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AJNR Am J Neuroradiol 1992, 13 (1) 189-196
http://www.ajnr.org/content/13/1/189

This information is current as of April 16, 2024.

Flow Dynamics of Lateral Carotid Artery Aneurysms and Their Effects on Coils and Balloons: An Experimental Study in Dogs

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Purpose: To investigate the hemodynamic characteristics of lateral carotid artery aneurysms in a canine model and to determine their influence on coils and balloons. **Materials and Methods:** Forty aneurysms were created in fourteen dogs and their hemodynamic characteristics and influence on coils and balloons were evaluated with angiography and color Doppler pre- and postplacement. Twenty aneurysms were treated with coils, eight with balloons, and 12 aneurysms served as controls. **Results:** The aneurysms demonstrated three distinct zones of flow: 1) an inflow zone entering at the distal aspect of the aneurysm ostium, 2) an outflow zone exiting at the proximal ostium, and 3) a central slow flow vortex. The inflow zone is a determining factor in the placement and stability of coils and balloons placed within the aneurysm and in the thrombosis of an aneurysm. The force of the inflow is considerable and can alter the shape of coils and displace both coils and balloons positioned within the aneurysm. **Conclusions:** Coils and balloons need to be of shapes and sizes that do not conform to the inflow and outflow zones. Filling the aneurysm and blocking or displacing the inflow zone can produce thrombosis of an aneurysm with preservation of the parent artery.

Index terms: Arteries, carotid; Interventional neuroradiology, experimental; Aneurysm, intracranial

AJNR 13:189–196, January/February, 1992

There is great interest and need for developing techniques for the endovascular treatment of aneurysms. In North America, the endovascular treatment of intracranial aneurysms with techniques allowing parent artery preservation has been used with only limited success in a selected group of patients with surgically unclippable intracranial aneurysms. Higashida et al. (1) have reported the treatment of 215 intracranial aneurysms with detachable balloons. In 127 aneurysms (59%), the parent artery was occluded and in 88 aneurysms (41%) the aneurysm was occluded with preservation of the parent artery. In the group treated by parent artery occlusion, complications included five deaths (3.9%), seven strokes (5.5%), and 10 transient ischemic events (7.9%). In the group treated with primary aneurysm occlusion and preservation of the parent artery, there were 16 deaths (18.2%) and nine strokes (10.2%). In the group treated by parent artery occlusion, only one aneurysm (0.8%) failed to undergo complete thrombosis whereas 22 aneurysms (25%) in the group treated with preservation of the parent artery failed to undergo complete thrombosis (1). Fox et al. (2), in a report of 65 patients with intracranial aneurysms treated by balloon occlusion of the parent artery, achieved complete thrombosis in 78% of the aneurysm, with 0% mortality and a 1.5% permanent morbidity. These studies illustrate both the risk and the limitations of currently available endovascular techniques as a method for the treatment of intracranial aneurysms.

There are many factors that influence the end result in the endovascular treatment of aneurysms. Hemodynamics, the anatomical relationship of an aneurysm to its parent artery, and the presence and extent of thrombus in an aneurysm all operate to influence the outcome of attempts at endovascular aneurysm obliteration.

We have previously reported our experience using coils for the treatment of surgically created lateral carotid artery aneurysms in a canine model (3). This model, a modification of one first de-

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Received June 4, 1991; accepted August 25 (no revision necessary).

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AJNR 13:189–196, Jan/Feb 1992 0195-6108/92/1301-0189

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scribed by German and Black (4) is reproducible and, in our experience, has a very low incidence of spontaneous thrombosis (<10%) (3, 4). The aneurysms have wide ostia (5 mm) without necks and are uniform in size with a diameter of about 8 mm (Fig. 1). The hemodynamic characteristics of these lateral aneurysms have been evaluated with both angiography and color Doppler. The hemodynamic characteristics observed were identical in all of the aneurysms and closely resembled those observed in a clinical series of lateral internal carotid artery aneurysms referred for endovascular treatment (5). They are also similar to those reported by others using mechanical, mathematical, and computer models of lateral aneurysms (6–10). The influence of these hemodynamic factors on the position and stability of endovascularly placed coils and balloons, as well as the effect of altered flow patterns caused by these devices on thrombosis of the aneurysms, have not been previously discussed. Our study reports our investigation of these phenomena using angiography and color Doppler.

