

3D reconstruction of the flow inside the left ventricle model

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Abstract A detailed comprehension of the blood flow inside the cardiac chambers and the principal arterial vessels is a relevant argument, both from the scientific point of view and for its social consequences. In this framework, the study of the flow inside the left ventricle is acquiring more and more interest due to clinical observations showing that an anomalous filling of the ventricle (i.e. the diastole phase) can be considered as a symptom of a subsequent anomalous systolic phase. This can reveal in a reduction of the heart's capability to pump the blood through the aortic valve into the circulation system; in this sense the knowledge of the fluid dynamics associated with the diastole phase can give an useful contribution to the diagnostic procedures. The objective of this study is to investigate the three-dimensional structure of the velocity field during the ventricle filling by analyzing the results obtained from time resolved velocity measurements in a flexible ventricle model. The laboratory model has been designed to reproduce any arbitrarily assigned law of variation of the ventricular volume with time, in the present study a physiologically shaped curve has been used. Velocity measurements have performed via an image analysis technique based on the Feature Tracking algorithm. The time evolution of the 2D velocity field has measured on two sets of 11 parallel planes being the two sets of planes orthogonal, on each plane a series of cycles have been acquired and phase average computed. The data related to the two views have combined in order to reconstruct the three-dimensional, three-component (3D3C) average velocity field. The obtained flow show a qualitative agreement with *in vivo* observations of the human cardiac flow: the geometrical arrangements of the atria and the ventricles redirect the flow with sinous, clearly asymmetric paths, thereby minimizing dissipative interaction between entering, recirculating and outflowing streams. Based on the obtained results, the relevance of a 3D characterization of this type of flow is then discussed.

1. Introduction

The flow inside the left ventricle represents one of the most interesting problem in biological fluid dynamics, depending on its relevance on the global functionality of the heart pump. Heart failure can arise from any condition that compromises the contractility of the heart (systolic heart failure), or that interferes with the heart's ability to relax (diastolic heart failure). Due to the complexity of the relationship between left ventricular filling and ejection, the diastolic function must be contemplated for the assessment of global left ventricular systolic function: impairment of diastolic filling may in fact result in a reduced pump function.

Since the early twentieth century, technological advances have had a major impact on diagnostic tools, therapeutic approaches, and instrumentation in the field of cardiology. However, despite all the progress achieved in medical sciences, cardiovascular diseases are still the leading cause of mortality and morbidity in the industrialized world. From micro to macro, our limited understanding of the heart's function continues to represent an obstacle to our ability to design strategies for proper detection and effective treatment of cardiac dysfunctions. Thus, the major challenge in solving the problem of dysfunctions in the cardiovascular system arises mainly from an inadequate understanding of the basic mechanisms governing the function of the system itself. In this sense improvements of the description of the phenomena supported by physically-based modelling of the physiological processes, can play a role in the possibility of early diagnosis and in the development of therapeutic procedures.

One of the most important fluid phenomena involved in the left ventricular diastolic flow is related to the presence of the vortical structures that develop with the strong jet that enters through the mitral valve. Left ventricular fluid dynamics has been studied by several authors with particular

attention on its filling (diastolic) phase, where the interaction between flow and tissues is found to be relevant in the heart functions (Mandinov et al. 2000; Vasan and Levy 2000). Several studies of the flow inside the left ventricle permitted the interpretation of diagnostic images in terms of vortex dynamics (Steen and Steen 1994; Vierendeels et al. 2002; Baccani et al. 2002) by comparison of the space–time map of the axial velocity with clinical echo-Doppler imaging (transmitral M-mode). These studies were performed using axially symmetric models. The presence of a three dimensional flow structure was recognized since the early experimental studies (Bellhouse 1972; Reul et al. 1981; Wieting and Stripling 1984). They observed that the transmitral jet quickly deforms into an asymmetric vortex wake. The pictures of the flow field typically show a large vortex behind the anterior mitral valve leaflet and a circulatory cell that persists until the systolic ejection.

Three-dimensional numerical models capturing the main flow patterns have been developed by several authors (Saber et al. 2001; Lemmon and Yoganathan 2000). The details of the three-dimensional flow during diastole have also been investigated numerically for an ideal left ventricle corresponding to a healthy child (Domenichini et al. 2005). This study has shown that the vortex ring wake developing behind the mitral valve follows a curved path that turns toward the lateral wall. One side of the ring occupies the center of the cavity and gives rise to the experimentally observed circulation. A study based on the same numerical model has shown that the intraventricular energy dissipation is significantly affected by the structure of the vortex flow (Pedrizzetti and Domenichini 2005).

