Revascularization with Saphenous Vein Bypasses for Complex Intracranial Aneurysms

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ABSTRACT

Most intracranial aneurysms can be managed with either microsurgical clipping or endovascular coiling. A subset of complex aneurysms with aberrant anatomy or fusiform/dolichoectatic morphology may require revascularization as part of a strategy that occludes the aneurysm or parent artery or both. Bypass techniques have been invented to revascularize nearly every intracranial artery. An aneurysm that will require a saphenous vein bypass is one that cannot be treated with conventional microsurgical clipping or endovascular coiling and also requires deliberate sacrifice of a major intracranial artery as part of the alternative treatment strategy. In the past 7 years the senior author (MTL) has performed a total of 110 bypasses, of which 46 were for aneurysms. Twenty-two of these patients received high-flow extracranial-to-intracranial bypasses using saphenous vein grafts, of which 16 had aneurysms that were giant in size. We review the indications for saphenous vein bypasses for complex intracranial aneurysms, surgical techniques, and clinical management strategies.

KEYWORDS: Subarachnoid hemorrhage, intracranial aneurysm, microsurgery, revascularization, saphenous vein graft, anastomosis

Currently, most intracranial aneurysms can be managed with either direct microsurgical clipping or endovascular coiling. A subset of complex aneurysms with atypical anatomy (such as a wide-neck, fusiform, or dolichoectatic morphology; in-

traluminal thrombus; or aberrant branches originating from the aneurysm) cannot be treated with these conventional techniques. Consequently, alternative, indirect approaches may be required, including trapping, proximal parent artery occlusion

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(Hunterian ligation), or distal occlusion. When deliberate sacrifice of a major intracranial artery is planned, revascularization of the involved territory is often a prerequisite. Negative results from the international, randomized trial examining therapeutic efficacy of extracranial-to-intracranial (EC-IC) bypass surgery for ischemic stroke have not dampened enthusiasm for bypass surgery for this specific indication, and these delicate procedures remain an essential part of the microsurgical management of select aneurysms.¹⁻³

Bypass techniques have been established for almost every intracranial artery that might require revascularization.⁴⁻¹⁸ These can be categorized into low-flow EC-IC bypasses, high-flow EC-IC bypasses, and IC-IC (in situ) bypasses. Low-flow EC-IC bypasses are the original and most widely used bypasses, created with a single anastomosis between the superficial temporal artery and the middle cerebral artery (STA-MCA bypass).¹⁹ Other bypasses in this category include anastomoses between the STA and other parent arteries like the superior cerebellar artery (SCA) or posterior cerebral artery (PCA), as well as anastomoses between the occipital artery (OA) and recipient arteries in the posterior circulation and PCA. High-flow EC-IC bypasses utilize large-caliber interposition grafts (either the saphenous vein or radial artery), require two anastomoses on each end of the graft, and deliver significantly more blood flow than the STA.^{2,20} Finally, IC-IC or in situ bypasses join two intracranial arteries with a single anastomosis (usually side-to-side), with one artery serving as a donor vessel and the other serving as a recipient vessel. Included in this category are the revascularizations performed after aneurysm excision with end-to-end reanastomosis of the parent artery. The IC-IC bypasses are entirely intracranial, are less vulnerable to injury or occlusion, do not require harvesting an extracranial artery, and use donor and recipient arteries with diameters that are well matched in size.^{11,21-23}

High-flow EC-IC bypasses using saphenous vein graft are the focus of this article. We present a brief history of these procedures, indications, and technical details.

HISTORY OF SAPHENOUS VEIN BYPASSES

The first successful saphenous vein bypass was performed by Kunlin in 1948 for lower extremity atherosclerosis.²⁴ This concept was applied to coronary arteries by Sabiston in 1962.²⁵ In 1967, Donaghy²⁶ and Yasargil²⁷ independently performed the first EC-IC bypasses, both STA-MCA bypasses. This was soon followed by the first EC-IC bypass with a saphenous vein graft in 1971 by Loughheed.²⁸

