OPENING OF THE MITRAL ORIFICE AFFECTS THE INTRAVENTRICULAR DIASTRIC FLOW.

Masanori Nakamura (1), Shigeo Wada (2)

(1) Research Institute for Electronic Science
Hokkaido University
Sapporo, Hokkaido
Japan

(2) Graduate School of Engineering
Tohoku University
Sendai, Miyagi
Japan

INTRODUCTION

The mitral valve is located between the left atrium (LA) and the left ventricle (LV) to regulate blood flow between these chambers. The valve consists of the mitral ring and the leaflets. The leaflets form a continuous veil attached to the circumference of the mitral ring. When the blood pressure in LA becomes larger than that in LV, the mitral valve opens from the commissure of leaflets, forming an orifice at their tips. Although some studies suggested the dependency of the intraventricular flow on the mitral valve leaflets [2], it has not been well understood how the change in the size of the mitral orifice during its opening affects blood flow in LV. According to Tsakiris et al. [1], it takes 0.04 sec for the mitral valve to open completely from its closing state. This is short compared to the entire length of diastole, however, it is suspected that the velocity profile of a transmitral flow and consequently intraventricular diastolic flow are affected by a change in the area of the mitral orifice that is accompanied with opening of the mitral valve. In the present study, we investigate the effects of opening of the mitral orifice on intraventricular diastolic flow by means of computational fluid dynamics (CFD).

METHOD

Configuration of the LV Model

The geometry of the luminal surface of LV at its maximum expansion is determined so that it approximates the general anatomy of a human LV. For simplicity, it is assumed that the geometry is symmetric with respect to the bisector plane of the mitral and aortic valves, and that the crosssection of LV, 'Ψ', obtained by cutting the LV model with a plane radiated out from the line of intersection of the planes containing the two valves is ellipsoid.

Motion of the Ventricular Wall

Motion of the ventricular wall is determined on the basis of a pre-set volume change. Times from the beginning of diastole ($t = 0$) to the peak of the rate of volume change and to the end of diastole, are set to be 0.12 sec and 0.24 sec, respectively, based on clinical data. The net change in the ventricular volume during diastole is 54 ml.

Two assumptions are made for the motion of the ventricular wall; 1) the movement of the ventricular wall is not affected by the intraventricular blood flow, and 2) a point on the wall moves in the direction of a line connecting the point itself and the centroid of the crosssection, Ψ. A spatial distribution of the moving velocity of the wall is fixed throughout the simulation, and it is set that the moving velocity of the wall takes the maximum at the apex and decreases as going away from the apex to the mitral and aortic valves. With these assumptions and the pre-set volume change, the configuration of the LV model at a new time step can be obtained consecutively from that at a current time step [3].

Opening of the Mitral Orifice

In this study, whilst the mitral valve leaflets are neglected, the mitral orifice is modeled as a planar and circular camera-shutter-like device that opens and closes axisymmetrically. Its opening and closing is expressed by changing the size of a circular orifice from its center or its circumference, respectively. The radius of the mitral orifice, $r(t)$, is expressed as a function of time using a trigonometric function so that the area of the mitral orifice ($A = \pi r(t)^2$) is C1-continous with respect to time. The LV model that has this mode of opening and closing of the mitral orifice is hereinafter referred to as an open-close model. For a comparison, the LV model with a fully open mitral orifice (open model) is also prepared where the mitral orifice is fully open from the beginning and throughout diastole.

Procedure of Computer Simulation

Computer simulations of intraventricular diastolic flow are carried out from the state of the maximum contraction. The geometry of the LV model at this point is obtained from that at the maximum expansion by reducing its volume by 60 ml. As an initial condition, blood in LV is assumed to be at a standstill. After advancing a time step and giving a volume change, a further expanded model of LV whose inside is divided into finite elements is constructed. The Navier-Stokes and continuity equations are solved by the use of ANSYS-FLOTRAN ver.5.6 (distributed by Cybernet Systems Co. Ltd., Tokyo). As boundary conditions, zero pressure and zero velocity are given to the opened and closed part of the mitral orifice, respectively, and a moving velocity of the wall is applied to the ventricular wall based on a non-slip condition. This process is repeated until the time reaches the end of diastole.

RESULTS AND DISCUSSION

Effect of Opening of the Mitral Orifice on Transmitral Flow

Figure 1 plots the velocity profiles of a transmitral flow for an open model (Δ) and an open-close model (O), respectively. In the open model, the blood started to enter the left ventricle evenly from the whole part of the mitral orifice, resulting in a flat velocity profile at the mitral orifice. As the ventricular expansion proceeds, the velocity profile developed into the one skewed to the anterior side. On the other hand, in the open-close model, blood was allowed to inflow only from the open part of the mitral orifice. During opening, a jet-type velocity profile was created where the maximum velocity was positioned at the center of the mitral orifice. Even after the mitral orifice had opened completely, this type of the velocity profile had been kept throughout diastole.

