Investigating the Effect of Velocity Inlet and Carrying Fluid on the Flow inside Coronary Artery

Mohammadreza Nezamirad, Nasim Sabetpour, Azadeh Yazdi, Amirmasoud Hamedi

Abstract**—** In this study OpenFOAM 4.4.2 was used to investigate flow inside the coronary artery of the heart. This step is the first step of our future project, which is to include conjugate heat transfer of the heart with three main coronary arteries. Three different velocities were used as inlet boundary conditions to see the effect of velocity increase on velocity, pressure, and wall shear of the coronary artery. Also, three different fluids, namely the University of Wisconsin solution, gelatin, and blood was used to investigate the effect of different fluids on flow inside the coronary artery. A code based on Reynolds Stress Navier Stokes (RANS) equations was written and implemented with the real boundary condition that was calculated based on MRI images. In order to improve the accuracy of the current numerical scheme, hex dominant mesh is utilized. When the inlet velocity increases to 0.5 m/s, velocity, wall shear stress, and pressure increase at the narrower parts.

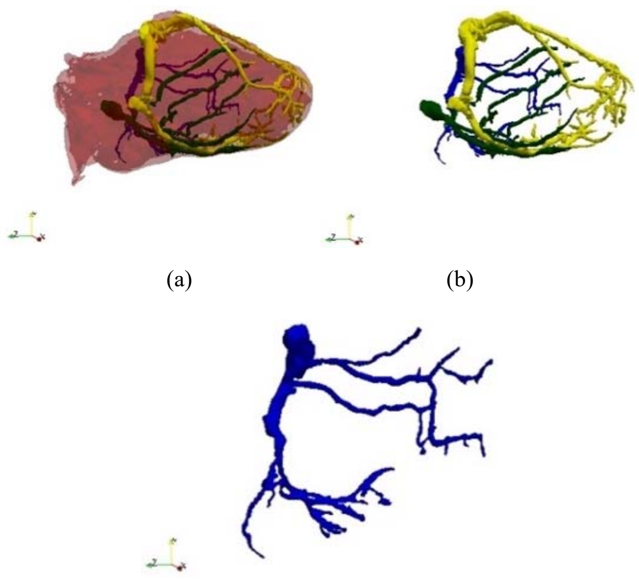
Keywords**—**CFD, heart, simulation, OpenFOAM.

I. Introduction

MODELING and simulation of the heart are very complex phenomena which can take a significant amount of time and research facilities. One of the biggest problems that nowadays donors and recipients are dealing with is the vast geographical differences that can make the process of compatible transplantation very hard and, in many cases, impossible [1], [2]. In large arteries, shear stress can be exerted linearly [3]. A model for the design of cardiovascular devices by the acquisition of COMSOL Multiphysics software was introduced [4]. Distention and wall shear stress were used to validate the mentioned model. Non-Newtonian blood flow was simulated by the acquisition of a laminar module in order to investigate lateral angle (LA) ratio main middle cerebral artery (MCDA), which can be correlated to aneurysm formation. It was found that varying MCDA bifurcation angles can increase aneurism due to wall shear stress and changes the fluid flow. Patient-specific modeling for measuring wall shear stress and hemodynamic in coronary arteries with aneurism, which was caused by Kawasaki Disease (KD), was investigated by Sengupta et al. [5]. In the current study, since our next purpose is heart cooling for transplant purposes, Gelatin and UW solutions was investigated beside blood for flow inside coronary artery.

II. Methodology

The human heart geometry used for simulations was obtained from three-dimensional, high-resolution MRI scans. Fig. 1 demonstrates different domain surfaces of the heart in different colors. Fig. 1 shows a complex model of the heart, which has three coronary arteries. According to Fig. 1 (a), a full heart model with three coronary arteries can be seen. Fig. 1 (b) shows three coronary arteries which are located in their correct places. The model, which is shown in Fig. 1, was obtained from an MRI image from the University of Minnesota. Fig. 1 (c) shows the coronary artery, which will be simulated in this study using OpenFOAM 4.4.2.



