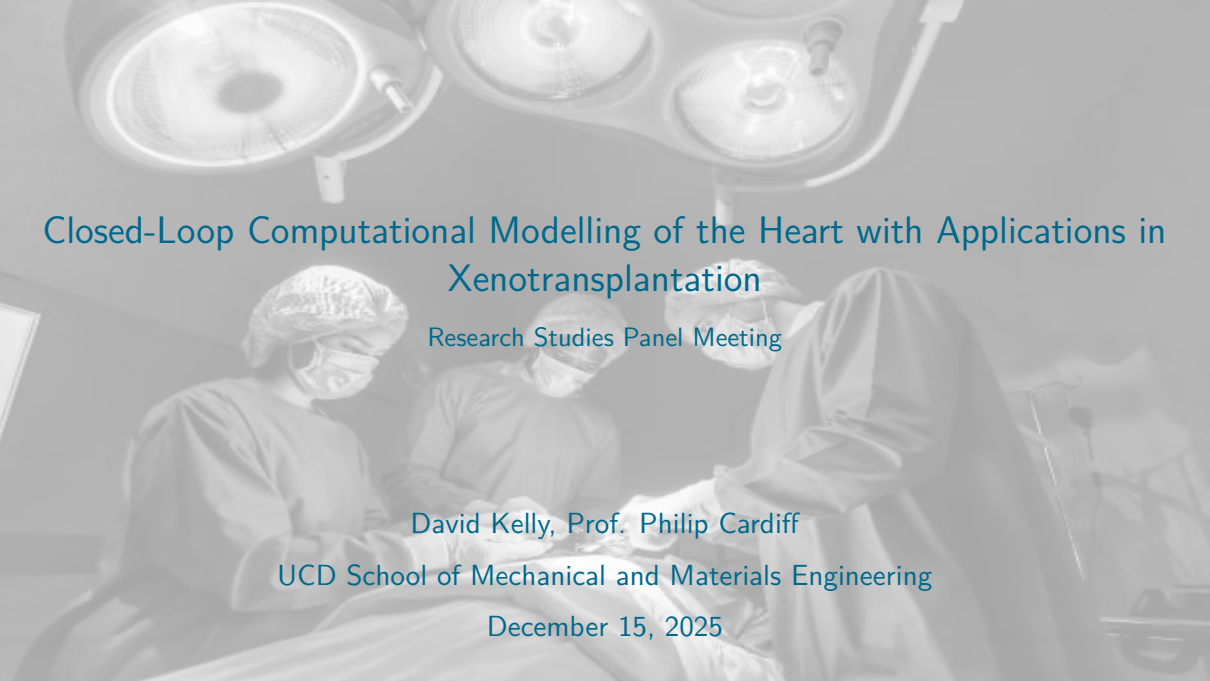


Closed-Loop Computational Modelling of the Heart with Applications in Xenotransplantation

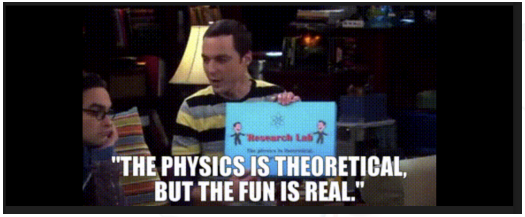
Research Studies Panel Meeting

David Kelly, Prof. Philip Cardiff

UCD School of Mechanical and Materials Engineering

December 15, 2025

A bit about me...



- Graduated Sept 2025 from Theoretical Physics in UCD
- Started PhD supervised by Prof. Cardiff in Sept. 2025
- Working on ERC-funded XenoSim project.

