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Endovascular Treatment of Fusiform Aneurysms with Stents and Coils: Technical Feasibility in a Swine Model

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PURPOSE: To assess the biomechanical feasibility of treating experimental fusiform aneurysms endovascularly with a combination of stents and coils. **METHODS:** An experimental model was surgically constructed in the necks of nine swine to simulate intracranial fusiform aneurysms possessing important "perforators" or side branches. Balloon-expandable metal stents were positioned across the aneurysms in eight swine. In five of these, additional treatment was intraaneurysmal placement of detachable microcoils. Attempts were made to deposit these coils strategically away from the origin of the side branch. **RESULTS:** Stent placement was successful in seven swine but failed in one swine because of stent-aneurysm size mismatch. Two swine treated with only stents showed no significant alterations in blood filling of the aneurysm or side branch. Satisfactory coil placement (outside the stent, within the aneurysm sac, and away from the orifice of the side branch) was achieved in four of the five swine treated with stents and coils. Careful fluoroscopic monitoring and controlled coil delivery were necessary to avoid covering the side-branch origin. These aneurysms could not be packed densely after detachment of the first coil because of the resultant radiographic overlap of multiple coil loops on the stent and its lumen in all projections. In one swine there was inadvertent untoward reentry of the coil tip into the expanded stent lumen during its delivery. **CONCLUSION:** Endovascular treatment of experimental fusiforms aneurysms using stents and coils is technically feasible. The stent maintains patency of the parent artery while allowing strategic coil placement in the aneurysm sac away from the origin of side branches. This technique may prove useful in the future treatment of intracranial fusiform aneurysms. However, potential sources of technical difficulties have been identified, and further long-term studies using an appropriate intracranial stent will be necessary before human application.

Index terms: Aneurysm, therapeutic blockade; Interventional instruments, coils; Interventional instruments, stents; Animal studies

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Fusiform aneurysms are defined as abnormal dilatations involving the total circumference of the arterial wall (greater than mere arteriectasis commonly seen in advanced atherosclerotic cerebral arteries), often in association with tortuosity and often of giant proportions (1–3). They are frequent complications of atherosclerotic arteries, particularly the basilar and internal carotid arteries (4), although a distinct subgroup of these aneurysms, termed *giant serpentine fusiform aneurysms*, most often affects the middle cerebral artery (5). Fusiform aneurysms are relatively rare, constituting fewer than 1% of cerebral aneurysms encountered clinically (4). However, their surgical and endovascular treatment is associated with considerable difficulties and/or limitations (6). In particular, there is no current satisfactory endovascular treatment for fusiform aneurysms (7, 8), and when this relatively less invasive therapeutic option is exercised, it is limited usually to parent vessel occlusion because of lack of a distinct aneurysm

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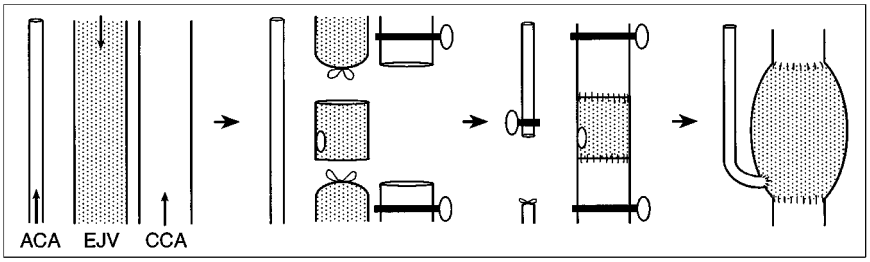


Fig 1. Schematic diagram shows sequential steps in the surgical construction of the fusiform aneurysm model. *ACA* indicates ascending cervical artery; *EJV*, external jugular vein; and *CCA*, common carotid artery.

neck, which may allow safe endosaccular coil placement. Even when vessel occlusion is performed, a surgical distal revascularization procedure may be necessary if collateral cerebral pathways are inadequate to prevent ischemia in distal territories.

Fusiform aneurysms are most frequently associated with compressive or ischemic symptoms, with intracranial hemorrhage being a less common clinical presentation (9). In common with saccular aneurysms, hope for overall improvement in the treatment of fusiform aneurysms and their sequelae depends, in part, on the continued development of new therapeutic measures. Recently, intravascular stents combined with (10, 11) or without (8, 12) aneurysm coiling have been evaluated as potential therapeutic devices in experimental saccular aneurysm models. The aim of this study was to assess the technical feasibility of endovascular stent implantation across experimental fusiform aneurysms in combination with coil placement within the aneurysm, with a view to flow preservation in the parent artery and in "perforators" or branches arising from the aneurysm itself. For this purpose, a fusiform aneurysm model was created in laboratory swine. Given the more-complex morphologic features and the distinct symptoms of intracranial fusiform aneurysms compared with simple saccular aneurysms, we critically assessed the suitability of stent and coil placement as a technique for treatment of experimental fusiform aneurysms.

Methods

All animal experiments were conducted in accordance with policies set by the local University Chancellor's Animal Research Committee and National Institutes of Health guidelines. Nine Red Duroc swine were used in this feasibility study. The animals were 3 to 4 months old, weighed 30 to 40 kg, were of mixed sex, and were maintained on a standard laboratory diet. After an overnight fast, each swine was premedicated with intramuscular 20 mg/kg ketamine and 2 mg/kg xylazine. General anesthesia was maintained with mechanical ventilation and inhalation of 1% to 2% halothane after endotracheal intubation.