(a) (b) (c)

Fig. 1 The whole heart geometry with three coronary arteries inside it

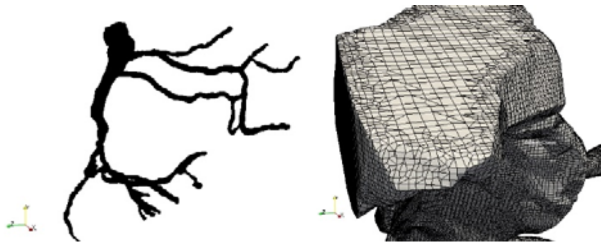
Mohammadreza Nezamirad is with the Department of Chemical, Biological and Materials Engineering, University of South Florida, Tampa, FL (corresponding author, e-mail: mnezamirad@usf.edu).

Nasim Sabetpour is with the Department of Computer Science, Iowa State University, Ames, Iowa (e-mail: nasim@iastate.edu).

Azadeh Yazdi is with the Department of Civil And Environmental Engineering, George Mason University, (e-mail: agharibr@gmu.edu).

Amirmasoud Hamedi is with the Department of Civil and Environmental Engineering, Florida International University, Miami, FL, USA (e-mail: amirmasoud.hamedi1@fiu.edu).

Fig. 2 shows the mesh which was used for the present study in order to investigate flow inside the coronary artery. Fig. 2 (a) is the whole geometry of the coronary artery. Fig. 2 (b) shows a close-up view of the inlet of the coronary artery with its mesh. In this study, three different boundary conditions for three different fluids were used. At first it was assumed that inlet velocity is 0.2 (m/s) and then inlet velocity was changed to 0.35 (m/s) and 0.5 (m/s). In all of the cases, outlet velocity was set to zero. Three different fluid that was used in this study are orderly, University of Wisconsin (UW) solution, Gelatin, and blood.

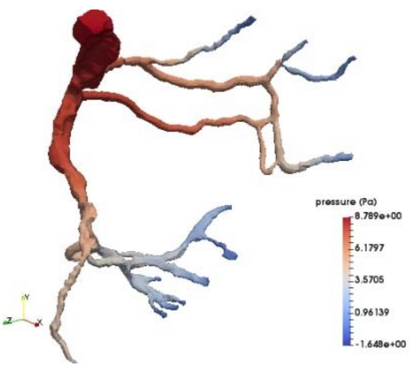


(a) (b)

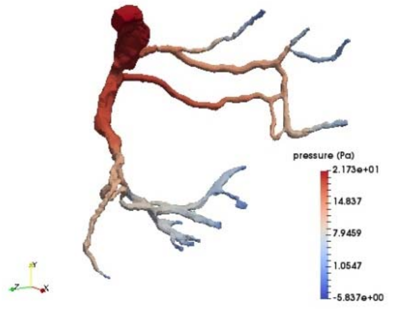
Fig. 2 Mesh used for coronary artery which was used for the present study

III. Result and Discussion

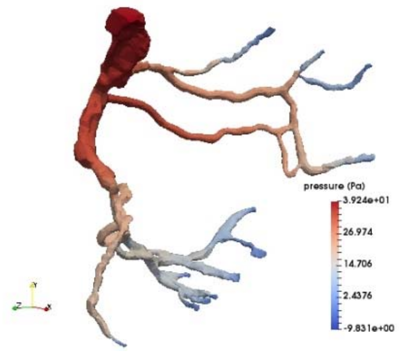
Fig. 3 shows pressure distribution when the UW solution was used. Fig. 3 (a) shows pressure distribution inside the coronary artery when inlet velocity is 0.2 m/s, and outlet velocity is zero. Fig. 3 (b) shows pressure distribution when inlet velocity is 0.35 m/s, and outlet velocity is zero. Fig. 3 (c) shows velocity distribution when inlet velocity is 0.35 m/s, and outlet velocity is zero. According to Fig. 3, increasing velocity from 0.2 m/s to 0.35 m/s increases pressure from 8.79 Pa to 20.2 Pa, which is nearly 130 percent. By comparing Figs. 3 (b) and (c), it can be inferred that as velocity increases from 0.35 m/s to 0.5 m/s, pressure increases from 20.2 Pa to 39.2 Pa, which shows a 94 percent increase in the value of pressure inside the coronary artery.



