Effects of Material Properties on Hemodynamic Parameters of the Coronary Artery

Xiuqing Qian, Yan Wang, Zhilun Zhou, Zhicheng Liu

Institute of Biomedical Engineering, Capital Medical University, Beijing, China

Abstract

The variation of the hydrodynamic parameters of the coronary artery is researched while the elastic property of the blood vessel and the effect of the heart muscle are considered. The coronary artery with geometry branches is reconstructed using the software Mimics based on the clinical detection of CT images of coronary angiography. Spring elements connected the vascular wall are used to simulate the effect of elasticity of the heart muscle. The effects of the material properties on hemodynamic parameter can be obtained by solid-fluid coupled analysis using the finite element method. The results show the blood velocity decreases with the decrease of the elastic modulus of the vascular wall and the blood velocity is highest when taking the vascular wall as rigid body. And the blood velocity increases with the decrease of viscosity of blood.

1. Introduction

Atherosclerosis is a kind of multifactorial disease in which conditions such as high cholesterol level, high blood pressure, which has been the subject of numerous previous investigations [1-4]. Most studies have been in the research on hemodynamics, in which the blood vessel is assumed as rigid body. However, coronary vessels are surrounded by myocytes, which contract and relax constantly and exert the periodic mechanical influence on coronary vessels and flows. The mechanical interaction between myocardium and coronary vessels yields the unique profile of coronary flow velocity [5]. Data show that the angle of cyclic flexion, and consequently the stresses due to cyclic flexion of the artery were greatest in the region of plaques that progressed over the period of observation. Such stresses may have contributed to tissue damage or fatigue resulting in a more rapid progression of the atheromatous plaques [6]. Thubrikar's study describes a rabbit model in which cast placement at reduced arterial pressure leads to inhibition of atherosclerosis at arterial branch sites [7]. Therefore, the coupled action of the coronary vessels and the blood should consider, and the effects of the material properties on the variation of the hemodynamic parameter is not been ignored.

It is found that most studies have been in the left main coronary bifurcation, although the right coronary artery (RCA) has been attractingso me recent interest [8]. So the analysis of solid-fluid couple of the right coronary artery is studied in this paper.

2. 3-D reconstructed coronary artery

The 219 CT images of coronary angiography of healthy human body are from Beijing An Zhen Hospital. The three dimensional reconstructed of the right coronary artery with geometry branches is reconstructed using the software Mimics, shown in Figure 1.

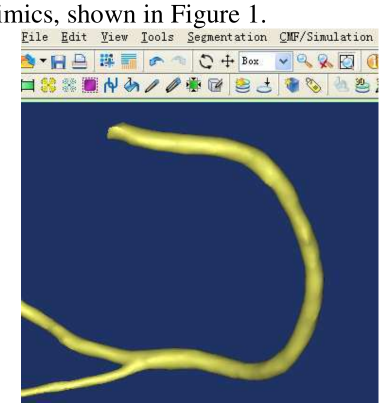


Figure 1. Three dimensional reconstruction of the coronary artery.

3. Coupled solid-fluid simulation

3.1. Finite element model

The finite element model can be gotten using the software Adina. The shell element is used to simulate the blood vessel wall. In order to simulate the effect of elasticity of the heart muscle, the spring elements are connected the vascular wall, shown in Figure 2. The materials properties of the blood vessel are taken as linear elastic materials, whose elastic modulus is taken as 1MPa, and the Poisson's ratio is taken as 0.49. The spring stiffness is taken as 10N/m.

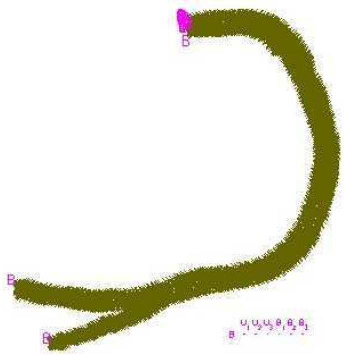


Figure 2. Finite element model of right coronary artery.

The blood is simulated using the brick elements, which are built using the software Adina based on the model of blood vessel. The blood is supposed as Newtonian flow, whose viscosity is taken as 0.0039235kg/ms and the density is taken as $1056kg/m^3$. The Reynolds number, which characterizes the ratio of the convective inertial forces of the fluid to the viscous forces, has an average value of Re=600. Under these conditions, the character of the flow can be safely presumed to be laminar.