Recent experiments, using image velocimetry techniques and high-speed cameras (Brucker et al. 2002; Cooke et al. 2004; Cenedese et al. 2005; Akutsu et al. 2005; Pierrakos et al. 2005; Querzoli et al. 2010) have shown quantification capabilities in particular for assessing the impact of prosthetic valves on intraventricular flow. As single point or planar measurements these analysis are intrinsically limited in the description of the phenomena.

To overcome this limitation and to perform a step forward in the characterization of the intraventricular flow, in this study we investigate the three-dimensional structure of the velocity field in a flexible left ventricle laboratory model. Obtained results show the asymmetric redirection of the jet that enters the ventricle, in this way supporting the results achieved from the *in vivo* evidences.

2. Definitions and Methods

The ventricular flow was simulated by means of the laboratory model shown in Fig. 1, already used for previous investigations (Cenedese et al. 2005; Querzoli et al. 2010). A flexible, transparent sack made of silicone rubber (Fig. 2), simulated the left ventricle and allowed for optical access. The sack was secured on a circular plate, 56 mm in diameter, connected by means of two Plexiglas conduits to a constant head reservoir. Along the outlet (aortic) and the inlet (mitral) conduits two one-way valves were mounted. During the experiments the function of the natural mitral valve was performed by a one-way valve along the inlet conduit, so to obtain a nearly uniform velocity profile. A rectangular tank (A) with transparent, Plexiglas walls housed the left-ventricular model. The volume of the ventricle was changed by moving the piston (D), placed on the side of the tank. The piston is driven by a linear motor (C), controlled by a personal computer by means of a speed-feedback servo-control. The speed input-signal to the motor has been obtained by digitizing a real tracing of an echocardiograph, scaling it with the required period and stroke volume, and finally taking the temporal derivative. In Fig. 3, the variation of the ventricular volume $\Delta V(t)$, and its derivative, $Q(t)$, are plotted as a function of time. $Q(t)$ represents the flow rate through the mitral during the diastole (0.00T–0.75T), and through the aortic valve during the systole (0.75T–1.00T).

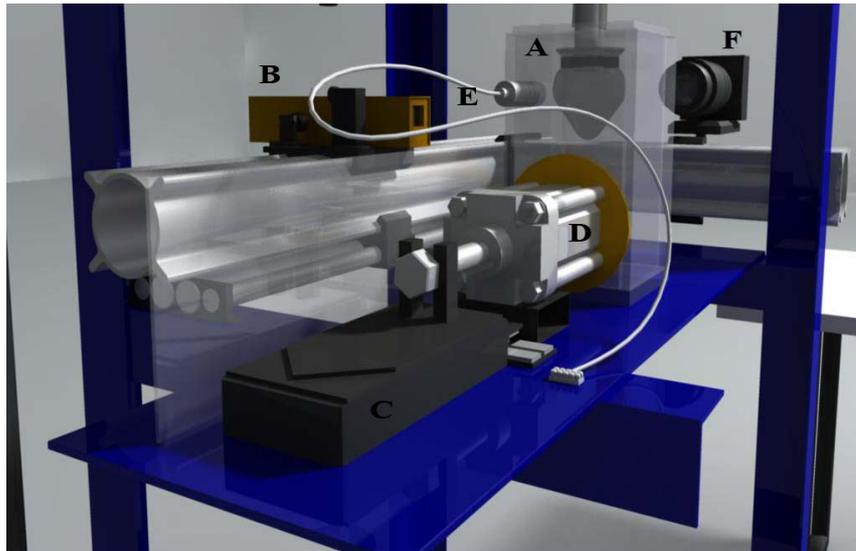


Fig. 1. Experimental set-up. **A:** Ventricle chamber; **B:** Laser; **C:** Motor; **D:** Piston; **E:** pressure transducer; **F:** fast camera



