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Temporal FLOW EVOLUTION ON A PEDIATRIC VENTRICULAR ASSIST DEVICE

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Abstract – The transplant line is long and slow for patients with cardiac diseases, especially children. The support of ventricular assist devices (VAD) may stabilize the patient until a suitable donor is found. VADs are auxiliary pumps that help the failing heart to pump the blood. However, the use of a VAD is associated with clinical complications due to blood trauma (hemolysis) or thrombus formation. The destruction of the blood cells is strongly correlated with the shear stress that is imposed in the flow through all the devices parts, while regions of very slow velocities (stagnation) may increase the probability of thrombus formation. One particularly difficulty lies in pediatric devices due to strong variations in sizes and flows to accommodate children of various ages. To allow future improvement in the PVAD, the present work aims to analyze the temporal flow evolution inside a pulsatile pediatric ventricular assistance device (PVAD) under development in our institution. The time resolved particle image velocimetry technique was used to observe the evolution of flow structures inside the device. In this study, three parallel planes were studied to visualize the three-dimensionality of the flow. In the experiments, the acquisition rate was 3250 Hz and pumping rate set at 70 bpm. The results show important asymmetries in the filling and ejection periods especially near the valves.

***Keywords*:** Particle image velocimetry, blood flow, Pediatric Ventricular Assist Device, Temporal evolution

1. Introduction

Ventricular assist devices (VAD) are auxiliary blood pumps that can be intracorporeal or extracorporeal. They may be used to treat cardiac failure in patients, acting as a bridge to heart transplantation [1], thus improving the chances of survival for patients on the waiting list [2]. However, the use of a VAD is associated with clinical complications due to blood trauma (hemolysis) or thrombus formation. The destruction of the blood cells is strongly correlated with the shear stress that is imposed in the flow through all the devices parts, while regions of very slow velocities (stagnation) may increase the probability of thrombus formation [3]. Currently, the majority of the pumps are centrifugal or pulsatile. The first generation of devices was pulsatile with a diaphragm and a chamber mimicking the functioning of the heart. Subsequent development lead to axial and then centrifugal pump aiming to reduce blood degradation, especially thrombus formation. However, these designs cannot deliver pulsatile flow and recently studies found severe risks to patient's health due to the lack of pressure fluctuation in the blood [4, 5]. Thus, pulsatile VADs can provide an oscillatory flow at a reduced cost and complexity. Still, this device needs improvements to minimize blood degradation. This can be achieved by optimizing constructive parameters like the diaphragm proprieties and valve angle. The development of a pediatric VAD (PVAD) presents even greater challenges compared to an adult VAD due to smaller and varied pump sizes needed to make it compatible with the cardiac function of children of different ages [6]. Besides, there is a lack in experimental data to support the development. Moreover, those devices can also be affected by variation between the cycles. Therefore, simple average analysis, used in low frequency velocimetry, cannot describe the real behavior in each beat. Therefore, a temporal evolution enables a better understanding of the real flow path inside the device and how its changes.

Particle image velocimetry is a non-invasive technique that allows indirect determination of the flow velocity distribution in the 2D or 3D domain using tracers. VAD's were analyzed with low frequency PIV [7], but the reduced frame rate prevents more detailed observation of flow structures in the temporal domain. In this context, ensemble average between cycles is used to obtain the mean velocity field in a point of the pumping cycle. However, this mean picture can differ from the instantaneous field and the impact of structures in the progress of the flow is absent or smoothly. Consequently, to make improvements to PVAD's more data are needed, especially regarding the route taken by the fluid.

Therefore, the objective of this work is to investigate the temporal evolution of the flow velocity inside a pulsatile PVAD under development by our group. For this, a 2D time-resolved particle image velocimetry (TR-PIV) system was used for the temporal measurement of a complete cycle. Three parallel planes were observed; one at the geometric center of the device, another closer to the pumping membrane, and the last closer to the dome. Thus, the behavior of the tridimensional velocity field and the fluid path could be inferred.

