

Flow Diversion Radial Artery Bypass Graft Coupled With Terminal Basilar Artery Occlusion for the Treatment of Complex Basilar Apex Aneurysms: Operative Nuances

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BACKGROUND: A subset of basilar apex aneurysms are unsuitable for either primary microsurgical clipping or endovascular coiling. These complex aneurysms can be treated by terminal basilar artery occlusion, but only if collateral circulation is adequate. To circumvent these complications, a high-flow vertebral artery-posterior cerebral artery or middle cerebral artery-posterior cerebral artery bypass may be performed to create an adequate collateral circulation to allow treatment of the aneurysm by basilar artery occlusion and/or clipping.

OBJECTIVE: To discuss the operative nuances of this approach in the case of a 47-year-old man with progressive hemiparesis resulting from brainstem compression from a giant, unruptured basilar apex aneurysm with absent posterior communicating artery collaterals and incorporation of bilateral superior cerebellar arteries and posterior cerebral arteries within the aneurysm neck.

METHODS: The patient underwent a staged bypass from V3 to P2 coupled with terminal basilar artery occlusion.

RESULTS: The patient initially presented as modified Rankin Scale score 2 with right hemiparesis. The aneurysm ruptured after the first stage of the operation, and the patient underwent a V3 to P2 bypass the next day. His postprocedural neurologic decline improved at the 14-month follow-up to modified Rankin Scale score 2, with substantial reduction in aneurysm size observed at 9 months. The outcomes for 3 other bypass cases for basilar apex aneurysms are also summarized.

CONCLUSION: We discuss the indications, preoperative diagnostic workup, operative management, and postoperative outcomes in managing challenging basilar apex aneurysms. In our experience, high-flow bypass procedures with or without Hunterian ligation in the treatment of these aneurysms are well tolerated with good long-term results.

KEY WORDS: Aneurysm, Basilar artery, Cerebral bypass, Hunterian ligation

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WHAT IS THIS BOX?

A QR Code is a matrix barcode readable by QR scanners, mobile phones with cameras, and smartphones. The QR Code above links to Supplemental Digital Content from this article.

Microsurgical clipping of small and some large basilar apex aneurysms can be safely performed as a result of significant advances in vascular and skull base microsurgery.

ABBREVIATIONS: BA, basilar artery; mRS, modified Rankin Scale; PCA, posterior cerebral artery; PCoA, posterior communicating artery; SCA, superior cerebellar artery; STA, superficial temporal artery; VA, vertebral artery

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The majority of these aneurysms can be accessed through frontotemporal-transcavernous, subtemporal-transzygomatic, or transpetrosal approaches.¹⁻¹⁰ Drake's experience since 1971 has demonstrated a combined 4.2% morbidity and mortality rate over 179 unruptured vertebrobasilar aneurysms up to 25 mm in diameter.² In a recent series, 21 patients with unruptured basilar tip aneurysms <7 mm who underwent microsurgical clipping all had a good outcome,¹¹ with only transient third nerve palsy observed in 38%.

Nonetheless, the modern treatment of basilar apex aneurysms has witnessed endovascular

approaches largely supplant microsurgical clipping with excellent results, provided that the aneurysm neck anatomy is favorable.^{12,13} However, endovascular treatment is associated with a high recurrence rate. Recurrences are usually managed by repeat coiling with or without the assistance of stents. For this reason, continued and close follow-up of such patients is obligatory because recanalization is observed in as many as 38.9% of patients, with retreatment required in 27.8% of patients without stents and 7.8% when stents are used.¹⁴

For very large or giant aneurysms, a different picture is seen despite the best contemporary techniques. These complex basilar apex aneurysms share features that preclude successful and durable occlusion in either the ruptured or unruptured state through endovascular or open microsurgical methods. They generally are large, spanning ≥ 19 mm, with some demonstrating mass effect via compression on the brainstem. Often, they are partially thrombosed or calcified, with involvement of parent vessels and perforators. In these cases, endovascular coiling and microsurgical clipping are not feasible treatment options.

The senior author has adopted an approach to complex basilar apex aneurysms that emphasizes high-flow bypass grafts with hunterian ligation and/or aneurysm clipping (partial occlusion of the aneurysm or the occlusion of 1 posterior cerebral artery [PCA]) when the natural collateral circulation is inadequate. The combination of robust collateral circulation provided by the bypass and the elimination of the flow jet effect into the lumen of the aneurysm by the occlusion of the basilar artery (BA) facilitates either complete thrombosis of the aneurysm or thrombosis with a small stable neck while perfusion through the perforators remains preserved.

In this article, we present 4 cases of complex terminal BA apex aneurysms treated by the creation of a new collateral artery from the vertebral artery (VA) to the PCA or the middle cerebral artery to the PCA using a radial artery interposition graft, followed by clipping of the aneurysm (1 case) and terminal BA occlusion (3 cases, one of which also had partial clipping of an aneurysmal sac), with a good functional and radiographic outcome in all patients. An illustrative case is discussed in detail. The indications, operative technique and nuances, and results are discussed. Our early results suggest that this technique may be more broadly applicable in the treatment of these difficult patients and may be a good alternative to both endovascular techniques and clipping under deep hypothermic circulatory arrest.

INDICATIONS AND PREOPERATIVE WORKUP

Patients with very complex BA apex aneurysms may be defined patients with aneurysms > 19 mm (some very large, some giant), those with considerable thrombus in their lumen, patients in whom 1 or both PCAs arise from the sac of the aneurysm, those with previously coiled or clipped BA aneurysms with recurrence, and those patients in whom the entire terminal BA is dilated and dysplastic in the form of an aneurysm. In cases in which a single posterior communicating artery (PCoA) supplies the posterior

circulation, the risk of stroke is 26%,¹⁵ and we generally forgo balloon test occlusion. Moreover, a symptomatic balloon test occlusion of the BA is not necessarily indicative of failure of hunterian ligation because the balloon may occlude brainstem perforators.¹⁶ Thus, in such cases, the judgment of the surgeon is imperative in determining the need for balloon test occlusion. Certainly, when both PCoAs are small, we opt to proceed with preparations for bypass in the setting of complex basilar apex aneurysms.

