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Mitral Valve Leakage Quantification by Means of Experimental and Numerical Flow Modeling

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BIOGRAPHICAL NOTES

Mathias Vermeulen was born in Ghent, Belgium in 1984. He graduated at the University College Ghent, Belgium as a M.Sc. in 2008. In his master thesis he studied the mitral valve leakage in a simplified atrium geometry. He is since 2009 active as a PhD student at the University College Ghent, Belgium in collaboration with Ghent University, Belgium. His current research interests include respiratory flow visualization on patient specific airways and particle image velocimetry.

KEY WORDS

Particle Image Velocimetry, Computational Fluid Dynamics, 2D Doppler Echocardiography, Mitral Valve Regurgitation, Heart Valve, Rapid Prototyping Modeling

ABSTRACT

Accurate quantification of mitral valve regurgitation (MR) is a challenging task in clinical cardiology. In order to develop and refine new algorithms for estimating the severity of MR using real-time 3D Doppler echocardiography (RT3DE), an experimental and numerical flow model have been designed and constructed. Using CAD, Rapid Prototyping Manufacturing (RPM) and five-axis milling technology, a hydraulic in vitro flow model, compatible for flow investigation with 2D normal speed Particle Image Velocimetry (PIV) and 2D Doppler Echocardiography. The same CAD model was used to conduct the Computational Fluid Dynamics (CFD) analysis. PIV, 2D Doppler Echocardiography and CFD results compare successfully in the upstream converging region and in the downstream turbulent regurgitated jet zone. These results are expected to improve the clinical assessment of mitral valve regurgitation severity by means of Doppler echocardiography.

INTRODUCTION

According to the American Heart Association, in 2008 almost 21000 Americans died

from the consequences of heart valve diseases [2]. Heart valve diseases are often caused by rheumatic fever, calcification due to the aging process, congenital defects and other cardiovascular injuries. A common heart valve injury is mitral regurgitation. Mitral regurgitation occurs when there is an abnormal backflow of blood through the mitral valve in the contracting or systolic phase of the heart cycle.
Although magnetic resonance imaging is the gold standard in grading MR, 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 or another. [6], [9], [10] Accordingly, it is difficult to obtain an accurate quantification of MR, which is of primary importance for guiding the patient's subsequent management. For the time being MR is classified in four stages where stage one is mild regurgitation and stage four means severe regurgitation. 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. Previous studies done by Fallon et al. [3], [4] and Amatya et al. [1] indicate that the flow profile obtained by a leaking jet into the left atrium has to be turbulent. A parameter to evaluate MR severity was investigated by Thomas et al. [8]. They concluded that the peak early diastolic inflow velocity (E-wave) which is easy to obtain in the clinical practice is a good screening tool to evaluate MR severity. To understand the impact of MR on the cardiovascular performance it is very important that research is done on the flow velocity profile in the left atrium.
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 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.

MATERIALS AND METHODS

Design and construction of the hydraulic model

To be able to compare the results from the different measurement techniques with each other, it had to be ensured that the same geometry was used for PIV, 2D Doppler echo measurements and CFD simulations. An hydraulic in vitro model has been built which complies with the requirements for both PIV and 2D Doppler echocardiography. The main requirements needed to perform PIV measurements are the transparency of the model and fluid medium for optical access of camera and lasersheet. In 2D PIV the camera has to stand perpendicular to the plane in which the velocities are measured. That plane should be illuminated with a powerful laser light. To avoid scatter of the laserlight, the wall roughness of the model must be as smooth as possible. To perform 2D Doppler echocardiography it is necessarily to obtain appropriate acoustic transparency of the used model materials and to use a test liquid containing acoustic scatterers. The acoustic transducer will be oriented apically and along the bulk of the measured velocities.
A CAD model (Solidworks 2008, Dassault systems S.A., Vélizy-Villacoublay, France) containing the left ventricle (LV, the rectangular cavity (Fig. 1, (2)), the left atrium (LA, the circular cavity (3)) connected to the four pulmonary veins (PV, (4)) and the mitral valve (MV, represented as a small orifice (1)) was developed. For this case a 4 mm orifice diameter was chosen.