(a)



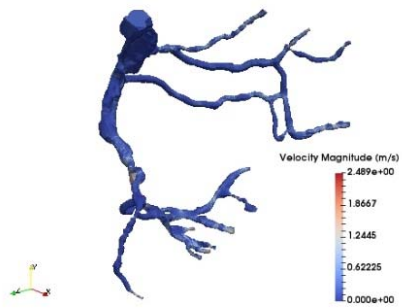
(b)



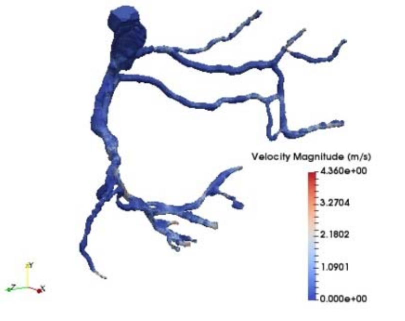
(c)

Fig. 3 Pressure distribution when UW solution was used ((a) Inlet velocity = 0.2 m/s, (b) Inlet velocity = 0.35 m/s, (c) Inlet velocity = 0.5 m/s))

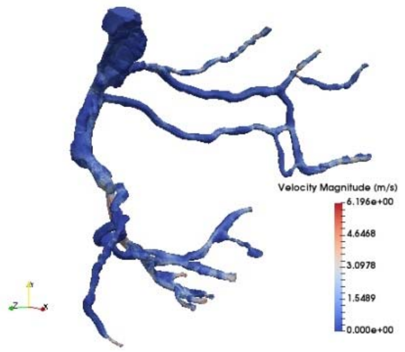
Fig. 4 shows velocity distribution along the coronary artery when the flowing fluid is UW. Three different cases were investigated. In case 1, inlet velocity was 0.2 m/s, and outlet velocity was set to zero. In case 2, inlet velocity was 0.35 m/s, and outlet velocity was zero m/s. Finally, in case 3, inlet velocity was 0.5 m/s, and outlet velocity was zero. From Fig. 4, it can be inferred that as the velocity inlet is 0.2 m/s, the maximum velocity inside the coronary artery reaches to 2.49 m/s. As inlet velocity increases to 0.35 m/s, maximum velocity reaches to 4.36 m/s. Finally, when inlet velocity increases to 0.5 m/s, maximum velocity reaches to 6.2 m/s. The maximum velocity in Fig. 4 can mostly be observed in the regions that the diameter of coronary decreases rapidly.



(a)



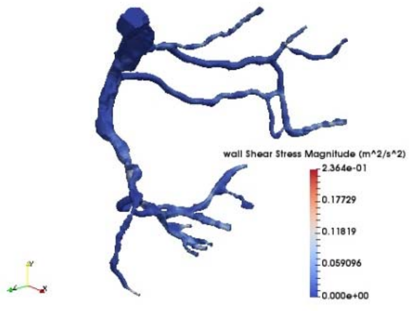
(b)



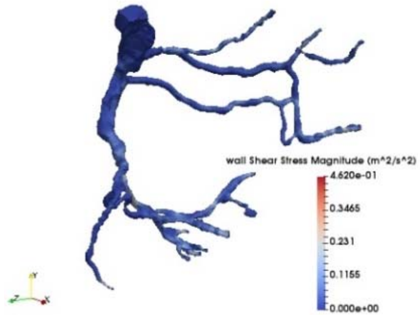
(c)

Fig. 4 Velocity distribution when UW solution was used ((a) Inlet velocity = 0.2 m/s, (b) Inlet velocity = 0.35 m/s, (c) Inlet velocity = 0.5 m/s))

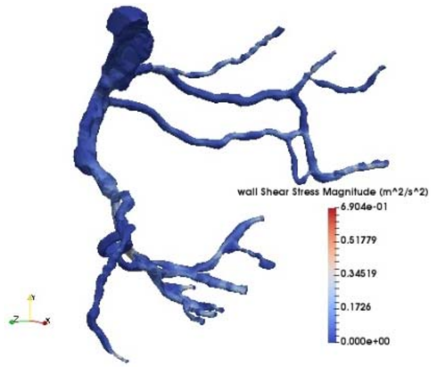
Fig. 5 shows the magnitude of wall shear stress as different inlet velocities were used to evaluate the flow field in coronary artery. As Fig. 5 (a) shows, when inlet velocity is 0.2 m/s, the maximum value of wall shear stress mostly forms toward the outlet of coronary artery and it reaches to its peak value which is 0.236 ($\frac{m^2}{s^2}$). After changing inlet velocity to 0.35 m/s, wall shear stress inside coronary artery increases to 0.462 ($\frac{m^2}{s^2}$), and it forms mostly in the regions which have a smaller diameter. Fig. 5 (c) shows when inlet velocity is 0.5 m/s, wall shear stress increases to 0.69 ($\frac{m^2}{s^2}$) and more regions experience higher amount of wall shear stress compared to the other regions.



