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In Vitro Flow Modelling for Mitral Valve Leakage Quantification

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ABSTRACT

In this study particle image velocimetry (PIV) is used to measure and visualise the blood flow through a leaking mitral heart valve. The results are compared with the results from Doppler echocardiography and computational fluid dynamics (CFD). Using CAD, five-axis milling and Rapid Prototyping Machining (RPM) technology, a hydraulic in vitro flow model was developed and constructed which is compatible with flow investigation with 2D normal speed PIV and 2D Doppler echocardiography. The same CAD model was used to conduct the CFD analysis. PIV results compared successfully with Doppler echo and CFD results, both in the upstream converging region and downstream the turbulent regurgitated jet zone. These results are expected to improve the assessment of mitral valve regurgitation severity with Doppler echocardiography in clinical practice.

Keywords- Particle Image Velocimetry, mitral regurgitation, heart valve, blood flow, five-axis milling, rapid prototyping, computational fluid dynamics, Doppler echocardiography.

1. INTRODUCTION

Mitral regurgitation (MR) is a very common valve injury in modern clinical practice. It occurs when there is an abnormal backflow of blood through the mitral valve, i.e. from the left ventricle to the left atrium.

In clinical practice patients with suspected or known MR are consistently evaluated using two-dimensional (Doppler) echocardiography. The assessment of MR severity via echocardiography, however, is complicated and all currently used methods have inherent weaknesses in one form ore another. Accordingly, it is difficult to obtain an accurate quantification of MR, which is of primary importance for guiding the patient's subsequent management. Real-time three-dimensional echocardiography (RT3DE) has the potential to improve the quantification of MR because of its capability to facilitate visualisation of intracardiac flow events. The clinical use of RT3DE, however, still limited due to the relatively low temporal resolution and the interpretation of the images which is rather complicated.

The aim of this study is to (i) design and construct a hydraulic model of the left atrium and ventricle using CAD, 5-axis CNC milling and rapid prototyping machining (RPM) technology to simulate the hemodynamic conditions encountered in typical MR, to (ii) design an identical in numero model and (iii) to investigate the complex three-dimensional flow phenomena with two reliable research techniques: Particle Image Velocimetry (PIV) and Computational Fluid Dynamics (CFD) and compare these with 2D Doppler echocardiography measurements.

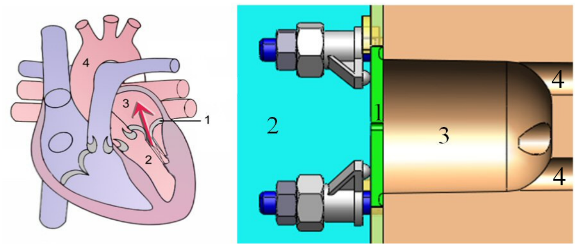
The knowledge gained from these experimental and numerical investigations should help to understand and interpret the phenomena observed on clinical echocardiography images. In addition it gives us the opportunity to refine the existing, or introduce new algorithms for examining the severity of MR by means of echocardiography.

2. MATERIALS AND METHODS

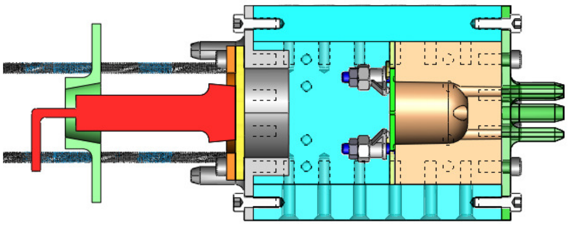
2.1 Design and construction of the hydraulic model

To be able to compare the PIV results with echocardiography, a hydraulic in vitro model has been built which complies with the requirements for both PIV and echocardiography. The main requirements for PIV are the transparency of the model for optical access of lasersheet and camera. The PIV camera has to stand perpendicular to the plane in which velocities are measured. The PIV experimental assessment is performed naturally in the same plane which is measured with the 2D (Doppler) echocardiography. The main requirements for echocardiography are to obtain appropriate acoustic transparency of the used materials and the use of a test liquid containing acoustic scatterers. The ultrasound transducer needs to be oriented apically and along the bulk of the measured velocities.

The developed CAD model (Solidworks 2008, Dassault Systèmes S.A., Vélizy-Villacoublay, France) consists of the left ventricle (LV, the rectangular cavity (figure 1A, (2)), the left atrium (LA, a circular cavity (3)) connected to the four pulmonary veins (PV). The mitral valve (MV) is represented as a small orifice of 4 mm (1).