The difference of the velocity profile of a transmitral flow was ascribed to the presence of opening of the mitral orifice. The transmitral flow velocity profile obtained in an open-close model was similar to that measured by Fujimoto et al. [4]. However, experimentally, not only the jet-type velocity profile but also various types including the skewed one have been observed in a transmitral flow [5 and references therein]. Therefore, it is not adequate to evaluate all of our results solely on the basis of a comparison with experimental studies. Thus, it is necessary to discuss the intraventricular flow dynamics created by the transmitral flow.

Effect of Opening of the Mitral Orifice on Intraventricular Flow

Figure 2 shows flow patterns in the symmetry plane of LV for the open model (upper) and the open-close model (lower). In the open model, blood flowed into the ventricular cavity evenly from the mitral orifice. On each of the images, the anterior side is on the left and the posterior side is on the left. As the ventricular expansion proceeds, the vortex was generated below the aortic valve. This vortex extended laterally to the posterior side along the sidewall. As a consequence, a vortex ring, which appears as a pair of vortices in the symmetry plane, was formed around a mainflow of the blood inflow. The vortex on the right to the mainflow (posterior) was greatly amplified during the rest period of diastole, and it became much larger than that on the left (anterior). As a result, the mainflow of blood inflow was directed to the anterior side, and it streamed not linearly but meanderingly towards the ventricular apex. In the open-close model, as was the case with the open model, the vortex was also firstly generated below the aortic valve. A lateral extension of this vortex to the posterior side resulted in the formation of the vortex ring around the mainflow. However, unlike with the open model, the vortex on the left to the mainflow became much larger than that on the right. In this case, the mainflow of blood, surrounded by the vortex ring, streamed linearly from the center of the mitral orifice to the apex along the long axis.

There was a difference in the size and location of vortices as well as those of the mainflow in LV, although a vortex ring was formed despite the mode of opening of the mitral orifice. The physical relationship between the vortex and the mainflow in the open-close model is similar to that found in a human heart [6]. However, in contrast, there is no experimental data to support the appearance of the vortex found in the open model. Taking into account the fact that the velocity profile of a transmitral flow is determined by the mode of opening of the mitral orifice, it can be considered that opening of the mitral orifice largely affects the location and size of the vortex ring formed about it during diastole.

CONCLUSION

Opening of the mitral orifice, though it occurs just at the beginning and accounting only 20% of the entire diastole, has play an important role in characterizing intraventricular flow during diastole.

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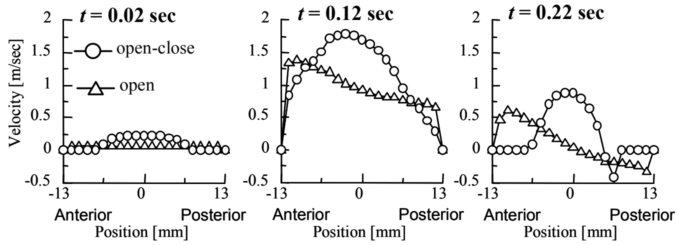

Figure 1. Plots of transmitral flow velocity profiles.

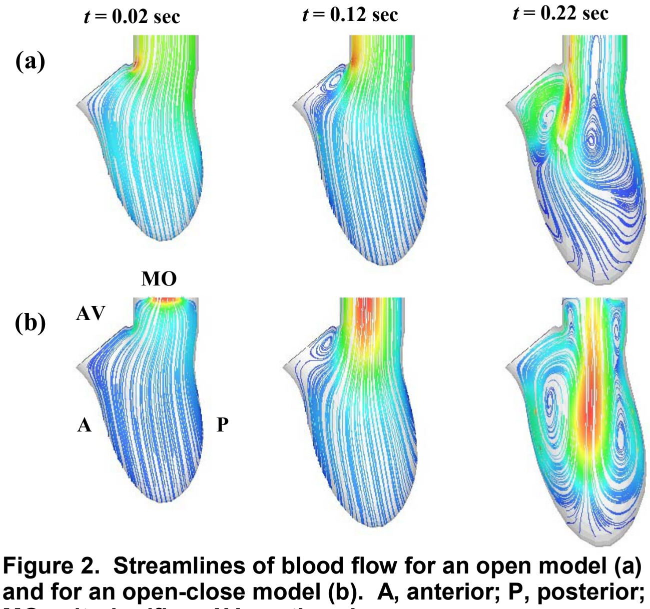

Figure 2. Streamlines of blood flow for an open model (a) and for an open-close model (b). A, anterior; P, posterior; MO, mitral orifice; AV, aortic valve.