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A New Index Measured by Cardiovascular Magnetic Resonance Imaging to Detect Mechanical Heart Valve Malfunction

J. Garcia, O. Marrufo, A.O. Rodriguez, P. Pibarot and L. Kadem

Abstract -- **More than two thirds of valve replacement operations performed each year used mechanical heart valve. These valves are subject to complications such: pannus and/or thrombus formation. One other potential complication is a malfunction in one of the valve leaflets. It is then important to develop parameters that will allow a non-invasive diagnosis of such valve malfunction. In the present study, we evaluated under steady low flow (1-8 L/min) and pulsatile flow (3, 5 and 7 L/min) a bileafleat mechanical heart valve with normal function, 50% and 100% of one valve leaflet malfunction. Image analysis was performed using cardiovascular magnetic resonance imaging to evaluate transvalvular pressure gradients (TPG), effective orifice area and a new index given by central/lateral velocity ratio downstream of the valve. Our results showed that the flow upstream and downstream of the defective valve is highly influenced by malfunction severity. TPG did not allow differentiating valve malfunction at low flow under steady and pulsatile conditions. However the new index given by central/lateral ratio allowed differentiating the presence of valve malfunction using a single transverse velocity measurement.**

I INTRODUCTION

Approximately 250,000 valve replacement operations are performed annually around the world and more than two thirds of these operations use mechanical heart valves (MHV) [1]. However, these valves are subject to complications such as pannus and/or thrombus formation causing malfunction in one or both valve leaflets. MHV malfunction has an incidence of 0.2-6% patients/year [2] and prevalence for pannus ingrowth of 0.14-0.65% patients/year [3]. MHV malfunctions are life-threatening events that require emergency surgery and may be masked in presence of low cardiac output. It is then relevant to define a method for accurately detecting MVH malfunction.

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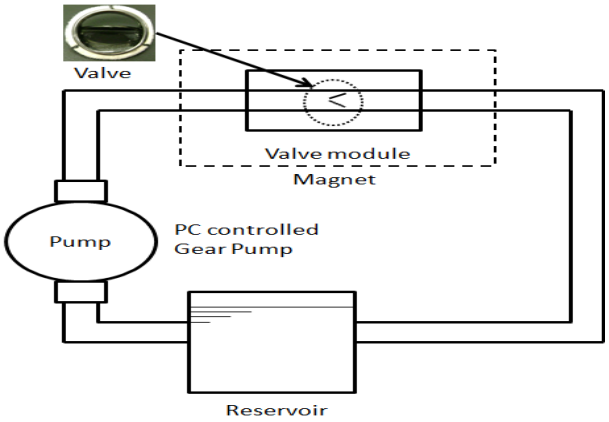

Figure 1. Schematic representation of the mock flow model.

Although Doppler echocardiography is predominantly used to study blood flow dynamics in the heart and great vessels and to assess cardiovascular diseases; this technique however does not provide satisfactory results in about 20-30 % of the patients due to inadequate acoustic window, angle-dependency of flow velocity measurement and other technical pitfalls [4, 5]. It is often not enough efficient in detecting and quantifying these malfunctions if the transvalvular gradient is high due to an intrinsic dysfunction of the prosthesis or to a localized benign phenomenon due to the specific geometry of bileaflet mechanical valves [6]. When Doppler echocardiography suggests the presence of valve malfunction a cinefluoroscopy study is usually performed to confirm valve motion of both leaflets [7].

A recent numerical study suggests that phase-contrast cardiovascular magnetic resonance (CMR) imaging may be useful to characterize MHV function [8]. Cardiovascular magnetic resonance imaging (CMR) techniques may help to overcome Doppler echocardiography limitations because it enables the acquisition of the complete flow map within the heart and great vessels. Hence, CMR may allow for an accurate description and quantification of blood flow pattern in a variety of pathological conditions [9-12]. In particular, information about the flow velocity and volume is crucial for the assessment of valvular hemodynamic.

The aim of this study was to examine the viability of CMR to detect in vitro MHV malfunctions at steady low flow conditions and under pulsatile flow conditions.

