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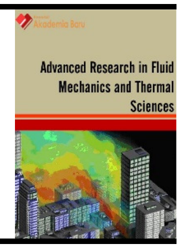

Numerical Study on Eccentric and Concentric Vascular Grafts Prototypes

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ABSTRACT

The recent advances in computational fluid dynamics (CFD) can be useful in observing the detailed haemodynamics in Coronary bypass grafts for clinical evaluation and treatment. The present study focuses on analysing the effects of anastomotic angle in a small diameter vascular graft. The idea is to focus on the successful determinants of coronary artery bypass surgery such as fluid flow geometry and flow distribution in the neighbourhood area of anastomosis. An attempt has been made to simulate CABG using CFD. 3D concentric and eccentric stenosed coronary bypass graft models are generated in CATIA V5 R 19 and transient analysis was carried out in ANSYS CFX 14.5. Different graft angles such as 30°, 45°, 60°, 75° has been investigated to determine the optimum angle considering the change in haemodynamics. The obtained simulation results provided basic understanding of flow behavior in eccentric and concentric stenosed models for various graft angles. It also provided useful information on influence of angle on the flow behaviour and chose the optimum angle for graft placement.

1. Introduction

Coronary Artery Bypass Graft (CABG) surgery continues to be one of the most commonly used and reliable methods of surgery to treat Coronary Artery Disease that causes Atherosclerosis. However, a number of grafts fail within one or more years because of the problem of restenosis [1]. Also, it was suggested that anastomotic angle i.e. the angle between the host artery and implanted bypass graft is an important factor responsible for the problem of restenosis [2]. Appropriate placement and through analysis of an ideal vascular graft prototype needs to be worked on for a better understanding of the effects of anastomotic angle on the blood flow in both concentric and

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eccentric stenosed artery with a complete bypass graft. Currently there is no standardized procedure for assessing the severity of stenosis; hence the doctors follow the conventional method of treating patients by CABG surgery based on patient symptoms. Application of numerical tool using CFD analysis has been recently developed which helps in a better understanding of the relation between haemodynamics and atherosclerosis and has received much attention in the past [3,4]. CFD allows analyzing various flow parameters such as velocity, pressure, shear stress and helps in generating the plots as a function of time and position in the desired models under investigation. It also provides numerical reasoning while designing operations and helps visualize the flow path after completing the operations [5,6].

Numerical simulations can be beneficial to the doctors than the traditional MRI/CT/Doppler Ultrasound imaging techniques as it gives a more detailed view of the stenosed region and more accurate understanding of flow behavior in bypass grafts [7,8]. Also information regarding the flow parameters such as velocity, pressure and wall shear stress might be helpful to the biomedical engineers to design better instruments for surgical modalities. The design and reliable analysis of small diameter vascular prosthesis (4-5 mm) continues to be a challenge in vascular surgical research. These grafts fail due to arterial graft occlusion and pose a problem in field of myocardial revascularization. Also, there is not sufficient information about the fluid structure, fluid interactions and compliance mismatch especially for small diameter arteries. Surgical injury intensified by compliance mismatch has proven to be one of the major reasons for intimal thickening [9,10].

Even though coronary grafts have been designed and various simulations have been carried out but an ideal anastomotic angle needs to be obtained in the light of fluid dynamics to overcome the problem of stenosis and graft failure. Thus there is a need of extensive research and mechanical analysis of coronary artery bypass grafts. Hence, the present study focuses on analyzing the effects of anastomotic angle in a small diameter vascular graft [11]. Main aim is to investigate the successful determinants of coronary artery bypass surgery such as fluid flow geometry and flow distribution in the neighborhood area of anastomosis. Therefore, an attempt has been made to simulate CABG using CFD. The model under investigation is an idealistic one and is studied considering various assumptions. The aim of this study is to bring to light that angle of anastomosis can play a major role in intimal hyperplasia and thus should be taken into account by the doctors and surgeons to minimize the chances of graft failure.

2. Methodology

The blood flow behavior in the coronary artery is assumed to be governed by the Navier–Stokes equations of incompressible flows as given in Equation (1) and (2) [12,13,14].

$$\nabla . u = 0 \quad (1)$$

$$\rho \left(\frac{\partial u}{\partial t} + u . \nabla u \right) = -\nabla p + \mu \nabla^2 u \quad (2)$$

Where ρ is the density, p is the pressure, μ is the viscosity and u is the velocity.