Aneurysm Construction

A single fusiform aneurysm was surgically constructed in the neck of each swine (Fig 1). One side of the neck was shaved and scrubbed with betadine solution, then draped in a sterile fashion. Under sterile conditions, a 10-cm incision was made in the neck parallel to the sternocleidomastoid muscle. Self-retaining retractors were used to facilitate exposure. Reflecting the sternocleidomastoid muscle medially, a 3-cm segment of the external jugular vein, free of tributaries, was dissected, isolated, and cleaned of adventitia. Next, a 1-cm segment of the common carotid artery and an adjacent 2-cm segment of the more laterally situated ascending cervical artery were also dissected, isolated, and cleaned of adventitia. Vasoconstriction caused by handling of the arteries and vein was relieved by topical application of papaverine hydrochloride. Each end of the isolated external jugular vein was ligated, and the segment was divided and removed to form a 1.5-cm open-ended vein graft to be used for constructing the aneurysm. Its lumen was cleaned before placement in heparinized saline. Two small vascular clamps were then placed at each end of the isolated common carotid artery segment to achieve temporary vessel occlusion. This isolated segment of the common carotid artery was then axially transected halfway between the clamps, and both exposed lumina were cleaned of blood. The vein graft was interpositioned between the two artery ends, and two end-to-end artery-to-vein anastomoses were performed using continuous 7-0 prolene sutures. Integrity of the anastomosis was tested by removal of the vascular clamps, and additional sutures were placed if necessary to achieve hemostasis. Next, the ascending cervical artery was ligated just above the thyroid division of the thyrocervical trunk. A small vascular clamp was placed on the artery 1 cm above this ligature, and the ascending cervical artery was divided just above the ligature. The exposed open end of the severed ascending cervical artery was cleaned of blood and mobilized toward the common carotid artery and its sutured aneurysm vein graft. The vascular clamps were reapplied to the common carotid artery, and a 2-mm venotomy was performed on the lateral aspect of the vein graft, facing the exposed end of the ascending cervical artery. This open end of the ascending cervical artery was then anastomosed end to side to the lateral aspect of the vein graft. All

three clamps were removed to restore flow in the common carotid artery, the expanded vein segment (ie, the aneurysm), and the ascending cervical artery. Subcutaneous tissues and skin were sutured in layers. During the procedure, the swine received 0.9 to 1.2 $\times$ 10^6 U of penicillin G intramuscularly.

Aneurysm Treatment

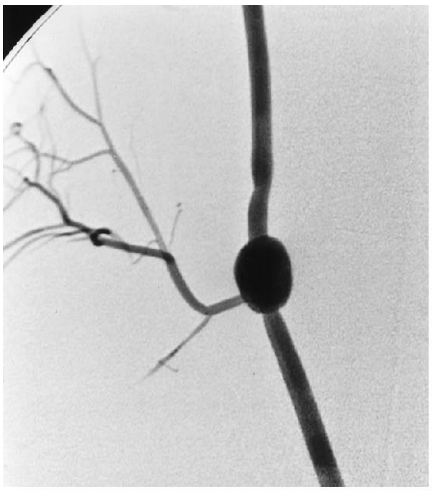
All endovascular treatments were undertaken in aneurysms immediately after their construction. Under general anesthesia, a 7F angiographic sheath was placed in the femoral artery after standard Seldinger puncture and catheterization. Via this transfemoral route, a selective common carotid arteriogram was performed using a tapered 5.5F-to-4F Viñuela catheter (Cook, Bloomington, Ind), and the aneurysm was outlined in multiple projections. A bolus of 3000 U of heparin was injected intraarterially. The Viñuela catheter was exchanged for a 3.4F catheter-mounted balloon-inflatable tantalum coronary stent (Boston Scientific, Watertown, Mass). Each stent was 2.5 cm in length and 4.5 mm in expanded diameter. The balloon catheter and mounted stent were advanced up the common carotid artery over a 0.015-in guide wire traversing the aneurysm. Using digital-subtraction angiography and a road-mapping mode, the stent was accurately positioned in the common carotid artery (through the aneurysm) so that its center coincided with that of the aneurysm. After this precise placement, the balloon was inflated, and the stent was positioned. The balloon catheter was exchanged for a 6F Royal Flush guiding catheter (Cook) positioned in the proximal common carotid artery, and another arteriogram was performed to assess the patency of the common carotid artery, the aneurysm, and the ascending cervical artery. Next, a Tracker 10 or 18 microcatheter and Seeker microguidewire combination (Target Therapeutics, Fremont, Calif) was advanced via the guiding catheter and through the mesh of the stent into the aneurysm, as described previously by Turjman et al (10). The tip of the microcatheter was positioned as far away as possible from the origin of the anastomosed ascending cervical artery side branch. A continuous flush with pressurized saline was performed through Touhy-Borst connectors to both the guiding catheter and microcatheter. Next, electrically detachable platinum coils (Guglielmi detachable coils, Target Therapeutics) were delivered into the aneurysm via the microcatheter, as described previously by Guglielmi et al (13). As the first coil was delivered, the position of its leading tip was monitored very carefully under fluoroscopy to ensure that it assumed its correct circular memory shape within the aneurysm sac. This precaution was necessary to prevent the tip of the coil crossing back into the lumen of the expanded stent through its mesh. If such reentry occurred, the coil was simply withdrawn and redelivered in a more satisfactory position. The lengths and diameters of the coils were chosen to avoid coil placement near the orifice of the ascending cervical artery side branch. Similarly, some control was exerted over positioning of the coils (by repeated retrieval and redelivery) so that the assumed configuration of the delivered coil mass was also satisfactory, that is, away from the side-branch orifice. After detachment of the final coil, the microcatheter was removed, and another angiogram was performed to assess the outcome of the treatment.