2. Methodology

2.1 PVAD and mock simulation look (MCL)

For the experiments, a transparent polyurethane pediatric ventricular assist device was used. Figure 1a shows the device. The PVAD has a blood and a pneumatic chamber separated by a diaphragm and two bi-leaf valves (at 0º with the membrane) to control in and outflows (figure 1b)., air from a pneumatic system inflate the diaphragm to pump the fluid at a rate of 70 bpm. Three different planes were observed (close, middle and distant), one at the geometric center of the device and the others at distances of 20 mm of the center towards the wall and towards the diaphragm (figure 1b). To simulate the left side of a heart, the pump was coupled to a mock simulation look (MCL). The MCL system consists three cambers (atrial compliance, systemic volume and arterial compliance) filled with a blood analog fluid and pressure loss given by a clamp of Hoffman (figure 2). This system allowed to keep the pressures constant across the PDAV experiments (120/80 mmHg) and had a similar dynamic response to the human body. In the experiments, the diastole phase corresponds to 2/3 of the total cycle and the systole to the remaining.

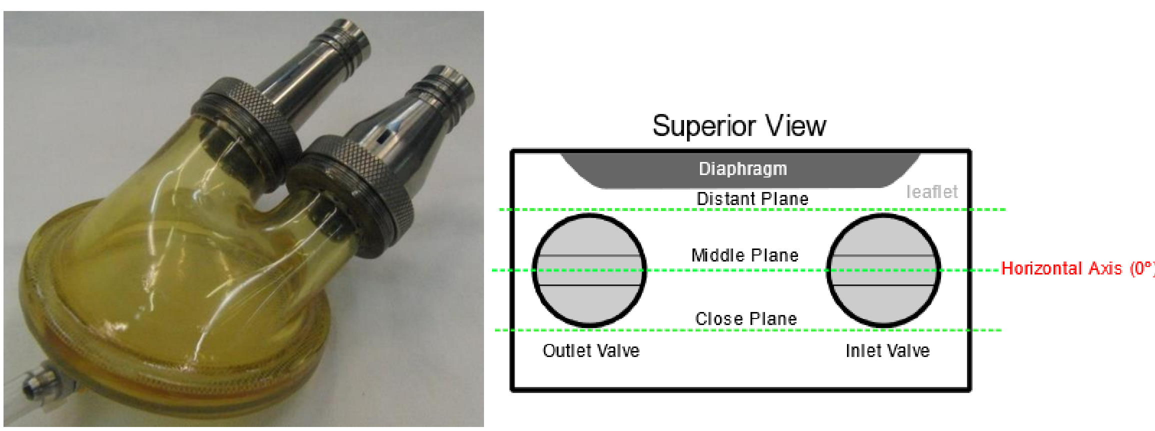

Figure 1 –The pediatric VAD (a) and a schematic view of the valves, membrane and laser planes (b).

2.2. Data acquisition

A time-resolved particle image velocimetry (TR-PIV) was used for data acquisition. This system is similar to a regular PIV, but with a high frequency laser and cameras. Therefore, the evolution of a particular fluid structure could be tracked, in this study, they were observed along a complete pumping cycle. In the experiments, a 527 nm laser was used as the light source and 30 µm polyamine particles were selected as tracking particles. A Camera (Vision Research, Phantom® Miro® R311) at 3250 Hz acquired the images for each plane in single-frame mode. Because the pump frequency was 70 bpm, in each VAD beat there were 2785 images. The image resolution was 55.56 for the central plane and 58.14 µm/pixel for the others. With the three observed the three-dimensional flow inside the device could be partially observed. The measurement in several planes allowed to trace the fluid path, even when the particles change from one plane plane to another, therefore, a more complete description of the flow can be drawn even with a planar technique.