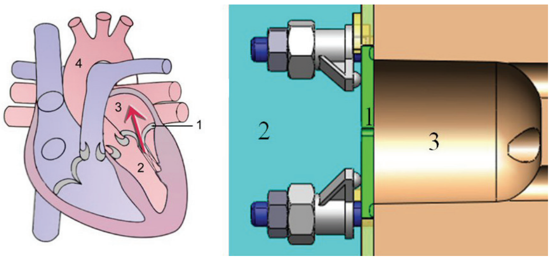

Fig. 1 *Mitral regurgitation modeling.* ***Left:*** *Schematic drawing of MR,* ***Right:*** *Sectional view of the corresponding CAD model*

Figure 2 shows the front view assembly of the hydraulic model including the ultrasound transducer placed in the (standard) apical position.

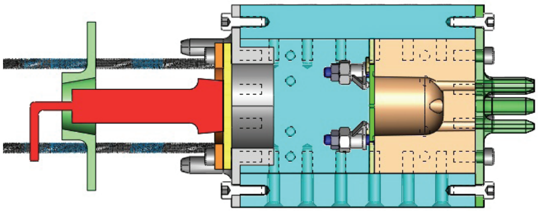

Fig. 2 *Front view of the hydraulic CAD model*

The core for the atrium, made from necuron 651 (Necumer GmbH, Bohmte, Germany), was constructed using 5-axis milling, and polished with ultrafine sandpaper to obtain a smooth surface. After Polishing the atrium core was filled with a pores filler to avoid adhesion of the silicone to the core. Then, four cylinders made of brass were inserted in the atrium core to model the pulmonary veins. After that, an inlet and outlet part was added to integrate this in vitro model into a mockloop. These parts were first designed as a CAD model, secondly pre-processing with Magics software (Materialise NV, Leuven, Belgium) and finally manufactured using a Rapid Prototyping Machining technology (Stereolithography). The middle part attaching the valve was manufactured using another Rapid Prototyping Technique (Selective Laser Sintering) The casting of the silicone around the left atrium and lumen was performed according to the method described by Hopkins et al. [5]. Hereby, a transparent silicone (Sylgard 184 silicone, Dow Corning) was vacuum casted around the atrium core. The rigid mitral valve disk was made from polymethyl methacrylate (PMMA). Fig. 3 illustrates the vacuum casting of the left atrium.

Experimental PIV model

Flow through the orifice was investigated with PIV using a closed-circuit mock loop including reservoir, pump and the model. The PIV measurements were performed at a pressure difference between in- and outlet of 90 mmHg. Figure 4 shows the mock-loop. A water-glycerin mixture was used as working fluid. The water glycerin volume ratio was experimentally determined to be 41% water and 59% glycerin to match the refractive index of the used silicon material. This mixture has a kinematic viscosity of 12,95x10^{-6} m^2/s and a density of 1150 kg/m^3.

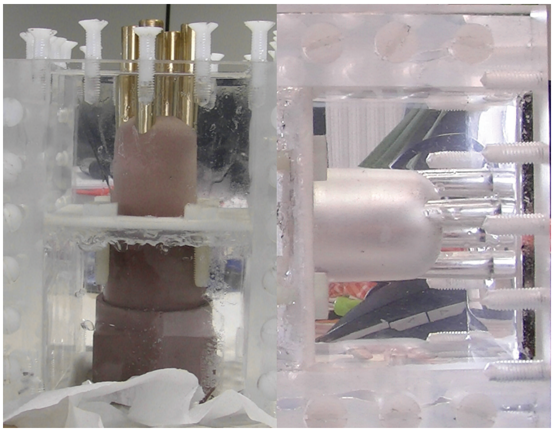

Fig. 3 *Casting of the left atrium;* ***Left:*** *the silicon block cast around the mould;* ***Right:*** *the left atrium silicon block*

