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Fluid Dynamic Characteristics of Systolic Blood Flow of the Left Ventricle

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ABSTRACT

Ejection of blood from the left ventricle to the aorta is studied using two-dimensional Navier-Stokes equations, the work-energy equation and the magnetic resonance imaging of a normal ventricular motion. Vortex shedding in the sinuses of Valsalva is dominated by the aortic jet, flow acceleration and valve motion. Momentums produced by ventricular contraction are in concert with vortices in the ventricle for blood ejection. Shear stresses and net pressures on the aortic valve are calculated during valve opening and closing. The rate of work done by shear and the energy dissipation in the ventricle are small. The Bernoulli energy flux delivered to blood from ventricular contraction is practically balanced by energy flux at the aortic root and the rate change of kinetic energy in the ventricle.

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INTRODUCTION

Analysis of blood ejection from the left ventricle is important to cardiovascular dynamics. In their 1969 paper, Bellhouse and Talbot [1] reported flow deceleration producing adverse pressure gradients for aortic valve closure. The peak velocity field in the sinuses of Valsalva was modeled as the Hill vortex. Lee and Talbot [2] discussed strong flow deceleration for an optimal valve closure. The effect of the Strouhal number on valve motion was reported by Van Steenhoven and Van Dongen [3]. Hemodynamic characteristics during aortic valve opening were studied as potential flow by Hung and Schuessler [4]. Flow past the mitral valve was investigated by Reul et al. [5]. In recent years various computational fluid dynamic (CFD) models for flow in the left ventricle (LV) were developed. They were classified as geometry prescribed CFD methods [6-8], immersed boundary (IB) methods [9-11], and fluid-structure interaction (FSI) methods [12-14]. Two-dimensional CFD models were used to study the opening angle of mechanical heart valves [15, 16]. Aluri and Chandran [17] and Lai et al. [18] reported 2D results of mechanical heart valve moving from a fully open position to close. Aortic flow through a bi-leaflet mechanical valve during the first half of systole was investigated by King et al. [19] via CFD and experimental studies. Based on a symmetrical FSI method De Hart et al. [20, 21] obtained velocity vectors around the aortic valve. Kilner et al. [22] described flow patterns in the normal LV for small dissipation of energy. Using a portion of a prolate spheroid with a moving wall, Domenichini et al. [23] reported that inflow to LV heart was optimal in term of minimization of energy dissipation.

Thompson and Mcveigh [24] calculated pressure drops from 2D velocities from phase-contrast MR imaging of the left ventricle and validated in a dog experiment with high-fidelity pressure transducers. Using color Doppler M-mode images, Yotti et al. [25] computed pressure difference between the ventricle apex and the outflow tract. Yoganathan et al. [26] reported in 2005 that more than 50 types of artificial heart valves were used worldwide annually for over 170,000 patients. From magnetic resonance phase-contrast velocity mapping Bolger et al. [27] showed changes of kinetic energy of the inflow to LV for normal and dilated left ventricles. Quantification of ventricular contraction by kinetic energy flux was demonstrated by Hung et al. [28] using velocity vectors of normal and dys-synchrony echocardiograms. Garcia et al. [29] reported 2D velocity measurements obtained from Doppler-echocardiography by considering large scales of the flow being approximately 2D in a LV plane. Faludi et al. [30] studied vortex formations in healthy left ventricles and discussed low resolutions of echocardiographic 3D imaging technology. Using an echocardiographic method, Uejima et al. [31] showed a vortex flow pattern during ventricular dilation. Eriksson et al. [32] obtained an onset mitral flow pathlines traced in 25 msec. Charonko et al. [33] employed 2D phase contrast MRI to evaluate temporal variations of pressure drop and kinetic energy of the mitral flow for 12 subjects. Using Doppler-echocardiography data to obtain 2D velocity field, Hendabadi et al. [34] discussed a trajectory-based blood transport patterns to assess stasis in the ventricle.

In the present study, MRI data of a normal left ventricle motion are used for a comprehensive two-dimensional analysis of blood flow to the ascending aorta. Flow

patterns during rapid acceleration and deceleration are correlated with the aortic valve motion, pressure drop, shear and net pressure on aortic leaflets. Kinetic energy transfer from ventricular contraction to blood and the rates of work done by pressure and shear are calculated along with kinetic energy change and dissipation of energy in the ventricle. The pressure-flow relationship and energy loss are compared with those of a three-dimensional model. The momentums produced by ventricular contraction are in concert with vortices for aortic flow and the Bernoulli energy is practically conservative in the ventricular flow.