The CABG model design was acquired based on [2,3]. The details of the generated 3D model are shown in the Table 1. 3D models of both eccentric and concentric stenosed graft models are generated using the CATIA V5 R19 and details are described in the Figure 1. Based on the structured mesh obtained from ANSYS WORKBENCH, ANSYS CFX 14.5 was used to carryout steady state analysis with 0.2 m/s velocity at inlet and zero traction at outlet for grid check on 30^0 concentric stenosed model [15].

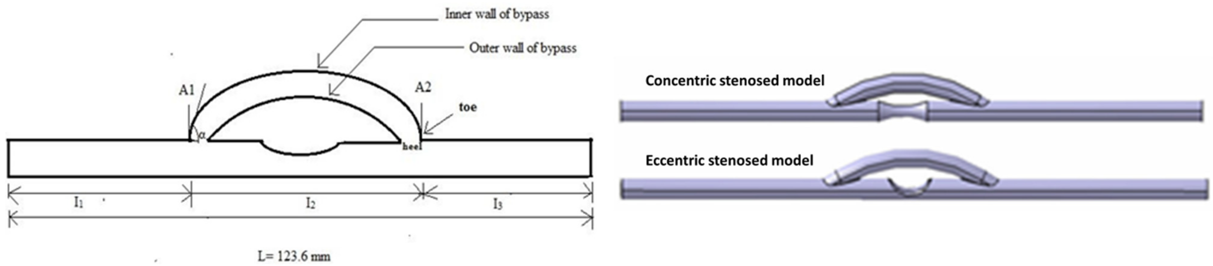

Fig. 1. 3D vascular graft models

Based on the averaged velocity and averaged pressure obtained at the cross-section of stenosed zone, structured mesh of 65,700 and 68,300 hexahedral elements was considered from the grid independency test. Further, transient flow analysis is carried out to understand and analyze the flow behavior in both eccentric and concentric stenosed coronary arteries for various graft angles (30°, 45°, 60°, 75°). The parameter considered in the analysis was the velocity at specified instances of pulse cycle which includes early systole, peak systole and diastole. The pulse cycle is distributed into 100 time steps ranging from 0.1s to 0.8s in order to simulate the flow behavior accurately. The early systole occurs at 0.2s, peak systole at 0.3s and diastole at 0.7s. The standardized input velocity waveform as shown in the Figure 2 is applied at the inlet, zero traction at the outlet and no slip wall condition along the length of the model [4,16].

Table 1
Vascular graft model details

Parameters	Units
Diameter (D) of the host artery and coronary bypass graft)	4 mm
Length (L) of the host artery	123.6 mm
Length (I1) from the inlet to the anastomosis region (A1)	44.81mm
Length (I2) from anastomosis region A1 to A2)	34.80 mm
Length (I3) from anastomosis region A2 to the outlet	43.94 mm
α (angle of anastomosis)	30°, 45°, 60°, 75°

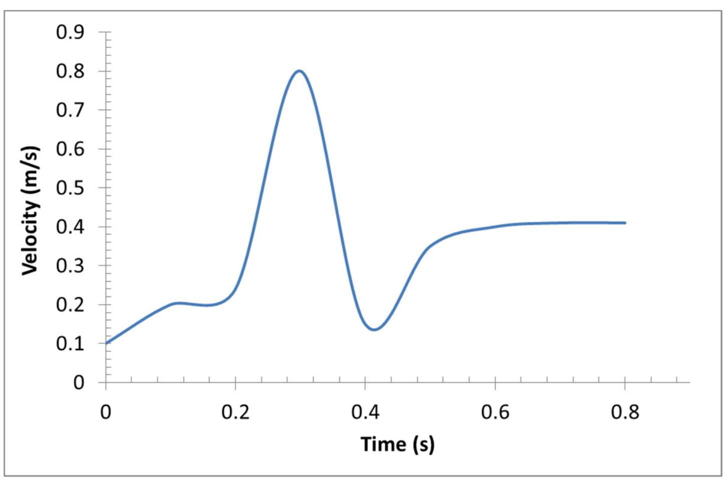

Fig. 2. Input velocity profile

Even though blood flow is non-Newtonian physiologically, however in the present study, since the focus in on large arteries, Newtonian assumption is acceptable as relatively high shear rate occurs. In medium and smaller arteries, non-Newtonian assumption is valid as shear rate is lower than $100s^{-1}$ and shear stresses depend non-linearly on the deformation rate. Hence, the density and dynamic viscosity of the blood is considered to be 1050 kg/m^3 and 0.004N-sec/m^2 respectively [15]. The low-Reynolds turbulence model was chosen to be k-omega model. The convergence criteria were set to be 10^{-5} and number of iterations steps ranged from 1 to 100. Based on these parameters, the simulation results obtained shall provide very useful data in quantifying the haemodynamic changes in understanding the various CABG cases.

