Effect of Flow Split on Separation and Stagnation in A Model Vascular Bifurcation

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SUMMARY This is a study of the flow disturbance in a plastic model of an asymmetric vascular bifurcation. A sidearm was attached to the mainlimb at an angle of 15° to the inlet flow axis. Water at steady flow was used and flow patterns were demonstrated by a dye injection technique. The proportion of inlet flow (Qi) exiting from the sidearm (Qs) was varied and flow patterns were recorded photographically. A laser Doppler anemometer (LDA) was used to measure near-wall velocity. At a physiologic Reynolds' number of 500, no flow disturbance occurred in the mainlimb when the sidearm was completely occluded. When the fraction of flow exiting from the sidearm (Qs/Qi) reached 0.19, a region of boundary layer separation developed along the wall of the mainlimb opposite the flow divider. This region of nearly static fluid spread circumferentially around the mainlimb as Qs/Qi increased. Near-wall velocity within the separation decreased and became negative when Qs/Qi = 0.31. When Qs/Qi reached 0.38, the separation enveloped the wall of the entire bifurcation with a shell of slowly moving fluid. At the same time, the rapidly moving mainstream impinged directly on the flow divider. There is a similarity between the region of separation seen in this model and the site of formation of atherosclerotic plaque at the carotid bifurcation. Separation may contribute to atherogenesis by creating a region of low wall shear at bifurcations.

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WHEN FLUID FLOWS through a pipe or vessel under laminar conditions, the fluid near the wall of the vessel moves much more slowly than fluid in the center. There is a very thin boundary layer of fluid attached to the wall by the interaction of wall friction and the viscous forces of the fluid.

The total energy of the fluid is equal to the sum of the pressure, or static head, and the kinetic energy, or dynamic head. If we assume a level system, the potential energy due to gravity can be ignored. Thus:

\[ E = P + \frac{1}{2} \rho V^2 \]

Where E is the total energy per unit volume, P is the pressure, \( \rho \) is the density of fluid, and V is the velocity of the fluid.

At a bifurcation, there is a sudden increase in diameter of the lumen. This results in a corresponding decrease in velocity of flow and loss of kinetic energy. Since the total energy is constant (neglecting friction loss) there is an increase in pressure equivalent to the loss of kinetic energy. At a bifurcation, where the cross-sectional area increases, there is a decrease in velocity and a corresponding increase in pressure. This results in a region where fluid is flowing against a small pressure gradient. The adverse pressure gradient acts to reverse the direction of movement of fluid. Since the fluid near the wall is moving slowly it can be stopped and its direction reversed even by a small adverse pressure gradient. The region of reversed flow (secondary flow) separates the mainstream (primary flow) from the wall, hence the term boundary layer separation.1 The more rapidly moving mainstream, because of its higher momentum, flows past the separation (fig. 1).

Previous studies4--5 evaluated fluid flow through bifurcations by mainstream visualization, demonstrating zones of boundary layer separation by upstream injection of visualizing material. Since the separation and secondary flow is superimposed on the primary flow it is difficult to determine the 3-dimensional structure of the flow field. The method of evaluation in this report allows observation of fluid motion within the boundary layer by infusing dye directly into the boundary layer in the region of the bifurcation. Using this technique we were able to demonstrate the separation regions and secondary flow patterns in 3-dimensions.

We demonstrated the presence of adverse pressure gradients and corresponding regions of separation in model side bifurcations.4 These bifurcations consisted of a mainlimb to which was attached a sidelimb at varying angles to the mainlimb. Three bifurcation were found, one in the mainlimb opposite the bifurcation and one in the sidearm just beyond the lip on the upstream side. This pattern of separation was consistent for bifurcation angles up to 135° to the inlet flow axis. The current study was designed to further characterize this region of separation at the side bifurcation. Specifically, the effect of the partition of outflow between the mainlimb and the sidearm on the separation region was studied. A 15° bifurcation angle...
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Inlet
\[ \text{Outlet} \]

Linear Pressure Gradient (Friction Loss)

Distance

Fluid/Wall Boundary

Separation Zone

Reattachment Point

FIGURE 1. Mechanism of separation. As fluid enters a region of adverse pressure gradient, the slowly moving fluid near the wall stops and reverses direction. This separates the mainstream from the wall. Because of its high momentum, the mainstream flows past the separation.

