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Comparison of Flow Characteristics of 45° Forward and 45° Backward Facing Proximal Anastomosis Models: A Particle Image Velocimetry Study

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Abstract

In order to gain a physical insight on the role of hemodynamics, especially at the proximal anastomosis, in the intimal thickening and graft failure, a two-dimensional Particle Image Velocimetry (PIV) system has been used to map the velocity vector in the actual scale (1:1) 45-degree forward and 45-degree backward proximal anastomosis models under pulsatile flow condition. At the peak flow phase, a low velocity region containing recirculation was found near the heel along the graft inner wall and a stagnation point was found at the graft outer wall. Large spatial wall shear stress variation was found near the heel and the toe for the 45-degree forward facing model. It is recommended that the 45-degree backward facing model is a better arrangement for the bypass operation.

Introduction

Anastomotic intimal hyperplasia (IH) is a major cause of long-term failure in small diameter vascular prostheses. This process leads to the gradual occlusion of the anastomosis from a sub-intimal proliferation of smooth muscle cells and extracellular matrix [1]. Various hypotheses have been proposed to explain this phenomenon, based upon both mechanical and fluid dynamic mechanisms [2]. It is suggested that these processes may be influenced by biological responses [3], and interactions between blood and the non-endothelialised graft surface [4]. Hemodynamic factors, including flow angle, high wall shear stress variation together with the low wall shear stress level, have long been suggested in causing of vascular disease and have been shown to play an important role on the deformation of arterial wall structure [5, 6, 7]. It is not surprising, therefore, that many studies have tried to relate hemodynamic effects to the localized development of intimal hyperplasia.

However, most of the previous studies were focused on the distal anastomosis and little effort has been put on the proximal side. It is possible that the proximal anastomosis provides the condition to form mitogens and activated platelets, and then they are convected down to the distal part [8]. The effect of flow patterns of the proximal side on the distal part has rarely been reported. Based on the preliminary in-vitro experiment under steady flow condition [9], this study aims to examine the flow structures that occur at the proximal anastomosis under pulsatile flow condition. It is hoped that the study will provide better understanding of the flow structure and its responsibility at the proximal anastomosis.

Methods

The flow models are designed and fabricated based on the clinical data from the National Heart Centre of Singapore, which had the same geometry as the computational model used in the simulation [10]. The internal diameter of aorta and graft are 20mm and 6mm respectively and the schematic view of the proximal anastomotic model with 45-degree backward facing graft was shown in Figure 1. Note in the present study, 45-degree forward facing graft model was also investigated.

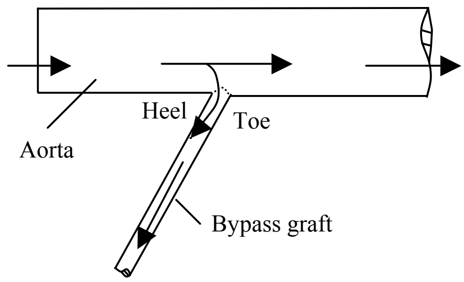


Figure 1: Schematic designs of the proximal anastomotic models.

A solution containing about 30% glycerin and 70% aqueous ammonium thiocyanate (NH_4SCN) by weight was used to provide a fluid with a viscosity comparable to blood and meet the requirement of refractive index. The aqueous ammonium thiocyanate solution was made up of equal parts of ammonium thiocyanate salt and distilled water by weight. The resulting viscosity and refractive index were measured by means of a controlled shear rate rheometer (Contraves Low Shear 40) and commercial refractometer (ATAGO 3T) respectively. The mixture adapted to yield a viscosity of $4.08\times10^{-3}\,\mathrm{Pa\cdot s}$ and a refractive index of 1.47. Polyamid Seeding Particle (38A2-121 PSP-50, Dantec Measurement Technology) was added into the fluid to highlight the flow field.

Figure 2 is a schematic presentation of the experimental arrangements for Particle Image Velocimetry measurements. The fluid is forced from a sump tank (1) by a centrifugal pump (2) into the reservoir and overflow container (3). Firstly the main flow from the head tank was allowed to fill up the whole circuit, including the piston tube and backpressure tank. Then the valve (4) was closed and the special designed cam device (10) started to generate pulsatile flow profiles. The special designed cam device was fabricated according to the typical flow waveform reported by Nichols and O'Rourke [11] and the pulsatile waveform generated by the cam device in the measurement was shown in Figure 3.

A Q-switched, double cavity pulsed Nd: YAG laser was used as the illumination source, which has a repetition rate of 10Hz and provides two thin (0.3-1mm) green laser sheets ($\lambda = 532nm$). An 80C42 DoubleImage 700 camera with a Nikon AF Micro-Nikkor lens 60/2.8 was used to capture two consecutive images. The images were analyzed using a cross-correlation algorithm yielding the local displacements vector for each interrogation area. The laser-timing unit was triggered to the beginning of the systole by means of the flowmeter signal. The marking dot with number on the curve represents the time interval in the cycle selected to show the velocity vector maps and the wall shear stress.