Fig. 2. Ventricle Model

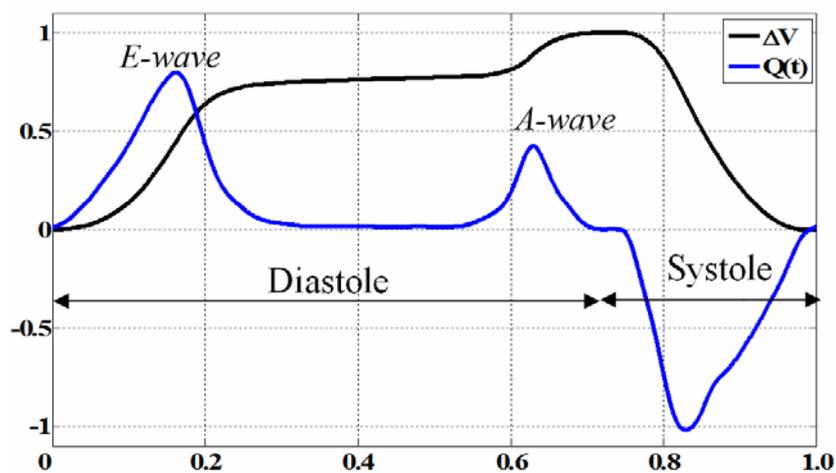


Fig. 3. Time law of variation of non-dimensional ventricular volume (black line) and flow-rate (blue line)

The diastole is characterized by two peaks separated by an interval, called diastasis, during which the ventricle volume is constant. The first peak, which corresponds to the dilation of the ventricle, is

called E-wave. The second peak, called A-wave, is due to the contraction of the atrium. The vertical mid-plane of the ventricular cavity was illuminated by a 12 W, infrared laser. The working fluid inside the ventricle (distilled water) was seeded with neutrally buoyant particles. The average particle diameter was about 30 μm . A high-speed digital camera ($F = 250$ frames/s, 1280x1024 pixel resolution) was triggered by the motor to capture the time evolution of the phenomenon at known instants of the cycle. The acquired images were analyzed to measure the velocity fields on a regular grid by means of a feature tracking algorithm.

The resulting spatiotemporal resolution was 1/250 s in time and 0.12 mm in space; high enough to identify the vortical structures generated in the left ventricle and to follow their evolution during the whole cardiac cycle.

The dynamic flow similarity (i.e. matching the ratio of inertial to viscous effects) between the natural heart and the experimental model, requires the equality of Reynolds and Womersley numbers:

$$Re = \frac{U \cdot D}{\nu} \quad Wo = \sqrt{\frac{D^2}{T \cdot \nu}}$$

where D is the maximum diameter of the ventricle, U the peak velocity through the mitral, ν the kinematic viscosity of the working fluid. The geometrical ratio was 1:1.

The phase averaged velocity fields presented below, and the relative statistics are derived from the acquisition of fifty cycles. Experiments parameters are listed in Table 1. The conditions of the experiment have been chosen so that the non-dimensional parameters are within the physiological range. All the showed results have performed using this parameters' setting.

Stroke Volume [ml]	T [s]	U [m/s]	Re	Wo
64	6	0.145	8322	22

Table 1. Experiments parameters

3. Results

3.1 2D Vorticity maps and 3D velocity field reconstruction

To reconstruct the 3D structure of the ventricle flow during the ventricle filling, measurements obtained from two sets of planar measurements acquired from two orthogonal views have been employed. In particular for each view we acquire 50 cycles of flow images on 11 parallel planes spaced of 4 mm (Fig. 4). Acquired images are then analyzed using a Feature Tracking algorithm (Cenedese et al. 2005). This method allows reconstructing the velocity field evolution in a Lagrangian framework. In these experiments at least 6000 particle trajectories have been simultaneously reconstructed during the cardiac cycles. After the interpolation of velocity vectors over a regular grid, the time evolution of Eulerian instantaneous velocity fields is obtained and derived quantities i.e. vorticity, velocity gradient and kinetic energy, have been evaluated. As a result a description of vortical structures dynamical evolution during the whole cardiac cycle is obtained.