Results

All swine tolerated the surgical and endovascular procedures with no ill effects. The first swine was used for assessing the feasibility of constructing the aneurysm model. Simple interpositioning of a vein graft along the course of the common carotid artery resulted in a diffusely dilated segment of the vein, having the angiographic appearance of a fusiform aneurysm with no side branches. On the other hand, anastomosing the ascending cervical artery to the side of the fusiform aneurysm (Fig 2) resulted in a much more realistic model of intracranial fusiform aneurysms, which frequently possess perforating arteries or side branches arising from the aneurysm and supplying other territories. Therefore, this more authentic model was chosen for use in the remainder of the study. The size and length of the vein graft, which could be altered at surgery, was the main determinant of the dimensions of the resultant fusiform aneurysmal dilatation. The overall length of the aneurysm in this study was dictated principally by the lengths of available stents.

Successful stent positioning was achieved in seven of the other eight swine. In these seven swine, anchoring the expanded stent in the parent artery at either end of the fusiform aneurysm resulted in satisfactory expansion of the device throughout the aneurysm length, despite the lack of vessel wall apposition within the aneurysm (Fig 3). In the remaining eighth swine, the aneurysm was constructed inadvertently using too long a vein graft relative to the lengths of available stents. The subsequent stent placement failed, because although the proximal end of the device was anchored satisfactorily in the common artery, the distal end seemed initially anchored in the parent artery but dislodged within a few minutes into the aneurysm sac (Fig 4).

Two aneurysm models were treated by stent placement only, without additional coil placement, to assess the influence of the metallic stent mesh alone on circulation within the aneurysm model. The presence of the expanded



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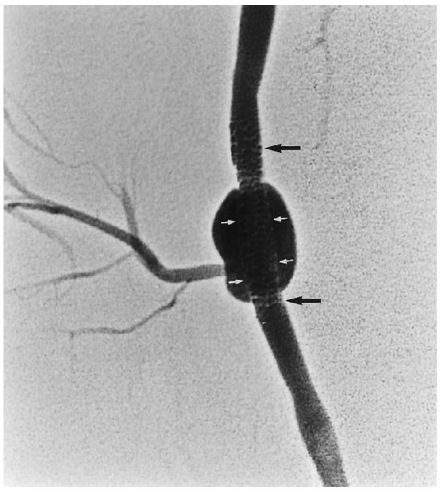

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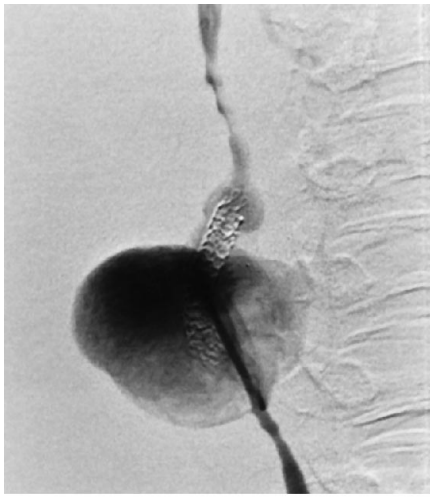
Fig 2. Right common carotid arteriogram shows a fusiform aneurysm with a side branch.

Fig 3. Common carotid arteriogram after satisfactory stent placement shows the stent spanning the aneurysm (*white arrows*) and anchored in the parent artery (*black arrows*). Note the patent side branch and normal distal runoff.

Fig 4. Common carotid arteriogram shows unsatisfactory stent placement. The cephalad end of the stent (*arrows*) has dislodged from the parent artery and into the aneurysm sac.

Fig 5. Common carotid arteriogram at 4 days after stent placement. There is massive enlargement of the aneurysm, nonfilling of the side branch, and marked distortion and spasm of the parent artery.



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stent in the common carotid artery (spanning the aneurysm) did not subjectively alter blood flow within the common carotid artery, the fusiform aneurysm, or the ascending cervical artery side branch when imaged on digital-subtraction angiograms at three frames per second. One of these stented aneurysms was followed up at 4 days after treatment by repeated angiography under general anesthesia. Persistent filling and massive enlargement of the aneurysm was observed, along with nonfilling of the ascending cervical artery side branch and considerable distortion of the parent common carotid artery (Fig 5).

The other five stented aneurysms were treated in addition by Guglielmi detachable coil placement outside the stent and into the aneurysm sac. Coils were placed immediately after stents on observation of persistent flow within the aneurysm sac. As with previous experience in saccular aneurysms (9), passage of a microcatheter and Guglielmi detachable coil delivery through the mesh of the stent was easy in all instances. Satisfactory coil placement (ie, outside the stent, within the aneurysm sac, and away from the orifice of the ascending cervical artery side branch) was possible in four models by strategic positioning of the microcatheter tip and coil delivery as distant as possible from the side-branch orifice (Fig 6). Furthermore, repeated retrieval and redelivery of each coil before detachment was possible so that the overall configuration of the coil mass showed no impingement on the side-branch orifice. This was aided by extreme fluoroscopic angulation, which was often necessary to see the position of coil loops in relation to the side-branch orifice. However, in the first treated aneurysm, the

