Particle Image Velocimetry Study of Pulsatile Flow in Bi-leaflet Mechanical Heart Valves with Image Compensation Method

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Abstract Particle Image Velocimetry (PIV) is an important technique in studying blood flow in heart valves. Previous PIV studies of flow around prosthetic heart valves had different research concentrations, and thus never provided the physical flow field pictures in a complete heart cycle, which compromised their pertinence for a better understanding of the valvular mechanism. In this study, a digital PIV (DPIV) investigation was carried out with improved accuracy, to analyse the pulsatile flow field around the bi-leaflet mechanical heart valve (MHV) in a complete heart cycle. For this purpose a pulsatile flow test rig was constructed to provide the necessary in vitro test environment, and the flow field around a St. Jude size 29 bi-leaflet MHV and a similar MHV model were studied under a simulated physiological pressure waveform with flow rate of 5.2 l/min and pulse rate at 72 beats/min. A phase-locking method was applied to gate the dynamic process of valve leaflet motions. A special image-processing program was applied to eliminate optical distortion caused by the difference in refractive indexes between the blood analogue fluid and the test section. Results clearly showed that, due to the presence of the two leaflets, the valvular flow conduit was partitioned into three flow channels. In the opening process, flow in the two side channels was first to develop under the presence of the forward pressure gradient. The flow in the central channel was developed much later at about the mid-stage of the opening process. Forward flows in all three channels were observed at the late stage of the opening process. At the early closing process, a backward flow developed first in the central channel. Under the influence of the reverse pressure gradient, the flow in the central channel first appeared to be disturbed, which was then transformed into backward flow. The backward flow in the central channel was found to be the main driving factor for the leaflet

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rotation in the valve closing process. After the valve was fully closed, local flow activities in the proximity of the valve region persisted for a certain time before slowly dying out. In both the valve opening and closing processes, maximum velocity always appeared near the leaflet trailing edges. The flow field features revealed in the present paper improved our understanding of valve motion mechanism under physiological conditions, and this knowledge is very helpful in designing the new generation of MHVs.

Keywords Hemodynamics · Bi-leaflet mechanical heart valve · Particle image velocimetry · Pulsatile flow · Refractive index · Image compensation · Phase-locking method

1 Introduction

In the healthy human heart there are four heart valves which function to maintain a one-way blood flow direction in every cardiac cycle. Under diseased conditions such as endocarditis, heart dilatation or injury to the aortic root or annulus fibrosis, valve incompetence or stenosis develops in one or more of the heart valves and causes extra pressure and/or flow load to the heart. The extra load on the heart induces heart hypertrophy and even heart failure in the long term. When the symptoms in the patients become serious, the diseased heart valves have to be replaced with artificial heart valves (AHVs). Mechanical heart valves (MHVs) and bio-prosthetics are two kinds of AHVs currently in use. Since the first invention and clinical application of AHV in 1960s, more than two million patients have been saved by the prosthetic heart valve replacement operation [1]. Heart valve replacement operation is proved to be an effective way of extending patients' lives. However, until now the performance of AHVs is still far from ideal. The most serious problems and complications associated with heart valve prostheses include thromboembolism, tissue overgrowth, infection, tearing of sewing suture, hemolysis (red blood cell destruction) and failure due to material fatigue. Besides biomaterial incompatibility, hemodynamic factors are believed to have a close relation to most of these problems [1–3]. In the past years extensive experimental and numerical studies have been carried out to investigate the hemodynamic performance of both the healthy heart valve and AHVs.

In vitro experimental investigation plays an important role in analyzing heart valve dynamics. Early experimental studies of blood flow in heart valves were mostly concentrated on qualitative descriptions based on visualization of the flow field using dye or air bubbles as flow tracers [4]. More accurate methods are now available and these include Laser Doppler Anemometry (LDA) [5–9], high-field magnetic resonance imaging [10], Doppler ultrasound [11], and Particle Image Velocimetry (PIV) [6, 9, 12–21]. Due to its specific advantage in easily acquiring the whole flow field on a selected plane, PIV has become a widely used technique in heart valve research.

PIV captures the instantaneous velocity distribution on a selected plane in the flow field that is illuminated by a laser sheet. In most PIV applications, tracer particles are added to the flow. When the selected plane in the flow field is illuminated by the laser sheet, the light scattered by the tracer particles on this plane is recorded with a camera. Sequences of flow field pictures are recorded in this way and stored for post-processing. In post-processing each recording or pair of flow field images is divided into small sub-areas called “interrogation areas.” The mean local displacement vector for the images of the tracer particles is determined for each interrogation area by means of statistical methods (auto-correction or cross-correction method). The processing of the interrogation is repeated for

all interrogation areas of the PIV recording, and the velocity distribution for the whole flow field is thus obtained [12].