One of the early indications for saphenous vein graft bypasses was to provide immediate high-volume collateral flow to the cerebral circulation in patients with impending cerebral infarction from advanced cerebro-occlusive disease.^{20,28} Their subsequent use in vascular neurosurgery was a natural extension of this early indication. The long length and large caliber of saphenous vein grafts make them ideal for a wide variety of bypasses. Different types of saphenous vein bypasses include long interposition bypasses from the cervical carotid artery to an intracranial vessel, short interposition bypasses from an intracranial vessel or a distal external carotid artery (ECA) branch to an intracranial vessel, tandem bypasses involving synthetic material and the saphenous vein graft, and bonnet bypasses with a contralateral proximal anastomosis. Table 1 summarizes the important bypasses that rely on the saphenous vein graft.^{4,18,28-46}

DIAGNOSTIC EVALUATION AND INDICATIONS FOR SAPHENOUS VEIN BYPASS

An aneurysm that will require a saphenous vein bypass is one that cannot be treated with conventional microsurgical clipping or endovascular coiling and also requires deliberate sacrifice of a major intracranial artery as part of the alternative treatment strategy.

Table 1 Summary of Saphenous Vein Bypasses

Name of Bypass	Proximal Anastomosis	Distal Anastomosis	Author
<i>Anterior Circulation Bypass</i>			
Cervical carotid artery-supraclinoid ICA bypass	CCA, ICA, ECA	Supraclinoid ICA	Lougheed et al (1971) ²⁸ ; Hunt, Snyder (1979) ²⁹ ; Iwabuchi et al (1979) ³⁰
Cervical carotid artery-MCA bypass	CCA, ICA, ECA	MCA	Diaz et al (1985) ³¹
Subclavian artery-MCA bypass	Subclavian artery	MCA	Spetzler et al (1980) ³²
Tandem bypass	Subclavian artery	MCA	Auguste et al (2001) ⁴
Cervical carotid artery-petrous ICA bypass	CCA, ICA, ECA	Petrous ICA	Fitzpatrick et al (1993) ³³
C ₃ -C ₅ bypass	Petrous ICA	Supraclinoid ICA	Spetzler et al (1990) ¹⁸
STA-MCA bypass with interposition graft	STA	MCA	Little et al (1983) ³⁴
Occipital artery-MCA bypass with interposition graft	Occipital artery	MCA	Little et al (1983) ³⁴
STA-ACA bypass with interposition graft	STA	ACA	Tanaka et al (1992) ³⁵
VA-MCA bypass	VA	MCA	Miele et al (2005) ³⁶
Bonnet bypass	Contralateral STA, ECA, MMA	MCA	Spetzler et al (1980) ³⁷ ; Kinugasa et al (1993) ³⁸ ; Owers et al (1987) ³⁹
<i>Posterior Circulation Bypass</i>			
Cervical carotid artery-basilar apex bypass	CCA, ICA, ECA	PCA, SCA	Sundt et al (1982) ⁴⁰
Cervical carotid artery-basilar trunk bypass	CCA, ICA, ECA	AICA	Sullivan et al (1999) ⁴¹
Cervical carotid artery-VA bypass	CCA, ICA, ECA	VA	Berguer et al (1998) ⁴²
Subclavian artery-VA bypass	Subclavian artery	VA	Berguer et al (1976) ⁴³ ; Takeuchi et al (1998) ⁴⁴
VA-VA bypass	VA	VA	Santoro et al (2002) ⁴⁵
VA-basilar apex bypass	VA	PCA, SCA	Takizawa et al (2001) ⁴⁶

CCA, common carotid artery; ICA, internal carotid artery; ECA, external carotid artery; MCA, middle cerebral artery; STA, superficial temporal artery; VA, vertebral artery; MMA, middle meningeal artery; PCA, posterior cerebral artery; SCA, superior cerebellar artery; ACA, anterior cerebral artery; AICA, anterior inferior cerebellar artery.

Treatment Failures with Conventional Clipping or Coiling

Certain aneurysm features that are apparent from diagnostic imaging can predict which aneurysms are likely to fail treatment with conventional techniques, the most important ones being fusiform or dolichoectatic morphology. These aneurysms have afferent and efferent arteries that are separated by aneurysm and typically cannot be clipped or coiled simply, the way that a saccular aneurysm can. Attempts at clip reconstruction and balloon- or stent-assisted coiling often result in incomplete obliteration of the aneurysm or occlusion of important branch arteries or both. Therefore, this morphology is a strong indication for a bypass,

followed by indirect aneurysm occlusion (trapping, proximal, or distal parent artery occlusion).