3. Results

Numerical simulation of both the concentric and eccentric coronary stenosed models is carried out to study the effect of anastomotic angle on blood flow in the host artery and the bypass graft. The simulation is carried out for 3 pulse cycle and results obtained in the last cycle are considered for the investigation. The CFD analysis was performed to study the effect of anastomotic angle on blood flow in the host artery and the bypass graft. Flow rate was analysed in both these regions under various time steps of the cardiac pulse cycle for concentric and eccentric stenosis with anastomotic angles 30° and 60°. The haemodynamics parameters like velocity, wall shear stress and pressure are studied at specific instants of pulse cycle like early systole, peak systole and diastole. WSS is considered to be the most crucial and interesting hemodynamic parameters related to the atherosclerotic progression. It varies with time due to the pulsatility of the flow waveform and the maximum value generally occurs at the peak systole when the inflow is found to be maximum.

The velocity contour plots of all anastomotic angles i.e. 30°, 45°, 60° and 75° were studied for concentric and eccentric stenosed models as shown in the Figure 3 and Figure 4. It was found out that as the angle (α) increases, the velocity increases in the host artery whereas in case of bypass graft the velocities are larger for smaller anastomotic angle. This is because in the host artery as the angle increases, it causes the blood to flow through the artery and impedes the flow of blood into the bypass graft. Also it can be clearly seen that the velocity is highest in the constrict region and the values of velocity were 0.362, 0.394, 0.422 and 0.449 (m/s) for 30°, 45°, 60° and 75° respectively in case of concentric models. Similarly the values of velocity for the eccentric models were 0.308, 0.325, 0.355 and 0.370 (m/s) for 30°, 45°, 60° and 75° respectively. So as the graft angle increases, the value of the velocity at the constricted area increases [17]. Low velocity regions were seen close to the stenosed zone, which are the upstream and downstream regions of the arterial walls.