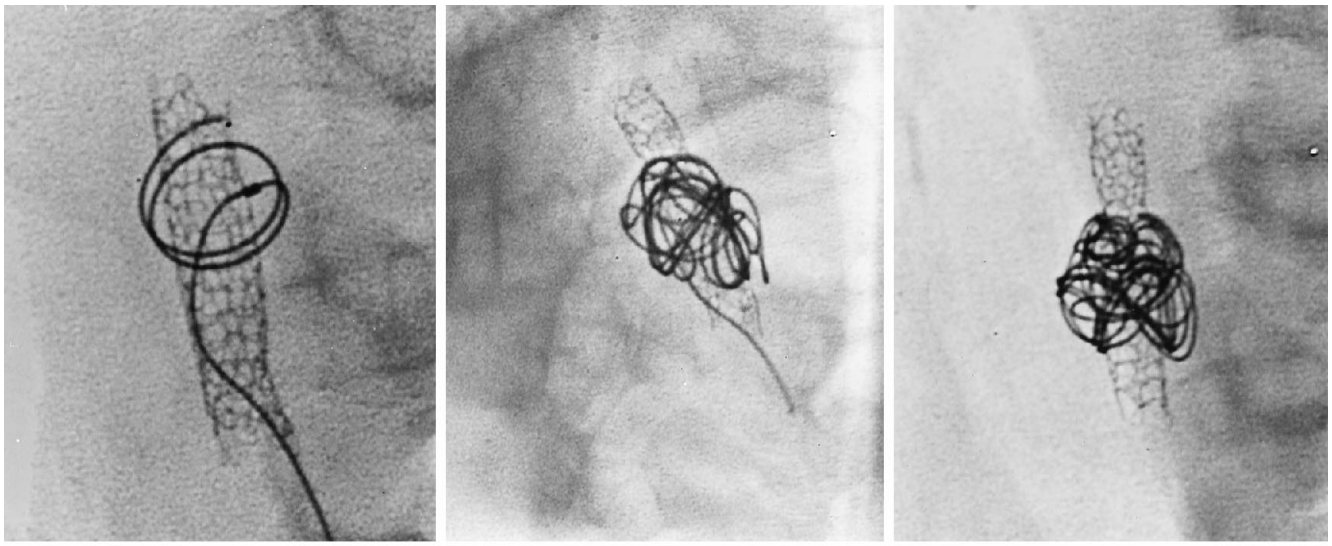


Fig 6. Sequential steps in coil placement within the aneurysm seen in Figure 3.

A, The microcatheter tip is positioned past the stent mesh and into the aneurysm sac. The delivered coil (40 cm) spirals around the outside of the stent as it assumes its circular memory shape.

B, Oblique projection necessary to check the position of the coil mass.

C, Final shape of the coil mass surrounding the stent.

D, Common carotid arteriogram showing patency of the side branch and normal distal runoff.

course of the leading tip of a 40-cm coil was not monitored fluroscopically, because it exited a correctly positioned microcatheter. This resulted in reentry of the coil tip into the lumen of the expanded stent (or possibly between the stent and the artery wall), as evidenced by frontal plane angiographic observation of the coil tip above the level of the cephalad common carotid artery–vein anastomosis (Fig 7). Therefore, although the remainder of the coil appeared in a satisfactory position on detachment (within the aneurysm sac and away from the side-branch orifice), the overall result was deemed unsatisfactory because of herniation of the coil into the parent artery. All five aneurysms were loosely packed with coils: four aneurysms with one coil each (40 cm in length), and one aneurysm with a 40-cm coil followed by a second 10-cm coil (Fig 8). On delivery, all 40-cm coils (which have a circular-shaped memory of 8-mm diameter) unraveled in a complete spiral fashion on the outside and around the stent, resulting in overlap of coil loops and stent mesh in all possible radiographic projections. The smaller 10-cm coil (diameter, 4 mm) remained in one segment of the aneurysm sac, near the tip of the delivery microcatheter, and was thus possible to see optimally in one tangential radiographic plane. Areas of dense coil packing within the aneurysm were observed, especially near exit of

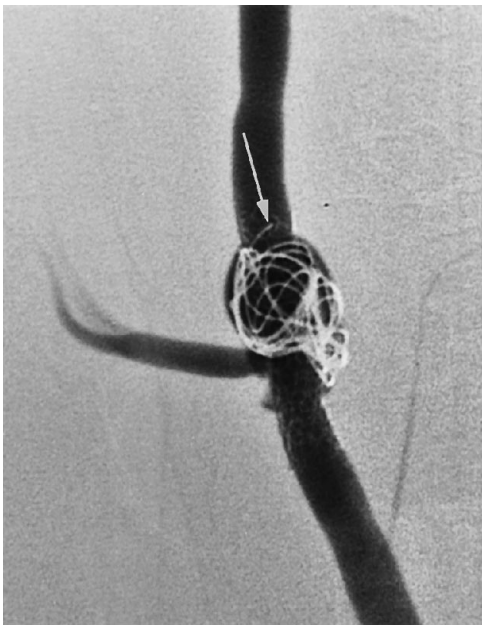


Fig 7. Common carotid arteriogram shows inadvertent entry of the coil tip (*arrow*) into the parent artery. Note the patent side branch.

