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AJNR Am J Neuroradiol 1983, 4 (3) 374-377
http://www.ajnr.org/content/4/3/374

Flow in Experimental Berry Aneurysms: Method and Model

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This study addresses two basic questions: What are the flow dynamics in aneurysms? Can these flows be modified to enhance retention of adhesive? Using Pyrex glass bifurcations, fluid flow was studied in a variety of aneurysms placed at varying positions around the bifurcations. Indicators injected into the slipstreams were recorded and studied both by stop-frame high-speed movie analysis and with 35 mm slides. Even at low-flow rates, a central slipstream strikes the apex of bifurcations, and may be partly responsible for the initial production of berry aneurysms. A low-pressure zone occurs at the lateral angle of bifurcations, probably explaining the formation of endovascular cushions. Flow into symmetrically placed narrow neck aneurysms did not occur. Indicator entered the aneurysm in a turbulent fashion only when there was orifice (lip) asymmetry. Both lip asymmetry and rapid flow favor intraaneurysmal turbulent flow.

Advances in the microneurosurgery of aneurysms and safer neuroanesthesia should have improved the chances and quality of survival in patients who have ruptured aneurysm. The facts are otherwise. Of the nearly 30,000 aneurysms that rupture each year in the United States and Canada, fewer than 5,000 patients are cured [1]. The Rochester group [2] surveyed three decades of results (1945–1975) and showed no significant reduction in morbidity after aneurysm rupture. Of 100 patients in that community, only 42 survived the initial hemorrhage to the end of the first month; at 6 months only 39 of the original 100 were in good neurologic condition. Other studies suggest similar outcomes [3–6]. Apparently, the good surgical results come by allowing patients to die, leaving a group that can tolerate the surgical manipulation. We wonder what would happen if percutaneous techniques of aneurysm obliteration were available. Would we then be able to take critically ill patients, occlude the aneurysm during the diagnostic angiogram, prevent the feared rebleeding, then improve cerebral perfusion to combat the effects of spasm?

Before attempting percutaneous treatment in humans, though, it seems worthwhile to identify flow patterns within human intracranial aneurysms. With this knowledge, one might better plan an approach, develop a methodology to allow aneurysm entry, and identify factors that would enhance deposition and retention of some occluding agent within the aneurysm sac.

Background Principles

In the human circulation, nutrients move by bulk flow, and it is necessary to understand rudimentary principles of flow dynamics in tubes. Poiseuille, a French physician, related the variables: *flow = pressure change* $\times \pi/8 \times$ *1/viscosity* $\times$ *radius*^{4}*/length*. Thus, flow will increase linearly if pressure increases and decrease if the viscosity of the fluid or the length of the tubing increases. Of most importance is the radius, as it is a fourth-power function. Doubling the radius increases flow 16 times.

Reynolds related the variables in a different fashion: *Re = density* $\times$ *velocity* $\times$ *tube diameter/viscosity*. The result is a dimensionless number that, if kept constant, allows one experimenter to compare his results with a different system from another laboratory. Beyond a certain Reynolds number (Re), turbulent flows occur. Nonturbulent, or laminar, flow is the normal state in most human arteries. Laminar intraarterial flow is best thought of as a series of concentric thin sleeves of material, with little flow at the artery wall (the boundary layer), and faster and faster flow as one approaches the center. Cutting the artery lengthwise shows the flow vectors to have a parabolic shape (fig. 1A). Curved tubes (as all arteries are) skew the parabola to the outside of the curve (fig. 1B).

Two types of flow disturbances may occur. An eccentric web or plaque generally forms downstream vortices (eddy shedding) (fig. 1C). Eddy shedding produces a high-pitched single-tone musical murmur. Increasing the Reynolds number beyond a certain point or creating a rough constriction in the stream yields real turbulance (random chaotic movement) (fig. 1D). Hydrodynamic theory states that no flow occurs with turbulence, but in the body movement does occur because of downstream runoff.

