Flow Patterns in the Human Carotid Artery Bifurcation

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SUMMARY To elucidate the connection between blood flow and the localized genesis and development of atherosclerosis and thrombosis at the human carotid artery bifurcation, detailed studies of the flow patterns and distributions of fluid velocity and wall shear rate in this region were carried out using a transparent segment of the carotid artery, prepared from a human subject postmortem, and cinemicrographic techniques.

It was found that a recirculation zone which consisted of a pair of complex spiral secondary flows, symmetrical about the common median plane of the bifurcation, was formed in the carotid sinus over wide ranges of inflow Reynolds numbers, $Re_0$, and flow rate ratios, $Q_i/Q_o$ (internal/common). The formation and the size of the recirculation zone were largely dependent on $Q_i/Q_o$, as well as on $Re_0$. The size of the recirculation zone increased from ~4 mm at $Re_0 = 300$ to a maximum of ~9 mm at $Re_0 > 800$. The results suggest that, under physiological conditions ($Re_0 \approx 600$, $Q_i/Q_o \approx 0.7$), a standing recirculation zone exists in the carotid sinus, thereby affecting local mass transfer and interactions of blood cells with the vessel wall, which may lead to the incidence of atherosclerosis and thrombosis in this region.

Stroke Vol 15, No 1, 1984
ious regions of disturbed flow in the mammalian circulation by directly observing and photographing the behavior of tracer particles and blood cells flowing through the isolated transparent blood vessels. The technique was first applied to venous valves to elucidate the mechanism of thrombus formation. The study has since been extended to the major arteries of the cardio- and cerebrovascular systems.

The present paper describes the detailed flow characteristics in the human carotid artery bifurcation. The study was motivated by the fact that one of the most frequent sites for the occurrence of cerebrovascular disease is the area of the carotid artery bifurcation where, because of the unusual geometrical structure, i.e., bulging of the internal carotid artery at the junction, flow is likely to be disturbed and eddies may form. In fact, formation of such eddies have been demonstrated in vitro using a glass model of the human carotid sinus. Flow separation, stasis and transient flow reversals in the carotid sinus have also been detected in vivo in human subjects. Thus, to gain further insight into this phenomenon, we have carried out in-depth studies of the flow patterns and distributions of fluid velocity and wall shear rate in the carotid artery bifurcation, using a transparent segment of an artery prepared from a human subject post-mortem.

**Methods**

A 10 cm long arterial segment containing the carotid bifurcation was obtained at autopsy from a 45 year old female within 24 hours of death from acute bronchopneumonia. After clearing the excess tissue, the artery was cannulated at the entrance (common carotid artery) and the two exits (internal and external carotid arteries). The remaining superior thyroid, lingual and facial arteries and other smaller side branches were ligated just downstream from their branching sites. The artery was then gently perfused with isotonic saline to wash out the blood and subsequently fixed by perfusing with a mixture of 2% glutaraldehyde and 4% formaldehyde in normal saline under a pressure of 80 mm Hg. Finally, the vessel and the surrounding tissues were fixed by immersion in a 2% formaldehyde solution and subsequently washed out with pure ethanol. The vessel was mounted on a glass plate and surrounded by a glass chamber. The assembly was then vertically positioned (with the inlet at the bottom) and the vessel was connected via plastic tubing to a head tank and two collecting reservoirs. Finally, the vessel and the surrounding chamber were filled with methyl salicylate (oil of wintergreen) under a transmural pressure of 80 mm Hg and the vessel became transparent.

The transparent vessel prepared by the present method lost its elasticity during the process of fixing and rendering it transparent, although the geometrical arrangement of the natural bifurcation was maintained. The advantage of this new method is that since the vessel walls are so well soaked in the suspending phase liquid (oil of wintergreen), they become transparent without any optical distortion. Thus, one can make observations and measurements of the flow from any direction without the errors arising from optical distortions (due to the difference in the refractive index between the vessel wall and the suspending liquid) which are inevitable when glass models and plastic casts are used.

