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3D Computer Model of Blood flow in the Coronary Artery Bypass Graft with Different Anastomotic Angles

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Abstract

A Coronary heart disease (CHD) is one of the most vital diseases that caused by atherosclerosis that builds a plaque on an arterial wall called atherosclerotic plaque. Stenosis artery is made by an atherosclerotic plaque leading to a breaking wall arteries and the effective way to cure this disease is a surgical treatment, a coronary artery bypass graft. The bypass grafted helps blood to flow conveniently, this is the main idea behind this work. However, trends of patients who have to repeat the surgery are growing up because of a frequently failure of implanted bypass graft such as a different of a physical structure of artery, the blood rheological behavior, and distribution of wall shear stress. In this study, the analysis of blood flow phenomena and wall shear stress in the stenosed coronary artery bypass graft is based on three-dimensional computer model. The effects of different anastomotic angles of 45, 60 and 90 degree and inlet flow situations (pulse and no pulse) are investigated. In the view of practical treatment, it is suggested the anastomotic angle of 45 degree is suitable for implement in a Coronary heart disease (CHD) problem. The results presented here can be used as the guidance for preplanning medical treatment.

***Keywords**:* bypass graft, 3D computer model, anastomotic angle, Newtonian, Pulse, blood flow, simulation

1. Introduction

The coronary artery disease (CAD) is the most common type of heart disease which happens when the arteries that supply blood to heart muscle become hardened and narrowed. This is due to the buildup of cholesterol and other material, namely plaque, builds up inside on the inner walls of coronary arteries. Due to the increasing trend of CAD patient and rate of death still rise up. As well as the rate of patient who has repetition surgery also increasing owing to fail in treatment operation. This is interesting to study CAD treatment by using technology to assist such as computer simulation in order to preplanning before operation and reduce reputation rate or surgery.

Nowadays, there are many researchers have studied and analyzed coronary artery. Owida et al., 2012 [1] Reviewed a recent numerical investigation of various coronary artery bypass grafts model and trend update in myocardial revascularization field. Alishahi et al., 2011 [2] studied pulsatile flow and arterial wall behavior of a stenosed aorta and iliac arteries. The blood is taken as non-Newtonian and the arterial wall is assumed as rigid and flexible. Vimmr and Jonásová, 2010 [3] studied blood flow in 3D bypass coronary and femoral arteries with occluded. The blood is considered to be a Newtonian and non-Newtonian fluid. Distribution of velocity and wall shear stress was investigated. Muraca et al., 2009 **[4]** investigated the stress properties of the surface at a connection between the plaque and the artery and study the relation of geometric between the angle of bifurcation and fluid structural properties. Sankar and Lee, 2009 [5] studied the effects of pulsatile blood flow through stenosed artery with non-Newtonian behavior. The variations of these flow quantities with different parameters of the fluid have been analyzed.

The bypass graft 70%-area occluded artery with different anastomotic angles, including 45, 60 and 75 degree are investigated by Ko et Al., 2008 [6]**.** Blood is considered to be a Newtonian fluid and study recirculation structure, secondary flow motion, mass flow rate and wall shear stress on the arterial wall. As well as Hong et al., 2008 [7] presented computer simulation of pulsatile flow and macromolecular transport in complex blood vessel. An axial velocity, secondary flow such as LDL concentration distribution is obtained. Politis et al., 2008 [8] also analysed an arterial coronary with different grafting distances. The stenosis effect was investigated for three different degrees of area stenosis, 25%, 50%, 75% and without stenosis as well as various inflow rate ratios are imposed to study restenosis, velocity and wall shear stress distribution. Wiwatanapataphee et al., 2006 [9] represented the blood flow through coronary arteries with an unsymmetrical stenosis, 25%, 50% and 65%, carried out the result such as the flow field, pressure field and wall deformation in a cardiac cycle. Sakanarayanan et al., 2005 [10] demonstrated graft flow dynamics and wall shear stress distribution at the anastomotic area of aorto-left and right coronary bypass graft model that base on real-life situations. Two different cardiac cycles, at the onset of ejection and during mid-diastole are used for both models.