In past decades numerous PIV investigations have been carried out in heart valve studies. In 1997 Brücker conducted a Digital PIV (DPIV) study of pulsating flow in artificial heart valves with an in-house developed video-based DPIV system [13]. Lim et al. studied steady and pulsatile flows in bio-prosthetic valves with the PIV technique in 1998 and 2001 [14, 15]. Zhao et al. (1998) conducted a PIV study of pulsatile flow in a 3:1 enlarged two dimensional bi-leaflet MHV model [16]. Bluestein et al. (2000) investigated vortex shedding in a bi-leaflet MHV during the deceleration phase of the heart cycle with computational fluid dynamics and DPIV techniques [17]. Subramanian et al. (2000) conducted a PIV investigation of the intra-valvular pulsatile flow field in a bi-leaflet MHV [18]. Manning et al. (2003) investigated the regurgitant flow in MHV in a simplified mitral flow test rig with the PIV method [19]. These works helped greatly in understanding the flow field in MHVs and in explaining certain in vivo physiological and pathological phenomena. However, due to the complexity of the flow in prosthetic heart valves and the limitation of the experimental apparatus, and more importantly due to the specific aims of each investigation in the above works, none of them provided an accurate flow field picture in the heart valve in the whole cardiac cycle under physiological conditions. Most of these studies fall very far from achieving this aim. Among them many studied only limited phases of the heart cycle: for instance, only some specified instances in the pulsatile flow process were captured in [14, 15, 17]; only the valve opening process was recorded in [13]; and the valve opening process was neglected in [18]. Also in those previous experiments, because the opaque valve ring and leaflets often obstructed the travelling of the laser sheet and thus caused incomplete illumination of the flow field, usually only certain specific regions of the valvular flow field were investigated, such as the near downstream region of the valve studied in [6, 13–15 and 17]. Besides these spatial and temporal limitations in measurement, many also had artificial deficiencies in flow field structure and used a modified system to facilitate optical observation. Examples are the closed and open tanks to represent the ventricular and atrial chambers in [9, 19] and the rectangular-shaped flow channel for aortic flow in [16], which deliberately used system structures different from the physiological situation in order to facilitate optical observations. In contrast, some other researchers kept the near physiological flow field configuration, but used additives such as sodium iodide, sucrose or dibutyl phthalate to mix with the blood analogue in order to correct the optical error caused by the difference of refractive indexes between the test section material and the blood analogue [6, 17, 18, 20 and 21]. Although the flow field geometry was maintained with this method, with the introduction of the additives (which often have different density and viscosity properties to that of the testing fluid) the properties of the testing fluid were changed, thus it is understandable that the system would demonstrate changed dynamic behaviour. Thus it is still necessary to investigate the flow in MHVs and obtain a clear and accurate global picture of the whole pulsatile flow process in MHVs in order to address the above limitations.

This paper presents a global study of the pulsatile flow structure in MHV covering the complete heart cycle. In the research, DPIV experiments were carried out to study the process of the pulsatile flow in two bi-leaflet MHVs: a St. Jude 29 mm (SJM 29) bi-leaflet MHV and an in-house developed transparent valve model that has the same geometry as the SJM size 29 valve. In the experiment, no additive was applied to the working fluid to compensate for the difference in optical refractive indexes between the test section and the testing fluid. However, an image processing technique was applied to correct the corresponding optical error caused by the curved surface of the transparent Plexiglas test

section wall. Without additives applied to the test fluid, the density of the blood analogue remained untainted and hence the dynamic similarity of the system was maintained.

2 Materials and Methods

The experiment was carried out in a computer-controlled physiological pulsatile flow test rig. Figure 1 shows the schematics of the pulsatile flow test rig arrangement. A computer-controlled piston moves back and forth in a cylinder to reproduce the volume change in the simulated left ventricular chamber. Downstream to the cylinder, a flow tunnel with circular cross-section was used to mimic the aortic conduit. The test valve was installed at a distance two times the aortic diameter downstream from the conduit inlet. A straight tube with a length of 20 times the diameter of the aorta was used to minimize the downstream reflection effect. Two flow control valves (valves A and B) and a compliance unit were used to simulate the physiological systemic after-load. The flow was directed back to the head tank to close the loop. The tank was connected with the cylinder through a one-way check valve to mimic the left atrium and the mitral valve. In the test loop, two piezo-electrical pressure transducers were installed 60 mm upstream and 70 mm downstream of the test valve to monitor the simulated ventricular and aortic pressures. The pulse period in the test rig was set at 0.833 s (corresponding to 72 beats/min). The shape and magnitude of the pulse waveform were set to make the systolic phase using 30% of the whole pulse period, with mean flow rate of 5.2 l/min. Figure 2a shows the near physiological ventricular and aortic pressure waveforms produced in the test rig, and Fig. 2b illustrates the corresponding simulated aortic flow waveform (waveforms were adequately filtered to eliminate environment noise). Thus in the valve flow test rig, the mean Reynolds number of the flow is about 1,300 using the valve diameter as length scale, and the peak Reynolds

Fig. 1 Schematic of the pulsatile systemic flow test rig

Fig. 2 (a) Ventricle and aortic pressure in the experiment; (b) Flow rate change in the test rig

number is 8,000. The corresponding Womersley number for the pulsatile blood flow is 18.8.