3.2. Control equation

To study the behaviour of blood flow in the right coronary artery, it must be assumed that blood can be represented by an incompressible fluid which is governed by the Navier-Stokes equations

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t}+\mathbf{v}\cdot\nabla\mathbf{v}\right)=-\nabla p+\mu\Delta\mathbf{v}$$

and the continuity equation

$$\nabla\cdot\mathbf{v}=0$$

where v is the 3D velocity vector, P pressure, ρ density.

The behavior of the blood vessel can be governed by the following equation

$$\rho\frac{d^2u_i}{dt^2}=\sigma_{ij,j} \qquad i,j=1,2,3$$

where σ is the stress tensor and the u is the displacement.

3.3. Boundary conditions

The boundary conditions required to solve the governing equations are as follows. On the solid walls of the artery (which are assumed to be elasticity), the no-slip condition is imposed on the velocities. At the inlet of the artery a uniform inlet velocity profile with the time varying forcing function given according to the right coronary artery of a normal 56-year-old female and contains some periods of reverse flow as well as periods of rapid acceleration and deceleration[4]. In order to get the stable results, the three cardiac cycles are calculated, shown in Figure 3. The reference pressure at the outlet is taken as 120mmHg.

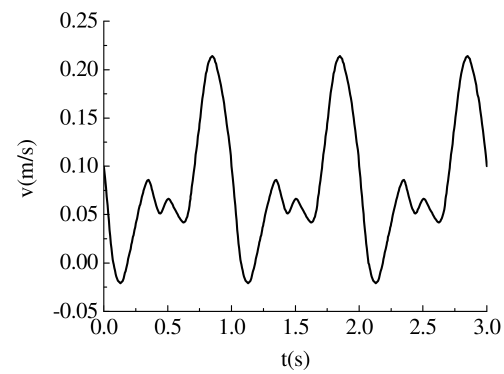


Figure 3. Inlet velocity.

Due to the entrance of the coronary artery is connected with the aorta, the boundary condition of the entrance of the coronary artery is taken as fixed. In addition, the normal velocity and normal force must keep continuous on the interface of the solid and fluid.

4. Results and discussion

It is found that there is the maximum value of the velocity at the node 1502 and the velocity of node 1502 varies with the time is shown in Figure 4. It is shown that the results of the second cardiac cycle are similar as the results of the third cardiac cycle. Therefore, the results of the second cycle are taken as the results. In the second cycle, the minimum value of velocity is at the time 1.147 and the maximum value of the velocity at the time 1.856. Therefore, the results at the time 1.147 and 1.856 are given in the following.

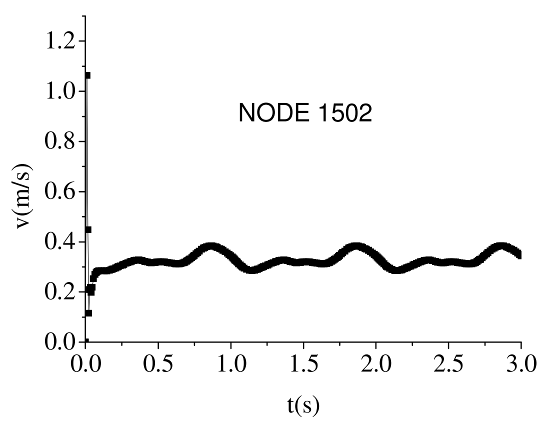
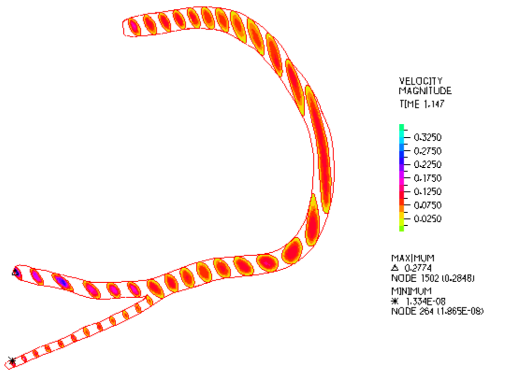


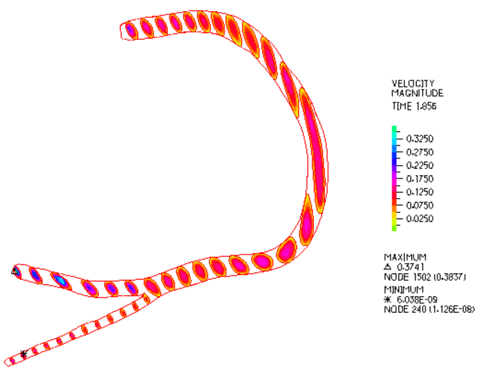
Figure 4. Velocity at the node 1502.

