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Left Ventricular Vortex Under Mitral Valve Edge-to-Edge Repair

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Abstract

Mitral valve (MV) edge-to-edge repair (ETER) changes MV geometry by approximation of MV leaflets, and impacts left ventricle (LV) filling fluid mechanics. The purpose of this study was to investigate LV vortex with MV ETER during diastole. A computational MV–LV model was developed with MV ETER at the central free edges of the anterior and posterior leaflets. It was supposed that LV would elongate apically during diastole. The elongation deformation was controlled by the intraventricular flow rate. MV leaflets were modeled as a semi-prolate sphere with two symmetrical circular orifices and fixed at the maximum valve opening. MV chordae were neglected. FLUENT was used to simulate blood flow through the MV and in the LV. MV ETER generated two jets deflected laterally toward the LV wall in rapid LV filling. The jets impinged the LV wall obliquely and moved apically along the LV wall. Jet energy was primarily lost near the impingement. The jet from each MV orifice was surrounded by a vortex ring. The two vortex rings dissipated at the end of diastole. The total energy loss increased inversely with the MV orifice area. The atrio-ventricular pressure gradient was adverse near the end of diastole and possibly in diastasis. Reduction of the total orifice area led to more increment in the transmitral pressure drop than in the transmitral velocity. In conclusion, during diastole, two deflected jets from the MV under ETER impinged the LV wall. Major energy loss occurred around the jet impingement. Two vortex rings dissipated at the end of diastole with little storage of inflow energy for blood ejection in the following process of systole. MV ETER increased energy loss and lowered LV filling efficiency. The maintaining of a larger orifice area after ETER might not significantly increase energy loss in the LV during diastole and the transmitral pressure drop. The adverse pressure gradient from the atrium to the LV might be the mechanism of MV closure in the late diastole.

Keywords

Mitral valve; Left ventricle; Vortex; Energy loss; Mitral valve closure

INTRODUCTION

Left ventricle (LV) fluid mechanics reflects the function of the LV as a moving boundary condition during a cardiac cycle. In diastole, LV relaxation starts from the mitral valve (MV) annulus plane and then propagates toward the LV apex. The LV dilation reduces LV pressure and induces an inflow jet through the MV orifice. Meanwhile, a distinct vortex ring surrounding the jet occurs beneath the MV. The jet is redirected from one side of the LV wall to the other because of the asymmetrical configuration of the MV in the LV. This intraventricular flow pattern develops a large vortex from the MV anterior leaflet, which moves down to the apex.¹³

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It has been noticed that the vortex can have a close connection to the cardiovascular function. However, there remains a great deal of uncertainty, even controversy, as to understanding the vortex. The vortex tends to dissipate after the rapid filling,²⁹ but it is also thought to persist in the whole diastole and help blood ejection in systole by redirecting blood flow asymmetrically toward the LV outflow tract and reducing resident time in the LV.^{5,10,13,18–21,27} The intraventricular flow pattern with the natural asymmetric structure of the MV and LV is regarded as optimal for minimal energy loss in a cardiac cycle.^{18,19} At the same time, however, the vortex can increase turbulent dissipation.²¹ The vortex may contribute to mitral valve closure,^{3,14} but the vortex contribution may be less than that of the atrio-ventricular pressure gradient from the atrium to the LV.²³

Due to insufficient understanding of the LV vortex, vortex knowledge has not been widely used in clinical practice. Nevertheless, results from imaging techniques show the potential of the vortex in diagnosis of LV dysfunctions. For example, by comparison with the normal LV vortex, the LV vortex in some LV pathology is incoherent and more pulsatile.^{8,10,12} MV pathologies can also significantly change the LV filling and the vortex pattern.^{6,19,21} The implantation of a prosthetic valve can reverse the vortex rotation and increase energy dissipation.^{6,19} The vortex formation downstream of a bioprosthetic valve is significantly weaker, compared with that of a mechanical mitral valve.²¹

