ABSTRACT

Measurements of the velocity field downstream of an artificial heart valve are performed by using Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PTV). The aim of the paper is to investigate the evolution of the flow field in time in such inhomogeneous, anisotropic and unsteady conditions. To do this, a high-speed video-camera is used to acquire images of the seeding particles illuminated by a continuous infrared LASER; high seeding density conditions are investigated using PIV to perform phase-sampled Eulerian averages, whereas low seeding conditions are used to determine particle trajectories and Lagrangian statistics using PTV. The investigated field corresponds to the region immediately downstream of the artificial valve outlet i.e. the initial ascending part of the aorta. An example of the bi-leaflet valve used in the experiments is given in figure 1, together with the velocity field measured by PIV 50 ms after the opening of the valve (descending part of the systolic peak).

The investigated flow field is extremely complex and the amount of acquired data is very high. A preliminary inspection of such data reveals the following features:

- the very high inhomogeneity and unstationarity of the phenomenon;
- the presence of large scale vortices within the field especially in the Valsalva sinuses and in the wake of the valve leaflets (as the one on the right part of figure 1);
- the strong stresses at the jet-wake interface downstream of the leaflets and close to large-scale vortices.

Fig. 1. An example of the flat bi-leaflet artificial heart valve (a) and the measured velocity vector field (t = 220 ms) with overlapped vortex detection (b). Peak Reynolds number equal to 3200 (D is the valve diameter).
1. MOTIVATION AND OBJECTIVES

A great interest has been recently reconsidered for the investigation of biological flows with new techniques at disposal. This interest depends not only on the very special applications related to crucial diseases for the life of many people, but even on the challenging problems for advanced numerical and experimental methods used in fluid mechanics. In particular, it has been reported that the blood shear stress field is closely involved into specific diseases; low shear regions induce settling of the heaviest blood components and thrombososes, while high shear regions stretch and damage blood cells (Fung 1985, Ku 1997, Grigioni et al. 1999).

Here, the attention is focused onto the flow field downstream of an artificial heart valve. Such a flow field has a complex geometry and is characterised by very high velocity gradients both in space and time; characteristic features of this problem are the order of magnitude of the inertial terms in the Navier-Stokes equations, which are larger than $10^3$ m s$^{-2}$, and a Womersley number up to 10.

In particular, the design of modern artificial heart valve while involves several relevant problems concerning the materials and the valve geometry and shape, simultaneously should be also focused in solving strong fluid mechanics undesired effects:

- to minimise the damaging effect of the flow field (and in particular of the stress field) on blood cells (haemolysis and thrombus formation) (Grigioni et al. 1999, Lu et al. 2001);
- to allow the flow field downstream of the artificial valve to reproduce the physiological field;
- to reduce as much as possible the backflow which affects the valve closing and the leakage phase.

These fundamental tasks cannot be solved without a detailed investigation of the fluid mechanics field. However, it should be considered the unsteady, inhomogeneous and anisotropic nature of such a flow field. It is also very important to consider that the required information on the flow field (mean velocity, $\text{rms}$ and stress values) must be provided simultaneously in a Eulerian framework (to identify the regions where characteristic phenomena are observed) and in a Lagrangian framework (to follow blood elements along their trajectories and to determine cumulative effects (Bludszuweit et al. 1995, Zimmer et al. 2000, Grigioni et al. 2001).

Although advanced numerical methods operate with similar complex geometries and can work with both Eulerian and Lagrangian approach, they do not always achieve the appropriate high resolutions (especially in time). This is why an experimental approach still has to be also considered. Moreover, in the ascending aorta, during the systole, the peak Reynolds number is up to 9000, which leads to a fully developed turbulent flow (Ku 1997). In such a complex and reduced flow field, optical methods for velocity measurements are required, although their use in these conditions is not straightforward. Among them, the use of Particle Image Velocimetry (PIV) techniques (including properly PIV and Particle Tracking Velocimetry (PTV)) now attains the desired high spatial and temporal resolutions; by changing the seeding density conditions, it is also possible to derive information in a Eulerian (PIV and PTV) or a Lagrangian (PTV) framework.

In this paper, the velocity field at the outlet of a flat bi-leaflet artificial heart valve is investigated by using PIV and PTV. The investigated field corresponds to the region immediately downstream the artificial valve outlet i.e. the aortic root. The aim of the paper is to investigate the evolution of the flow field in time using a high-speed video-camera; the PIV technique in high seeding density conditions is used to perform phase-sampled Eulerian averages, whereas low seeding is used to determine particle trajectories and Lagrangian statistics using PTV.