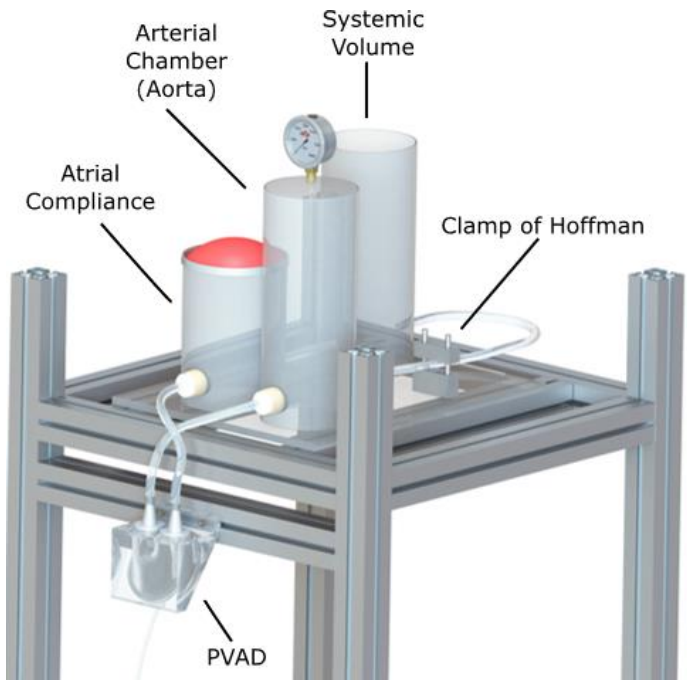

Figure 2 - Schematic view of the experimental setup with the PVAD and the MCL;

2.3. Data processing

All the frames were pre-processed to enhance the particle visibility and correct the image distortion caused by the PVAD curvature. The distortion is particularly intense in the plane closer to the wall and on the borders of all images; in this case a custom-made algorithm was able to correct the image with high precision using a calibration target. After, the undistorted and calibrated image were filtered using a Gaussian, an RMS and an intensity cap filters to reduce the noise level and enhance the definition of the particle´s image.

The multigrid PIV process [8, 9] was used to correlate the single-frame images, in this process the frames were paired in the form: 1-2, 2-3, 3-4… The multigrid method allowed higher spatial accuracy, is less susceptible to loss of correlation, noise, and can accommodate a greater range of displacements. Besides, the standard cross correlation (SCC) algorithm was used. The initial interrogation windows size was 32 pixels and after four iterations with an overlap of 25%, the final window had 15 pixels.

After, every field was post-processed to eliminate outlier and ensure the validity of the vector. First, all correlations with a signal-to-noise ratio inferior to 1.3 were discarded. Then a universal outlier detector strategy was used to eliminate spurious vectors, if a vector was more than three times the median of its vicinity (3x3) it was discarded. Besides, if the vector also differs more than three times from the time average, using three consecutives frames, it was discarded. All rejected vectors were replaced by interpolated values [10].

3. Results

The system was synchronized to the start of the diastole using as reference the electro-mechanical pulse that switches the airflow in the membrane. Thereby a small delay was observed in the end of the cycle due to inertia of the fluid-mechanical system

Figure 3 shows the velocity magnitude for the three planes (close, middle and distant) in different moments of the diastole. In the beginning of the cycle (figure 3a, 3b and 3c), the inlet valve is open and the membrane occupies most of middle and distant planes.