Recently, a new MV repair technique, edge-to-edge repair (ETER) was introduced to correct MV regurgitation. This repair creates two MV orifices by the suturing of the anterior and posterior leaflets at the free edges (depending on lesion).^{1,7} ETER creates two deflected jets through the two orifices in the LV filling instead of one jet in the normal case.^{22,25} The intraventricular flow pattern due to MV ETER is unknown. In this paper, we used computational fluid dynamics to investigate the LV vortex during diastole after MV ETER. We discussed such information as the flow pattern of the vortex, energy loss, the atrio-ventricular pressure gradient from the atrium to the LV, and their relations with the total orifice area.

METHODS

Left Ventricle Model

The LV geometry is shown in a symmetric half in Fig. 1a.^{22,28} The whole flow domain was partitioned into four zones from the atrium to the LV apex. Zone-I was formed by the cylindrical atrium wall and the MV leaflets after ETER; Zone-II was isolated by the top LV wall, the MV and the aortic valve (mainly the LV outflow tract and the region below the MV); Zone-III was a cylinder as part of the LV, which could apically expand; Zone-IV was a semi-prolate spheroid as part of the LV. GAMBIT (ANSYS Inc. Canonsburg, PA) and ABAQUS (SIMULIA Inc, Providence, RI) were used to create the geometry.

In diastole, LV dilation starts from the MV annulus plane and then propagates toward the LV apex. The LV enlarges along the apical and short axes and with twist. Elongation along the apical axis may be significant.^{4,26} In this study, we assumed that the LV deformation elongated along the apical axis. Zones-I and II were fixed. Zone-III elongated with the same velocity as Zone-IV, moving apically downward.^{4,26} The elongation of Zone-III was controlled by the intraventricular flow rate curve in Fig. 1b, which was derived from the diastolic LV volume curve in the general normal adult case. The diastole, lasting 0.6 s, was divided into three consecutive phases: rapid filling (E-wave filling, $0 \leq t \leq 0.2$ s), diastasis (slow filling, $0.2 \text{ s} < t \leq 0.4$ s), and atrial systole (A-wave filling, $0.4 \text{ s} < t \leq 0.6$ s).^{4,18,22} The maximum intraventricular flow rate, 0.24 L/s, appeared at E-peak ($t = 0.1$ s) in the rapid filling. Such an intraventricular flow rate could yield a stroke volume of 0.056 L. The initial diastolic LV volume was set at 0.06 L.²² Thus, the controlled elongation deformation would

eventually result in flow through the MV and in the LV without consideration of fluid–structure interaction.

Mitral Valve Model

MV chordae were neglected.^{17,22} The MV annulus plane was apically sloped downward by 30° from the LV base plane (the xoz -plane), as shown in Fig. 1c. We assumed that ETER suture done at the central free leaflet edges created two symmetric circular orifices.²² The two MV leaflets after ETER were modeled as part of a prolate sphere without thickness.^{2,17,22} The MV was fixed at the maximum opening without fluid–structure interaction. The leaflet lengths determined the suture position. The lengths of the anterior and posterior leaflets were fixed at 2.6 and 1.6 cm,^{16,25} which created a 1.2 cm-displacement of the suture downward from the MV annulus plane. The shorter suture length (forced coaptation length by multiple stitches) generally corresponded to the larger orifice area. In GAMBIT, each orifice was generated by a cylinder cutting through the MV wall: the cylinder axis passed through the center of the MV annulus plane, and the cross-sectional area of the cylinder was defined as the orifice area in this study. According to the experiment setting in Shi et al. and Redaelli et al.,^{22,25} the suture lengths of 1.5, 0.9, and 0.3 cm yielded the total double-orifice areas of 3.2, 4.0, and 6.2 cm², respectively, which were used in this study. The areas of such three double-orifices projected on the MV annulus plane were 1.2, 2.1, and 4.0 cm², which were 17, 30, and 56% of the MV annulus area of 7.1 cm², respectively. The papillary muscles were created by the use of two semi-prolate spheroids with the half minor axis of 0.3 cm and the half major axis of 2.0 cm, beneath the MV orifices and on the LV wall. The two papillary muscles deflected toward each other by 10°, and separated by a distance of 2.3 cm measured between their apices (Figs. 1c, 1d). The two apices of the papillary muscles were about 2.4 cm lower than the MV annulus center. The symmetric plane (the xoy -plane) was determined by the symmetric setting of the two orifices and two papillary muscles. The orifice-PM (papillary muscle) plane passed the orifice centers, suture and the papillary muscle axes, and was perpendicular to the symmetric plane (Fig. 1a).

