Localization of bypass-induced changes in flow in coronary artery models

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Right coronary artery bypass restores blood flow through heart tissues. This also induces changes in flow leading to its failure. By this work the sites which are prone to such changes are localized. The bypass models are developed from transparent silicon rubber of elastic properties similar to arterial tissues. Flow visualization is carried out by photoelasticity technique by using dilute solution of vanadium pentoxide. This analysis carried out under pulsatile flow conditions shows that the proximal stenotic region continues to contribute to the alteration in flow in the hood region of the bypass. Thus making its proximal and distal regions prone to flow-induced changes, which may lead to its blockage over the long duration.

Keywords: Arterial bypass, Bypass-induced changes, Coronary artery, Flow visualization technique

The coronary arteries are the most prominent sites in the circulation for localization of atherosclerosis plaques. Their formation tends to be localized on the inner curvature of the coronary arteries that contact the heart surface. The superficial coronary arteries, which follow the curvature of the epithelial surface, are generally affected by this process. During this the diameter of the arterial vessel is decreased, which leads to reduction in blood flow. With further development of the constriction same as that of vessel diameter the blood flow is reduced to zero. Blood flow is restored by construction of a bypass by implanting a part of saphenous vein. This bypass is subjected to varying flow conditions during the various phases of pulsatile blood flow, depending on graft to artery diameter, graft angle, and graft-hood length. Despite these efforts, due to occurrence of secondary flow and its unsteadiness, the restenosis occurs in femoral, iliac and coronary arteries. Statistically this has been shown that 50% of the saphenous vein grafts are totally occluded after 10 years and the remaining 50% are more than 50% occluded.

The main coronary artery system is a very complex structure. Coronary angiography reveals the three-dimensional variation of the curved portions of this vessel. Despite accounting of this shape variation, these grafts are still slowly occluded under varying flow conditions. Flow visualization in the distal section of the graft has shown the involvement of various arterial and graft regions. But for precise localization of the regions associated with flow changes, which may lead to changes in the graft or arterial sections, the flow visualization in the complete arterial bypass model is required.

For model construction the three-dimensional structural details of the main curved section of right coronary artery prior to its first branching are obtained from Hayashi and Yamaguchi and adjoining sections from the cast of the human heart. The first model of this is made of copper tube with an internal diameter 6.0 mm. The bypass is placed at an angle 5° on the upper surface of the tube, similar to the procedure adopted for bypass reconstruction for coronary arteries. Wax casts of this model are made. For coronary artery model (CA) the bypass section from the wax model is removed. From the bypass model the wax models with normal artery section (B1) and 100% stenosed artery (B2) are prepared. These models are coated with multiple thin layers of silicon rubber. Thereafter, the wax is melted out. After the traces of wax were cleared out with isopropanol, the silicon models of bypass with normal artery (a), right coronary artery (b) and bypass with stenosed artery (c) are obtained (Fig. 1). The silicon rubber models are elastic and transparent and thus ideal for flow visualization.

Figure 2 shows the schematic of the flow visualization technique. Pulsatile flow 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. This system is calibrated to maintain systolic pressure at approximately 120 mmHg and diastolic pressure around 80 mmHg. The bypass model with stenosed artery is placed between the crossed polarizer and analyzer. The linearly polarized light is perpendicular to the direction of flow of dilute solution of vanadium pentoxide (birefringent solution) in the model. At any location of the model the polarized light hits the particles which are distributed over the entire diameter. The particles are in statistical disorder as the velocity gradient at the apex of the velocity profile is zero. Across the apex of the fully developed velocity profile a beam of light passes through the entire tube without any change and is extinguished at the crossed analyzer. Other portions of the beam illuminated the particles which are oriented over the whole cross-section depending on the shear gradient. After passing through the analyzer, depending on the orientation of particles, the transmitted light component shows variation in the light intensity at different locations indicating the flow changes.

For three-dimensional flow visualization, both ends of the model are mounted on plastic tubing, which are passed through airtight double 'O' rings joint system. After smoothing the movement by applying the silicon lubricant, the models are mounted in the flow system to visualize at the control (I) position, and by rotating by 90° (II) and by 135° (III) from the control position.

The pulsatile flow is resumed at the mean Reynolds number 250 and Womersley parameter 3.85. The birefringent pattern is recorded at analyzer positions at 0° (for full view of the model) and 15° (for detailed viewing of input end) with digital video camera MV500i (Canon, Japan). Images of fluid flow through various models at the systolic and diastolic phases are recorded at a frequency of 60 beats per min and are analyzed by computer by image processing software. To observe the changes due to increase in flow, Reynolds number (Re) is further increased from 250 to 625.