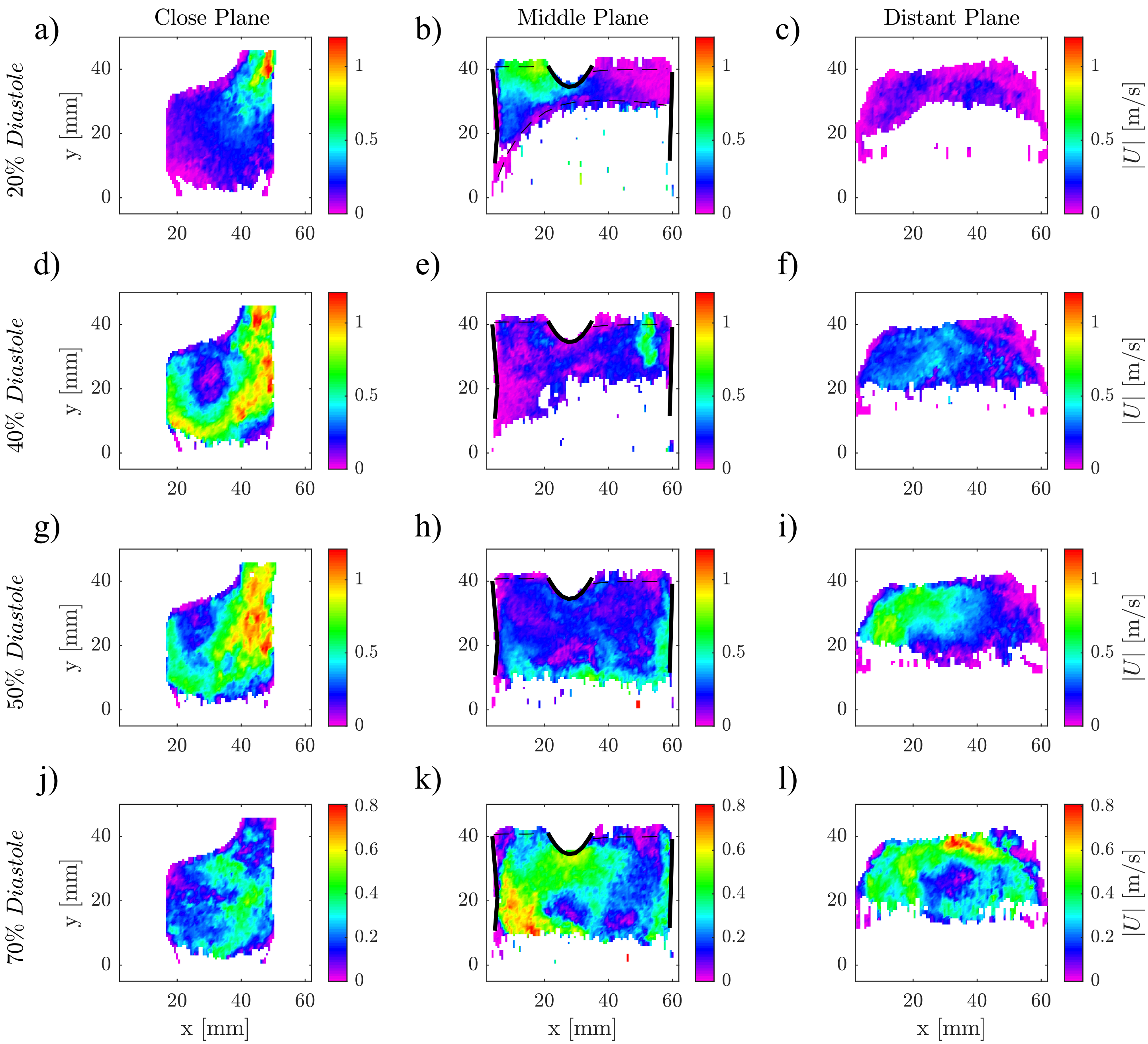

Figure 3 – Velocity magnitude fields during diastole. The moment is given as percentage of the total diastole time.

The inlet jet is visible only in the near plane and there is a small fluid flow through the outlet valve. This indicates that the flow is asymmetrical in the inlet section with a preferential flow near the front wall, besides there is still a small recirculation in the other valve from the previous systole. At 40% of diastole, the close plane (figure 3d) displays a fully developed inlet jet with following the curvature of the PVAD. In the middle plane (figure 3e), the inlet flow is visible but it but it is smaller, and in the far plane no inlet flow is observed (figure 3f).