Materials and Methods

As it is difficult to see through blood and arteries of the size we must study, an optically clear system was made. Glass bifurcations were constructed of varying size and with varying bifurcation angles. Spherical aneurysms were placed at varying points around the bifurcation. Fluid flowing at varying velocities was passed through the system and indicators, either isobaric dyes or neutral-density spheres, were injected into the flowing fluid. The path and behavior of the indicators were recorded on high-speed 16 mm movie film and 35 mm frame film. Pattern analysis was done both by analog and by stop-frame movie analysis. A perfusion apparatus modified from Stehbens [8] was used, which consisted of a constant pressure reservoir with the pressure level kept constant by an overflow. This reservoir was connected by Tygon tubing to the glass model. The outflow passed through stopcocks and was pumped back into the overhead reservoir. Graduated cylinders placed under the stopcocks measured flow. All bifurcations were placed horizontally to avoid gravity effects. A 26 gauge needle used to inject the materials caused no appreciable flow disturbance.

Results

Figure 2 shows one model as seen from above. Direction of flow is indicated by the arrow. The flowing fluid in a more lateral slip-

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AJNR 4:374–377, May/June 1983 0195-6108/83/0403-0374 $00.00

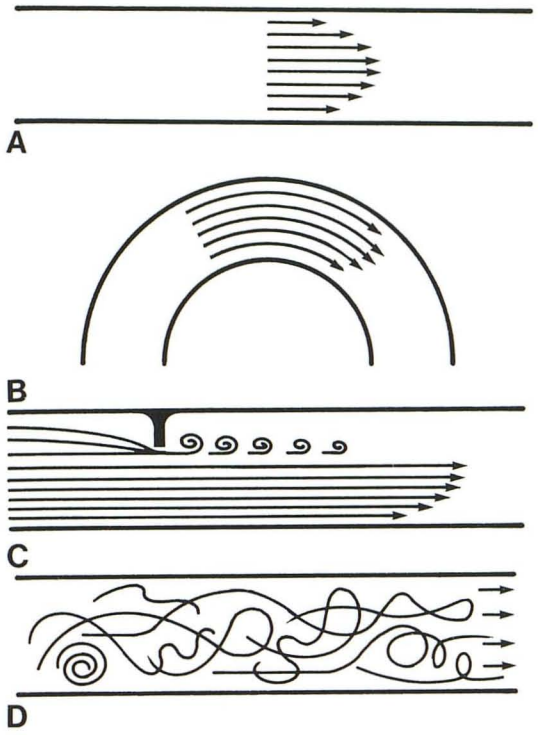

Fig. 1.—**A**, Longitudinal section through central plane of tube. Nonturbulent (laminar) flow from left to right. Velocity vectors form parabola, with most rapid flow in central slipstream, and almost no flow along wall (boundary layer). **B**, Modified laminar. Curved tubes (as all arteries are) skew parabola. **C**, Vortex formation (eddy shedding) beyond partial obstruction. Eddies gradually cease, dampened by viscous forces in fluid. **D**, Turbulence occurs when flow velocity exceeds critical number. Motion is random, chaotic, and antithesis of laminar flow. (Adapted from [3].)

stream passes gently into the side arm of the bifurcation. As it passes beyond the right lateral angle it moves away from the wall, and the boundary layer widens.

Figure 3 demonstrates injection of indicator into the most central (fastest flowing) lamina. Note how the fluid strikes the apex of the bifurcation.

Figure 4 shows an aneurysm constructed at the apex of the bifurcation. The lips or entry area into the aneurysm are symmetrical, and the opening is small (about one-half aneurysm diameter). The central slipstream impinges on the centrum of the orifice but, surprisingly, does not enter the aneurysm. Even with turbulent flow, no entry occurs. The indicator rebounds from this stagnant area as though no aneurysm were present and then passes distally down one of the limbs.

Figure 5 shows an aneurysm constructed at the bifurcation but with its location not exactly at the center of the apex of the bifurcation. Its lips are thus asymmetric. The indicator entered this model with ease. Increasing the Reynolds number just to the point of turbulence caused turbulent flow in the aneurysm.

Discussion

The physical factors influencing blood flow have received scant attention until recently. In 1960 McDonald's book, *Blood Flow in Arteries* [9], ushered in a period of rapid growth of knowledge. In 1972, *Cardiovascular Fluid Dynamics* [10] summarized and updated the knowledge to that point. Since then, the number of rheologic studies has increased exponentially.