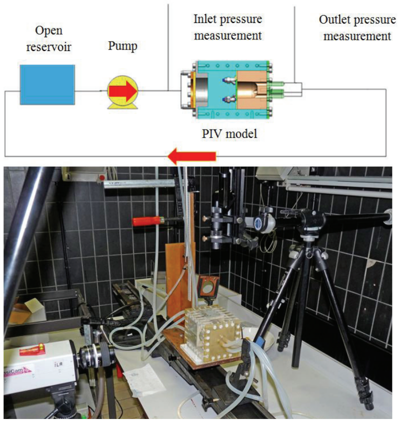

Fig. 4 *Mock-loop of the MR model*

A Standard 2D normal speed PIV system (ILA GmbH, Juelich, Germany) was employed to perform the flow analyses. A double pulsed Nd:YAG laser reaching the maximum energy of 120mJ was used as a light source. A CCD Sensicam QE camera (PCO, Kelheim, Germany) with a maximum resolution of 1376x1040 pixels was used to record the images which were stored in bitmap format afterwards. Polyamid microspheres particles with a density similar to the fluid density and an average diameter of 57µm were used as tracer particles. Post processing of the images was performed with commercial VidPIV 4.6 software (ILA GmbH, Juelich, Germany). In the region of interest, in plane velocity vectors and magnitudes were computed. The stationary results were computed from the statistical average of 1000 instantaneous flow field measurements. During stationary flow measurements the image pairs were taken at a frequency of 8Hz.

2D Doppler echocardiography model

The 2D Doppler echocardiography measurements were performed on the same hydraulic model used for the PIV investigations. 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 2. The reflection of the ultrasound waves was improved by adding polyamide microspheres with a diameter of 57µm to the water/glycerin fluid.

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 Fig. 2. Since the jet flow will be turbulent, 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 pulmonary veins as illustrated in Fig. 5.
The internal fluid domain is extracted from the CAD assembly model (Fig. 2) and imported as a parasolid data file into the meshing software. Gambit 2.2 (ANSYS, Lebanon, NH, USA) was used to mesh the model. A basic 3D unstructured tetrahedral mesh containing $1,6x10^6$ cells was created on the basis of the hierarchical CAD topology, as illustrated in Fig. 5. Geometry based mesh refinement was done in the vicinity of the leakage orifice, at the boundaries of the atrium and in the four veins. In the initial grid, no mesh refinement was adapted 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 $2,6x10^6$ cells.

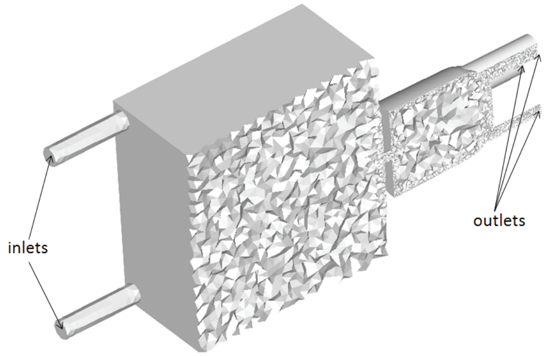

Fig. 5 *Section view along the midplane of the initial unstructured tetrahedral mesh of the numerical model*

RESULTS AND DISCUSSION

The results of the PIV measurements, 2D Doppler echo measurements and the CFD simulations, obtained by the same boundary conditions were evaluated and quantitatively compared to each other. The results in this paper focus on the flow dynamics in the midplane of the leaking valve. Figure 6 shows the used region of interest.

