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BASAL TO NEAR HYPEREMIC PULSATILE FLOW IN A DEPLOYED CORONARY STENT

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ABSTRACT

The present study focuses on developing basal to near hyperemic flow through the entrance region of a deployed stent in a coronary artery segment. Stents that are presently available in market differ significantly in design. Hence, there is a need to optimize its design such that the magnitude of wall shear stress is within physiologic limit, thus minimizing the patho-physiological effects. For near hyperemic flow, the analysis showed a 20 fold increase in the positive values of wall shear stress at the stent wires exposed to the blood flow. Further, at the void next to the entrance, the wall shear stress was an order of magnitude lower than the values typically observed in similar downstream regions.

INTRODUCTION

Coronary stents are important in the treatment of atherosclerotic disease and are key to the advancement of interventional techniques. Coronary stent system is used in patients eligible for percutaneous transluminal balloon coronary angioplasty [PTCA] with symptomatic disease due to discrete *de novo* lesions in native coronary arteries [length $\leq$ 30 mm] with a reference vessel diameter of 3-4 mm. Essentially, stenting is intended to improve coronary luminal diameter. Current stent products, although aligned to the same goals of the mechanical enlargement of the vessel lumen, reduction in restenosis and the incidence of complications, differ significantly in terms of their design.

METHODS

A pulsatile flow analysis for basal (50 ml/min) to near hyperemic condition (150 ml/min) is performed for a freshly deployed stent in a human coronary artery having a three dimensional geometry with an axial length of 10 mm and a diameter of 3 mm. Following the deployment of the stent, it is assumed that half of the stent is exposed to the blood flow whereas the other half is embedded in the arterial wall. Volume mesh [Figure 1A] with ~650,000 cells of hexahedral elements were generated in Gambit™ using the Cooper scheme. In order to mesh the deployed stent, the flow domain was sub-divided into two independent regions with non-conformal interfaces between them. Computational fluid flow analysis was carried out using Fluent 6.0.

For the present study, a constant blood density of 1.05 gm/cc and an infinite-shear-rate viscosity of 3.45 cp were considered. Time-varying, uniform velocity boundary condition was imposed at inlet boundary with a user-defined subroutine. The uniform velocity boundary condition simulated the worst possible location of the deployed stent in the coronary artery and thus, it provided an upper bound [maximum] of desired flow parameters [e.g. shear stress]. In other words, this model mimics the stent being placed near the entrance region of a branched coronary artery. The numerical computation was conducted for 3 consecutive pulse cycles [Figure 1B] with a pulse time period of 0.8 s. The results for the 3rd cycle (1.6 s to 2.4 s) are presented here. Time at 1.86 s is the early acceleration phase ($u=0.5u_{max}$), 2.02 s ($u=u_{max}$) represents peak flow, whereas 2.19 s ($u=0.75u_{max}$) and 2.30 s ($u=0.5u_{max}$) are the early and late deceleration phase of the pulse. Segregated, second-order time-implicit solver with second-order discretization for pressure and momentum was used.

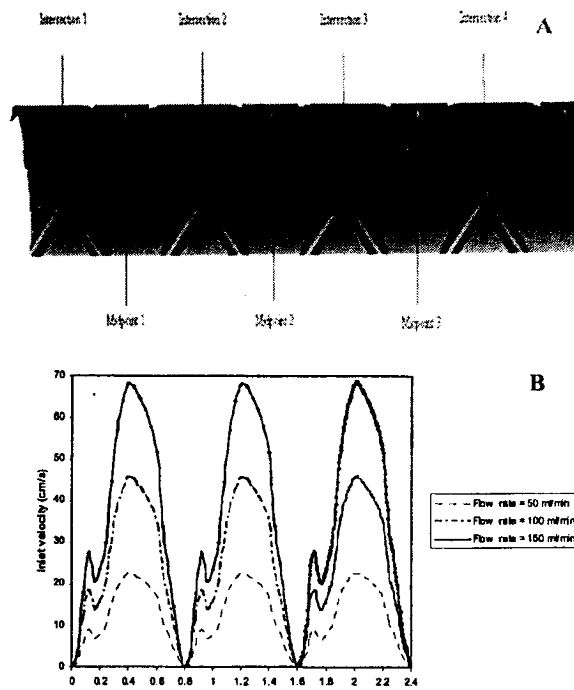

Figure 1: The geometry showing the flow domain of the coronary artery with deployed stent (Fig. A). Figure B shows 3 consecutive pulse cycles for basal to near hyperemic flows.