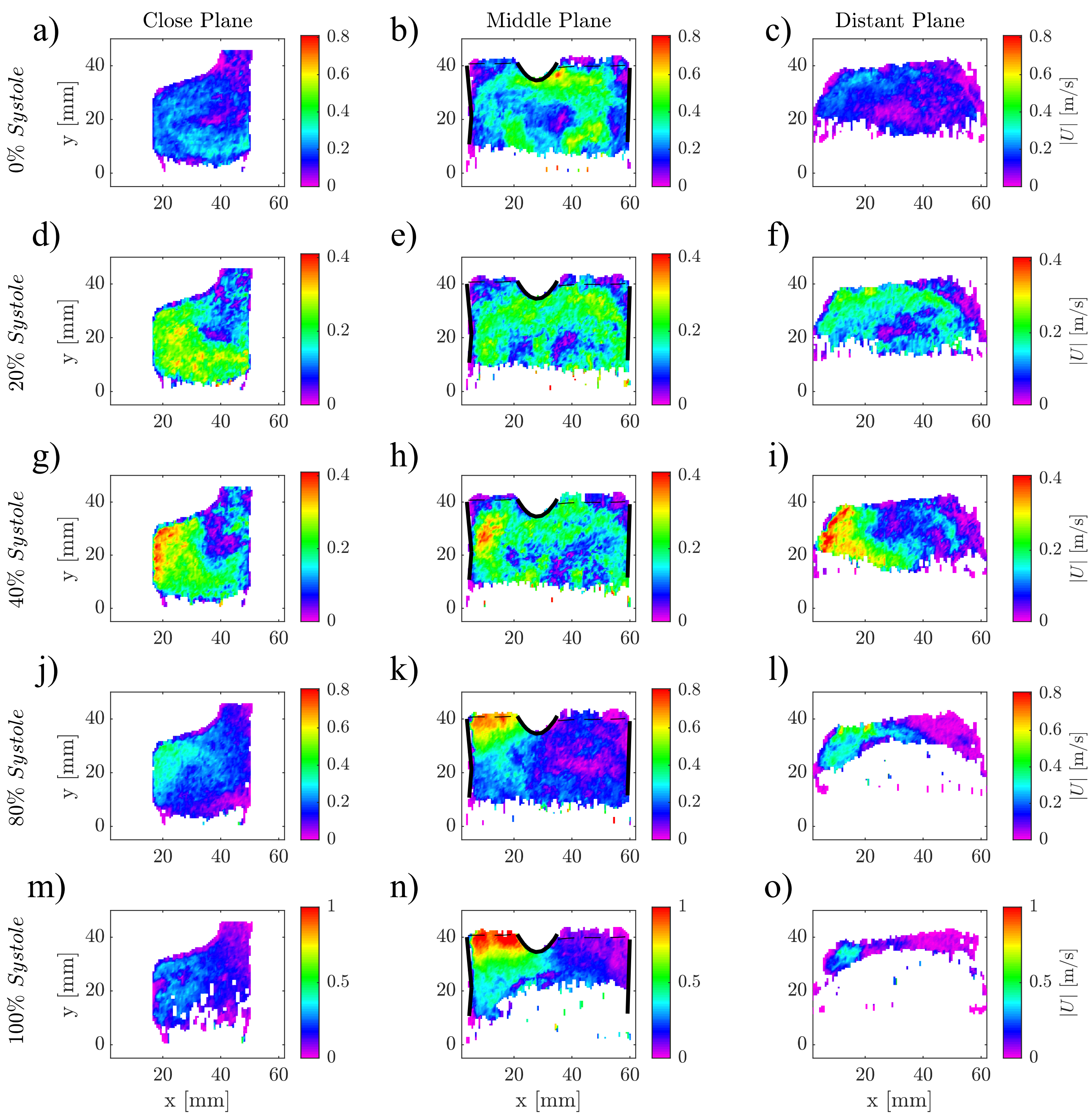

Figure 4 Velocity magnitude fields during systole. The moment is given as percentage of the total systole time.