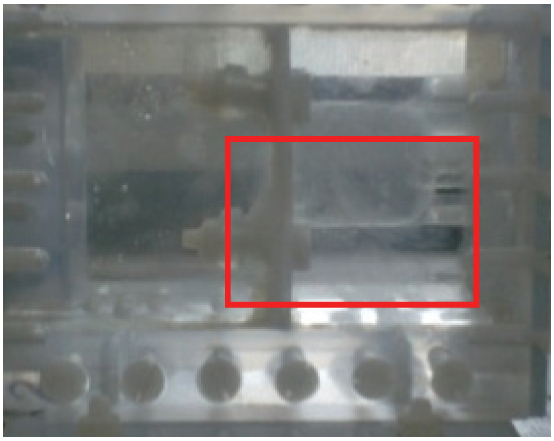

Fig. 6 *ROI: midplane of the leaking valve*

Figure 7 shows (A) the results of the PIV measurements, (B) the obtained CFD simulation results and (C) the 2D Doppler echocardiography results. Depending on the used camera settings, particles and other measurements settings, the 2D PIV images were recorded with a pulse distance of 150µs. The 3D CFD results show the in plane 2D velocity vectors ranging from blue to red corresponding low and high velocities.
All of the used techniques, PIV, 2D Doppler echo and CFD were able to capture the following flow phe-