II METHOD

Experimental Setup

The in vitro setup consisted of a PC controllable pump generating steady flow (1 to 8 L/min) and pulsatile flow (3, 5 and 7 L/min, systolic time = 300 ms and heart rate = 70 bpm), a compatible module with CMR 3T magnet, a valve module to introduce a MHV in the testing zone and a fluid reservoir (Figure 1). Flow rate was measured with a Transonic flow probe 16A415 (accuracy: ±4%, on full scale) connected to a T206 Transonic flowmeter (Transonic, USA) and was calibrated using a standard flow measuring method. A 65% saline and 35% glycerine (in volume) solution at room temperature was used to mimic viscous proprieties of blood at 37°C [13]. The use of such Newtonian fluid is justified by the fact that blood behaves like a Newtonian fluid in the ascending aorta [14-16].

Flow Imaging Experiments

A bileaflet MHV (St Jude Medical Inc, MN, USA) with an inner diameter of 25 mm was placed in the CMR valvular module. Steady and pulsatile flow rates were applied to a normal and partial valve malfunction of 50% and 100% leaflet opening restriction for one leaflet effective orifice area (EOA). Malfunction was generated using epoxy resin (ITW PolyMex S.A de C.V, Mexico) to mechanically block one leaflet. The testing zone was placed at the center of the magnet during the tests and all data were collected with the use of a clinical 3 Tesla magnetic resonance scanner with a dedicated phase-array receiver coil (Achieva, Philips Medical Systems, Best, Netherlands). An ECG patient simulator (model 214B, DNI Nevada Inc, USA) was used to synchronize scanner gating with the PC controllable pump. A standard examination was performed by initial acquisition of SSFP cine images in standard longitudinal and transverse plans for acquisition planning. Phase-contrast retrospective examination was performed in standard transverse plans 12 mm upstream and 10 mm downstream of to the MHV plan and longitudinal plan perpendicular to the leaflets (Figure 2). CMR imaging parameters consisted of: TR/TE of 17.99/3.97ms, flip angle 15°, 50 phases, pixel spacing 1.66 mm, slice thickness 10 mm, acquisition matrix of 256x256 and encoding velocity (2 × maximal velocity).

Velocity Measurements

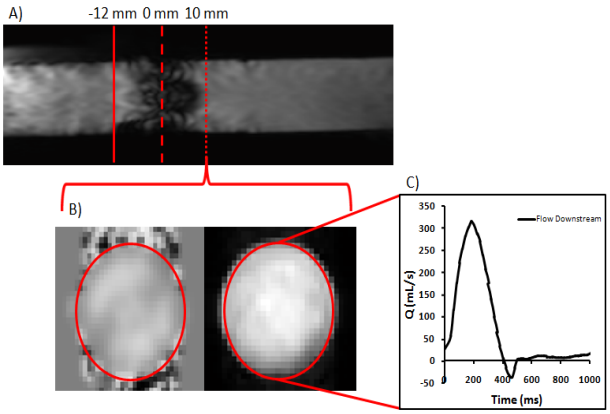

Figure 2. Velocity flow acquisition plans. Panel A shows the longitudinal plan of the mechanical heart valve used for planning and for velocity measurements in the flow direction. Panel B shows the transverse plan images of phase (velocity) and magnitude at 10 mm downstream the valve. Panel C shows the transvalvular flow rate measured in the region of interest defined on red for a normal mechanical heart valve under pulsatile flow conditions.

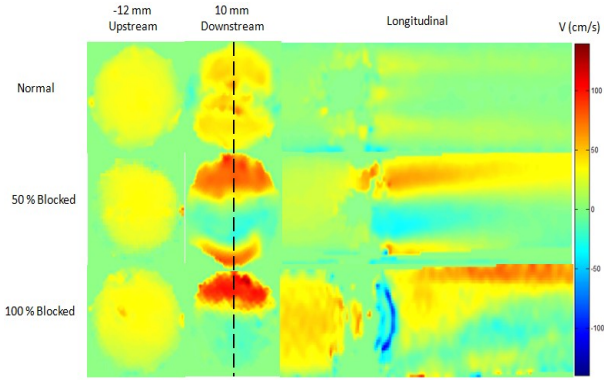

Figure 3. Longitudinal and transverse velocity plans at 8 L/min steady flow for valve malfunctions. Dashed line shows the longitudinal location for velocity measurements.