Fig. 1. Control aneurysm, 30 days postconstruction, 10-μm thick sections with hemotoxylin and eosin stain, wide ostium (*arrows*); thrombus (*T*) in dome.

Materials and Methods

Forty lateral carotid artery aneurysms were constructed in 14 mongrel dogs under a protocol approved by the University of Wisconsin Animal Care Committee. The surgical technique and natural history of this canine lateral carotid artery aneurysm model have been previously reported (3).

The flow characteristics of these aneurysms were evaluated with angiography and color Doppler both before and after endovascular treatment. Seven dogs had two aneurysms on the right and one aneurysm on the left, three dogs had two aneurysms bilaterally, three dogs had single aneurysms bilaterally, and one dog had a single aneurysm. All 40 aneurysms were evaluated both pre- and posttreatment by angiography and 21 aneurysms were evaluated both pre- and posttreatment by color Doppler using an Acuson 128 computed sonography system (Acuson Corporation, Mountainview, 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).

Platinum coils (0.014–0.015 outside diameter; 4–10 cm length) with simple and complex curves without fibers and complex curves with silk fibers were used to treat 20 aneurysms (six with nonfibered coils, 14 with fibered coils) via a transfemoral approach using a 5-French guiding catheter and a coaxial 2.2-French variable stiffness catheter (Tracker 18, Target Therapeutics, San Jose, CA).

Silicone detachable balloons (DSB 1.5 L, Interventional Therapeutics, South San Francisco, CA) were used to treat eight aneurysms. These were placed into the aneurysm lumen via a transfemoral approach using either a 2-French delivery catheter or an extended tip Tracker catheter. The balloons were inflated either with isotonic nonionic contrast (iohexol) (four balloons) or with 2-hydroxyethyl methacrylate (four balloons) (11).

Twelve aneurysms were used as controls and received no treatment. Angiography was carried out in all 40 aneurysms prior to treatment, immediately posttreatment, and at time intervals of 1 week, 5 weeks, 3 months, and delayed intervals between 6 months and 1 year. Color Doppler evaluations were carried out in 21 of the 40 aneurysms pretreatment and at the time of their last angiogram.

Results

The hemodynamic characteristics of all of the experimental lateral carotid aneurysms were identical. Three distinct zones of flow were identified by both angiography and color Doppler studies: 1) an inflow zone entering the aneurysm at the distal aspect of its ostium, 2) an outflow zone exiting the aneurysm at the proximal aspect of its ostium, and 3) a central slow flow vortex (Fig. 2). In angiographic studies contrast enters an aneurysm at the distal aspect of its ostium, con-

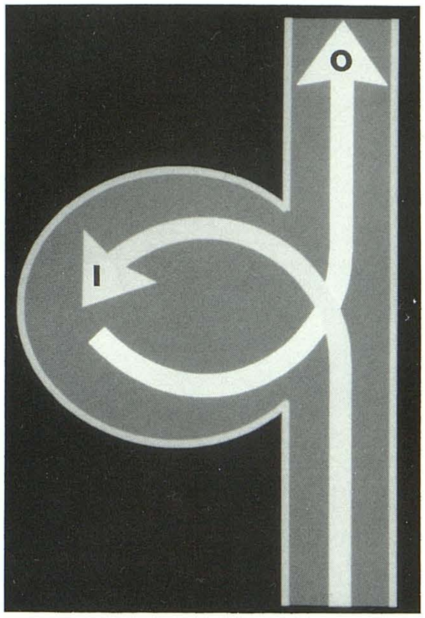

Fig. 2. Inflow, (*I*) arrow at distal ostium and out flow, (*O*) arrow at proximal ostium in control aneurysm.