Three-dimensional digital subtraction angiography is performed on all patients, which provides a good understanding of the aneurysm conformation and its relation to large brainstem perforators, the origin of the PCA and superior cerebellar artery (SCA) branches, and the location of the vein of Labbé. The Allcock test, in which 1 or both carotid arteries are compressed during injection of the VA, is used to confirm that the PCoA collaterals are small.^{15,17} In conjunction with cerebral angiography, we use computed tomographic angiography information to understand the relationship of the aneurysm to the skull base and magnetic resonance imaging to better define the true size of the aneurysm in relation to the soft tissues. Information garnered from both imaging modalities is particularly useful in the preoperative study of giant aneurysms harboring significant intraluminal thrombosis and calcification, which may prevent successful clip application.

Bilateral radial artery and saphenous vein mapping is performed by duplex scanning, and an Allen test is performed to test the adequacy of the palmar arch collateral. We prefer to use a radial artery that is well collateralized by the ulnar artery and is at least 0.2 cm in diameter, preferably > 0.23 cm. If a suitable radial artery is not available, a saphenous vein graft that is at least 0.25 cm in diameter and about 15 cm in length may be harvested. The course of the saphenous vein is outlined on the skin surface at the time of the ultrasound examination, which facilitates subsequent harvesting. If neither the radial artery nor saphenous vein is available, the anterior tibial artery may rarely be used if sufficiently collateralized by the posterior tibial artery. Vessel extraction must be planned during patient positioning, and the vessel is exposed at any time during the operation but is removed just before the anastomosis procedure. After removal from the patient, both the radial artery and the saphenous vein are flushed with heparinized saline and then pressure distended to avoid postoperative spasm, which is especially important when radial artery grafts are used.^{18,19}

ANESTHESIA AND NEUROPHYSIOLOGICAL MONITORING

Total intravenous anesthesia is used in patients, allowing monitoring by compressed spectral array electroencephalography, somatosensory evoked potentials, and motor evoked potentials. Brainstem auditory evoked responses may also be monitored when possible. During temporary occlusion for bypass procedures, the patient is ordinarily kept normotensive and placed in burst

suppression with the use of propofol for cerebral protection. During surgery, the brain must be as relaxed as possible, and in addition to mild hyperventilation and diuretics, a ventriculostomy may be used. The patient is placed on aspirin 325 mg preoperatively, and its efficacy is tested with the VerifyNow aspirin activity test (Accumetrics, Inc, San Diego, California). Provisions are usually made for intraoperative angiography, although because of the use of micro-Doppler flowmetry, somatosensory evoked potential/motor evoked potential/brainstem auditory evoked response monitoring, and indocyanine green angiography, it is rarely necessary.

OPERATIVE TECHNIQUE

Craniotomy

The patient is positioned supine with the head turned 45° away from the side of the operation when a frontotemporal orbitozygomatic approach is used and in a supine lateral position (head turned 70°, heavy roll under the shoulder) when a transpetrosal approach combined with the exposure of the VA is used.

In case of the frontotemporal, orbitozygomatic approach, the entire operation can be performed in a single stage. In case of the transpetrosal–far lateral approach, the operation may be accomplished in 2 stages, which allows the skull base exposure to be performed on the first day and the graft exposure and extraction, bypass anastomosis, and BA occlusion to be undertaken on the following day. This staging allows the entire surgical team to perform optimally throughout the course of the operation. Nevertheless, when dealing with a ruptured basilar apex aneurysm, every effort should be made to complete the operation in 1 day.

Craniotomy and Skull Base Exposures

For the frontotemporal approach, a frontotemporal craniotomy is performed, followed by an orbitozygomatic osteotomy, with decompression of the superior orbital fissure and an anterior clinoidectomy. The donor vessel for the bypass may be the M2 branch of the middle cerebral artery (as used in patient 3 in the Table), the external carotid artery in the neck, or the last portion of the internal maxillary artery²⁰ if the size is adequate as assessed on preoperative angiography. After dural opening, the Sylvian fissure is split widely. The temporal lobe (usually on the right side) may need to be mobilized laterally after the anterior temporal bridging veins are divided. If this lobe is very full as a result of subarachnoid hemorrhage, then the medial portion of the temporal lobe may be resected to afford more room and to avoid retraction-related problems. The tentorium must be carefully divided posterior to the entrance point of the trochlear nerve, and its edge may be retracted with a traction suture placed into the floor of the middle cranial fossa.

For the transpetrosal–far lateral approach, the right side is generally preferred. However, the left side may be selected either because of a larger PCA or because of the desire to explore the aneurysm and determine whether it can be clipped when more

eccentric to the left side. In these cases, a question mark-shaped temporal and retrosigmoid skin incision is made, and the temporalis muscle is separated into 2 parts longitudinally. The posterior portion of the temporalis muscle is rotated to cover the mastoidal air cells and antrum at the time of closing. The VA is exposed in its V3 segment, and if necessary, the foramen transversarium of C1 is opened and the terminal V2 portion of the VA is unroofed to mobilize the VA. This allows more space during application of a temporary clip and for suturing the anastomosis. Any bleeding arising from the vertebral venous plexus is controlled by either bipolar cautery or the injection of fibrin glue.²¹ Then, a temporal and retrosigmoid craniotomy is performed, following which a mastoidectomy is completed to obtain a presigmoid exposure. A partial labyrinthectomy and petrous apicectomy may be performed if the presigmoid space is inadequate because of a large sinus.²² The dura is opened in the presigmoid and retrosigmoid space and in the temporal region, with care taken to avoid the main vein of Labbé. After ligation and division of the superior petrosal sinus, the tentorium is carefully divided, avoiding any injury to the SCA or cranial nerve IV. The Meckel cave may be opened to gain more space anteriorly. The ipsilateral PCA (P2 segment) and the BA proximal to the aneurysm are dissected out, and the aneurysm can be simultaneously explored at this point if it is reasonable to do so.

