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Aneurysm Hemodynamics: An Experimental Study

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Purpose: To study the flow of blood in aneurysms. **Methods**: A canine model was used to study the hemodynamics of lateral, bifurcation, and terminal aneurysms with angiography and color Doppler techniques. *Findings*: Flow within experimental aneurysms, although not laminar, is seldom if ever turbulent, but rather is highly predictable, varying primarily according to the relationship of the aneurysm to its parent artery. **Conclusons**: These studies support earlier in vitro work and provide further evidence that not all aneurysms share similar stresses. A more complete understanding of these hemodynamic features will be useful in the establishment of criteria that allow recognition of those aneurysms that are more or less likely to rupture, to grow, or to thrombose.

Index terms: Aneurysm, hemodynamics; Interventional neuroradiology, experimental; Cerebral angiography

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The occurrence, growth, thrombosis, and rupture of intracranial saccular aneurysms can all be directly related to the effect of hemodynamic forces. Strong evidence favors the notion that aneurysms of this nature occur because of a hemodynamically induced degenerative vascular injury (1). Although less direct, the data associating the enlargement, thrombosis, and rupture of saccular aneurysms with the effects of hemodynamic forces is also convincing. In spite of extensive in vitro studies over the last decade, however, the exact mechanisms of the action of these stresses remain to be fully understood and, guidelines for determining the likelihood that a particular aneurysm will rupture, grow, or thrombose do not exist (2–4).

Ferguson, in a series of studies using glass models, direct phonocatheter recordings taken from the surface of both human intracranial arteries and aneurysms, and pressure measurements taken from within aneurysms during surgery, demonstrated the presence of increased hemodynamic stresses at arterial bifurcations (5, 6). These early studies also established the occurrence of non laminar flow within the lumen of saccular aneurysms. More recently, Perktold et al. used numerical calculations and computer simulations to predict flow fields and particle paths is an axisymmetrical aneurysm model (7, 8). These results indicated the presence of complex but consistent intra aneurysmal flow fields with the occurrence of varying shear stresses in different portions of an aneurysm.

Flow conditions, velocities, and hydrodynamic stresses have recently been evaluated using a laser-Doppler technique in both glass and silastic aneurysm models made to simulate the geometry of lateral, bifurcation, and terminal aneurysms (3, 4, 9). In these investigations, the geometrical relationship between an aneurysm and its parent artery was found to be the principal factor that determined the intraaneurysmal flow pattern. Flow instabilities representing intermediate stages between laminar flow and turbulence, ie, full chaotic motion, were observed in all three types of aneurysm geometries.

Clinical studies of aneurysm growth, rupture and thrombosis have given little attention to the importance of the geometrical relationship between an aneurysm and its parent vessel as a factor that determines the degree of stress induced by hemodynamic forces. Using a canine

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model, we have studied the flow characteristics of lateral, bifurcation, and terminal type aneurysms by standard angiography, selective angiography done by injection of contrast medium within the aneurysms, and color Doppler techniques.

Materials and Methods

Aneurysms were created in adult male mongrel dogs using modifications of a technique first described by German and Black and further developed and modified in our laboratory over the last 3 years (10, 11). All procedures were performed under sterile conditions and with general anesthesia. In all instances, aneurysms were constructed from a venous pouch made from a 2-cm segment of excised external jugular vein, one end of which had been closed with 7-0 proline suture. The aneurysm pouch was connected to the parent artery directly following creation of a 5-mm diameter arteriotomy with a circular Hancock vascular punch. Three types of aneurysms were constructed: 1) lateral, 2) bifurcation, and 3) terminal (Fig. 1).

Lateral aneurysms were constructed in the midcervical segment of a common carotid artery by attaching a venous pouch to the artery in an end to side anastomosis. Three lateral aneurysms were made in each of 7 dogs, two on one common carotid and one on the other.

Bifurcation aneurysms were constructed by first ligating the midsection of the left common carotid artery and then transferring the distal segment of the vessel beneath the trachea and anastomosing it end to side into the midportion of the right common carotid artery. A venous pouch was then incorporated into the junction of this anastomosis. A total of four bifurcation aneurysms were made.