Dilute suspensions of a mixture of 15, 32 and 200 μm diameter polystyrene microspheres (ρ = 1.06 g/cm³, Particle Information Services, Grants Pass, Oregon) in oil of wintergreen (ρ = 1.18 g/cm³, η = 0.030 g/cm sec) were subjected to steady flow through the vessel, and the motions of the tracer particles were observed through a microscope at nominal magnifications of 1× to 15× and simultaneously photographed on 16 mm cine films using a Locam 16 mm cine camera (Red Lake Labs., Santa Clare, CA) at film speeds from 50 to 500 pictures per second. Tungsten or mercury arc illumination was provided by a Reichert Binolux twin-lamp assembly.

The developed films (Kodak double X-negative) were projected onto a drafting table and the particle paths were analyzed frame by frame using a Vanguard Motion Analyzer (Vanguard Instrument Corp., Melville, N.Y.).

**Results**

(a) Anatomical Structure of the Bifurcation

It has been shown that the vessel diameter at the carotid artery bifurcation changes considerably with age. In their post-mortem studies, Peterson et al. reported that there was little change in the external carotid, but a substantial increase in the size of the common and internal carotid arteries. The cross-sectional area was found to double in the common carotid and increase more than three times in the internal carotid artery between the ages of 30 and 70 years. Such changes in vessel geometry will certainly affect the distribution of blood in the internal and external carotid arteries which, in turn, will result in the modification of the flow patterns at the bifurcation. Thus, first, it is necessary to describe the geometrical arrangement of the carotid bifurcation. In the present investigation, we attempted to obtain post-mortem arterial segments from relatively young subjects, thereby avoiding the abnormalities in their anatomical structure arising from pathological changes of the vessel walls through the development of atherosclerotic lesions.

Four transparent carotid artery bifurcations were prepared from post-mortem human subjects whose ages ranged from 23 to 45 years and in whom the major cause of death was neither a cerebro- nor cardiovascular episode. Atherosclerotic plaques were found in two vessels. They were localized on the lateral and outer walls of the internal carotid artery at the site of the carotid sinus, leaving the flow divider and the inner walls distal to it intact. The degree of dilation at the sinus was approximately the same for all four bifurcations, while the branching angles varied from ~ 30° to...
A series of flow experiments were carried out over a wide range of inflow Reynolds numbers, \( Re_0 = D_o U_0 \rho / \eta \) (\( \rho \) and \( \eta \) being the respective density and viscosity of the suspending phase liquid, and \( D_o \) and \( U_0 \) the respective vessel diameter and fluid mean velocity in the common carotid artery at 15 mm upstream from the flow divider), from 50 to 1200, while varying the flow rate ratio \( Q/Q_o \) (internal/common carotid).

To obtain a three-dimensional view of the flow through the bifurcation, observations were made along two different diametrical planes located at right angles to each other: the common median plane of the two daughter branches (internal and external carotid arteries) and the plane normal to it.

