Stereo High Speed PIV Measurements behind two different Artificial Heart Valves

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Abstract   The flow behind artificial prosthetic heart valves (PHV) is assessed in order to innovate designs for better qualitative and quantitative performance. One of the major problems is still blood damage, due to the interaction with the valve. It is of high clinical importance to optimize shear stresses loading, avoid cavitation and minimize the backflow. Moreover, various heart valve types have different efficiency, beside others, mostly given by the quality of the flow in all regions across the valve. The flow is highly unsteady and turbulent, therefore it is needed to obtain detailed, high resolution, flow field results in order to assess existing or create new PHVs to achieve better valve hemodynamics. Particle Image Velocimetry (PIV) is already a widely accepted experimental technique for visualization of the flow behind the PHVs in even two-dimensional vitro conditions. Extending this promising technique with the latest developed hardware we were able to achieve the 3rd velocity component in high resolution time scale. Two high speed cameras in a stereo setup allow the measurement of all three velocity components as a function of time. For our study we fixed a PHV into a silicone mock aorta. This aorta was specially designed to mimic the human anatomy and elasticity. A modified, commercially available, Vivitro mock loop was used to simulate the human blood circulatory system. Stereo High Speed Particle Image Velocimetry (SHSPIV) was monitoring the flow 50 mm downstream the valve plane. A Nd:YLF high-repetition-rate double-cavity laser was combined with two high frame rate CMOS cameras getting a detailed acquisition of the time-dependent flow structure behind the valve. The aim was to compare a clinical bileaflet and a prototype of a monoleaflet tilting disc valve. The results confirm the existing of a complex three dimensional mixing flow. Typical three jet streams flow pattern for bileaflet valve is presen, while the flow behind the monoleaflet is more turbulent with one major and one minor jet stream. The measured velocity values of component in z axis are almost three times higher in the monoleaflet compared to the tested valve.

1. Introduction

Since 1950 more than eighty different models of the artificial prosthetic heart valves (PHV) have been developed. There are two major groups of PHVs, biological and mechanical. Biological valves or bioprosthesis, have limited life time because of calcification, in contrast with the durability of mechanical PHV. Nevertheless the mechanical durability is satisfactory, the performance of the valve is still less than natural heart valves. The opening mechanisms of PHVs are quite different compared to the human one and thus the flow through the valve differs. Thubrikar et al. (1979) already identified the important role of the opening mechanism of heart valves doing in vitro experiments in dogs. There are basically three systemically different types: cages ball, monolealfet and bileaflet valves. Monoleaflet and bileaflet valves are commonly used in clinic for the aortic heart valve replacement. Bileaflet have less thromboembolic complications compared to the monoleaflet and this is one of the reasons why they are more often used, but the need a life-ling coagulation treatment. There are several different designs of both bileaflet and monoleaflet models available on the market, but optimal hemodynamic solution is not available yet. One of the newer bileaflet models is the ATS valve (Advancing The Standard, Minneapolis).

Therefore we used to use this valve as a reference to compare to recently developed new monolaflet prototype.

Particle Image Velocimetry (PIV) is already a well established and accepted technique to investigate the flow behind the PHVs in vitro conditions. Standard PIV technique is determining the results of velocity in a plane and gives information about velocity components u, v and out of that absolute velocity. The measurement frequency, depending on the resolution, reach maximum of 8 Hz. Therefore the results are mostly presented as statistical average of chosen amount of instantaneous PIV measurement acquired in a phase locked mode. This method is mostly used because of comfortable and cheap financial and time costs. However, the highly unsteady flow behind PHV is expected to be turbulent and thus 3 dimensional. In order to catch this character, 2nd camera is added, to enable so called Stereo PIV technique, which is applied to gain also 3rd velocity component w. Castellini et al. (2004) used stereo technique to reveal the 3rd velocity component. The common characteristic for latter methods is the statistical result, respectively an average over a hundreds of instantaneous flow fields computed in a phase locked measurement. This way we have the information about flow development in general. Due to the cyclic pumping of the ventricle, the valve opens and closes, leading to a pulsatile flow in arterial and pulmonary circulation and across the valves. Therefore the real instantaneous velocity field may significantly differ from the statistical average. To identify the value of velocity fluctuation at entire ROI we calculate standard deviation over all measurement. Recent development of the technology enables to acquire instantaneous flow field with frequencies higher than 1500 Hz. The cameras are used for technique High Speed Particle Image Velocimetry (HSPIV). The latter technique was employed to investigate the flow through heart valves by Pierrakos et al. (2004), Akutsu et al. (2005) and Kaminsky et al. (2006). Since typical frequency of human heart in rest condition is 55 to 75 Hz, with HSPIV is possible to visualize the entire cycle of heart beat in a continuous time resolved way. In order to obtain three component velocity vectors in detailed time resolved domain, we used two high speed cameras to perform Stereo High Speed Particle Image Velocimetry (SHSPIV). This technique should reveal the truly flow behavior behind a PHV.