Terminal aneurysms were made by first ligating and then dividing both common carotid arteries in their midcervical segment. The distal segment of the left common carotid artery was then transferred beneath the trachea and was anastomosed end to end with the distal segment of the right common carotid artery. To complete the construction, the proximal segment of the right common carotid artery was anastomosed end to side into the undersurface of the U formed by this linkage and a vein pouch was attached at the site of an arteriotomy made immediately above this anastomosis. Four aneurysms of this type were made.

Following completion of the surgical procedure, a baseline transfemoral angiogram was done to determine the patency of the aneurysm pouch. The animals were allowed to recover and were maintained in the Animal Care Facility of the University of Wisconsin for at least 2 weeks prior to further study. The long-term patency rate in these aneurysms was high, with only three of the 21 lateral aneurysms showing any evidence of spontaneous thrombosis.

Angiographic studies were obtained following both the power injection of 8 mL of contrast medium through a 4-F single-end hole catheter placed 5–8 cm below the level of the aneurysm and by the hand injection of 2 mL of contrast medium through a variable stiffness 2.2-F single-end hole catheter (Tracker-18; Target Therapeutics, San Jose, CA) placed directly into the aneurysm lumen. Both tape recordings of video fluoroscopy and film screen angiograms were used for angiographic analysis.

Duplex color Doppler examinations were carried out using an Acuson 128 computed sonography system (Acuson Corporation, Mountain View, CA) with a 7-MHz linear array transducer. The technical factors were set in each case to maximize the direction of flow (red toward the transducer and blue away from the transducer) and also to display velocity. In every case, color flow examinations were recorded with static color images. Pulsed Doppler waveform information was analyzed from both videotape and hard-copy images.

Results

Lateral Aneurysms

When contrast medium was injected into a parent artery proximal to a lateral aneurysm, the

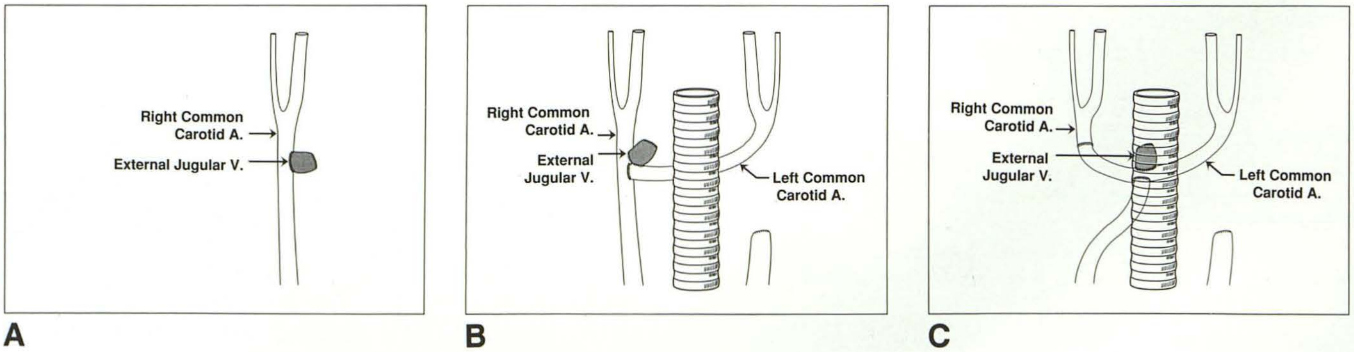


Fig. 1. Diagrams of three types of aneurysms studied. *A*, lateral; *B*, bifurcation; *C*, terminal.

inflow into the aneurysm occurred at the distal extent of the aneurysm ostium. Opacification of the lumen then proceeded in a cranial-to-caudal fashion and the outflow developed at the proximal extent of the ostium. In every instance, a central vortex opacified and cleared slowly. Stagnation of contrast medium within the lumen of these aneurysms was pronounced, with contrast medium remaining with the aneurysm sac for as long as several minutes after the injection. These angiographic characteristics were noted in both single and tandem lateral aneurysms. Although they were most easily observed by reviewing injections recorded on videotape, they could also, however, clearly be seen on examinations done with standard film screen techniques (Fig. 2).

The color Doppler examinations of all lateral aneurysms demonstrated a similar pattern of inflow, central vortex, and outflow. In addition, the color Doppler images revealed the inflow circulation zone to be comprised of at least two components with a central higher velocity region being encompassed in an area of lower velocity (Fig. 3). Disturbed laminar flow was also noted within a segment of the parent artery adjacent to and just beneath the aneurysm ostium. There was no difference noted between the color Doppler findings of tandem lateral aneurysms as compared to those of single lateral aneurysms.