(A)



(B)

Figure 1 (A) Mitral regurgitation modelling. *Left:* schematic drawing of MR, 1: Mitral valve plane; 2: left ventricle; 3: left atrium; *Right:* sectional view of the corresponding CAD model
(B) Front view of the hydraulic model assembly including the positioned ultrasound transducer (in red).

Figure 1B shows the assembly of the hydraulic model including the ultrasound transducer placed in the 'apical' position. The mould for the atrium was made from necuron 651 (Necumer GmbH, Bohmte, Germany), constructed using 5-axis milling, and polished to obtain a smooth surface. After the pre-processing with Magics software (Materialise NV, Leuven, Belgium) Rapid Prototyping Machining technology such as Selective Laser Sintering (SLS) and Stereolithography (SLA) were used for manufacturing the components of the hydraulic in vitro model. The casting of the silicone around the left atrium was adapted from [1]. Vacuum casting was used for casting the transparent silicone (Sylgard 184 silicone, Dow Corning) around the necuron 651 mould. The rigid mitral valve disk with an orifice of 4 mm was made from polymethyl methacrylate (PMMA).
Figure 2 illustrates the vacuum casting of the left atrium.

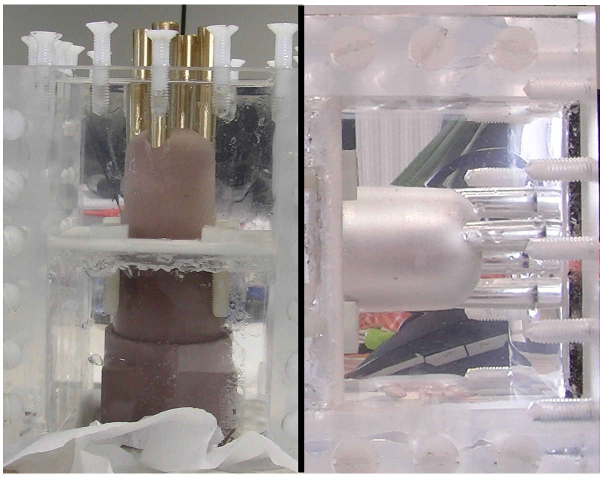


Figure 2 casting of the left atrium; *left:* the silicon block cast around the mould; *right:* the left atrium silicon block

2.2 Experimental PIV model

A 4 mm orifice was investigated with PIV in a closed-circuit mock loop including reservoir, pump and the model. The PIV measurements were performed at a constant inlet (LV) pressure of 120mmHg and an outlet (PV) resistance pressure of 60mmHg. According to our preliminary results [2] this pressure drop results in a Reynolds number of:

$$Re = \frac{\rho \times D \times v}{\mu} = 1082$$

based on the maximum orifice velocity. A water-glycerin mixture was used as working fluid. The water-glycerin volume ratio was experimentally determined to be 41% water, 59% glycerine to match the refracting index of the used silicon material (RI = 1.43). This mixture has a density of 1156 kg/m³ and a kinematic viscosity of 12.945 10^{-6} m²/s.
A standard 2D normal speed PIV system (ILA GmbH, Juelich, Germany) was employed to perform the experiments. A pulsed Nd:YAG laser reaching the maximum energy of 25mJ was used as a light source. A CCD Sensicam QE camera with a maximum resolution of 1376 x 1040 pixels was used to record images which were stored in bitmap format afterwards. The pulse distance varied between 200 µs and 1500 µs. Polyamid microspheres particles with a density of 1016 kg/m³ and an average diameter of 57 µm were used as tracer particles. Post processing of the images was done with commercial VidPIV 4.6 software (ILA GmbH, Juelich, Germany). In the region of interest, 'in plane' velocity vectors and magnitudes were computed. The results are computed from the statistical average of 1000 instantaneous flow field measurements.

2.3 Two-dimensional Doppler echocardiography model

The 2D Doppler echocardiography measurements were performed on the same hydraulic model that was used for the PIV measurements. The echocardiography measurements were done using a commercially available ultrasound system (Vivid 7, GE Vingmed Ultrasound, Horten, Norway) equipped with a cardiac M3 1.7/3.4-MHz matrix transducer. The transducer was positioned in the apical position as illustrated in figure 1B. The reflection of the ultrasound waves was improved by adding polyamid microspheres particles to the working fluid.