2. Materials and methods

In this experimental study a commercial heart valve tester Vivitro pulse duplicator (VIVITRO SYSTEM INC., Canada) simulating heart and peripheral blood circulation was modified. The modifications were done in order to allow inserting a silicone mock aorta with a diameter of 28 mm, which was designed by Simons (2002) to mimic the anatomy and the elasticity of the human aorta. The pulse duplicator was running with the frequency of 72 Hz. Left ventricular and aortic and ventricular pressures were monitored with Labview (National Instruments, Austin) custom programmed software receiving signals from SETRA (SETRA Systems, Boxborough) pressure sensors. Below the aortic valve an electromagnetic flow meter (VIVITRO SYSTEM INC., Canada) was measuring the volume flow. The heart valves were fixed to the aorta by clamping with cable tie. The cable tie was tightly wrapped around the valve's orifice and silicone wall of the aorta was pressed in between. In these circumstances the valve was in a fixed position relative to the mock aorta but relatively free to the other components of the mock loop. The aorta was emerged in a chamber filled with fluid under certain pressure acting like compliance of the surrounding organs of the human body.   As the working fluid we used a 38% glycerin/water solution, which has a similar dynamic viscosity as the human blood. The running frequency was approximately 75 bpm. The ratio systole to diastole 35/65 was propagated corresponding to a stroke volume of 63.7 ml.

The Stereo High Speed Particle Image Velocimetry (SHSPIV) measurements were performed with CMOS chip based cameras Photron APX RS (Photron Limited, Marlow) having a maximum