A St. Jude 29 mm bi-leaflet MHV and an in-house developed transparent MHV model were used as the test valve models in the experiment. The St. Jude valve was selected because of its relatively short valve body, which facilitated experimental observation. The in-house developed transparent valve model was made of transparent Polycarbonate (PC). Its density is about $1.2 \times 10^3 \text{ kg/m}^3$, slightly less than the density of the pyrolytic carbon (PyC) leaflets in the St. Jude valve, which is in the range of $(1.5 \sim 2.0) \times 10^3 \text{ kg/m}^3$ [22]. The transparent PC valve model was manufactured to mimic the geometry of the SJM 29 valve. It was used to facilitate measurement of certain regions of the flow field that otherwise could not be observed by using the real SJM 29 valve, which was fabricated from the opaque PyC. The transparent model was also used to compare the relative effect caused by the density difference between the two test valve materials.

The PIV system used in this experiment was a TSI® Insight™ PIV system (TSI Incorporated, MN 55164, USA). The PIV system is showed in Fig. 3. Connected with the hardware system, a computer was used for global control and monitoring of the system. A synchronizer was used to aid the computer for implementation of the control and synchronization tasks. The PIV system was powered with a 532 nm wavelength Nd:Yag pulsed laser that provided the field illumination. To have optimal measurement results, the pulse separation time for the two laser beams should be adapted for each measurement instant based on the instantaneous flow velocity. Since this operation mode is not supported directly in the TSI system, in this research the pulse separation time for the two laser beams was set at 500 μs , so that in the peak flow situation the particles' displacement was less than half the length scale of the interrogation cells. Two optical lenses were installed at the laser output window to adjust the laser beam into a 0.3 mm thick laser sheet. A CCD camera (PICCAM 10-30, model 630046) enhanced with a micro-lens (Micro-Nikkor 60 mm f/2.8D) and a frame grabber was used for capturing the images of the flow field. The flow field image covers a physical area of $30 \times 20 \text{ mm}$, and has an image resolution of $1,000 \times 1,016$ pixels. Insight™ version 3.0 running on a Pentium III computer (450 MHz CPU, 256 MB RAM) under Windows NT version 4.0 was used to manage the system.

To obtain detailed information about the pulsatile flow field around the tested valve in one whole heart cycle, especially the valve opening and closing processes, it was estimated

that the PIV system should have a minimum working frequency of 50 Hz [13]. This requirement was difficult to meet with the current PIV technology because of the limitations in both the laser source and the CCD camera. Other factors such as the timing accuracy of the PIV system made the situation even more difficult. To address the working frequency problem, a phase-locking method used by Subramanian et al. [18] was applied to the current experiment. In this method it was assumed that the periodic changing of the flow field was ideally repeated from cycle to cycle. A triggering computer sampled the displacement of the ventricle driving motor, and the sampled signal was analyzed to define the “starting point” of a heart period. For each set of experiments, the PIV measurement was repeated for several runs, and the above-mentioned “starting point” was marked as the reference point of all the successive runs. In each run, when the reference point was detected, the triggering computer waited for a precisely controlled delay time Δt , before generating a standard TTL pulse series at a frequency of 10 Hz. This impulse series was then fed into the PIV system synchronizer to trigger the illumination and the capture of the pictures. Typically 26 runs were taken in each set of experiments, and the time delay Δt was varied from 0 to 100 ms, with 4 ms increment. The results from all these runs were then analyzed and typical pictures were selected and combined to compose the series of pictures for a complete pulse cycle.

In the current experiment, a mixture of 37% glycerine and 63% distilled water (by volume) was used as the working blood analogue fluid. This mixture had a density of $1.06 \times 10^3 \text{ kg/m}^3$, a dynamic viscosity of 3.5 cP and a kinematic viscosity of $3.4 \times 10^{-6} \text{ m}^2/\text{s}$ at $24 \pm 1^\circ\text{C}$. Such fluid has the same properties as natural blood under similar conditions [23]. 8–12 μm silver-coated hollow glass spheres (Spherical®, Potter Industries Inc.) was used as seeding particles, with a density of $(0.1 \sim 1.5) \times 10^3 \text{ kg/m}^3$. The silver-coated surface greatly enhanced the light scattering capability of the particles, and thus enhanced the image quality.