An important factor predicting failure of microsurgical clipping is surgical accessibility, which varies with aneurysm location. Aneurysms in the posterior circulation are less accessible than those in the anterior circulation, with the exception of aneurysms at the basilar apex and posterior inferior cerebellar artery (PICA). Aneurysms between these locations require skull base surgical approaches that are highly invasive, morbid, and unappealing to patients. In the anterior circulation, similar difficulties arise along the carotid artery from the petrous segment to the clinoid segment. Aneurysm clipping requires a pliable neck that can be closed by clip blades, making atherosclerotic or

heavily calcified aneurysms prone to failure. Neck calcification is best appreciated on computed tomography (CT) scans, but can be obscured by surrounding subarachnoid blood. Increasingly, unruptured aneurysms are diagnosed on magnetic resonance (MR) imaging and patients proceed to angiographic evaluation without ever undergoing CT scans. Neck calcification is more difficult to appreciate on MR images and, therefore, can be missed. A high index of suspicion and a preoperative CT scan are needed when considering surgical clipping in older patients with atherosclerosis elsewhere. Most surgical failures can be predicted preoperatively by careful analysis of these factors on diagnostic imaging studies.

Failures of endovascular coiling often relate to aneurysm morphology, specifically a broad aneurysm neck (high neck:dome ratio), extremes of size (small aneurysms < 3 mm in diameter, "blister," large, and giant aneurysms), outflow arteries incorporated in the aneurysm base or walls, and fusiform/dolichoectatic morphology. A broad aneurysm neck is problematic for two reasons. First, coils deployed in the sac typically assume a rounded shape that can result in herniation of coils into the parent artery lumen (when coils are densely packed to completely obliterate the aneurysm) or neck remnants (when coils are packed more distally to avoid herniation into the parent artery lumen). Balloon- and stent-assisted coiling techniques are useful for some broad-neck aneurysms, but each technique introduces additional risk of parent artery ischemia, perforation, distal thromboembolism, and occlusion of adjacent perforators and branch arteries by the lattice of the stent. Second, broad-neck aneurysms probably have a higher rate of aneurysm recurrence, because the hemodynamics at the inflow zone are more complex, the coils are not seated well in the sac, or for other reasons that are poorly understood. Extremely small aneurysms are difficult to coil because they will often have high neck:dome ratios and because their tight packing requires sharp turns of the coil. Large and giant aneurysms can often be obliterated with coils, but the late recurrence rate associated with these lesions is significantly higher

than with smaller aneurysms. In addition to the reasons mentioned above, these late failures may also be related to incomplete obliteration initially, pretreatment thrombus within the lumen, and incomplete endothelialization of the aneurysm orifice.

Endovascular therapy may also fail due to poor radiographic visualization of the aneurysm anatomy and its adjacent branches. Additional oblique angiograms or selective catheterization of the aneurysm may elucidate some of this anatomy. Poor arterial access to the aneurysm, either due to extreme tortuosity of the afferent arteries or atherosclerotic stenosis or occlusion, can also lead to treatment failures.

Testing Tolerance to Arterial Sacrifice

Recognizing these anatomical features that lead to treatment failure with microsurgical clipping and endovascular coiling is critical to identifying aneurysms that might require revascularization. In addition to the unsuitability for direct clipping or coiling, to be considered for a bypass an aneurysm must also require an alternative treatment that involves the planned occlusion of a major intracranial artery. Planned arterial occlusion includes proximal parent artery occlusion, distal occlusion, trapping, and the reversal blood flow through an aneurysm. The safety of planned arterial occlusion depends on a careful assessment of the patient's collateral circulation on a diagnostic angiogram and tolerance to the planned occlusion with a balloon test occlusion (BTO).

Angiography examines collateral circulation in leptomeningeal vessels and the circle of Willis, explicitly demonstrating competence of the posterior communicating arteries (PCoA), anterior communicating artery (ACoA), A1 anterior cerebral artery (ACA), and P1 PCA. However, angiography cannot predict whether a patient will tolerate an arterial occlusion. We exploit a BTO with a hypotensive challenge and cerebral blood flow studies because this technique offers a safe and reliable method for predicting tolerance. The protocol for BTO includes