resolution of 1024x1024 pixel at 3000 frames per second (fps). Due to the limited hard drive size, the recording time was only 1.365 s. Since the duration of 1 cycle is 0.833 s, we recorded approximately 1.63 cycles. A Nd:YLF double-cavity laser New Wave Pegasus (New Wave Research, Fremont) was synchronized via the synchronizer (ILA GmbH, Jülich). Each cavity is able to reach a maximum energy of 10mJ at a repetition rate of 1 kHz. The laser beam was guided through an articulated mirror arm to the light sheet (LS) optics. The LS was placed in the central plane of the mock-up, parallel to the flow direction. The PIV setup is shown in Figure 1.
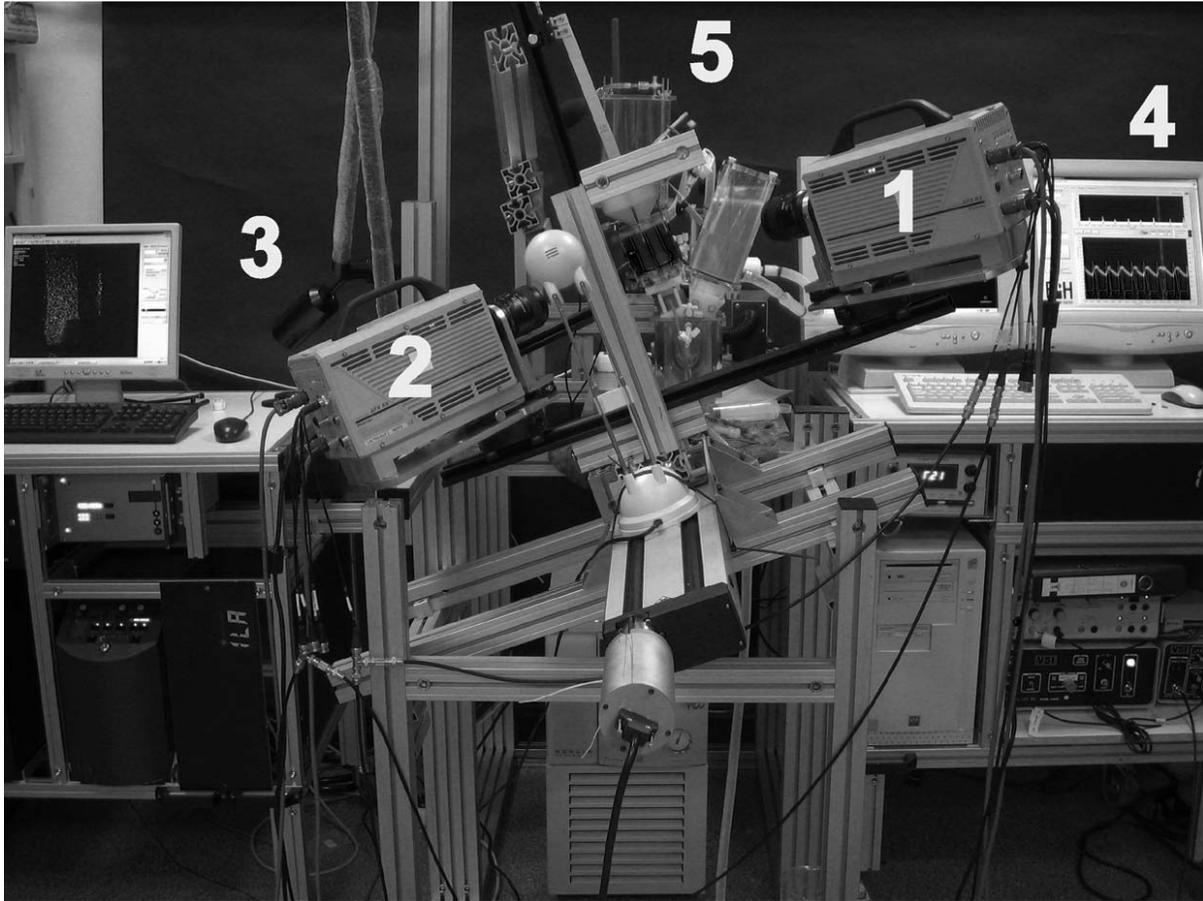

Fig. 1. Stereo High Speed PIV set up applied on a heart valve duplicator (Number 5). Number 1 and 2 are both cameras, number 3 stands for maser unit and synchronizer and number 4 is pressure and flow monitoring equipment.

To ensure equal start of the measurement sequence for both valves, the acquisition was externally triggered receiving a 5V signal from the pump. The sequence started at the end of diastole.

The chosen region of interest (ROI) was 40x30 mm behind the valve plane (Fig. 2). The resolution of the camera was set to 1024x512 pixels. The calibration of the images was performed with a planar target with a printed crosses 3 mm from each other in x and y axis. The crosses were printed in a matrix form with 10 crosses in x and 13 crosses in y direction. The target was coupled to precise micro traverse unit in order to calibrate the images in a z axes as well. The cameras were set to each other orthogonally but in 45° oriented to the measurement plane. To achieve scheimpflug conditions the CMOS chip has to be tilted against the objective. Therefore the cameras were mounted on a specially designed scheimpflug tilt adapters. To increase the accuracy, resolution, of the measurement close to the aortic wall and leaflets of the valve we were working with red fluorescent micro spheres having a diameter of 50 μm, which were added to the flow as a seeding. The excitation wavelength of the laser λ_{exc}= 527 nm was return back from the particles in a range of