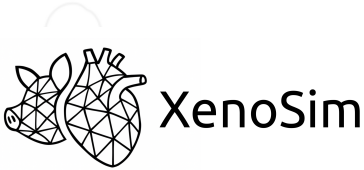
Background & Motivation

Big Picture

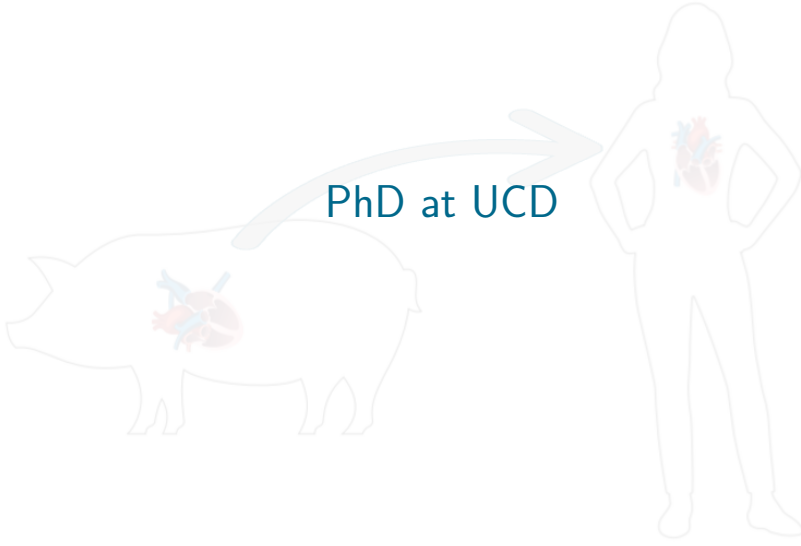
- Donor heart shortage continues to limit cardiac transplantation.
- Xenotransplantation is a promising alternative, but haemodynamic performance remains poorly understood.
- Porcine-to-human implantation introduces distinct haemodynamic and electromechanical challenges.

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.



PhD at UCD



The Credits (all 30 of them!)

Completed (Hopefully)

- *ACM40660* – Scientific Programming Concepts (ICHEC) (5 Credits)
- *MEEN40150* – Computational Continuum Mechanics II (5 Credits)

Potential Future Modules

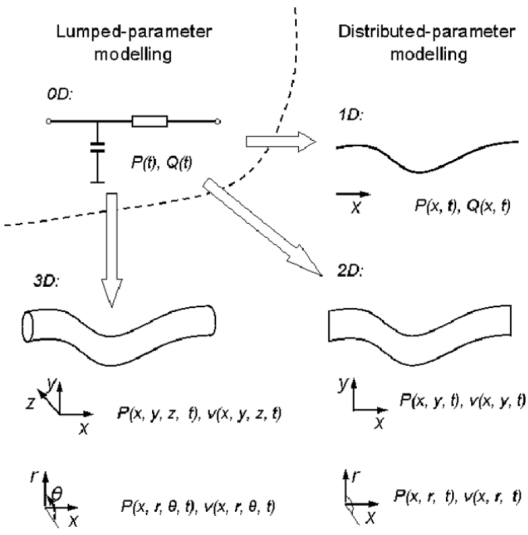
- *ACM40640* – High Performance Computing (ICHEC) (5 Credits – Spring)
- *ACM41000* – Uncertainty Quantification (5 Credits – Spring)
- *ACM40290* – Numerical Algorithms (5 Credits – next Autumn)
- *MEEN40910* – Teaching Assistant in MME (5 Credits – next Autumn)

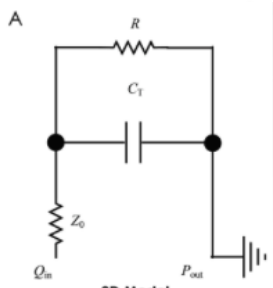
Additional Activities

- Completed online Research Integrity Training on Brightspace
- Abstract accepted to Bioengineering in Ireland Conference (BINI) 2026

Current Knowledge, Research Gaps & Objectives

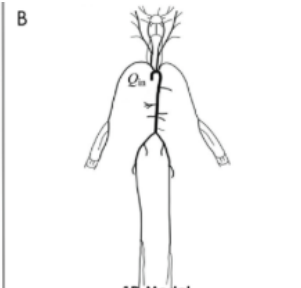
0D & 1D Cardiovascular Models





0D Model

- Uses electrical circuits, e.g. impedance (Z), capacitance (C) and resistance (R)
- Pressure (P) and flow (Q) per compartment



1D Model

- Pressure and flow computed along the 1D vessel networks
- Represents parts of the CVS

Why Closed-Loop 0D/1D Coupling?

Motivation

- Xenotransplantation is fundamentally an **interaction problem**: a porcine heart operating under **human vascular loading**.
- Closed-loop circulation models provide a physiologically consistent way to impose **afterload, preload, and feedback** on the 3D heart.