In this study, the three-dimensional computer of bypassed artery models of 45, 60 and 90 degree are represented. The effects of pulse and no pulse situations and fluid properties (Newtonian and non-Newtonian) are also investigated. The phenomena of blood flow and shear-stress on artery wall are studied.

The Finite volume method (FVM) is used to solve 3D computer model and Naviar-stoke equation governing this problem.

The objective of this study is to propose the modeling of the coronary artery bypass model to achieve an optimum bypassed degree for coronary artery disease treatment. The effect of related parameters to understand blood flow phenomenon for help to preplanning treatment application and performed. Furthermore, this study can be the database for the future research where the purpose is to reduce risk for repetition in practical treatment. In this study, bypassed artery models of 45, 60 and 90 degree in situations of pulse and no pulse will be systematically investigated.

2. Problem definition and procedure

2.1 Physical model and boundary condition

Fig. 1 shows 3D computer model with the specified dimension and geometry for the simulation. This model was modified from T.H. Ko [6]. The diameter of host and bypass arteries are 2 and 1 mm respectively. The main artery is modeled to be of length 30 mm and partially constricted (50%-area). The anastomotic angle of the host artery and bypass graft is denoted by Ө.

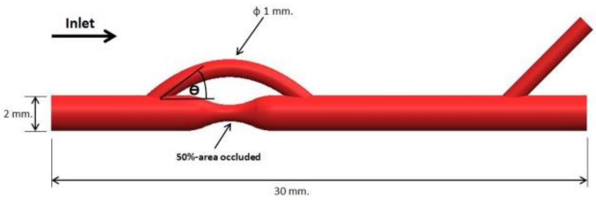


Fig. 1 The physical model of the problem

The boundary conditions and the assumptions of this work are the entire arterial wall is assumed to be a non-slip condition and rigid. The blood flow is assumed to be a laminar flow and incompressible fluid with a density (ρ) of 1060 k/m^3. Dynamic viscosity (μ) of 0.0035 Pa.s is used for a Newtonian blood flow. Blood viscosity is directly taken from Vimmr and Jonášová, 2010 [3] in case of non-Newtonian blood flow (Carreau-Yasuda model). Inlet flow situations profile with pulse situation referred to the flow-rate waveform at the left coronary artery of Sakanarayanan et al., 2005 [10] that the heartbeat is 9 second per time as indicated in Fig. 2 as below.

2.2 Governing equations

The Naviar-Stokes and the Continuity equation governing the blood flow in a coronary artery with bypass graft are modeled and written as follows,

Continuity equation :

$$\frac{\partial \rho}{\partial t}+\vec{\nabla}\cdot\left(\rho\vec{V}\right)=0 \qquad (1)$$

Momentum equation :

$$\frac{\partial(\rho u)}{\partial t}+\vec{\nabla}\cdot\left(\rho u\vec{V}\right)=-\frac{\partial P}{\partial x}+\frac{\partial \sigma_x}{\partial x}+\frac{\partial \tau_{xy}}{\partial y}+\frac{\partial \tau_{xz}}{\partial z}+\rho f_x \qquad (2)$$

$$\frac{\partial(\rho v)}{\partial t}+\vec{\nabla}\cdot\left(\rho v\vec{V}\right)=-\frac{\partial P}{\partial y}+\frac{\partial \sigma_y}{\partial y}+\frac{\partial \tau_{yx}}{\partial x}+\frac{\partial \tau_{yz}}{\partial z}+\rho f_y \qquad (3)$$

$$\frac{\partial(\rho w)}{\partial t}+\vec{\nabla}\cdot\left(\rho w\vec{V}\right)=-\frac{\partial P}{\partial z}+\frac{\partial \sigma_z}{\partial z}+\frac{\partial \tau_{zx}}{\partial x}+\frac{\partial \tau_{zy}}{\partial y}+\rho f_z \qquad (4)$$