Vessel Anastomosis

The P2 segment of the PCA, which is normally devoid of perforators, is exposed lateral to the midbrain and isolated with a small rubber dam. If large perforators emerge from the P2, they are carefully preserved. Temporary clips are applied at either end of the anastomotic site. Temporary occlusion of the PCA can be performed for as long as 50 minutes under burst suppression.¹⁹ The patient is given 3000 U heparin intravenously, and the activated clotting time is monitored to achieve a goal of >250 seconds. In addition to burst suppression, blood pressure may be transiently elevated by 20% to augment collateral flow when the aneurysm is unruptured. A 3- to 5-mm ovoid arteriotomy in the PCA is generated and an end-to-side anastomosis is completed after anchoring sutures are placed at each end of the arteriotomy to the graft. Next, suturing is started at heel of the distal graft, progressing to the toe of the graft with interrupted or running sutures using 8-0 or 9-0 sutures. Suturing is performed on the side deep to the surgeon and then flipped back to complete the closure more superficially.^{19,22,23} During the entire procedure, the field is irrigated free of blood with heparinized saline, and at the end, the graft is primed with heparinized saline to eliminate any kinks or twists and to flush out trapped air. A temporary clip is applied to the graft about 2 cm proximal to the anastomotic site. The temporary clips are then removed from the PCA, and any large leaks along the suture line are sealed with additional interrupted stitches.

TABLE. Treated Patients, Aneurysm Locations and Characteristics, and Follow-up^a

Case	Age	Sex, y	Aneurysm Architecture	History	Procedure	Filling Volume, mm		
						AP	Transverse	Height
1	47	M	Basilar apex incorporating bilateral PCAs and SCAs; small PCoAs bilaterally	Progressive right hemiparesis; right pronator drift and intermittent facial numbness; dizziness for 2 mo	Left presigmoid, transpetrosal, and subtemporal exposure; 2 d later, left V3 to P2 bypass with a radial artery graft and hunterian ligation of the BA below the SCA takeoffs	25	23	32
2	62	F	Basilar apex incorporating bilateral PCAs; large PCoA on right, small PCoA on left	Previous coil embolization 4 times; now with progressive spastic right hemiparesis, dysphagia, Parinaud syndrome, and right facial droop	Left far lateral partial transcondylar approach with exposure of the V2 and V3; 3 d later, left V3 to P2 bypass with a saphenous vein graft (radial arteries not suitable) followed by hunterian ligation of the upper basilar trunk inferior to the superior cerebellar artery	16	16	17
3	45	M	Fusiform basilar apex aneurysm incorporating bilateral PCAs and SCAs, large PCoA on left	Ruptured BA aneurysm clipped 5 y earlier with recurrence and rebleed	Right frontotemporal craniotomy; right external carotid to P2 radial artery bypass; clip ligation of the aneurysm	9	9.2	8.6
4	72	F	Basilar apex incorporating bilateral PCAs; large PCoA on right, small PCoA on left	Previous coil embolization 5 times; Hunt-Hess grade 4 with improvement to mRS 2; re-presenting with interval growth of aneurysm	Right frontotemporal craniotomy; right MCA to right P2 radial artery graft; clip ligation of the aneurysm with occlusion of the right PCA	21	19	25

Case	Postoperative	Residual Lumen on Follow-up Angiography	Treated Filling Volume, mm			Preoperative mRS	Follow-up mRS	Follow-up, mo
			AP	Transverse	Height			
1	Intraoperative rupture after first stage; ventriculoperitoneal shunt placement; postoperative aphasia and right hemiparesis with gradual recovery	Partial thrombosis	8	5.9	5	2	2	14
2	No neurological change postoperatively	Partial thrombosis	6	7.5	9	4	3	19
3	Postoperative bypass thrombosis with re-exploration on postoperative day 1; small left pontine stroke; 3-mo hospitalization; persistent short-term memory deficits but able to live independently	No residual	...	...	...	2	2	19
4	Transient decline postoperatively for 1 wk with improvement to baseline at 3 mo; delayed thrombosis of bypass at 18 mo; no sequelae	No residual	...	...	...	2	2	48

^aAP, anteroposterior; BA, basilar artery; MCA, middle cerebral artery; mRS, modified Rankin Scale; PCA, posterior cerebral artery; PCoA, posterior communicating artery; SCA, superior cerebellar artery.

The proximal anastomosis is performed next. In the case of the frontotemporal approach, the graft is brought to the donor artery site without twisting the graft. This is accomplished by temporarily distending the graft and holding it dilated by means of a temporary clip or a small ligature at the proximal end. A saphenous vein graft should be sutured under slight tension because it will expand under arterial pressure.¹⁹ After temporary clips are placed on the donor artery, an arteriotomy is created using a vascular punch, usually 3.5 or 4 mm in diameter, depending on the diameter of the graft vessel. The graft is then sutured end to side with 8-0 nylon sutures. Just before the last suture is tied, the temporary clip on the graft is released to flush out air and thrombus that may have formed during the creation of the bypass; the proximal and then the distal clips are removed in succession. Any leaks that have formed are closed with interrupted sutures. In the case of the transpetrosal-far lateral approach, the graft is brought deep to the sigmoid sinus to exit in the retrosigmoid area, and the anastomosis is performed to the VA.

Aneurysm Treatment After Bypass

After the bypass is completed, the upper BA is closed with a permanent aneurysm clip, usually just inferior to the SCA origin and above any perforators arising from the mid BA. Direct clipping of the aneurysm or a prominent lobe of the aneurysm can also be attempted if the morphology is suitable (Table). The somatosensory evoked potentials and motor evoked potentials should be rechecked at this time. Micro-Doppler probe (Mizuho America, Inc, Beverly, Massachusetts) insonation of the graft, the ipsilateral SCA, and the PCA and indocyanine green angiography are then performed. Together, they are used to assess patency of the graft and flow through the PCA, SCA, and associated perforators and to confirm reduction or obliteration of flow to the aneurysm.