2.4 Numerical CFD model

A 3D CFD analysis of the MR model has been conducted using finite volume discretisation of the internal fluid domain of the CAD model presented in figure 1B. Previous leaking jet studies [3], [4] and [5] show that for the present Reynolds number, the jet flow has to be turbulent. Because of these previous studies, the Reynolds Averaged Navier-Stokes equations (RANS) have been solved with the standard k-ε turbulence model for incompressible flow. The simulations were performed with Fluent 6.3 (ANSYS, Inc., Lebanon, NH, USA). An implicit steady time calculation in combination with second order central space discretisation has been used. As medium, an incompressible newtonian liquid with the same properties as the used water-glycerin mixture for PIV and echo measurements was programmed. The static pressure boundary conditions from the in-vitro model were applied at the inlet of the LV and at the outlet of the four PV's as illustrated in figure 3.
The internal fluid domain is extracted from the CAD assembly model (figure 1B) and imported as a parasolid data file into the meshing software. We used Gambit 2.2 (ANSYS, Lebanon, NH, USA) to mesh the model. A basic 3D unstructured tetrahedral mesh containing 1.6 10^6 cells was created on the basis of the hierarchal CAD topology, as illustrated in figure 3. Geometry based mesh refinement was done in the vicinity of the leakage orifice, at the boundaries of the atrium and in the four PV's. In the initial grid, no mesh refinement was performed in the region of the expected jet. During the simulation, the mesh size and quality was improved by a velocity gradient adaptive mesh refinement. Mesh convergence was obtained using a mesh with approximately 2.6 10^6 cells.

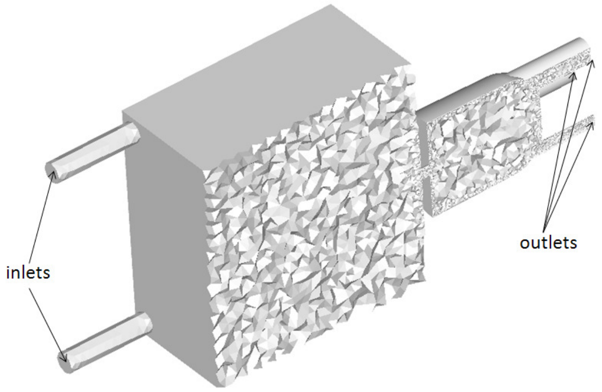


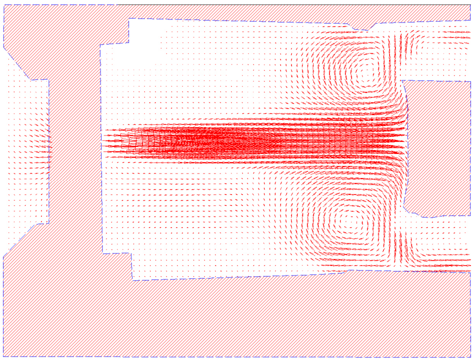
Figure 3 Section view along the midplane of the initial unstructured tetrahedral mesh of the numerical model.

3. RESULTS

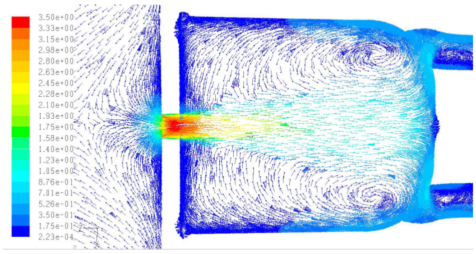
Results of the PIV measurements and CFD simulations are qualitatively compared to each other before they are quantitatively compared with 2D Doppler echocardiography. Figure 4 shows (A) the results of the PIV measurement, (B) the results obtained by CFD (k-ε turbulence model) and (C) the (Doppler) echo results.

Depending of the used camera settings, particles and other measurement settings, the 2D PIV images were obtained with a pulse distance of 500 µs. The 2D PIV image shows the 2D velocity vectors in the midplane.

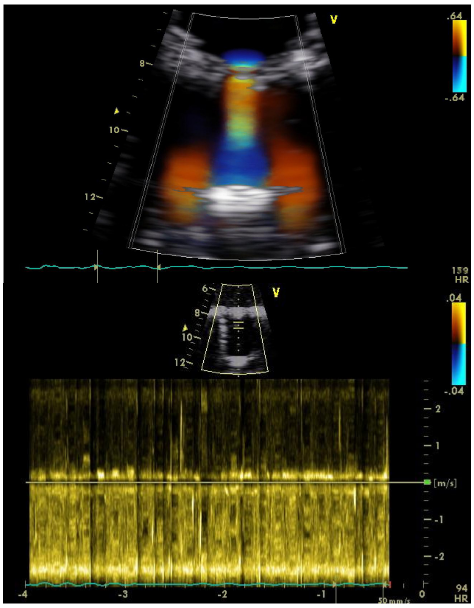
The 3D CFD results are obtained on the finest grid of 2.6 10^6 cells and show the projected 2D velocity vectors are shown in figure 4 (panel B). The colour represents the velocity magnitude of the 2D vectors ranging from blue to red corresponding to low and high velocities.