BOUNDARY LAYER SEPARATION

was selected for the study as it approximated the angle between the external and common carotid arteries (~15.8°) determined in an analysis of 57 angiograms. It should be noted that data extracted from angiograms are an approximation because of the limitation of planes in which x-ray images are taken.

Methods

A model bifurcation was constructed from clear plastic blocks and tubing. The internal diameter of the conduits was 8 mm, similar to the internal diameter of the human common carotid artery. A sidearm of equal diameter was attached to the main limb in the plastic block. A length of straight inlet tubing equal to 100 lumen diameters (80 cm) was precisely countersunk into the block and the junction of the tube and block was polished so that no flow disturbance would be induced at this point. The length of inlet tubing was selected to ensure ample length for the inlet flow to become fully established. Multiple 1.0 mm diameter ports were drilled in the region of the bifurcation and along the inlet and outlet tubing. These ports were used for dye injection (fig. 2).

A constant pressure head tank was used to provide steady inlet flow. Flow was measured by timed collection. Inlet water temperature was constantly monitored. The mean inlet Reynolds number was calculated from \( \text{Re} = \frac{\text{V} \times \text{D} \times \rho}{\mu} \), where \( \text{V} \) is the velocity of flow, \( \text{D} \) is the vessel diameter, \( \rho \) is the fluid density, and \( \mu \) is the viscosity. The flow split at the bifurcation was controlled by screw clamps on the outlet tubing and the fraction of inlet flow exiting from the sidearm \( \left( \frac{Q_s}{Q_i} \right) \) was calculated.

Toluidine blue O dye was infused through the wall ports using a Harvard syringe pump. This produced fine streamlines of dye, which traveled along the wall of the tubing, unaffected by the entry of the ports into the lumen of the model. The sites of infusion into the wall streamlines were varied so as to best demonstrate the flow pattern at the bifurcation. Acid Fuchsin (red) dye was injected into the central stream of the inlet by rapid bolus injection. The arrival of this mainstream bolus at the bifurcation was recorded by still photography (fig. 3), cine photography and by videotape.

The separation and reattachment points were determined by direct visual inspection of dye patterns and by review of videotapes. The reattachment point was taken as the furthest point downstream from which retrograde flow could be demonstrated. Dye ports were utilized both distal and proximal to the reattachment point, to visualize its position. Distances were measured from the flow divider and divided by the vessel diameter to give a non-dimensional length. As can be seen in figure 3, dye from the various ports intermingle in the region of separated flow and become indistinguishable from each other.

In order to illustrate numerically the visual observations of velocity changes across boundary layer separation, an argon laser Doppler anemometer* was used to determine near-wall velocity. Our equipment

\[ \text{Mainlimb outlet} \]

Flow from head tank

Bolus injection into central flow stream

FIGURE 2. Experimental model. Wall streamlines were demonstrated using a syringe pump for slow infusion of dye. The mainstream was demonstrated by bolus injection upstream.
did not have the capacity for continuous micrometer control of the sampling volume. It was therefore necessary to select a single site for sampling. The model bifurcation was positioned in the path of the laser beam and dye studies were performed to demonstrate the region of flow separation. The region of greatest stagnation within the secondary flow was determined by visual inspection. This was located on the sidewall opposite the flow divider (figs. 4–7). The sampling volume was positioned at a distance of 0.5mm ± 0.2mm from the wall at this location. Latex microspheres (3.14 μ diameter) were added to the inlet water to improve the signal to noise ratio of the velocity measurements. The velocity of flow was determined as Qs/Qi was varied while maintaining an inlet Reynolds number of 500.