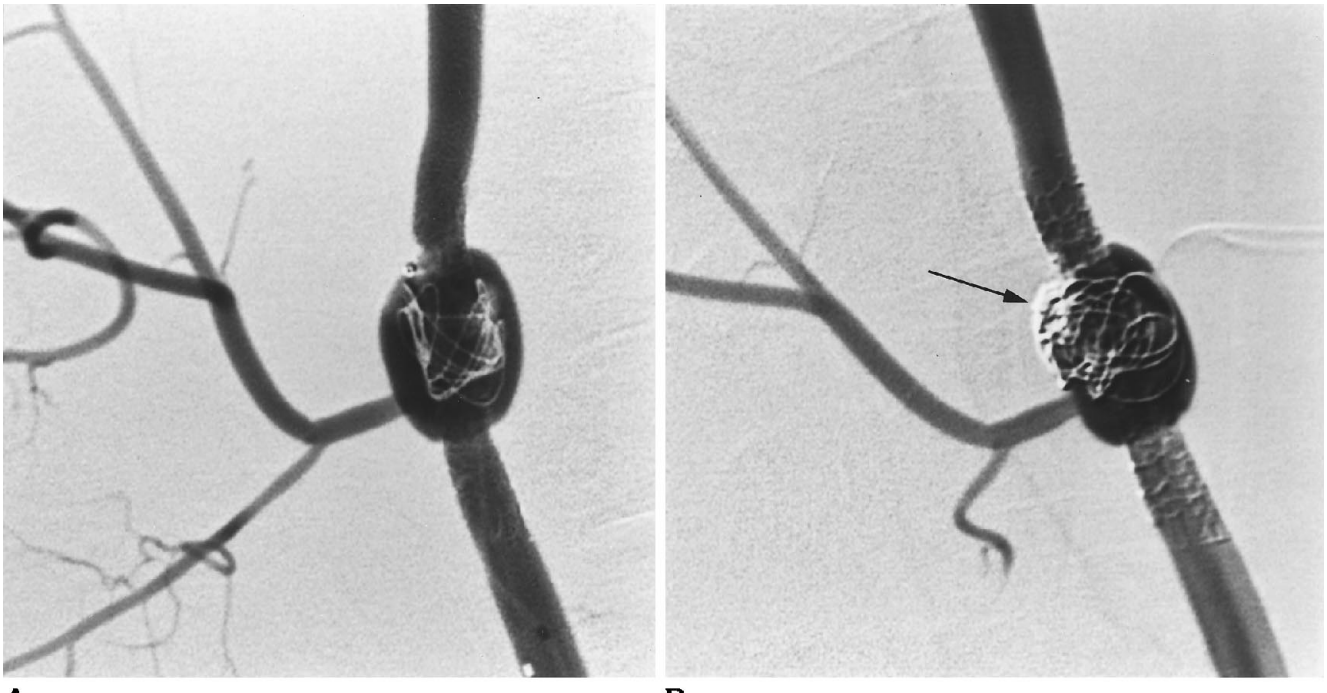
the coils from the microcatheter and in the aneurysm receiving two coils. Otherwise, loose packing and persistent contrast filling in the interstices of the coil was usually achieved. No follow-up investigations of aneurysms treated with stents and coils were performed in this preliminary technical feasibility study.

Discussion

Fusiform Aneurysm Model

In this study, we developed an experimental model of intracranial fusiform aneurysms, suitable for investigation of new endovascular therapies. The surgical construction of experimental aneurysms seems to provide the most reliable method of replicating the structural and dynamic features of human intracranial aneurysms (14). These in vivo models also incorporate unpredictable functions of "biovariability" (15), making them more suitable than in vitro models for laboratory testing and refinement of new endovascular devices and techniques.

Previous experimental models of fusiform aneurysms have included the interpositioning of a simple vein graft in the abdominal aorta of rabbits (16), the interpositioning of a Dacron or other synthetic fusiform conduit in the abdomi-



A B

Fig 8. Common carotid arteriogram after delivery of a 40-cm coil (*A*) and after further delivery of a 10-cm coil (*B*). Dense coil packing (*arrow*) is seen in the vicinity of microcatheter tip. Note the patent side branch.

nal aorta of dogs (17), and the injection of elastase or collagenase in the walls of arteries to induce their weakening and fusiform dilatation (18). Most of these models were created in an attempt to replicate abdominal aortic aneurysms. None of these models have taken into consideration the presence of side branches originating from the aneurysm itself, because the fate of these (eg, lumbar or inferior mesenteric arteries) may be of relatively low priority in the overall therapeutic strategy for abdominal aortic aneurysms (17). In contrast, intracranial fusiform aneurysms, being most commonly situated on the basilar or internal carotid arteries, often possess important side branches or perforating arteries (3). These may even be invisible on selective angiography or aneurysmography—as evidenced by their occlusion during acute therapeutic thrombosis of the aneurysm causing cerebral infarction or death (19). Thus, the fate of such important side branches in intracranial fusiform aneurysms is of considerable importance when deciding the success of any new treatment. With this in mind, we attempted to establish a morphologically more realistic experimental model than previously available. The anastomosis of the ascending cervical artery to the lateral aspect of a conventional fusiform aneurysm model (a vein graft interpositioned on the common carotid artery) results in the blood supply to the neck musculature arising from the fusiform aneurysm itself—analogous to, for example, a cerebellar artery arising from a basilar artery aneurysm or an ophthalmic or posterior communicating artery arising from an internal carotid artery aneurysm. Although such a fusiform aneurysm model differs histologically from intracranial lesions and in its remoteness from sensitive neuronal tissue, its overall favorable morphologic features and ease of access in the animal's neck make it suitable for testing and angiographic assessment of new endovascular therapeutic techniques.

Treatment of Fusiform Aneurysms

As for giant saccular aneurysms, the surgical treatment of giant fusiform aneurysms is a complex and risky procedure (6, 20). For giant aneurysms (saccular and fusiform), postoperative major morbidity and mortality is about 10% each but can be greater than 50% in the vertebrobasilar system (21). Surgical options include parent vessel ligation with or without distal bypass revascularization, trapping, wrapping, aneurysmorraphy, or application of angled fenestrated clips to the aneurysm (20, 22, 23). Surgical exclusion of the aneurysm and its parent artery from the circulation (eg, by trapping) may be particularly dangerous for fusiform aneurysms because of concomitant thrombosis of perforating arteries arising from the aneurysm itself (3). The strategies available for endovascular treatment of these aneurysms are usually limited and include partial coil occlusion of the aneurysm sac as suggested by Numaguchi et al (24); however, coil herniation into the parent artery and its subsequent occlusion makes this also a risky technique. The more usual method is of proximal parent vessel balloon occlusion (25). This less invasive option is itself far from satisfactory, because it ideally necessitates prior rigorous angiographic, clinical, neurophysiologic, and cerebral hemodynamic evidence of collateral pathways and/or neuronal tolerance (in territories supplied by the parent artery and by branches arising from the aneurysm) during test occlusion. This test occlusion may fail, or a surgical revascularization procedure may also be necessary to supplement circulation most distal to the aneurysm, or delayed cerebral ischemia/infarction may occur despite tolerance of a test occlusion (26). Given these limitations of current endovascular treatments, the present study was undertaken to evaluate the potential role of stent and coil treatment (a combination suggested previously for treatment of experimental saccular aneurysms [10, 11]) in a realistic animal model of intracranial fusiform aneurysms. By maintaining the patency of the parent artery and of aneurysm side branches, while inducing thrombosis in much of the aneurysm sac, many of the problems associated with current treatments could in theory by eliminated. The biomechanical feasibility of such a method and technical considerations pertaining to its use in a fusiform aneurysm model were therefore addressed in this study.

