Assessment of Transcatheter Heart Valve Migration and Embolization Risk Following Valve-in-MAC

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Abstract

Transcatheter Valve Embolization and Migration (TVEM) is a rare, but catastrophic event where the prosthesis moves due to heamodynamic forces acting on the frame. TVEM following Transcatheter Mitral Valve Replacement (TMVR) is largely undocumented. Haemodynamic forces cannot be estimated during pre-procedural planning and conventional imaging does not allow to compute them after replacement. To shed light on this issue, this study focusses on modelling haemodynamics after TMVR in 3 patients with Mitral Annular Calcification (MAC) known as Valve-in-MAC (ViMAC). Three-dimensional flow simulations are performed using the computational fluid dynamics (CFD) package STARCCM+. Results of the simulation are processed to compute the fluid forces acting on the device and pressure gradients in the left ventricular outflow tract (LVOT). Anatomical measurements are performed on CT data sets to assess the mitral valve size and shape, the extent and location of the calcification and the size of the LVOT after implantation. Our results show that the force distribution on the device is largely influenced by LVOT anatomy and contraction patterns.

1. Introduction

Transcatheter mitral valve replacement (TMVR) is a minimally invasive technique performed via the groin where a bioprosthetic heart valve is placed inside the mitral annulus, often to resolve mitral regurgitation (MR). Transcatheter Valve Embolization and Migration (TVEM) is a rare, but serious event where the prosthesis dislodges and moves into the left atrium or left ventricle, during or immediately after the procedure. TVEM is associated with a four-fold higher mortality and three-fold higher stroke rate at 30 days' post transcatheter heart valve replacement [1]. Reports on Transcatheter Aortic Valve Implantation (TAVI) have shown that TVEM increases the 1-year mortality rate from 14.6% to 38.5% [2]. Heamodynamic forces acting on the device play an important role in TVEM. However, TVEM for TMVR is largely undocumented. This study is focussed on the replacement of the mitral valve for patients with Mitral Annular Calcification (MAC) known as Valve-in-MAC (ViMAC). In cases of MAC the soft mitral annulus becomes covered in a solid layer of calcium salts, reducing its flexibility and potentially causing paravalvular leakage (PVL) [3]. This solid layer also reduces the size of the annulus and TMVR devices are therefore too large, in this situation transcatheter aortic valves may be considered for the mitral position. As aortic devices are small and circular, while the mitral annulus is large and saddle-shaped, this mismatch can increase the risk of TVEM. The aim of this study is to improve pre-procedural assessment for ViMAC using numerical models to predict heamodynamic forces acting on the valve and pairing imaging data to assess the risk of TVEM.

2. Methods

Full three-dimensional flow simulations are performed using the computational fluid dynamics (CFD) package STARCCM+. The end-systolic left ventricle endocardium is segmented for each case to create a patient-specific simulation domain in the form of a surface mesh. The endocardium deformation is tracked throughout the cardiac cycle using the medical imaging wall motion tracking software Eidolon [4]. Eidolon produces a new surface mesh for each CT frame and nodal positions are then interpolated between CT frames to a temporal resolution of 0.5ms. A CAD model of the bioprosthetic device is implanted into the domain at the position of the mitral annulus and the LVOT area is measured. This workflow allows us to simulated patient-specific blood flow during the cardiac cycle. Results of the simulation are finally processed to collect the haemodynamic forces acting on the device and other relevant metrics such as pressure gradients.

2.1. Patients

Three patients assessed for ViMAC at the Guy's and St Thomas' Trust dedicated transcatheter mitral valve clinic were selected. All patients exhibited severe symptoms of valvular disease and MAC. All three were deemed at high surgical risk, with two patients with acceptable levels of LVOT obstruction (LVOTO) and one deemed excessive. The baseline characteristics of the patients, referred to as VIM-1, VIM-2 and VIM-3 are summarised in Table 1. No patient had symptoms of unstable angina and all were appropriately revascularized prior to procedure.

Table 1- Patient Data

	VIM-1	*VIM-2*	*VIM-3*
Sex	Male	Female	Female
Heart Rate (bpm)	70	61	90
Ejection Fraction (%)	43	45	65
LV Length (mm)	67.6	74.7	59.5
LV diameter (mm)	26.1	29.1	29.4
Aortomitral Angulation (degrees)	113.1	108.9	130.5
Septal Distance (mm)	18.7	19.0	19.6
MAC Thickness (mm)	5.87	2.98	7.80
MAC Height (mm)	332.59	322.89	273.56

2.2. Image Processing

Segmentation of the LV blood pool was performed using MITKWorkbench. The mitral calcification around the annulus was also segmented and the resulting reduced mitral orifice measured. After embedding the CAD model of the bioprosthetic device into the LV mesh, the outflow tract reduced area was measured (Neo-LVOT). To ensure patient-specificity and validate the anatomical model, the LV length, diameter, aortomitral angle and septal distance are compared from CT to simulation domain.