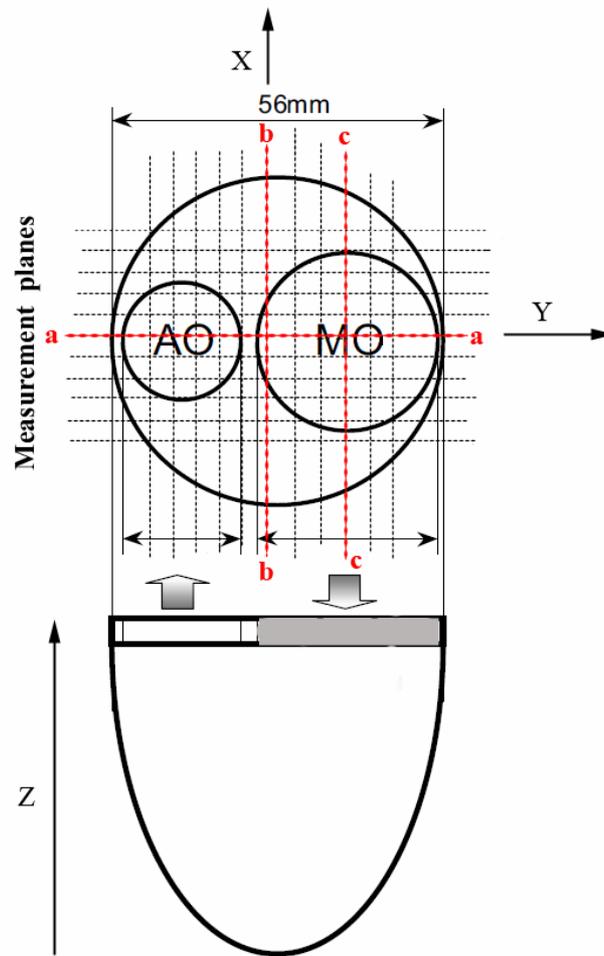


Fig. 4. Position of all the measurement planes (red and black dashed lines). Results for the planes indicated with the dashed red lines (a-a, b-b, c-c sections) are shown in the following section. AO: aortic orifice. MO: mitral orifice

The descriptions of 2D time evolutions of the phenomenon are shown in Fig. 5, 6 and 7, where phases averaged on 50 cycles of velocity and vorticity fields are plotted. The six most meaningful stages has been chosen, in each figure the non-dimensional time with respect to cycle period is indicated; also the flow-rate curve with a red dot indicating the current instant is inserted at the bottom left corner. Fig. 5 is related to the Y-Z view and the plots correspond to measurements in the middle-plane (a-a plane, Fig. 4).