LV and MV fluid mechanics with a normal MV was also studied as a baseline. We used the sine function to model the curved MV anterior, posterior and commissure leaflets.¹⁶ The lengths of the anterior, posterior and commissure leaflets were 2.1, 1.2, and 0.6 cm, respectively. The leaflets fixed at the maximum orifice area formed a tubular passage perpendicular to the MV annulus plane. The MV annulus area was 7.1 cm² and used as the orifice area in the normal MV case.^{2,16,22}

Hemodynamics Model

We assumed that blood was an incompressible Newtonian fluid with constant density ρ of 1060 kg/m³ and viscosity μ of 0.0027 Pa s.^{17,22} The continuity and Navier–Stokes equations governed the LV blood flow (neglecting body forces):

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

in which $\vec{V}$ is the velocity vector, p is pressure, and ν is kinematic viscosity (the ratio of viscosity to density, μ/ρ).

Two types of boundary conditions were set in FLUENT (ANSYS Inc. Canonsburg, PA): no-slip conditions at all walls, and pressure-inlet conditions at the atrium inlet (with constant pressure and zero velocity gradient²⁴). Initially, the flow field was at rest with uniform

pressure of zero. The elongation deformation of the LV would generate flow through the MV and in the LV.

We used the dissipation function $\Phi = \left[\nabla \vec{V} + (\nabla \vec{V})^T \right] : \nabla \vec{V}$ to estimate the LV energy loss. It describes the energy irreversibly transferred to heat due to viscosity. $\mu\Phi$ indicates the

energy loss rate in Pa/s, and $\int_{t_1}^{t_2} \mu\Phi dt$ is energy loss in Pa from t_1 to t_2 . We introduced the λ_2 -criterion to identify the vortex.^{11,15} According to this criterion, two of the eigenvalues of $\mathbf{S}^2 + \mathbf{\Omega}^2$ in the vortex region should be negative, in which $\mathbf{S}$ and $\mathbf{\Omega}$ are the strain-rate tensor and the vorticity tensor, respectively. If the three eigenvalues of $\mathbf{S}^2 + \mathbf{\Omega}^2$ are in order $\lambda_1 \geq \lambda_2 \geq \lambda_3$, the vortex identification is equivalent to the condition $\lambda_2 < 0$. In this study, we used the negative λ_2 to visualize the vortex region. We also introduced the dimensionless parameter of formation time defined by Gharib *et al.* to interpret the vortex further.^{8,9} The following formula was used to estimate the formation time T_8 :

$$T = \frac{4}{\pi \bar{D}^3} (SV - Vol_A) \quad (2)$$

in which SV is the stroke volume, Vol_A is the blood volume entering the LV due to atrial contraction (here taken $t = 0.3$ – 0.6 s as the atrial contraction period), and $\bar{D}$ is the name diameter of the total orifice area. In the normal MV case, the name diameter was the same as the orifice diameter; in the ETER MV cases, the name diameter was $\sqrt{2}$ times the diameter of the single orifice so that the area defined by the name diameter could equal the total double-orifice area.