Bifurcation and Terminal Aneurysms

The angiographic analysis of the flow characteristics of the bifurcation and terminal type aneurysms yielded similar findings. When contrast medium was injected into the parent artery at a point well proximal to one of these types of aneurysms, it was impossible to identify a distinct inflow or outflow circulation. Unlike the lateral aneurysms, the circulation inside the bifurcation and terminal aneurysms was rapid and there was never any angiographic evidence of vortex formation or stasis.

When contrast medium was injected directly into one of these types of aneurysms, the outflow from the aneurysm was always seen to pass entirely into one of the two "branches." This feature was noted regardless of where the contrast medium was injected within the aneurysm lumen and it also appeared to be independent of the speed of injection (Fig. 4). As measured from the angiographic studies, there was 1 mm or less difference in the diameter of the arterial "branches" related to all of these aneurysms. Our technique did not allow accurate determination of the angle between either an aneurysm and its parent artery, ie, the stem, or of the angles between an aneurysm and its "branches."

There was not in any instance a consistent difference in the color Doppler findings of the bifurcation aneurysms as compared to those of the terminal aneurysms. Without exception, however, both of these two types of aneurysms had color Doppler features that were distinctly different from those of the lateral aneurysms.

In all of the bifurcation aneurysms, the color Doppler examinations revealed that the inflow occurred at the edge of the ostium closest to the long axis of the parent artery, ie, stem, while outflow occurred through the opposite corner of the ostium. The Doppler studies, like the angiographic studies made following selective injections of contrast medium into the aneurysms, also showed that the outflow occurred exclusively into one of the two "branches" associated with the aneurysm. This was always into the branch opposite to the side of the ostium through which the inflow occurred. Rapid flow was always present in these aneurysms (Fig. 5). Within the lumen, flow was rotatory in the direction of the outflow branch.

In the terminal aneurysms, the inflow occurred at the side of the ostium that was closest to a straight line drawn through the center of the parent artery, ie, stem. Outflow was at the other extreme of the ostium and was seen to pass exclusively into the "branch" nearest to the outflow portion of the ostium. Like the bifurcation aneurysms, flow within these aneurysms was also rapid and rotatory (Fig. 6).

Discussion

Over the last two decades, there has been considerable in vitro investigation and computer simulation/mathematical modeling of the hemodynamic features of saccular aneurysms. There has been, however, little in vivo inquiry into these phenomena. Although our canine aneurysm model and laboratory techniques do not allow quantitative analysis of flow characteristics, velocities, or vascular stresses, the phenomena observed in our studies do contribute information that correlates with the more quantitative studies.

The flow characteristics of the various geometrical types of saccular aneurysms, as well as the altered hemodynamics present within various regions of a particular aneurysm and its parent

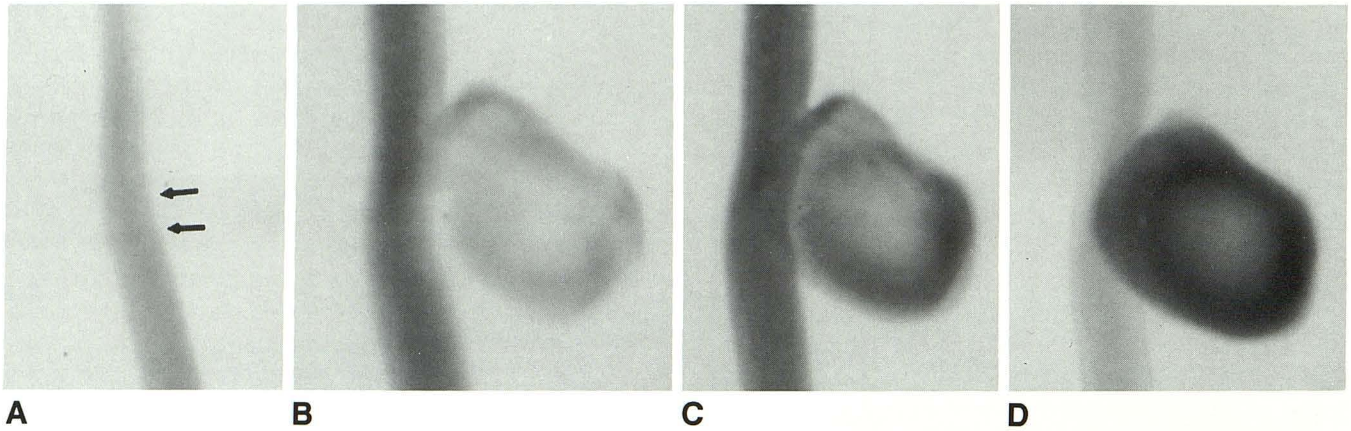


Fig. 2. Angiographic study of lateral aneurysm done following contrast injection into parent artery.

