Hemodynamic insights of bileaflet mitral prosthetic valve thrombosis: a CFD study

A. Dimasi[1], D. Piloni[1], L. Spreafico[1], M. Meskin[1], E. Votta[1], R. Vismara[1], G.B. Fiore[1], L. Fusini[2], M. Muratori[2], P. Montorsi[2], M. Pepi[2], and A. Redaelli[1]

[1] *Dept of Electronics, Information and Bioengineering, Politecnico di Milano, Italy; email:annalisa.dimasi@polimi.it*

[2] *Centro Cardiologico Monzino IRCCS, Italy; email:mauro.pepi@ccfm.it*

***Abstract*— Prosthetic valve thrombosis (PVT) is a serious complication affecting prosthetic heart valves. The mean pressure gradient derived from Doppler echocardiography used to diagnose PVT may result in false negatives, mainly in cases of bileaflet mechanical valves (BMVs) in mitral position. In this study, we implemented computational fluid dynamic (CFD) analyses to investigate a mitral commercial BMV using a fluid structure interaction (FSI) approach. Three different valve configurations were studied: a fully functional valve and two different stenotic conditions, characterized by one and two hypomobile leaflets, respectively. The fluid dynamic field across the valve was analysed, showing flow inhomogeneities and disturbances in the two stenotic configurations, particularly present in the asymmetric stenotic configuration. Such disturbances may be the cause for altered Doppler acquisitions and Bernoulli-derived mean pressure gradient in patients.**

***Keywords*— Prosthetic valve thrombosis, Bileaflet mechanical valves, Computational fluid dynamics, Fluid-structure interaction.**

I. Introduction

PROSTHETIC valve thrombosis (PVT) is a serious complication of prosthetic heart valves. It consists of a thrombus or pannus formation that hinder the movement of the valve leaflets. In bileaflet mechanical valves (BMVs), the thrombus can involve one leaflet or both, up to complete orifice obstruction. PVT has an incidence of 6% per patient-year, with higher frequency in mitral position [1] and an associated mortality of 10% [2]. The *mean pressure gradient* (MPG) is the diagnostic index derived from transthoracic Doppler echocardiography used to diagnose PVT [3]. Clinical studies [4] revealed that the MPG may result in false negatives in the detection of PVT in BMVs (Doppler silent thrombosis).

In the present study, computational fluid dynamic (CFD) analyses were implemented to simulate the hemodynamics of a commercial BMV in different configurations, replicating well-functioning as well as PVT conditions. Indeed, CFD analyses of complex flow field, such as those across BMVs, can help elucidating on the clinical paradox of Doppler silent thrombosis.

II. Methods

A. Bileaflet mechanical valve configurations

In this study, the Sorin Bicarbon Fitline size 25 mm (Sorin Group SpA, Italy) used in mitral position, was investigated by means of CFD analyses. Three different valve configurations (Fig. 1) were identified for the study:

- well-functioning valve (N60), with a symmetric leaflet opening angle of 60°;
- stenotic symmetric valve (SS35), with a symmetric leaflet opening angle of 35°;
- stenotic asymmetric valve (SA57), with one leaflet open at 57°, and the second leaflet completely closed.

SS35 and SA57 represent two equivalent conditions of PVT as for valve obstruction (flow area reduced by 50%), but characterized by different configurations that replicate PVT affecting only one leaflet (SA57) or both (SS35).

FIG. 1. Valve configurations: a) well-functioning valve (N60), b) dysfunctional symmetric stenosis (SS35), and c) dysfunctional asymmetric stenosis (SA57). Opening angles of the leaflets are shown.