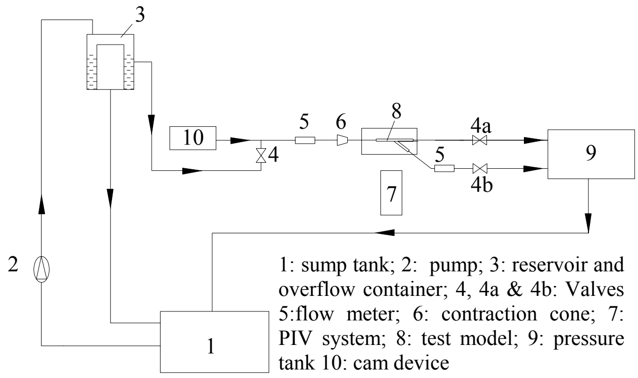


Figure 2: Schematic presentation of in-vitro experimental arrangement.

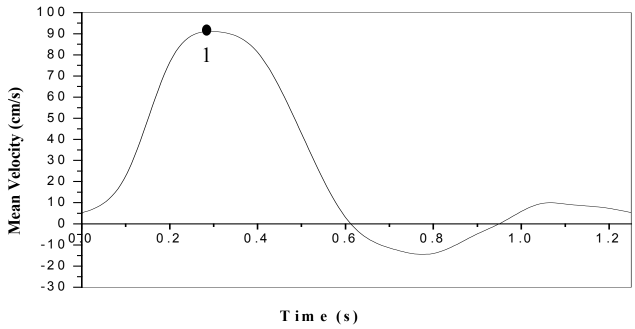


Figure 3: The pulsatile velocity waveform.

Post-processing of the results included the calculation of WSS and spatial WSSG, the two parameters believed to be associated with IH formation [5, 6, 7]. The wall shear stresses, τ_w, along the graft inner wall and outer wall were calculated using the following relation:

$$\tau_w = \mu \frac{\partial u}{\partial y} |_{y \to 0} \tag{1}$$

Where $\partial u / \partial y$ is the velocity gradient close to the wall. The wall shear stress gradients, WSSG, along the graft inner wall and outer wall were calculated using:

$$WSSG = \partial \tau_w / \partial x \tag{2}$$

Results and Discussion

The flow measurements as shown in Figure 4 reveal that a recirculation region, which spans a distance of 10 mm (about 1.6 times of graft diameter), is observed along the graft inner wall of 45-degree forward facing model during the peak flow phase (t=0.3s). The colour map in Figure 4 represents the velocity magnitude. Note that within the recirculation region, the magnitudes of the velocity vectors are much smaller than the main stream.

Figure 5 shows the flow field of 45-degree backward facing graft model under the peak flow phase (t=0.3s). Similarly a small low velocity region was found along the graft inner wall near the heel. Comparing Figure 5 with Figure 4, it was found that the low flow region in 45-degree backward facing graft model occupies a much smaller space. The low flow region which was believed to be suffered from low shear stress may allow prolonged residence times for circulating pro-inflammatory cells to adhere to the endothelial monolayer cells of the vessel, and have thus increased the chances for forming mitogens and activating platelets [12]. Once the mitogens formed and the platelet activated, they may be transported down to the distal site during the physiological cycle and fastened the formation of the intimal hyperplasia [13].

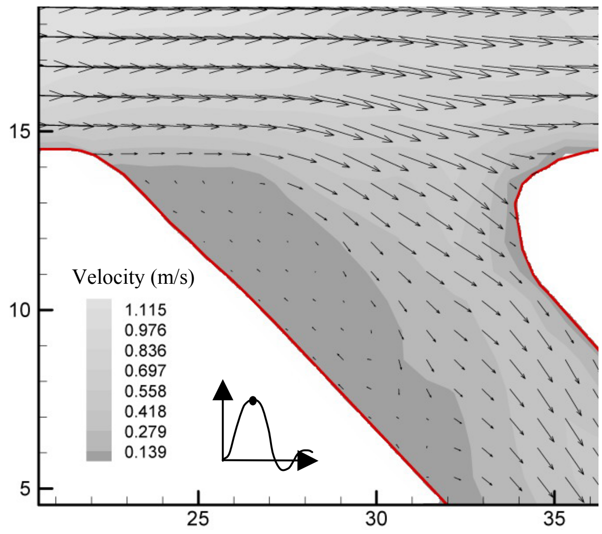


Figure 4: Flow patterns and velocity magnitude distribution in 45-degree forward facing graft model under peak flow phase (t=0.30s).