Results

When no flow exited from the sidearm (Qs/Qi = 0), there was no separation in the mainlimb. A wall streamline remained attached as it passed the bifurcation (fig. 4). When Qs/Qi reached 0.19, a separation formed in the mainlimb. The configuration of this separation is illustrated in figure 5. Dye injected into a proximal wall streamline fanned out along the wall of the mainlimb just opposite the flow divider. The separation assumed a saddle-like shape which partially enveloped the mainstream and caused the mainstream to deviate so that it came in contact with the flow divider. The movement of dye within this separation was extremely slow compared to the velocity of a wall streamline when there was no separation. The dye was observed to recirculate within the separation. The separation continued to enlarge and encircle the mainstream as Qs/Qi was increased. When Qs/Qi reached 0.24, the separation completely encircled the mainstream and began to exit from the sidearm (fig. 6). There was less recirculation as the movement of dye within the separation began to develop a circumferential pattern flowing from the mainlimb wall opposite the sidearm around the mainstream to the sidearm. In addition, there was slow retrograde flow from the reattachment point around the mainstream to the sidearm. During this phase, the dye in the separation was not as stagnant as in the earlier phase.

When Qs/Qi reached 0.38, the separation enveloped the mainlimb and encircled the sidearm until it nearly reached the far wall of the sidearm (fig. 7). The strong secondary flow within the separation was retrograde and circumferential from the mainlimb to the sidearm. The mainstream was completely surrounded by a shell of separated flow within the bifurcation region and was further deviated across the flow divider.

The length of the mainlimb separation was measured as Qs/Qi increased with an inlet Reynolds' number of 500. The distance from the flow divider upstream to the separation and downstream to the reattachment points was measured by observation of the
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Mainlimb separation

FIGURE 5. Flow pattern in a 15° side bifurcation when 0.19 < Qs/Qi ≤ 0.24. As flow in the sidearm increases the dye in the inlet wall streamline (A) fans out just opposite the flow divider. A region of slowly recirculating, nearly stagnant flow is established which begins to encircle the mainstream in a saddle-like configuration. The rapidly moving mainstream deviates and impinges directly on the flow divider. A second region of separation is established in the sidearm where dye travels retrograde in the wall streamline to the proximal lip of the bifurcation from points (a), (b), (c). Port (c) is located four vessel diameters downstream from the proximal lip of the bifurcation. The site of the sampling volume of the laser Doppler anemometer was chosen as the point of greatest stagnation on visual inspection of the separation pattern. This point was along the wall of the mainlimb as shown in the cross section.

dye patterns. The separation point was easily seen at all flow splits. The reattachment point was less well defined by visual inspection especially at higher flow splits. Under these conditions, the reattachment point was determined as the furthest downstream position from which retrograde secondary flow could be demonstrated either during injection into wall streamlines or dye washout as seen on videotape. The separation increased in length mainly by movement of the reattachment point downstream. The separation point moved a correspondingly smaller distance upstream toward the proximal lip of the bifurcation.

The laser Doppler anemometer study demonstrated a decrease in near-wall velocity as Qs/Qi increased. When Qs/Qi reached 0.31, the near-wall velocity at the sampling site was zero. Above this, the near-wall velocity became negative but remained low as compared with the baseline state when Qs/Qi = 0 (fig. 8).

A second region of separation was found on the upstream side of the sidearm. This separation was always present at an inlet Reynolds number of 500 and it became correspondingly smaller as the mainstream separation increased in extent, or as Qs/Qi increased. The reattachment point of the sidearm separation was not as clearly discernible as in the mainlimb. As flow split increased, the separation point was seen to move slightly forward (less than 2 inlet diameters). The reattachment point shifted rapidly under these conditions to a maximum point over 6 inlet diameters downstream. The separation zone, therefore, increased in length mainly by movement of the reattachment point downstream.

Discussion

The Reynolds' number for blood in large vessels under resting conditions is between 100 and 500.* The use of the Reynolds' number makes it possible to compare fluids on the basis of the principle of fluid

FIGURE 6. Flow pattern in a 15° bifurcation when 0.24 < Qs/Qi ≤ 0.38. The separation in the mainlimb forms a nearly complete ring around the mainstream. Dye within the separation begins to exit from the sidearm but some dye also continues along the wall of the mainlimb. Dye injected into a wall streamline downstream (B) travels antegrade. The separation in the sidearm is smaller, with retrograde flow from ports (a) and (b) only, point (b) being 2.6 diameters from the proximal lip of the bifurcation.