Numerical Techniques

The three-dimensional unsteady problem was solved by means of the segregated solver in FLUENT. The momentum equations were discretized with the second-order upwind scheme in space and the first-order implicit formulation in time. PISO (Pressure-Implicit with Splitting of Operators) was used for the pressure–velocity coupling. Zones-I, II and IV were meshed with tet/hybrid elements in GAMBIT, and Zone-III with hex/wedge elements. Zone-III was deformable and was re-meshed by use of the layering dynamic-mesh technique in FLUENT. Zone-IV moved apically downward as a rigid body without re-meshing. No dynamic-meshes were set in Zones-I and II. The re-meshing of Zone-III and displacing of Zone-IV were executed at the beginning of every time step. The initial computational domain was meshed to 129 K cells. The cell number rose to 134 K at the end of diastole when the LV reached its maximum volume. Six hundred time steps were needed to finish a diastolic simulation of 0.6 s with a fixed time interval of 1 ms.

RESULTS

Inflow Jet and Vortex Development

Velocity distributions on the orifice-PM plane as shown in Figs. 2a–2d demonstrated a jet through each MV orifice in the rapid filling for the total orifice area of 4.0 cm². The jets appeared around $t = 0.02$ s (Fig. 2a), and impinged the LV wall at $t = 0.05$ s (Fig. 2b). Then the jets turned toward the apex along the LV wall (Fig. 2c), and later were hindered by the papillary muscles (Fig. 2d). Afterward, they slowed down and tended to vanish.

With the jet development, a vortex ring appeared around each jet. On the orifice-PM plane in Figs. 2a–2d, each vortex ring displayed a pair of cross-sectional vortices: the vortex that

was close to the MV annulus was designated as the annulus vortex, and the other near the suture as the suture vortex. The two vortices in each planar vortex pair rotated in opposite directions. The annulus vortices were confined in the annulus region and dissipated quickly. The suture vortices moved apically in the middle of the LV cavity and contacted the papillary muscles (Fig. 2d). A similar intraventricular flow pattern occurred when the process of atrial systole started with the weaker vortices. The other two ETER MV cases demonstrated similar jet and vortex development.

3D Vortex Structure

Figure 3 shows the three-dimensional vortex ring structure at E-peak for the three ETER MV cases and the one normal MV case. In the ETER MV cases, two vortex rings surrounded two jets (Figs. 3a–3c), instead of one vortex ring around one jet in the normal MV case (Fig. 3d). For each vortex ring, the section near the LV wall tended to dissipate much more than the other sections farther from the LV wall. The vortex rings with the smallest total orifice area of 3.2 cm² developed quickly and dissipated intensely in Fig. 3a, as compared with the other two ETER MV cases in Figs. 3b and 3c.

Spatial Energy Loss

Figure 4 shows the maps of velocity, energy loss rate and vorticity in the LV at E-peak for the total orifice area of 4.0 cm². The energy loss mainly occurred in the jet impingement region (Figs. 4a, 4b). The jet shear layers also contributed to a certain amount of energy loss (Fig. 4b). However, energy loss was low in the vortices (Fig. 4b). The vorticity showed a distribution similar to that of the energy loss (Figs. 4b, 4c). The vorticity was lower in the vortices than in the jet shear layers, and also lower than that in the jet impingement region at the LV wall (Fig. 4c). The other two ETER MV cases had a similar energy loss distribution in space.

Temporal Energy Loss

Figure 5 shows that the energy loss rate $\mu\Phi$ and the energy loss $\int_0^t \mu\Phi dt$ varied with time in diastole for the total orifice area of 4.0 cm². Energy was lost more quickly in the rapid filling than in atrial systole. The total energy loss of 32.5 Pa (0.24 mmHg) was about 1/7 of that (218.5 Pa) with a total orifice area of 3.2 cm², 3.5 times that (9.2 Pa) with a total orifice area of 6.2 cm², and 9 times that (3.0 Pa) in the normal MV case. Figure 6 shows the energy loss distributions in percentage in the three diastolic phases for the four MV cases. In each case, the main energy loss occurred in the rapid filling. As the total orifice area decreased, there was a greater energy loss in the rapid LV filling than in other diastolic phases.

