THE INFLUENCE OF JUNCTION ANGLE ON MASS TRANSPORT IN DOWNSTREAM GRAFT/ARTERY JUNCTIONS

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INTRODUCTION

One of the leading modes of failure of peripheral vascular bypass grafts is the formation of intimal hyperplasia (IH) at defined regions within the geometry. These key locations are the heel, toe, suture line and bed of the downstream junction. IH formation at the suture line is generally attributed to the natural healing process, along with a proposed hypothesis of the mismatch in compliance between the host artery and the graft. IH formation at the heel, toe and bed of the junction is believed to be the result of abnormal hemodynamics [1].

The transport of dissolved gases and macromolecules from blood to the artery wall is highly dependent on local hemodynamics. Regions of separation, recirculation and stagnation will modify transport to and from the artery wall with a potentially atherogenic response.

METHODS

2-dimensional representations of an idealized downstream junction were created with equal artery and graft diameters of 6mm. The junction angle was varied to include angles of 30°, 45° and 60°. Applying the finite-element technique, the models consisted of approximately 15,500 elements. Due to the high Peclet number associated with mass transport in large arteries (Pe = 545,000) triangular 3-noded elements were used to mesh the geometries [2]. The commercial finite element analysis (FEA) package, ADINA 7.5 (Watertown, MA, USA) was used to carry out the analyses. The momentum equation, the incompressible form of the 2-D Navier-Stokes equation and the mass transfer equation were used to perform the steady-state analysis.

A number of simplifying assumptions have been included in the analysis of mass transport. It was assumed that the presence of erythrocytes does not influence oxygen diffusion, the co-efficient of diffusivity for the species phase is 2.75 x 10^{-9} m^2 s^{-1} and the species concentration across the inlet is constant [3]. As a result, the fluid was modeled as plasma, with a viscosity of 1.2 x 10^{-3} kg m^{-1} s^{-1} and a density of 1024 kg m^{-3}. An inlet velocity of 0.25 m s^{-1} was applied to all models. A no-slip condition applied to the walls. The mass transport from the plasma to the wall occurs due to the concentration gradient that exists between to the plasma and the wall. The mass fraction of species in the plasma was fixed to 0.5% with the wall mass fraction set to 0%. The numerical analysis assumed rigid wall and zero proximal outflow.

RESULTS

The downstream junction produces a large variation in flow patterns with flow separation occurring at the heel and toe, a stagnation point occurring at the bed of the artery and a large recirculation region occurring proximally to the stagnation point. It is at these locations that the largest contours in species concentration occur. This is due to presence of a mass diffusion boundary layer where the particles are continuously circulated within the recirculation regions away from the wall. Examples of contours of species concentration for the downstream junction with different junction angles can be seen in figures 1 and 2. These results are presented for a specific species, oxygen.

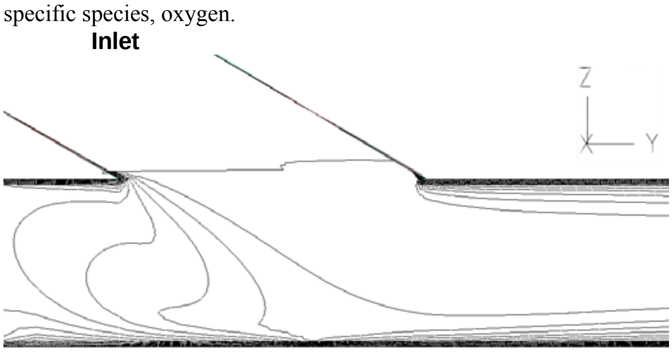

Figure 1. Contours of Oxygen Concentration - 30° Model

Figure 3 illustrates the disturbed mass transport on the bed of the junction along with the radial component of the near wall velocity. A close correlation between the magnitude of the radial component of near wall velocity and the extent of mass transport is evident. The

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values presented in figure 3 are located at a distance of 200 microns from the bed of the junction.