Closure

The dura is closed in a circumferential fashion using a free autologous pericranial graft for closure. In patients with a presigmoidal exposure, the mastoid bone air cells and antrum aditus are sealed with bone wax, and the posterior half of the temporalis muscle and accompanying pericranium are rotated over the mastoidal defect to promote healing and to avoid cerebrospinal fluid leak.²⁴ Bone is replaced and plated, provided that excess brain edema has not occurred. If there is any concern for possible swelling, we store the bone flap at -80°C and perform an autologous cranioplasty in 10 to 14 days after surgery once the swelling has subsided.

Postoperative Care

Aspirin is administered daily for about 6 months after surgery. Transcranial Doppler flowmetry is performed daily to assess the patency of the graft and to calculate estimated flow volumes. Blood pressure is generally tightly controlled in the first few days after the bypass, with gradual relaxation of parameters 2 days after surgery. An

immediate postoperative computed tomographic angiography and a cerebral angiogram the next morning are performed to assess the graft and flow to the aneurysm. Longer-term follow-up is assessed via computed tomographic angiography and cerebral angiography.

CASE PRESENTATION

History

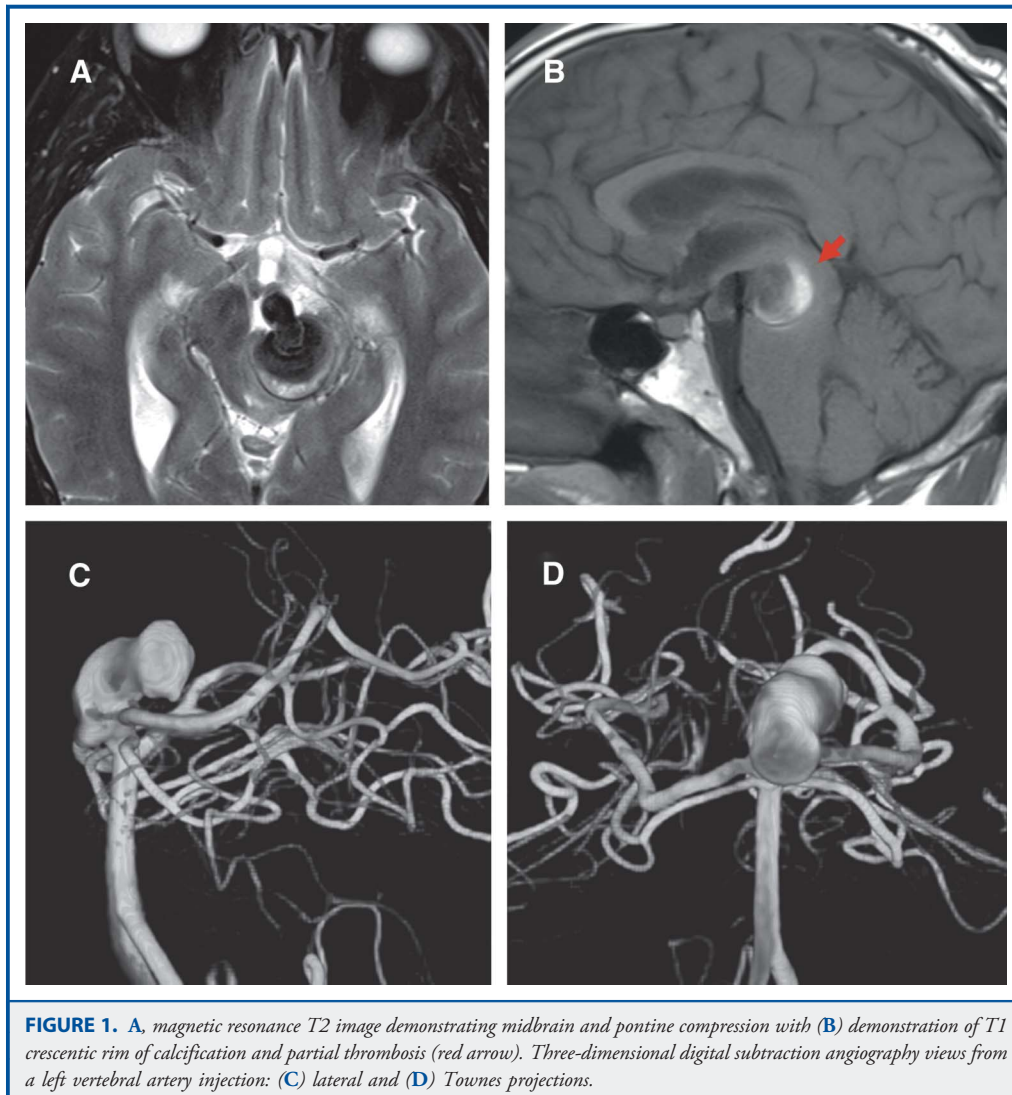
A 47-year-old man with a 1-month history of progressive right hemiparesis, right pronator drift, and intermittent facial numbness and 2-month history of dizziness was found to have a giant basilar tip aneurysm measuring $32 \times 25 \times 23$ mm, demonstrating substantial midbrain compression (Table, patient 1 and Figure 1). He was at modified Rankin Scale (mRS) score 2 preoperatively. Cerebral angiography demonstrated the absence of PCoA collaterals bilaterally (Figure 2), and the aneurysm was partially thrombosed, incorporating the takeoffs of both the SCAs and PCAs at its neck (Figure 1C and 1D).

Surgery

We opted to perform a 2-stage operation, with a left presigmoid, transpetrosal, and subtemporal exposure and placement of a frontal ventriculostomy at the first stage without dural opening (Figure 3A). The patient sustained a small, self-limited rupture from the aneurysm after the first-stage procedure. This hemorrhage may have been due to the tenuous nature of the aneurysm. The next day, the patient underwent a left V3 to P2 bypass with a radial artery interposition graft and terminal BA occlusion (Figures 3B-3D and Figure 4A; see also Video 1, Supplemental Digital Content 1, <http://links.lww.com/NEU/A524>, which demonstrates a V3 to P2 bypass with radial artery interposition graft and terminal BA occlusion). Postoperatively, the patient was aphasic with a dense right hemiplegia, possibly caused by partial thrombosis of the aneurysm or involvement of one of the perforators. However, his condition began to improve after 10 days, ultimately progressing to inpatient rehabilitation. At the 3-month follow-up, his functional status improved to an mRS score of 3, with 4/5 strength on the right side and improvement in his speech fluency. By 14 months, he had improved to functional independence (mRS score of 2). Follow-up imaging at 9 months demonstrated a small residual aneurysm neck measuring 8 mm wide and 5 mm tall with a widely patent bypass graft (Figure 4B-4D).

