Project number　73

In silico/in vitro interactive modelling of a paediatric pulmonary valve reconstruction

［1］Research group
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Expenditure report of research funds：
Consumables 130,000YEN

［2］Research setup

This project provides an in vitro design evaluation and performance testing for a paediatric pulmonary heart valve. Artificial ePTFE valves have been applied for congenital heart failure as valved conduits for right ventricular outflow tract reconstruction. An anatomically identical trileaflet valves have been used for a long time, but some investigation indicated that the long time use, especially in young patients, might cause calcification followed by low performance of valve leaflets. In vitro design evaluation and performance testing includes design characterisation of the integrated structural components, such as leaflets, conduits, and individual subcomponents. As pre-clinical testing, the experimental flow characterisation by in silico/in vitro evaluation is performed to determine shear or turbulent flow regions in the valved conduit.

Artificial ePTFE valves have been applied for congenital heart failure patients. This project provides a preclinical assessment for the modification of design of the valve leaflet as well as its anatomically identical shapes.

The purpose of this project is to develop a combined numerical and experimental approach to the study of valve function using fluid-structure interaction (FSI) to represent both the valve leaflet (solid) and the local blood flow (fluid). FSI analyses will be informed by in vitro / in vivo experimental measurement and visualisation techniques. In vivo imaging of pulmonary valve leaflet dynamic behaviour will be used to inform understanding of the pathophysiological effects observed in patients with chronic pulmonary heart valve disease. Experimental in vitro studies will integrate the natural (in vivo) valve characteristics in highly sophisticated mock circulatory systems to replicate the mechanisms of low pressure valvular dynamics in the pulmonary arteries.

The sensitivity of valve function to parameters associated with valve geometry (local valvular stenosis and valve sinus geometry) and material properties (arterial wall and valve leaflets) will be investigated in silico based on the in vitro/in vivo examinations at IDAC labs to determine target parameters for optimisation during valve-related surgical interventions.

We performed the in vitro/in vivo experimental part using valve testers based at IDAC and the University of Sheffield from the hydrodynamic or haemodyamic experimental point of view.

A numerical modelling for the pulmonary circulation using 3D model has been tested to investigate paediatric pulmonary arterial pressure and flow dynamics in FY2022. In FY2023, the new modelling approach based on 0D lumped circulatory model will be conducted based on in vitro/in vivo haemodynamic data obtained in IDAC.

［3］Research outcomes

（3－1）Results

A new 0D lumped circulatory modelling was conducted for representing the investigation results followed by asymmetric valve opening behaviour as

shown in Figure 1.

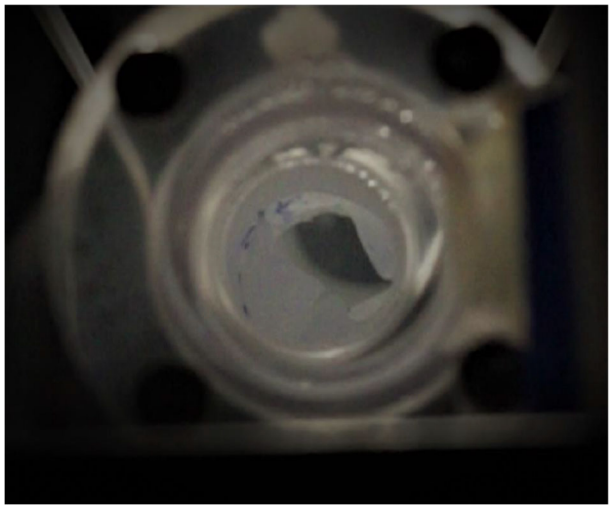

Fig. 1. An example of asymmetric flow opening of an in-development PTFE valve examined in vitro.

The convergence analyses of pressure drop against CFD mesh size for both valve type models were examined in the project. An optimum minimum mesh element size (MMES) and mesh size was investigated that seems reasonable to accept for the purpose of this stream of simulation work. The mesh convergence results indicate an optimum MMES of 0.001 m for the radial stenosis type valve models, and an MMES of 0.00075 for the 'hole-in-plate' type models.

Figure 2 demonstrates how CFD results can be combined with the 0D model to assess variability in valvular pressure drop as a result of both changes in systemic parameters, such as Systemic Vascular Resistance (SVR) and valve parameters, such as the Stenotic Area Ratio of the valve, which can be used to represent incomplete opening of the valve leaflets, as shown in figure 1 above.

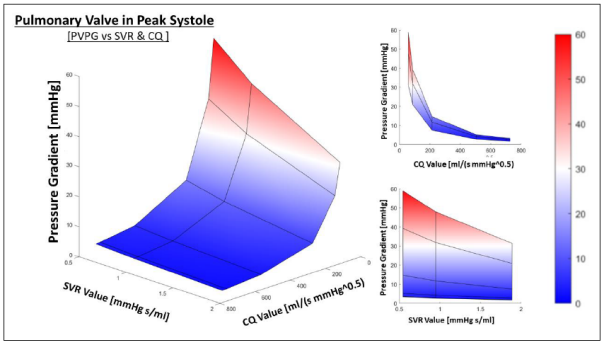

Fig. 2. Figure 6.14. Sensitivity analysis of Pulmonary Valve Pressure Gradient (PVPG) variation for different Systemic Vascular Resistance (SVR) values of the patient model and Stenotic Area Ratio (SAR) values of the valve model. (SVR range taken from a population of healthy 70kg adults). Colour bar represents peak systolic PVPG value in mmHg.

This analysis allows the combined effect of the valve and the patient-specific properties of the systemic circulation to be studied in an efficient manner, as the 3D CFD is used to provide a reduced order model of the valve in the 0D modelling framework, which is very computationally efficient.

（3－2）Future perspectives

Based on our joint project outputs from mutual preclinical studies, the preliminary evaluation has been started in a working group on the preclinical evaluation methodology in Japan to establish domestic guidelines for use in paediatric patients. Since 2015, the need to evaluate the use of paediatric devices as an extension for adult patients has been presented. The part of the project outcomes contributes to supporting the limited evidence of paediatric use of medical devices examined by interactive, interdisciplinary scientific evidence bases.

Paediatric circulatory diseases, and adult congenital cardiovascular therapeutic devices are highly expected for the clinical application. These results will lead to the development of in vitro/ in vivo/ in silico systems towards a global standard for preclinical evaluation method.

［4］List of Papers

In preparation.

This research has led to two student project reports within the current period, as follows:

Nicholas Rhodes, Simulation for the enhanced design of pulmonary valve prostheses. Final Year BioEngineering MEng project report, May 2023. University of Sheffield, UK.

Rui Duan, Simulation for enhanced design of pulmonary valve prostheses. Interim BioEngineering MSc project report, March 2024. University of Sheffield, UK.