A, Early film just before opacification of the aneurysm begins. Note slight deflection of contrast column along ostium of the aneurysm (arrows).

B, Subsequent film showing inflow of contrast medium into the aneurysm with opacification of the lumen in a cranial to caudal fashion.

C, Slightly later, the entire lumen is opacified.

D, Late film showing the central vortex and stagnation characteristic of this type of aneurysm.

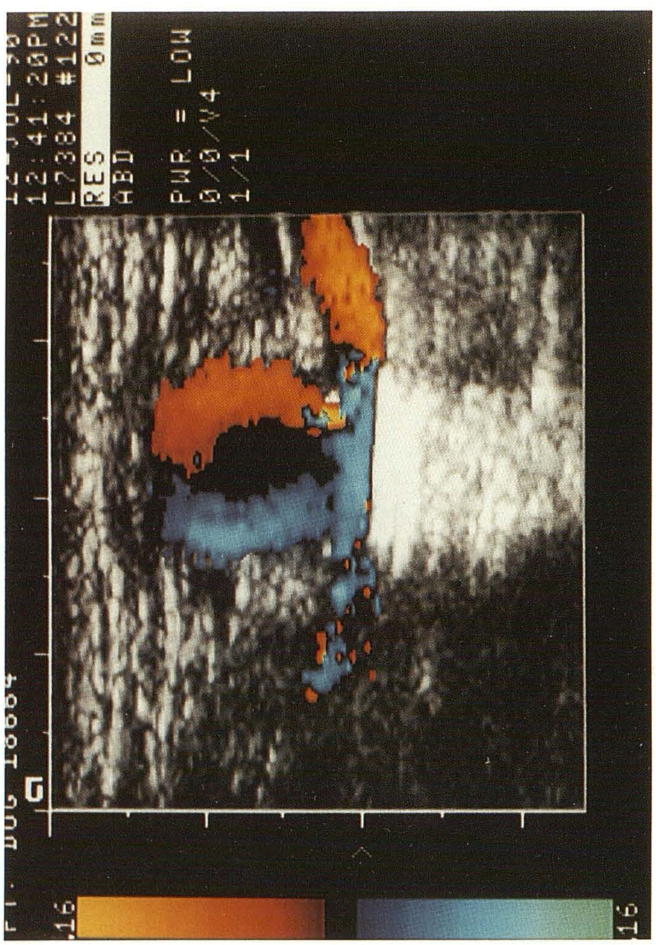


Fig. 3. Color Doppler examination of lateral aneurysm showing the inflow, outflow, central vortex, and zone of high-velocity flow in the inflow circulation.