Figure 2 illustrates general flow patterns in the common median plane, obtained in the vessel shown in figure 1. As shown in the figure, a recirculation zone was formed in the internal carotid artery at the site of the carotid sinus. The formation and the size of the recirculation zone were largely dependent on the flow rate ratio \( Q/Q_o \) as well as on \( Re_0 \). The critical Reynolds number, \( Re_c \), for the formation of recirculation zones was measured by observing through a microscope the motion of the smallest (15 \( \mu \)m) diameter polystyrene microspheres located near the outer walls of the two daughter branches (internal and external carotid arteries). The results are shown as a plot of \( Re_c \) vs. \( Q/Q_o \) in figure 3. At the geometrical flow rate ratio (the flow rate ratio calculated by assuming that the flow into the two branches is distributed proportionally to their cross-sectional areas), \( Q/Q_o = 0.65 \) (indicated by the vertical broken dashed line in the figure), a recirculation zone was formed only in the internal carotid artery at \( Re_0 \sim 170 \), grew in size with increasing \( Re_0 \), but was always confined to the carotid sinus. In the external carotid artery, a recirculation zone was formed only when the external carotid artery was severely occluded (\( Q/Q_o > 0.8 \)). The size of the recirculation zone in the carotid sinus was also measured as a function of \( Re_0 \). Figure 4 shows a plot of the measured length of the recirculation zone, \( L_c \) (distance between the separation point, \( S \) and the stagnation point, \( R \)) vs. \( Re_0 \) with the flow rate ratio, \( Q/Q_o \), as a parameter. As evident from the figure, the size of the recirculation zone is largely dependent on the flow rate ratio in the two daughter branches. At the geometrical flow rate ratio (\( Q/Q_o = 0.65 \)), the recirculation zone was formed at \( Re_0 \sim 170 \), grew in size with increasing \( Re_0 \) and reached a maximum of approximately 9 mm at \( Re_0 \sim 800 \), then it decreased slightly as a strong counter-rotating double helicoidal flow developed just downstream from the stagnation point (indicated by the letter \( R \) in fig. 2 and 5).

(c) Detailed Flow Characteristics

To obtain further insight into the recirculation flow in the internal carotid artery, studies were focussed on the flow patterns in the carotid sinus. Figure 5 shows the detailed flow patterns (upper) and distributions of fluid velocity and wall shear rate (lower) in the common median plane of the bifurcation. Here, the veloc-
FLOW PATTERNS IN THE CAROTID BIFURCATION/Motomiya and Karino

**FIGURE 3.** Plot of the measured critical Reynolds number, $Re_c$, for the formation of recirculation zones in the internal and external carotid arteries at their junction region against the flow rate ratios $Q_1/Q_o$ and $Q_2/Q_o$. The vertical dashed line indicates the geometrical flow rate ratio for this bifurcation.

Velocity distributions at various axial locations were obtained by plotting the particle translational velocities (calculated from the tracings of the paths of the tracer particles located in or very close to the common median plane of the bifurcation) and taking the highest value at each radial distance from the vessel wall. Wall shear rates were determined from the slopes of the tangents drawn at the vessel wall on the best fit curves of magnified velocity profiles at various axial locations. As shown in figure 5 (upper), particles were deflected at the flow divider, and traveled laterally and very slowly along the vessel wall above and below the common median plane, almost at right angles to and encircling the mainstream. They then changed direction, moving backward along the outer wall of the internal carotid artery at the site of the sinus, then suddenly changed direction again and were entrained by the rapid mainstream in the common median plane.

**FIGURE 4.** Plot of the measured length, $L_s$ (the distance between the separation point, $S$, and the stagnation point, $R$) of the recirculation zone which forms in the carotid sinus in steady flow against the inflow Reynolds number, $Re_o$, with the flow rate ratio, $Q_1/Q_o$, as a parameter. Note that $L_s$ is largely dependent on $Q_1/Q_o$ as well as on $Re_o$.

Downstream from the stagnation point (indicated by R), a strong double helicoidal flow developed. When observed along the common median plane, it was found that the recirculation zone shown in figures 2 and 5 (upper) actually consisted of a pair of spiral secondary flows located symmetrically about the common median plane of the bifurcation.

The velocity profiles on the common median plane (figure 5 lower) were strongly skewed towards the inner walls of the bifurcation, thereby creating a high shear field along the vessel walls downstream from the flow divider where a stagnation point was located. In the carotid sinus, the wall shear rate was extremely low. However, due to the presence of the standing recirculation zone, the wall shear rate, and hence the wall shear stress, changes sign and becomes negative at the separation point (S), and then becomes positive again downstream from the stagnation point (R). Thus, in the carotid sinus, there are regions where the vessel wall is stretched (near the stagnation point, R) or compressed (near the separation point, S) by the counter-directed wall shear stresses.