conventional arterial occlusion with a balloon-tip catheter and assessment of neurological condition for 30 minutes. During this time, distal arterial back pressures are measured as an indirect assessment of collateral circulation. Patients who tolerate BTO subsequently undergo hypotensive challenge, decreasing mean arterial pressure 15 to 20 mm Hg with an intravenous vasodilating agent (nitroprusside drip). Patients also undergo a cerebral blood flow study during the BTO, either with xenon-computed tomography study, single photon emission CT study, or more recently with a CT perfusion study. Patients failing the conventional BTO are candidates for revascularization if direct treatment of their aneurysms will require deliberate arterial sacrifice. With these patients, a high-flow EC-IC bypass is typically needed to replace the blood flow that is lost with the intervention. Patients who tolerate conventional BTO, but have either low back pressures, neurological deterioration with hypotensive challenge, or perfusion defects on the cerebral blood flow study, are also candidates for bypass procedures if direct treatment of their aneurysms will require deliberate arterial sacrifice. However, these patients may need only a low-flow bypass, such as with an STA donor artery or an in situ donor artery.

Without the use of BTO in therapeutic planning, the alternative approach would be universal revascularization, or simply bypassing all patients in whom an intracranial artery is surgically or endovascularly occluded. This approach eliminates the risks of BTO, false-negative test results, and the risk of delayed ischemic deficits, but there will be patients in this treatment strategy who undergo needless bypass procedures and are exposed to surgical risks. In our experience at University of California, San Francisco, the risks of BTO and selective revascularization have been sufficiently low to favor what we consider a more selective and rational approach with BTO and hypotensive challenge combined with cerebral blood flow studies. However, one of the limitations of BTO is that not every artery that is considered for sacrifice can be evaluated with it. Some arteries like the PCA or PICA are too small in caliber for the type of

catheter used in the BTO. In these patients, the decision about whether to perform a bypass becomes biased and we utilize a more aggressive or universal revascularization approach.

SURGICAL TECHNIQUE

Harvest of Saphenous Vein Graft

The patient's thigh is positioned for harvesting the saphenous vein graft by bending the leg slightly at the knee and externally rotating the leg (Fig. 1A). The femoral artery's pulse is palpated at the inguinal ligament and an incision is made just medial to the artery. Subcutaneous tissues are dissected until femoral vein is identified medial to femoral artery in the femoral sheath. The femoral vein is exposed, tracing it superiorly to the inguinal ligament until the saphenous vein is identified where it merges with this vein. The saphenous vein is dissected in the subcutaneous tissues down to the knee. When the saphenous vein is not identified from its confluence with the femoral vein in the manner, it is possible to mistake other subcutaneous veins (like the anterior femoral vein) for the saphenous vein, and these other veins are not suitable for high-flow bypass grafts.

The skin incision is extended to the knee as the dissection progresses, following the course of the vein. Blunt finger dissection above the vein enables monopolar cautery to be used to cut down to the surgeon's finger and quickly expose the vein. Once a 30-cm length of vein (which is more than adequate for most bypasses) is exposed, the vein's branches are ligated and cut. The vein is marked with an ink line (the so-called Garret line) to prevent inadvertent twisting of the graft when it is tunneled later. The vein is cut distally and an irrigating needle is cannulated and secured with a ligature. The proximal vein is cut to release the graft, which is flushed with heparinized saline and occluded distally with an aneurysm clip. The graft is dilated and leaks are closed with 4-0 silk ligatures.

Intracranial Anastomosis

The intracranial anastomosis is usually performed first because it is usually more difficult than the extracranial anastomosis and having complete mobility of the vein graft facilitates the procedure. The recipient artery is exposed through standard craniotomy, but consideration should be given to widening exposure if the anastomosis is deep or particularly difficult, as with bypasses to posterior circulation arteries or to the segments of the carotid artery adjacent to the cavernous sinus. In these cases, an orbitozygomatic approach provides this additional exposure.

After the recipient artery is exposed, steps are taken to insure that the anastomotic site remains clear during the suturing. Hemostasis at this site and around the edges of the surgical field is essential. Background material is placed under the artery not only to create a stage for the anastomosis, but also to protect the underlying brain and provide contrast to better visualize the often transparent arterial walls (Fig. 1C, yellow contrast material). A drain is placed under this background material and secured by running it underneath a retractor blade (Fig. 1D, arrow). When connected to continuous suction, this drain keeps the anastomotic site clear and allows the assistant to irrigate the stage liberally.