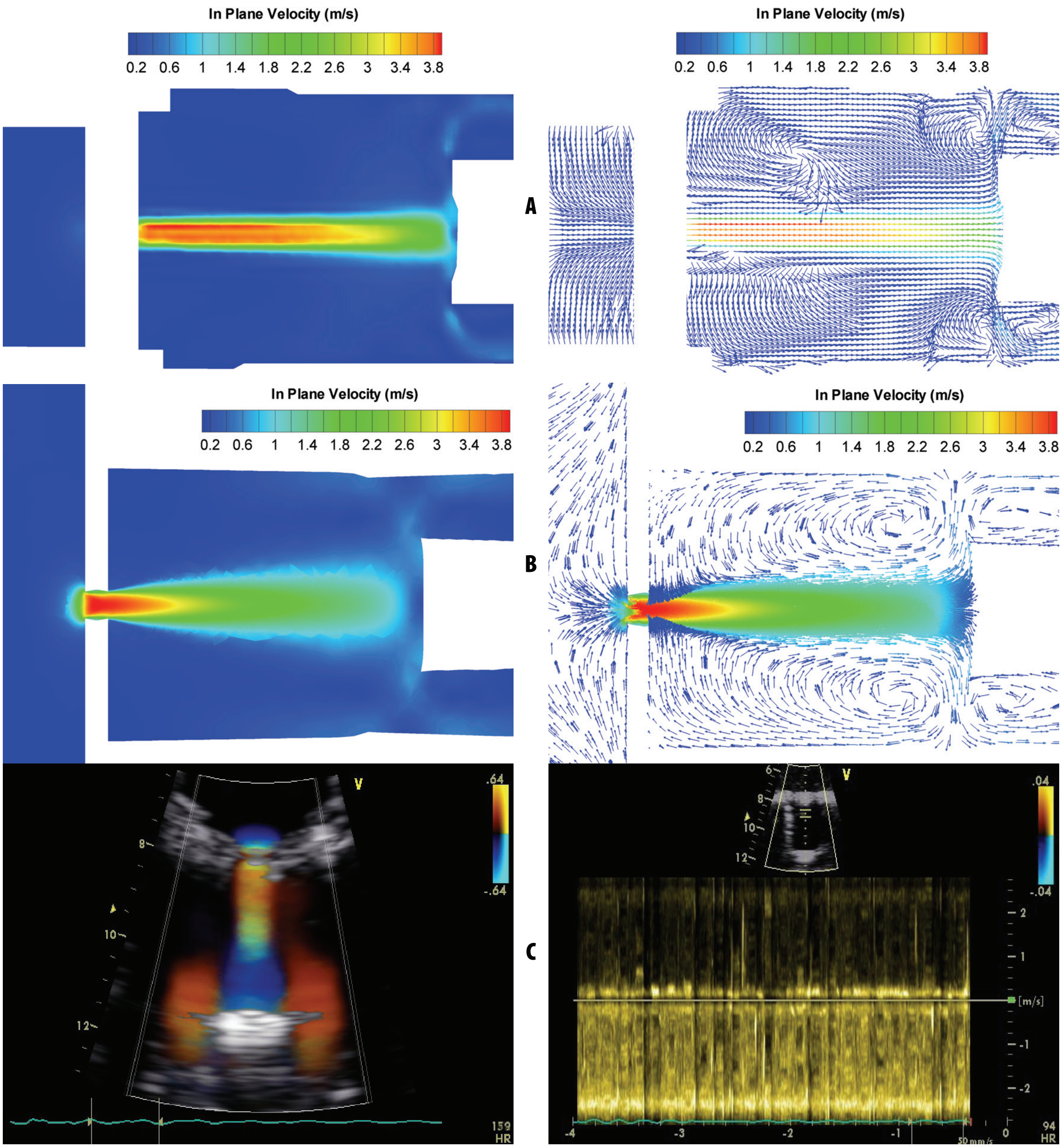

Fig. 7 *Velocity profile results obtained by (A) PIV measurements B) CFD simulations and (C) 2D and pulsed wave Doppler Echocardiography measurements*

nomena:

- *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 color coded map obtained with 2D Doppler echocardiography in Fig. 7(C) represents velocities along the ultrasound beam and shows the jet and recirculation zones. The red colors represent the flow towards the transducer while the blue colors represent the velocity in the opposite direction. Due to aliasing, the beginning of the jet is colored red. This means that the velocity at the beginning of the jet exceeded the maximum velocity of the color scale, resulting in inversion of the color scale in this

region.
The jet velocities obtained by PIV and CFD range from almost 4m/s when the jet leaves the 4 mm orifice and to about 0 m/s at the stagnation point at the back of the LA. With the 2D pulsed wave Doppler echocardiography investigation it is only possible to measure the velocity in a point. In this paper the velocity in the jet is measured at a distance from the orifice of one fourth of the atrium height. The velocity of the jet in that point is about 2.6 m/s which matches the velocity obtained by CFD. It can be noticed that the jet measured with PIV and 2D Doppler Echocardiography maintains a higher velocity than the jet in the CFD results. This might be due to the fact that the used k-ε turbulence model for incompressible flow uses the standard settings for turbulence intensity and turbulence length. Figure 8 shows the velocity distributions obtained by PIV and CFD at multiple distances from the orifice.
It can be noticed that the center of the developed vortexes in the LA are shifted to the top of the atrium. These vortexes will generate a backflow in the atrium which will amplify the jet stream generated by the leaking valve.

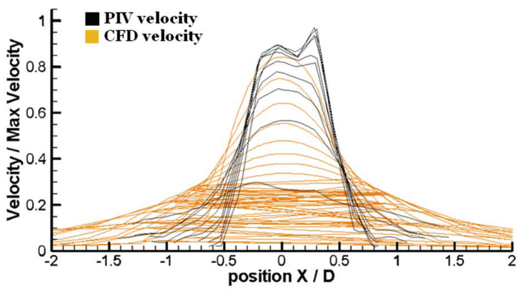

Fig. 8 *Velocity distribution obtained by PIV and CFD at multiple distances from the orifice*

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 2D normal speed PIV, 2D Doppler echocardiography and CFD. As working fluid a water-glycerin mixture was used which kinematic viscosity is three times higher than the kinematic viscosity of blood. The reason was to match the refractive index of the model in order to avoid image deformation.
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 measured PIV jet is maintained longer than in the CFD simulations. An explanation could be that the used turbulence model and its parameters are suboptimal for this model. Recommendations to future work will exist of trying to optimize the used CFD turbulence model, extension of the velocity measurements in 2D Doppler Echocardiography and a comparison of the obtained velocity jet data with the data of Reichardt [7].

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