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On the Left Ventricular Vortex Reversal after Mitral Valve Replacement

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Abstract—The blood flow in the human left ventricle is known to develop a vortical motion that should facilitate the ejection of blood into the primary circulation. This study shows that such a rotary motion can be totally reversed after the implant of a prosthetic valve. This phenomenon, in agreement with clinical observation, appears mostly imputable to the symmetry of the implant. The reversed rotation increases energy dissipation and modifies the pressure distribution with the potential development of new pathologies. The results provide preliminary, physically based, elements for the improvement of surgical procedures or prosthesis.

Keywords—Cardiac fluid dynamics, Vortex dynamics, Left ventricular flow.

INTRODUCTION

The left ventricle (LV) is the most energetic chamber of the human heart that pushes the blood to supply oxygen and nutrients to tissues and parenchymas in the whole body. Its performance is clinically described in terms of global volumetric measures (ejection fraction, cardiac output) or through the contractile strength of individual myocardial segments. Although strongly connected with the theme of energy consumption and system efficiency, fluid dynamics and its space-time arrangement inside the heart is of little or no use in the clinical setting and it is not taken into account for the design of therapeutic procedures. LV fluid dynamics is known to develop a circulatory, vortical motion that accompanies the redirection of the rapid flow entering from the mitral valve toward the opposite facing outflow tract.[7,10] The presence of the intraventricular vortex plays a central role in the overall synchronicity of the beating heart. Its dynamics are connected with the natural ventricular rhythm while its perturbation correlates with diseases.[9] In fact, the quantification of such a vortex is now driving novel attempts to improve understanding of cardiac diseases.[4,5]

The intraventricular circulation is a consequence of the asymmetry of the mitral orifice with respect to the ventricular chamber, where the eccentric inflow gives rise to an asymmetric rotatory motion. Modifications of the mitral valve geometry, due to valvular diseases or to the implant of artificial valves, may have a negative impact on the cardiac vorticity. Only few attempts have been made to understand the effect of prosthetic valves on the intraventricular fluid dynamics because of the lack of both analytical approaches and precise quantitative indicators; nevertheless, it has been recognized that valvular surgery indeed influences the resulting LV flow.[1,8]

The present theoretical study emerged from the systematic analysis of the intraventricular flow field in a group of 40 randomized patients that underwent elective mitral valve substitution in the past five years. The artificial valves were either mechanical or tissue (20 + 20 patients). Mechanical bileaflet valves, produced by three different manufactures, all had similar geometric features, consisting of a circular ring with two identical flaps which rotate about a single axis; biological valves, by two manufacturers, were composed of three equal tissue leaflets attached to a ring. The LV flow was visualized by echocardiography on a longitudinal plane across the mitral and aortic orifices. The qualitative flow pattern was characterized by visual assessment with a complete agreement between two observers. In 38 out of 40 cases, the intraventricular flow still presented a circulatory pattern but, remarkably enough, the sense of rotation was *opposite* to that found in the normal LV flow pattern. In the two remaining cases no evident circulatory motion was detectable.

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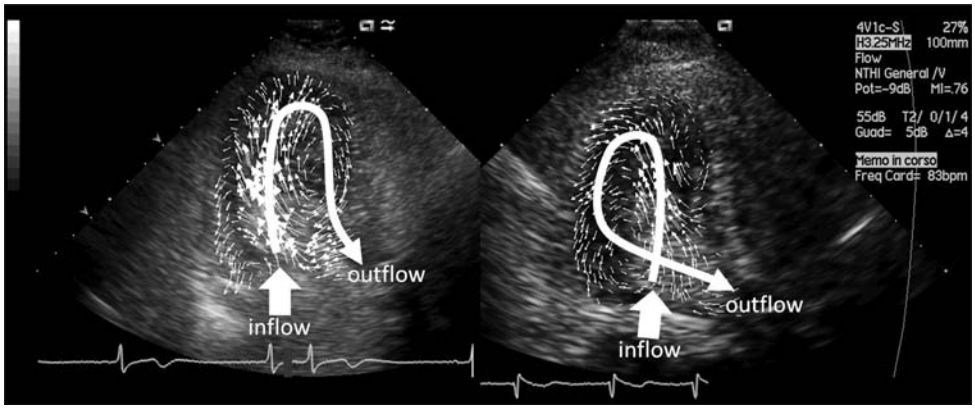

FIGURE 1. Echocardiographic visualization of the left ventricle (shown upside-down in the pictures) in a normal subject (left) and in a subject with mechanical mitral valve (right). Images are taken during the final stage of the flow entrance (end-diastole), the estimated velocity vectors are superimposed, and the qualitative flow path is sketched with the thick line.