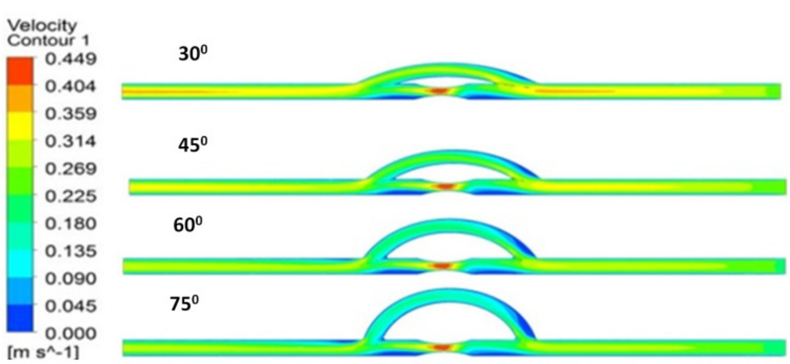

Fig. 3. Comparison of velocity contours in concentric stenosed models

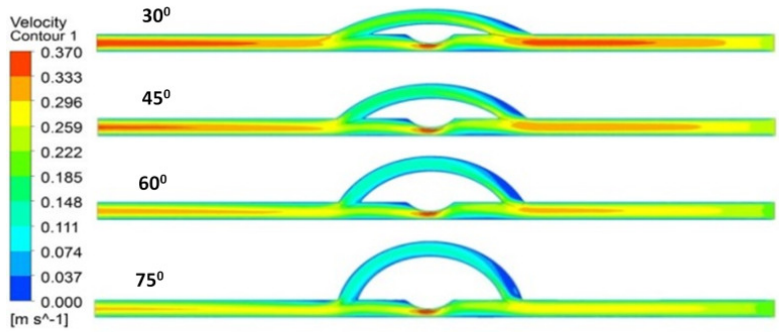

Fig. 4. Comparison of velocity contours in eccentric stenosed models

It is seen near the graft entrance that the velocity seemed higher in the inner region than the outer region. Also, the velocity along the curvature of the bypass graft forces the higher velocity to transfer towards the outer region. As this blood reaches the outer region, velocity is slower in the inner region as compared to the outer region. Thus, velocity was higher in smaller anastomotic angles [18]. The velocity contour plots for α = 30°, 45°, 60°, 75° are shown in Figure 3 for concentric and Figure 4 for eccentric stenosed models. There are two retrograde flows along the arterial walls near the heel position whereas there is flow separation with low velocity away from the toe position towards the host artery wall. The velocity of recirculating jet flow is higher for higher anastomotic angles and the peak velocity is in the region immediately after stenosis [16,17]. The pressure in the host artery was found to gradually decrease as the angle of anastomosis increased as shown in Figure 5 and Figure 6 for concentric and eccentric stenosed models respectively. As the pressure decreases, it minimizes the chances of restenosis. In the bypass graft, as the angle increases the pressure increases which leads to decrease of shear stress. This increases the chances of re-blockage.

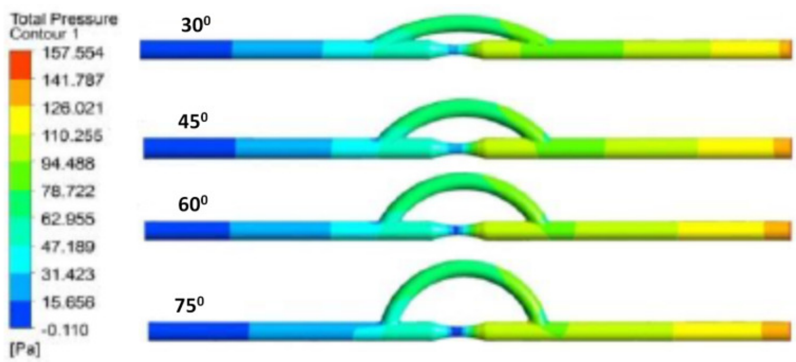

Fig. 5. Comparison of pressure contours in concentric stenosed models

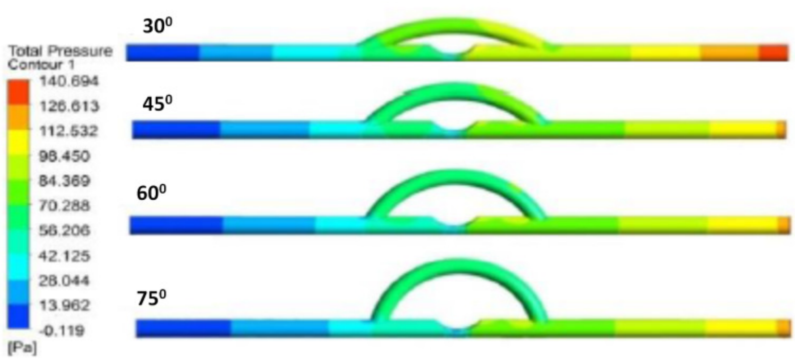

Fig. 6. Comparison of pressure contours in eccentric stenosed models

From the wall shear stress plots, it can be clearly seen that the regions where the effect of angle of anastomosis is evident are the stenosed region, between heel and toe and the region near the graft entrance [8,9]. Shear stress is maximum in the stenosed region while it is reasonably high near the junction area of the host artery and bypass graft. The wall shear stress at the heel position was 0.967, 1.398, 1.426 and 1.760 whereas in stenosed region the values was 2.900, 2.795, 3.208 and 3.519 all measured in Pascal (Pa) for 30°, 45°, 60° and 75° respectively in case of concentric model as shown in the Figure 7. Similarly, the wall shear stress at the heel position was 0.867, 1.166, 1.286 and 1.532 whereas in stenosed region the values were 1.734, 1.749, 2.143 and 2.298 in Pascal respectively in case of eccentric model as shown in the Figure 8. According to the plots of shear stress distribution, it can be understood that as the graft angle increases, shear stress increases in the host artery and possibility of re-blockage reduces at the beginning and end of the sutured graft. Whereas in case of bypass graft, on increasing the angle shear stress reduces and chances of restenosis goes up. To choose the most suitable angle for stenosis, the total shear stress within the graft and at the inlet and outlet were compared and it was found out that the shear stress was more in 30° as compared to 45° and so 30° seemed to be most ideal one.