590 to 610 nm. In front of the CMOS chip of the cameras a red band pass filter was placed allowing to pass the light in a range λ=580-620 nm. This way we were able to avoid reflections of the aortic wall and leaflets and determine the velocities close to those structures. The chosen frame rate for the acquisition was 3000 fps which results in a measurement frequency of 1500 Hz. Due to the limited internal storage capacity of camera we were able to acquire only 1365 ms, which is about 1.78 cycles.
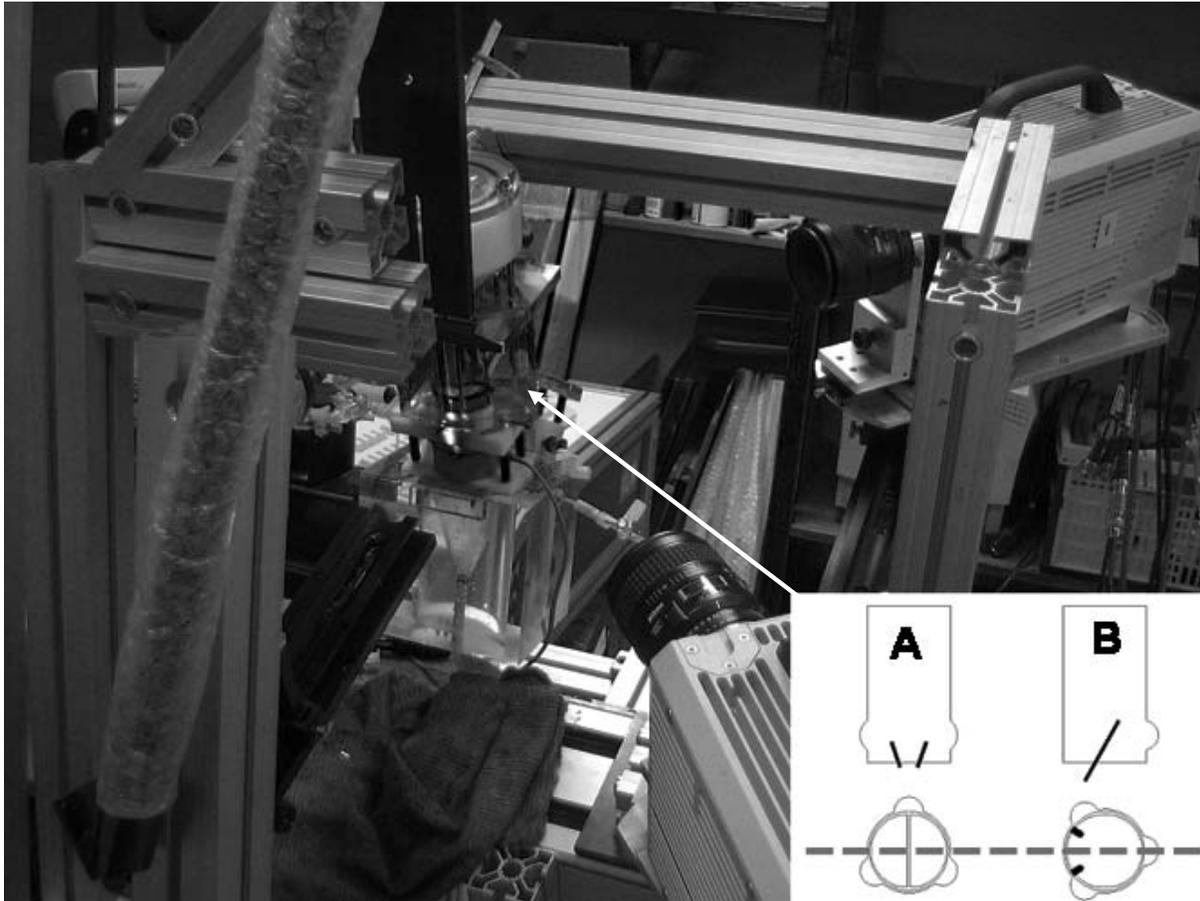

Fig. 2. Detailed view on the measurement section with orthogonally inclined cameras which are oriented to the ROI in angle of 45°. The respective measurement plane where the light sheet (dashed line) was placed is illustrated in the right bottom corner, case A stands for the bileaflet valve (ATS), case B for monoleaflet prototype. The sinuses of aorta are respectively oriented as preferred anatomical position for both bileaflet and monoleaflet prosthetic valve.