What 0D vs 1D adds

- **3D–0D:** robust, efficient closed-loop boundary conditions (mean pressure/flow and PV behaviour).
- **3D–1D:** captures spatial wave propagation and reflections $\Rightarrow$ time-varying, phase-dependent afterload.
- Both support: **"pig heart + human circulation"** experiments in-silico.

3D–1D Coupling: Current Knowledge & Research Gaps

Current Knowledge

- Coupling of 3D vessels or stenosis (*Hilhorst et al.*, *Formaggia et al.*) with 1D circulatory tree.
- Limited studies couple with 3D heart chambers, primarily focus only on **left ventricle only**.
- Caforio *et al.* couple a 3D human LV electromechanical model to a 1D arterial system.
- Found only one CFD-based studied (Chen *et al.*) couple 3D left ventricle to 1D circulation models.

Research Gaps

- Extension of 3D–1D coupling beyond the LV to **multi-chamber heart models** is largely unexplored.
- Existing 3D–1D frameworks are restricted to **human physiology**.
- CFD-based (Chen *et al.*) approaches do not incorporate full cardiac electromechanics.
- Electromechanical approaches (e.g. Caforio *et al.*) do not resolve intraventricular flow or fluid–structure interaction.
- **No existing framework combines multi-chamber 3D modelling, closed-loop 1D circulation, and xenogeneic (pig–human) configurations.**

3D–0D Coupling: Current Knowledge & Research Gaps

Current Knowledge

- Closed-loop coupling of 3D cardiac models with lumped-parameter (0D) circulation models is well established.
- Several studies couple multi-chamber **human** heart models to full systemic LPMs.
- Zingaro *et al.* demonstrate coupling of the full left heart (LV, LA, valves) to a closed-loop 0D circulation.
- 3D–0D coupling provides robust and computationally efficient haemodynamic prediction.

Research Gaps

- Existing 3D–0D frameworks are restricted to **human cardiac anatomy and physiology**.
- No models investigate porcine heart behaviour under **human circulatory loading**, even at the 0D level.
- Limited reuse or extension of existing frameworks to support xenogeneic configurations.
- **A predictive 3D–0D framework for porcine hearts operating within a human circulatory system is absent.**

Aim & Objectives

Overall Aim

To develop a multiscale computational framework for cardiac haemodynamics, and to apply it to the study of porcine hearts operating within a human circulatory system.

Specific Objectives

1. Develop a stable closed-loop coupling between reduced-order circulation models and 3D cardiac chambers.
2. Extend existing 1D–3D coupling approaches beyond the left ventricle to multi-chamber heart models incorporating electromechanics and fluid–structure interaction.
3. Apply the framework to xenogeneic configurations by coupling a 3D porcine heart with a human circulatory model.

Methodology Overview

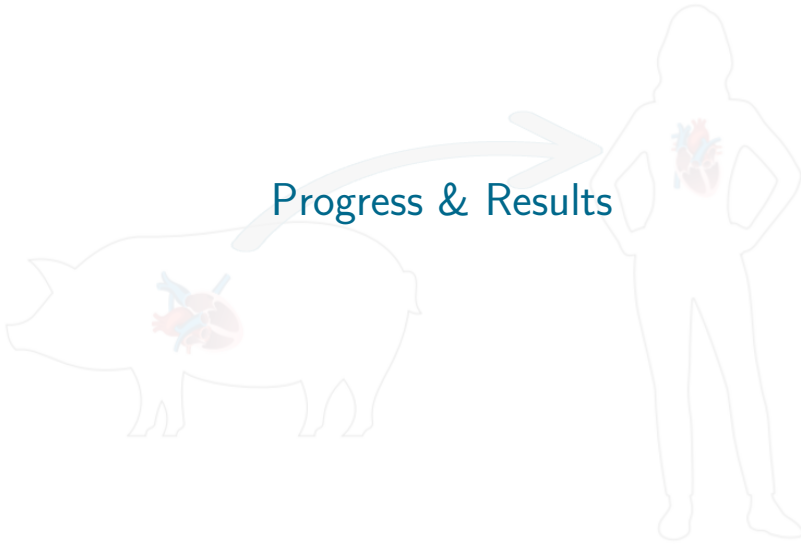
Modelling Framework

- Lumped-parameter (0D) and one-dimensional (1D) circulation models.
- Three-dimensional cardiac chamber models within OpenFOAM.
- Closed-loop pressure–flow coupling at physiological interfaces.

