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COMPUTATIONAL STUDY OF STEADY BLOOD FLOW SIMULATION IN A COMPLETE CORONARY ARTERY BYPASS ANASTOMOSIS MODEL

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ABSTRACT

Coronary artery Bypass surgery is the most widely used and reliable treatment option for highly occluded coronary artery. In this study a computational technique is used to estimate the velocity profile and Wall shear stress distribution in a complete anastomosis model. Coronary artery is supposed to be fully occluded and the blood flow issued from the bypass graft is investigated. An optimized bypass model is proposed for Coronary artery bypass surgery. Complex flow patterns are found near the both proximal and distal part of anastomosis. Low velocity recirculation zone are found both upstream and downstream of the stenosis. Wall shear stress distribution is calculated at the different location of anastomosis, which is the main factor in the bypass graft failure.

Keywords: Blood flow, bypass anastomosis, proximal region, distal region, wall shear stress, ansys.

INTRODUCTION

The major cause of death in both developed and developing countries is cardiovascular disease. It is well known that atherosclerosis (narrowing of the artery) would cause partial or total blockage of artery and could result in the heart attack, strok, or even death. Atherosclerosis mostly occurs around curvatures, junctions and bifurcation of artery Chakravarty and Mandal (1997). For the cases of serious blockage in the coronary artery, bypass surgery is the most reliable treatment to restore blood flow but this surgery is not without complications. A significant number of bypass graft fail one or more years after the surgery because of restenosis. Initial Hyperplasia has been considered as a major cause for the developing the restenosis. For bypass surgery, the ability to predict changes in blood flow would enable a surgeon to evaluate the efficiency of a treatment strategy Steele *et al*. (2006). Previous studies indicate that Intimal hyperplasia is most frequently seen in the distal part of the bypass anastomosis. Restenosis due to distal anastomotic Intimal hyperplasia, a leading cause of arterial bypass graft failure, is thought to be promoted by hemodynamic effects, specially ‘abnormal’ wall shear stress patterns Ethier *et al*. (1998). Researchers have shown that the local flow dynamics and wall mechanical conditions play a major role in the developments of Intimal hyperplasia in bypass graft with subsequent graft failure.

It has been proved that the development of Intimal hyperplasia is related to different hemodynamic factors including low and high or unidirectional wall shear stress Perktold *et al*. (2002), Lie *et al*. (2001) and Keynton *et al*. (2001). Furthermore geometric factors such as bypass angle Jackson *et al*. (2001), curvature of the artery wall Wang and Bassingthwaighte (2003) Flow rate ratio and Waveform Ethier (1998) have been proved to influence the development of stenosis. Some studies (Ballyk *et al*. (1994), O’Callaghan *et al*. (2006) and Lu *et al*. (2006) have investigated the effect of Newtonian and non-Newtonian representation of blood and the wall shear stress distribution in the bypass graft anstomosis. Chua *et al*. (2005) clearly indicated in his study that non-Newtonian effects on any vessel only leads to a maximum of 10% difference in the magnitude of wall shear stress. A lot of studies (Ethier *et al*., 1998; Ballyk *et al*., 1994; Keynton *et al*. 2001; Langille *et al.,* 2001; Lie *et al.*, 1997; Lu *et al*., 2006) have discussed the flow behaviour only in the distal part of bypass anastomosis. The proximal region is also affected by the diversion of flow in the graft since the entrance and exit junctions of the bypass are the two critical locations, where the flow is complicated Lie *et al*. (2001). However Chua *et al* (2005), Lee *et al*. (2005), Steele *et al*. (2006), Ghista *et al*. (2005) have investigated the complexity of blood flow in the complete model of arterial bypass. Liepsch *et al*. (2003) experimentally investigate the changes in fluid flow through elastic models of arterial bypass under pulsatile flow conditions. They observed that under normal circumstance the flow through the straight section of vessel is high than that of the bypass section, which is attributed to increase in flow resistance and placement of graft in fully occluded arterial segment with minimum angle, minimize the flow disturbances. Similarly Wang *et al*. (2003) have proved that curvature, in general, lowers the resistance of a tube, but increases the shear stress near the inside wall. Lee *et al*. (2005) found that substantial area reduction leads to flow recirculation in both upstream and downstream of the stenosis and in the host artery near the toe, while diminishes the recirculation zone in bypass graft near the bifurcation junction.