tinues around the periphery of the lumen in a crainocaudal direction and then exits into the parent artery in a well-defined outflow zone at the proximal extent of the ostium, with a central area of persistent contrast in the central zone (Fig. 3A). On color Doppler studies, the inflow zone (red), outflow zone (blue), and the central zone (black) were identical to the respective zones demonstrated by angiography (Fig. 3B). In addition, the color Doppler studies demonstrated a discreet central higher velocity jet in the initial segment of the inflow zone that was not identified in the outflow zone (Fig. 4). The results of the endovascular placement of the coils and balloons within the aneurysms are tabulated in Table 1.

Four of seven linear nonfibered coils placed in three aneurysms and five of five curved nonfibered coils placed in three aneurysms were unstable and migrated along the path of the inflow and outflow zones. All four of the linear nonfibered coils immediately migrated after placement. Three of these migrated to the dome and one passed into the parent artery. Two of the curved nonfibered coils also migrated immediately after placement. One migrated to the dome of the aneurysm and another passed into the parent artery. The other three of these curved nonfibered coils were stable initially, but migrated during the first week after placement. One migrated to the dome of the aneurysm and two passed into the parent artery. Only four of the 40 complex curved fibered coils placed in 14 aneurysms were unstable. Two of these migrated immediately after placement to the dome of the aneurysm. Two were stable initially, but during the first week after placement changed position. One migrated to the dome and one passed into the parent artery. Coils that migrated after placement (immediate or delayed) always migrated either to the dome of the aneurysm or into the parent artery (Fig. 5) and each of the coils that migrated showed a change in shape after placement (Fig. 6). Following placement of coils within the aneurysm lumen, the inflow and outflow pattern described previously persisted in all 13 aneurysms that did not undergo complete thrombosis (Fig. 7). Seven of 20 aneurysms treated with coils underwent complete thrombosis with no residual flow. The parent artery was preserved in 19 of the 20 aneurysms treated with coils with thrombosis of only one parent artery.

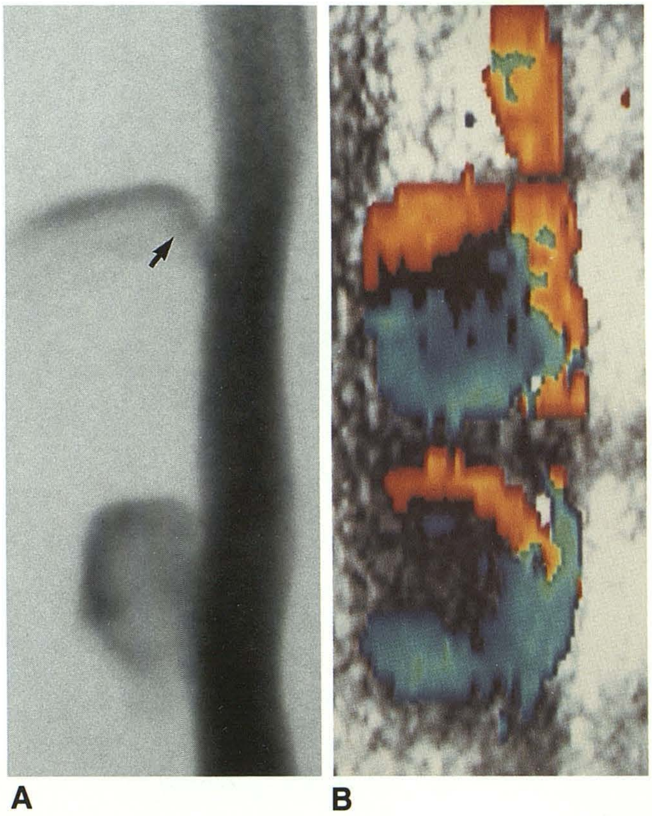

Fig. 3. *A*, Early phase in angiogram of lateral tandem control aneurysm showing inflow zone (*arrow*) in superior aneurysm with later progression in proximal aneurysm.

