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Computer and Experimental Modelling of Blood Flow through the Mitral Valve of the Heart*

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Abstract

This paper reports the first steps in determining the effects of fluid flow on the performance of the mitral valve of the heart that is relevant to surgical repair of the valve. In this paper, blood flow in idealised two-dimensional models of the mitral valve was studied using a numerical fluid-structure interaction (FSI) and experimental models and an experimental problem designed to validate the computational model. Both the experiments and simulation predicted a large vortex behind the anterior leaflet during inflow of blood into the left ventricle, in agreement with MRI scans available in the literature. Leaflet deformations agreed with results from experiments in the literature and with our previous experimental results.

Key words: Mitral Valve, Fluid-Structure Interaction Modelling, Biomechanics, Flow Visualisation

1. Introduction

The mitral valve is found between the left atrium (LA) and ventricle (LV) of the heart (Fig. 1 and 2). It closes during systole to prevent regurgitation of blood into the LA, allowing blood-flow through the aorta to body, and opens during diastole to enable efficient LV filling with blood. Failure of the valve (either poor closure during systole, or poor opening during diastole) reduces the efficiency of blood pumped to the body. Failure can be the result of chordal rupture, annular dilation, and/or alteration to material properties. Severe failure of the mitral valve of the heart can be fatal if the valve is not repaired surgically or replaced with prosthesis(1,2,3,4,5).

Fluid flow around the mitral valve may influence its movement and, therefore, its ability to function; such effects may have an influence on the results of surgical techniques for repairing the valve. Computational Fluid Dynamics (CFD) has been used to analyse heart valves in order to determine flow through mitral valves, including simulations of surgical repair(6,7). Several Finite Element (FE) models of the mitral valve have been developed(8,9,10), however, there are fewer that account for the effect of fluid flow through the valve(11,12,13,14). These Fluid-Structure Interaction (FSI) models of the mitral valve have simulated the flow of blood through the valve in a conduit and generally ignored the effect of the left ventricle of the heart on blood flow(11 -15). Furthermore, little validation of the

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predicted flow, under such conditions, involving valve deformation, has been provided. For the aortic valve, De Hart *et al.*[16] did use a two-dimensional fluid-structure interaction model, which they validated experimentally using laser Doppler anemometry for measuring the fluid flow and digitised high-speed video recordings to visualise the leaflet motion in corresponding geometries. This aortic valve FSI model used Lagrange multipliers to couple the two phases (using a fictitious domain method). Similarly, Stijnen *et al.*[17] used the fictitious domain CFD method for predicting dynamic response of two dimensional stiff aortic valve with a sinus cavity and validated the results using PIV techniques.

Sacks *et al.* [18] presented a study of the surface strains in the anterior leaflet in the functioning MV. The three dimensional spatial positions of markers placed in the central region of the MV anterior leaflet in a left ventricle-simulating flow loop over the cardiac cycle were determined. The resulting two-dimensional in-surface strain tensor was computed from the marker positions using Lagrangian quadratic finite element. Their results demonstrated that during valve closure the anterior leaflet experienced large, anisotropic strains with peak stretch rates of 500%–1000%/s.

Visualisation techniques used to investigate flow through heart valves, experimentally include particle imaging velocimetry (PIV) [19,20] and Laser Doppler Velocimetry (LDV) [21]. In earlier work, by Bellhouse[22] tea-leaves were used to visualise fluid flow into a model left ventricle, through a synthetic mitral valve that included chordae. PIV techniques enable whole field visualisation, while LDV methods enable accurate measurement of flow at individual points over time. Recently, streak photography has been applied to experimentally visualise flow through biological systems[23].

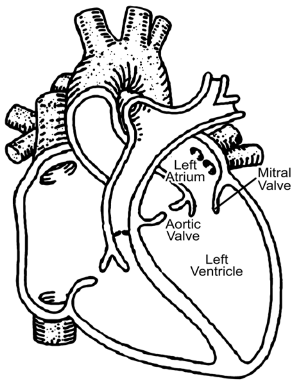


Figure 1: Basic anatomy of the heart.

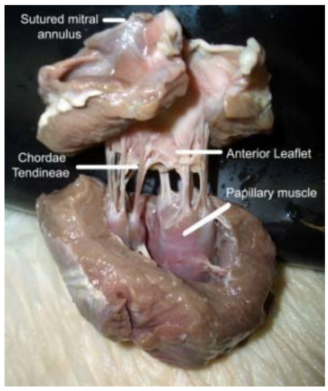


Figure 2: The mitral valve with a small segment of left ventricular muscle left connecting the papillary muscles.

This paper describes the coupling of an existing idealised two-dimensional FSI model of the mitral valve including the left ventricle[24] with experimental flow visualisation using streak photography for the model valve undergoing deformation.