However above studies are very important in order to predict the development of Intimal hyperplasia but the problem of restenosis and Intimal hyperplasia is still not

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fully solved. A lot of investigations are still going on to reduce the problem of early graft failure. It has been found that computational fluid dynamics plays a major role in the study of blood flow complexities in different arterial models. Recently Qiao *et al*. (2005) proposed a novel geometric configuration with two symmetrically implanted grafts for the purpose of improving the hemodynamics, but the new technique needs a large number of animal experiments to verify its practical viability. Previously some authers (Chua *et al*., 2005 and Ghista *et al*., 2005) have demonstrated the models of complete coronary bypass in which one end of bypass is connected with coronary artery and the other end is connected with aorta.

In this study we have proposed a new model of coronary artery bypass in which both ends of bypass tube is attached with the host coronary artery. The objective of this paper is to investigate the flow patterns of blood and the distribution of shear stress in a complete Bypass anastomosis model in coronary artery using computational fluid dynamics.

Geometrical model and theory:

The bypass models simulating the flow field in coronary artery bypass are shown in fig (1). The 100% occluded coronary artery is taken of diameter 3mm. The centerline of bypass graft follows a circular arc with departure/ arrival angles of 30 degree from/to host artery. The length of coronary artery is 44mm and the length of stenosis is 8mm. the distance between inlet of bypass and outlet of bypass is 24 mm. In present model, the diameter of bypass artery is 3mm, which is same as the diameter of host artery (Fig. 1).

Blood is considered as Newtonian homogeneous and incompressible fluid and by further ignoring the terms of inertial and body forces, the continuity and momentum conservation equations in cylindrical polar coordinates with axial symmetry used for computing two-dimensional laminar flow can be written as follows.

$$\rho\frac{\partial u}{\partial t} = -\frac{\partial p}{\partial r} + \mu\left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} - \frac{u}{r^2} + \frac{\partial^2 u}{\partial z^2}\right) \qquad (1)$$

$$\rho\frac{\partial w}{\partial t} = -\frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial r^2} + \frac{1}{r}\frac{\partial w}{\partial r} + \frac{\partial^2 w}{\partial z^2}\right) \qquad (2)$$

$$\frac{\partial w}{\partial z} + \frac{\partial u}{\partial r} + \frac{u}{r} = 0 \qquad (3)$$

The following boundary conditions are used in this study.

1. Zero velocity at artery wall corresponding to no-slip boundary condition.
2. The inlet velocity is assumed to be fully developed with a parabolic flow profile. The inlet mean velocity is 40 cm/sec, based on the physiological data.
3. At the outlet a constant zero pressure is given.

Commercial software-ANSYS 10.0 based on the finite element method is used to solve the Navier-stokes equations for the two dimensional flow. We have tested several cases with different size and number of elements. A maximum size of 0.02 cm was used to ensure equally size elements. Whole domain of coronary artery with graft was discretized in to 5228 quadrilateral elements. The solution was running using 40 iterations for getting the convergence.