Atrio-Ventricular Pressure Gradient

The atrio-ventricular pressure gradient was defined as the volume-averaged pressure difference between the pressure in the atrium (mainly Zone-I) and the pressure in the LV (mainly Zones-II to IV).²³ Each atrio-ventricular pressure gradient curve in Fig. 7 was normalized by its maximum positive value. The values used to normalize the curves were 4435.1, 387.0, 122.6, and 123.6 Pa for the total orifice areas of 3.2, 4.0, 6.2, and 7.1 cm², respectively. For the ETER MV cases, the atrio-ventricular pressure gradient was positive during the rapid filling and the early atrial systole; it became so small as to be adverse in diastasis at the total orifice area of 6.2 cm²; it turned adverse near the end of diastole. In the normal MV case, the atrio-ventricular pressure gradient became adverse during the diastolic phases as in the ETER MV cases, but in an enlarged and preceding time scale and in a relatively significant magnitude, as shown in Fig. 7.

DISCUSSION

We summarized the key features of LV and MV flow during diastole under MV ETER with the central suture as follows:

1. The intraventricular flow pattern was unique: two jets and two vortex rings;
2. The large anterior vortex did not clearly exist after the rapid filling;
3. Energy loss increased with the decrease of the total orifice area after ETER.

To validate the elongation model of LV deformation in diastole, we first computed a single-orifice case using axisymmetric geometry and flow conditions similar to those used by Redaelli *et al.*²² In their study, the LV was considered as a fixed control volume and the deformation of the LV wall was replaced by a spatial-temporal velocity distribution.²² Result comparison showed that the two LV models yielded similar pressure and velocity distributions (<10% in difference) along the apical axis at E-peak. For the current model used in this study, the transmitral pressure drops (area-averaged pressure differences between the MV annulus plane and the MV surface toward the LV) at E-peak were 4329, 430, 106, and 54 Pa for the total orifice areas of 3.2, 4.0, 6.2, and 7.1 cm², respectively; the transmitral velocities (area-averaged at the orifice) were 1.2, 0.7, 0.5, and 0.3 m/s with increasing total orifice area. The transmitral pressure drop and the total orifice area roughly followed a power law relation with an exponent of about -5.0. Similarly, we used the power law to curve-fit the relation between the transmitral velocity and the total orifice area with an exponent of about -1.5. The exponents in the two power law relations indicated that the total orifice area influenced the transmitral pressure drop much more than it did the transmitral velocity. For example, if the total orifice area decreased by 10%, the transmitral pressure drop would increase by 50% and the transmitral velocity by only 15%. Using the axisymmetric model with a single orifice, Redaelli *et al.* showed that the transmitral velocity was reciprocal to the total orifice area, whereas the transmitral pressure drop was reciprocal to the total orifice area squared.²² Their study agreed well with the mass conservation law and the Bernoulli relation, and also indicated the greater influence of the total orifice area on the transmitral pressure drop than on the transmitral velocity. In terms of the transmitral pressure drop, keeping a total orifice area as large as possible might be a concern in ETER practice.

MV ETER changed one orifice of the normal MV into two orifices, through which two high speed jets were generated. The jets were deflected toward the LV wall, depending on the suture position and coaptation length.²⁵ The deflection made the jet impinge the LV wall earlier in the ETER MV cases than in the normal MV case. The jet impingement at the LV wall formed regions with high shear, where major energy loss occurred. Furthermore, the smaller orifice resulted in the greater speed of the jet and the greater energy loss. Such a flow pattern was the main reason that energy loss was higher in the ETER MV cases than in the normal MV case.