Barbiturates administered to the point of electroencephalogram (EEG) burst suppression are used as a cerebroprotectant during the time of temporary occlusion of the recipient artery. Small

temporary clips are placed on the recipient artery, which is then arteriotomized with a beveled #27-gauge needle and microscissors. The arteriotomy is lengthened until it is approximately three times the vessel's diameter. Visualization of the arterial walls is improved by drawing an ink line on the artery before incising it. The wide end of the vein graft is brought into the field after first stripping it of its adventitia and cutting the end cleanly. Using this end of the vein graft results in a caliber mismatch between the graft and the intracranial artery, but preserves the natural direction of flow in the graft, obviating the need for valvulotomy.

Monofilament 9-0 nylon suture is typically used for this anastomosis, with the first suture placed to approximate the vein graft and one end of the arteriotomy. Running continuous stitches are placed loosely from one end of the arteriotomy to the other (Fig. 1D). A second suture is used to anchor the opposite end of the arteriotomy and the vein graft; the loops of the first suture are then tightened and this suture is tied to the tail of the second suture. The luminal side of the anastomosis is carefully inspected before completing the other half of the anastomosis in the same manner. The vein graft typically must be repositioned to visualize the other side of the anastomosis. Leaving the suture loose until all stitches are placed facilitates visualization of the delicate tissues during the suturing and insures that the suture is tied tightly at the end. Temporary clips are removed to re-establish flow in the recipient artery, with temporary

Figure 1 Surgical technique illustration. (A) Harvest of saphenous vein graft. The patient's thigh is positioned by bending the leg slightly at the knee and externally rotating the leg. The skin incision is extended to the knee as the dissection progresses, following the course of the vein. (B) Extracranial anastomosis. The proximal anastomotic site is exposed through a standard carotid endarterectomy approach. For end-to-side anastomoses, a 4- or 5-mm aortic punch is used to cut a circular hole in the carotid artery (white arrow). A suction drain is also used for this anastomosis to keep the field clean (black arrow). (C) Intracranial anastomosis. Background yellow material is placed under the artery not only to create a stage for the anastomosis, but also to protect the underlying brain and provide contrast to better visualize the often transparent arterial walls. (D) A drain is placed under this background material and secured by running it underneath a retractor blade (arrow). When connected to continuous suction, this drain keeps the anastomotic site clear and allows the assistant to irrigate the stage liberally. Monofilament 9-0 nylon suture is used for this anastomosis, with the first suture placed to approximate the vein graft and one end of the arteriotomy. Running continuous stitches are placed loosely from one end of the arteriotomy to the other. Leaving the suture loose until all stitches are placed facilitates visualization of the delicate tissues during the suturing and insures that the suture is tied tightly at the end. (E) A continuous field from the cranial exposure to the cervical exposure is draped. The vein graft is tunneled from the cranial field to the cervical field using a #28-French chest tube. (F) Notches in the bone flap are created to prevent obstruction of flow in the bypass (black arrow).

occlusion times rarely exceeding 30 minutes. Bleeding at the anastomosis is controlled with fibrillar Nu-knit[®] (Ethicon Inc., Johnson & Johnson Co., Somerville, NJ) and the vein graft will fill back to the first valve with good pulsations.

Extracranial Anastomosis

The proximal anastomotic site is exposed through a standard carotid endarterectomy approach (Fig. 1B). During initial preparation, a continuous field from the cranial exposure to the cervical exposure is draped. The carotid bifurcation is exposed, and the decision about where to connect the graft depends on tolerance to carotid occlusion and individual anatomy. Patients needing a saphenous vein bypass often have poor tolerance to carotid occlusion, making the ECA an excellent donor artery. Temporary occlusion of the ECA does not result in cerebral ischemia, whereas temporary occlusion of the internal carotid artery (ICA) does. This anastomosis can be either end-to-end or end-to-side, but the former is preferred because the calibers of artery and vein are well matched, hemodynamics of this connection are better, and occlusion of ECA is well tolerated. An end-to-end anastomosis takes 15 minutes to perform, making an anastomosis to the ICA possible in patients with at least this tolerance on BTO. The common carotid artery (CCA) is used as a donor artery in patients with high carotid bifurcations or poor surgical exposure or both.

