Journal of Biomechanics 50 (2017) 71–76

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Three-dimensional diastolic blood flow in the left ventricle

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ARTICLE INFO

Article history:
Accepted 2 November 2016

Keywords:
Blood flow
Left ventricle
Navier–Stokes equation
Vortices
Work energy equation

ABSTRACT

Three-dimensional blood flow in a human left ventricle is studied via a computational analysis with magnetic resonance imaging of the cardiac motion. Formation, growth and decay of vortices during the myocardial dilation are analyzed with flow patterns on various diametric planes. They are dominated by momentum transfer during flow acceleration and deceleration through the mitral orifice. The posterior and anterior vortices form an asymmetric annular vortex at the mitral orifice, providing a smooth transition for the rapid inflow to the ventricle. The development of core vortex accommodates momentum for deceleration and for acceleration at end diastolic atrial contraction. The rate of energy dissipation and that of work done by viscous stresses are small; they are approximately balanced with each other. The kinetic energy flux and the rate of work done by pressure delivered to blood from ventricular dilation is well balanced by the total energy influx at the mitral orifice and the rate change of kinetic energy in the ventricle.

1. Introduction

Study of blood flow in the left ventricle (LV) is to identify cardiac function and dysfunction. Using magnetic resonance velocity mapping, Kim et al. (1995) reported a large counterclockwise vortex in the ventricle during diastole. Kilner et al. (2000) indicated that flow patterns in the normal LV do not have excessive energy loss for blood ejection from the left ventricle. Asymmetric vortices were reported by many investigators (Baccani et al., 2002, 2003; Ebbers et al., 2002; Vierendeels et al., 2000; Saber et al., 2003, 2001). Pedrizzetti and Domenichini (2005) and Domenichini et al. (2005) presented flow patterns in a prolate spheroid CFD model, discussing the normal heart motion being optimal in term of minimal energy dissipation. Long et al. (2003, 2008) reported a main counterclockwise vortex during the inflow and the influence of boundary motion to flow patterns. Schenkel et al. (2009) studied asymmetry vortices with time-dependent mitral and aortic orifices without modeling valve leaflet movements. Other CFD modeling included immerse boundary (IB) methods (McQueen and Peskin, 1989, 1997; McQueen and Peskin, 2000) and fluid-structure interaction (FSI) methods (Cheng et al., 2005; Krittian et al., 2010; Watanabe et al., 2004). The majorities of the LV numerical simulations were focused on normal subjects to understand the LV fluid dynamics, while some studies considered the patient-specific LVs in heart failure (Khalafvand et al., 2014). From magnetic resonance phase-contrast velocity mapping, Bolger et al. (2007) showed the kinetic energy of inflow for normal and dilated left ventricles. Hung et al. (2008) employed velocity vectors of echocardiogram to show kinetic energy flux for normal and dys-synchrony ventricular contractions. Faludi et al. (2010) discussed low resolutions of echocardiographic 3D imaging technology and vortex formations in healthy left ventricles. Using an echocardiographic method, Uejima et al. (2010) showed vortex flow patterns for inflow to the ventricle. Eriksson et al. (2011) studied pathlines traced in 25 ms during an onset mitral flow. From 2D phase contrast MRI Charonko et al. (2013) calculated temporal variations of pressure drop and kinetic energy of the mitral flow for 12 subjects.

The present study is focused on kinematic, dynamic and energy characteristics of diastolic flow in a normal left ventricle motion. The 3D flow patterns are presented by spiral streamlines and analyzed by the Lagrange stream function (2D streamlines) on various longitudinal sections. This approach shows the development of anterior and posterior vortices, resulting in an asymmetric ring vortex during the rapid filling phase of blood to the ventricle. A counterclockwise core vortex is formed during diastolic flow

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http://dx.doi.org/10.1016/j.jbiomech.2016.11.032
0021-9290/Published by Elsevier Ltd.

deceleration, followed by momentum transfer from the main flow to vortices during end diastolic acceleration and deceleration. The inflow characteristics are further studied using the work-energy equation. The kinetic energy flux and the rate of work done by pressure during cardiac dilation are calculated for energy transfer in the ventricle. The rate of work done by shear stresses and energy dissipation are obtained to be relatively very small.

2. Methods

2.1. MRI geometry reconstruction and grid generation

MRI scanning was performed on a healthy adult with a 1.5T Siemens scanner using steady state free precession cine gradient echo sequences (Avanto, Siemens Medical Solutions, Erlangen). The ventricular 2-chamber, 4-chamber, and short-axis planes were acquired with 12–14 equidistant slices for the left ventricle and atrium. The field of view was typically 320 mm with in-plane spatial resolution less than 1.5 mm. Each slice was acquired in a single breath hold, with 25 temporal phases per cardiac cycle. The reconstruction of LV geometry for CFD simulation was made by using a semi-automatic method. Fig. 1a shows the ventricle at end-diastole and end-systole. For each time step, unstructured grids consisting of tetrahedral cells were generated using a semi-automatic method. The grid topology for the computational domain is shown in Fig. 1b. To obtain a refined resolution, intermediate time steps and geometries were generated by cubic spine functions. To have the Courant number less than unity, 75 time steps were generated for each interval of the 25 geometries, resulting in 1800 time steps ($=24\times75$) for one cardiac cycle of computation. The velocities on the LV wall were calculated from differences between the current and former grids. To find an optimum number of elements (cells) for modelling of the LV chamber, the grid convergence index (GCI) was used for assessing grid invariant solution (Roache, 1998). A grid dependency study was made for five different cases with number of finite volumes increased from 50,000 to 75,000; 112,500, 168,750 and 253,125. Test results indicated that flow features obtained from 112,500 and 168,750 finite volumes were practically the same. The latter was chosen for this study.