Stenting of Fusiform Aneurysms

Previous studies by Turjman et al (10) and Szikora et al (11) have demonstrated the feasibility of combining stents and coils for endovascular treatment of experimental saccular aneurysms. The stent maintains the patency of the

parent artery while allowing total aneurysm occlusion by endosaccular coil placement and complete packing through the stent's mesh. This technique may be appropriate for saccular aneurysms, for which the aim of treatment is total aneurysm exclusion from the circulation to avoid rupture and hemorrhage. This is not the case for most intracranial fusiform aneurysms. These lesions usually present with compressive or ischemic symptoms and rarely with rupture. The ischemic sequelae of fusiform aneurysms have been attributed to: (*a*) thromboemboli originating in the aneurysm sac (3, 9), which often contains mural thrombus; (*b*) distortion or thrombosis of perforating arteries arising from the aneurysm (3, 4, 9, 27); and (*c*) progressive encroachment of the mural thrombus onto the parent artery to produce stenoses and eventual spontaneous aneurysm and parent artery occlusion (5, 28). Furthermore, unlike saccular aneurysms, the walls of a these aneurysms may be 1 to 4 mm thick (2), which accounts for their reluctance to rupture. Therefore, these distinct morphologic characteristics and differences in symptoms demand therapeutic approaches and aims that vary from those for saccular aneurysms. In particular, if considering the use of stent and coil combinations for treatment of fusiform aneurysms, then specific alterations to current experimental techniques other than mere coil packing of the aneurysm outside the stent are likely to be required.

The results of this study demonstrate the technical feasibility of treating experimental fusiform aneurysms possessing side branches or "perforators" with a combination of endovascular stent implantation in the parent artery and coil placement within the aneurysm sac, without obstructing the origin of side branches. Stent placement through the aneurysm resulted in good flow in the parent artery and a normal distal runoff. The presence of an expanded stent spanning the aneurysm was alone insufficient to reduce filling of the aneurysm and side branch. Furthermore, marked growth of the aneurysm was observed in the one model followed up after stent implantation alone. This was most likely a result of the loosely knit mesh of the stents used in this study offering little resistance to continuous passage of blood into the aneurysm. A similar finding was obtained in an animal study of stent treatment in abdominal aortic aneurysm models (29). In the same study, the use of a stent with a much tighter knit resulted in thrombosis of the aneurysm sac. The persistent aneurysm filling after stent implantation observed in all aneurysms in our study differed from the varying rates of occlusion and patency reported previously after the same treatment in saccular aneurysms (8, 12). This is most likely a reflection on the presence of a comparatively large surface area (in effect, a very wide "aneurysm neck") between the parent artery and the aneurysm sac, allowing relatively large volumes and high flow of blood to perfuse the aneurysm—more than sufficient to offset the hemodynamic disturbances induced by the loose mesh of the stent (8). Elucidating the important relationships between stent geometric and structural parameters and morphologic characteristics of aneurysms undergoing treatment will be necessary in future studies.

Although intracranial fusiform aneurysms uncommonly cause subarachnoid hemorrhage, the rationale for inducing thrombosis within the aneurysm sac (ie, outside the expanded stent) should not be solely to reduce the chances of aneurysm rupture (as is usually the case for saccular aneurysms), but rather to reduce ischemic events and an aneurysm mass effect as well. Therefore, placement of occlusive coils in the aneurysm sac is required to offset the inadequacy of loosely knit stents alone to thrombose the aneurysm. A loose packing of a fusiform aneurysm, as performed in this study, may be sufficient to promote further thrombosis of much of the aneurysm sac by inducing significant hemodynamic alterations facilitating thrombosis, as previously reported by Numaguchi et al (24). In addition to protecting the aneurysm wall from the uncommon possibility of rupture, the resultant thrombosis may eliminate expansile pressure within the aneurysm—the mass effect may decrease as the organized thrombus shrinks, and the aneurysm wall retracts (20, 30). Halbach et al (31) have noted that even subtotal endovascular obliteration of an aneurysm presenting with a mass effect may alter its natural history and in most patients causes resolution or improvement of signs and symptoms of the mass effect. However, this resolution occurs more commonly in aneurysms with lesser wall calcification. The loose coil packing in the aneurysm sac may afford another theoretical advantage, in that the resultant thrombus may remain compressible, allowing the natural shrinkage of the aneurysm to occur in a timely fashion (20). The combination of

stent and coils may also reduce the ischemic complications of fusiform aneurysms if these are caused by thromboemboli or clot propagation causing parent vessel stenosis, because a thin fibroproliferative or neointimal spread across the stent mesh when the thrombus is present on the outside of the stent results in an eventual smooth lining of its lumenal surface (29). On the other hand, this technique would not be appropriate if the ischemia were caused by distortion or thrombosis of perforating arteries arising from the aneurysm. However, if these perforators or larger side branches are noncompromised, then their preservation by strategic coil placement in segments of the aneurysm sac away from the origins of these branches seems technically feasible, as demonstrated in this study. The creation of a nonthrombosed segment of an aneurysm in direct relation to the origin of the side branch acts, in effect, as an open conduit channeling blood from the stent lumen (ie, the fashioned "parent artery"), across the openings of the stent mesh toward the side branch. The creation of a similar direct channel, occurring after partial embolization with coils (but no stent), and further clot propagation within the aneurysm, was also documented by Numaguchi et al (24) to result in preservation of a direct route between an afferent vertebral artery and an efferent basilar artery in a posterior fossa fusiform aneurysm. These arteries may be regarded as analogous to the fashioned parent artery and the side branch in our model. These above-proposed mechanisms, however, remain speculative and would have to be substantiated in further long-term studies using stents appropriate for intracranial use.