When $\vec{\nabla}=\frac{\partial}{\partial x}\bar{i}+\frac{\partial}{\partial y}\bar{j}+\frac{\partial}{\partial z}\bar{k}$

Where ρ = blood density, u, v, w = blood velocity in x, y, z direction respectively, $\vec{V}$ =velocity vector, t = time, P = pressure, τ = shear stress, f = body force, σ = normal stress

The Carreau–Yasuda model that was applied for non-Newtonian blood flow taken from Vimmr and Jonášová, 2010 [3] is written as follows,

$$\eta(\dot{\gamma})=\eta_\infty+(\eta_0-\eta_\infty)[1+(\lambda\dot{\gamma})^a]^{(n-1)/a} \qquad (5)$$

Where η_0 = zero shear viscosity, η_∞ = infinite shear viscosity, λ = characteristic relaxation time, n = flow index and a = the positive parameter that controls the transition to the lower Newtonian range.

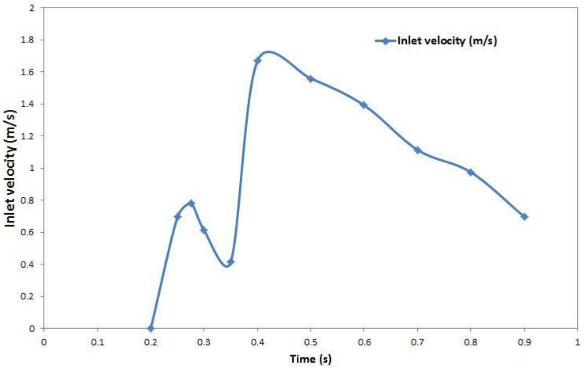
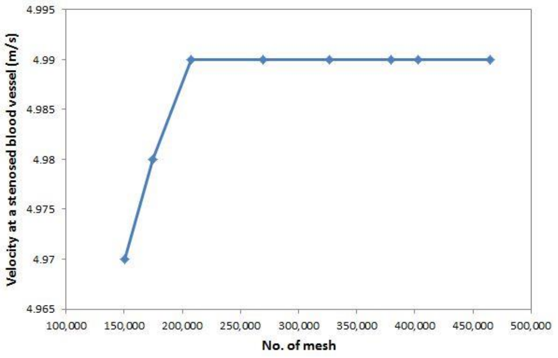


Fig. 2 Inlet flow situations profile for pulsatile cases.

2.3 Numerical procedure

In this study, the Naviar-Stokes equation and related boundary conditions are numerically simulated by using FVM with ANSYS (CFX) software. A convergence test of blood flow with pulse and no pulse situations are performed to identify the suitable number of elements required for simulating blood velocity in stenosis area. The convergence curve resulting from the convergence test is shown in Fig. 3. This convergence test leads to a grid with approximately 207,500 elements. It is reasonable to confirm that at this element number, the accuracy of the simulation results is independent from the number of elements in calculation procedure.

(a)



(b)

Fig. 3 Grid Independent test in case of coronary artery bypass graft with 45 degree anastomotic angle and no pulse situation.
(a) Mesh used in the model
(b) Grid independent testing.

3. Results and discussion

3.1 Verification of the model

This study, the presented simulated results has been validated against the numerical result which was directly taken from the work of Ko et Al., 2008 [6] .Here, the bypassed artery with anastomotic angle of 45 degree was selected in this validation case. The blood property is assumed to be Newtonian fluid with the density of 1000 kg/m^3 and viscosity of 0.0035 kg/m/s. The comparisons of velocity contour on the symmetric plane for both cases are demonstrated in Fig. 4. It is found that a good agreement of the velocity contour on the symmetric plane between Ko et Al., 2008 [6] and presented solution is clearly shown. This favorable comparison lends confidence in the accuracy of the present numerical model. It is important to be noted that there are some errors in simulation which might be generated from the input some properties and difference of numerical scheme.