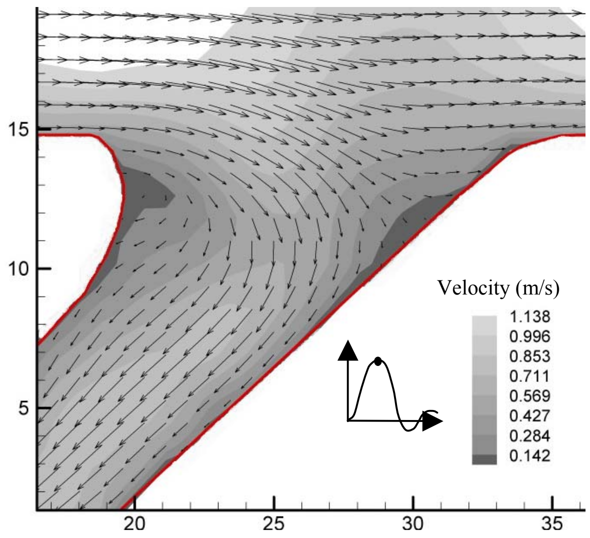
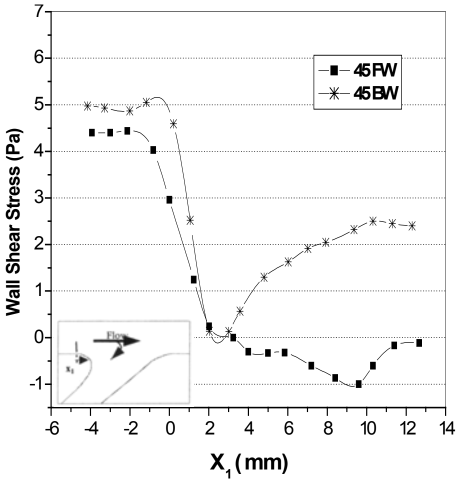


Figure 5: Flow patterns and velocity magnitude distribution in 45-degree backward facing graft model under peak flow phase (t=0.30s).

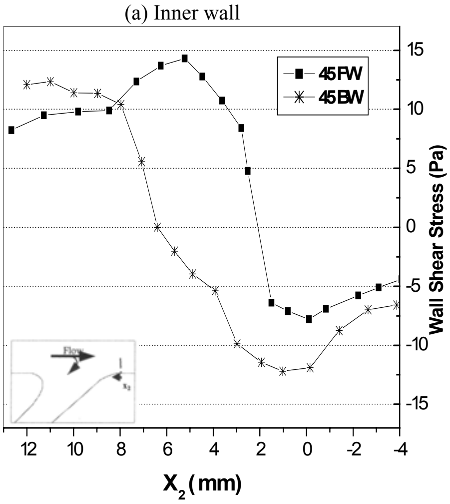
Wall shear stress (WSS) is an important factor which can stimulate and affect the development of intimal hyperplasia [14], and is the main cause for the bypass graft failure. Furthermore, the suture joint is more prone to the intimal thickening. Low WSS [5], high or unidirectional shears [15] were believed to be closely related to the development of intimal hyperplasia at the suture joint. In order to study the effect of anastomotic angle on the wall shear stress distribution, the comparison among the WSS distributions of 45-degree forward and 45-degree backward facing graft models under the peak flow condition has been conducted and presented in Figure 6. This is because the flow fields under peak flow condition were found to be much more complicated than other phases, and have much higher WSS and can correspondingly induce the release of growth factors from the endothelium, followed by smooth muscle cell proliferation [3]. Note the coordinates used to express the wall shear stress profiles are shown schematically at the corner of the figure. The annotation, x_1 and x_2 are the points selected approximately at the end of the straight aortic wall and are going along the direction of the graft inner and outer walls respectively.

From Figure 6 (a) it is observed that the wall shear stress distributions of the two models have the similar trend in general, which is due to the same inlet flow condition. The wall shear stresses reach a peak value and then drop sharply to a low level and maintain at the similar order of magnitude before increasing at further downstream. However, they also have some differences, the low stress region is quite short in the case of 45-degree backward facing model. And a large negative wall shear stress region was found from $x_1 = 3mm$ to $x_1 = 12mm$ in the 45-degree forward facing graft model, which indicates the existence of the recirculation region there.

Along the graft outer wall, it is noted that the magnitude of wall shear stresses are much higher than those of graft inner wall for the two models, as shown in Figure 6 (b). From the figure it is observed that the stagnation point of the 45-degree forward facing model locates at further upstream ($x_2 = 2mm$) compared with that of 45-degree backward facing model ($x_2 = 4.7mm$). It is also noted that 45-degree forward facing model has the highest positive wall shear stress and much steeper increase of WSS along the graft outer wall. Significant flow disturbances which have resulted in locally elevated WSS has been proposed to cause damage to the endothelial cells and endothelium dysfunction, and have also played an important role in platelet activation, and ultimately IH formation [16].