Figure 3 shows the dramatic differences in the vortex structure. According to the study of Gharib *et al.*, the position of a steady vortex ring core was nearly proportional to the formation time.⁹ This meant that the vortex with the longer formation time should need more space to develop. Using the expression (2), we obtained the vortex formation times in the four cases studied here: 20.1, 4.9, 2.5, and 2.1 with the increase of the total orifice area. For the piston model in Gharib *et al.*⁹ (at the maximum stroke ratio of 14.5, the piston diameter of 2.54 cm and the Reynolds number of 6000), a displacement of 21.7 cm away from the exit of the vortex generator was estimated to be necessary to show the entire vortex structure at the formation time of 20.1, while only 1.8 cm-displacement was needed at the formation time of 2.1. The four cases here had nearly the same LV geometries. Therefore

the vortex with the longer formation time tended more to be confined by the LV wall, and to dissipate. The vortex structure in Fig. 3a was the most chaotic, in which the formation time was the longest and the total orifice area the smallest. The confinement effect of the LV wall on the vortex was also observed through magnetic resonance imaging. For example, the vortex developed more unsteadily in the normal LV than in the dilated LV²⁹; the vortex near to the LV wall was tended to dissipate more.⁶ From the study of Gharib *et al.*, it could also be estimated that the total circulation of the vortex ring increased with the formation time.⁹ The normal case had the greatest total orifice area, the shortest formation time, and the weakest vortex strength (the volume in accordance with the iso-surface regions in Fig. 3 was roughly proportional to the vortex strength), as shown in Fig. 3d. Generally, the vortex phenomenon in Fig. 3 agreed with the study of vortex formation time.⁹

With MV ETER, the clear anterior vortex similar to that in the normal MV case did not appear in the rapid filling. Nevertheless two small vortex rings around the two jets occurred and interacted with each other in the center of the LV. After the rapid filling, the vortex tended to dissipate in both the ETER and normal MV cases. The vortex rings caused less energy loss than the jet impingement did, as seen from the energy loss rate map in Fig. 4b. In other words, the vortex could store kinematic energy, though the vortices dissipated and caused energy loss after the rapid filling.^{5,13,18–20} Our results indicated that the two vortex rings due to MV ETER dissipated quickly and did not develop into the large anterior vortex at the end of diastole. Closely related to the shear strain, the energy loss and vorticity had similar distributions (Figs. 4b, 4c). The vorticity in the vortex ring was relatively low (Figs. 4a, 4c).

For both ETER and normal MV cases, most energy loss occurred in the rapid filling (Fig. 5). A larger total orifice area might reduce the energy loss percentage in the rapid filling to 50% or so, the level in the normal MV case (Fig. 6). Compared with the normal MV case, ETER increased energy loss by altering mitral geometry and reducing the total orifice area. But the energy loss was only 2.5 times that in the normal MV case if 87% ($6.2 \text{ cm}^2/7.1 \text{ cm}^2$) of the total orifice area could be maintained after ETER. This indicated that energy loss due to ETER might be no more than twice that in the normal case if a greater total orifice area (for example, more than 87% of the normal orifice area) could be maintained after ETER.

The fixed MV impeded direct study of the relation between the vortex and MV motion. But the results implied a similar conclusion to that drawn by Reul *et al.* on the mechanism of MV closure: the pressure instead of the vortices predominated in MV closure.²³ Our results showed that, after the rapid filling, the vortices were significantly weakened. Even though the vortices around the jets could appear a second time due to atrial contraction in atrial systole, the vortices were essentially weak. This phenomenon of the vortex being weakened was observed in the experiments of Reul *et al.*²³ Their experiments further demonstrated that the MV closed in nearly the same way both with and without the LV vortices. Figure 7 shows that the adverse atrio-ventricular pressure gradient appeared near the end of diastole and possibly also in diastasis. A similar phenomenon was displayed in the experiments: the adverse atrio-ventricular pressure gradient in diastasis corresponded to partial MV closure after the rapid filling and before atrial systole; the adverse atrio-ventricular pressure gradient near the end of diastole corresponded to complete MV closure after the second MV opening due to atrial contraction.²³ Even though the vortices might apparently contribute to MV closure, we tended to agree with Reul *et al.* that the apparent vortex contribution was due to the correlation of the vortices to a certain force distribution that favored MV closure.²³