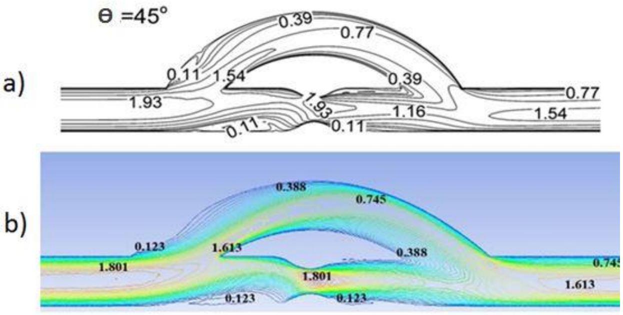


Fig. 4 The comparisons of velocity contour on the symmetric plane in the three-dimensional model
a) velocity contour of Ko et Al., 2008 [6]
b) velocity contour of presented study.

3.2 Effect of anastomotic angles

Fig. 5 shows the velocity contour on a symmetric plane with time of 9s of Newtonian blood flow with no pulse situation. The highest velocity in any cases occurs at a center of stenosis coronary artery that caused by changing the cross-section area into constricted blood vessel. Consider the effect of anastomotic angles, the simulated results show that the velocity of bypassed coronary artery with 45 degree is equal to 3.704 m/s, which less than 60 and 90 degree that equal to 3.816 m/s and 4.041 m/s respectively. This is because it has partial blood flowed into the bypass graft. Moreover, the most convenient blood flow phenomena plays an important role at 45 degree bypassed as well.

The results of shear stress on blood vessel wall with different anastomotic angles are shown in Fig. 6. It is observed that the remarkable point is followed the velocity contour in Fig.5. The lowest wall shear stress and the most convenient blood flow always display at coronary artery bypass graft with 45 degree anastomotic angle.

3.3 Effect of inlet flow situations

The Inlet flow situation affects to characteristic of blood flow as shown in Fig.7 and Fig.8.

Fig.7 and 8 demonstrate velocity contour with flow time of 4s in case without pulse and with pulse, respectively.

The figures show that maximum velocity of blood at a center of stenosed coronary artery in case of bypassed and no pulse is 3.704 m/s while artery with pulse is 6.071 m/s at the same time. It is found that blood velocity at stenosis area with no pulse is slower when compared to pulse situation due to the highest systole is occurring with time of 4s. Furthermore, the inlet pulse flow situations is similarly an actual systolic than that the bypassed coronary artery with no pulse situation as shown in Fig. 9

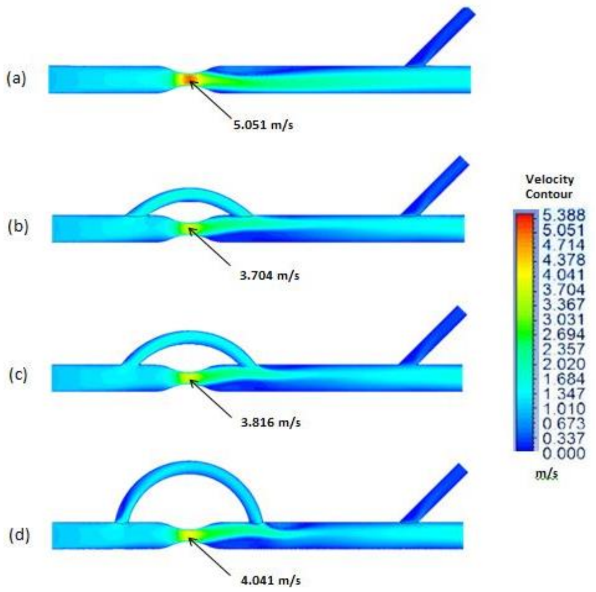


Fig. 5 Velocity contour on the symmetric plane in case of Newtonian fluid and no pulse situation with time of 0.9 s
(a) Without bypass, (b) Θ = 45°,
(c) Θ = 60° and (d) Θ = 90°