Wall motion tracking was performed using a temporally sparse free-form deformation algorithm. Deformation of the endocardium was quantified as a vector field and interpolated to the surface mesh for each CT frame. LV length, diameter, aortomitral angle and septal distance measurements were taken again at each time interval to validate against image-derived measurements.

2.3. Device Modelling

A CAD model of the Sapien 3 bioprosthetic device was created in accordance to the device manufacturers specifications. The device multi-layered design was simplified to a single layered cylinder that matches height and diameter of the inner valve from the datasheet. The device was positioned in the annulus to achieve an extension into the ventricle equal to 50% of its total height, replicating its standard deployment in the procedure.

2.3. Simulation

Three-dimensional flow simualtions were performed using STARCCM+ (Siemens PLM). The final volume mesh of the LV with embedded CAD model of the Sapien 3 device comprised approximately 1.2 million elements. A mass flow condition based on the volume change derived from the wall motion tracking was prescribed on the mitral and aortic boundaries. The temporally-sparse free-form deformation algorithm for the motion tracking determines the ventricle surface and volume at every CT frame, which is then interpolated to the timestep on the simulation. The blood density was set to 1060 Kg/m_3, and the viscosity to $3.5\times10_{-3}$ $Pa\ s$.

3. Results

The forces on the valve was measured throughout the simulation alongside the momentum thrust and pressure. The maximum systolic pressure gradient (PG) and maximum force exerted on the valve both occurred during peak systole and are reported in Table 2. The maximum pressure gradient observed was below the clinically accepted threshold for LVOTO (50mmHg) in cases VIM-1 and VIM-2. However, VIM-3 showed a pressure gradient in excess of 80mmHg. The excessive gradient generated by the simulation is consistent with the clinical analysis of VIM-3 being rejected for TMVR due to excessive risk of LVOTO.

Table 2 - Results of systolic pressure gradients and the force acting on the valve frame

	VIM-1	*VIM-2*	*VIM-3*
Max Systolic PG LVOT (mmHg)	19.5	2.5	80.6
Max Force on Valve (N)	0.235	0.14	1.18

displacement and pressure can be seen in Figure 1. VIM-1 (left) and VIM-3 (right) shows a unidirectional aortic jet than VIM-2 (Fig. 1 A, G), while the momentum thrust pattern in VIM-2 suggests a loss of coherence in the aortic outflow with thrust directed not only towards the aortic valve but also to the inside of the mitral device frame (Fig. 1 D). The contraction patterns visualized through the tracked wall displacements show that in VIM-1 and VIM-3 the ejected flow is driven by a contraction originating in the anterior wall in the mid and apical regions, whilst in VIM-2 the contraction seems to occur predominantly in the basal region near the mitral valve (Fig. 1 B, E, H).