There were several other limitations in this study. We used only one pair of anterior and posterior leaflet lengths, and the suture position and distance from the MV annulus plane were fixed, not concealing the effect of the leaflet height on the LV vortex. The neglect of

MV chordae possibly caused errors in local fluid mechanics, but might not have affected the overall LV flow pattern of the two jets and vortex rings.^{22,23} The LV geometry was a simplified model. The LV actually dilates in both radial and apical directions and with twist. The apical elongation in our model was a simplification of the LV deformation. However, the elongation deformation of the LV could have had a major influence on the vortex flow structure in the LV.^{5,19}

CONCLUSIONS

MV ETER, performed at the central leaflet edges, generated two high speed jets in the rapid filling. Each jet was deflected laterally and impinged the LV wall, which caused major energy loss at the impingement sites. Two vortex rings dissipated quickly at the end of diastole with little storage of inflow energy for LV blood ejection in the following systolic process. MV ETER increased energy loss and lowered LV filling efficiency. The maintaining of a larger orifice area after ETER might prevent significant energy loss and transmitral pressure drop during diastole. The adverse pressure gradient from the atrium to the LV might be the mechanism of MV closure in the late diastole.

Acknowledgments

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FIGURE 1.

(a) The sectional view of the MV-LV geometric model in the symmetric half and the view of the orifices projected on the MV annulus plane. Zone-I: the cylindrical atrium and the region separated from the LV by the MV leaflets after ETER; Zone-II: the region isolated by the MV, the top LV wall and the aortic valve (the LV outflow tract and the region below the MV); Zone-III: an apically extensible cylinder as part of the LV; Zone-IV: a semi-prolate spheroid including the papillary muscles and the LV apex. The orifice-PM (papillary muscle) plane passed the papillary muscle axes and cut the MV orifices nearly at the orifice centers. (b) The intraventricular flow rate as a function of time during diastole. (c) The symmetric view of the MV-LV geometry (projection toward the negative z -axis). (d) The lateral view of the MV-LV geometry (projection toward the positive x -axis). Cylinder diameter of Zone-III: 4.6 cm; MV annulus diameter: 2.8 cm; atrium diameter: 3.2 cm; aorta diameter: 2.1 cm.

FIGURE 2.

The velocity vector fields at $t =$ (a) 0.02 s, (b) 0.05 s, (c) 0.1 s, and (d) 0.16 s for the total orifice area of 4.0 cm^2 on the orifice-PM plane. The signs, “+” and “-”, denoted vortex rotation directions and centers on the yo_z -plane.

FIGURE 3.

The vortex rings in the LV at E-peak and at the total orifice areas of (a) 3.2 cm^2 , (b) 4.0 cm^2 , (c) 6.2 cm^2 , and (d) 7.1 cm^2 (the normal MV case). The λ_2 -levels of the iso-surfaces were -2000 in $1/\text{s}^2$ in the ETER MV cases (a–c), and -900 in $1/\text{s}^2$ in the normal MV case (d). The meshes approximated the jet regions.

FIGURE 4.

(a) The velocity vector field, (b) the distribution of energy loss rate $\mu\Phi$, and (c) the vorticity distribution for the total orifice area of 4.0 cm^2 on the vertical orifice-PM plane at E-peak.

FIGURE 5.

The energy loss rate and energy loss under ETER for the total orifice area of 4.0 cm^2 . The dissipation function Φ was volume-averaged in the entire flow region.

FIGURE 6.

The energy loss percentage distributions in the three diastolic phases for the three ETER MV cases and the one normal MV case. The energy loss percentage was the ratio of the energy loss in a diastolic phase to the total energy loss in the whole diastole.

FIGURE 7.

The atrio-ventricular pressure gradients during diastole in the three ETER MV cases and the one normal MV case.