2. EXPERIMENTAL SET-UP

The present experimental study is performed over a 1:1 model of the aortic root downstream of an artificial bi-leaflet heart valve (an example of the valve is shown in figure 1). The determination of the correct artificial valve to be used in a given condition has involved several scientists in the last years; the selection of bi-leaflet valves gained success on the market as the one which better reproduces the most important physiological features. In this work, the attention is not focused on the determination of an optimal artificial valve, rather on how to derive information useful for biomedical purposes from a multi-point measurement technique.
Concerning the set-up of the experimental apparatus (shown in figure 2) which simulates the initial part of the aorta downstream of the valve, it is important to point out that several phenomena should be taken into account for a proper simulation. Particular care has been given to the following items (Barbaro et al. 1998):

- the working fluid has been selected in order to reproduce the kinematics and dynamics of the blood but still preserving the fluid transparency to allow optical access; a solution of de-ionised water and glycerol with a small fraction of sodium chloride for EM flow-meter function has been used;

- the geometry of the aorta (made by blown glass), corresponds as much as possible to the physiological case with the correct scaling (as reported in figure 2b); at the outlet of the valve, the three Valsalva sinuses are placed at equispaced radial positions (120°) and for the artificial case are always void so that they always take part to the fluid dynamics (Reul et al. 1993);

- the elastic properties of the aorta walls are considered by inserting a windkessel model for compensation into the hydraulic circuit which reproduces the systemic circulation; the pressure in the system is controlled through pressure taps positioned along the circuit which is shown in figure 2a;

- the driving system reproducing the periodic heart flow is provided by a mechanical system consisting of a motor, a transmission screw and a piston; the wave forms used to control the system are generated by a computer using also a position transducer as feedback control.

Due to the previously described geometry and depending on the prosthetic valve standard, the flow field is really three-dimensional and measurements on a single plane can highlight only a part of the phenomenon; nonetheless, it is particularly important to investigate the flow field in the Valsalva sinus region on the plane orthogonal to the leaflet plane where the highest stress are expected (on account of the high velocity gradients imposed by the presence of the leaflets). In this case, the bi-leaflet prosthetic valve gives the possibility to measure also in 2D the main features of the flow field (Fontaine et al. 1996).

The behaviour in time of the ventricular and aortic pressure for the typical measurement conditions used in this work (mean flow rate equal to 1 l/min) are given in figure 3. As reported in the figure, the field is highly unsteady (especially the ventricular pressure) and the period of the heart cycle is about 0.8 s; the points A and B correspond to intersections between the two pressure curves. They trigger the possibility for the valve to open (A) and to close (B) for a given number of heart pulse per cycle. The mean aortic pressure is about 100 mmHg. In the same figure, the instantaneous flow rate is also given; it allows to determine exactly the complete opening and closing of the valve. The opening of the valve starts at about 130 ms from the beginning of the cycle, while the maximum instantaneous flow rate is obtained at the systolic peak i.e. at about 170 ms and the complete closing of the valve takes place at about 430 ms. In such a condition (as almost always in the cycle except for the systolic peak), there is a backflow towards the valve, which is typical of mechanical heart valves. The velocity which is used as reference in the following is just obtained from the maximum flow rate and is equal to about 0.626 m/s; using the valve nominal diameter as reference length ($D = 19$ mm), the Reynolds number is equal to about 3200.

The measurements region (about 3 cm $\times$ 2 cm, at the middle plane of the aortic arch) is illuminated by a light sheet from an infrared laser (power = 12 W, wavelength = 800 nm); the light scattered by strongly basic anion exchanging particles (mean size = 10 µm) is acquired by a high-speed video-camera (frame rate = 1 KHz, resolution (at this frame rate)= 320 $\times$ 156 pixel) and transferred on a PC for further analysis. An example of the acquired images is given in figure 4; the contours clearly show the boundaries of the measurement region with the artificial valve at the top and one sinus of Valsalva intersected by the measurement plane at the right side of the figure 1b, the other two sinuses being symmetrically disposed at opposite sides of the measurement plane. The data are acquired at a discharge condition equal to about 1 l/min, at a mean aortic pressure equal to 100 mmHg; in terms of frame number, the periodicity of phenomenon (0.8 s) is about 800 frames. About 60000 images have been acquired, which correspond to about 90 periods; each image sequence is triggered by the driving system to perform phase sampling.
Images are acquired in the limits of low and moderate particle concentrations to be analysed using Particle Tracking Velocimetry (PTV) and Particle Image Velocimetry (PIV), respectively. The former is performed using a frame by frame tracking procedure to obtain particle trajectories and to compute Lagrangian statistics (Cenedese and Querzoli 2000; on the present flow field it allows to validate about 10 tracer images per frame and to follow them for several consecutive frames. As typical for PTV, data are obtained at random positions in space and interpolation algorithms are required to derive results on a regular grid and to compute Eulerian statistics.