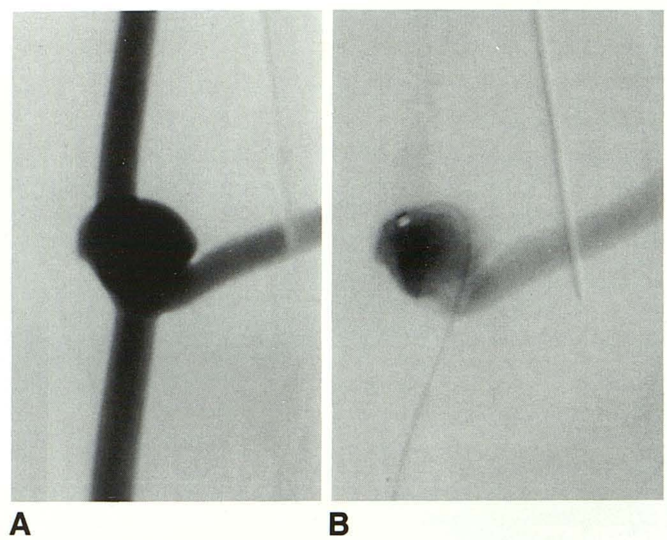
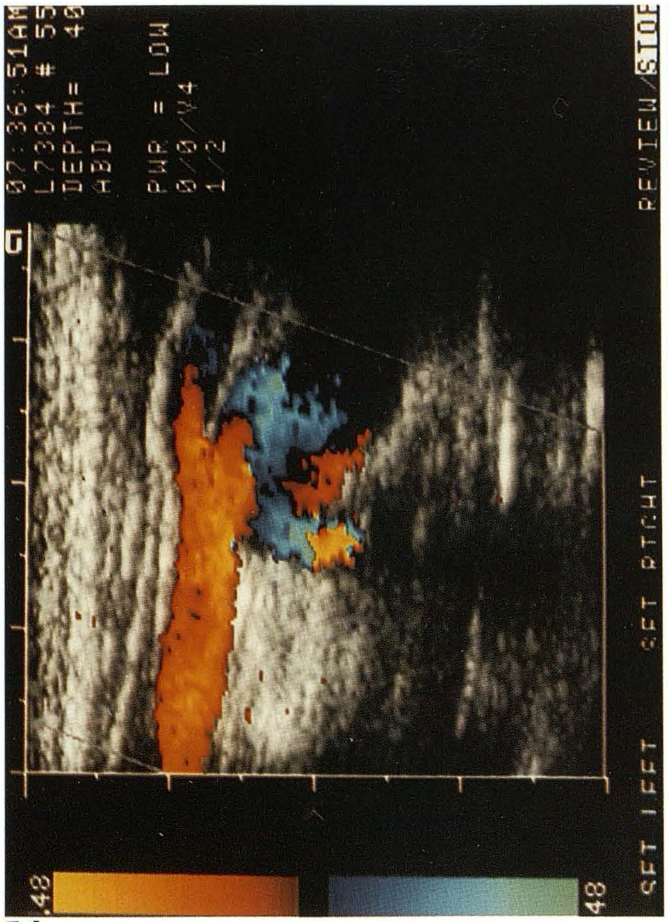


Fig. 4. *A*, Angiogram of bifurcation aneurysm done following injection of the contrast medium into the parent artery, ie, stem. The flow within this aneurysm is rapid and no differences in opacification of the "branches" related to it could be recognized.

B, Angiogram of same aneurysm made after hand injection of contrast into the aneurysm. The outflow of contrast medium from the aneurysm appears to be exclusively into one of the two "branches."

artery and branches, are of importance to those applying endovascular techniques for the treatment of patients with these lesions. Decisions such as the type and configuration of catheter that may most easily be used for aneurysm catheterization, the location within an aneurysm where a particular endovascular device is likely to be most stable, and the size and type of device



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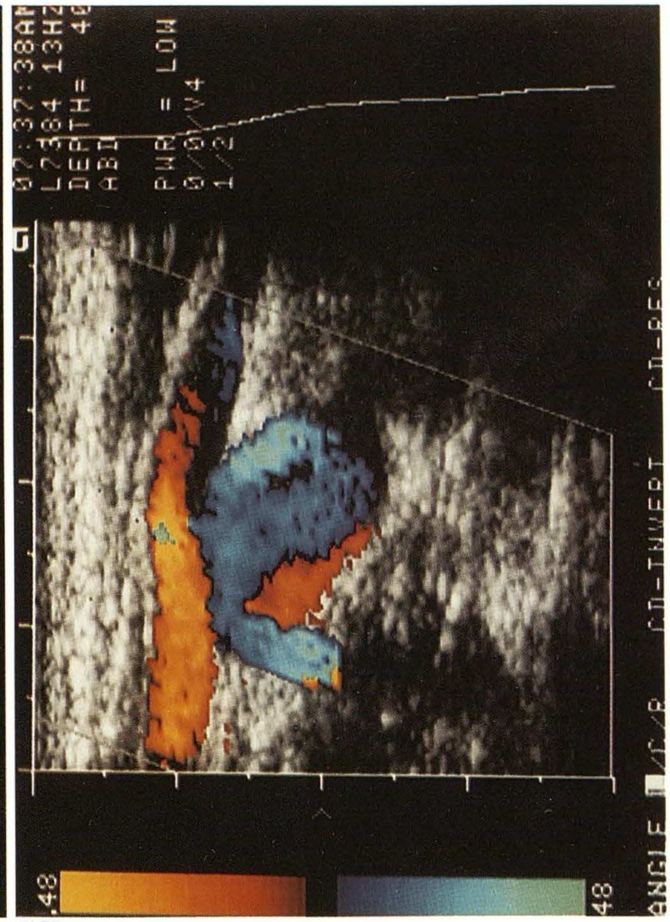