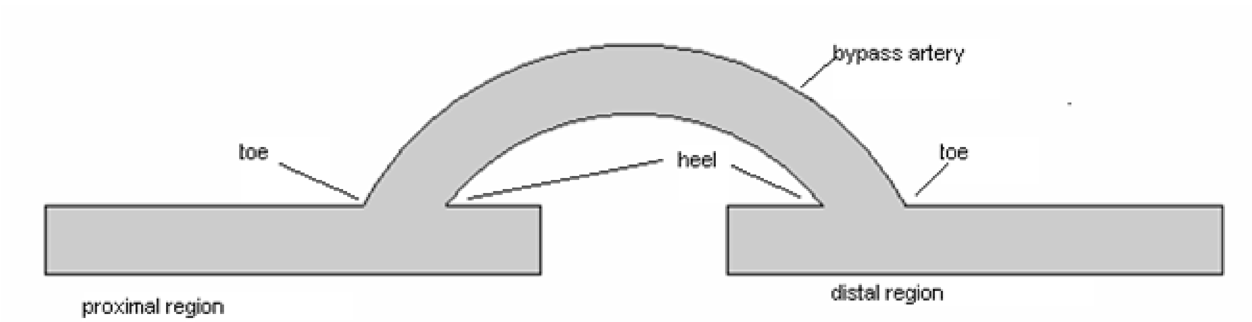
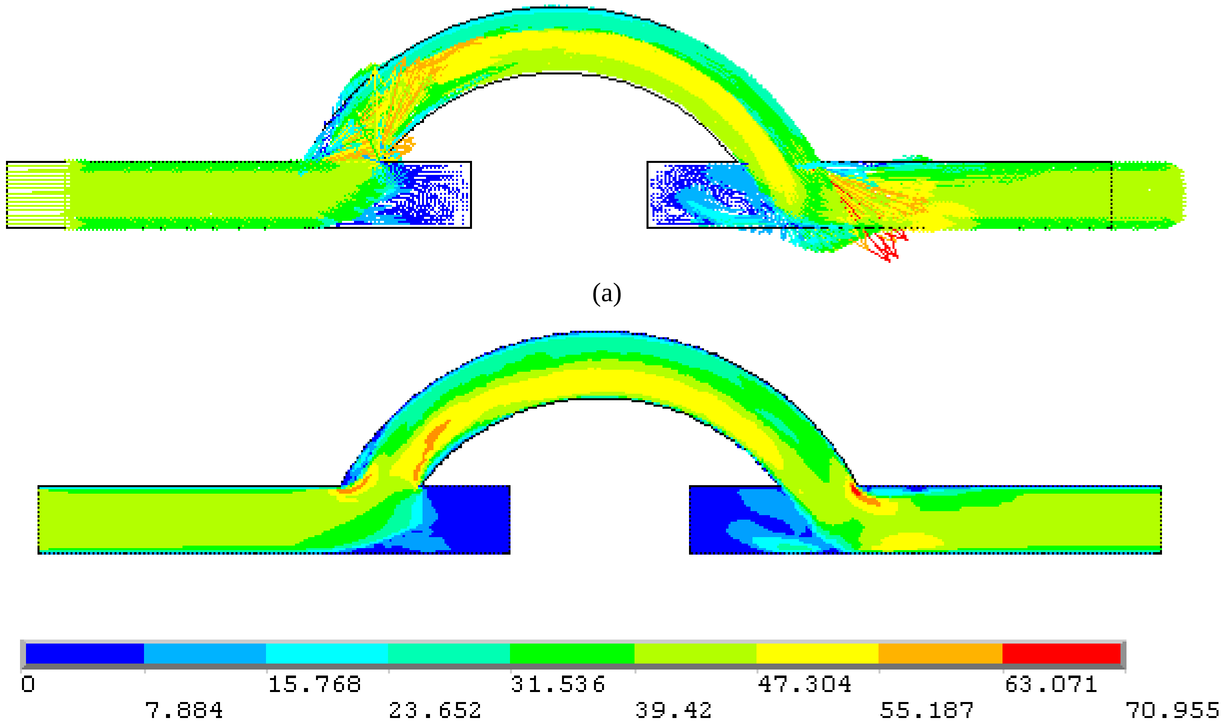


Fig 1. Model of Complete Arterial Bypass Anastomosis

RESULTS AND DISCUSSION



(a)

(b)

Fig . 2.(a) Vector Representation and (b) Contour Plot of Velocity Profile in Bypass Model.