4.1. Velocity distribution

The distributions of the velocity at the time 1.147 and 1.856 are shown in figure 5.



(a) t=1.147



(b) t=1.856

Figure 5. Distribution of the velocity.

There are the low velocity field of the blood flow at the curve part of the blood vessel and neighborhood of the branches of the vascular wall. For example, the distribution of the low velocity field at the time B is shown in Figure.6. The colored zone represents the velocity is larger than 0.11m/s, and the block zone represents the velocity is smaller than 0.11m/s.

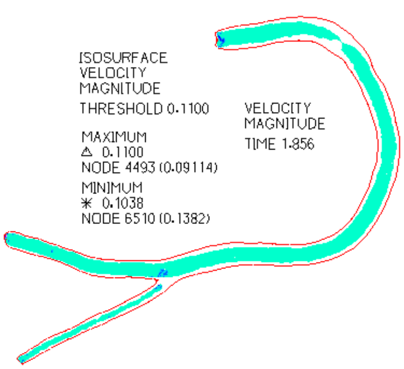
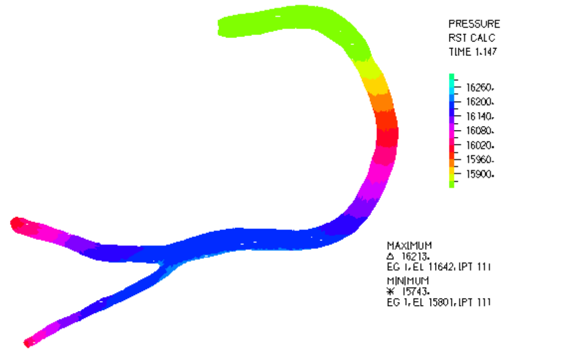


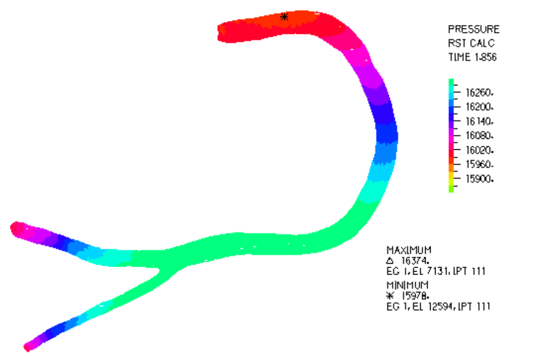
Figure 6. Low velocity field.

4.2. Pressure distribution

The pressure in the blood vessel at the time 1.147 and 1.856 are shown in Figure7.



(a) t=1.147

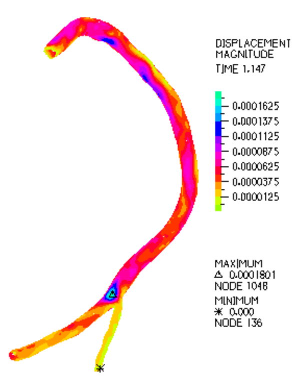


(b) t=1.856

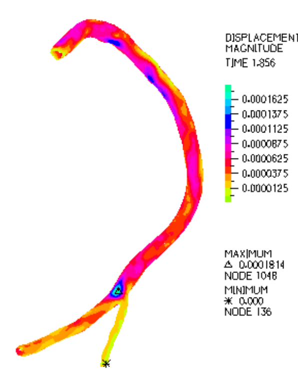
Figure 7. Distribution of the pressure.

4.3. Displacement of blood vessel

The displacement of the blood vessel at the time 1.147 and 1.856 are shown in Figure 8.



(a) t=1.147



(b) t=1.856

Figure 8. Distribution of the displacement.

4.4. Effects of material properties on hemodynamic parameter

It is often found that the elasticity of the blood vessel will change for patients with elevated blood pressure. The velocity vary with the variation of the elastic modulus of blood vessel should be considered. The variations of the elastic modulus of the blood vessel are taken from 1 to 5MPa. At the same time, the case which the vessel wall is assumed as the rigid body is calculated. The results are shown in Figure 9. It is found that the blood velocity decreases with the decrease of the elastic modulus of the vascular wall and the blood velocity is highest when taking the vascular wall as rigid body.

It is obvious that the velocity will decrease with the increase of the viscosity of blood, shown in Figure 10.