Computational approach

The arbitrary Lagrangian-Eulerian (ALE) formulation of the Navier-Stokes equations can be expressed as [35]:

$$\frac{\partial}{\partial t} \int_A \rho \vec{v} dA + \int_s \rho \vec{v} (\vec{v} - \vec{v}_b) \cdot \vec{n} ds = - \int_s p \mathbf{I} \cdot \vec{n} ds + \int_s \boldsymbol{\tau} \cdot \vec{n} ds \quad (1)$$

where $\vec{v}$ is the velocity vector, $\vec{v}_b$ the velocity along the boundary s , p the pressure, $\mathbf{I}$ the unit tensor, $\vec{n}$ the unit normal vector, $\boldsymbol{\tau}$ the viscous stress tensor, and ρ the blood density. The integral form of the continuity equation is

$$\frac{\partial}{\partial t} \int_A \rho dA + \int_s \rho (\vec{v} - \vec{v}_b) \cdot \vec{n} ds = 0 \quad (2)$$

The moving boundaries are based on MRI data which provide the wall and valve motions for the computational analysis.

The MRI scanning was performed for a healthy adult on a 1.5T Siemens scanner (Avanto, Siemens Medical Solutions, Erlangen) using steady-state free precession cine

gradient echo sequences. The data were acquired from 2-chamber, 4-chamber and short-axis planes using 2-14 equidistant slices for 3D reconstruction of movements of the left ventricle and atrium. The endocardial wall motion was obtained from 25 MRI frames for one cardiac period T ($= 0.88$ seconds). The temporal ventricle volume, $vol(t^*)$, is shown in Fig. 1 in which $t^* (= t/T)$ is the dimensionless time, and vol_{max} the end diastolic volume. A grid dependency study was conducted for five cases with number of triangular elements increased from 6000 to 9000, 13500, 20250 and 30375. The test results showed that the flow patterns were the same when the number reached 20250. This number of elements was used along with the Courant number criterion, resulting in 1800 time steps for one cardiac period (0.88 second).

The Navier-Stokes equations with moving meshes were solved using a finite volume CFD solver: ANSYS Fluent. The velocity $V_O(t^*)$ was prescribed at the downstream section of the sinuses of Valsalva for modeling systolic flow produced by LV contraction. The diastolic flow was due to LV dilation with $V_D(t^*)$ at the left atrium inlet. The motions of ventricle and the aortic valve were implemented by the user defined functions (UDFs) for each time step. The dynamic grids were monitored for grid quality based on face skew angle below 40° with a re-meshing procedure of ANSYS Fluent software. The resulting algebraic equations for pressure were solved using the implicit PISO (Pressure Implicit with Splitting of Operators) algorithm [36].

Kinematic and Dynamic Characteristics

The present study is based on a cardiac contraction with end diastolic volume of 162.5 ml. and end systolic volume of 113.7 ml. resulting in a normal stroke volume of 48.8 ml. and an ejection fraction of 70%. In addition to the moving LV chamber, the other boundary conditions are the velocity $V_D(t^*)$ at the left atrium inlet for diastolic flow, and $V_O(t^*)$ at the downstream section of the sinuses of Valsalva for systolic flow. They are shown in Fig. 2 as negative and positive curves, respectively. The temporal inlet and outlet diameters, $D_1(t)$ and $D_2(t)$, are used to define the Reynolds numbers for diastolic and systolic flows in the ventricle:

$$Re_D(t) = \rho V_D(t) D_1(t) / \mu \quad (3a)$$

$$Re_O(t) = \rho V_O(t) D_2(t) / \mu \quad (3b)$$

in which μ is the dynamic viscosity of blood. The corresponding flow rates can be evaluated by $Re^2 \mu^2 \pi / 4 \rho^2 V$. Since blood flowing in large arteries can be treated as homogeneous Newtonian fluid, the blood density and viscosity used are 1050 kgm^{-3} and $0.00316 \text{ Pa}\cdot\text{sec}$, respectively. The numerical solutions of the Navier-Stokes equations became periodic after four cycles of computation. The results of systolic flow are presented in this paper.