For the image processing and results evaluation a commercially available VidPIV (ILA, Jülich) software package was used. This image processing software includes, besides others, iterative window deformation described by Scarano et al. (2002, 2004) and Lecordier et al. (2003), B-spline grey value interpolation described by Thevanez et al. (2000), phase correlation described Wernet et al. (2005) and Whitaker peak fit described by Meijering et al. (2002). For the visual interpretation of the results we used commercially available Tecplot 10 software (Tecplot, Bellevue).

3. Results

The flow visualization through two different prosthetic aortic heart valves was performed by means of Stereo High Speed Particle Image Velocimetry (SHSPIV). The measurement acquisition was started 10 minutes after initializing the pulse duplicator. The mean aortic pressure drop was 40 mmHg. The standard deviation was less than 2 mmHg over 7 monitored cycles. The maximal and minimal aortic pressure values at the monoleaflet prototype (PROT) valve were approximately of 8 mmHg lower. We measured ventricular pressure drop in a range of 110 to 120 mmHg. The measured maximal systolic volume flow through the ATS was around 400 ml/min. The backflow during the closing of the valve was fluctuating between 160 and 220 ml/min. The maximal systolic flow through the PROT valve was reaching quite stable value of 400 ml/min and backflow of 160 ml/min with small deviation of maximum 10 mmHg (Fig 3). The mean stroke volume flow through the ATS was 61 ml and the same through the PROT. The mean leakage volume during the diastole phase through the bileaflet valve is 8.8 and through the monoleaflet valve 8 ml/min.
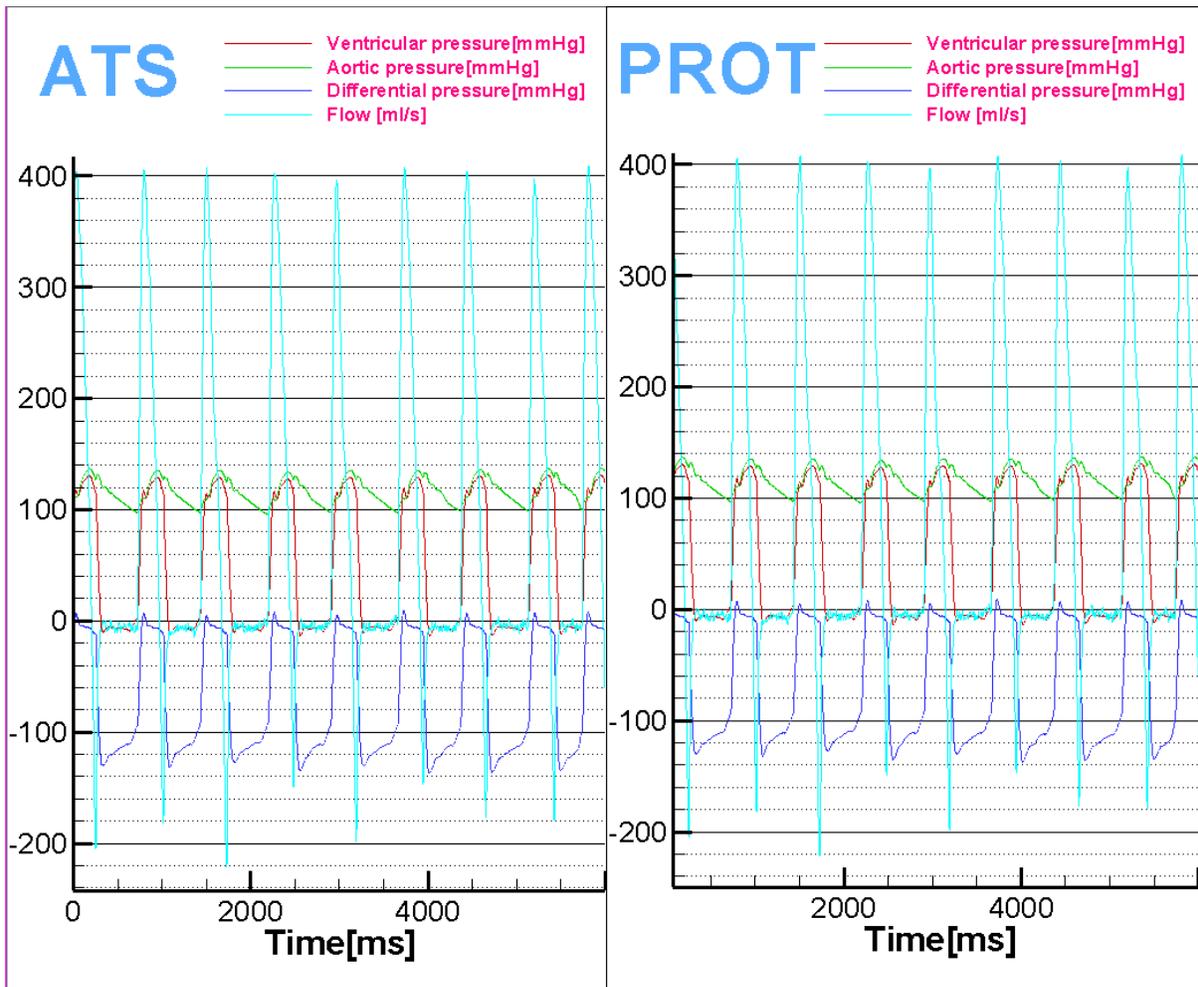