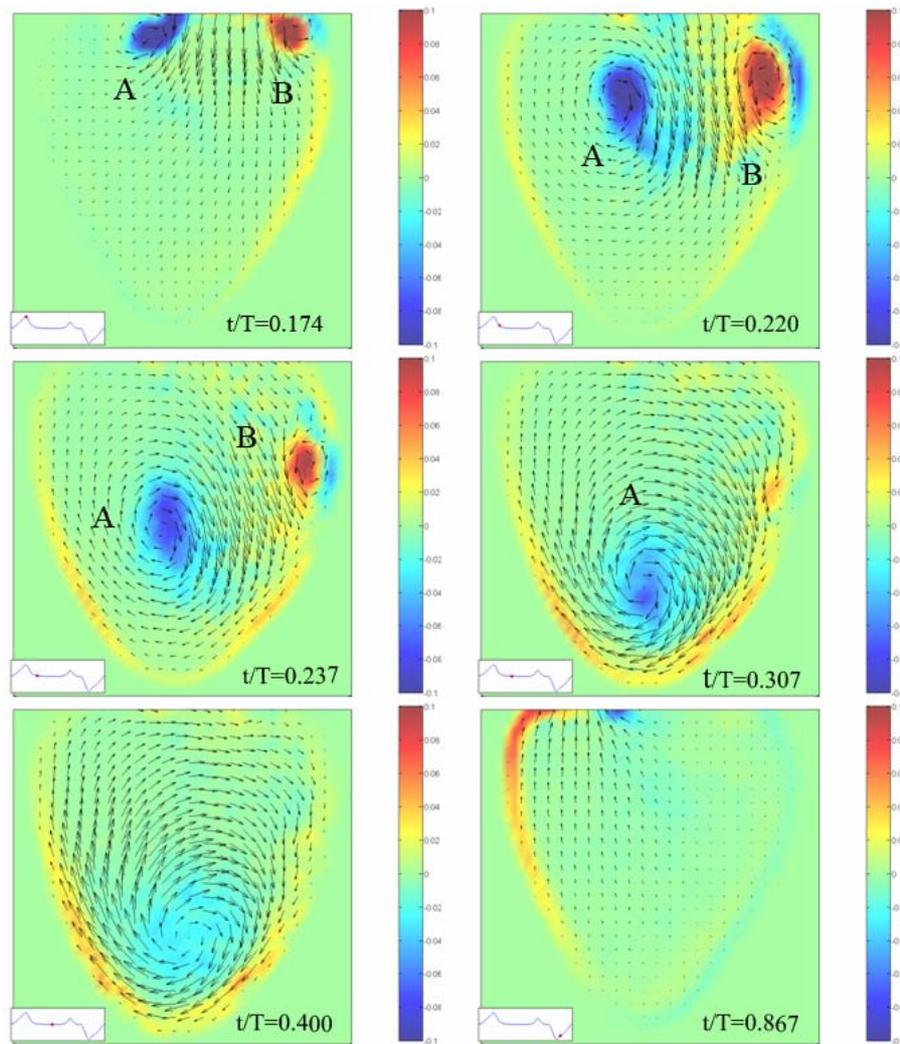


Fig. 5. Y-Z View (a-a plane, $X = 0$): velocity and vorticity fields evolution

At $t/T = 0.174$, corresponding to the E-wave peak, the vorticity layer at the jet edges has begun to roll itself up to create a vortex ring which moves through the ventricle main axis. Two peaks are observed in the vorticity map (A, B) and the measured vorticity reaches at that point of the cycle its maximum value. At $t/T = 0.220$ the vortex B begins to interact with the ventricle wall; the non-slip condition determines a negative vorticity layer at the wall, which tends to slow down the vortex B in its downward motion, and to increase the dissipating effects due to high velocity gradients. At the end of E-wave ($t/T = 0.237$), the vortex ring separates from the vorticity layer generated by the trailing jet (the so called pinch-off). Vortex B, which is slower, covered a shorter distance, while vortex A has now propagated to the centre of the ventricle, becoming sensitively larger than vortex B. At $t/T = 0.307$, vortex A reaches the bottom wall of the ventricle in proximity of the ventricle apex, its dimension being still increased; even vortex B has reached the wall and begins to go back upwards, while its dimensions tend to diminish. Instant $t/T = 0.400$ corresponds to the centre of the diastasis, that is the time interval during which the ventricle volume remains constant. At this stage the structures, being generated during the first diastolic peak, almost completely vanish; both velocity and vorticity do not have meaningful features except for the presence of vortex A, extremely weak, which remains in proximity of the ventricle apex. At last, during the systolic peak ($t/T=0.867$), any flow structure is destroyed and an exit flow is generated; there is still a partial memory of diastolic flow and in fact it is possible to recognize a main circulation upwards along the walls and to the aortic valve.

Fig. 6 shows the X-Z view (b-b plane, Fig. 4) and give a different and a more complicated picture. At $t/T = 0.174$, that corresponds to the E-wave peak, the jet enters the ventricle and two peaks (A' e B') are observed in the vorticity map.