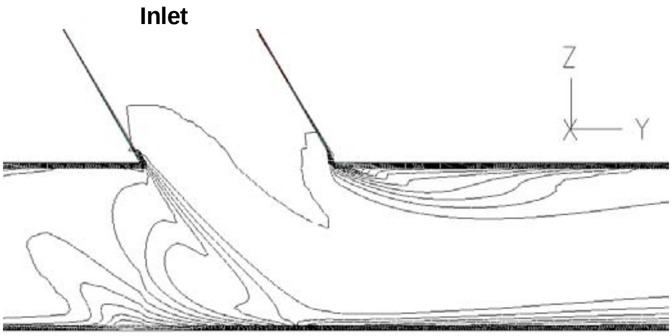

Figure 2. Contours of Species Concentration - 60° Model

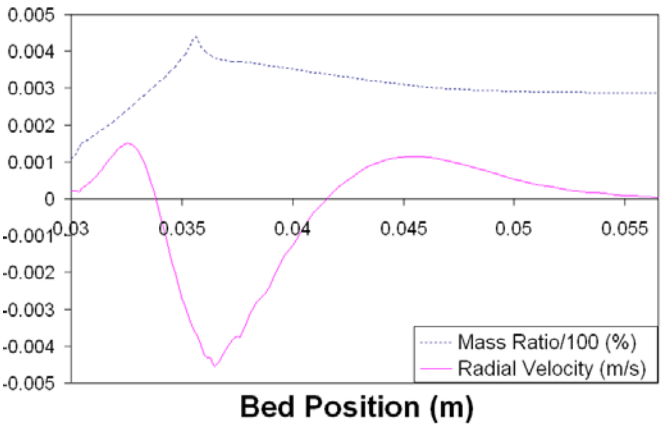

Figure 3. Illustration of Mass Transport and Radial Component of Velocity Along the Junction Bed (60° Model)

The maximum radial component of velocity exists at the stagnation point in the flow field, which is located at an axial distance of 0.0365 m from the upstream end of the arterial segment of the model. The region of recirculation is represented by the velocity values upstream of this axial location.

DISCUSSION

The formation of IH in the downstream graft/artery junction is localized to well-defined regions. From the computational analyses presented here these regions all experience a disturbance in local hemodynamics, leading to modified mass transport to the artery wall.

Mass transport in large arteries is highly convective as has been demonstrated previously by the high Peclet number. This highly convective transport is clearly represented in figures 1 and 2 as the concentration of species remains constant along the majority of the center of the flow field. This highly convective flow condition accounts for the peak concentration value existing near the stagnation point. At the stagnation point the axial (y) component of the velocity vector is equal to zero. Therefore, the transport of species near stagnation point is both convective and diffusive as the flow is perpendicular to the diffusing surface. This increase in mass transport at the stagnation point could lead to an accumulation of potentially atherogenic substances along the bed of the artery.

The convective nature of mass transport is further illustrated by the linear decrease in species concentration downstream of the stagnation point. In this region the flow is progressively recovering to flow that is parallel to the bed of the junction. Without any radial components of velocity, mass transport occurs purely by the concentration gradient that exists between the plasma and the wall.

A comparison between anastomotic angles was performed to investigate if a correlation between the extent of disturbed mass transfer and the junction angle exists. It is evident from figure 2 that a reduction in the anastomotic angle will lead to a reduction in disturbed mass transport as the flow patterns within the 30° model are less disturbed than the 60° model. Recirculation is present in all three geometries. However, larger regions of recirculation at both the toe and bed of the junction in the 60° model lead to the formation of mass diffusion boundary layers. These regions of recirculation, and correspondingly regions of reduced mass transport, are located in areas where there exists a reduction in wall shear stress. This phenomenon is evident in figure 3 where a large reduction in species concentration within the recirculation region can be clearly identified. It follows that for the case when the species of interest provides a beneficial function to the artery wall, such as oxygen or nutrients, a reduction in its transport would have a detrimental effect.

The areas of disturbed mass transport do not only affect the artery wall when considering transport to the wall. The successful transport of harmful species, such as waste products and carbon dioxide, from the wall to the blood is also a concern. A combination of reduced oxygen transport to the wall and reduced carbon dioxide transport from the wall could greatly compromise the functionality of the artery.

By increasing the anastomotic angle, an increase in the disturbance of mass transport to the artery wall will occur. Based on this observation the surgical technique of using an interposition cuff between the graft and the artery [4], which increases the radial component of junction velocities, could result in large mass transport disturbances. Conversely, the surgical technique of using a patch to "smooth" the flow entry into the junction [4], which reduces the radial components of junction velocities, could result in the minimum possible mass transport disturbance.

CONCLUSIONS

It is evident that regions of highly disturbed mass transport exist in the downstream graft/artery junctions. A strong correlation exists between the radial component of the junction velocities (and consequently junction angle) and the modified mass transport in the junction.

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