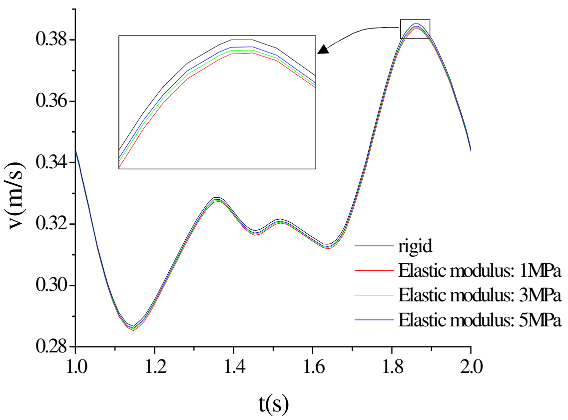


Figure 9. Velocity variation with the different elastic modulus of blood vessel.

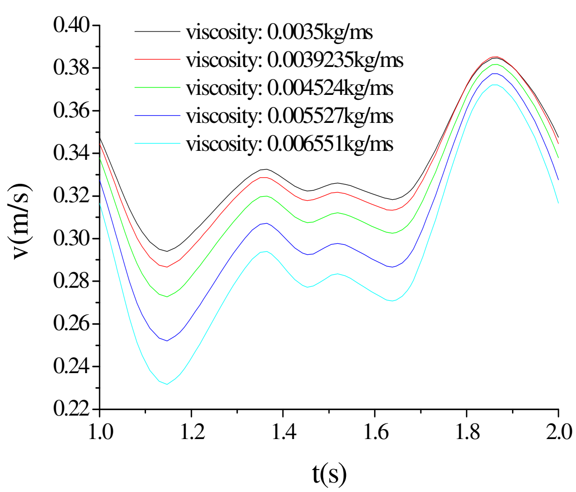


Figure 10. Velocity variation with the different viscosity of blood.

It is found that the effects of the elastic modulus of the blood vessel on the velocity of blood are not obvious. The reason might be the movement of the heart is not been considered although the effect of the elasticity of the heart muscle is simulated using the spring elements.

Acknowledgements

The authors thank to the Funding for this work supplied by elitist project of Beijing (PYZZ 090417001 147) and funding project for Academic Human Resources Development in Institutions of Higher Leading Under the Jurisdiction of Beijing Municipality No. PHR201008398.

References

[1] Soulis JV, Giannoglou GD, Chatzizisis YS, Farmakis TM, Giannakoulas GA, Parcharidis GE, Louridas GE. Spatial and phasic oscillation of non-Newtonian wall shear stress in human left coronary artery bifurcation: an insight to atherogenesis. Coronary Artery Disease 2006; 17(4): 351-358.
[2] Boutsianis E, Dave H, Frauenfelder T, Poulikakos D, Wildermuth S, Turina M, Ventikos Y, Zund G. Computational simulation of intracoronary flow based on real coronary geometry. European Journal of Cardio-Thoracic Surgery 2004; 26: 248-256.
[3] Prosi M, Perktold K, Ding ZH, Friedman MH. Influence of curvature dynamics on pulsatile coronary artery flow in a realistic bifurcation model. Journal of Biomechanics 2004, 37: 1767-1775.
[4] Johnston BM, Johnston PR, Corney S, Kilpatrick D. Non-Newtonian blood flow in human right coronary arteries: Transient simulations. Journal of Biomechanics 2006; 39: 1116-1128.
[5] Matsumoto T, Kajiya F. Coronary microcirculation: Physiology and mechanics. Fluid Dynamics Research 2005; 37: 60-81.
[6] Stein PD, Hamid MS, Shivkumar K, et al. Effects of cyclic flexion of coronary arteries on progression of atherosclerosis. Am J Cardiol 1994; 73: 431-437.
[7] Thubrikar MJ, Baker JW, Nolan SP. Inhibition of atherosclerosis associated with reduction of arterial intramural stress in rabbits. Artheriosclerosis 1988; 8: 410-420.
[8] Johnston BM, Johnston PR, Corney S, Kilpatrick D. Non-newtonian blood flow in human right coronary arteries: steady state simulations. Journal of Biomechanics 2004; 709-720.

Address for correspondence.

Name: Xiuqing Qian
Full postal address: No.10 Xitoutiao, You an men,
Institute of Biomedical Engineering,
Capital Medical University, Beijing, 100069, P. R. China
E-mail address: qianxq@ccmu.edu.cn