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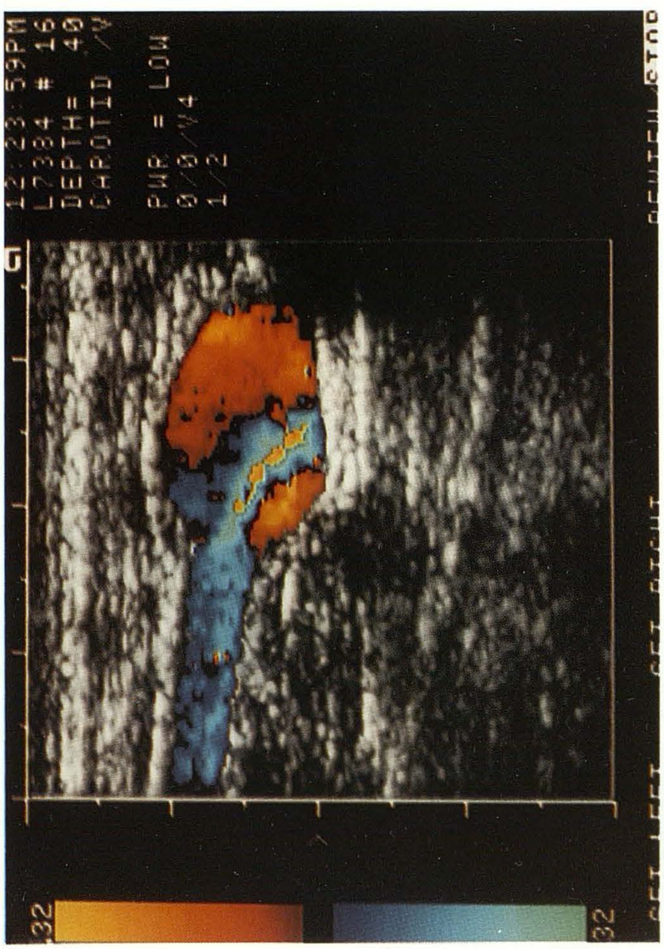

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Fig. 5. Color Doppler examination of bifurcation aneurysm.

A, Inflow is seen in the portion of the ostium nearest the long axis of the parent artery, ie, stem.

B, Image from a slightly different plane shows the outflow passing through the opposite portion of the ostium and exclusively into one of the two branches. These images also illustrate the rotatory flow present in bifurcation aneurysms.

Fig. 6. Color Doppler examination of terminal aneurysm. Image is in plane of the parent artery, ie, stem, and long axis of the aneurysm. Note the high-velocity zone within the inflow circulation.

which can best be used for treatment can all be logically based on an understanding of these hemodynamic features (12).

As discussed below, the observations from our study also provide some possible additional insight into the mechanisms involved in the growth, rupture, and thrombosis of saccular aneurysms.

Importance of Hemodynamic Factors in Determining Growth of Saccular Aneurysms

A prominent angiographic characteristic of all of the lateral aneurysms in our study was stasis of contrast medium within the aneurysm sac. This is not a new observation, the phenomenon first having been described by German and Black in 1954 (13). Stagnant flow has also been reported in in vitro flow experiments as well as in computer simulation/mathematical models of flow in lateral aneurysms, as well as in one type of terminal aneurysm, ie, the aneurysm fundus is in the plane of the stem of the parent artery and there is balanced outflow into the efferent vessels (3, 4, 7, 8). Stasis is also a commonly observed feature in angiographic studies of many large and giant intracranial aneurysms in humans.

The common analogy of an aneurysm to a weak spot in an inner tube that will necessarily rupture when the strength of its thinning wall can no longer contain the tension upon it is not accurate, since the wall of an aneurysm is alive and can, under certain conditions, reinforce itself. Enlargement of an aneurysm does not thus necessarily imply thinning of its wall (14).