In the experimental set-up, the Perspex cylindrical test section had a refractive index of 1.47. The refractive index of the blood analogue was 1.45. Thus the curvature of the cylindrical test section would distort the visual image from that of the actual flow field. To compensate for this optical distortion, early researchers applied additives such as sodium

Fig. 3 Hardware configuration of the PIV system

iodide (NaI) or sucrose ($C_{12}H_{22}O_{11}$) to the working fluid, trying to change its refractive index to match that of the test section wall material [6, 17, 18, 20 and 21]. However, it was found that these additives also changed the other properties of the working fluid. Subramanian et al. used sodium iodide as additive, and the fluid density was changed to $1.74 \times 10^3 \text{ kg/m}^3$ [18]. Besides the density change, the additives also changed the viscosity of the working fluid, hence affecting the dynamic similarity of the overall experiment [24]. To address the optical distortion problem, Brücker proposed a new method that makes use of an image processing technique [13]. This technique was developed and applied to the current research. In the present paper we ignored the aortic sinuses for simplicity. Hence in the test section (see Fig. 4), the curvature existed only in the circumferential direction. Thus the optical deformation occurred only in the radial direction of the flow field.

Figure 5a–e illustrate the image compensation method. In the image frame, the zero point of the coordinates is in the upper left corner. The X coordinate is from left to right, and the Y coordinate from top to bottom, as shown in Fig. 5a. In the image compensation method, a mirror function is sought to transform the distorted image in the left panel to the un-deformed image as in the right panel shown in Fig. 5a. As explained previously, the image deformation is only in the Y direction. According to the refraction law in optics, the deformation in the radial direction is a trigonometric function of the image pixel positions, and the mirror function has the form:

$$y' = y + A \cdot \sin \frac{(y - Y_c)\pi}{Y_s}, \quad Y_c - \frac{Y_s}{2} \leq y \leq Y_c + \frac{Y_s}{2}$$

where y' is the new Y coordinate of a pixel point in the corrected image of the flow field, y is the Y coordinate of the same pixel point in the flow field image with optical distortions, A is the coefficient for the image correction operation, Y_c is the Y coordinate of the central line of the flow channel in the distorted image, and Y_s is the span of pixels for the flow field in the Y direction for the distorted image. The coefficients A , Y_c and Y_s are determined through image calibration.

To determine the coefficients for the mirror function in optical compensation, a standard grid was inserted into the flow channel in the test section, and the test section was exposed under the same conditions as that in the PIV experiment. The picture of the grid and the test section was then captured. Next, the deformed part of the grid was compared with its un-deformed counterpart, and the optimal coefficients for A , Y_c and Y_s are determined through numerical experiments. The mirror function is then constructed to transform the picture of the deformed part into a picture that could match the original grid. The coefficients A , Y_c and Y_s are affected by various factors such as image resolution, camera orientation and focal length, etc. Figure 5b illustrates the mirror function used in the current research. The solid line is the mirror function used, and another dashed line for the linear function $y'=y$ is

Fig. 4 Geometry of the test section in the experiment

Fig. 5 Image compensation (a) Conceptual illustration of mirror function; (b) Input-output relation of mirror function; (c) Image of grid being inserted into the test section and both are immersed into the working fluid; (d) Comparison of the original grid and the deformed grid; (e) Comparison of the original grid and the compensated grid

also shown as a reference for comparison (the linear function $y'=y$ corresponds to the situation of no image compensation).

Figure 5c–e further illustrate the implementation process for the image compensation technique. Figure 5c shows the original picture of the test section and the grid as immersed in the working fluid. Figure 5d compares the images of the un-deformed part and the deformed part of the grid. To compensate for the deformation, the above mirror function

was constructed through numerical experimentation on the deformed and un-deformed images. Figure 5e compares the images for the un-deformed part and the compensated part of the grid. Through image manipulation, it was evaluated that by using the current image processing method the image distortion was reduced to 0.78%.

The experiment was carried out in an isolated dark room with temperature controlled at $23^{\circ}\pm 2^{\circ}\text{C}$, and the relative humidity kept at 64%. During experiment, the room was totally isolated from outside light sources, and the laser source provided the only illumination for the plane in the flow field measured.

In PIV measurement of unsteady flows such as in the heart valve, at each instant a number of measurements should be taken; the mean flow field is constructed by averaging these measurements ([9, 15, 21 and 25]). This processing helps to eliminate the effect of noise in the environment, but it necessitates certain extra module for data processing, which is not included in the standard TSI PIV system. In the current initial stage of the PIV study, such average processing has not been implemented yet, and one pair of images for each instant is used to compute the instantaneous flow field. The average processing of repetitive measurement results for each instant will be implemented in the next stage of study by enhancing the PIV system with in-house developed software modules.