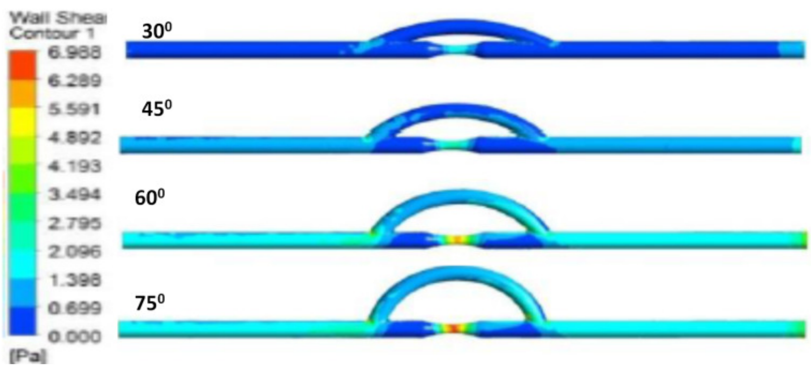

Fig. 7. Comparison of WSS contours in concentric stenosed models

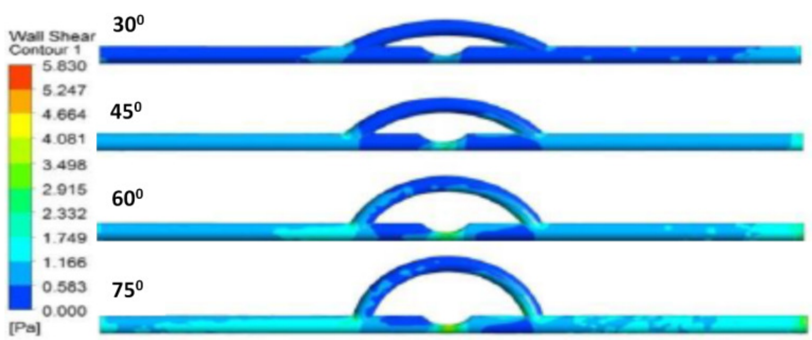

Fig. 8. Comparison of WSS contours in eccentric stenosed models

Flow rate was analysed in both concentric and eccentric stenosed models regions under various time steps of the cardiac pulse cycle with anastomotic angles 30° and 60°. Figure 9, 10 and 11 highlights the velocity profile during early systole, peak systole and diastole at inlet, outlet and bypass graft region respectively. The cross sectional view of both the host artery and bypass graft was considered for generating plots of velocity (m/s) vs. distance (mm). It was observed that blood flow rate in the graft region for concentric stenosis during peak systole was lower than early systole for both the anastomotic angles. While, comparing these two angles it was found out that flow rate was higher in 30° than 60°. Likewise for eccentric stenosis at 30°, the velocity was found to be comparatively higher than 60°. On analysing the diastole stage of the cardiac pulse cycle, it was realized that the blood flow rate *i.e* the velocity in the bypass region was very low as compared to the other two stages. For concentric stenosis, it was found to be higher in case of 30° angle of anastomosis as compared to 60°. Also for eccentric stenosis at 30° the velocity was fairly higher than 60°. Therefore, the present investigation provides basic understanding of flow behaviour in eccentric and concentric stenosed models for various graft angles. It provided useful information on influence of angle on the flow behaviour and chose the optimum angle for graft placement.

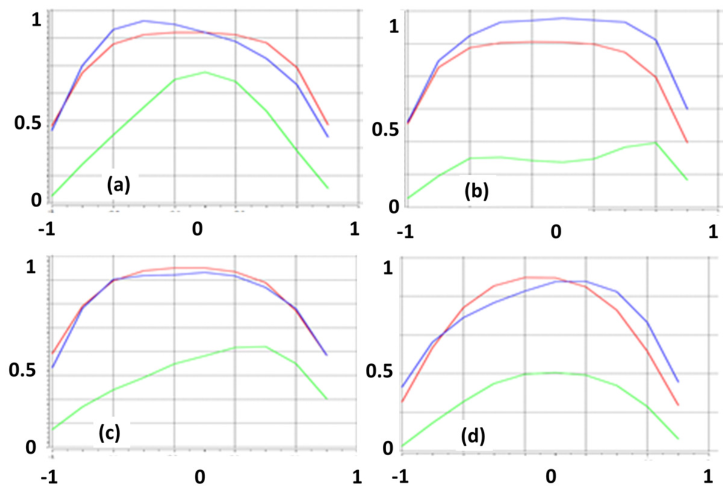

Fig. 9. Velocity profile during early systole at vessel cross-section (a) concentric 30° (b) concentric 60° (c) eccentric 30° (d) eccentric 60° (Red – Inlet, Blue – Outlet, Green – By-pass graft)