(a)



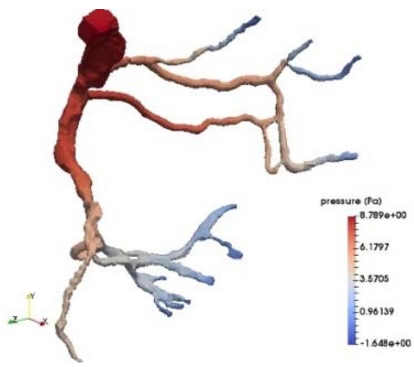
(b)



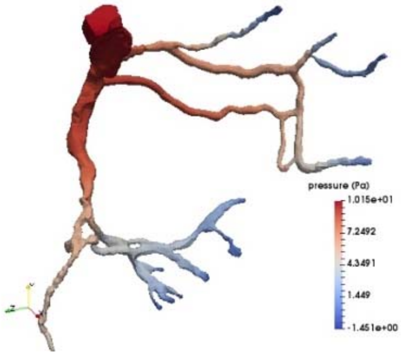
(c)

Fig. 5 Magnitude of wall shear stress for three different cases ((a) Inlet velocity = 0.2 m/s, (b) Inlet velocity = 0.35 m/s, (c) Inlet velocity = 0.5 m/s))

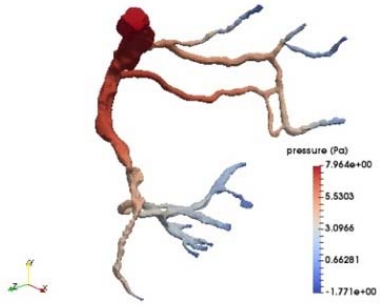
Fig. 6 shows the pressure inside the coronary artery when inlet velocity is 0.2 m/s, and outlet velocity is zero. For case (a) in Fig. 6, UW solution was used and as mentioned before the pressure reaches to 8.79 Pa. By comparing Figs. 6 (a), (b) and (c), it can be found that since Gelatin has the greatest amount of kinematic viscosity ($51e^{-7}\,\frac{m^2}{s}$), the biggest amount of peak pressure (10.15 Pa) also occurs in this case. Blood due to the lowest amount of kinematic viscosity ($28e^{-7}\,\frac{m^2}{s}$) has the lowest amount of peak pressure (7.96 Pa).



(a)

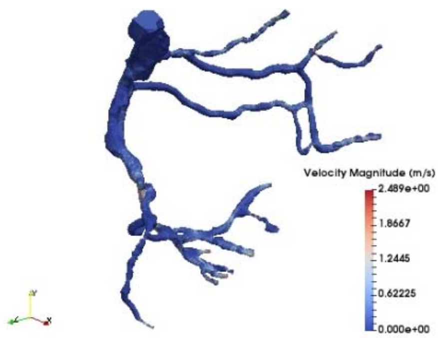


(b)

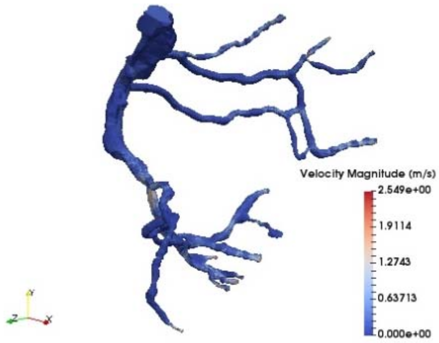


(c)

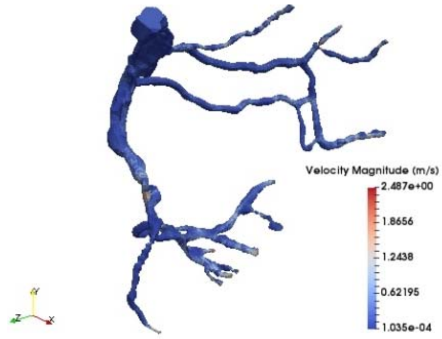
Fig. 6. Pressure inside coronary artery when three different solutions was used and inlet velocity was 0.2 m/s ((a) UW solution, (b) Gelatin, (c) blood)



(a)



(b)