After the PIV measurement procedure, picture of a ruler was taken and analysed for image calibration, and the post-experiment data processing was carried out. A parabolic peak search algorithm was used for cross-correlation processing of the two frame images. 64×64 pixel processing windows with 50% overlap were chosen to give the optimal processing result. The initial velocity vectors obtained in the post processing contained a certain amount of noise, and thus a global range filter, a median filter and a local mean filter were applied to remove the abnormal vectors. An interpolation was then implemented to fill those holes in the vector fields. Finally as the standard module in TSI's program, a first order central difference scheme was used to calculate the vorticity distribution in the flow field based on the vorticity magnitude method.

3 Results

For convenience of analysis, the whole pulse cycle was partitioned into four consecutive phases: (a) opening process, (b) fully open phase, (c) closing process and (d) fully closed phase. Figure 6 gives the general structure of the flow field. Figures 7, 8, 9, 10, 11, 12, 13, 14, 15 and 16 show the velocity vector and vorticity distribution in the flow process for the entire pulse cycle. In all these figures, the grey regions represent the valve leaflets. θ_1 and

Fig. 6 Conventions used in the PIV results

Fig. 7 Velocity field from an experiment using the SJM size 29 valve; opening process, $t=0.008$ s, $\theta_1=56^\circ$, $\theta_2=55^\circ$

θ_2 are the rotating angles of the upper and lower leaflets with respect to the central line of the valvular flow field, which change between 60° (for fully closed position) and 5° (for fully open position). The flow field is separated into three flow channels by the two leaflets: a central flow channel and two side channels. A central jet stream is formed between the leading edges of the two leaflets, and two side jet streams are formed between the valve housing wall and the adjacent leaflet trailing edge.

For completeness, the experiment was carried out on both the real SJM 29 valve and the transparent SJM 29 valve model. The general results for these two tested cases showed much similarity in flow field structure, although the detailed flow field values are different due to the difference of the valve leaflet materials. Since the result for the transparent SJM 29 valve model reveals more details about the flow field that cannot be observed in the real SJM 29 valve due to the obstruction of the opaque valve ring and leaflets, the following description of the experimental result is based on the result for the transparent SJM 29 valve model, and the result for the real SJM 29 valve is briefly referred to when necessary.

Figures 7 and 8 illustrate the velocity vectors of the flow field downstream of the valve in certain instances in the opening and closing processes of the valve motion for the real SJM 29 valve. Figures 9, 10, 11, 12, 13, 14, 15 and 16 show the corresponding results for the transparent SJM29 valve model. From the PIV measurement result for the transparent

Fig. 8 Velocity field from an experiment using the SJM size 29 valve; closing process, $t=0.284$ s, $\theta_1=23^\circ$, $\theta_2=31^\circ$

Fig. 9 Velocity field from an experiment using the transparent valve; opening process: (a) $t=0.004$ s, $\theta_1=51^\circ$, $\theta_2=52^\circ$; (b) $t=0.008$ s, $\theta_1=41^\circ$, $\theta_2=41^\circ$; (c) $t=0.024$ s, $\theta_1=26^\circ$, $\theta_2=27^\circ$; (d) $t=0.028$ s, $\theta_1=24^\circ$, $\theta_2=24^\circ$; (e) $t=0.056$ s, $\theta_1=20^\circ$, $\theta_2=18^\circ$

valve model, it is observed that generally the whole heart period of 0.833 s can be divided into four consecutive phases as following: (a) 0.056 s for the opening process, (b) 0.122 s for the fully open phase, (c) 0.114 s for the closing process, and (d) 0.541 s for the fully closed phase.

3.1 Opening Process

The whole flow field shows smooth and symmetrical forward flow during the opening process (see Figs. 9 and 10). Due to the valve leaflet motion, flow in the valve exhibits the features of three-channel flow with varying channel openings. Strong jet flows always exist in the nozzles of the two side-flow channels, while the area in the central channel experiences a transition from leaflet-driven flow to jet flow. From the early stage of the valve opening process, flows in the two side flow channels have begun to develop as jet flows, and they become stronger as the valve inlet velocity increases. Flow in the central channel is weak in the early stage of the valve opening process (before $t=0.024$ s), and it becomes stronger in the middle stage (after $t=0.028$ s), until at the end stage of the opening process the central jet flow becomes the strongest jet in the whole flow field. In the region near the inner surfaces and the outer surfaces of the two leaflets, the flow clearly shows features of fluid-leaflet interaction in the early stage of the opening process (before $t=0.024$ s), and the flow field agrees well with the rotating movement of the leaflets. Especially near the inner surfaces of the leaflets, the velocity component perpendicular to the leaflet surface closely follows the leaflet surface motion. Its magnitude reduces in the direction from the leaflets to the centre of the flow field. After $t=0.024$ s, with the growing inlet velocity and the development of central channel flow, the relative effect of fluid-leaflet interaction is not so obviously demonstrated as before, and the velocity component perpendicular to the leaflet surfaces is greatly covered by the strong forward flow in the axial direction. Accompanying this change, flows near the inner surfaces of the leaflets evolve into chaotic weak vortex flows under the combined action of the leaflet motion and the strong jet flows in the three channels. In this stage high velocity gradients exist between the strong jet flow regions and the weak vortex flow regions.