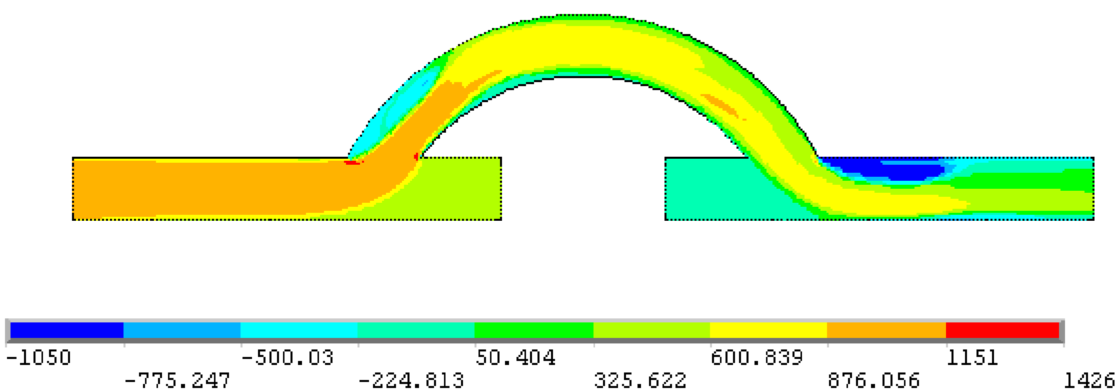


Fig. 3. Wall Shear Stress Distribution

The velocity distribution in the complete bypass model is shown in fig 2(a), (b). In fig 2(a), velocity vectors and in fig 2(b) velocity contours are shown at various sections of two dimensional complete bypass models. Velocity profiles in different regions of host and bypass artery are graphically shown in fig (4, 5, 6, 7, 8, 9, 10, 11, 12).

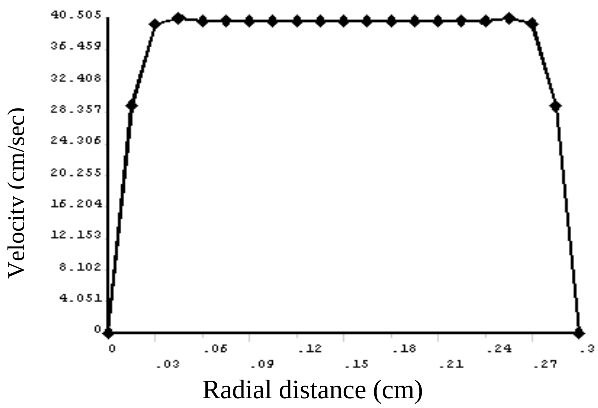


Fig. 4. Velocity Profile at the Inlet of Host Artery

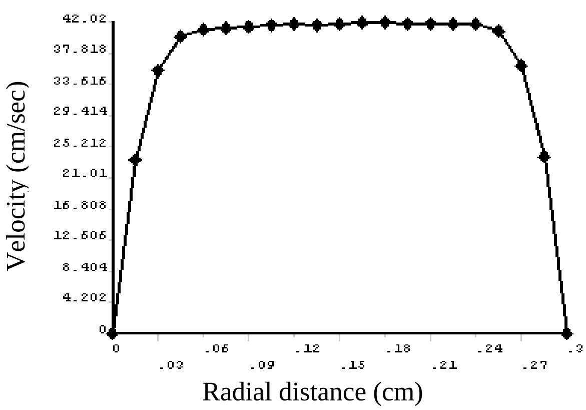


Fig. 5. Velocity Profile at the Outlet of Host Artery.

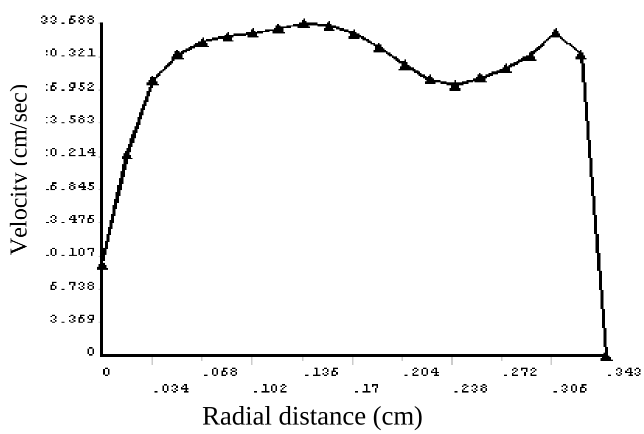


Fig. 6. Velocity Profile at the Entry Region of Bypass Artery.