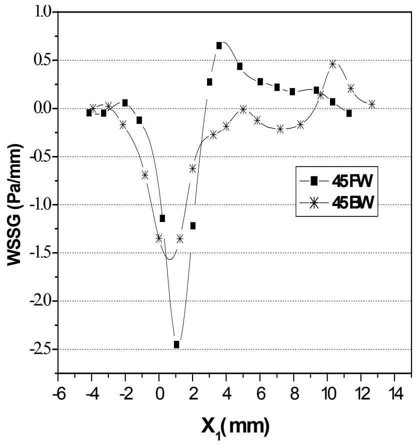
(a) Inner wall



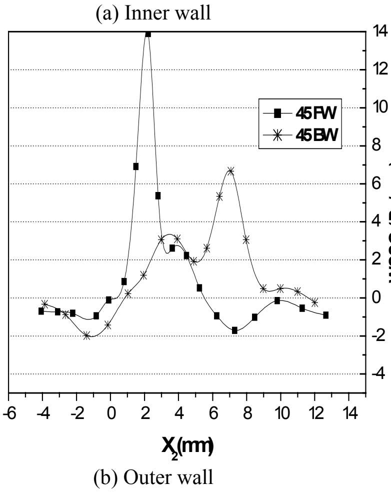
(b) Outer wall

Figure 6: Wall shear stress distributions of the anastomotic joint in different anastomotic models under peak flow condition (t=0.30s). (a) Inner wall; (b) Outer wall.

Spatial wall shear stress gradients (WSSG) along the graft inner wall and outer wall of both models were calculated in the study, as shown in Figure 7. It could be observed in Figure 7(a) that for the two cases there existed a dramatic decrease of WSSG when the flow accessing the heel region. The largest negative WSSG values are $-2.45\,Pa/mm$ and $-1.6\,Pa/mm$ at 45-degree forward facing and 45-degree backward facing models respectively. After the heel region the WSSGs increase which is corresponding to the increase of wall shear stress along the graft. The WSSGs reached an asymptotic value close to zero at the further downstream, which indicated much more uniform flow along the graft. Along the aorta at the toe region, as shown in Figure 7 (b), the WSSGs in both cases are negative in value before increasing sharply when approaching the graft outer wall, which is due to the definition of x_2 coordinate. The magnitude of WSSG of 45-degree forward facing graft was found to be much higher than that of the other model, and reaches its highest value of 14 Pa/mm at $x_2 = 2.0mm$. The peak value of WSSG at 45-degree backward facing graft model appears much more downstream, at $x_2 = 7.0mm$, and smaller in magnitude of only 6.8 Pa/mm when comparing with that of 45-degree forward facing graft model. Large spatial WSSG was found to induce morphological and functional changes in the endothelium, which contributee to elevate wall permeabilities and hence possible atherosclerotic lesions [16]. Therefore the relatively low WSSG values along both inner and outer walls of 45-degree backward facing graft once again suggested that it should be recommended for anastomosis.



(a) Inner wall



(b) Outer wall

Figure 7: Wall shear stress gradients of the anastomotic joint in different anastomotic models under peak flow condition (t=0.30s).(a) Inner wall; (b) Outer wall.

Conclusion

At the peak of the pulsatile flow, a low velocity region containing recirculating flow is formed at the graft inner wall in the 45-degree forward facing model and briefly on the 45-degree backward facing model. It is also found that there is a stagnation point at the graft outer wall. The existence of recirculating flow and stagnation point may accelerate the formation of intimal hyperplasia.

The wall shear stress distributions at the peak flow phase also demonstrate significant variations along the walls of the anastomotic joint. Large wall shear stress variation (ranging from –15 Pa to 14.8Pa) was found around the anastomotic joints. The small region near the heel had low wall shear stress level (ranging from –0.5 Pa to 1Pa). In addition, near the stagnation point of the outer wall, there was a small region, which had the low wall shear stress level in the two models. At peak flow phase, the 45-degree forward facing model was found to have the highest positive wall shear stress. The 45-degree forward facing model was found to have the extreme high WSSGs at both heel and toe regions, however, the 45-degree backward model has the lowest WSSG obtained. The high wall shear stress gradient together with the low wall shear stress level were associated with the formation of intimal hyperplasia [5, 6, 7].

In summary, the 45-degree backward model may provide the best conduit between the aorta and coronary artery, which should be able to reduce the potential of IH formation uttermost. This could be useful in the design of sleeve for bypass operation and would be reported in due course.

Acknowledgments

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