Fig. 3. Left ventricular and aortic pressures and flow plots of 7 monitored cycles for ATS on left panel and PROT valve right panel.

The maximum absolute velocities of the flow through the ATS valve don't exceed 1.3 m/s. The systole begins at a time 94 ms after measurement started. At a time 125.3 ms there is already two jet stream flow pattern built with the highest velocity of 1.2 m/s reached in the cores of the jets on left and right side of the aorta lumen. The central jet stream located between the leaflets starts to grow

at a time 128.6 ms, however the velocity doesn't exceed 1 m/s. The time of peak systole is 170 ms. At a time of about 180 ms the velocity in all 3 jet streams has got relatively same value of 1.05 m/sec. The deceleration phase is characterized by quite homogeneous velocity distribution with velocity values of 0.3 to 0.7 m/s in the lumen of the aorta. There are vortices created in the valsalva sinuses during the deceleration phase. The valve closed in the moment of 394 ms and the flow is rebound back to the lumen. Due to this wave like effect the leaflets are again shortly elevated and closed. After 600 ms the valve is completely closed. The velocities during the early diastolic phase reach in small locations maximum of about 0.3 m/s. Lower velocities are observed accross the orifice. The out of plane velocity vectors *w* reach value of ±0.4 m/s only as a local maximum in the valsalva sinuses