FIGURE 7. Flow pattern in a 15° bifurcation when Qs/Qi > 0.38. The shell-like separation in the mainlimb now envelops the mainstream and reaches to the opposite wall of the sidearm. All dye within the separation exits via the sidearm. Dye injected into a wall streamline (B) located 4.0 diameters downstream from the flow divider travels retrograde and circumferentially to the sidearm. The separation in the sidearm continues to decrease in extent with retrograde flow coming only from point (a) which is 1.0 diameters from the proximal lip of the bifurcation.
symmetry, i.e. for a given geometry fluids having identical Reynolds' numbers have similar dynamics. The same is true of the use of non-dimensional distances which can be applied to other models or vessels provided the Reynolds' numbers are similar. The separation patterns established for water are also valid for blood in similar tube models under steady flow conditions. In the present study, we show that at an asymmetric bifurcation there are regions of boundary layer separation characterized by very slow movement of fluid near the wall. At the same time, there is an immediately adjacent region at the flow divider where the wall is in contact with the very rapidly moving mainstream. These profound local variations in wall shear may account for the predilection of atherosclerosis to localize at bifurcations.

Of particular interest in this study is the region of separation and secondary flow which develops opposite the origin of the sidearm. At an inlet Reynolds' number in the clinical range, the fluid in this region is nearly stationary when \( Q_s/Q_i = 0.31 \). Similar conditions exist at the carotid bifurcation where flow in the external carotid is about 30% of common carotid flow so that \( Q_s/Q_i \approx 0.30 \). This, when normal conditions exist at the carotid bifurcation, this may result in marked stasis along the wall of the common carotid opposite the origin of the external carotid. This is often the location of plaque in the carotid bifurcation (fig. 9), as suggested by autopsy studies. Our work supports the view that the sites of formation of atherosclerotic plaques correlate best with regions of separation. Although the precise mechanism whereby this might occur remains obscure, Platelet aggregates form in low shear separation regions. Low regional shear may result in local alterations in the exchange of materials between the blood and the vessel wall. This phenomenon of shear dependent mass transfer could act to cause a biochemical injury to the intima. The injury would then be compounded by platelet adhesion and proliferation of smooth muscle cells and fibroblasts.

The sidearm near the bifurcation also exhibits a region of reversed flow at inlet Reynolds' numbers in the clinical range. This effect may be significant although the area of near stagnation in this region is very small as compared to that of the mainlimb. As the fraction of flow exiting in the sidearm increases, the separation in the sidearm decreases. If an atherosclerotic plaque begins to form in the mainlimb at the region of greatest stagnation it would gradually obstruct the mainlimb and cause \( Q_s/Q_i \) to increase. Thus the separation in the sidearm would gradually decrease and would not be a major site of atherosclerotic plaque formation.

Our model illustrates the relationship between flow split and the flow disturbance at a side bifurcation, but the model is only an approximation of the geometry of the carotid bifurcation. It does not take into account...
the angle between the internal and common carotid arteries, size differences between the vessels, or the shape of the carotid sinus. Laser Doppler anemometer studies, in a more precise model of the carotid bifurcation, have demonstrated low shear separation regions nearly identical in location to those seen in our model. We show that changes in the flow split at the bifurcation can cause marked changes in the location and size of the separation as well as in the magnitude and direction of secondary flow. Our limited study with laser Doppler anemometer illustrates how the velocity of secondary flow within the separation is dependent on flow split. The flow split between the internal and external carotid may be one of the factors determining the predilection for a given individual to develop a plaque at the carotid bifurcation. The flow split of the resting carotid bifurcation is known to be close to that at which we demonstrated that near-wall velocity in the separation region crosses zero. The circle of Willis provides for an inter-relationship of flow in the carotid and vertebral vessels which influences the flow split, as for example, on turning the head. Slight alterations in anatomy of the circle of Willis, postural habits, etc. might contribute to variability in the flow split and may have marked effects on near-wall velocity at the carotid bifurcation. These variations may explain individual patterns of atherosclerosis.

It is unlikely that mechanical factors alone induce the formation of atherosclerotic plaque at arterial bifurcations, as a patient must first have the physiological or biochemical predilection for atherosclerosis. The flow disturbance at a bifurcation may be a contributing factor which tips the balance toward local development of the atherosclerotic plaque. Understanding the nature of the flow disturbance which favors atherosclerosis may provide insight into the physiological or biochemical events involved in this disease. The results of this study support the view that separation and low shear are the flow characteristics favoring atherogenesis.

References

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