For PIV, cross-correlations between consecutive frames are performed; the use of a high-speed video camera enables to follow the time evolution with a quite high resolution \((\Delta t = 0.001 \text{ s}, \Delta t u_{\text{max}}/D \approx 0.05)\). The PIV algorithm is a classical one which employs advanced improvements for image analysis by cross-correlation functions as the window-offset and the sub-pixel Gaussian interpolation. (AEA Visiflow®). The image analysis was performed using 32 pixel × 32 pixel windows with 75% overlapping. In figure 4, an example of image analysis slightly before the systolic peak (at \(190 \text{ ms after the beginning of the heart cycle}\) is given; on the left side of the image, the flow is mostly directed towards the bottom (initial section of the aorta), while on the right side there is a large vortex.
For both PTV and PIV data, due to the periodic nature of the flow field, images have to be analysed using phase averaging techniques; this means that averages are computed by considering velocity samples at the same phase for every cycle. As described before, about 90 heart cycles are used for phase averaging and this procedure is repeated for the whole cycle so that about 800 average velocity fields are obtained (the possibility of a further average in time has been also considered, but this has been rejected due to the strong observed unsteadiness, especially during the systole). The previous procedure allows us to evaluate the evolution of the flow field in space (within each average field) and in time (at a given phase) as requested for the considered flow field.

3. PRELIMINARY FLOW VISUALIZATIONS

Preliminary flow visualizations have been performed using multi-exposure and long exposure image acquisition procedures. The frame rate was selected at 250 Hz (instead of 1 kHz) so that the tracer particles appear as streaks on the images. In figure 5a, a multi-exposure image is given (a different colour is used for each frame); it corresponds to about 180 ms from the beginning of the heart cycle, i.e. immediately after the systolic peak. It is interesting to observe the formation of wake vortices downstream of the left leaflet (indicated by the left upper arrow) with growing size. They correspond to the well known starting vortices of a wing which are convected downstream by the mean flow.
Due to the non axisymmetric configuration, the observed features are different from those on the right hand side of the field, within the Valsalva sinus, where a re-circulation region is forming. This is shown in greater detail in figures 5b and 5c (using long time exposure). Before the complete aperture of the valve (figure 5b), the flow still follows the sinus geometry without any major separation; on the other hand, after the aperture of the right leaflet (figure 5c) there is a vortex as large as the sinus which grows within the sinus. From the length of the particle traces, the velocity within the field can be estimated to be larger than 1 m/s, i.e. substantially higher than the reference velocity derived from flow rate measurements. The behaviours noticed in these visualisations must be confirmed by quantitative measurements.

4. RESULTS OF PIV MEASUREMENTS

A sequence of eight phase-averaged vector fields derived from PIV measurements is given in figure 6 (the axes x and y are oriented respectively parallel and orthogonal to the leaflet plane (when closed) and the corresponding velocity components are denoted as \( u \) and \( v \)); in the figures, the time interval occurred after the beginning of the heart cycle and the position of the leaflets are also given.

For a proper vortex identification, vorticity plots should not be used due to the fact that sometimes they hide vortical structures in shear flows. Jeong and Hussain (1995) proposed a vortex detection criterion based on the eigenvalues of the velocity gradient tensor which overcomes this problem.
Fig. 5. Flow visualisations using multiple frame overlapping at the systolic peak (a) and long exposure time acquisitions in the Valsalva sinus (b, c). The vertical arrows indicate the position of the two leaflets when opened; images (b) and (c) correspond to 150ms and 180ms after the beginning of the cycle. Frame rate equal to 250 Hz.

In a two-dimensional flow, it is sufficient to verify that the following invariant quantity

\[ \Delta = \left( \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \right)^2 - 4 \left( \frac{\partial u}{\partial x} \frac{\partial v}{\partial y} - \frac{\partial u}{\partial y} \frac{\partial v}{\partial x} \right) \]

is negative. The above criterion can be successfully extended to the two-dimensional analysis of three-dimensional flows (such as the one of this experiment) since they permit anyway the identification of the vortices with axis orthogonal to the investigated plane. Colour maps of the invariant \( \Delta \) are overlapped to the vector fields given in figure 6; they allow to identify and to follow vortical structures quite clearly.