SUMMARY OF CASES

The 4 patients treated by this operative technique are summarized in the Table. It should be noted that 1 patient (patient 3, Table) suffered an injury to the radial artery graft with a drill at the time of closure, but this was successfully revised. All of the patients had an mRS score of 2 to 3, with an improvement from or return to the preoperative condition. Three of the bypasses were patent at the long-term follow-up, but 1 saphenous vein graft occluded spontaneously as a result of enlargement of the patient's ipsilateral PCoA, and this was clinically



asymptomatic. Two aneurysms were completely occluded, whereas 2 others had small but stable neck remnants.

DISCUSSION

The treatment of very large (≥ 19 mm)²⁵ or giant (≥ 25 mm) basilar apex aneurysms is associated with substantial postoperative morbidity, as high as 19.4%.²⁶ Direct surgical clipping of giant vertebrobasilar aneurysms was not possible in some 66% of patients from Drake's series.^{3,15,27-31} Unruptured giant basilar apex aneurysms presenting with symptoms of mass effect are associated with a risk ratio for poor outcome of 80, and surgical morbidity, excluding third cranial nerve palsy, was observed in 23.5% of patients with giant ruptured or unruptured aneurysms.²⁶ Endovascular therapy also falls short in the treatment of these larger aneurysms.^{26,32} For very large and giant basilar tip aneurysms, a 26%

incomplete occlusion rate and a 25% recurrence rate are reported for endovascular coiling therapy.³³ Furthermore, broad-necked aneurysms incorporating the PCA origins are not suitable for coil embolization,³⁴ and the use of stents in ruptured aneurysms is generally contraindicated because of the requirement of prolonged antiplatelet therapy. Such aneurysms often feature calcified walls with partial thrombosis and incorporate parent and perforator vessels.³⁵ Clip reconstruction, thrombectomy, resection of the atheroma, and aneurysmorrhaphy can be treacherous in such cases because flow to involved perforators can be compromised, and the time for temporary occlusion will usually be >10 minutes.³⁶ Some of these aneurysms have undergone failed coil embolization, with recurrence observed over time despite repeated treatments.^{36,37} The deep hypothermic circulatory arrest technique has been used for such aneurysms to prolong the safe ischemic time, but the aneurysm still needs to have a "neck" allowing repair, and an observed mortality of

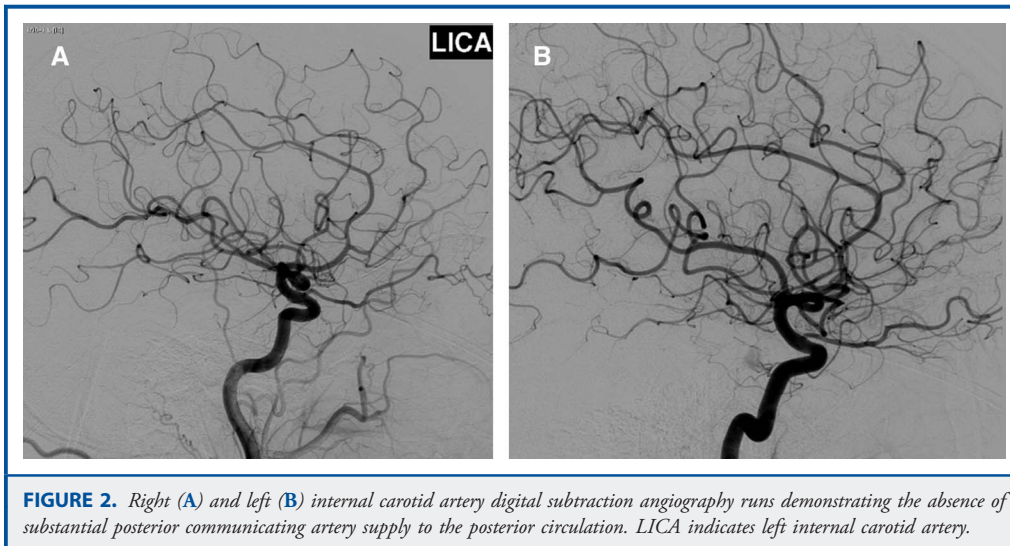


FIGURE 2. Right (A) and left (B) internal carotid artery digital subtraction angiography runs demonstrating the absence of substantial posterior communicating artery supply to the posterior circulation. LICA indicates left internal carotid artery.

14 to 15% is associated with the deep hypothermic circulatory arrest technique.^{38,39} The results are also unpredictable, with severe brain ischemia seen even after an arrest time of <30 minutes (L.N.S., unpublished data).

In cases when direct basilar tip aneurysm obliteration cannot be directly accomplished, flow diversion can be performed with the goal of altering flow dynamics to encourage aneurysm involution or thrombosis.³⁷ The most straightforward method for flow diversion