Examples of the *in vivo* ventricular flow are shown in Fig. 1 during the LV filling phase (the automatically estimated velocity vectors[6] are superimposed to facilitate the flow reading). The normal flow, on the left, shows the clockwise rotation accompanying blood from the entrance to the outflow; in the prosthetic case, right picture, the dominant circulation is counter-clockwise that implies a crossed flow path to eventually reach the exit. This unexpected behavior can be related to many details concurring in the surgical procedure. These observations motivated a purely fluid mechanical analysis capable to uncover the physical phenomena associated to such a drastic change.

METHODS

The analysis is performed by the direct numerical solution of the Navier–Stokes and continuity equations

$$\frac{\partial \upsilon}{\partial t} + \upsilon \nabla \upsilon = -\nabla p + \nu \nabla^2 \upsilon, \quad \nabla \cdot \upsilon = 0, \qquad (1)$$

where υ is the velocity vector and p is the pressure (normalized with the fluid density), $\nu = 3 \times 10^{-6}$ m^2/s is the kinematic viscosity of blood assumed as an incompressible Newtonian fluid. The time-varying geometry (the LV endocardial border) is extracted from echocardiographic imaging of a normal young man. To reduce the variability due to specific geometric features, the LV cavity is approximated at every instant with that of half a prolate spheroid with the same volume. The chamber geometry is thus defined by the functions $D(t)$ and $H(t)$ (t is the time), which are the temporal variations of the equatorial diameter and of the major semi-axis. In this case, $D(t)$ ranges from 3.57 to 4.97 cm, and $H(t)$ from 5.49 to 6.40 cm, corresponding to a volumetric ejection fraction of 55%.

Equation (1) is solved in a computational box, where the LV boundaries are immersed, with an version of the Immersed Boundary method.[2] Box periodicity is assumed along x and y to allow a spectral representation and fast solution methods, centered second-order finite differences are used along z. Time advancement is performed with an explicit third-order Runge-Kutta scheme combined with the standard fractional-step approach to impose the mass conservation constraint. The numerical box ($6.6 \times 6.6 \times 7.0$ cm^3) is approximated with 128 harmonics along the x and y periodic directions and 128 points along z. An extensive validation has been performed to ensure that the solution is independent from the numerical choices. The comparison with existing results obtained with different techniques[3] resulted in negligible differences.

The definition of the velocity profile assigned at the inlet boundary is a crucial element, because its properties reflect the geometry of the valvular orifice. Physically, the mitral plane that contains the valve is not horizontal, its axis is deflected $\simeq 15°$ and points toward the LV center. Such an inclination is compensated by the *asymmetry* of the two leaflets, where the central one is much longer than that adjacent to the wall. As a result, the mitral jet enters into the LV directed downward, with minor deviations from being parallel to the LV axis (see sketch above Fig. 2). This natural inflow is modeled here by a vertical blunt velocity profile

$$\upsilon_z(r,\theta) = \mathcal{C}(t) e^{-\sigma^{-8}\left[(r\cos\theta-\varepsilon)^2+(r\sin\theta)^2\right]^4}, \qquad (2)$$

where (r, θ) are polar coordinates on the equatorial plane. The parameter σ is the characteristic size of the jet and ε is its eccentricity, here assumed equal to 1.2 and 0.6 cm, respectively; the coefficient $\mathcal{C}(t)$ is automatically evaluated to comply with the cavity volume variation.

When the native valve is replaced by a prosthetic implant, the natural leaflets' asymmetry is lost. Therefore, the mitral jet is not directed vertically, but it is inclined toward the ventricle center. This is confirmed from the echographic visualization of the clinical cases where the angle of the prosthetic jet with respect to the LV axis was manually estimated (average 14.5° with standard deviation 6.6°). The numerical simulation modeling prosthetic conditions has been performed under identical conditions of the previous case with the only difference that the inflow profile (2) enters with an inclination of 15° with respect to the z-axis.