2. Materials and Methods

2.1 Geometry of the Flow Models

In this study, the left ventricle (LV) was idealised as an ellipse with major and minor axes of 70 mm and 24 mm respectively, while the dimensions of the valve leaflets were approximately 20 mm long and 0.7 mm thick. These dimensions were used for both numerical and the experimental models and they are based on our previous experimental measurements. An idealised geometry for the heart (as a prolate spheroid) has been used previously[25].

2.2 Flow Assumptions and Parameters

In order to simulate the peak diastolic inflow of blood through the mitral valve, steady flow conditions were assumed. The viscosity of blood and the elastic properties of the valve leaflets, used in the CFD Model, were obtained from the literature(26,27,28,29,30) (Table 1).

Table 1. Values of parameters used to describe blood and heart valves during simulations.

Parameter	Value
Blood density (kg/m^3)	1.06×10^3
Blood viscosity (Pa.s)	2.70×10^{-3}
Leaflet density (kg/m^3)	1.06×10^3
Anterior leaflet Young's modulus (MPa)	2.0×10^6
Posterior leaflet Young's modulus (MPa)	1.0×10^6
Leaflet Poisson's ratio	0.49

2.3 FSI Model Overview

A two-dimensional FSI model of the mitral valve within the heart was generated using Comsol Multiphysics (Version 3.2). Lagrange multipliers have been used to apply the forces exerted on the deforming structure due to the flow of fluid, as is typical for simultaneous fluid structure interaction simulations(31).

Briefly, velocity constraints are applied to the fluid on the fluid-structure boundary, to ensure fluid nodes at that location move at the same velocity as the moving structure. While loading applied to the structure, that undergoes deformation, is determined through the use of Lagrange multipliers, from the fluid parameters at those nodes(32). Structural deformation and fluid dynamics are determined simultaneously. The use of a moving Arbitrary Lagrange Euler (ALE) mesh enables simultaneous fluid-structure interaction simulations, the use of a moving ALE mesh for such simulations is discussed elsewhere(11)

The simplified elliptical model has been used to simulate systolic ventricular pressures applied to generate blood flow within the heart chamber, opening the valve during diastole, and blood flow into the ventricle.

Inflow boundary conditions were applied to simulate valve opening during diastole. During diastole an inflow velocity was applied at the atrium and a pressure condition was applied at the apex of the heart, to apply the relevant ventricular pressures.

To establish the mesh independence of the numerical solution, smaller mesh sizes were used during initial trials while developing the model, after which a 'simulation time-mesh size' compromise was reached (the typical mesh had over 1000 elements).

2.4 Water Channel and Physical Flow Model

The experiments were performed in a re-circulating water channel that was built for this study. A schematic of the channel is shown in Fig. 3. The idealised model of the left ventricle was built using 10 mm thick non-porous Styrofoam board (Roofmate © produced by Dow Chemical Company). A hot-wire cutter was used to cut the profile of the two dimensional left ventricle. Compliant plastic sheet (1 mm thick) was used to make the two leaflets of the mitral valve. These leaflets cover the entire thickness of the LV model. A clearance of 1 mm was left between the bottom of the water channel and the lower part of the leaflets to facilitate their opening.

2.5 Flow Visualisation Techniques

Flow visualisation was achieved using streak photography. The flow upstream of the left ventricle model was seeded with silver colour glitter dust and 12 mega pixels digital camera (Nikon D300) was used to record the flow. When the wheel of the channel was running at low speed, the mitral valve was closed. As the speed of the wheel increased, the mitral valve opened allowing water to flow.

2.6 Research Limitation

There are a number of limitations related both to the materials used to manufacture the models and the nature of the flow through them. The walls of both CFD and physical models are rigid compared to the compliant walls of the physiological tissue. The outflow at the apex of the ventricle does not mimic the real flow and hence flow in the left ventricle can represent only a short moment of the peak diastolic conditions when the left ventricle is completely filled. While modelling two dimensional flow problems using CFD techniques is a straightforward matter, this is not the case for the flow in the water channel. In this research the experimental flow is averaged across the height of the channel. Hence, the flow visualisation results can be used to qualitatively validate the CFD results.

3. Results

3.1 FSI Results

The flow of blood caused the valve leaflets to deform, in turn altering the flow of blood. The simulation predicted a large vortex behind the anterior leaflet during inflow of blood into the left ventricle as shown in Fig. 4.