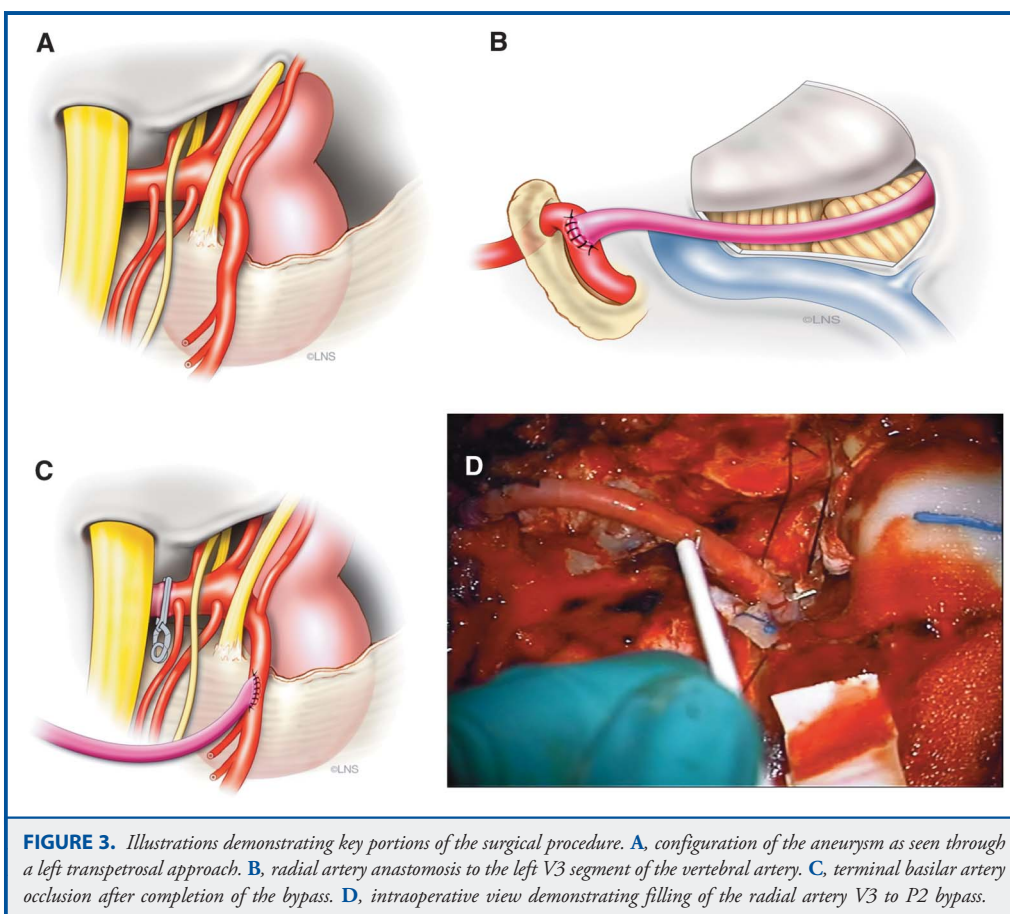
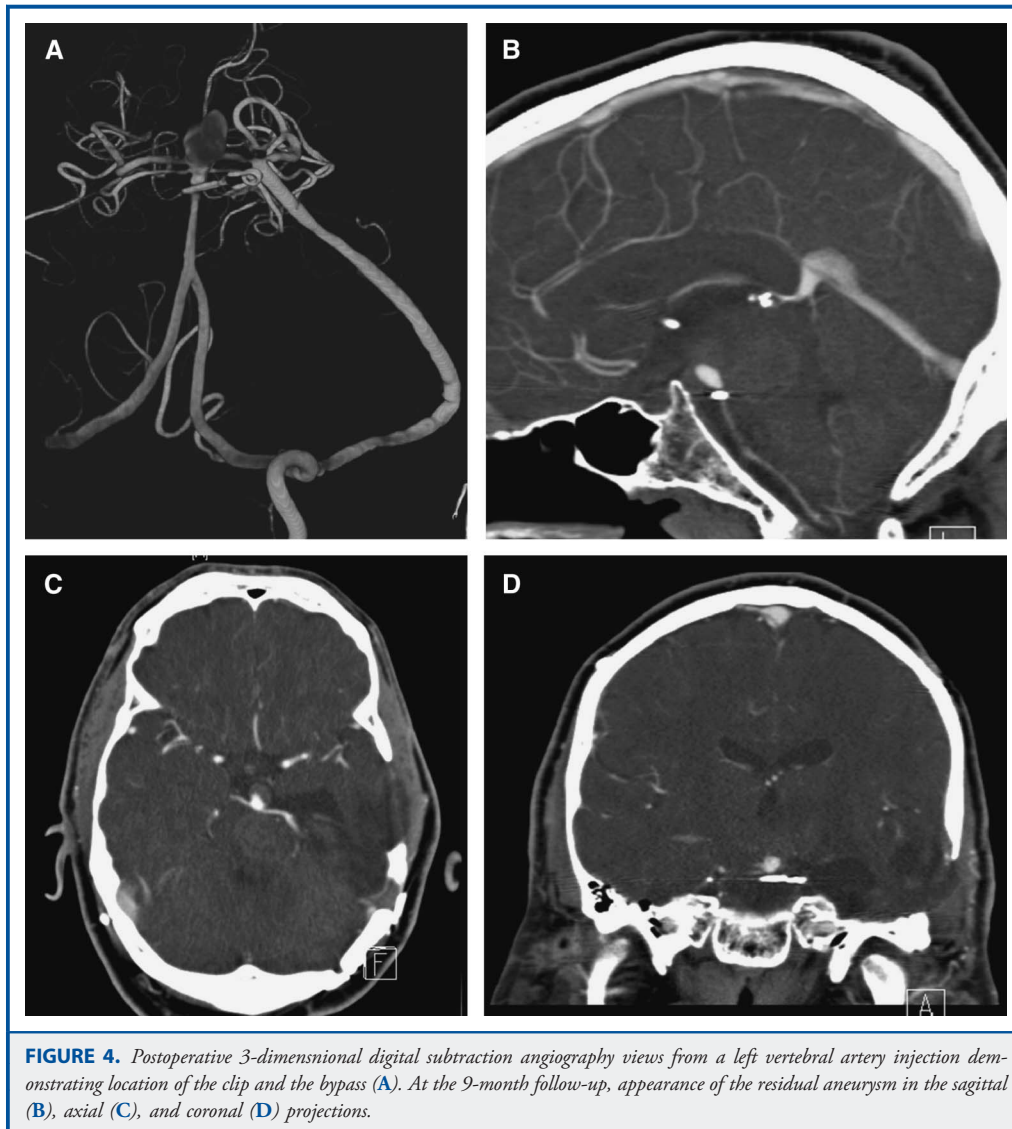