B, Color Doppler of same control aneurysm showing inflow zone (red), outflow zone (blue), and central vortex as (black).

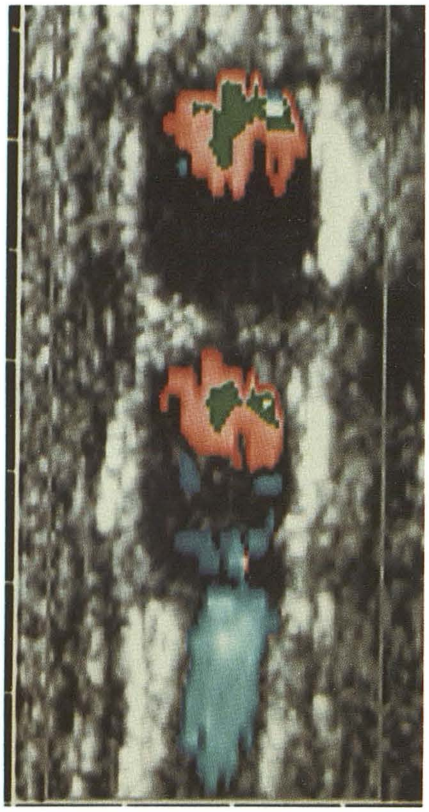

Fig. 4. Color Doppler of lateral tandem control aneurysms, inflow (red), outflow (blue), color encoded for velocity with higher velocities in green and the highest velocities in white, demonstrating a central discreet high velocity jet within the inflow zone.

TABLE 1: Results of the endovascular placement of the coils and balloons within the aneurysms

No. of An	Treatment	Coil Migration		Bo Ro	Aneurysm			Parent Artery		
		Dome	PA		CT	PT	NT	CT	PT	NT
3	Straight coils NF	2	1			1	2			3
3	Curved coils NF	2	2			1	2			3
14	Complex coils SF	3	1		7	4	3	1		13
8	Balloon			7	8			5	1	2
12	Controls						12			12

Note.—PA = parent artery, CT = complete thrombosis, PT = partial thrombosis, NT = no thrombosis, NF = no fibers, SF = silk fibers, An = aneurysm, Bo = balloon, Ro = rotation.

Seven of the eight balloons placed within the eight aneurysms showed delayed migration. This was manifested as rotation of the balloon about its long axis. The direction of rotation was always cranial to caudal, matching the direction of flow within the aneurysm. Although there was complete thrombosis of the aneurysm in all eight

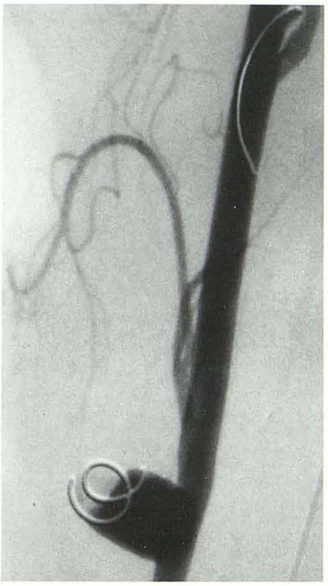

Fig. 5. Angiogram of single lateral aneurysm showing coils that have migrated into the dome of the aneurysm and out into the distal parent artery.