Before 0.028 s, the vorticity mainly resides in the near wall region and near the surface of the leaflets. In the later stage of the opening process, the strong vorticity also exists in the central flow channel.

Fig. 10 Vorticity plot from an experiment using the transparent valve; opening process ($t=0.024$ s, $\theta_1=26^\circ$, $\theta_2=27^\circ$)

Fig. 11 Velocity field from an experiment using the transparent valve, fully open

3.2 Fully Open Phase

In this phase, the flow field is very similar to the end stage of the opening process (see Figs. 11 and 12). Flow in the two side channels shows uniform forward velocity of about 0.97 m/s. Flow in the central channel is the strongest in the flow field, with maximum velocity reaching about 1.22 m/s and occupying most of central area. Low velocity regions exist downstream to the valve's leading edges along the inner surface of the leaflets in the central channel, and a strong velocity gradient exists between the strong forward flow in the centre of the central channel and the weak flow near the leaflet inner surfaces. The weak flow regions extend about 0.2 cm downstream to the valve's trailing edges; after that, the flow in the three channels begins to merge.

In the fully open phase, peak vorticity of about 141/s exists in the near wall regions, near the surface of the two leaflets, and in the wake regions downstream to the two leaflets.

3.3 Closing Process

In the closing process, the flow field is filled with vortices and exhibits a chaotic state most of the time (see Figs. 13 and 14). At the beginning of the closing process ($t=0.156$ s),

Fig. 12 Vorticity plot from an experiment using the transparent valve, fully open

Fig. 13 Velocity field from an experiment using the transparent valve, closing process; (a) $t=0.156$ s, $\theta_1=16^\circ$, $\theta_2=13^\circ$; (b) $t=0.256$ s, $\theta_1=21^\circ$, $\theta_2=22^\circ$; (c) $t=0.264$ s, $\theta_1=35^\circ$, $\theta_2=35^\circ$; (d) $t=0.268$ s, $\theta_1=47^\circ$, $\theta_2=46^\circ$; (e) $t=0.292$ s, $\theta_1=59^\circ$, $\theta_2=60^\circ$

Fig. 14 Vorticity plot from an experiment using the transparent valve; closing process ($t=0.264$ s, $\theta_1=35^\circ$, $\theta_2=35^\circ$)

the general flow field still keeps the same flow image as that in the fully open phase, but the forward flow velocity begins to decrease, and the downstream part of the central flow channel begins to be slightly disturbed by certain changes in the valve downstream. From $t=0.256$ s, a backward flow begins to develop in the downstream area of the central flow channel, and becoming stronger during the valve closing process. Under the action of this central backward flow, flows in the two side-channels also change direction and develop as ever-stronger backward flows. The backward flow in the central channel pushes the two leaflets to close, and the induced leaflet motion compresses the fluid near the leaflets' leading tip area, thus producing a central jet in the nozzle part of the central flow channel. This fluid-structure interaction effect becomes clearer from the middle stage of the valve closing process (after $t=0.256$ s). The fluid-structure interaction effect is also more clearly demonstrated by the fluid motion near the leaflets' surfaces. In this stage near the trailing edge of the inner surfaces of the leaflets, the fluid velocity component perpendicular to the leaflet surfaces closely follows the leaflet surface motion, and, in the region near the outer surfaces of the two leaflets, the flow field also agrees well with the rotating movement of the leaflets. This situation is similar to that in the valve opening process, but with reversed directions in leaflet rotation and fluid flow. Near the leading edges of the leaflets in the central flow channel, the flow is chaotic under the combined action of the leaflet motion and the downstream backward flow in the central channel. This situation continues until the end stage of the closing process. At this time ($t=0.292$ s), under various random factors one leaflet reaches the fully closed position earlier than the other. The flow field is thus not symmetric because of the asynchronous movement of the two leaflets. In the downstream area of the flow field, large area of backward flow occupies the central of the flow field. In the vicinity of the valve, flow field is greatly affected by the status of the leaflets. For the stationary leaflet that has already reached its fully closed position, weak random forward and backward flows occupy the near field. For the closing leaflet, the nearby flow field shows strong evidence of driving flow/boundary interaction. Flow near the surface of this leaflet is shown to distinctly follow the rotating movement of the leaflet, with a peak velocity region existing near the leaflet's trailing edge.

Throughout the closing process, strong vorticity mainly exists near the surface of the leaflets, in the near wall regions and in the downstream strong backward flow area.