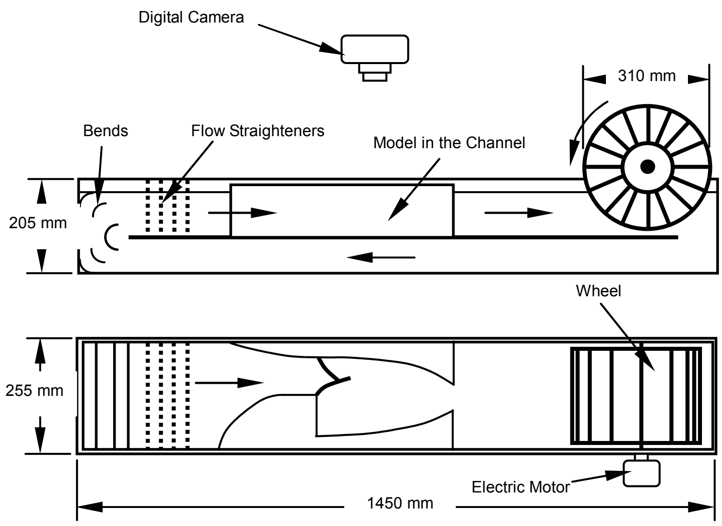
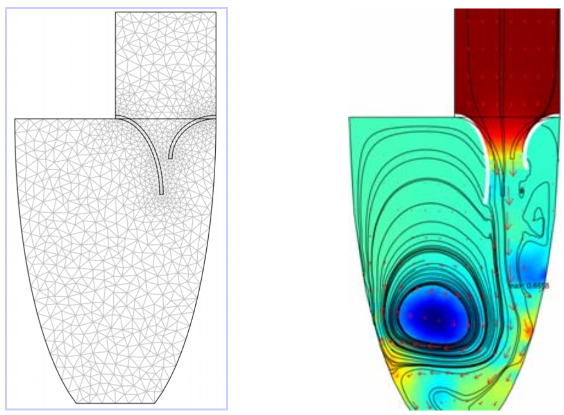


Figure 3: Schematic of the circulating water channel & the flow model.



a b

Figure 4: (a) Sample of the computational mesh and (b) large vortex behind anterior leaflet generated during diastole.

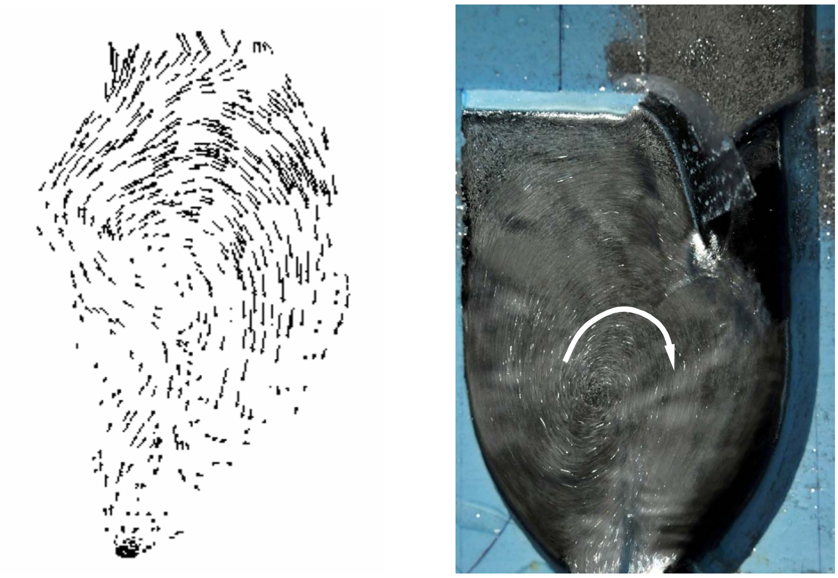
3.2 Experimental Results

A sample of the experimental results (Fig. 5) shows the flow structures downstream of the mitral valve as the waters passed from the left atrium to the left ventricle. Both flow structures and leaflets deformation in Fig. 5 agree well with the results of the FSI model as shown in Fig 4 (b). Although no velocity measurements are available, the similarity between flow patterns of the numerical and experimental models serves as a validation for the numerical findings.

The flow visualisation results show that the flow through the mitral valve caused the valve leaflets to deform, in turn altering the flow of water creating a large vortex behind the anterior leaflet during inflow of water into the left ventricle. This is a strong indication that both the idealised two-dimensional model used and the flow visualisation technique are suitable for modeling blood flow across healthy and diseased mitral valves. The next stage of the project will involve the study of different valves featuring the different geometric characteristics resulting from different surgical repair techniques. This is expected to aid assessment of performance of repair techniques, building on previous work that did not quantify flow patterns(33).

4. Discussion

Two-dimensional FSI and experimental models of blood flow through the mitral valve of the heart have been constructed. Transient simulations and flow visualisation studies have been performed. Simulations performed include the inflow of blood into the left ventricle of the heart. Overall, our predicted results show good agreement with observations available in the literature, such as MRI scans of flow through the mitral valve(34,35). This model will be used in future, to determine stresses experienced by mitral valves undergoing *in vitro* testing, along with flow parameters.



a b

Figure 5: (a) Flow patterns in the left ventricle based on MRI scans(34). (b) Visualisation of flow structures in the model of the left ventricle.

5. Conclusions

A computational method for investigating the fluid-structure-interaction of the mitral valve has been combined with an experimental technique used to determine flow patterns through a model heart valve based on the same boundary conditions. The experimental technique validated the simulated flow patterns, and showed similar valve deformation. This steady-state model represents a successful preliminary stage in developing realistic models of the behaviour of the mitral valve.

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