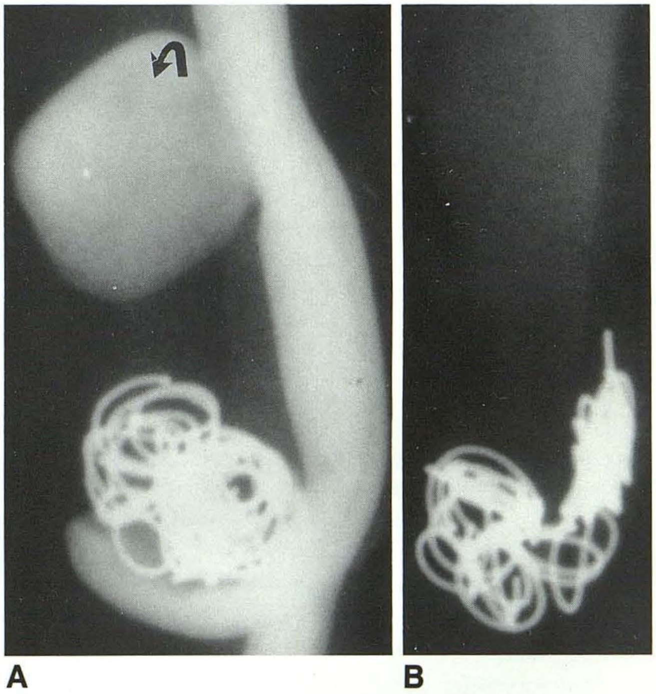

Fig. 6. *A*, Angiogram of lateral tandem aneurysms with 3 coils 8 cm long in the lower aneurysm with persistent inflow and outflow; note normal inflow zone in upper aneurysm (*curved arrow*).

B, One-month follow-up angiogram shows marked deformity of the coil mass with migration in to the parent artery and occlusion of the parent artery.

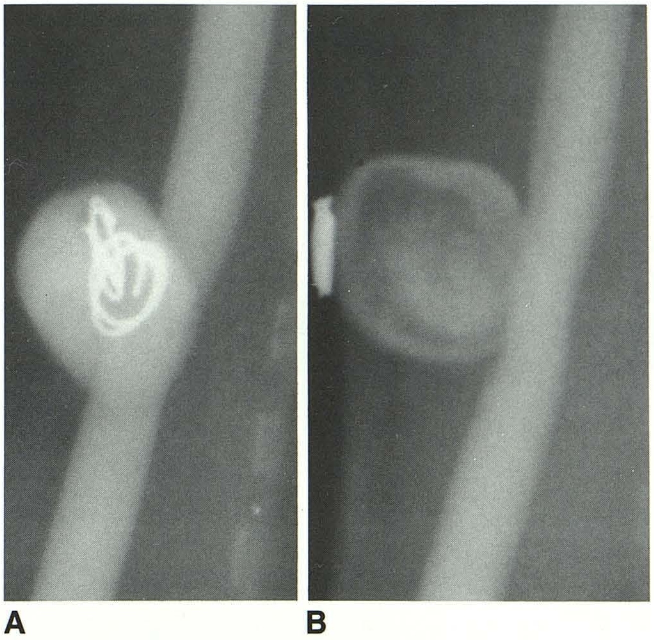

Fig. 7. *A*, Angiogram of single lateral aneurysm with coil positioned in the inflow zone of the aneurysm ostium.

B, One-month follow-up angiogram shows coil migration to the dome of the aneurysm and persistence of the inflow-outflow pattern.

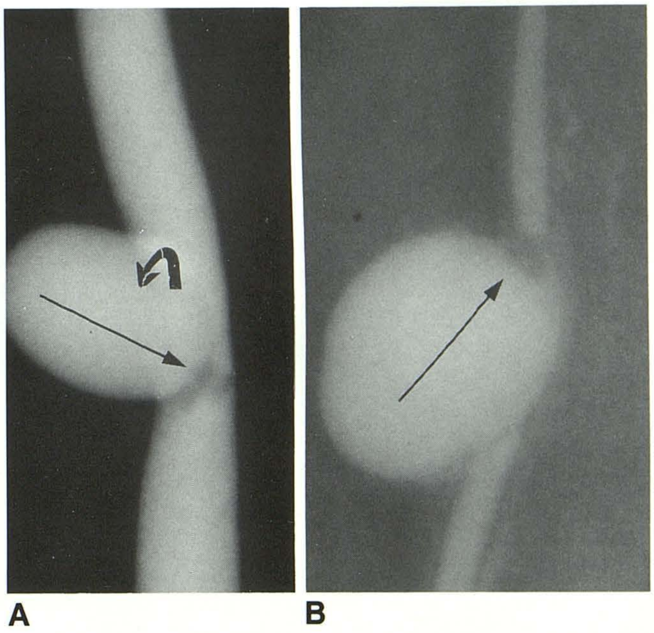

Fig. 8. *A*, Angiogram of single lateral aneurysm with balloon partially occluding the aneurysm with a persistent inflow zone (*curved arrow*) perpendicular to the long axis of balloon and balloon valve (*straight arrow*).