2.2. The Navier–Stokes equations

The filling and ejection of blood flow in the left ventricle are calculated by using a finite volume method for the arbitrary Lagrangian–Eulerian (ALE) formulation of the Navier–Stokes equations. The integral form of the continuity equation for a volume (dV) with surface (S) is expressed as

$$\frac{\partial}{\partial t}\int_V \rho dV + \int_S \rho\left(\vec{v} - \vec{v}_b\right)\cdot\vec{n}\, dS = 0 \tag{1}$$

where $\vec{v}$ is the velocity vector, $\vec{v}_b$ the velocity on the boundary, $\vec{n}$ the normal vector and ρ the blood density. The momentum equation is

$$\int_V \frac{\partial}{\partial t}\left(\rho\vec{v}\right)dV + \int_S \rho\vec{v}\left(\vec{v} - \vec{v}_b\right)\cdot\vec{n}\, dS = -\int_S p\mathbf{I}\cdot\vec{n}\, dS + \int_S \boldsymbol{\tau}\cdot\vec{n}\, dS \tag{2}$$

where p is the pressure, $\mathbf{I}$ the unit tensor, and $\boldsymbol{\tau}$ the viscous stress tensor. Blood flowing in large arteries can be treated as homogeneous Newtonian fluid with density of 1050 kg m^{-3} and the dynamic viscosity of 0.00316 Pa s. Computational results are obtained from the MRI data of an adult with end systolic volume of 48.8 ml and end diastolic volume of 162.5 ml, resulting in a normal stroke volume of 113.7 ml and a normal ejection fraction of 70%. The cardiac period (T) is 0.88 s with 0.55 s of diastole and 0.33 s of systole (see Fig. 2). The normalized temporal ventricle volume based on a set of 25 LV geometries during the cardiac period is shown in Fig. 2a. The periodic flow patterns are computed from an initial hydrostatic condition with the motion of the left ventricle and atrium, velocity $V_D(t)$ at the atrial inlet for diastole, and no flow at the aortic outlet. The inclusion of the left atrium is to facilitate modeling inflow to the mitral orifice. During systole velocity $V_O(t)$ is prescribed at the outlet with no flow at the atrial inlet. Because of the noncircular inlet and outlet, the instantaneous hydraulic radius is used to define the

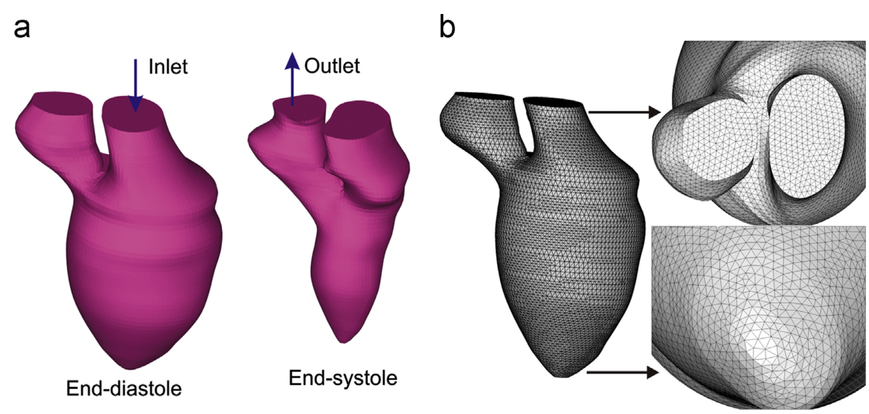

Fig. 1. (a) Reconstruction of left ventricle geometries, left atrium and ascending aorta at end-diastole and end-systole. (b) Grid topology of proximal left atrium and ascending aorta.

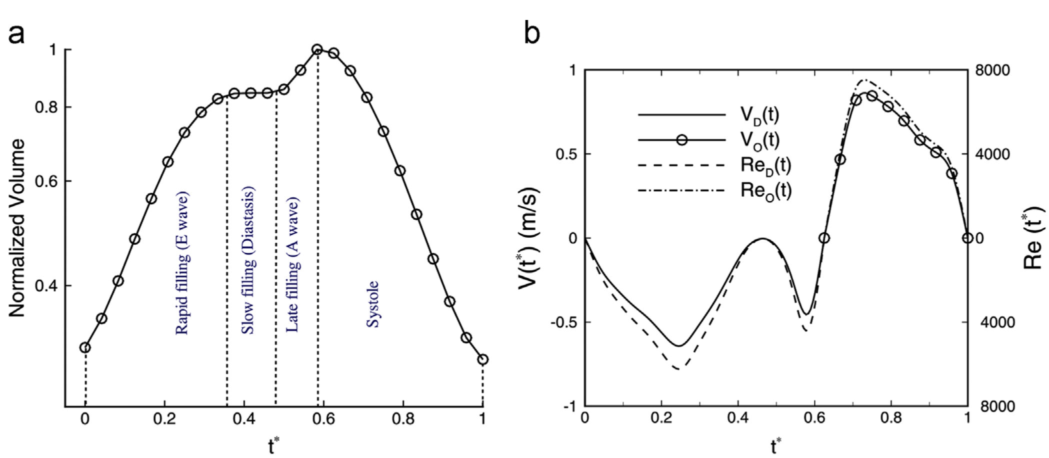

Fig. 2. (a) Temporal variation of the left ventricle volume; $t^*=t/T=0$ for the onset diastole and $t^*=1$ for end systole. (b) Temporary variation of velocity $V_D(t)$ and $Re_D(t)$ at inlet for diastolic flow; $V_O(t)$ and $Re_O(t)$ at outlet of systolic flow.