

Stereo high speed PIV measurements behind two different artificial heart valves

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Introduction: 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. 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.

Materials and Methods: 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 prosthetic heart valve (PHV). For our study we fixed a PHV into a silicone mock aorta of 28mm diameter. This aorta was specially designed to mimic the human anatomy and elasticity in a modified commercially available Vivitro heart valve tester. 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.

Results: The measurement acquisition started 10 minutes after initializing the heart valve tester. The mean aortic pressure drop was 40 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. The mean stroke volume flow through the ATS was 61 ml and the same through the PROT. The mean leakage volume during the iastole phase through the bileaflet valve is 8.8 and through the monoleaflet valve 8 ml/min. The maximum absolute velocities of the flow behind 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 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 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. 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. 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. 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.

Discussion: 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, like the opening and closing of the 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.