B, One-month follow-up angiogram shows balloon rotation in the direction of the inflow, with partial thrombosis of the parent artery.

aneurysms treated with balloons, there was also complete parent artery thrombosis in five, partial thrombosis (Fig. 8) in one, and preservation of the parent artery in only two of these eight aneurysms. Parent artery thrombosis was due to mechanical obstruction of the vessel by the rotation and herniation of the balloon into the parent artery.

Discussion

The effect of intraaneurysmal blood flow on a coil placed within an aneurysm is directly related to, among other factors, the size and shape of the coil. A coil whose shape and size is such that it can be contained within the zones of the inflow and outflow circulation, or whose malleability allows it to deform and thus conform to the shape and size of these flow zones, will be unstable and is likely to migrate. In our study, linear- and tubular-shaped coils were particularly unstable when compared to more complex-shaped coils. The addition of silk fibers to the coils increased their stability and also seemed to increase the extent of thrombosis.

The effect of the force of the inflow zone and outflow zone on coils is considerable and was capable of altering the shape of the coils. In four of 20 aneurysms, these forces resulted in displacement of coils out of the aneurysm lumen and into the parent artery (Fig. 6). Following placement of coils within the aneurysm lumen, if there was incomplete thrombosis, the residual aneurysm lumen exhibited the same flow characteristics as did the untreated aneurysm (Fig. 7). This was observed in every case of incomplete thrombosis.

The effect of intraaneurysmal flow on balloons was also significant and was capable of modifying the position of the balloon, particularly when the balloon was positioned so that the force of the inflow was directed perpendicular to the long axis of the balloon. If, after placement of a balloon in the lumen of an aneurysm, there was a persistent inflow zone and a residual lumen, the balloon was unstable and rotation occurred in a cranial to caudal direction along the direction of flow. This resulted in compromise of the flow in the parent artery. If, however, the balloon completely blocked the aneurysm and no inflow zone was present, the balloon was stable in position and did not rotate into the parent artery and the aneurysm remained occluded without compromise of the flow in the parent artery. Complete filling of the aneurysm lumen by a balloon was difficult to achieve in this model due to the geometry of the aneurysm, orientation of the parent artery, and the wide ostium of the aneurysm relative to the size of the aneurysm lumen. Thrombosis of the aneurysms occurred in five of eight aneurysms following placement of a balloon in the aneurysm lumen, after rotation of the balloon produced mechanical obstruction and thrombosis of the parent artery.

The force of the inflow was determining factor in the placement and stability of coils and balloons within the lumen of an aneurysm and, ultimately, the thrombosis of the aneurysm and patency of the parent artery. In this study, three different techniques that caused modification of the inflow zone were noted to produce thrombosis of an aneurysm while also allowing preservation of the parent artery: 1) complete filling of the aneurysm by coils or balloon, 2) obstruction of the inflow zone by coils or balloon, and 3) displacement of the inflow zone.

Complete filling of the aneurysm lumen was accomplished by placing either coils or a balloon into the lumen of the aneurysm until it was completely filled and there was no evidence of intra-aneurysmal flow on either angiography or color Doppler examination. These aneurysms proceeded to complete thrombosis (Fig. 9). Six of six aneurysms completely filled with complex curved coils with silk fibers, with no evidence of intra-aneurysmal flow, underwent complete thrombosis of the aneurysm lumen with preservation of the parent artery in five of these six aneurysms, and parent artery thrombosis in only one. Only two of eight aneurysms treated by balloons showed no evidence of intra-aneurysmal flow and these aneurysms remained occluded with preservation of the parent artery.