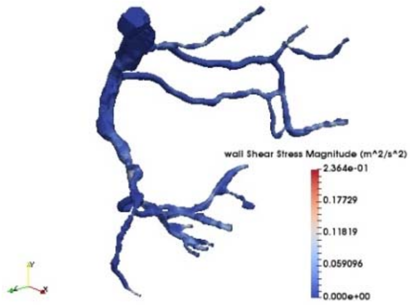


(c)

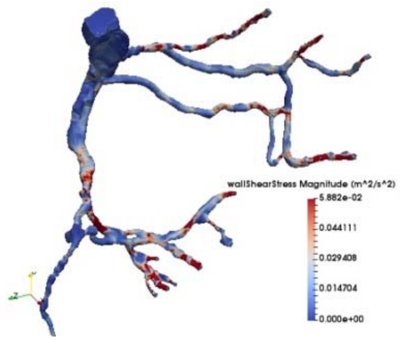
Fig. 7 Velocity inside coronary artery when three different solutions were used and inlet velocity was 0.2 m/s ((a) UW solution, (b) Gelatin, (c) blood)

Fig. 7 shows velocity distribution inside the coronary artery when three different fluids were used. Since the difference in kinematic viscosity cannot affect velocity significantly, velocity inside the coronary artery as kinematic viscosity changes does not change noticeably.

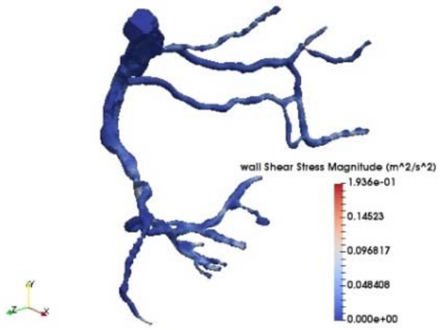
In OpenFOAM, the unit of wall shear stress is $\frac{m^2}{s^2}$. Fig. 8 shows the distribution of wall shear stress when three different fluids were used. Among the three different cases which are shown in Fig. 8, case (a) which is UW solution, has the highest amount of wall shear stress but it only occurs in few regions of coronary artery. Using Gelatin (case (b)) can be a reason for low value of maximum wall shear stress even though in some regions of case b high values of wall shear stress is noticeable which is due to the nature of complex geometry used in this study.



(a)



(b)



(c)

Fig. 8 Magnitude of wall shear stress inside coronary artery when three different solutions were used and inlet velocity was 0.2 m/s ((a) UW solution, (b) Gelatin, (c) blood)

IV. CONCLUSION

In this study, OpenFOAM 4.4.2 open source software was used to simulate flow inside coronary artery. SimpleFOAM solver was used to solve Reynolds Average Navier Stoks (RANS) equations. It was found that as inlet velocity increases inside coronary artery, pressure, velocity and wall shear stress increases when the carrying fluid is UW. Also, three different carrying fluids was used in order to investigate the effect of different fluids on velocity, pressure and wall shear stress distribution and it was found that using Gelatin can cause higher value of peak velocity and pressure. Amazingly the highest value of pressure was for UW solution and occurred in few regions. Although the lowest value of wall shear stress was for Gelatin, maximum value of wall shear stress occurred in numerous regions.

REFERENCES

[1] Vikas Kannojiya, Arup Kumar Das, Prasanta Kumar Das. (2021) Simulation of Blood as Fluid: A Review from Rheological Aspects. IEEE Reviews in Biomedical Engineering 14, 327-341.

[2] Siamak N. Doost, Liang Zhong, Boyang Su, Yosry S. Morsi. (2016) The numerical analysis of non-Newtonian blood flow in human patient-specific left ventricle. Computer Methods and Programs in Biomedicine 127, 232-247.

[3] Collins M. J., Moainie S. L., Griffith B. P., and Poston R. S., "Preserving and Evaluating Hearts with ex vivo Machine Perfusion: an Avenue to Improve Early Graft Performance and Expand the Donor," European Journal of Cardio-thoracic Surgery, 34 318—325, 2008.

[4] Garry Leonard Howe, "A MULTIPHYSICS SIMULATION OF A CORONARY ARTERY", master thesis, California Polytechnic State University.

[5] Sengupta, D., Kahn, A. M., Burns, J. C., Sankaran, S., Shadden, S. C., & Marsden, A. L. (2012). Image-based modeling of hemodynamics in coronary artery aneurysms caused by Kawasaki disease. Biomechanics and modeling in mechanobiology, 11(6), 915-932.