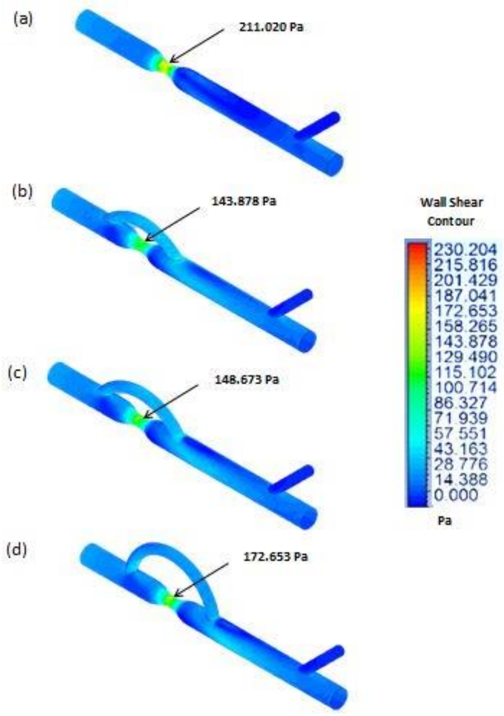


Fig. 6 Wall shear stress distribution in case of Newtonian fluid and no pulse situation with time of 0.9 s
(a) Without bypass, (b) ϴ = 45°,
(c) ϴ = 60° and (d) ϴ = 90°

3.4 Relationship between velocity and length for three anastomotic angles

Fig. 10 shows the relationship of velocity at a center of blood artery and length for three different anastomotic angles with pulse input situation and considered blood as a Newtonian fluid with time of 4s. The result shows remarkable that all testing cases have the highest velocity at 0.01 m of length because this length is the narrowest cross-section area. Furthermore, the result of 45 degree bypassed angle has the least velocity at 0.01m of length and reached the smoothest flowing more than other angles.

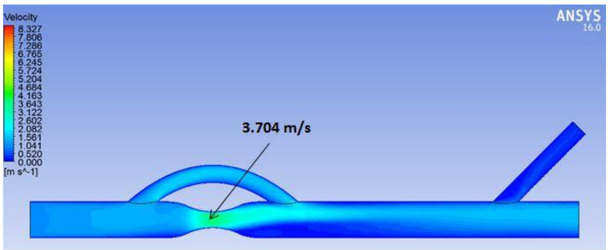


Fig. 7 Velocity contour on a symmetric plane in case of Newtonian fluid with no pulse situation with time of 4s

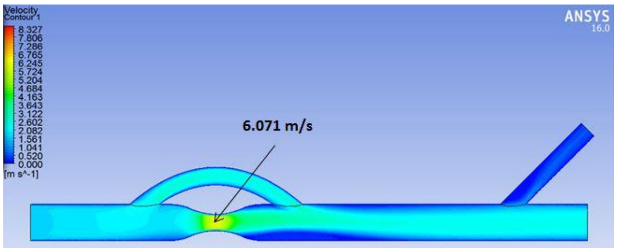


Fig. 8 Velocity contour on a symmetric plane in case of Newtonian fluid with pulse situation with time of 4s

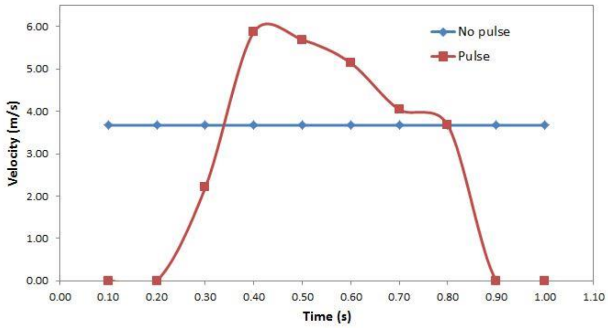


Fig.9 Comparison of the velocity with elapse time at a center of stenosed coronary artery with bypassed 45 degree anastomotic angle and Newtonian fluid between no pulse and pulse situations.

