COUPLING A 3D FINITE-VOLUME LEFT VENTRICULAR MODEL WITH 0D LUMPED PARAMETER CIRCULATION USING OPENFOAM

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INTRODUCTION AND MOTIVATIONS

Cardiac xenotransplantation has recently moved from conceptual possibility to emerging clinical reality, illustrated by the first pig-to-human heart transplant in 2022[1]. Long-term success, however, requires a deeper understanding of the physiological and mechanical consequences of implanting an anatomically dissimilar porcine heart into the human circulatory environment. Many haemodynamic and electro-mechanical phenomena related to xenotransplantation cannot be captured experimentally, making high-fidelity in-silico models an essential tool for exploring these mechanisms.

Lumped parameter models provide efficient, low-dimensional representations of circulatory dynamics while preserving physiologically relevant pressure-flow relationships[2]. Their computational simplicity makes them ideal for coupling with high-resolution, three-dimensional cardiac models, where they act as boundary conditions that provide the global circulation context that a local 3D model cannot represent on its own.

As an initial step toward developing coupled fluid-electro-solid interaction models of human and porcine hearts, we have developed the boundary-condition framework required to interface a 3D finite-volume model of the human left ventricle in OpenFOAM with a corresponding 0D lumped parameter model. This early-stage coupling allows pressure, flow, and volume information to be exchanged between the two domains and forms the basis for future integration of systemic and pulmonary circulation models, including those parameterised for porcine physiology.

MATERIALS AND METHODS

A three-dimensional finite-volume model of the human left ventricle was implemented in OpenFOAM using an existing geometry and passive material law. At this early stage of the work, the 0D left ventricle component of the lumped parameter circulation model was removed and replaced by the 3D left ventricle, forming the initial basis for a coupled 3D-0D framework.

The boundary-condition system linking the 3D and 0D domains was constructed incrementally. As a first step, a simplified closed-loop model comprising of a resistor and a capacitor (a two-element Windkessel) was implemented. This configuration enables a minimal closed-loop interaction, allowing the 3D ventricle to respond to evolving circulatory loading conditions in a controlled setting. The governing relationships describing pressure, flow and volume evolution in this reduced-order subsystem were derived and discretised within OpenFOAM, allowing these quantities to be exchanged dynamically between the 3D ventricle and the circulation model. This initial configuration provides a controlled pathway for testing the stability and behaviour of the coupled system and serves as the basis upon which more physiologically complete lumped parameter model components will be added.

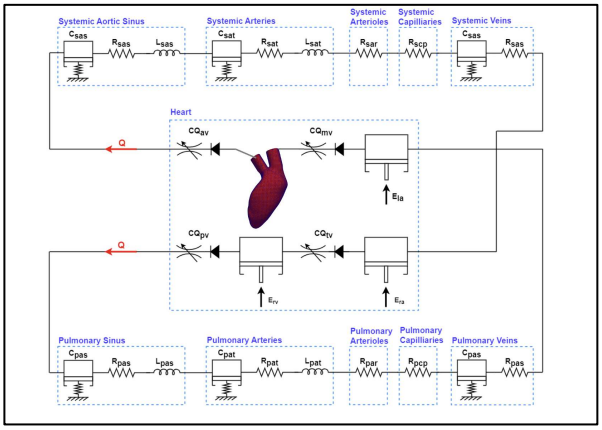

Figure 1 Cardiovascular lumped parameter model with 0D left ventricle replaced with 3D model.

ONGOING AND FUTURE WORK

Current development is focused on extending the simplified network to a full closed-loop circulation with systemic and pulmonary components. A key next step is adding further 3D chambers, starting with the left atrium, to form a fully 3D left heart and allow more realistic inflow and arterial-ventricular interaction.

In parallel, the circulation model will be updated with porcine-specific parameters, and the human left ventricle geometry will be replaced with a porcine model. This will enable simulations in which both the 3D ventricle and the lumped parameter model represent pig physiology, supporting direct comparisons between human and porcine cardiac behaviour and contributing to the goal of understanding porcine heart performance under human circulatory loading.

REFERENCES

1. Phillips (et al.), Circulation 152:58-73, 2025.
2. Shi (et al.), BioMedical Engineering OnLine 10:33-71, 2011.