While complete obstruction of the inflow zone was accomplished by selectively placing a complex curved coil with silk fibers in the ostium of the aneurysm, it was difficult to position a coil in the inflow zone and have it remain there. This was attempted in five aneurysms and was successful in only one aneurysm. In the one aneurysm in which the coil remained in the ostium and blocked the inflow zone, the aneurysm proceeded to complete thrombosis with preservation of the parent artery (Fig. 10).

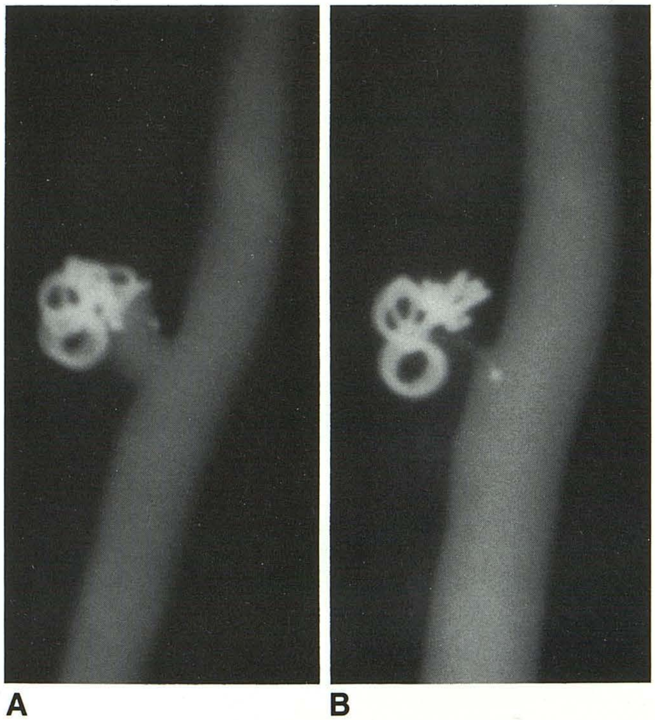

Fig. 9. *A*, Angiogram of single lateral aneurysm with 3 coils 6 cm long with silk fibers filling the aneurysm.

B, One-month follow-up angiogram shows occlusion of the aneurysm with patency of the parent artery.

Displacement of the inflow zone was achieved by deflecting the inflow zone of an aneurysm from its normal entry site at the distal aspect of the ostium of the aneurysm. This occurred when a balloon or coils placed in the proximal aneurysm of a set of two tandem aneurysms disturbed the flow pattern to the more distal aneurysm. This produced displacement of the inflow zone from its characteristic location at the distal aspect of the ostium of the aneurysm to a position in the midostium of the aneurysm. These aneurysms (three of three) showed a marked decrease in size with preservation of the parent artery (Fig. 11). Aneurysms that did not have displacement of the inflow zone did not show any decrease in size.

Conclusion

Flow dynamics in this lateral canine carotid artery aneurysm model are reproducible and are consistent with those predicted by mechanical, mathematical, and computer models. They also closely mimic the flow characteristics observed in a clinical series of lateral internal carotid artery aneurysms. In aneurysms of this geometry, there are three distinct flow zones: 1) an inflow zone