Figure 3a shows the vortices at the end diastole after the ventricular chamber remaining stationary for 0.02 second. Without modeling an isovolumetric contraction, the onset aortic flow is simulated from the Navier-Stokes equations for the Reynolds number (Re_O) rising from zero to 100 and 200 in 6 mini-seconds. As shown in Fig. 3b and 3c, a rapid generation and shedding of vortices in the sinuses of Valsalva are obtained from the 2D CFD computation. These flow patterns do not have much physiological

significance but demonstrating the rapid development of vortices in the refined computational analysis with MRI data of LV contraction. Also revealed is blood in the ventricle remaining dominated by vortices produced at end diastole. Further vortex shedding in the sinuses is demonstrated in Fig. 4 for $Re_O = 400, 800$ and 1200 during early opening phase of the aortic valve. Although the results are based on uniform velocity profiles specified at the outlet, vortices in this region reflect the dominance of upstream aortic flow. Should the aortic arch be included in the model, the vortices would be longer with higher velocities on the inner bend of the aorta during flow acceleration (Hung et al. 1989). The 2D results indicate that momentum transfer and vortices in the sinuses are primarily due to the aortic jet and the valve motion. During early systole, momentums of LV contraction do not disturb much of vortices in the ventricle (refer to Figs. 3 and 4). They follow and merge with vortices toward the aortic valve. Figure 5 depicts flow patterns for Re_O increased from 1750 to 1890 in 0.01 sec. The streamlines in the ventricle indicate that part of the aortic flow is contributed by the ventricular vortices. The flow patterns in Fig. 6 further portray flow acceleration for $Re_O = 2404, 2836$ and 3270 from $t = 0.627$ to 0.648 sec. They are characterized by diverging and converging streamlines from wall contraction to the aortic valve with shrinking vortices, while velocities in the sinuses remain driven by the aortic jet and valve motion. The characteristics of these vortices can be identified by evaluation of dynamic and energy characteristics.

The dynamics of blood ejection are demonstrated by pressure contours, shear and net pressure on the aortic valve. Figure 7a shows pressure distribution during the

163 aortic opening phase when $Re_O = 1825$. Low pressures appear at strong vortex centers
164 downstream from the aortic valve, indicating centrifugal force effects. The pressure
165 difference between the ventricle apex and the outlet is shown in the figure by $\Delta P_O = 420$
166 Pa (3.16 mmHg). The net pressures on the aortic valve are indicated by $P_L = 2058$ and
167 2105 Pa on the right side of Fig. 7a. They are related to the acceleration of valve leaflets
168 and vortices in the sinuses. The 3D effect on pressure distribution is anticipated to be
169 secondary (refer to Fig. 12). The complexity of pressure pattern for $Re_O = 1825$ reflects
170 that pressure gradients are neither dominated by the ventricular contraction nor by the
171 vortices alone. As the flow rate increases (see Fig. 6b), vortices in the ventricle continue
172 to reduce, contributing outflow to the aorta. Pressure contours for $Re_O = 2836$ (see Fig.
173 7b) correlate well with convergent streamlines in the ventricle. The tongue-shape
174 pressure contours in Fig. 7c for $Re_O = 3270$ are associated to flat velocity profiles of the
175 aortic jet. Also, pressure contours lower than 3450 Pa split and enclose vortices on both
176 sides of the aortic jet. Streamlines for other fully aortic open positions are shown in Fig.
177 8a and 8b. Because of small leaflet movements, no significant viscous effect is
178 developed on both sides of valve leaflets. Streamlines in Figs. 8c and 9 show aortic valve
179 closure during flow deceleration with adverse pressure P_L on the valve (Fig. 10b). On the
180 sinus side, streamlines move with closing valve leaflets. The MRI data and pulse rate are
181 fully identified as normal cardiac function; no aortic regurgitation occurs as the Reynolds
182 number reduces from 2031 to zero in 0.074 seconds. Figure 10a presents pressure
183 distribution for $Re_O = 2031$ where the contour lines 1580, 1450, 1425 and 1350 Pa
184 correlate well with the diverging and converging streamlines in Fig. 8c. Similar pressure

variations during systolic deceleration are evident in Fig. 10b for $Re_O = 1738$. The adverse net pressure ($P_L = 1671$ Pa or 12.5 mmHg) on the aortic leaflets becomes stronger when $Re_O = 1534$ (Fig. 10c). It is associated with the acceleration of valve closure.