Studying flow in biophysical models outside the body is risky, as not only is bifurcation geometry important, but vessel tethering modifies fluid behavior too. Roach [11] stated that, in general, "The models used to date seemed to have produced less useful information than one might expect . . . probably because of a lack of some biological data with which to test them." Now, there is a

Fig. 2.—Glass bifurcation model, viewed from above. Flow direction (*arrow*). Left lateral angle (**L**) = 45°; right lateral angle (*arrowheads*) = 90°. Indicator placed in nearly central slipstream enters downstream limb, but attempts to continue in straight line. Boundary layer widens markedly (cf. fig. 5A). Slipstreams swirl gently, then straighten again in a few tube diameters. A = apex.

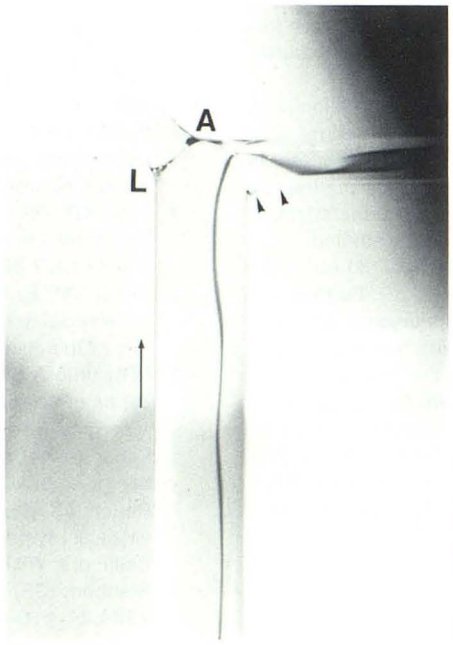

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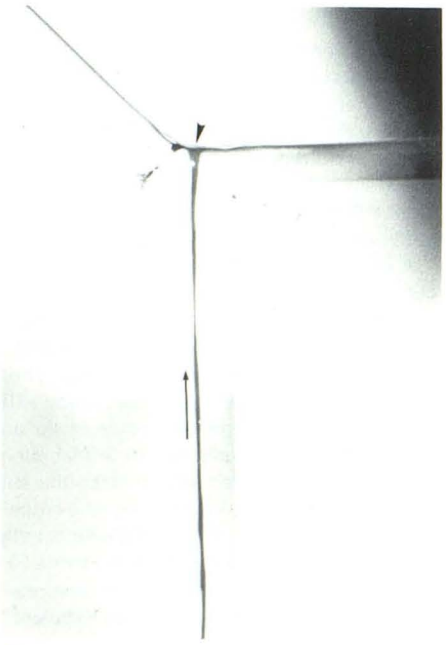
Fig. 3.—Indicator injected into central slipstream vigorously strikes apex (*arrowhead*). At higher flow rates, it rebounds, swirling gently, then enters limbs. Direction of flow (*arrow*).