The many physical and chemical characteristics of metallic stents are important design criteria that govern stent behavior at the host site after implantation (32). Therefore, the current lack of an appropriate intracranial stent limits the scope of this study to research of the biomechanical and technical feasibility of fusiform aneurysm treatment in experimental models, while using a metallic stent designed for placement elsewhere in the body. This limitation has precluded the performance of any meaningful natural history investigations of treated aneurysms in this study. Nevertheless, several limitations of the proposed technique have emerged from this preliminary feasibility study. Stent placement across a fusiform aneurysm has to be performed with a higher degree of vigilance and accuracy than for saccular aneurysms, because stent anchorage relies on a smaller surface area of the stent available for contact with the parent artery at either end of the aneurysm. Because the neck of a saccular aneurysm originates from a segment (ie, not all) of the circumference of a parent artery, secure stent placement is achievable more often for a saccular aneurysm than for a fusiform aneurysm. If an expanded stent spanning a fusiform aneurysm is poorly anchored at either end of the aneurysm, then it may dislodge from the parent artery and migrate and embolize more distally or fall into the aneurysm sac, causing obstruction of the parent artery. These complications may occur especially during attempted manipulation of the tip of a microcatheter through the stent mesh and into the aneurysm sac. Therefore, care is necessary in choosing the correct length and diameter of a stent for any given fusiform aneurysm and in correct positioning of the stent across the aneurysm before deployment.

Another problem encountered with the proposed technique concerned the process of coil delivery into the aneurysm sac. As mentioned previously, unlike the relatively simple placement of coils in a saccular aneurysm (which can be safely performed using one radiographic plane to depict the aneurysm neck–parent artery junction), that in a fusiform aneurysm requires continuous fluoroscopic monitoring of the tip of the first coil as it emerges from the microcatheter, in multiple radiographic projections. This should be performed until the coil assumes its memorized circular shape within the aneurysm sac. If this maneuver was not performed, it was found that the coil could inadvertently reenter the lumen of the expanded stent. This may not be appreciated once more of the coil is delivered, because of radiographic overlap of the coil loops on the stent mesh in all radiographic planes. Angioscopy or a tomographic imaging modality capable of displaying axial images through the stent would be necessary to see a herniated coil tip and loop within the stent. This radiographic appearance was also the reason it was not possible in this study to pack fusiform aneurysms with coils more extensively. Unraveling of the first coil within the aneurysm sac was usually accompanied by spiraling on the outside of the expanded stent. After detachment of this first coil, seeing the

leading tip of a second coil precisely on its delivery became even more difficult, and it was usually impossible to exclude its reentry into the lumen of the expanded stent. For this reason, only one long coil was delivered in all but one aneurysm in this study. In one aneurysm, it was possible to deliver a second shorter coil, because it assumed its small-diameter shape away from the stent and the side-branch origin, as seen in an optimal tangential radiographic plane. All these issues make coil placement within the lumen of a fusiform aneurysm more complex than for a saccular aneurysm. Further studies will be required using coils of different lengths, sizes, and shapes to establish possible means of further aneurysm packing using this technique.

Inadvertent occlusion of the side branch by coil loops represents another potential problem when using this technique. Therefore, care had to be exerted in positioning of the microcatheter tip within the aneurysm sac, in choosing coils of the correct length and configuration, in controlling the delivery of the coils, and in finding the correct radiographic plane to see clearly the orifice of the side branch—often requiring steep radiographic angulation. However, potential deleterious propagation of thrombus beyond correctly positioned coils also remains a theoretical possibility. This, again, would depend to some extent on the physicochemical characteristics of the stent in use. Moreover, the presence of a relatively large surface area of bare stent metal could help promote thromboemboli in the parent artery and the side branch. All these factors regarding the fate of side branches and the possible mechanisms of endothelialization of the stent mesh (including the contribution from circulating multipotent undifferentiated cells [33]), coupled with influences of systemic anticoagulation on the outcome of treatment, should be investigated in future studies using a more appropriate stent, that is, a stent and delivery catheter capable of reaching aneurysms situated on small tortuous intracranial vessels, and also possessing favorable physicochemical properties for safe and effective placement within the brain. Clearly, the absence or relative unimportance of any side branches emerging from the aneurysm would make it technically much simpler to use this proposed method for aneurysm occlusion.

Conclusion

We have demonstrated the technical feasibility of an endovascular method for treating experimental fusiform aneurysms possessing side branches or perforators. The stent maintains the patency of the parent artery, while allowing strategic coil placement in the aneurysm sac. This technique may prove useful in the future treatment of intracranial fusiform aneurysms. However, potential sources of difficulty associated with this technique have been identified, and further long-term angiographic, hemodynamic, and histologic studies using a suitable intracranial stent will be necessary before human application.