Because the flow is produced by ventricular contraction with flow induced valve motion, shear stresses are small. As shown in Fig. 11 the shear stresses on aortic leaflet and sinus for $Re_O = 3270, 3370$ and 1534 are far below that might lead to blood trauma. The duration for red blood cells and platelets through the aortic jet is very short in comparison with that of blood trauma experiments using viscometers. The pressure difference, ΔP_S , between the ventricle apex and the aortic root shown in Fig. 12a is compared with pressure drop, ΔP_O , between the apex and the outlet section. The difference between ΔP and ΔP_S is the pressure drop for blood flow past the aortic valve of the 2D model. Because of the predominant longitudinal momentum, the pressure drop ΔP_S is comparable to that for 3D case shown in Fig. 12b.

Energy Transfer Characteristics

The fluid dynamics of cardiac ejection can be further analyzed from energy transfer characteristics. The work energy equation can be expressed in an integral form as:

$$\begin{aligned} & \int_W \left(\frac{\rho V^2}{2} \right) V_N d\ell + \int_W (p) V_N d\ell + \iint \left(\frac{\rho}{2} \frac{\partial V^2}{\partial t} \right) dx dy - \int_s (p_s) V_s d\ell - \int_s \left(\frac{\rho V_s^2}{2} \right) V_s d\ell - \int_{W+s} \vec{V} \cdot \vec{\tau} d\ell \\ & + \mu \iint \left(2 \left(\frac{\partial u}{\partial x} \right)^2 + 2 \left(\frac{\partial v}{\partial y} \right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 \right) dx dy = 0 \end{aligned} \quad (4)$$

204 in which u and v are the velocity components in the Cartesian coordinates, V_s and p_s are
 205 the velocity and pressure at the aortic root, respectively, and V_N is the normal velocity
 206 on the ventricle wall [37, 38]. The first term is the rate of kinetic energy transfer to
 207 blood from ventricle contraction. The calculated results are presented as curve A in Fig.
 208 13a and 13b (for an amplified scale). This quantity is directly calculated from the velocity
 209 of wall motion and is an useful index for quantification of echocardiograms [28]. The
 210 sum of the first two integrals in Eq. 4 is the total energy flux from the ventricle and is
 211 shown by curve B. The difference between curves B and A is the rate of work done by
 212 wall pressures. The result is based on a reference pressure of 10 mmHg (1330 Pa) at the
 213 ventricle apex. It is much lower than the actual one dominated by a rapid rise of
 214 ventricular pressure from end diastole to systolic pressure (about 120 mmHg). The third
 215 term in Eq. 4 is the rate of kinetic energy change in the ventricle. It is presented by the
 216 gap between curves C and B, and is positive when C is higher than B, otherwise,
 217 negative. The fourth integral is the rate of work done by pressure across the aortic root
 218 and is indicated by the difference between curves C and D. The associated kinetic
 219 energy out flux is the fifth integral, and is shown by the gap between curves D and E.
 220 Thus, the difference between curves C and E is the total energy out flux to the aortic
 221 valve. If the pressure, $p_R(t)$, is known at the aortic root, the rate of work done by
 222 pressure at this section and that on the wall can be adjusted by adding a value of

$p_R(t)V_S(t)D_S$ (D_S is the aortic root diameter). The last two integrals in Eq. (4) are, respectively, the rate of work done by shear and the rate of dissipation of energy. They are shown in figure 13*b* as the gap between curves E and F, and between F and G, respectively. Both of them are small for normal blood ejection from the left ventricle to the aortic root. The small viscous effect is due to streamlines moving with the wall and valve leaflets and no twist motion in the 2D computation. Curve G in Fig. 13*b* is the sum of all the energy terms of Eq. 4; it should be zero. The small residues indicate a good balance of numerical results of this equation, which could not be accomplished unless numerical solutions of the Navier-Stokes equations are quite accurate. Notice that curve E is also very small, indicating that the Bernoulli energy pumped from the ventricular contraction is practically balanced by the energy out flux at the aortic root and the rate of kinetic energy in the ventricle. The small energy loss is balanced by the rate of work done by viscous stress. In other words, the Bernoulli energy is practically conservative for normal cardiac pumping. Figure 14 shows a comparison of the Bernoulli energy flux at the aortic root between the 2D (curve 1) and 3D (curve 2) models using the same $V_O(t^*)$. Curve 3 is the results of curve 1 multiplied by the ratio of 3D and 2D flow rates. Because of the effect of spiral flow for the 3D case, curve 2 is higher than the projected small energy loss of curve 3.