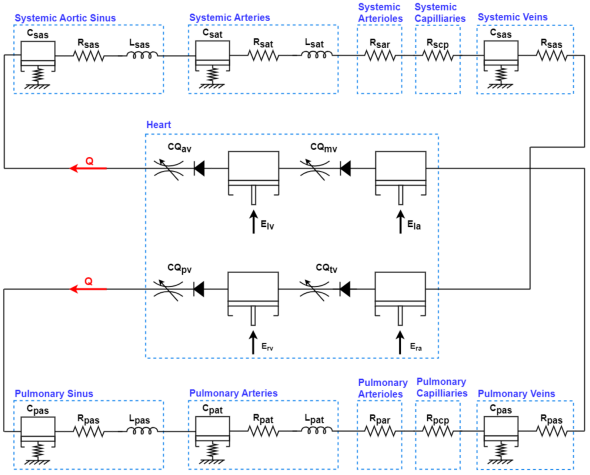
Verification & Assessment

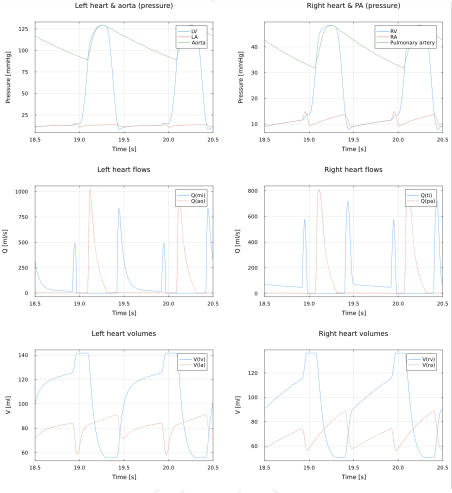
- Verification via volume conservation and flow balance.
- Comparison against published human physiological benchmarks.

Progress & Results

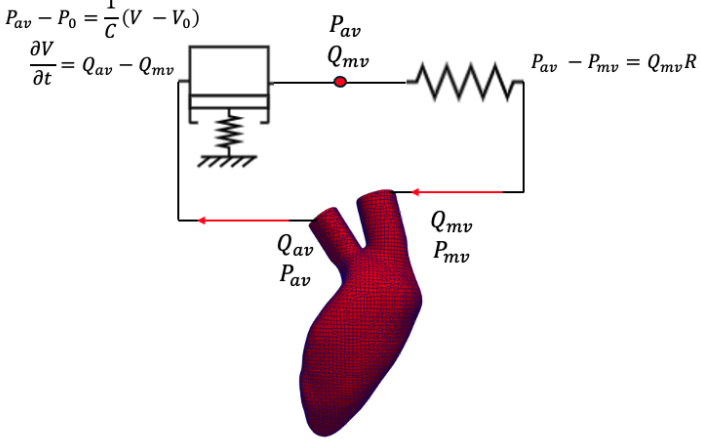


Completely Lumped System





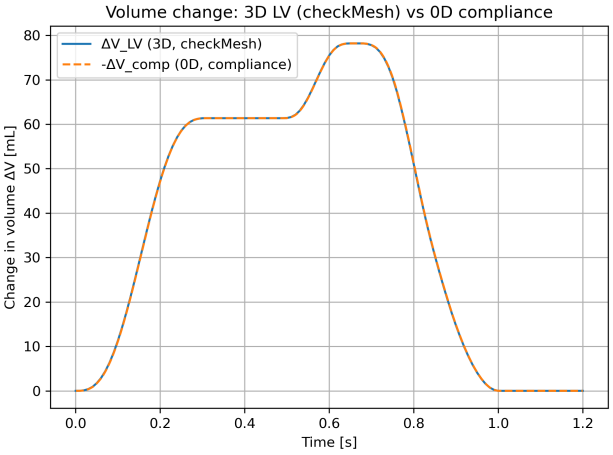
Incorporating a 3D Left Ventricle in OpenFOAM