3.5 Effect of fluid properties

The result shows that fluid properties, namely Newtonian and non-Newtonian blood, are in the same direction and similarly result as shown in Fig. 10 wall shear stress on arterial wall is in the same way. Therefore, we can consider blood to be a Newtonian fluid for a convenient that conform to Vimmr and Jonásová, 2010's research [3].

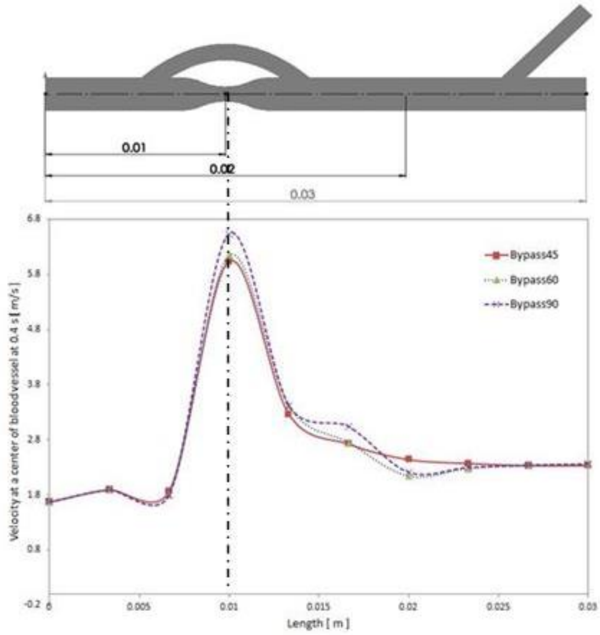


Fig. 10 Relationship between velocity at a center line and length for different anastomotic angles with Pulse input situation with time of 0.4s

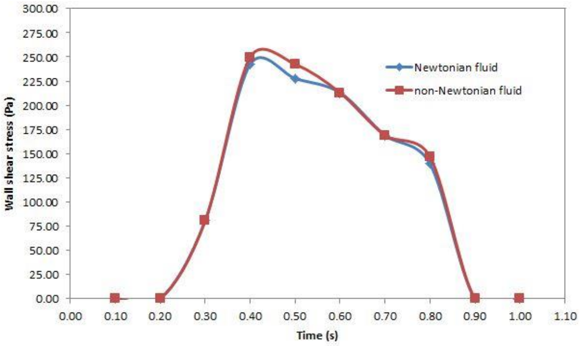


Fig. 11 Comparison of wall shear stress at stenosed area with different fluid properties (in case of coronary artery bypass graft with 45 degree anastomotic angle and pulse situation).

4. Conclusion

This research is study the flow behaviors in 3D computer model of a stenosed coronary artery bypass graft with varying anastomotic angles, inlet flow situations (pulse and no pulse situation), and fluid properties in case of Newtonian and non-Newtonian blood. Effects of these different parameters on the velocity and wall shear stress during blood flow in the coronary artery bypass graft are systematically investigated.

Regarding to

The anastomotic angle that connected the host artery and bypass graft 45, 60 and 90 degree. the result show that the velocity at stenosed coronary artery bypass graft with 60 and 90 degree are more than 45 degree bypassed artery.

The fluid properties, Newtonian and non-Newtonian fluid show the similarly result, therefore, blood flow properties can consider as Newtonian fluid for a convenient according to Vimmr and Jonásová, 2010 [3].

The inlet flow velocity situations, no pulse and pulse situation, the inlet pulse flow situations show an appropriate result more than the other one because of it alike a realistic systolic.

In this studied, case of the coronary artery bypass graft with 45 degree anastomotic angle is the best proper model for implement in a Coronary heart disease (CHD) problem because the velocity at a stenosis and wall shear stress on the arterial wall is less than other angles. Moreover, case of considered blood flow model as a non-Newtonian fluid and used pulse input situation is the most closely to the reality situation as well.

The result presented here can be used as guidance for the medical treatment and help to predict the outcome of the treatment.

6. Acknowledgement

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7. References

7.1 Article in Journals

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