FIGURE 3. Illustrations demonstrating key portions of the surgical procedure. A, configuration of the aneurysm as seen through a left transpetrosal approach. B, radial artery anastomosis to the left V3 segment of the vertebral artery. C, terminal basilar artery occlusion after completion of the bypass. D, intraoperative view demonstrating filling of the radial artery V3 to P2 bypass.



uses the principle of hunterian ligation or proximal artery occlusion. In the case of basilar apex aneurysms, occlusion of the BA is achieved just proximal to the SCAs in a perforator-free zone.^{15-17,40} A landmark series published by Steinberg et al¹⁵ in 1993 demonstrated the results from basilar or VA occlusion in 201 patients with posterior circulation aneurysms; of these, 41% of the patients harbored aneurysms of the basilar apex. Excellent or good outcomes (good defined as approximately an mRS score of 3) were achieved in 64% of patients with basilar apex aneurysms. Through their analysis, Steinberg et al demonstrated that a key factor in the avoidance of postoperative brainstem ischemia was the presence of sufficient collateral circulation. The presence of bilateral small PCoAs, defined as < 1-mm caliber each, was associated with a 45% chance of ischemic deficit in the setting of upper BA occlusion.¹⁵ A single large PCoA \geq 1 mm was associated with a 26% significant

stroke rate compared with a situation in which both PCoAs were large, which led to a 4% stroke rate.^{15,40} In more recent work using this approach, 20% of patients sustained neurological deficits after hunterian ligation of complex BA aneurysms,¹⁶ with 87% observed to have excellent long-term outcome (mRS score \leq 2). These data emphasize the importance of careful screening of candidates for proximal occlusion therapy, namely the presence of robust collateral flow demonstrated by the presence of at least 1 suitable-caliber PCoA³⁴ and preferably 2 large PCoAs.

In situations when adequate collateral flow through the PCoA does not exist for large or giant basilar apex aneurysms, several groups have reported using low-flow bypass methods, namely superficial temporary artery (STA) to PCA or STA to SCA bypasses in conjunction with hunterian ligation^{41,42} or endovascular coil embolization of the BA.^{43,44} These methods are often

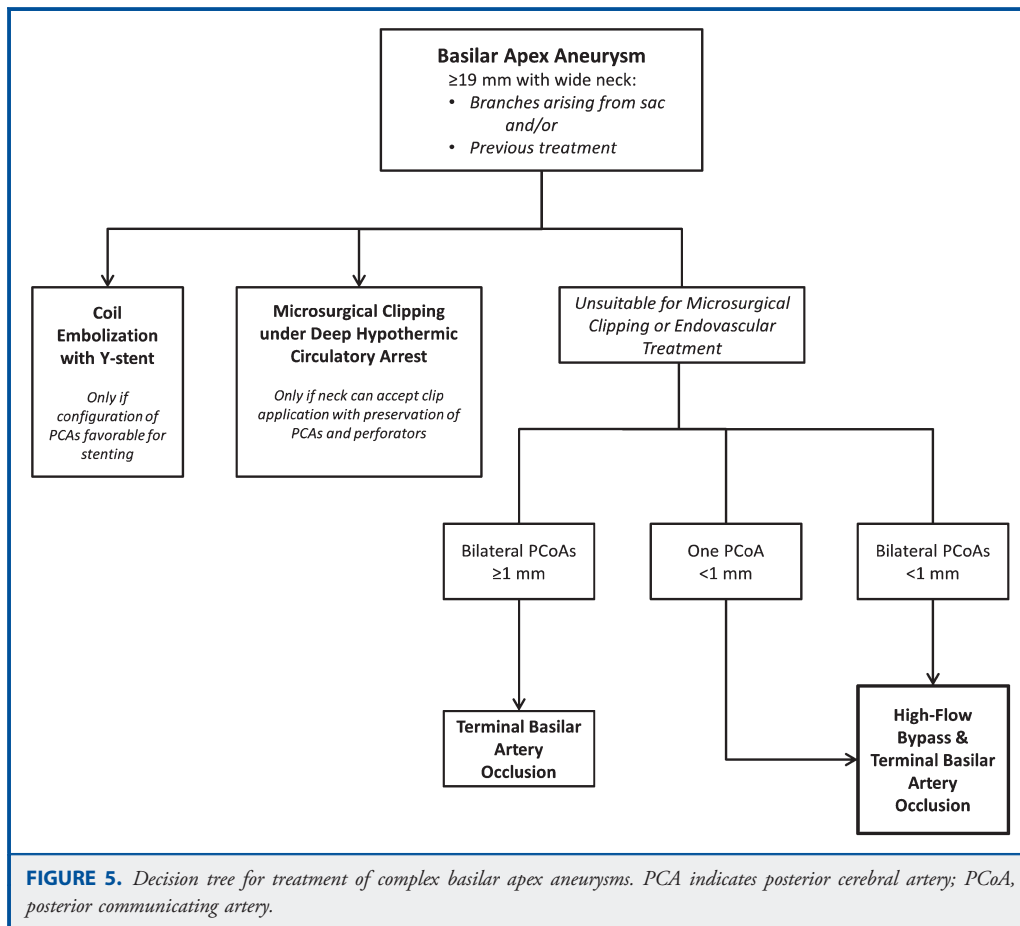
multistage operations in which collateral flow is established first and then basilar and PCA occlusion is sequentially performed for flow redirection.^{41,45} High-flow bypass methods with external carotid artery-PCA^{18,46} or middle cerebral artery-PCA^{18,37} have also been reported in several cases, with mixed results.