During the systole (which starts at \( t = 135 \) ms), in about 40 ms the velocity abruptly rises from almost zero to 0.6 m/s. In this phase, the velocity vectors are directed almost vertically all over the field except for small wakes downstream the leaflet (\( t = 150 - 160 \) ms). At the systolic peak (\( t = 165 - 170 \) ms), there are three major vortical structures, roughly corresponding to the Valsalva sinus and the leaflets wakes. The size of the vortices is a relevant fraction of the reference length (about 0.2 - 0.3 \( D \)), while their trajectories (not shown) reveal that during the heart cycle they move downstream following the wall geometry of the Valsalva sinus. During the reduced ejection, the flow decelerates more slowly to an almost zero mean velocity (in about 200 ms); in this phase two of the previously observed vortices persist within the field (they are strengthened by flow coming out from the valve). After this phase, the velocity almost vanishes even if a small backflow (already noticed in the instantaneous flow rate given in figure 3) is observed. These observations confirm the fact that the phenomenon is strongly unsteady and that fluctuations on phase-averaged quantities are observed on a time scale in the order of a few milliseconds (at least during the systolic phase).
Fig. 6. Sequence of eight phase-averaged vector fields with overlapped vortex identification criterion by Jeong and Hussain (1995); in the figures, the positions of the leaflets (at the top), the time interval from the beginning of the heart cycle and the maximum reference velocity (on the right) are also given.
For a detailed knowledge of the flow field, velocity profiles are much more useful than vector maps; the former can be derived from the latter and compared for different times from the beginning of the heart cycle at a given position. In figure 7, several of these profiles along the transverse direction (x) for the axial velocity component (u) are reported; they are obtained at the largest measurement section which corresponds to the centre of the Valsalva sinus (0.71 cm from valve plane and y/d = 0.5 in the image-relative reference system). As previously noticed, there is a strong variation (more than two order of magnitude) in the absolute value of the velocity during the cycle; this also confirms the perfect applicability of the measurement technique to the present experimental conditions. Secondly, it is important to point out that during the systole the velocity profile shows an increasing asymmetry so that the flow coming from the left leaflet is faster than the one from the right one (figure 7a). This phenomenon is observed even when two distinct jets coming from the leaflet openings are present (figures 7a); the configuration moves into a three jet condition during the systolic peak when also at the centre of the field there is an effective flow (figure 7b). During the deceleration phase (figure 7c), the flow configuration returns to be almost symmetric showing also a clear backflow (even at this distance from the valve). The diastolic phase (figure 7d) is characterized by a constant velocity backflow, necessary to avoid fluid stagnation near the valve and the possibility of hinges failure. The previous observations, coupled with those on the vortex in the Valsalva sinus, suggest that the vortical structure in the sinus modifies the local flow field thus deviating the flow towards the left hand side of the field; this should provide different forces on flow elements passing on the left or right side of the valve.
This is confirmed by the measured phase averaged total stress field (shear stress + Reynolds stress) calculated as

$$\tau_{tot} = \mu \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) - \rho u'v'$$

whose profiles are given in figure 8. The four peaks observed during the systole correspond to the presence of two jets (figure 8a); the total shear (especially on the left hand part of the field) exceeds 5N/m². The configuration changes after the systolic peak when the right and central part of the field attain the larger stress (up to 50N/m²); to evaluate this phenomenon, it is important to point out that the major contribution (more than 90 %) to the total stress is given by the Reynolds stress contribution. Therefore, the vortex structure in the Valsalva sinus squeezes the jet passing through the right hole of the valve, toward the centre of the aortic root. This means an increase of the velocity gradients at the interface between the fluid outgoing from the valve and the recirculating flow within the Valsalva sinus. After the valve closing, the total stress decreases to values which are about 100 times smaller than before.

5. RESULTS OF PTV MEASUREMENTS
Preliminary PTV measurements have been also performed; in figure 9, the trajectories obtained by PTV before the systolic peak (figure 9a) and after that (figure 9b) are given; the trajectories have a colour code which is related to their starting region when they pass at the valve position. It is clearly observed that particles from the centre have almost no intersections with those from the side before the systolic peak; on the other hand, there is a spreading of the central jet during the diastole. Moreover, in these conditions the re-circulating motions within the Valsalva sinus are completely established. The measured trajectories are the basis for a further evaluation of Lagrangian statistics coupled with the previous measured Eulerian quantities by PIV.

6. COMMENTS AND CONCLUSIONS

Measurements of the velocity field downstream an artificial heart valve are performed using PIV and PTV. The use of a high – speed video-camera allows to derive information both in time and space which are required for such inhomogeneous, unsteady field. The measurements revealed the following features:

- the field is strongly inhomogeneous and unsteady;
- large scale vortices are detected especially in the Valsalva sinus and in the wake of the valve leaflets;
- the strong shear stresses at the jet-wake interface downstream of the leaflets and close to the large-scale vortices.

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Fig. 9. Overlapping of particle trajectories measured by PTV during the time interval $t = (140 – 165) \ s$ (a) and $t = (200 – 340) \ s$ (b) after the beginning of the heart cycle.

REFERENCES