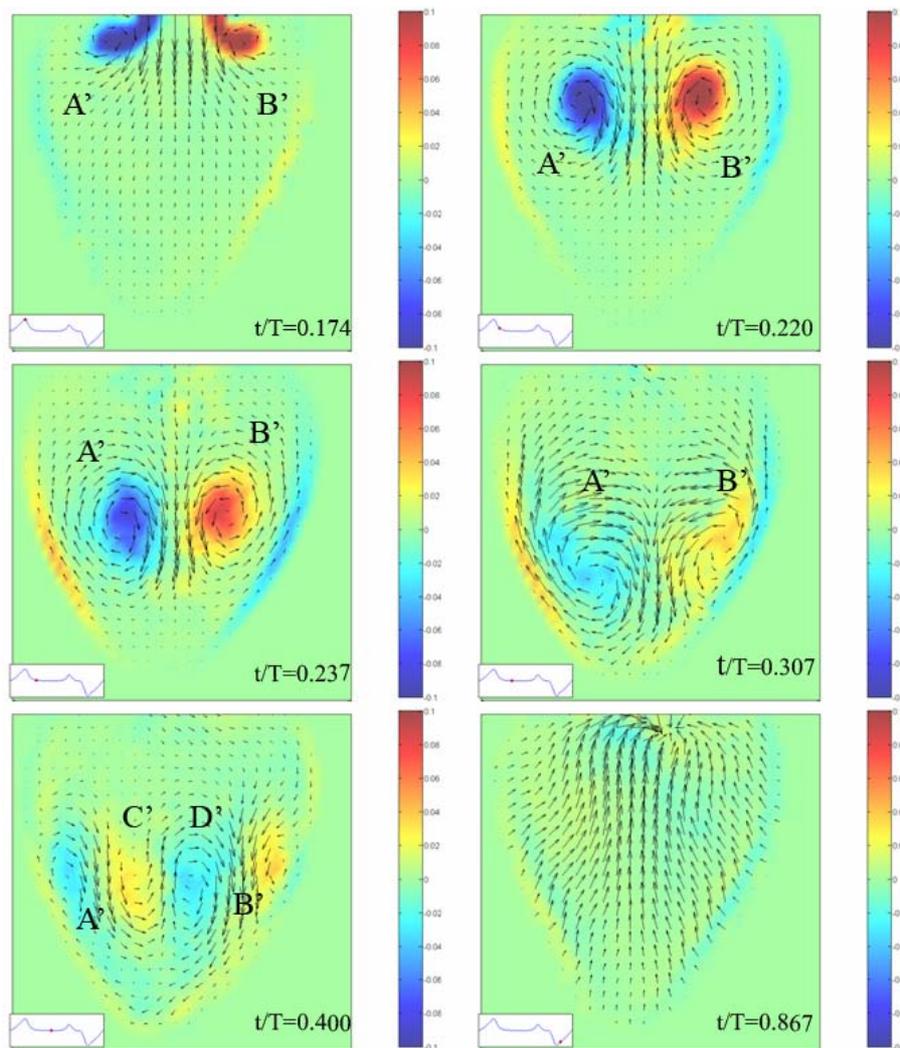


Fig. 6. X-Z view (b-b plane, $Y = 0$): velocity and vorticity field evolution

At the end of the E-wave ($t/T=0.220$) the jet is strongly symmetric, the vorticity peaks moves more or less at the same velocity and at $t/T=0.237$ they separate from the vorticity layer generated by the trailing jet (pinch-off phenomenon, the same as the Y-Z view description). During the diastasis phase the vorticity map is only characterized by the presence of the peaks A' and B' ($t/T=0.307$) next to the ventricle's apex; their dimension being still increased. At $t/T=0.400$ a second vortical structure (apparent by the peaks C' and D') is induced by the interaction with the surrounding flow. In Fig. 7 the 2D measurements in the c-c plane (Fig. 4) located in the middle of the mitral orifice are shown.