At the inlet of the coronary artery mean flow velocity 40 cm/sec is applied to get the fully developed parabolic profile in the coronary artery. It is clear that most of the flow is diverted to the bypass graft, when it reached the bifurcation point. However some of the blood with low velocity flow in the direction of stenosis and return back. So, low velocity recirculation zones are formed in this region. The flow enters the bypass graft with a high velocity towards the inner wall in comparison to outer wall. After entering the graft, most of the flow turns towards center of the graft. Again the parabolic profile is found in the bypass artery.

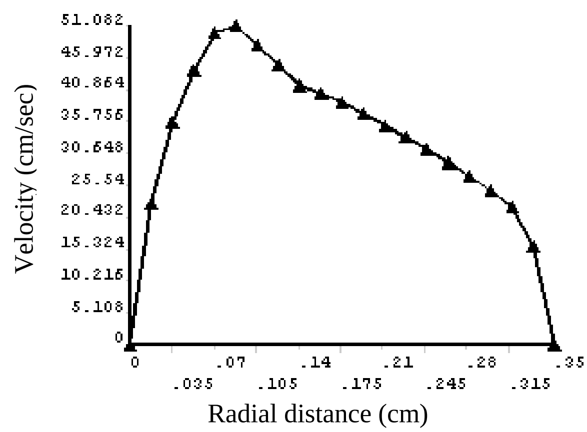


Fig. 7. Velocity Profile at the Exit of Bypass Artery.

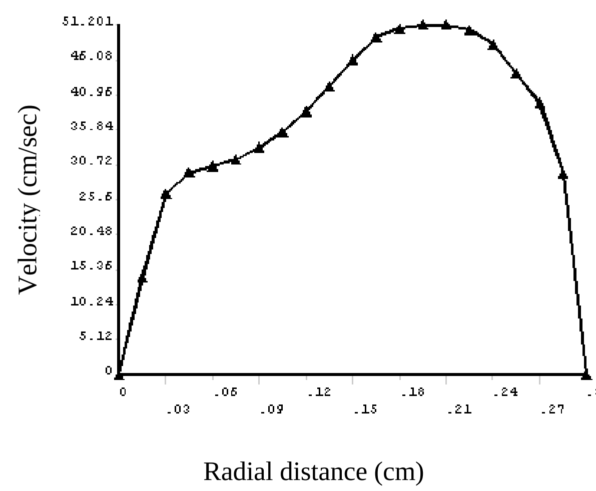


Fig. 8. Velocity Profile at the Middle of Bypass Artery

When the flow exits the graft, it hits the bed of host artery, and goes towards the outlet of artery. Some of the flow enters the region downstream to the stenosis with a small velocity. So the small recirculating zone towards the outer wall is formed in this area. Flow is also recirculated towards the inner wall in the toe of distal region with a low velocity.