Figure 3 shows the outline of a fully blocked model. The regions at the input and output attachment sites are given as Toe, Heel and Floor, and Toe, Heel and Floor. The marked arrows show the directions of flow in various sections of the model. The proximal and distal outlet segments at the input and output sections of the model artery are shown by POS, and DOS, and POS, and DOS.

![Fig. 1 — Schematic of flow visualization system through arterial models.](image)

![Fig. 2 — Right coronary artery models of silicon rubber, developed from the wax models of copper tube: (a) Bypass model without stenosis, (b) right coronary artery model, and (c) bypass model with 100% stenosis.](image)

![Fig. 3 — Schematic of the bypass model with fully blocked arterial section. The various abbreviations are: POS, DOS, POS, and DOS, for proximal and distal outlets of input and output sections with their toe, heel and floor regions.](image)
Figure 4 shows the flow changes during the systolic phase of pulsatile flow in the B2 at various Reynolds numbers. Flow is diverted to the main vessel and bypass but this induces some flow-dependent activity in the proximal and distal regions of the stenosis. These observations are taken at zero degree position with crossed polarizer. The flow is associated with vortex formation and strong velocity fluctuations over the whole cross-section in the entire artery and bypass section. These vortices disappear at the output section of the model (Fig. 4a). With the increase in Reynolds number to 500, the velocity disturbances are increased, which travel through the bypass section not only to affect the Floor but also proximal section at the output end of the artery (Fig. 4b). With the increase of Re to 625 the flow disturbances are further increased. These are observed not only in the input section but also in the stenotic section (Fig. 4c). These velocity fluctuations are reduced in the output section of the model. These fluctuations are further decreased during the diastolic phase of the pulsatile flow.

By turning the model different sections of the bypass are observed. Figure 5 shows the details of the flow changes observed in the model at various angles. At the control position of the model the main arterial section is clearly observed (Fig. 5a) but by turning this to 90° position, due to overlapping of the arterial and bypass sections, only the stenotic section is observed (Fig. 5b). By further turning to 135° from the normal position the stenotic sections are clearly observed (Fig. 5c). The changes observed are during the systolic phase of the pulsatile cycle at Reynolds number 625. Both ends of the stenosis are active.

![Figure 4 - Flow changes in the bypass model with 100% constriction at normal position of the model at Reynolds number (a) 250, (b) 500 and (c) 625 during the systolic phase of pulsatile flow cycle viewed at zero degree position of the analyzer.](image1)

![Figure 5 - Flow changes as observed in the bypass model at Re=625 at various positions: at normal position (a) and by turning about its axis by an angle 90° (b) and 135° (c), viewed at 15° position of the analyzer.](image2)
during this flow that means the fluid moves in and out of the stenosed section. From the input section the fluid moves into the bypass and then to output section of the artery. However, high velocity fluctuations can be seen in the whole model.

The present study, based on flow through three-dimensional model of the right coronary artery, shows that the flow is never fully developed. This is also associated with the increase in flow resistance compared to that of a straight vessel. However due to this the vortex formation and velocity fluctuations, which dominates the entry section, are minimized in the next bend of the artery model and the flow calms down in the output section.

The flow through the bypass depends on various parameters, and the input, output and hood length of the graft. The grafting angle is of vital importance as a larger angle leads to higher resistance (unpublished observations). In the present work the graft is placed at an angle of $5^\circ$, which is of shorter length. Such grafts tend to moderate or reverse the adverse effect of wave reflections. At low Reynolds number the flow is calm with velocity peak shifted towards the outer wall. With increase of Reynolds number the flow is associated with vortices. These vortices vanish over the length of the curved section. Flow division and merging lead to formation of flow separation regions at the Floor, and Floor. The stenotic region continues to be influenced by the flow through the graft as this is associated with reverse flow, which increases with increase in flow in the graft section.

For fully blocked coronary artery the addition of a bypass is of significant importance for restoring the flow. To maintain the smooth internal surface, suturing of the saphenous vein is avoided by Ni-Ti fitting. This also avoids bulging of the graft and provides streamline flow. For the present study a graft with a smooth inner wall is considered, which minimizes the effects due to variation in internal structure such as that caused by suturing. The present observations show that flow regions at the input and output ends are affected. These changes are dominant during the systolic phase of the pulsatile cycle.

In conclusion by the present technique the bypass locations which are prone to changes are identified. These could be improved either by changing the design of the bypass or modifying the stented area. This also highlights the involvement of stenotic area of the artery, which needs to be minimized. Thus this methodology helps in improving the design of the graft which may last longer compared to the existing ones.

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References