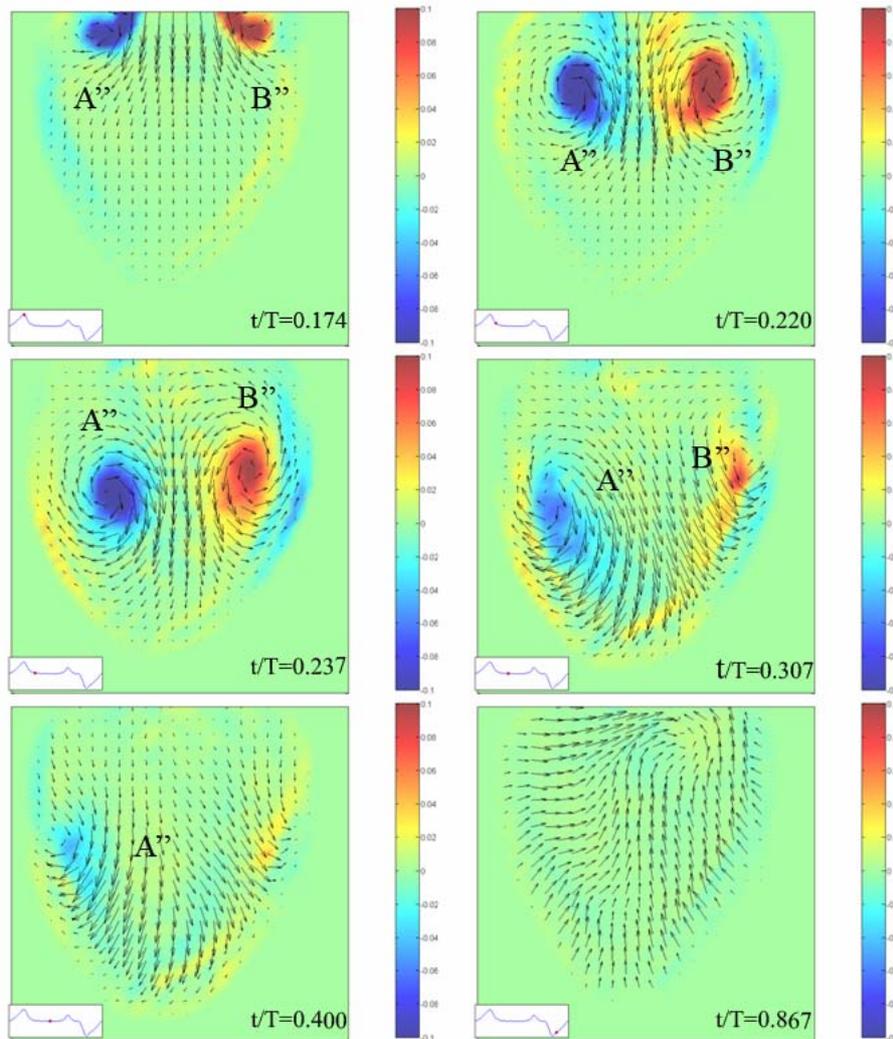


Fig. 7. X-Z view (c-c plane): velocity and vorticity field evolution

The vorticity and velocity fields show a less symmetric trajectory that in the centre of the circular plate (b-b plane in the X-Z view, Fig. 4): the movement of the vortex ring through the ventricle follows a trajectory towards the low in the right side. This result in association with the Y-Z view analysis, suggests that the three-dimensional movement of the flow is associated with an asymmetric flow redirection in the ventricle model, mainly due to the non-axial position of the mitral orifice, the vortex ring interaction with the surrounding flow inside the ventricle, the interaction with the ventricle walls. The result related to the jet's asymmetry during the ventricle filling has been confirmed by the visualization of the 3D vertical velocity field.

Fig. 8, 9 and 10 show the velocity component along the Z axis, U_z , at three salient instants: end of the E-wave ($t/T=0.220$), during the diastasis phase ($t/T=0.307$) and at the end of the diastasis itself ($t/T=0.425$), the represented red and blue isosurfaces corresponds respectively to $U_z = 5.4$ cm/s and $U_z = -5.4$ cm/s.

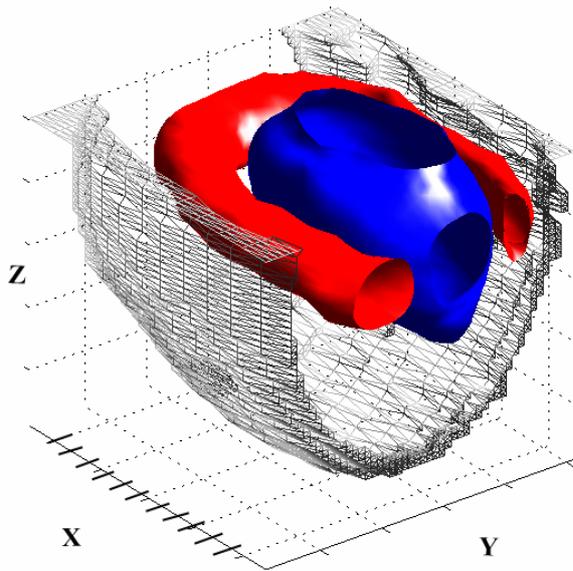


Fig. 8. Vertical velocity isosurface: $U_z = -5.4$ cm/s (blue), $U_z = 5.4$ cm/s (red); $t/T=0.220$

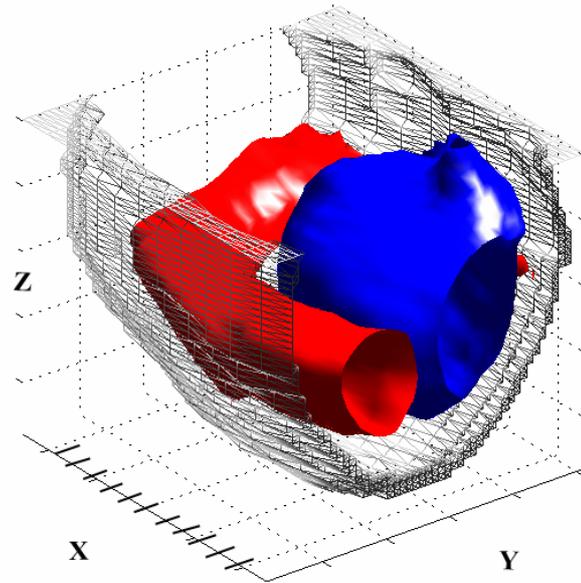


Fig. 9. Vertical velocity isosurface: $U_z = -5.4$ cm/s (blue), $U_z = 5.4$ cm/s (red); $t/T=0.307$

Fig. 8 shows the end of the first diastolic peak when the central jet enters the ventricle: the velocity field is characterized by negative velocities that are located in a central position (blue surface) whereas the positive velocity (red surface) starts to develop at the edges.