Fig. 15 Velocity field from an experiment using the transparent valve, fully closed

3.4 Fully Closed Phase

During the fully closed phase, the flow field demonstrates a chaotic motion (see Figs. 15 and 16). At 0.390 s, on the downstream side of the valve, a weak backward flow lingers in the centre of the flow field, with mean velocity of about 0.08 m/s. As the front of the backward flow meets the leaflets, it turns back and interacts with the mainstream, forming vortices near the leaflets. On the upstream side, random motions of about 0.08 m/s mean velocity appear in the flow field. One streak of the backward flow in the upstream side has a peak velocity of 0.16 m/s. At 0.590 s, random motions still exist in the flow field, with diminished velocity.

In the fully closed phase, as the overall flow field has no clear main flow direction, peak vorticity seldom exists in the near wall regions, and is found mainly in the inner area of the flow field.

3.5 Changing of Leaflet Angular Positions and Maximum Flow Velocity in a Heart Cycle

Figure 17 shows the comparison of the angular positions of the leaflets for the two cases of flow in the valve. From Fig. 17 it is observed that the two leaflets in each case move almost

Fig. 16 Vorticity plot of experiment using transparent valve, fully closed

Fig. 17 Change of valve opening angles in a heart cycle

synchronously in the opening and closing processes. Table 1 illustrates the time durations for each phase of valve motion in the two studied cases in a heart cycle. From Fig. 17 and Table 1 it is observed that in the experiment using the transparent model valve, the opening and closing responses are faster than that using the real St. Jude valve. This is the immediate result of the density effect of the leaflet. The lower density of the transparent model valve results in a smaller moment of inertia and hence a faster response. Certain manufacturing errors caused the peak opening angle in the transparent valve model to be slightly larger than in the real St. Jude valve.

In the measurement results it is observed that, in the valve opening process, most of the time the maximum velocity exists near the trailing edges of the two leaflets. In the fully open phase, the peak velocities reside in all three flow channels in the valve. In the closing process, the maximum velocity changes direction and appears not only near the leading edges and the trailing edges of the leaflets, but also in the centre of the flow field downstream from the valve. Figure 18 illustrates the maximum velocity as a function of time in the two studied cases. It is illustrated that maximum velocity reaches a slightly higher absolute value (in both forward and backward flow phases) in the experiment using the transparent model valve than that using the actual St. Jude valve. Again, this is due to the difference of leaflet densities. Since the boundary condition is the same in both cases, such changes of maximum velocity suggest that in the valve with heavier leaflets the flow field tends to be more homogenous.

Table 1 Comparison of time duration for the valve movement in the experiments

Experiment	Current experiment		Subramanian's [18]
	Real SJM 29 valve	SJM 29 valve model	
Opening process (s)	0.056	0.056	0.080
Fully open (s)	0.128	0.122	0.463
Closing process (s)	0.120	0.114	0.020
Fully closed (s)	0.529	0.541	0.270
Total (s)	0.833	0.833	0.833

Fig. 18 Change of maximum velocity in the flow field in a heart cycle

4 Discussion

In the present paper, we have studied the pulsatile flow field in a St. Jude 29 mm bi-leaflet MHV and a transparent SJM 29 valve model under simulated physiological conditions. The DPIV experimental results show that the flow field is partitioned into two side channels and a central channel due to the presence of the two leaflets. In the opening process, flow in the two side channels is first formed and developed. Flow in the central channel develops at the middle stage of the opening process. Forward flow in the three channels exists from the late stage of the opening process, until the early stage of closing. In the opening process and the fully open phase, smooth and uniform flow is observed in most areas of the flow field. During the early closing process, a backward flow develops downstream of the valve and flow in the central channel is disturbed. Under the influence of the backward flow, flow in the central channel becomes chaotic, and later is also adopted into the backward flow. The backward flow in the central channel appears to be the main driving factor in the valve closing. After the valve is fully closed, random flow patterns appear in the flow field. They interact with each other and produce decaying vortices in the field.

In the valve opening process, the main flow develops first in the two side flow channels, and this is followed by flow in the central channel. In the valve closing process, however, the main flow is first established in the central regions of the flow field, and later extends into the side flow regions.

In the valve opening process, the valve leaflet motion produces three flow channels with varying openings. Strong jet flows exist in the nozzles of the three flow channels, while the areas close to the leaflet inner surfaces experience a transition. In the early stage of the opening process, flows in most of leaflet inner surface areas follow the rotating motion of the leaflets and show features of a fluid-structure interaction effect. In the late stage of the opening process, the fluid-structure interaction effect is greatly masked by the strong jet flows in the three channels, and flows near the leaflet inner surfaces evolve into weak vortex flows under the combined action of the leaflet motion and the strong jet flows in the three channels. In this stage, high velocity gradients exist between the strong jet flow regions and the weak vortex flow regions. This suggests that during the opening process, and in the fully open phase, the flow field near the inner surfaces of the leaflets are the potentially high-risk areas for thromboembolism and hemolysis to take place. (This is a rough guideline based on the PIV observation. The detailed situation may change

depending on the exposure time of the blood cells to the local high shear stress produced.) In the closing process, the maximum velocity of the flow field always exists in the centre of the flow field downstream of the valve. In this phase, vortices always spread into the downstream area of the valve.