**Discussion**

We have described the detailed flow patterns in an isolated, fixed, transparent human carotid artery bifurcation. The experiments were carried out in steady flow using a rigid-walled vessel. Thus, one may argue the applicability of the results to a real situation where...
the vessel wall is not rigid but elastic and the flow is not steady but pulsatile. In connection with this, Patel et al.21 in their study on the mechanical behavior of blood vessels, have shown that the change in cross-sectional area during the cardiac cycle for the human carotid artery is negligibly small (only ±1.0% of the mean value). Thus, we assumed that the elasticity of the vessel wall would not affect the general flow patterns in the bifurcation. With regard to the pulsatility of the flow, it has been shown in models of stenoses that in pulsatile flow, the size and intensity of the standing vortices formed distal to the stenoses vary periodically in phase with the change of the driving pressure.22 With the axial location of the vortex center and the reattachment point oscillating between maximum and minimum points about the mean which corresponded to the vortex in the absence of the oscillatory flow component. Judging from these previous results, we can expect that in pulsatile flow, the recirculation flows in the carotid sinus would behave in the similar fashion as the annular vortex described above. However, there is some possibility that the sharp pulsation, possibly with slight back flow, which occurs in vivo may facilitate shedding of the eddies (counter-rotating double helicoidal flows) formed downstream from the stagnation point. In this respect, the results presented here may require more careful interpretation.

Nevertheless, the use of the newly developed technique for making large vessels from animals and humans post-mortem transparent has, for the first time, enabled us to obtain the exact flow patterns and distributions of fluid velocity and shear rate existing in the human carotid artery bifurcation. The results demonstrated convincingly that the flow separation and formation of paired spiral secondary flows, previously observed in glass models of the carotid bifurcation11,16 do occur in the natural arteries as well. Of particular interest here was the finding that, in the carotid sinus, a large standing recirculation zone was formed at Re0 ≈ 170, which is well below the physiological value of Re0 ≈ 600.21,24 Thus, there is no doubt that there exists a standing recirculation zone in the human carotid sinus under normal physiological flow conditions. This may explain some of the phenomena clinically observed in vivo; such as the stagnation of the injected radio-opaque contrast media in the origin of the internal carotid artery12,17 and the transient reversals of flow in the carotid sinus.18,19

The significance of the present finding lies in the potential of the standing recirculation zone in the carotid sinus to act as a promoter of the vascular diseases, atherosclerosis and thrombosis, which tend to be localized in this region.

Though there has been little information on the precise location and distribution of thrombosis and atherosclerosis in the human carotid artery bifurcation, the existing data indicate that atherosclerotic lesions and thrombus formation do occur most frequently at the origin of the internal carotid artery where the carotid sinus is located. Further close examination of the area revealed that the incipient atheromatous plaques are localized on the lateral and outer walls of the internal carotid artery in the region of flow separation, flow reversal and low wall shear stress,10,13,23 strongly emphasizing the importance of the local flow patterns in the carotid sinus in atherogenesis.

In our previous investigation on the flow behavior and interactions of red cells and platelets in an annular vortex formed distal to sudden tubular expansions (serving as models of axisymmetric stenoses), it was demonstrated that the vortex provided favorable conditions for the genesis, growth and trapping of platelet aggregates.5,26 In the successive platelet adhesion experiments, where the effect of local flow patterns on the initial deposition of platelets onto the vessel wall was...
was investigated in detail, it was also shown that the adhesion of cells to the vessel wall was significantly enhanced in the region of disturbed flow. Both in steady and pulsatile flow, platelet adhesion was localized within the vortex and downstream on either side of the reattachment point with a local minimum at the reattachment point itself. The localization of cell adhesion became more pronounced as the hematocrit increased. The mechanism of this localization of platelet adhesion was explained as being due to the enhanced transport of platelets to the wall along the radially directed streamlines existing in the vicinity of the reattachment (stagnation) point as shown in figure 6. The significance of the above finding is that this same mechanism may apply not only to cellular elements but also to macromolecules such as plasma proteins and lipids including cholesterol. The effect will be further enhanced by the convective motion of red cells around the reattachment point. This will, in turn, result in an increased diffusion and convective transport of materials in the blood as well as across the endothelium, eventually leading to their accumulation in the vessel wall in the region of disturbed flow on either side of the reattachment (stagnation) point. It follows from this hypothesis that the deposition of platelet thrombi and early atherosclerotic lesions will be localized wherever there is a stagnation point (or a reattachment point if it is associated with flow separation) where blood cells are carried by the flow toward the vessel wall along curved streamlines having a pronounced radial velocity component.