during the beginning of the systole and closing of the valve. The values in the rest of the aortic lumen during the systole and diastole don't exceed 0.15 m/sec in positive neither negative *z* direction and in about 50% of the ROI are close to 0. Figure 4 displays velocity measurements captured during the acceleration phase for a time step of 4ms from beginning of the systole on.
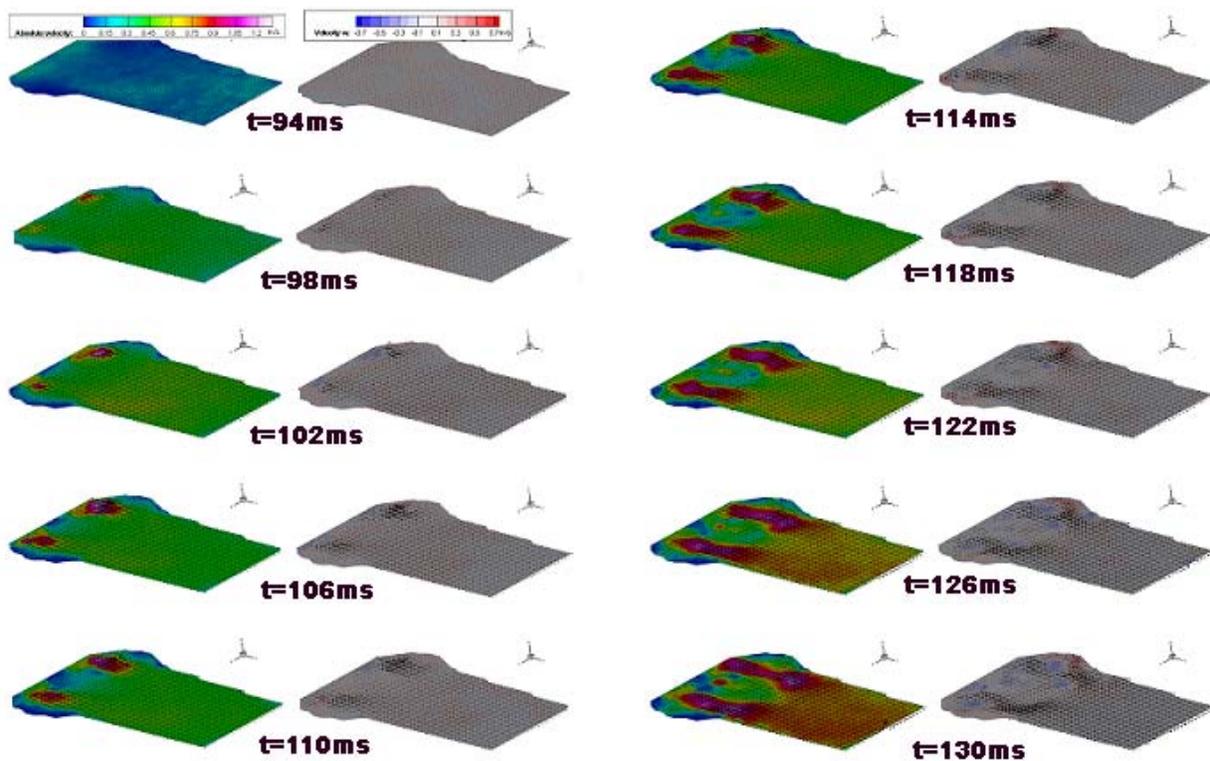

Fig. 4. Velocity magnitude scaled in color behind the ATS valve. The shown 10 results are from beginning of the systole for a 4 ms time step. Absolute and w component velocities respectively for each time step are displayed.

Measuring the flow through the PROT valve, we observed, that the systole starts at 92.66 ms. Maximum absolute velocity values of 1.4 m/sec are reached in small locations below the occluder at a time of about 100 msec. At this time the major jet stream above larger opening of the valve is developed but above minor opening the velocities reach only 0.4 m/s. At a time of 140 msec also a minor jet stream is developed with velocities around 0.8 to .9 m/s. After a 153 msec the velocities in core of minor jet stream raise up to 1.25 m/s but the further flow above this region is flowing with 0.5 m/s. The peak systole was reached at a time of 160 msec. The larger jet stream up to 38 mm above the valve plane is covering about 30% of the aortic lumen with velocities in a range of 0.6 up