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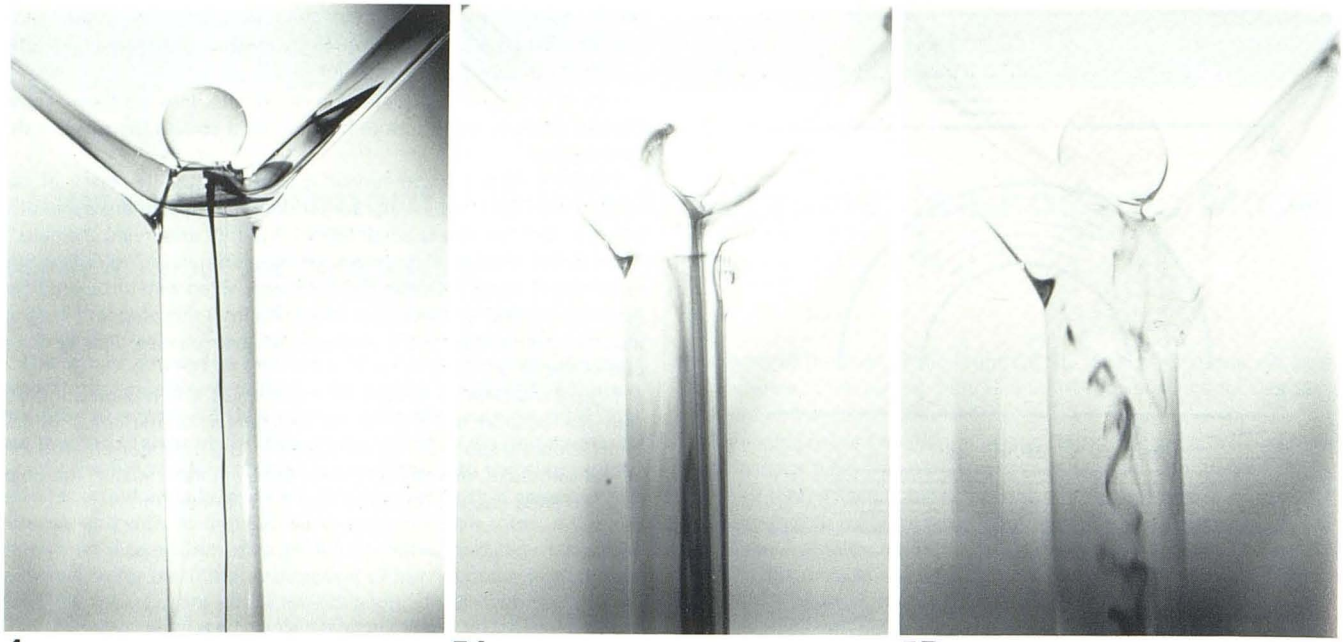

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Fig. 4.—Aneurysm model placed symmetrically at apex of 90° bifurcation. Indicator in central slipstream surprisingly fails to enter aneurysm, and rebounds, swirls, then passes into limbs. Orifice size is one-half aneurysm diameter.

Fig. 5.—Aneurysm placed asymmetrically into apex of 90° bifurcation. Even at low flow, indicator enters dome. **B**, Increasing flow rate to point of turbulence causes indicator to enter aneurysm in turbulent fashion.

general agreement that the quality of blood flow at bifurcations produces disease such as atherosclerosis and aneurysms, and many have studied this critical site both with mechanical [12–16] and mathematical [17, 18] models to elucidate the pathologic physiology there.

Figure 2 shows the flow changes encountered at the lateral angles of a 90° bifurcation. Note how the boundary layer widens as the slipstream tries to continue in a straight line. The reattachment point downstream becomes more distal as the Reynolds number increases. This widening is thought to be responsible for the formation of endovascular cushions [15, 19, 20], which are widely regarded as precursors of atheromatous disease.

As aneurysms invariably occur at the apex of a bifurcation [21], the visualization of the forceful impingement of the central slipstream there (fig. 3) leads one to postulate that this force vector is important in the initiation and growth of human saccular aneurysms. What influence the force will have on both the initial catheterization of the sac and on occluding agent retention must be studied.

It was surprising to us that this central slipstream did not enter our aneurysm (fig. 4) as it has in other models [22]. Further, we were disturbed by the laminar flow in our aneurysms, because Ferguson [23, 24] has directly measured turbulence in human intracranial aneurysms during surgery. Thus, our model must be invalid. Further analysis (and discussion with M. Roach, personal communication) suggested orifice or lip asymmetry, as well as orifice size in the production of intraaneurysmal turbulence. She and coworkers had already stressed the importance of the bifurcation geometry [22]. We then made a model with asymmetric lips, that is, the aneurysm did not originate exactly from the apex of the bifurcation (fig. 5). Then, even at moderate Reynolds number (about 250), but especially with turbulent flow, the indicator entered the aneurysm, and flow in the sac was turbulent.

In summary, nondistensible models are of some value as they allow development and refinement of methodology and may also yield some data about basic flow patterns. The geometry of bifurcations is so complex though, and the stakes are so high, that we must not be satisfied with anything less than direct castings of the circle of Willis and viscoelastic production from those castings. Only then will we approximate the conditions found in life.

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