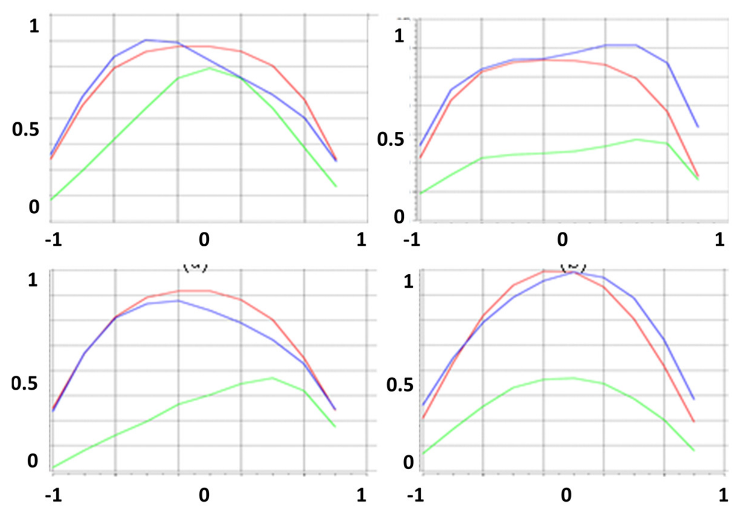

Fig. 10. Velocity profile during peak systole at vessel cross-section (a) concentric 30° (b) concentric 60° (c) eccentric 30° (d) eccentric 60° (Red – Inlet, Blue – Outlet, Green – By-pass graft)

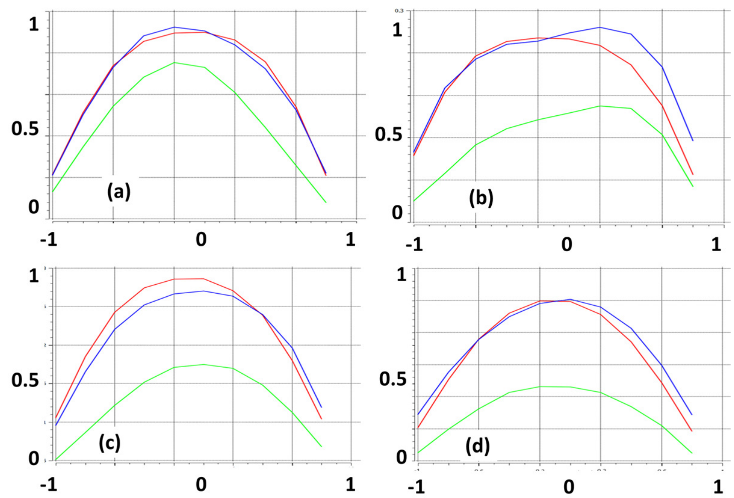

Fig. 11. Velocity profile during distole at vessel cross-section (a) concentric 30° (b) concentric 60° (c) eccentric 30° (d) eccentric 60° (Red – Inlet, Blue – Outlet, Green – By-pass graft)

4. Conclusions

Numerically simulated present case of concentric and eccentric stenosed models provided useful understanding of flow behaviour in bypass grafts. The results obtained emphasized on the fact that anastomotic angle plays a major role in restenosis. Various mechanical factors such as velocity, total pressure and wall shear stress were analysed for both the host artery and bypass graft region. From the analysis, it was found out that both velocity and wall shear stress are highest in the stenosed region. It was also found out that velocity was higher for smaller anastomotic angle. This is because as the angle increases it causes the blood to flow through the host artery and impedes the flow of blood through the bypass graft. Similarly wall shear stress and pressure were also analysed and the above results confirmed that wall shear stress had a major effect on restenosis whereas pressure had a minimal effect. It is also observed that flow rate was responsible for occlusion of arteries and failure of the graft. Numerical simulation proves to be an effective tool to analyse the determinants of bypass surgery such as flow field geometry and flow distribution in the neighbourhood of anastomosis. It was finally concluded that 30° seem to be an ideal anastomotic angle for the graft design.

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