B. CFD models

Simulations were performed with the finite volume solver ANSYS Fluent v14.5 (Ansys Inc, USA) using the grid deformation method integrated with a strongly-coupled ALE-based fluid structure interaction (FSI) approach [5]. CFD models were implemented replicating experimental testing conditions of the valve in a test bench developed by our group for testing mitral valves *in vitro* [6]. The valve is housed into an atrial-ventricular system (Fig. 2) comprising the valve housing, the atrial and ventricular chambers, an inlet conduit connected to the atrial chamber and an outlet conduit, corresponding to the pump connection in the experimental set-up. A flow straightener downstream of the inlet stabilizes the flow entering the atrial chamber.

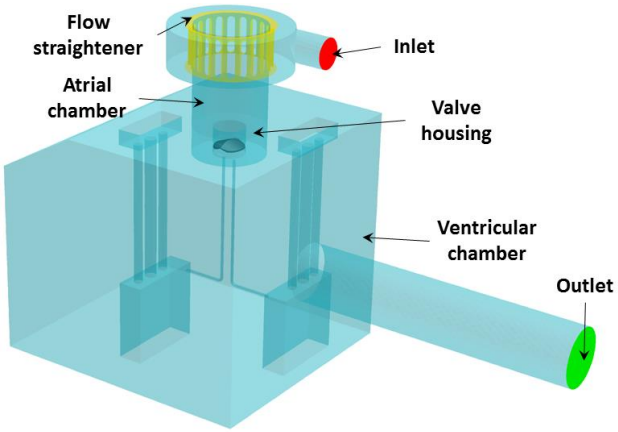

FIG. 2. Model of the test bench housing the BMV. The valve housing is located between the atrial and ventricular chambers. Inlet and outlets conduits, as well as the flow straightener are shown.

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The fluid domain was discretized with 4.5 10^6 tetrahedral elements in Meshing (Ansys Inc, USA). The flow straightener was treated as an effective porous zone with permeability and inertial coefficients derived from experimental characterizations. The fluid was modeled as Newtonian and incompressible with rheological properties of blood (1060 kg/m^3 density and 3 mPa s dynamic viscosity). A physiological transmitral flow rate derived from the normal tracing of a continuous wave Doppler of a stable patient with a Sorin Bicarbon Fitline in mitral position was imposed at the inlet, and zero pressure was set at the outlet. The valve leaflets were modelled as rigid bodies with one degree of freedom (the rotation around the axis passing through the hinges), whose angular acceleration was computed from local pressure distributions through user-defined subroutines. Kinematic constraints were applied to control the opening configurations of the valve (N60, SS35 and SA57). The entire cardiac cycle (0.8s) was simulated with a time step of 0.02 ms.

III. RESULTS

In N60, the flow through the valve is well distributed in the three orifices, determining the typical triple-jet structure of bileaflet MVs (Fig. 3A), with peak velocity (about 2 m/s) within the normal range of mitral prosthetic valves.

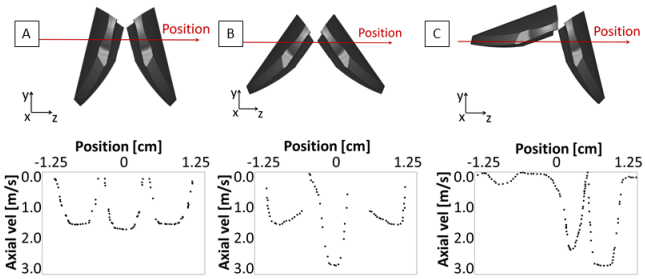

FIG. 3. Velocity profiles in the mid-section plane of the valve at the instant of peak flow rate: A) N60, B) SS35, C) SA57.

Flow inhomogeneities are observed in the SS35 model, while significant flow disturbances are present in the SA57 model (Fig. 3B,C). The latter are also observed by the pathlines at the instant of peak flow rate (Fig. 4).

