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Review Article

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Flow Visualization in Realistic Arterial Bypass Graft Model

Megha Singh[¶], SeHyun Shin

School of Mechanical Engineering, Kyungpook National University

Abstract

Background: Coronary atherosclerosis artery disease is the leading cause of morbidity and mortality. Coronary artery bypass grafting (CABG) which utilizes the saphenous vein graft, has helped in alleviating the suffering of these patients. Newer techniques are being developed to improve upon the techniques. Still there is significant number of failures, leading to re-grafting or re-vascularization. Some studies have helped in identifying the high and low shear stress regions. Further studies based on their realistic models are required.

Material, methods and results: we developed the realistic model of fully blocked right coronary with bypass graft placed at angle of 5^0 with curvature similar to that of artery. Pulsatile flow of birefringent solution through this model by polarized light was visualized. The images of complete flow field in the model were recorded and analyzed. Regions of high flow disturbances which are prone to further changes are identified. Existence of recirculation in the blocked coronary may initiate new blood-tissue interactions deleterious to bypass graft.

Conclusion: Our study shows that by selecting the procedure to place bypass graft at minimum angle with curvature similar to that of artery and smooth sutures may improve the life span of the graft. This study also identified that coronary blocked regions contributing by recirculation flow at the proximal and distal regions of bypass which may require further studies.

Key words: right coronary artery, bypass model, flow visualization, vortex formation.

Introduction

Coronary artery disease (CAD) is the single leading cause of mortality in developed and developing countries. Due to shortage of supply of oxygen and other nutrients, the heart muscle tends to become non-functional, leading to heart attack or myocardial infarction. The CAD has not yet been eradicated by preventative measures but the role of cholesterol and dietary fat in the development of this disease has really been understood (1).

These procedures show that the placement of venous or arterial bypass does help in restoring flow through infracted region but these are prone to various changes during post-operative period ranging from months to years. The blood flow pattern has to be restored as close as possible to normal flow. Thus flow visualization in the altered geometries to detect changes in flow is highly relevant. Majority of theoretical and experimental studies have shown the existence of high shear stress in the floor region at the distal end of the arterial bypass. The toe region is associated with high shear stress, whereas, heel region is associated with vortex formation (12-14). For realistic model the complete bypass geometry, covering the proximal and distal ends, has to be considered. A recent numerical analysis of coronary-aorta bypass has shown that the shear stress distribution over the distal region is higher than that at the proximal region. The velocity profiles in the graft section are slightly skewed due to its curvature (15). But these studies are generally confined to two-dimensional analysis, whereas, the heart vessels are confined to three-dimensions.

¶ Biomedical Engineering Division, Indian Institute of Technology, Madras-600 036, India

Matrials and methods

Model construction

For model construction the three-dimensional structural details of the main curved section of right coronary artery, prior to first branching, are obtained from Hayashi and Yamaguchi (18) and adjoining sections from the cast of the human heart. The base model of this is made of copper tube with an internal diameter 6.0 mm (figure 1).

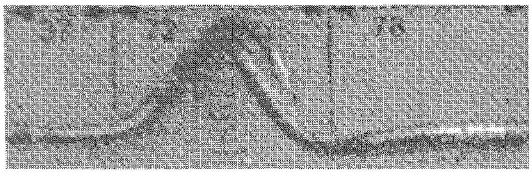

Figure 1. Right coronary artery model of copper tube for making wax model, which was used to develop bypass model of silicon rubber with 100% stenosis

For bypass reconstruction brass tube of same diameter is placed at an angle 5° on the upper surface of the tube, a procedure similar to as adopted for bypass reconstruction for coronary arteries. From the die of this model the wax model with 100% stenosed.

artery is prepared. For preparation of silicon rubber model, which is elastic and transparent as required for flow visualization (19), the wax model is coated with multiple thin layers of silicon rubber,. After overnight drying of this model, the wax is melted out. After clearing the traces of wax with isopropanol, the silicon bypass model of fully blocked right coronary artery is obtained.

Flow visualization

Figure 2 shows the schematic of the system which is calibrated to maintain systolic and diastolic pressures at approximately 120 and 80mmHg, respectively. Pulsatile flow of dilute solution of vanadium pentoxide (birefringent solution) in the model is achieved by combining steady component generated by pushing the fluid in the model by nitrogen gas and oscillating component produced by a membrane pump. The silicon rubber bypass model with 100% stenosis is placed between the crossed polarizer and analyzer. The linearly

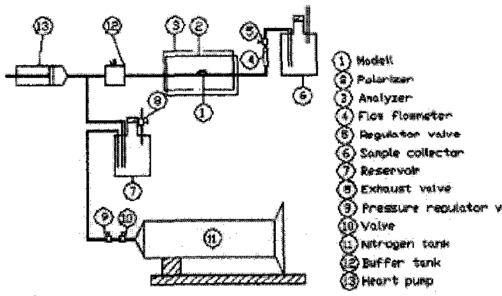

Figure 2. Schematic of the flow visualization system.

polarized light is incident upon the model perpendicular to the direction of flow, thus providing overall distribution of particles over the entire diameter. The particles are in statistical disorder as the velocity gradient at the center of the model is zero, thus allowing light to pass through the entire model which is extinguished at the crossed analyzer. At other locations, depending on the shear gradient, the particles are oriented over the whole cross-section. The light beam after passing through the analyzer, depending on the orientation of particles, shows respective variation in the transmitted light component which directly corresponds to the flow changes (19).