Large and giant aneurysms most commonly involve the internal carotid artery (59%) or the tip of the basilar artery (16%) (15). Aneurysms of the cavernous and supraclinoid segments of the internal carotid artery are the geometric equivalent of the lateral aneurysm used in our canine experiments. Large and giant basilar tip aneurysms in our experience most often occur when there is a close symmetry in size between the two proximal segments of the posterior cerebral arteries and a near perpendicular orientation of the aneurysm sac to its parent artery, ie, stem. As already discussed, it is in these two geometrical types of aneurysms that in vitro studies have shown that stasis is prominent and flow is sluggish (3, 4).

Stagnation of blood flow is known to result in the accumulation of both platelets and leukocytes along intimal surfaces, as well as in an impairment of the diffusion of oxygen and metabolites from blood to the vascular wall. Either together or separately, these two factors may operate to cause intimal damage and thus lead to both thrombus formation and wall thickening (16, 17). Both of these events, ie, thrombus formation and wall thickening, have been proposed as factors important in the growth of an aneurysm (18).

We have found it impossible to duplicate the terminal aneurysm geometry associated with stasis in our canine model, since in all of our terminal aneurysms there was significant angulation between the aneurysm sac and its parent artery, ie, stem. Terminal aneurysms of this geometry are characterized in vitro by the absence of stasis (3).

One possible explanation, which to our knowledge has not been previously proposed, for the predilection of large and giant aneurysms to involve the internal carotid artery and the tip of the basilar artery may be, therefore, simply that these sites favor a geometrical configuration between the parent artery and aneurysm that results in the presence of hemodynamic conditions favoring stagnation of flow within the aneurysm from its inception. This stagnation then results in an environment that promotes thickening and reinforcement of the aneurysm wall and thereby favors overall growth of the aneurysm over its rupture. Again, such conditions appear most likely to occur either in aneurysms with lateral configurations or in terminal type aneurysms that have balanced branches and a near perpendicular orientation of the aneurysm sac to the parent artery.

Importance of Hemodynamic Factors in Determining Rupture of Saccular Aneurysms

The concept of turbulent flow within the lumen of saccular intracranial aneurysms dates from the work of Ferguson (19) in 1972, prior to the establishment of the current notion of turbulence as representing a state of fully random motion. Simkins and Stehbens, and later Steiger and Reulen, have provided strong in vivo and in vitro evidence for the presence of intraaneurysmal flow patterns that are not turbulent but that rather represent intermediate stages between laminar flow and turbulence (9, 20). Our studies of flow in aneurysms of various geometries further documents that the circulation within aneurysms is regular and is predictable primarily according to the geometrical relationship between the aneurysm and its parent artery and branches.

Steiger has also shown in a variety of aneurysm geometries that the maximum shear stresses and velocity gradients are not found at the dome of an aneurysm but rather near the aneurysm neck (3). Fluctuations in flow are known to induce added mechanical stress, vibrations, and perhaps even resonance, all of which may contribute to aneurysm rupture (3, 9, 19). Our Doppler studies, while not quantitative, also clearly demonstrate in lateral, bifurcation, and terminal aneurysms a zone of unstable high-velocity flow at the region of the aneurysm ostium where inflow occurs. It thus appears that in some instances greater hemodynamic, ie, mechanical, stress is transmitted to the tissue at an aneurysm's ostium than to that at its dome. The significance of this requires additional investigation.

Currently, the main criteria used to judge the risk of a particular aneurysm rupturing is its size. The increasing availability and usefulness of transcranial Doppler techniques, magnetic resonance angiography, and quantitative/dynamic techniques of digital subtraction angiography make it evident that it will soon be possible to determine, with little risk, the hemodynamic characteristics of intracranial aneurysms in a manner greatly superior to that which has been previously possible. Such data combined with an understanding of the stresses and strains associated with altered hemodynamics should allow a much more rational decision to be made about the chance of growth, rupture, or thrombosis of any particular aneurysm.

In conclusion, although our studies are qualitative, they provide new in vivo observations that support the pioneering work of German and Black, Ferguson, Stehbens, Steiger, Liepsch, and their colleagues. Flow within these experimental aneurysms, although not laminar, is seldom if ever turbulent, but rather is highly predictable, varying primarily according to the relationship of an aneurysm to its parent artery. A more complete understanding of these hemodynamic factors may be useful in establishment of criteria that allow recognition of those aneurysms that are more or less likely to rupture, grow, or thrombose. Such an understanding will also help in optimizing future attempts at the endovascular treatment of saccular intracranial aneurysms.

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