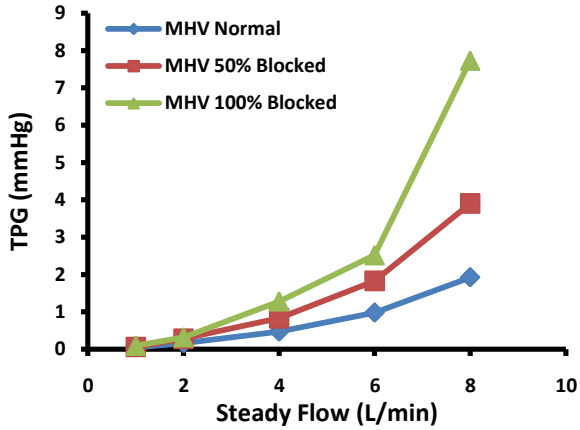

Figure 4.Transvalvular pressure gradient (TPG) measured at 10 mm downstream of the valve for different malfunctions under steady flow conditions.

A custom-made research application was developed using Matlab software (Mathworks, Natick, Ma) to process and analyze in vitro images [10]. Initial spatial resolution of CMR images (initial resolution: 1.66 mm) was artificially improved by a factor of four using a bicubic averaged interpolation (final resolution: 0.42 mm) and image stack was processed to filter background noise. All image data was analyzed with specially written Matlab programs (Mathworks, Natick, MA). Bernoulli's simplified equation was used to compute peak transvalvular pressure gradients (TPG):

$$TPG = V_{max}^2. \quad (2)$$

where V_{max} is the maximum velocity in m/s. Simplified continuity equation was used to compute effective orifice area (EOA) under pulsatile flow:

$$EOA = SV / VTI_{Ao} \quad (3)$$

where SV is the stroke volume determinated by 1/3 Simpson's rule and VIT_{Ao} is the velocity-time integral of maximal velocities downstream the valve at the aortic section. Furthermore, a new index given by central and lateral velocity ratio was also computed as parameter for evaluating valve malfunction [8].

III RESULTS

Longitudinal and transverse velocity maps at different locations with a flow rate of 8 L/min are shown in Figure 3. The dashed line represents the location where long-axis measurements were taken. It was possible to differentiate flow patterns from valve malfunctions in all planes. A plot of TPG vs. steady flow rate is shown in Figure 4. In general, we observed that TPG doubled for every 50% increase in valve malfunction. Central/lateral velocity ratios vs. steady flow by valve malfunction severity were plotted on Figure 5. Valve malfunctions induced a marked reduction in central/ lateral velocity ratio in transverse plan (Figure 5.A), 0.40 and 0.15 for 50% and 100% respectively and also in longitudinal plan (Figure 5.B), 0.35 and 0.15 for 50% and 100%, respectively. A plot of TPG vs. pulsatile flow rate is shown in Figure 6. Pulsatile TPG for valve malfunction relayed closer at low flow and started to diverge at normal and high flow rate. Central/ lateral ratios vs. pulsatile flow rate were shown in Figure 7 for transverse plan (panel A) and longitudinal plan (panel B). Longitudinal ratios were overshaped at low and normal flow rate and relatively closer for high flow rate. Using transverse plan not overlapping appeared for central/lateral ratios. Notice for both plans measurements malfunction ratio is clearly lower comparing with normal valve opening. Effective orifice areas computed using continuity equation were 2.15±0.19 cm^2, 1.31±0.04 cm^2 and 0.93±0.06 cm^2 for normal valve opening, 50% and 100% malfunction respectively.

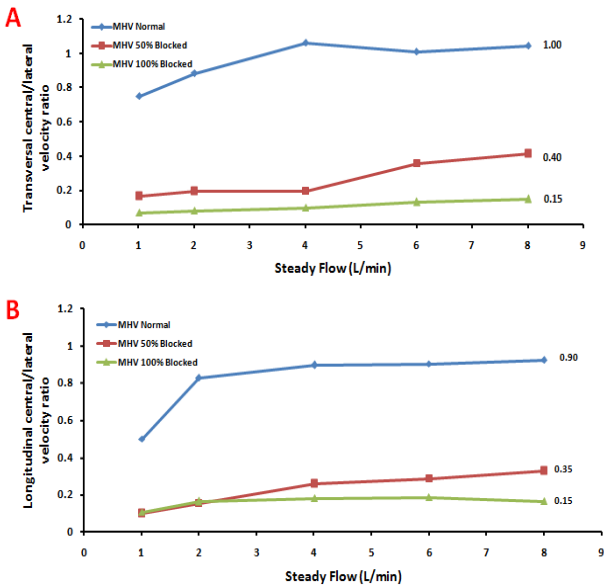

Figure 5. Central/lateral velocity ratios under steady flow conditions. Panel A shows the central/lateral velocity ratios using transverse plan at 10 mm downstream of the valve. Panel B shows the central/lateral velocity ratios using longitudinal plane at 10 mm downstream of the valve.