The vein graft is tunneled from the cranial field to the cervical field using a #28-French chest tube. A notch in the zygoma is drilled (Fig. 1E) and bone from the temporal bone flap is reduced in size (Fig. 1F, black arrow) before tunneling to prevent obstruction of flow in the bypass. The tunnel is created with blunt dissection through the subcutaneous tissue and a chest tube is inserted. A slit is cut in the chest tube to enable the vein to be placed directly inside, taking care to maintain the alignment of the graft. The chest tube is pulled through to the cervical field and the vein is removed from the tube.

The vein graft is cut to a length that brings the proximal end to the anastomosis site. The vein graft usually expands when exposed to arterial pressure, so the length of the graft does not need to be generous.

For end-to-end anastomoses, the donor artery is isolated between clamps and transected. For end-to-side anastomoses, a 4- or 5-mm aortic punch is used to cut a circular hole in the carotid artery (Fig. 1B, white arrow). The vein graft is spatulated to increase the orifice of the vein graft. A 7-0 prolene double-arm suture is used for this anastomosis, with a running continuous stitch. A suction drain is also used for this anastomosis to keep the field clean (Fig. 1B, black arrow). The two arms are tied together after each half of the anastomosis is completed, and Nu-knit is again used to control bleeding at this site. Clamps are removed from the carotid artery and vein graft to initiate flow in the bypass. Surgical occlusion of the parent arteries or the aneurysm can then be performed or deferred for staged therapy.

CLINICAL MANAGEMENT

Revascularization is usually just the first step in a process to treat an aneurysm, enabling subsequent maneuvers that occlude the parent artery or aneurysm without the associated risks of ischemic complications or neurological morbidity. Indirect aneurysm occlusion after bypass is often easier than a direct attack on the aneurysm and can be performed during the same surgery or later, after confirming patency of the bypass and optimizing the patient's medical and hemodynamic conditions. Parent artery or aneurysm occlusion can be accomplished surgically or endovascularly.

In select patients, staged revascularization and aneurysm occlusion are favorable for several important reasons. First, staged therapy allows the bypass graft to mature before it bears its full hemodynamic load. The time interval between bypass and aneurysm occlusion is usually 3 days, which may be adequate time for the anastomosis to endothelialize.

Second, patency of the bypass is established angiographically before permanent occlusion of a major artery. In our experience with revascularization, graft occlusion occurs rarely, usually within 24 hours of initial surgery, and those that are patent beyond 24 hours will remain so. Therefore, staged occlusion with a subsequent endovascular technique insures that the bypass is functioning when the aneurysm is occluded. Third, the BTO can be repeated after the bypass is completed to verify tolerance in patients who failed the test preoperatively, thereby confirming the functional hemodynamics of the bypass. The extent of preoperative failure with the BTO is used as a guide to the type of bypass needed, with a range of flow offered by low-flow bypasses (using STA, occipital artery, or intracranial donor arteries), intermediate-flow bypasses (radial artery grafts), and high-flow bypasses (saphenous vein grafts). Repeat BTO with the bypass serves as a final check before permanent occlusion, one which is not available intraoperatively when patients are anesthetized with only EEG and somatosensory evoked potentials to gauge tolerance after permanent occlusion. Fourth, staged aneurysm occlusion enables the use of anticoagulation to limit thrombosis of the aneurysm and avoid thromboembolic complications involving adjacent arteries or perforators. Anticoagulation with heparin is not an option with intraoperative arterial occlusion because of elevated risk of postoperative bleeding. Finally, postocclusion hemodynamics can be optimized during endovascular occlusion better than during surgical occlusion, where there are intraoperative blood loss and fluid shifts.

Disadvantages of staged bypass-aneurysm occlusion are the lack of demand on the bypass and the risk of aneurysm rupture between procedures. In our experience, the lack of demand during this time interval has not led to graft occlusions and, in fact, often initiates the aneurysm thrombosis even before the afferent artery is occluded. We have not had an aneurysm rupture between procedures, either. In patients with ruptured aneurysms treated with bypass and aneurysm occlusion, thought should be given to performing these concurrently.

RESULTS

Between August 1997 and December 2004 (7.4 years), a total of 1133 aneurysms were treated surgically by the senior author (MTL) in 914 patients. During that same period, a total of 110 bypasses were performed, of which 46 were for aneurysms. Eleven patients received low-flow EC-IC bypasses using STA as the donor artery and 13 patients received in situ bypasses. The remaining 22 patients received high-flow EC-IC bypasses using saphenous vein grafts (Table 2). The most common aneurysm location was the cavernous ICA (13 patients). Other locations included the supraclinoid ICA (4 patients), MCA (2 patients), ophthalmic artery (1 patient), ICA bifurcation (1 patient), and basilar trunk (1 patient). Sixteen patients had aneurysms that were giant in size.