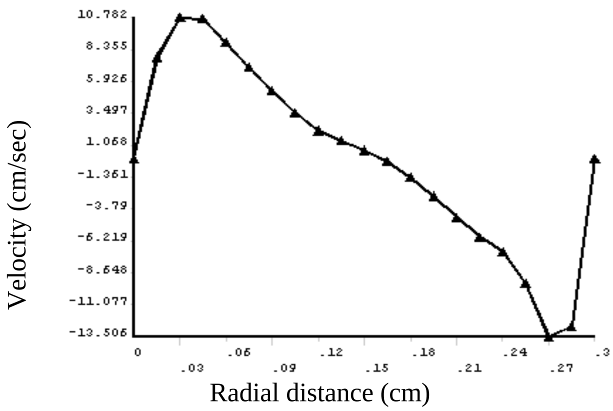


Fig. 9. Velocity Profile at the Heel of Distal Region

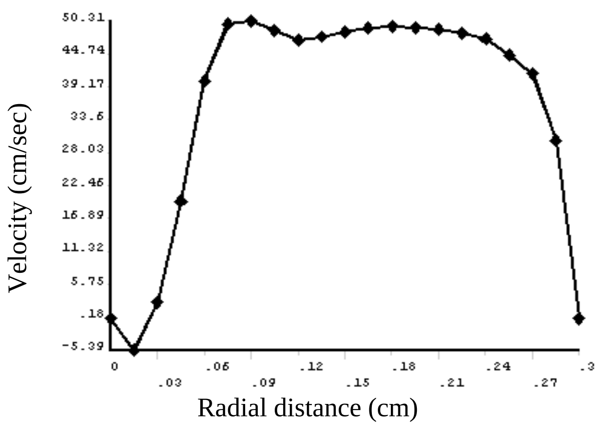


Fig. 10. Velocity Profile at the Toe of Distal Region

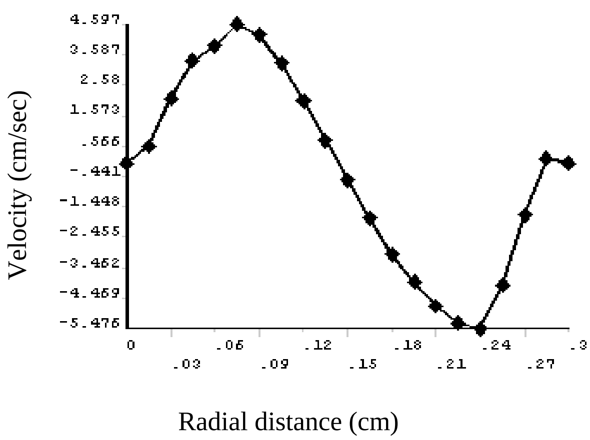


Fig. 11. Velocity Profile at the Heel of Proximal Region

So, it is clear that very low velocity recirculating zones are found in four regions of host and bypass artery. In the host artery, it found at the upstream and downstream to the stenosis and the toe of distal region towards the inner wall. In the bypass artery, it found near the entry region towards the outer wall of bypass artery.

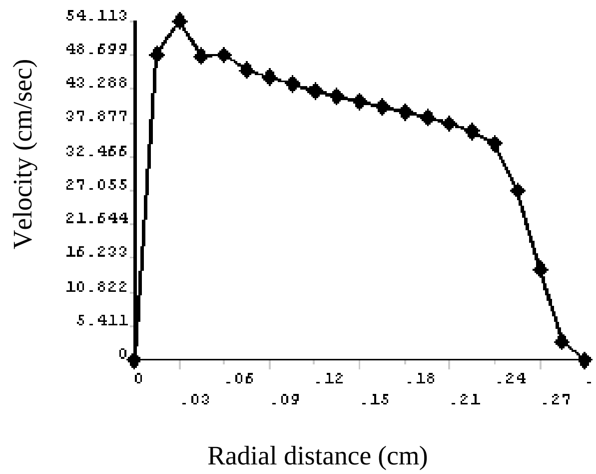


Fig. 12. Velocity Profile at the Toe of Proximal Region

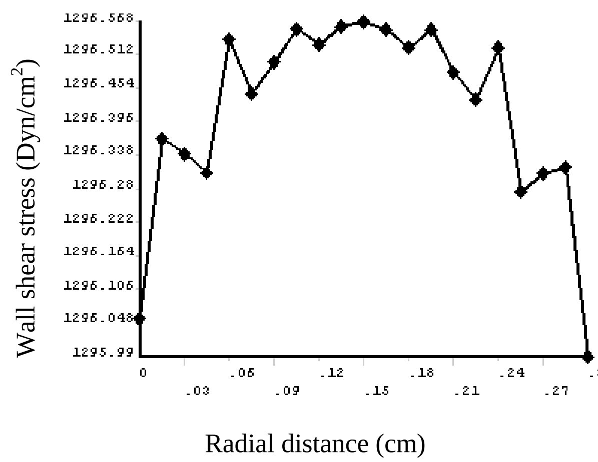
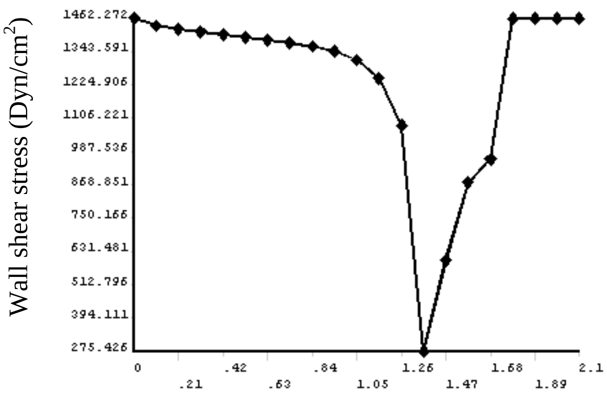