Conclusions

Kinematic, dynamic and energy characteristics of blood flow in the ventricle are studied from a refined CFD analysis with MRI data. Momentums produced by cardiac

contraction do not interrupt vortices in the ventricle; they are in concert with vortices for aortic flow. As the flow accelerates and decelerates with ventricular contraction, vortices in the ventricle gradually reduce, contributing to the outflow. The aortic jet produces rapid vortex shedding and momentum transfer in the sinus of Valsalva without producing high shear field. Net pressures on the aortic valve are associated with leaflet motion during flow acceleration and deceleration. Both the work done by shear stresses and the energy dissipation in the ventricle are small, and they are almost balanced each other for the normal ventricular contraction and dilation. The insignificant viscous effect is attributed to streamlines moving with the ventricle motion. The Bernoulli energy delivered from the left ventricle to blood is practically equal to the total energy out flux at the aortic root and the rate change of kinetic energy in the ventricle, making the Bernoulli energy being conservative during the normal cardiac pumping. All the kinematic, dynamic and energy characteristics complement the optimal diastolic flow reported by Kilner et al. [22] and Pedrizzetti and Domenichini [39], and the results of diastolic flow of this study [40].

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Figure Captions List

- Fig. 1 Temporal variation of the left ventricle volume, $vol(t^*)$; $t^*=0$ for the onset diastole and $t^*=1$ for the end systole.
- Fig. 2 Temporary variation of velocity $V_O(t)$ and $Re_O(t)$ at outlet of systolic flow; $V_D(t)$ and $Re_D(t)$ at inlet for diastolic flow.
- Fig. 3 Streamlines at (a) $t=0.572$ sec (b) $t=0.575$ sec (c) $t=0.578$ sec. Streamlines colored by velocity (cm/sec).
- Fig. 4 Streamlines at (a) $t=0.581$ sec (b) $t=0.584$ sec (c) $t=0.588$ sec. Streamlines colored by velocity (cm/sec).
- Fig. 5 Streamlines at (a) $t=0.593$ sec (b) $t=0.603$ sec (c) $t=0.613$ sec. Streamlines colored by velocity (cm/sec).
- Fig. 6 Streamlines at (a) $t=0.627$ sec (b) $t=0.638$ sec (c) $t=0.648$ sec. Streamlines colored by velocity (cm/sec).
- Fig. 7 Pressure contours and average of net pressure on the aortic valve leaflets during opening at Reynolds numbers (a) 1825 (b) 2404 (c) 3270. The dimension of the numbers is Pa.
- Fig. 8 Streamlines at (a) $t=0.664$ sec (b) $t=0.775$ sec (c) $t=0.812$ sec. Streamlines colored by velocity (cm/sec).
- Fig. 9 Streamlines at (a) $t=0.830$ sec (b) $t=0.849$ sec (c) $t=0.886$ sec. Streamlines colored by velocity (cm/sec).

- Fig. 10 Pressure contours and average of net pressure on the aortic valve leaflets during closing for Reynolds numbers (a) 2031 (b) 1738 (c) 1534. The dimension of the numbers is Pa.
- Fig. 11 Vorticity and shear stress distributions of flow past the aortic valve for the Reynolds number equals to (a) 3270 (b) 3370 (c) 1534.
- Fig. 12 Pressure difference $\Delta PD(t^*)$ for diastole; $\Delta PO(t^*)$ and $\Delta PS(t^*)$ during systole for (a) 2D modelling of LV (b) 3D modelling of LV.
- Fig. 13 Rate of energy transfer of 2D model of systolic flow in the left ventricle: Curve A= kinetic energy flux on the wall, (B-A)= rate work done by pressure on the wall, (C-B)= rate change of kinetic energy, (C-D) = rate of work done by pressure at the outlet, (D-E)= kinetic energy out flux, (E-F)= work done by shear on the wall, and (F-G)= rate of energy dissipation.
- Fig. 14 Comparison of the rate of energy dissipation between the 2D model (curve 1) and the 3D model (cure 2), curve 3 is the 2D results multiplied by the ratio between 3D and 2D flow rates.

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Figures

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Figure 3

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Figure 9

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Figure 11

Figure 12

Figure 13

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Figure 14

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