A high-flow bypass to the PCA, in conjunction with terminal BA occlusion, redirects collateral flow, leading to conversion of a BA aneurysm to a side-wall aneurysm.^{36,37,45} Thrombosis of the perforating arteries, including the thalamoperforators or circumflex arteries of the brainstem, has been observed in lower-flow bypass settings,⁴⁵ and a tailored flow reduction strategy^{41,42,45} may not be suitable in the absence of sufficient flow through existing PCoAs. A high-flow bypass may reduce the risk of delayed perforator occlusion. From a technical standpoint, using larger-caliber radial artery or saphenous vein grafts avoids the problem of luminal narrowing over the length of the anastomosis faced when using smaller caliber vessels such as the STA for bypass. We believe that high-flow grafts are easier to manipulate and to use for the anastomotic procedure. Furthermore, we have shied away from low-flow bypass approaches, given the possibility that they may be inadequate to supplant the posterior circulation in the absence of robust PCoAs when the terminal BA is

occluded. Nevertheless, a sufficiently large STA or occipital artery may suffice in specific cases.

We have now used this technique successfully in 4 patients with good results in the very limited sample size. The treatment algorithm is summarized in Figure 5. Although external carotid artery-PCA bypasses are feasible, our recent shift to VA-PCA bypasses in the treatment of complex basilar tip aneurysms demonstrates their viability as an approach. The benefit is that the transpetrosal approach, helpful in exposing large or giant basilar apex aneurysms, is amenable to simultaneous exposure of the V2 and V3 segments of the VA required for the bypass procedure, as well as excellent exposure of the terminal BA territory. It should be noted that incomplete aneurysm thrombosis after bypass, combined with clipping or hunterian ligation, mandates very close follow-up. To date, we have not observed significant late complications, although long-term monitoring is required to determine whether those with residuals present a risk for rupture.

There is no question that the emergence of newer flow-diversion techniques will aid the treatment of posterior circulation aneurysms, including aneurysms previously refractory to clipping or coiling. Nevertheless, we see a clear role for high-flow bypass in



conjunction with proximal vessel sacrifice for the treatment of rare but complex and surgically refractory basilar apex aneurysms, in particular those lacking robust PCoA flow bilaterally to the posterior circulation. As we gain experience, we anticipate that this approach will be successfully extended to basilar trunk aneurysms.

Disclosures

Dr Sekhar has shares in SPISURGICAL Inc and Viket Medical. Dr Kim has shares in SPISURGICAL Inc. The other authors have no personal financial or institutional interest in any of the drugs, materials, or devices described in this article.

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COMMENTS

The authors present an interesting report of 4 complex basilar apex aneurysms treated with good results via high-flow bypass and flow redirection. The authors present their treatment algorithm, rationale, and technical experience. Similar techniques have been used to treat basilar apex/trunk aneurysms not amenable to clip or coil treatment, but the unique aspect of this small series is the use of a high-flow bypass. Further experience is required, however, to precisely define the specific population in need of a high-flow vs low-flow graft, the comparative morbidity associated with these more extensive (in some cases, 2-stage) procedures, and the long-term rupture and occlusion rates for treated aneurysms. The ideal treatment for these patients remains uncertain, but the authors' experience certainly supports their strategy as a viable alternative.

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Robert F. Spetzler
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The authors have described their technique of performing a high-flow bypass to treat large and giant unclippable aneurysms at the basilar apex. The cases that they have presented do not have an effective endovascular or direct surgical treatment for the aneurysms. Hunterian ligation of the upper basilar artery seems to be the only viable treatment. It is well tolerated in most patients who demonstrate adequate posterior communicating arteries. For patients who have small or no posterior communicating arteries, a high-flow vascular bypass from the external carotid artery to the posterior cerebral artery precedes the hunterian ligation to avoid ischemic deficits, as described by some authors.

In the present report, the authors have used skull base approaches to access the recipient vessel and to explore the aneurysm. Their procedure differs from prior reports in the choice of the donor site for the bypass. They have chosen to implant the proximal end of the venous or radial artery graft in the middle cerebral artery (1 case), external carotid artery (1 case), and V3 segment of the vertebral artery (2 cases). Apart from the ease of having the donor and recipient sites of the grafting procedure in the same surgical field, there does not appear to be a significant advantage of using the external carotid artery as the donor vessel. These are high-risk operations, and there

appears to be an additional risk that the ipsilateral hemisphere is exposed to when the middle cerebral artery is used as the donor vessel. Although there are only 4 patients, the patency rates and aneurysm obliteration numbers are in keeping with the existing literature, although the patients have maintained modified Rankin Scale score of < 3. As the authors have pointed out, the 2 patients with filling of the residual neck need to be monitored closely. The authors are highly skilled and have shown that this is an alternative way of revascularizing the posterior circulation with a high-flow bypass with excellent results. An external carotid donor site is still an attractive choice for most surgeons attempting this operation.

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The authors describe the details of their operative approach for revascularization using radial artery or saphenous vein graft in the setting of proximal vessel occlusion for the treatment of complex basilar tip aneurysms. Such aneurysms, thought to be unsuitable for both endovascular therapies and direct clipping, pose a significant management challenge. As noted in the Discussion, the concept of proximal basilar occlusion to create flow diversion in this setting is well described, as are the techniques for bypass to the posterior cerebral artery. In this report, the authors outline particular nuances of their technique, including use of intraoperative monitoring, routine administration of aspirin and intraoperative heparin, and either an orbitozygomatic or a transpetrosal approach for exposing both the location of anastomosis and the basilar apex. It is important to note, however, that this exposure can also be accomplished with a standard subtemporal approach.¹

The relative advantages of a fully intracranial bypass using the middle cerebral artery as a donor vs the external carotid artery, use of radial artery vs saphenous vein, and other nuances are subject to debate and difficult to resolve in a small case series. The algorithm outlined highlights the reliance on angiographic determination of posterior communicating artery collateral, given the difficulty of interpretation for balloon test occlusion in the basilar artery. However, the notion that "high-flow" bypass required in this setting is synonymous with a radial artery or vein interposition graft, ignores the option for objective determination of the adequacy of simpler donors such as the superficial temporal artery and OA, using direct intraoperative blood flow measurements.² Such intraoperative flow measurements also allow immediate confirmation of bypass function and adequacy at the time of surgery.

Overall, the authors are to be congratulated for highlighting that good outcomes in experienced hands are feasible with revascularization and proximal occlusion in the management of these challenging basilar apex aneurysms.

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