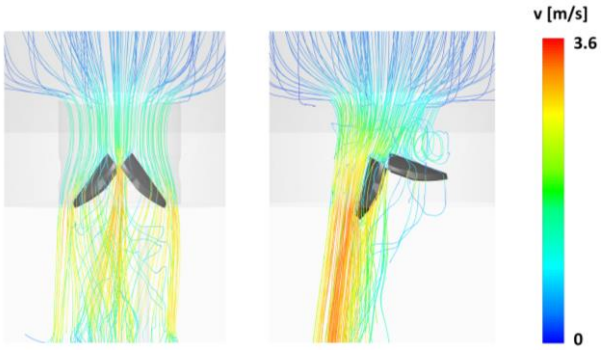

FIG. 4. Pathlines across SS35 and SA57 models at the instant of peak flow rate.

Such disturbances result in higher pressure drops monitored across the SA57 valve, as reported in Table I, in which average (time-averaged over the diastolic period) and maximum pressure drops are reported for the three models.

TABLE I
AVERAGE AND MAXIMUM PRESSURE DROP ACROSS THE VALVE DURING THE DIASTOLIC PERIOD.

	Average ΔP [mmHg]	Max ΔP[mmHg]
N60	6.38	12.60
SS35	19.73	38.73
SS57	22.56	56.57

Interestingly, the two stenotic configurations, despite having the same flow area are characterized by two different hydraulic resistances, with higher pressure drops in SA57 model. Both SS35 and SA57 reported high pressure drops (average ΔP) which would be classified clinically as PVTs (average ΔP >8 mmHg). However, as shown in Fig. 3, the fluid jets of the stenotic configurations (mainly the asymmetric one) are characterized by flow disturbances, which may affect the *in vivo* estimation of the mean pressure gradient by Doppler, in which the Bernoulli approximation is used to derive pressure drops from acquired velocities. In this context, the use of the mean pressure gradient as an index for diagnosing PVT should be carefully evaluated and analysed.

IV. CONCLUSION

In this study, we implemented CFD analyses of BMVs in normal and stenotic configurations using a FSI in-house developed approach. CFD analyses allowed to evaluate flow distributions and hydraulic resistances of different valve configurations. From CFD computed pressure drops, both the stenotic configurations analysed would be classified as thrombotic (mean pressure gradient > 8 mmHg). However, it may be claimed that flow disturbances arising in stenotic valves could alter the estimation of pressure drops with Doppler acquisition and Bernoulli approximation. To this end, future studies will involve Doppler acquisitions in *in vitro* tests of BMVs, to better elucidate on the paradox of Doppler silent thrombosis.

REFERENCES

[1] F.M. Caceres-Loriga, et al., "Prosthetic heart valve thrombosis: Pathogenesis, diagnosis and management". Int. J. Cardiol. vol. 110, pp. 1–6, 2006. doi:10.1016/j.ijcard.2005.06.

[2] R. Roudaut, et al., "Thrombosis of prosthetic heart valves: diagnosis and therapeutic considerations." Heart vol. 93, pp. 137–42, 2007.

[3] W.A. Zohgbi, et al. "Recommendations for Evaluation of Prosthetic Valves With Echocardiography and Doppler Ultrasound. A Report From the American Society of Echocardiography's Guidelines and Standards Committee and the Task Force on Prosthetic Valves, Developed in Conjunction." J. Am. Soc. Echocardiogr. vol. 22, pp. 975–1014, 2009.

[4] M. Muratori, et al. "Feasibility and diagnostic accuracy of quantitative assessment of mechanical prostheses leaflet motion by transthoracic and transesophageal echocardiography in suspected prosthetic valve dysfunction" Am. J. Cardiol. vol.97, pp. 94–100, 2006.

[5] A. Redaelli, et al. "3-D simulation of the St. Jude Medical bileaflet valve opening process: fluid structure interaction study and experimental validation" J. Heart Valve Dis. vol.13, pp. 804-14, 2004.

[6] R. Vismara, et al., "A pulsatile simulator for the in vitro analysis of the mitral valve with tri-axial papillary muscle displacement" Int. J. Artif. Organs vol. 34, pp. 383–391, 2011.

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