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References

1. Stehbens WE. Intracranial arterial aneurysms. In: Stehbens WE, ed. *Pathology of the Cerebral Blood Vessels*. St Louis: Mosby, 1972:351–353
2. Horowitz MB, Yonas H, Jungreis C, et al. Management of a giant middle cerebral artery fusiform serpentine aneurysm with distal clip application and retrograde thrombosis: case report and review of the literature. *Surg Neurol* 1994;41:221–225
3. Little JR, St Louis P, Weinstein M, et al. Giant fusiform aneurysm of the cerebral arteries. *Stroke* 1981;12:183–188
4. Stehbens WE. The pathology of intracranial arterial aneurysms and their complications. In: Fox JL, ed. *Intracranial Aneurysms*. New York: Springer-Verlag, 1983:272–357
5. Segal HD, McLaurin RL. Giant serpentine aneurysm: report of two cases. *J Neurosurg* 1977;46:115–120
6. Aymard A, Hodes JE, Rüfenacht D, et al. Endovascular treatment of a giant fusiform aneurysm of the entire basilar artery. *AJNR Am J Neuroradiol* 1992;13:1143–1146
7. Hallbach VV, Higashida RT, Heishima GB, et al. Aneurysms of the petrous portion of the internal carotid artery: results of treatment with endovascular or surgical occlusion. *AJNR Am J Neuroradiol* 1990;11:253–257
8. Wakhloo AK, Schellhammer F, de Vries J, et al. Self-expanding and balloon-expandable stents in the treatment of carotid aneurysms: an experimental study in a canine model. *AJNR Am J Neuroradiol* 1994;15:493–502
9. Echiverri HC, Rubino FA, Gupta SR, et al. Fusiform aneurysm of the vertebrobasilar arterial system. *Stroke* 1989;20:1741–1747
10. Turjman F, Massoud TF, Ji C, et al. Combined stent implantation and endosaccular coil placement for treatment of experimental wide-necked aneurysms: a feasibility study in swine. *AJNR Am J Neuroradiol* 1994;15:1087–1090
11. Szikora I, Guterman LR, Wells KM, et al. Combined use of stents and coils to treat experimental wide-necked carotid aneurysms: preliminary results. *AJNR Am J Neuroradiol* 1994;15:1091–1102

12. Turjman F, Acevedo G, Moll T, et al. Treatment of experimental carotid aneurysms by endoprosthesis implantation: preliminary report. *Neurol Res* 1993;15:181–184
13. Guglielmi G, Viñuela F, Sepetka I, et al. Electrothrombosis of saccular aneurysms via endovascular approach, I: electrochemical basis, technique and experimental results. *J Neurosurg* 1991; 75:1–7
14. Graves VB, Partington CR, Rüfenacht D, et al. Treatment of carotid aneurysms with platinum coils: an experimental study in dogs. *AJNR Am J Neuroradiol* 1990;11:249–252
15. Cheong J. The use of animals in medical education: a question of necessity vs. desirability. *Theor Med* 1989;10:53–57
16. Stehbens WE. Experimental production of aneurysms by microvascular surgery in rabbits. *Vasc Surg* 1973;7:165–175
17. Laborde JC, Parodi JC, Clem MF, et al. Intraluminal bypass of abdominal aortic aneurysm: feasibility study. *Radiology* 1992; 184:185–190
18. Boudghene F, Anidjar S, Allaire E, et al. Endovascular grafting in elastase-induced experimental aortic aneurysms in dogs: feasibility and preliminary results. *JVIR* 1993;4:497–504
19. Forsting M, Resch KM, von Kummer R, et al. Balloon occlusion of a giant lower basilar aneurysm: death due to thrombosis of the aneurysm. *AJNR Am J Neuroradiol* 1991;12:1063–1066
20. Litofsky NS, Viñuela F, Giannotta SL. Progressive visual loss after electrothrombosis treatment of a giant intracranial aneurysm: case report. *Neurosurgery* 1994;34:548–551
21. Drake CG. Ligation of the vertebral (unilateral or bilateral) or basilar artery in the treatment of large intracranial aneurysms. *J Neurosurg* 1975;43:225–274
22. Makita K, Tsuchiya K, Furui S, et al. Nondissecting vertebral fusiform aneurysm: embolization using wire-directed detachable balloons. *AJNR Am J Neuroradiol* 1993;14:340–342
23. Sugita K, Kobayashi S, Inoue T, et al. New angled fenestrated clips for fusiform vertebral artery aneurysms. *J Neurosurg* 1981; 54:346–350
24. Numaguchi Y, Pevsner PH, Rigamonti D, et al. Platinum coil treatment of complex aneurysms of the vertebrobasilar circulation. *Neuroradiology* 1992;34:252–255
25. Fox AJ, Viñuela F, Pelz DM, et al. Use of detachable balloons for proximal artery occlusion in the treatment of unclippable cerebral aneurysms. *J Neurosurg* 1987;66:40–46
26. Eckard DA, Purdy PD, Bonte FJ. Temporary balloon occlusion of the carotid artery combined with brain blood flow imaging as a test to predict tolerance prior to permanent carotid sacrifice. *AJNR Am J Neuroradiol* 1992;13:1565–1569
27. Nishizaki T, Tamaki N, Takeda N, et al. Dolichoectatic basilar artery: a review of 23 cases. *Stroke* 1986;17:1277–1281
28. Watanabe T, Sato K, Yoshimoto T. Basilar artery occlusion caused by thrombosis of atherosclerotic fusiform aneurysm of the basilar artery. *Stroke* 1994;25:1068–1070
29. Hagen B, Harnoss BM, Trabhardt S, et al. Self-expandable macroporous nitinol stents for transfemoral exclusion of aortic aneurysms in dogs: preliminary results. *Cardiovasc Intervent Radiol* 1993;16:339–342
30. Drake CG. Giant intracranial aneurysms: experience with surgical treatment in 174 patients. *Clin Neurosurg* 1979;26:12–95
31. Hallbach VV, Higashida RT, Dowd CF, et al. The efficacy of endosaccular aneurysm occlusion in alleviating neurological deficits produced by mass effect. *J Neurosurg* 1994;80:659–666
32. Tominaga R, Kambic HE, Emoto H, et al. Effects of design geometry of intravascular endoprostheses on stenosis rate in normal rabbits. *Am Heart J* 1992;123:21–28
33. Robison KA, Roubin G, King S, et al. Correlated microscopic observations of arterial responses to intravascular stenting. *Scanning Microsc* 1989;3:665–679

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