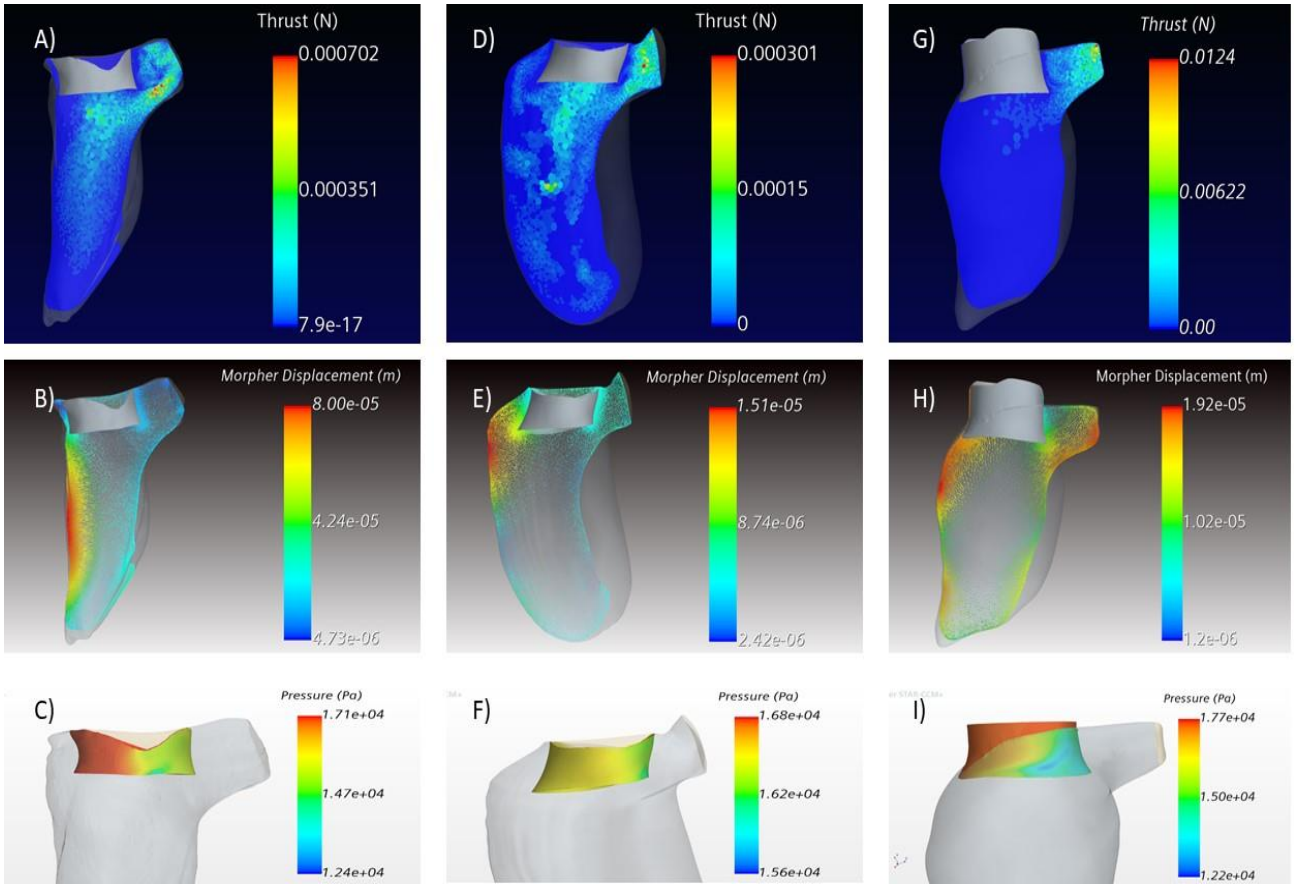

Figure 1 -visualisation of thrust, morpher displacement and pressure fields for VIM-1 (A-C), VIM-2 (D-F) and VIM-3 (G-I)

The maximum force exerted on the valve follows a similar pattern to the pressure gradient with VIM-3 exhibiting the maximum pressure gradient and force on the valve of the three patients at 1.18N. The systolic pressure gradient of VIM-1 is 7.8 times greater than VIM-2 and the gradient for VIM-3 is 32 times greater. The force acting on the valve is 1.68 times greater for VIM-1 and 8.42 times greater for VIM-3.

Results for the visualization of momentum thrust, wall

The maximum value of thrust is proportional to the pressure gradient and hence the maximum aortic jet velocity for all patients and is 7e-4N, 3e-4N and 1.2e-2N for VIM-1, VIM-2 and VIM-3 respectively.

The pressure distribution on the valve surface shows a large gradient from the anterior to the posterior side of the valve frame in cases VIM-1 and VIM-3 of 14.2 mmHg and 26.3 mmHg respectively (Fig. 1 C, I). However, in VIM-2 the pressure distribution is uniform across the whole frame (Fig. 1 F), with a gradient of 1.5mmHg.

5. Discussion

The study confirmed a proportionality between the LVOT pressure gradient and the force acting on the valve for all patients, as expected. Therefore, consideration to the level of obstruction, which is in turn proportional to the pressure gradient in the LVOT [5] could potentially be used as surrogate metrics to identify the risk of TVEM during image-based preprocedural assessment. The study also found that the contraction pattern of the myocardial wall has a significant impact on direction and momentum of the aortic jet. This parameter can be derived from multi-phase CT scans and thus assessed prior to TMVR. However, a larger in-silico cohort is needed to define thresholds values and precise contraction features that can result in excessive thrust on the valve, with the present explorative study only highlighting a mechanistic explanation for the haemodynamics observed in a limited case series.

The pressure gradient observed in the outflow tract is inversely proportional to the Neo-LVOT area measured for each patient, consistent with previous clinical and computational studies. Due to the conservation of momentum, a reduced outflow tract area will increase the free-stream velocity and hence the pressure gradient between the ends of the aortic jet. The force acting on the valve however, showed a proportional increase from VIM-1 to VIM-2 (VIM-3 PG and force is 4 times that of VIM-1) but exhibited a higher than expected value for VIM-2. Possibly the force acting on the valve is increased by the aortic jet sweeping up into the device frame as a result of an abnormal contraction pattern observed for this patient. We hypothesise therefore that during preprocedural assessment it is not only important to analyse the pressure gradient increase as a result of obstruction, but also to consider the contraction pattern and resultant ventricular dynamics for a specific patient.

6. Limitations

The sample size of the study is limited to three patients and thus further studies in larger cohort are needed to generalise our conclusion. The Sapien 3 prosthetic device used in these simulations has been approximated to a simple non-rigid cylinder with limited dynamic change throughout the cardiac cycle. Inclusion of a more detailed structure of the frame and different material components would potentially result in a more precise distribution of the forces on the device. Finally, the endocardium of the left ventricle has been smoothed and papillary muscles excluded to reduce the complexity of the mesh and the associated increase in computational time, therefore reducing flow disturbances that can be attributed to the valve implantation. The accuracy of the ventricle volume and motion is also limited by the temporal resolution of the CT scan, which in these cases includes 10 frames.

Acknowledgments

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