RESULTS

The numerical results are shown in Fig. 2 on a transversal plane, corresponding (after rotation) to the echographic view. In the normal case, shown in Figs. 2a and 2b, as previously reported in literature (e.g. Kilner *et al.*,[7] Pedrizzetti and Domenichini,[10] Hong *et al.*,[5] Kheradvar *et al.*,[6] Domenichini *et al.*,[3] and references therein), the mitral jet is immediately deflected toward the closer (lateral) wall, vorticity rolls-up in the center of the cavity where a dominant clockwise circulatory pattern develops. The three-dimensional vortex dynamics, shown in Figs. 3a and 3b, is characterized by the formation of a vortex ring during diastole and by its propagation toward the apex. During contraction the vortex structure is stretched toward the outflow track. The flow corresponding to the prosthetic valvular settings is shown in Figs. 2c and 2d: the mitral jet crosses the ventricle center, impacts on the opposite wall (intraventricular septum), and develops a dominant counter-clockwise circulatory pattern. The eventual crossed flow path evidenced in the two-dimensional description reveals its complex three-dimensional nature in Figs. 3c and 3d, where the entering vortex ring must undergo an intense

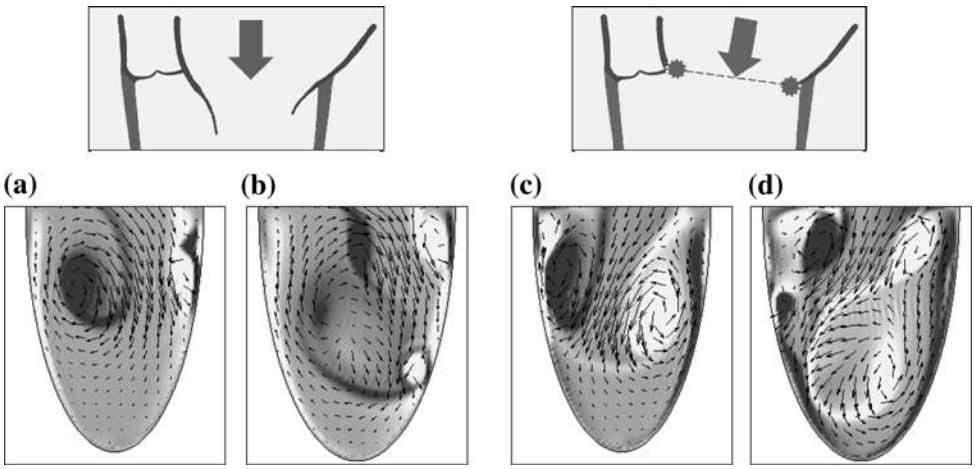

FIGURE 2. Flow in the left ventricle visualized on a transversal plane (crossing either the mitral and aortic orifices) for the case of natural asymmetric valve (a, b) and symmetric artificial valves (c, d), as sketched on top of the images. The two instants correspond to the peak (a, c) and the deceleration (b, d) of the entry flow, $t/T \simeq 0.15$ and $t/T \simeq 0.25$ in Fig. 4, respectively. The velocity vectors are drawn and the vorticity field is reported on grayscale (black = clockwise rotation).