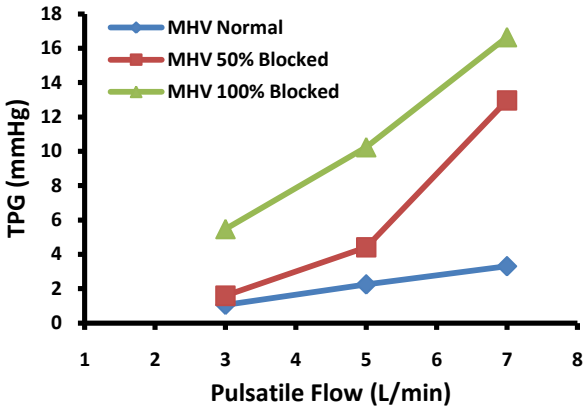

Figure 6.Transvalvular pressure gradient (TPG) measured at 10 mm downstream of the valve for different malfunctions under pulsatile flow conditions.

IV DISCUSSION

This in vitro study showed that TPG is significantly increased in the presence of valve malfunction. However, the values obtained were not clinically significant (TPG > 40 mmHg) [7]. This could be explained by the load used on this study that did not consider physiological pressures and aortic compliance. However, this model is enough for preliminary

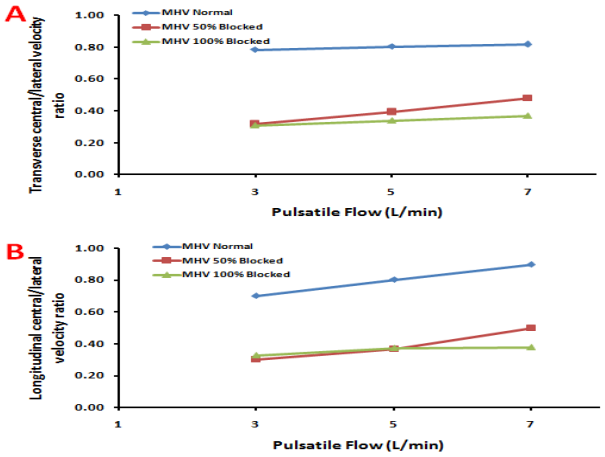

Figure 7. Central/lateral velocity ratios under pulsatile flow conditions. Panel A shows the central/lateral velocity ratios using transverse plan at 10 mm downstream of the valve. Panel B shows the central/lateral velocity ratios using longitudinal plane at 10 mm downstream of the valve.

analysis of flow patterns produced by valve malfunction. The results presented showed that at low flow rate TPG should not be used to evaluate potential valve malfunction because TPG remained closer to normal TPG. So TPG did not allow the valve malfunction differentiation. Interestingly, central/lateral velocities ratio may indentify MHV malfunctions. In particular, transverse velocity analysis allowed differentiating velocity ratios of valve malfunction. Velocity differences between short and long axis measurements could be explained by leaflets' turbulence, artefacts and pressure recovery phenomena. However, a larger in vitro and in vivo evaluation is required to validate this parameter under malfunction conditions.

The clinical relevance of this study is based on the fact that CMR may be used in substitution of cinefluoroscopy for the evaluation of valve motion and the evaluation of an eventual malfunction. Furthermore in comparison with the cinefluoroscopy CMR allows the hemodynamic evaluation of the valve at the same time and does not expose the patient to ionizing radiation. Importantly, CMR may be helpful to detect mild degree of dysfunction that is often difficult to identify with the use of conventional Doppler-echocardiography or cinefluoroscopic indices.

V CONCLUSIONS

In conclusion, cardiovascular magnetic resonance imaging assessment of flow patterns and central/lateral velocity ratio may allow the detection of mild to severe mechanical heart valve malfunction even at low flow rate. This new method may be useful to accurately identify mechanical valve dysfunction that is often life-threatening.

ACKNOWLEDGMENTS

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