Case Example 1: Tandem Bypass

A 71-year-old man presented with a sudden, severe headache and associated confusion and somnolence. Two years earlier, his symptomatic left CCA atherosclerotic disease was treated with a subclavian artery-to-ICA bypass using a Dacron interposition graft at an outside institution. CT scan demonstrated subarachnoid hemorrhage in the left carotid and sylvian cisterns, as well as hydrocephalus (Fig. 2A). A cerebral angiogram demonstrated a dolichoectatic supraclinoid ICA aneurysm extending

Table 2 Summary of Saphenous Vein Bypasses by Senior Author

Bypass	Patients
C ₃ -C ₅ bypass	2
CCA-MCA bypass	4
ECA-MCA bypass	9
ICA-MCA bypass	4
Subclavian-MCA bypass	2
ECA-SCA bypass	1
Total	22

CCA, common carotid artery; MCA, middle cerebral artery; ECA, external carotid artery; ICA, internal carotid artery; SCA, superior cerebellar artery.

Figure 2 Tandem bypass. Preoperative axial computed tomography scan (A) reveals subarachnoid hemorrhage in the left sylvian and ambient cisterns from rupture of the ICA aneurysm. (B) Preoperative digital subtraction angiography shows Dacron graft from the subclavian artery to the ICA on the left. (C) Selective ICA injections show a dolichoectatic ICA aneurysm in the anteroposterior view. (D) Intraoperative photographs show that about a 1-cm length of Dacron graft was opened for the proximal anastomosis site. (E) The completed back wall of the proximal anastomosis can be seen as the front wall is being sutured. (F) The completed distal end-to-side anastomosis between the saphenous vein and the MCA is shown, using a running suture. (G) Postoperative distal subtraction angiography of the proximal anastomosis as seen in the anteroposterior view shows the contoured occlusion of the distal Dacron graft. (H) Anteroposterior views show the distal anastomosis and the filling from the tandem bypass is both anterograde in the distal MCA territory and retrograde to supply the distal ICA and anterior cerebral artery. The aneurysm has been trapped with clips and no longer fills. Modified from Auguste et al.⁴ ICA, internal carotid artery; MCA, middle cerebral artery.

from the ophthalmic artery to the ICA bifurcation (Fig. 2B,C).

The patient was taken to the operating room and the aneurysm was exposed through a pterional approach. The aneurysm's dolichoectatic morphology and its atherosclerotic walls made direct clipping impossible; instead, the aneurysm was bypassed and trapped. The Dacron graft of the reconstructed cervical carotid artery was exposed and followed rostrally to the anastomosis with the cervical ICA. The carotid bifurcation was too high for an anastomosis to the ICA; the mandible would have made this procedure difficult and would have created a tortuous course for the vein graft.

The proximal end of the vein graft was connected to the Dacron graft, also with an end-to-side anastomosis (Fig. 2D,E). The vein graft was sutured to the larger of two M2 branches in an end-to-side anastomosis (Fig. 2F). This bypass from subclavian artery to Dacron graft to saphenous

vein graft to MCA is the so-called "tandem bypass." The aneurysm was trapped during the same surgery with clips on the distal CCA graft, on the supraclinoid ICA, just proximal to the anterior choroidal artery, and on the posterior communicating artery as it exited the aneurysm (Fig. 2G,H).

The patient tolerated his procedure without complication. One year later, he had no residual neurological deficits or symptoms and reported a higher level of activity than before his hemorrhage.

Case Example 2: ECA-SCA Bypass

A 60-year-old woman presented with multiple lower cranial nerve deficits that were progressive over a period of 1 year. A giant vertebrobasilar artery aneurysm was identified on MR imaging with brainstem compression and confirmed on angiography (Fig. 3A,B). The patient was managed