RESULTS AND DISCUSSION

Figure 2 shows axial velocity profile at various times [e.g. time t = 1.86 s {acceleration}, and 2.02 s {peak}, 2.19 s and 2.30 s {deceleration}] of the pulse cycle for near hyperemic flow of 150 ml/min at strut intersections 1 and 4 (shown in Fig. 1A) of the stent. The developing velocity profile shows a maxima next to the strut location (r = 0.125 cm; intersection 1 shown in Fig. 1A). For near hyperemic flow, a maximum velocity of 105 cm/s is observed near the strut at peak diastole whereas a velocity of only 72 cm/s is observed at the center of the artery. A similar trend is also observed at lower flow rates, e.g. basal flow of 50 ml/min. In general, due to entrance flow effect, the velocity at the center of the artery is less as compared to the velocity near the strut. Further, the velocity gradient is high at strut locations causing elevated wall shear stress values. As the flow develops, the velocity profile changes to more parabolic in shape as seen in strut intersection 4.

Figure 3 shows variation of maximum wall shear stress with flow rate at strut intersections 1 through 4 of the stent and at the mid-point of the void locations 1 through 3 (shown in Fig. 1A). Due to the developing nature of the flow, a local maximum value of (+)290 dynes/cm^2, about 20 times higher than the normal value and greater than the developed flow [at downstream location] wall shear stress values, is observed at the upstream locations of the exposed stent wire. At the void next to the entrance, a local minimum of (+)1 dynes/cm^2, which is also an order of magnitude lower than the typical values obtained in the downstream regions, is observed. As the flow develops along the axial direction of the exposed stent wall, sharp variations in wall shear stress magnitude and pressure values between the exposed stent wall and the adjacent void regions are gradually reduced.

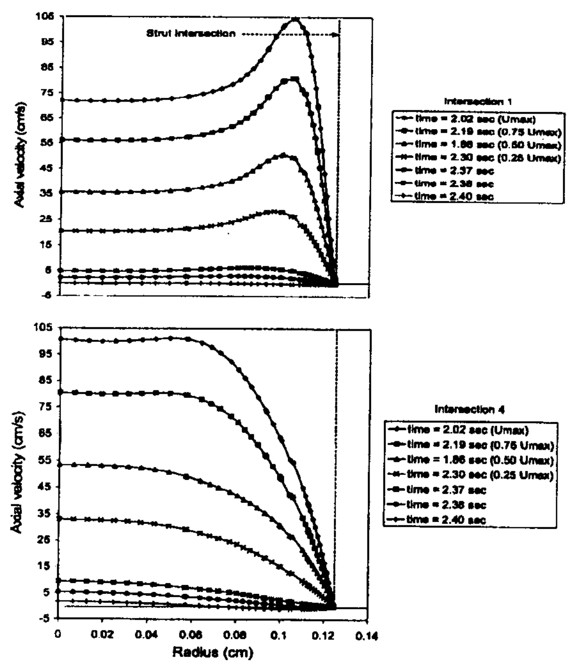

Figure 2: Axial velocity profile for near hyperemic flow of 150 ml/min at the entrance region (strut intersections 1 and 4 are shown in Fig. 1A) of the stent.

At late diastole, significant recirculation zones are formed in the voids created by cross-links of stent wires. At the void next to the entrance, the low wall shear stress was an order of magnitude lower than the values typically observed in similar downstream regions. Essentially, recirculation zones have low shear areas that are susceptible to the deposition of macromolecules, e.g., cholesterol, lipoproteins, and other lipid derivatives (Caro et al., 1969; Nerem and Levesque, 1987). These low shear areas lead to restenosis (Berry et al., 2000; Henry, 2001).

In contrast to the low shear regions, it is also necessary to minimize the high shear region on the stent wire wall that is exposed to the blood flow. The present results of developing hyperemic flow through the entrance region of a deployed stent in a coronary artery segment showed a 20 fold increase in the positive values of wall shear stress at the stent wires exposed to the blood flow. A high shear region due to an improper stent design may cause detrimental patho-physiological effects in the coronary artery.

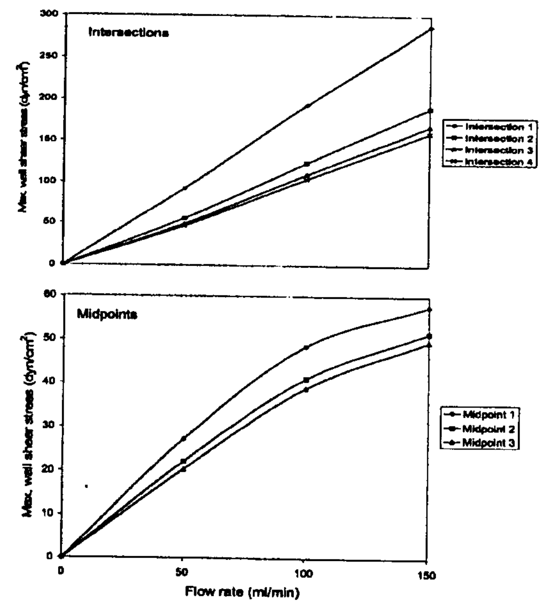

Figure 3: Variation of maximum wall shear stress with flow rate at strut intersections 1 through 4 of the stent and mid-point of the void locations 1 through 3 (shown in Fig. 1A).

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