At $t/T=0.307$ (Fig. 9) the vortex ring moves through the ventricle along an oblique direction: the less intense velocity field is the positive one, it is located at the wall and begins to decrease. The negative velocities are more or less in the middle of the ventricle.

At the end of the diastasis phase ($t/T=0.425$, Fig. 10) it is recognizable only a single circulation through the ventricle that is characterized by a negative velocity field that moves down while the positive velocity field comes up along the left ventricle wall.

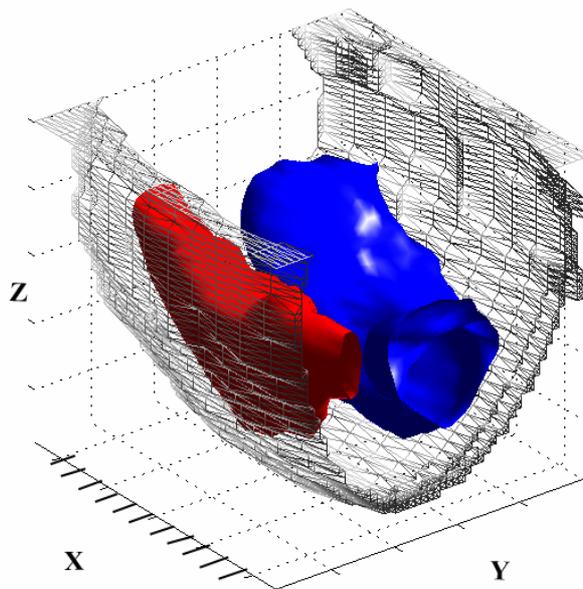


Fig. 10. Vertical velocity isosurfaces: $U_z = -5.4$ cm/s (blue), $U_z = 5.4$ cm/s (red); $t/T=0.425$

In agreement with previous evidences (Pedrizzetti and Domenichini 2005), our results indicates a redirection of the entering jet towards the side wall and an asymmetric development of the vortex ring. As a matter of fact, the vortex side closer to the ventricular wall dissipates faster while the opposite vortex portion fully occupies the ventricle's apex (clockwise circulation at $t/T = 0.400$ in Fig. 5) with a basically two-dimensional structure.

4. Discussion

The 3D structure of the flow inside the left ventricle has been experimentally analyzed and described in terms of velocity and vorticity fields during whole the cardiac cycle and during the diastole i.e. when most of the flow complexities develop. The analysis of the vertical velocities qualitatively confirms the deflection of the mitral jet toward the lateral wall.

The most important goal achieved in this study is the agreement with *in vivo* observations and with other experimental evidences that indicate an apparent asymmetry of the incoming flow field due to the non-axial position of the orifice and to the leaflet sizes and shapes found in the *in vivo* studies. Specifically, with the anterior native leaflet being longer than the posterior, the vortex shedding initiates from the latter, followed by a smaller vortex shed from the anterior leaflet. In turn, the larger vortex on the posterior side induces a shift towards the apex. Fig. 11 provides a qualitative illustration of the fundamental physical phenomena observed inside the left ventricle through the natural valves tested during the current experiment, accordingly with the observed flow pattern of the natural valve as indicated in an MRI measurement by Laas et al. (2000) and in the laboratory model of Reul et al. (1981).

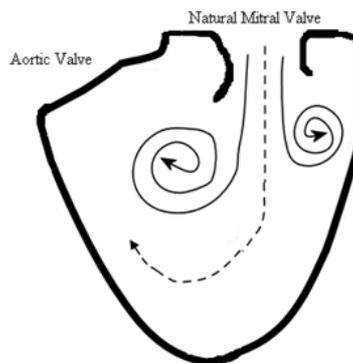


Fig. 11. Schematic of the flow inside the natural LV

Our results highlight the need for a three-dimensional analysis of these phenomena to characterize its complexity. Nevertheless a reorganization of the three-dimensional vortex ring in a single, mainly two-dimensional structure, during its evolution is also observed and it represents an interesting aspect to be investigated in future work. As a matter of fact it is related to the asymmetric pattern of the diastolic entering jet whose reduction (i.e. a possible flow symmetrization) has found to be related to several cardiac diseases (Pedrizzetti and Domenichini 2005).

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