to 1.26 m/s. A large vortex is developed behind the leaflet tip. During the deceleration phase of the systole the vortices are built up above the occluder top and in the valsalva sinus. The valve closes at a time 388 msec. The flow is rebound and the wave is going downstream. The velocities during early diastolic phase are locally reaching values up to 0.45 m/s. and there are also vectors with lower velocities values observed around the orifice. During the beginning of the systole the out of plane velocity component *w* reaches value of 0.7 m/s in both directions in regions close to the valve orifice. Later the values decrease down to 0.4 m/s and are distributed in entire ROI with higher concentration on the right side, above the larger opening of the valve orifice. At a time of 234 msec the positive highest values are observed above the minor valve orifice.
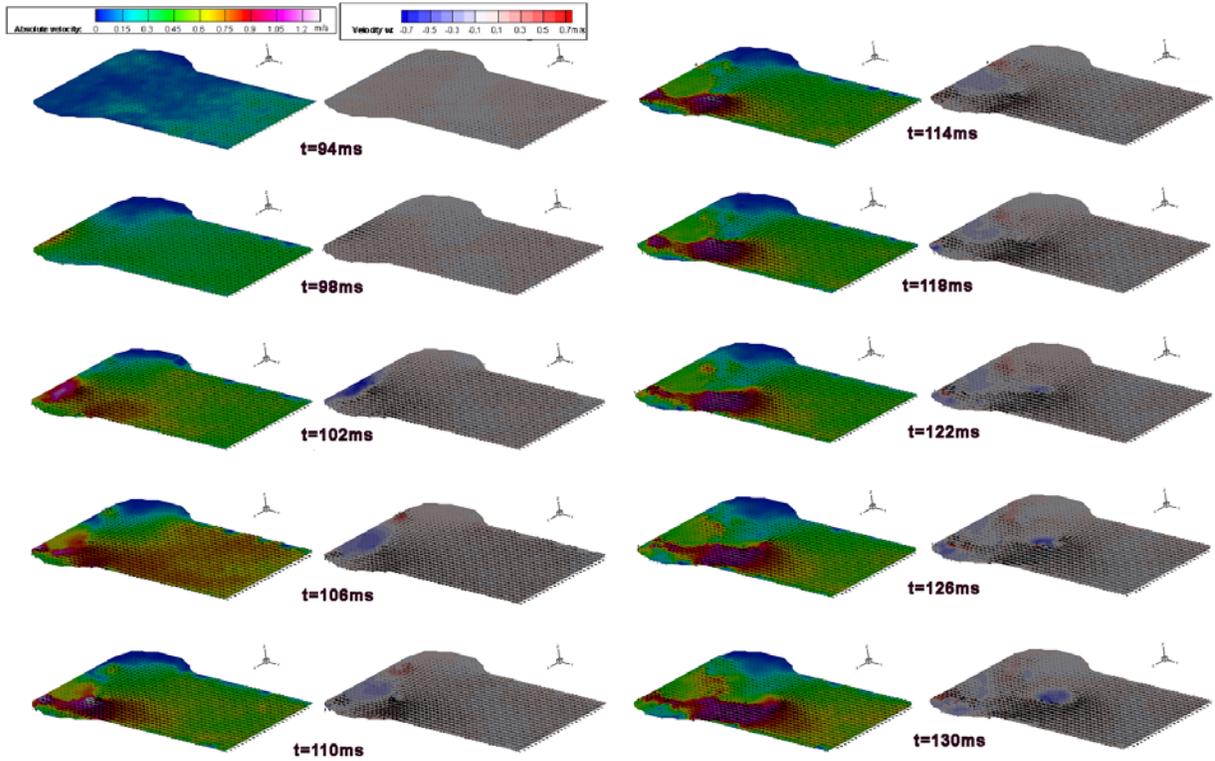

Fig. 5. Velocity magnitude scaled in color behind the monoleaflet PROT valve. The shown are from beginning of the systole for a 4 ms time step. Absolute and w component velocities respectively for each time step are displayed.

4. Discussion

Visualization of the aortic flow through the prosthetic aortic bileaflet ATS and monoleaflet prototype (PROT) heart valve was performed with High Speed Particle Image Velocimetry (HSPIV). The results are in agreement with the expected general flow behavior. Typical three jet stream structure is flowing through the orifice of the bileaflet valve with low out of plane velocity component in contrast with the measured velocity component in z axis through the monoleaflet prototype. There is nearly no difference in measured mean volume and mean leakage flow between both valves. This explains the higher absolute velocity values behind the PROT valve but better distribution of moderate values in the entire ROI behind the bileaflet valve. High temporal resolution is resulting in a very fine quantification of the flow development even in very dynamic moments of the tester cycle as the opening and closing valve. Using the stereo approach we reveal the high ratio between the z velocity components of compared valves. The local velocity extremes behind the PROT valve identify the vortex structures. It is expected that high speed stereo particle image velocimetry technique will bring valuable information about the quality of the flow which will help to better understand and to assess existing or create new prosthetic heart valves.

5. References

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