For three-dimensional flow visualization, both ends of the model are mounted on plastic tubing, which are passed through air-tight double 'O' rings joint system. The model is mounted in the flow system at 0° (normal position) to visualize the flow through entire model. The flow through stenosed area is viewed by turning the model by 135° from normal position. The details of various sections of bypass, as mentioned in the following section, are given in figure 3. The different parts of the bypass are proximal foot, hood

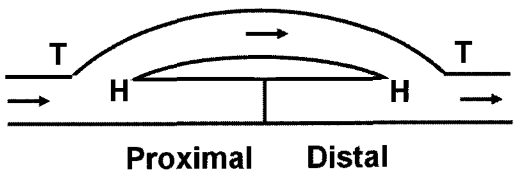

Figure 3. Schematic of the bypass model with fully blocked arterial section. The abbreviations T and H are for toe and heel of the bypass at proximal and distal regions of the model

(central part) and distal foot. The pulsatile flow parameters are maintained within physiological range (mean Reynolds number 250 and Womersley parameter 3.85. To observe the changes at high flow rate the flow during systolic phase at Reynolds number (Re) 625 (higher than normal) is considered. Images are recorded at frequency 60 beats per min and analyzed by computer by image processing software. Further details of the procedure are given elsewhere (20).

Results and discussion

The objective of bypass surgery is not to repair or remove blocked coronary arteries, but to detour blood around a blockage by using arteries or veins from other parts of the body (grafts). There are several parameters which need to be considered for a long lasting bypass graft. From fluid mechanics concept the roughness of the internal surfaces is one of the causes for flow disturbances. Therefore, outer surfaces of the copper tube model and of the wax model are made perfectly smooth. Entire surface of the wax model is also made smooth. Thus the disturbances in flow due to roughness of the surfaces are minimized. After trials with different angles for bypass fitment, the placement at 5^0 is selected as this produces less disturbances than that at 10^0 and 15^0 This is primarily attributed to the flow separation at the heel region at the proximal end of the bypass. With larger angle the flow is associated with secondary flow close to its toe region similar to as observed in branching arteries (21, 22). In a recent comparative study, Anayiotos et al. (23) have shown that the graft placed at 30^0 perform better that that at 45^0. But from our experience such a higher angle may lead to development of the secondary flow and complicate the flow in and around the feet of the bypass. As the contact area of bypass with the artery varies inversely with the contact angle, this may be convenient to suture saphenous vein of larger lumen with coronary artery of smaller diameter at small angles (24). As the smoother surface produces no change in flow, the suturing process should maintain the smoothness of the surface. In this regard the Nitinol fitting for the coronary anastomosis has shown promising results (23).

Flow through full anastomosis at Reynolds number 625 during the systolic phase of pulsatile flow is shown in figure 4. At the proximal end the flow enters into the bypass producing maximum flow disturbances at the heel area. The flow is associated with vortex formation and strong velocity fluctuations over the entire cross-section of artery and bypass section. After passing through hood region these disturbances are reduced. At the toe region of distal section the flow disturbances are highly increased. Floor region at this end is equally affected. At the heel region the flow is associated with vortex formation. These results are in agreement with as reported by others (15, 25). In addition to these we have also observed that there is recirculation of the fluid through the entire distal region of blocked model (shown by dotted circle). This backflow may produce

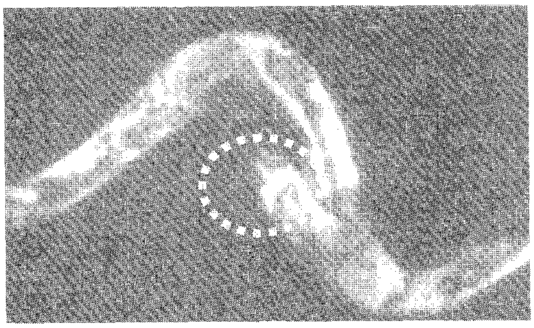

Figure 4. Flow changes in the bypass model recorded at normal position of the model and at 0° position of the analyzer for full view of the model at Reynolds number 625 during the systolic phase of pulsatile flow cycle. The circled part shows the re-circulation in the blocked distal region of the right coronary artery model.

changes in this section of the artery reaching up to the heel region of the bypass. The presence of the roughness over the foot region may further enhance these changes.

In the normal position of the model the changes induced by flow in the proximal blocked region could not be observed. To observe these the model is turned by 135^0 from its normal position and the analyzer turned by 15^0 from its initial position. Figure 5 shows the changes which are occurring in the stenotic region. There is fluid recirculation in the entire blocked proximal section (shown by dotted circle). The fluid movement is much slower which may initiate new series of reactions with the endothelium of the human artery starting from the heel region of the bypass. The procedure to minimize the effect of the complex recirculation in the blocked regions require further studies

The development of the aneurysm in the hood region, especially made of saphenous vein, is a serious problem (9, 10). Our study shows that this effect could be minimized by selecting the procedure to place bypass graft at minimum angle with curvature similar to that of artery with smooth sutures. As this model is a realistic three-dimensional one, the data obtained by this study show the various changes at different sections of the bypass,

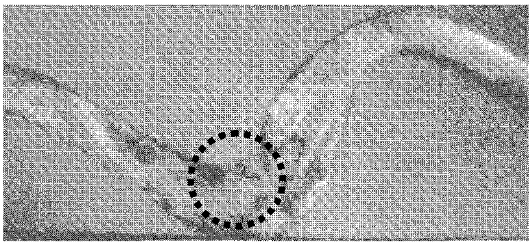

Figure 5. Flow changes in the bypass model recorded at normal position of the model and at 15° position of the analyzer for full view of the input end at Reynolds number 625 during the systolic phase of pulsatile flow cycle. The circled part shows the recirculation of fluid in the proximal part of the fully blocked artery model.

thus highlighting the complexities involved with this procedure. Whether this operation is carried out through CABG or off-pump CABG or robotically controlled procedures, the implementation of the above may be helpful in achieving long lasting bypass grafts.

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