(A) PIV



(B) CFD



(C) 2D doppler echocardiography

Figure 4 Results of the MR model obtained by: (A) PIV, (B) CFD (in m/s) and (C) 2D Doppler echocardiography (in m/s).

Both PIV and CFD results capture the following flow phenomena:

- Turbulent leaking jet flow in the LA
- Flow convergence zone in front of the MV
- Stagnation point at the back of the LA
- A 3D recirculation zone or vortex in the LA
- Separation zones at the entrance of the PV's.

The maximum velocity measured with PIV was 2.5 m/s and was found at the beginning of the jet. Figure 5 shows the velocity contour plot measured with PIV.

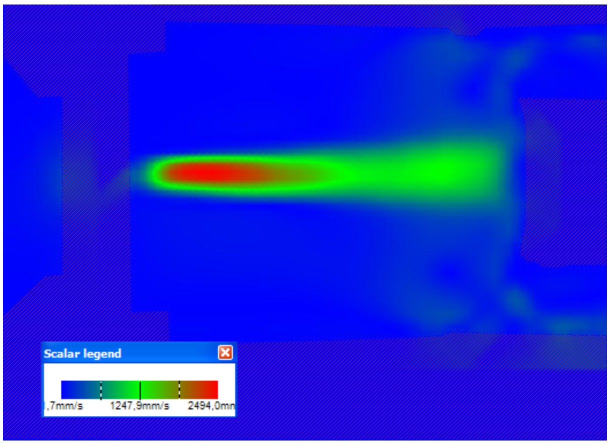


Figure 5 velocity contour plot measured with PIV

The maximum velocity obtained with CFD is 3.5 m/s. This velocity is computed inside the orifice. Because optical access to that location is not possible in the in vitro model, PIV velocities remain unknown. However CFD results do confirm PIV results in the region of the highest PIV velocities (2.6 m/s).

The maximum velocity of the 3D vortices at the end of the LA was measured in this test case with PIV with a pulse distance of 1ms. The maximum velocity measured with PIV was 0.3 m/s while the CFD value was considerably higher (0.6 m/s).

The colour flow map obtained with 2D Doppler echocardiography is shown in figure 4C. The colour coded map represents velocities along the ultrasound beam and shows the jet and recirculation zones. The red colours represent the flow towards the transducer while the blue colours represent the velocity in the opposite direction. Due to aliasing, the beginning of the jet is coloured red. This means that the velocity at the beginning of the jet exceeded the maximum velocity of the colour scale, resulting in inversion of the colour scale in this region. However, pulsed wave Doppler confirmed the maximum velocity to be 2.4 m/s at the beginning of the jet. We can clearly distinguish three phenomena; the leakage jet, the flow convergence zone in front of the MV and the reversed flow in the 3D vortex.

DISCUSSION AND CONCLUSIONS

PIV leaking jet studies are often performed in a simple straight tube. By considering a new hydraulic model of mitral regurgitation which includes the left atrium and the four pulmonary veins, a more realistic flow pattern can be achieved. Using CAD, CNC and RPM, a new hydraulic in vitro model has been designed and constructed for analysing MR flow with PIV and 2D Doppler echocardiography. The flow field caused by the leaking mitral valve was investigated with PIV, 2D echo and CFD. As working fluid a water-glycerin mixture was used which kinematic viscosity is three times higher than the kinematic viscosity of blood. Following table summarises the measured velocities

	PIV	**echo**	**CFD**
Jet velocity (m/s)	2.5	2.4	2.6
Vortex velocity (m/s)	0.3	/	0.6

Table 1 mitral regurgitation velocity comparison

The results show a good quantitative agreement between PIV, CFD and (pulsed Doppler) echo of the velocity of the leaking jet. However the velocity of the 3D vortex at the back of the atrium, showed a considerably higher velocity simulated with CFD than obtained with PIV. This difference could be due to the fact that the simulated jet is wider than the jet measured with PIV. An explanation could be that the used turbulence model and its parameters are suboptimal for this model.

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