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



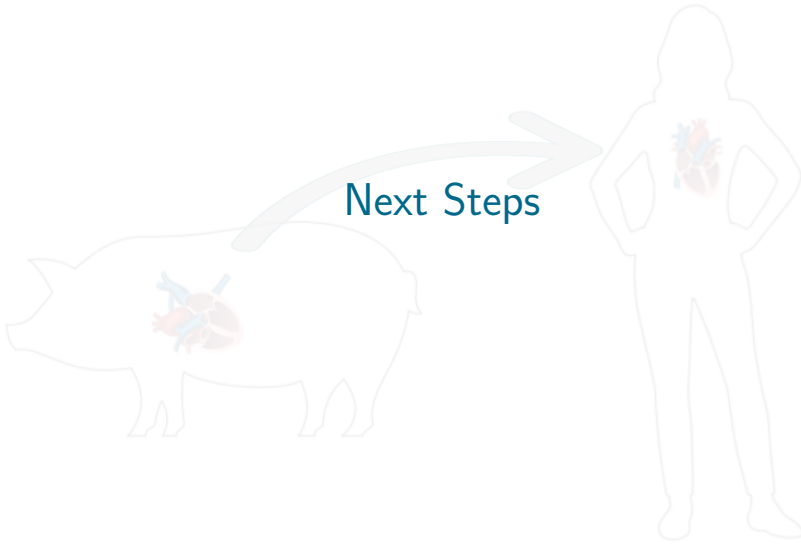
Discretisation

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

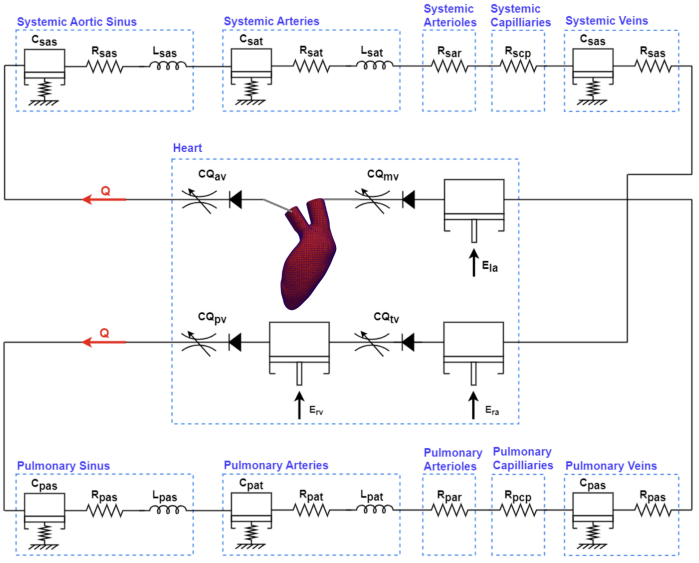
$$P_{av}^{[n]} = \frac{4\,P_{av}^{[n-1]} - P_{av}^{[n-2]} + \frac{2\Delta t}{C}\left(Q_{av}^{[n]} + \frac{P_{mv}^{[n]}}{R}\right)}{3 + \frac{2\Delta t}{RC}}$$

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

Next Steps



WIP: Fully Coupled 0D – 3D System



Planned Work (Next 6–12 Months)

Timeline

- **0–3 months:** complete integration of the full lumped-parameter circulation with a 3D left ventricle in closed loop; verify numerical stability and conservation properties.
- **3–6 months:** incorporate additional cardiac chambers and develop a modular OpenFOAM framework enabling interchangeable 0D and 3D heart components within the closed loop.
- **6–12 months:** introduce 3D porcine heart representations and perform initial xenogeneic simulation studies under human circulatory loading.

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- Hilhorst P.L.J., et al. *A Comparison of Coupling Strategies for 1D–3D Simulations of Coronary Hemodynamics* International Journal for Numerical Methods in Biomedical Engineering, 2025.
- Formaggia L., et al. *On the physical consistency between three-dimensional and one-dimensional models in haemodynamics* Journal of Computational Physics, 2013.
- Caforio, F., et al. *A coupling strategy for a first 3D-1D model of the cardiovascular system to study the effects of pulse wave propagation on cardiac function*. Computational Mechanics 2022.
- Chen, W.W., et al. *Study of cardiovascular function using a coupled left ventricle and systemic circulation model*. Journal of Biomechanics, 2016.
- Zingaro, A., et al. *A multiscale CFD model of blood flow in the human left heart coupled with a lumped-parameter model of the cardiovascular system*. Discrete and Continuous Dynamical Systems , 2022.

Thank you!

Happy to take questions.