The flow pattern in the carotid sinus resembles to some extent that of the annular vortex described above. Hence, if the above mechanism operates in the human carotid artery bifurcation, one would predict a relative-ly higher adhesion of platelets, hence higher risk of thrombus formation, and a higher incidence of athero-

References


Acknowledgments

The authors gratefully thank the late Dr. M.H. Finlayson for providing the human arteries post-mortem. C. Artigas and E. de Heuvel for their technical assistance, Drs. H. L. Goldsmith and C.A. Goresky for their encouragement and advice, and P. Lilley for typing the manuscript.
Cerebral Angiographic and Clinical Differences in Carotid System Transient Ischemic Attacks Between American Caucasian and Japanese Patients

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SUMMARY Cerebral angiographic findings of 32 Japanese patients with carotid system TIA's were compared with those of an equal number of age and sex matched American Caucasians. The end points included irregularity, ulceration, stenosis or occlusion of the carotid artery appropriate to the side of TIA. Atherosclerotic changes were found in 27 patients (84.4%) of the Japanese and 30 patients (93.7%) of the American patients. Mild lesions (49% stenosis and below) were similar in either frequency of topography between both groups; namely 25 intracranial and 17 extracranial lesions in Japanese as well as 29 intracranial and 10 extracranial in Caucasian patients. There was, however, an extra-intracranial difference in severe lesions (50% stenosis and above) between American Caucasian and Japanese patients; 10 of 12 severe lesions in Japanese were located intracranially, while 17 of 20 severe lesions present in the American group occurred in the extracranial portion of the internal or common carotid arteries.

CEREBRAL ANGIOGRAPHIC and pathologic studies have shown a difference in the atherosclerotic changes in stroke patients between Japanese and United States populations;1-2 Japanese patients have been shown to have more severe lesions intracranially, whereas American patients have more severe lesions extracranially. In patients with transient ischemic attacks (TIA), the cervical portion of the carotid artery has been the focus of etiological attention in Western nations. In Japan, however, the intracranial portion of the carotid artery or the stem of the middle cerebral artery have been found to be the likely site of severe arterial lesions in patients with TIA.3-5 Therefore this study compares the cerebral angiographic findings in Japanese patients with those of age and sex matched American Caucasian patients.

Material and Methods
The Japanese patient group consisted of 25 men and 7 women. All had carotid system TIA's that consisted of a focal neurologic deficit, ischemic in etiology, that cleared within 24 hours. Four of the patients were admitted to Kyushu University Hospital between 1964 and 1968, and 28 patients were admitted to Fukuoka University Hospital between 1969 and 1982. Each patient had cerebral angiography at the time of investigation of the TIA.

The American Caucasian group were selected from patients with carotid system TIA in the TIA Registry of the Cerebrovascular Research Center, Bowman Gray School of Medicine and who had been admitted to North Carolina Baptist Hospital, Winston-Salem,
Flow patterns in the human carotid artery bifurcation.

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Stroke. 1984;15:50-56
doi: 10.1161/01.STR.15.1.50

Stroke is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1984 American Heart Association, Inc. All rights reserved.
Print ISSN: 0039-2499. Online ISSN: 1524-4628

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