Figure 3 ECA-SCA Bypass. (A,B) A 60-year-old woman presented with a giant basilar artery trunk aneurysm and brainstem compression syndrome. She underwent a right orbitozygomatic-pterional craniotomy, cervical carotid artery exposure, harvest of saphenous vein graft, and ECA-to-SCA saphenous vein bypass graft. (C) Small temporary clips are placed on the SCA, which is then arteriotomized with a beveled #27-gauge needle and microscissors. The arteriotomy is lengthened until it is approximately three times the vessel's diameter. The contrast material is under the vessel. (D) Monofilament 9-0 nylon suture was used for this anastomosis. (E) Temporary clips were removed to re-establish flow in the recipient artery and back flow is appreciated into the saphenous vein graft. (F,G) The extracranial anastomosis is appreciated through a standard carotid endarterectomy approach. A suction drain is also used for this anastomosis to keep the field clean in (G). Postoperative angiogram (H) proximally and (I) distally revealed a patent bypass graft with excellent flow. (J) On postoperative day 3, the nondominant right vertebral artery was occluded endovascularly with coils. ECA, external carotid artery; SCA, superior cerebellar artery.

conservatively for 6 months, but returned with continued progression of symptoms. BTO of both vertebral arteries showed that her diminutive posterior communicating arteries were inadequate to support her posterior circulation after vertebral artery occlusions. A treatment plan was developed that included saphenous vein bypass from ECA to SCA and staged occlusion of both vertebral arteries. This strategy was designed to change the aneurysm's hemodynamics, promote its thrombosis, and prevent further enlargement or neurological deterioration.

The patient underwent a right orbitozygomatic-pterional craniotomy and a saphenous vein bypass was created between the ECA and SCA (Fig. 3C–G). The orbitozygomatic exposure created additional working space for this deep bypass. She tolerated the procedure well and postoperative angiography showed a patent bypass (Fig. 3H–J). On postoperative day 3, the nondominant right vertebral artery was occluded endovascularly with coils placed just distal to the origin of the PICA (Fig. 3J). BTO of the dominant left vertebral artery was well tolerated, with the bypass perfusing the basilar artery retrograde (Fig. 3H,I). Therefore, this left vertebral artery was permanently occluded. The aneurysm was thereby proximally occluded, with reversal of blood flow in the basilar artery. She was anticoagulated with heparin for 3 days after the vertebral artery occlusions.

DISCUSSION

Revascularization remains a unique surgical contribution to the overall management of intracranial aneurysms, one that endovascular techniques cannot match at present. Bypass procedures are not indicated for large numbers of aneurysms, only select complex ones that cannot be treated with conventional clipping or coiling techniques. The infrequent need for revascularization makes it difficult for many neurosurgeons to remain proficient in these advanced and meticulous techniques. This

article is intended to encourage and instruct those neurosurgeons who find the need for a saphenous vein bypass in the management of such an aneurysm.

Although we have emphasized saphenous vein grafts in this review, vascular neurosurgeons are increasing their use of radial artery grafts. Radial artery grafts are appealing because they have arterial architecture, are easily harvested, provide intermediate to high flow, and improve overall patency rates. Reports in the cardiac surgery literature comparing radial artery and saphenous veins grafts demonstrate higher patency rates with radial artery grafts at 1 year.⁴⁷ No such studies have been published for cerebral revascularization. The group at the Mayo Clinic published their results in 202 patients with saphenous vein grafts for cerebral revascularization, with patency rates of 86%, 82%, and 73% at 1, 5, and 13 years, respectively.²⁰ Therefore, while radial artery grafts may improve these numbers, the expected patency with saphenous vein grafts is still sufficiently high.

We have limited this article to saphenous vein bypasses and their applications for intracranial aneurysms. However, it is worth remembering that they are applicable to other aneurysms, ischemic conditions, and skull base tumors that encase the carotid artery.^{2–4,48–51} Dissecting aneurysms at the skull base and traumatic pseudoaneurysms are other aneurysms that are best dealt with by revascularizing the carotid circulation and occluding the parent artery or aneurysm, similar to the methods already described herein. Many of the other bypasses performed in the senior author's experience were for ischemic conditions, including atherosclerotic carotid artery occlusions, moyamoya disease, and MCA occlusive disease. Most of these conditions require only a low-flow EC-IC bypass, but in some cases higher flow is needed. Finally, tumors involving the skull base that cannot be aggressively resected without carotid sacrifice also benefit from first placing a saphenous vein bypass. Bypasses for meningiomas, esthesioneuroblastomas, and squamous cell carcinomas have all been performed at our institution to facilitate radical tumor resection.

DISCLOSURE

None of the authors of this study has any financial interest in any of the instruments or methodologies used in this study.

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