In the figure 3g, the velocity in the inlet of the near plane is almost homogenous and there are a significantly in the bottom left. In this moment, the jet in the middle plane is pushed to the lateral wall (figure 3h). Finally, a high field is visible in the left side of the distant plane (figure 3i). This pattern indicates that the incoming fluid moves to the of the PDAV, sinks in the bottom left reappearing in the far plane. Therefore, the data indicates a tridimensional movement inside the PDAV. In the last phase (figure 3j, 3k and 3l), a low flow is observed through the inlet valve, thus the velocity magnitude is reduced in the close plane while in the middle and distant ones a recirculation vortex is visible.

This observation was unexpected because due to the symmetry of the bi-leaf valve the inlet jet should be uniform in all planes, even more than the first measurement is less than 10 mm away from the valve in all planes. Therefore, the flow through the inlet valve seems heterogeneous. Moreover, stagnation is predominant in the center of the device and near the valves, but analyzing all the diastole, the stagnation regions are small and temporary.

In the beginning of the systole (figure 4a, 4b and 4c), the recirculation motion decayed significantly in the near and far plane and is most visible in the middle plane of the device. At 20% of the systole (figure 4d, 4e and 4f), the membrane started to move compressing the vortical movement that is more homogeneous in all planes. However, the velocities near the outlet valve remain below the recirculation speed. In the sequence (figure 4g, 4h and 4i), the diaphragm starts to occupy the visible part of the distant plane. Furthermore, the flowing the outlet intensifies in the near and backplane but there is a delay in the center plane. This indicates an asymmetry in the exit. At 80% (figure 4j, 4k and 4l) of the systole, the membrane occupies most of the further plane and the velocities in that plane and in the near one are significantly smaller. In the middle of the device, the outflow accelerates and velocities around 0.5 m/s are observed. Therefore, there is a shift in behavior when compared to the 40% of systole in which most of the outflow comes from the front and distant plane. Finally, as the membrane progress (figure 4m, 4n and 4o) the velocity field in the near and far plane is close to 0 m/s while in the center plane there is a strong motion in the outlet valve. Interestingly, in the end of the systole occurs the greater velocities in the exit valve, therefore is clear that the fluid is still leaving the pump despites the change in the electro-mechanical system. This inertia creates a delay in the fluid when compared to the cycle of the control system. Moreover, the flow speed at the outlet valve is more than 1 m/s in the middle plane reinforcing the heterogeneity characteristic the PDAV discharge.

4. Conclusion

These results underline the complexity of the filling and discharging motion inside the pediatric VAD, especially near the valves. We observed the occurrence of asymmetrical filing and discharge, and non-uniform flow near the valves.

In the diastole phase, the velocity was higher in the close plane in almost all the observed instants. This indicates a preferential path to fill the device. Besides, the recirculation is continuously formed along the cycle until 70% of the diastole where it is completely developed. This demonstrates the importance of the time resolved, as it can underline the complete temporal evolution along the beat. At the beginning of the systole, the recirculation is already decayed substantially and is clear a delay until the fluid start to be expelled. The fields also indicate a heterogeneity with higher velocities in the far and close plane before the middle plane.

It is also important to highlight that all the data is confined to a single beat observed with the PIV. Therefore, the variations between each cycle could not been observed with the present analysis. However, this technique allowed such studied to be performed in the near future. An important limitation the perpendicular component was not measured, so flux between planes could only be inferred by observing the velocity change in the three planes. Besides, particle image velocimetry has a relatively low spatial resolution, compared to others punctual techniques, but as a trade-off measures the whole field simultaneously.

Finally, with the time-resolved PIV it was possible to stud the temporal evolution of the flow inside the PDAV in development. Those results could open new possibilities to improve the currently design as they presents a new picture of how the flow progress inside the device.

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