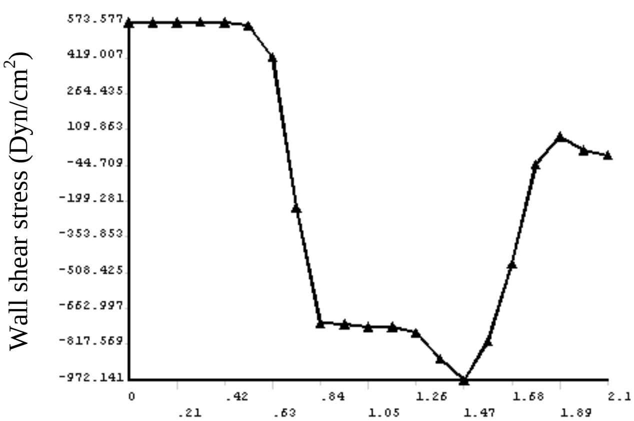
Fig. 13. Wall Shear Stress at the Inlet of Host Artery

WSS contours are shown in the whole domain of bypass model in fig (3) and WSS at various regions are graphically shown in fig (13, 14, and 15). A uniform wall shear stress distribution profile is found in the fully developed region at the inlet of coronary artery. Changes in the shear stress are found near the bifurcation point. At the inlet of graft, pressure is low negative near the outer wall of bypass artery and it starts increasing as the flow enters the bypass graft. Again a nearly uniform shear stress distribution is found before the exit region of bypass graft. In the middle of bypass artery shear stress is small at the outer wall in comparison to inner wall. In the region of upstream and downstream to the stenosis, low shear stress near to zero indicate the location of recirculation zone. Shear stress again starts increasing from the heel of distal region. A negative Shear stress is found near to the inner wall of toe of distal region indicates the small back flow. A large decrease in wall shear stress is found near the bifurcation regions in host artery.



Axial distance(cm)

Fig. 14. Wall Shear Stress in the Proximal Artery



Axial distance(cm)

Fig. 15. Wall Shear Stress in the Distal Artery.

The above results obtained by this study give the favorable indications regarding the regions of restenosis. WSS distribution obtained in this model is comparable to the same obtained by Wiwatanapataphee *et al*. (2006) at the distal part of anastomosis. Since the wall shear stress distribution in the proximal part is also affected by the complex blood blow near the bifurcation point, so this study has an advantage as we have calculated the WSS in the complete model of bypass. The extrapolation of these results to the clinical practice is interesting. It may be clinically effective to reduce the problem of early graft failure, if an optimum bypass graft is manufacturable by the simulation of blood flow using computational fluid dynamics.

Angle of bypass plays an important role in bypass surgery because of recirculation of flow occur at the upstream and downstream of the graft. Different bypass angles have been proposed by various investigators. Fully blocked arterial segment requires placement of graft with minimum angle to reduce the flow disturbance Liepsch *et al*. (2003). Lee *et al*. (2005) have taken the grafting angle 45 degree, while in the present study an optimum angle of 30 degree is adopted, which results the reduction in the formation of low velocity recirculation zone.

CONCLUSION

We have shown that computational fluid dynamics can be used to predict the distribution of blood flow in coronary artery bypass model. The study clearly indicates that both the proximal and distal junctions are sensitive for the development of restenosis. Care should be taken by the surgeons regarding the position and angle of bypass. The present study is for fully occluded coronary artery, but for clinical point of view it is essential to extend such type of analysis for different types of blockage. The optimum angle of bypass and the position for placing the graft depends on the size of artery as well as stenosis. For the adopted artery in this study, the above model would be the appropriate for bypass surgery. The present study clearly helpful both for the clinicians and bypass graft manufacturers to design an optimized bypass graft. We are extending this study for bypass in the bifurcated artery, since the problem of stenosis commonly occurs near to bifurcation points.

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