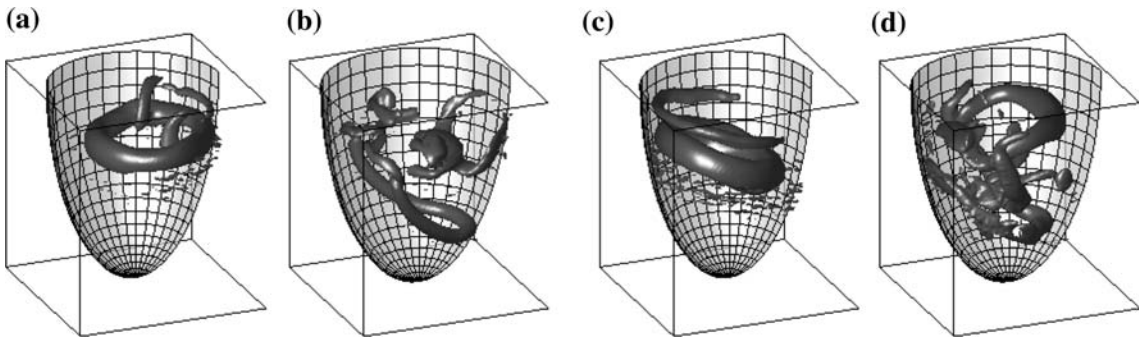

FIGURE 3. Flow in the left ventricle visualized by its main three-dimensional vortex structure (through the λ_2 isosurfaces method) for the case of natural asymmetric valve (a, b) and symmetric artificial valve (c, d). The two instants correspond to the peak (a, c) entry flow and the very beginning of contraction (b, d), $t/T \simeq 0.15$ and $t/T \simeq 0.6$ in Fig. 4, respectively.

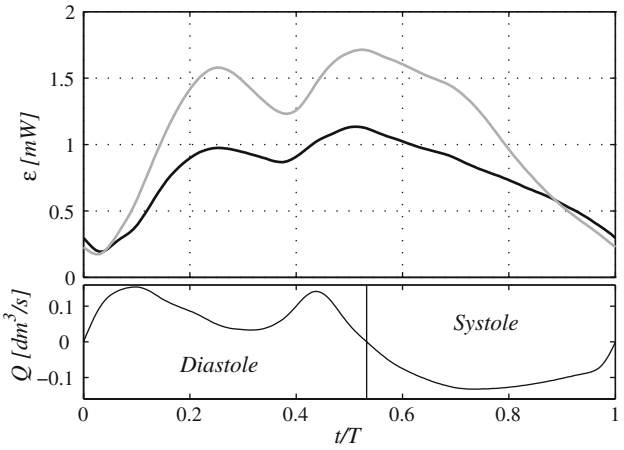

FIGURE 4. Energy dissipation during the heartbeat, normal flow (black line), and artificial valve flow (gray line). The entering-exiting discharge is shown below.

deformation to lead its farther portion toward the outflow tract giving rise to small vortex structures and weak turbulence.

The associated energy dissipation $\varepsilon(t) = \int_{LV} S_{ij} \frac{\partial v_i}{\partial x_j} dV$, where S is the stress tensor, is shown in Fig. 4. A significant increase of energy losses is found, on average over 30% with instantaneous peaks that exceed 50% during flow deceleration, when the vortex is deformed and dissipated.

DISCUSSION

In normal conditions, the blood moves from the atrium to the ventricle in a constant, extremely organized fashion that is determined by a proper combination of asymmetric elements. The atrial flow is captured between the valvular leaflets and is redirected longitudinally along the LV lateral wall. The fluid is thus driven along its motion and smoothly accompanied by the spoon-like curvature without being ever subjected to sharp turns. The vortex structure acts like a ''fly-wheel'' that transforms the intermittent flow that enters the LV in a nearly continuous motion at the apex where the flow is redirected toward the outflow tract. In this way, the systolic contraction of the ventricle further propels blood that is already moving toward the aortic outflow minimizing the loss of momentum.

Prosthetic valves introduce an unnatural geometric symmetry that forces the flow path with a different orientation. It gives rise to a crossed flow pattern with reversed rotation at the apex that steers the blood back in the direction of the inlet. Thus, at the onset of systolic contraction, the blood tends to stagnate in the region between the apex and the outflow tract and more energy must be spent to accelerate it toward the aorta. As a further consequence, the distribution of pressure along the ventricle wall is substantially altered. Extreme pressure values increase in magnitude and their position is shifted from the lateral to the septal wall. Therefore, the normal equilibrium that developed along the boundary between pressure, tissue curvature, and stiffness is modified and some regions are subjected to stresses larger than those they were physiologically adapted to. Actually, the reshaping of the ventricular chamber is a common drawback found in the follow-up after mitral valve substitution (although this fact can be also imputable to other causes like the cut of the chordae tendineae connecting the valve to the papillary muscles).

CONCLUSION

The implant of a mitral prosthesis may lead to the reversal of the vortical flow inside the left ventricle. The reversed circulation is caused by the redirection of the mitral jet after surgery. It increases energy dissipation and modifies the spatial pressure distribution. These changes may influence the development of post-procedural complications.

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