In the current experiment, for comparison, the pulsatile flow in the real SJM 29 valve is investigated, although the detailed results are not presented. It is understandable that, due to the density difference of the valve leaflet material in the two cases, the time durations for each of the four phases of the valve leaflet motions, the maximum velocity, and the maximum vorticity are different between the result for the real SJM 29 valve and that for the transparent SJM valve model. Table 1 compares the time durations of all four phases of the heart cycle for both experiments. It is observed that in the experiment using the transparent model valve, the opening and closing responses are faster than those using the actual valve. This is the immediate result of the density effect on the leaflet. The lower density of the transparent valve model results in a smaller moment of inertia and hence a faster response. Besides the difference in the time duration, it is also speculated that maximum velocity and maximum vorticity would reach higher values in the experiment using transparent valve model than that using SJM 29 valve, although the detailed values cannot be compared because the flow field areas of interest for measurement in the two case are only partly overlapped. Since the lower density of the leaflet results in a smaller moment of inertia but a higher closing velocity, it is hard to predict whether the leaflet impact on the valve housing wall becomes larger or smaller. Yuan et al. studied the leaflet impact velocity upon valve closure with numerical simulation [26], and predicted a 1.13 m/s leaflet closing velocity, which is greater than the value of 0.82 m/s deduced from the maximum flow velocity in the valve closing process in the current PIV measurement. The leaflet impact velocity is closely related to the squeezing flow and cavitation effect in the MHV upon valve closure, thus it deserves further investigation with both numerical and experimental studies.

Subramanian et al. also conducted a similar PIV experiment on the pulsatile flow in an in-house made bi-leaflet MHV model [18], while their model was installed in the mitral position. Their experiment has much similarity with the current work. The flow field showed the same trend of changes as in the current work, and, in both experiments, jet-like flows in the three flow channels were clearly observed in the fully open phase and the closing process. Also, high vorticity areas were found near leaflet surface regions in both experiments. However, there are also clear differences between the two studies. For the experimental conditions, Subramanian et al.'s experiment was carried out to investigate simulated physiological flow at 3 l/min mean flow rate using a fabricated acrylic model mitral valve, and they used sodium iodide as additive to the blood analogue to match the refractive indexes between the fluid and the test section wall. In contrast, the current experiment is performed to study simulated physiological flow of 5.2 l/min using a St. Jude 29 mm aortic valve and a transparent St. Jude 29 mm valve model. Also, the current research uses image compensation to correct the optical distortion caused by the refractive index problem. This difference in experimental conditions cause the different time durations of each phase in the heart cycle, as shown in Table 1. In the current experiment, the time durations of the opening and the closing processes are similar to Subramanian et al.'s results, but the period for the fully open phase is much shorter and that for the fully closed phase is much longer. Furthermore, the different experiment conditions cause certain variations in the flow field structure. In the early stage of the closing process, the evolution of the 'hairpin' shaped low velocity regions in the central channel and in regions adjacent to the leaflet surface and the wake area as reported by Subramanian et al. was not observed in

the current work. Instead, a backward flow develops downstream of the valve, disturbing the flow in the central channel. Under the influence of this backward flow, forward flow in the central channel evolves to chaos, which is adopted into the backward flow later, while the forward flow downstream to the leaflet's trailing edges evolves to a chaotic pattern, and then changes to regional weak backward flows. These differences suggest that the test condition has great influence on the produced flow field.

In the current research, pulsatile flow in both the real SJM 29 valve and the SJM valve model were investigated with PIV technique. The flow field showed similar features, and the time duration for each of the four phases of the valve motion were generally comparable in the two cases. This suggests that using the transparent valve model in further study of flow in MHVs is justified, while the difference in flow field values due to the density difference of valve leaflet needs to be noted. Using the image correction method instead of the conventional approach of introducing additives to correct the optical distortion helps to maintain the dynamic similarity of the test system.

The shortcoming of the current paper is that due to the effort devoted to the development and validation of image compensation method, no attempt has been made to adapt and enhance the capability of the commercial PIV system for the specific application of pulsatile flow measurement. In future work, in-house developed programs will be used to improve the system performance in achieving adaptation of laser pulse time delay based on instantaneous flow velocity, repetitive measurement of velocity field to get the mean velocity distribution in each specific instant, and using the λ_2 criterion for better detection of the coherent structures of the vortex [21], among other improvements.

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