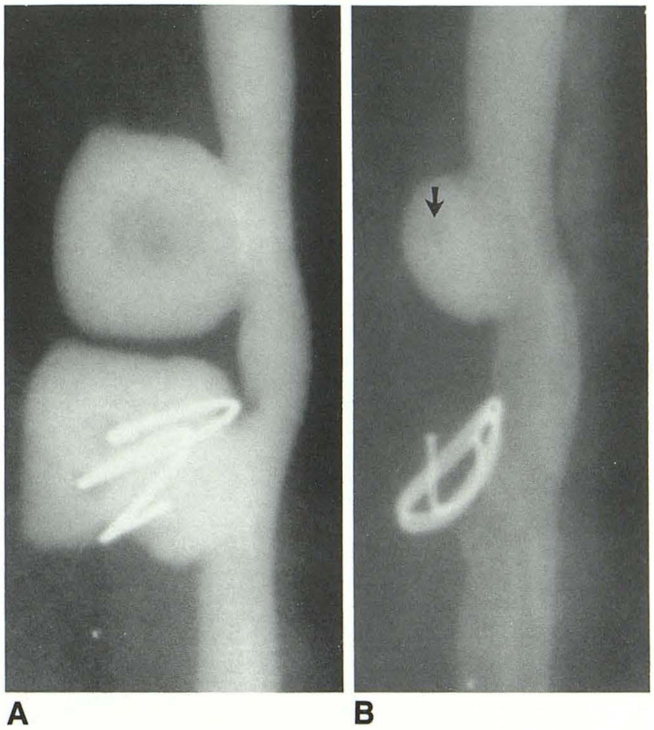

Fig. 10. *A*, Angiogram of lateral tandem aneurysms with coil across the inflow and outflow zones of ostium of lower aneurysm.

B, One-month follow-up angiogram shows coil-occluding aneurysm with patency of the parent artery. Upper aneurysm has decreased in size; note disturbed flow pattern with displacement of vortex from center of aneurysm (*arrow*).

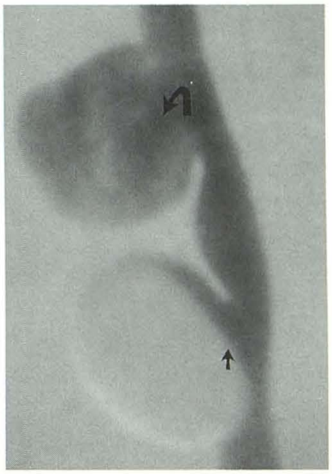

Fig. 11. Angiogram of tandem lateral aneurysms with balloon in the lower aneurysm and persistent inflow zone (*straight arrow*). Note that the inflow zone to the upper aneurysm has been displaced from the usual entry site at the distal ostium to the proximal and midregion of the aneurysm ostium (*curved arrow*). At 1 month, this latter aneurysm showed marked reduction in size.

entering the aneurysm lumen at the distal aspect of its ostium; 2) an outflow zone exiting the aneurysm lumen at the proximal aspect of its ostium, and 3) a central slow flow vortex. The inflow zone has a central discreet zone of higher velocity in its initial segment that is not present in its outflow zone.

The inflow zone is a major determining factor in the placement and stability of both coils and balloons in aneurysms. If the shape, size, or malleability of a coil or balloon allows it to conform and be contained within the inflow and outflow zones, it is less stable than those that do not. The force exerted by the inflow is considerable and is sufficient to alter the shape and size of coils and can also displace coils and balloons. Endovascular devices (coils and balloons) should be of a shape, size, and malleability that will not conform to the inflow and outflow zones. Complex coil shapes and the addition of silk fibers increased the stability and thrombogenicity of the coils. If the characteristic inflow and outflow pattern persists after placement of coils or balloons in the lumen of the aneurysm, it is unlikely to undergo complete thrombosis.

Complete filling of the aneurysm lumen with coils was a successful technique for producing thrombosis of the lumen of the aneurysm and preserving the parent artery. Complete filling of the aneurysm lumen with a balloon was difficult to achieve in this model due to the geometry of the aneurysm, orientation of the parent artery, and the relatively wide ostium. Persistent inflow forces resulted in rotation of the balloon, producing mechanical obstruction and thrombosis of the parent artery.

Modification of the inflow zone by blocking or displacing it can be used to produce thrombosis of an aneurysm with preservation of the parent artery. Displacement of the inflow zone from its characteristic location at the distal aspect of the ostium of the aneurysm can lead to thrombosis of the aneurysm with preservation of the parent artery.

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