Revascularization for complex intracranial aneurysms

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The modern management of intracranial aneurysms includes both constructive and deconstructive strategies to eliminate the aneurysm from the circulation. Both microsurgical and endovascular techniques are used to achieve this goal. Although most aneurysms can be eliminated from the circulation with simple clip reconstruction and/or coil insertion, some require revascularization techniques to enhance tolerance of temporary arterial occlusion during clipping of the aneurysm neck or to enable proximal occlusion or trapping. In fact, the importance of revascularization techniques has grown because of the need for complex reconstructions when endovascular therapies fail. Moreover, the safety and feasibility of bypass have progressed due to advances in neuroanesthesia, technological innovations, and ~ 5 decades of accumulating wisdom by bypass practitioners. Cerebral revascularization strategies become necessary in select patients who possess challenging vascular aneurysms due to size, shape, location, intramural thrombus, atherosclerotic plaques, aneurysm type (for example, dissecting aneurysms), vessels arising from the dome, or poor collateral vascularization when parent artery or branch occlusion is required. These techniques are used to prevent cerebral ischemia and subsequent clinical sequelae. Bypass techniques should be considered in cases in which balloon test occlusion demonstrates inadequate cerebral blood flow and in which there is a need for Hunterian ligation, trapping, or prolonged temporary occlusion. This review article will focus on decision making in bypass surgery for complex aneurysms. Specifically, the authors will review graft options, the utility of balloon test occlusion in decision making, and bypass strategies for various aneurysm types. (DOI: 10.3171/FOC.2008.25.2.E21)

KEY WORDS • balloon test occlusion • cerebral revascularization • complex intracranial aneurysm • extracranial-intracranial bypass

THE modern management of intracranial aneurysms includes both constructive and deconstructive strategies to eliminate the aneurysm from the circulation; deconstructive procedures involve sacrifice of the parent artery with or without bypass. Constructive strategies, on the other hand, preserve the parent vessel while excluding the aneurysm with clips. Both microsurgical and endovascular techniques are used to achieve this goal.

Abbreviations used in this paper: ACA = anterior cerebral artery; AICA = anterior inferior cerebellar artery; AP = anteroposterior; BA = basilar artery; BTO = balloon test occlusion; CA = carotid artery; CBF = cerebral blood flow; DS = digital subtraction; ECA = external CA; EC-IC = extracranial-intracranial; EEG = electroencephalography; ELANA = excimer laser-assisted nonocclusive anastomosis; GOS = Glasgow Outcome Scale; ICA = internal CA; MCA = middle cerebral artery; OA = occipital artery; PCA = posterior cerebral artery; PICA = posterior inferior cerebellar artery; RA = radial artery; SAH = subarachnoid hemorrhage; SCA = superior cerebellar artery; SELANA = sutureless ELANA; STA = superficial temporal artery; SV = saphenous vein; VA = vertebral artery.

Rationale for Bypass

Although most aneurysms can be eliminated from the circulation with simple clip reconstruction and/or coil placement, some require revascularization techniques to enhance tolerance of temporary arterial occlusion during clipping of the aneurysm neck or to enable proximal occlusion or trapping. In fact, the importance of revascularization techniques has grown because of the need for complex reconstructions when endovascular therapies fail. Moreover, the safety and feasibility of bypass procedures have progressed due to advances in neuroanesthesia, technological innovations, and ~ 5 decades of accumulating wisdom by bypass practitioners.

Cerebral revascularization strategies become necessary in select patients whose vascular aneurysms are challenging to treat due to size, shape, location, intramural thrombus, atherosclerotic plaques, aneurysm type (for example, dissecting aneurysms), vessels arising from the dome, or poor collateral vascularization when parent artery or branch occlusion is required.⁴³ These techniques, which were first successfully described by Yaşargil in the late 1960s, are used to prevent cerebral ischemia and

subsequent clinical sequelae.¹ Bypass techniques should be considered in cases in which BTO demonstrates inadequate CBF and in which there is a need for Hunterian ligation, trapping, or prolonged temporary occlusion.¹ In addition to increasing the safety profile of proximal occlusion and trapping, bypass procedures can render unclippable aneurysms clippable by supplying blood flow to branches that could not otherwise be preserved. In this article, we will focus on decision making in bypass surgery for complex aneurysms. Specifically, we will review graft options, the utility of BTO results in decision making, and bypass strategies for various aneurysm types.

Bypass Options and Flow Rates

When considering direct cerebral revascularization as a management option, several bypass grafts are available. These include pedicled arterial grafts such as the STA or OA, which allow for low-flow bypasses as well as interpositional venous or arterial grafts. The free grafts include the SV graft and the RA graft, which allow for high-flow bypasses. Other conduits may be used for side-to-side revascularization within the circle of Willis, including the MCA, ACA, and PICA. Choosing an adequate graft is an important component of the presurgical planning algorithm and depends on several factors: size of the recipient vessel, amount of blood flow needed, availability of donor vessel and graft material, and location of revascularization. Operator experience factors into this decision as well.

The STA Bypass

The STA is a small-caliber vessel with a diameter of ~ 2 mm³³ and an initial flow rate ranging between 15 and 30 ml/minute.^{8,40} This flow rate may increase with time.⁴³ It is chosen when some collateral flow is present and a low-flow bypass is needed to cover a relatively small territory of the brain with a small blood volume. Recipient arteries may be the MCA, PCA, or SCA. In rare cases, the ACA may also be a recipient; however, its deep location renders the bypass quite challenging due to the length of STA required. The STA-MCA bypass is the most commonly used procedure for anterior circulation revascularization.³³ The STA may also be used as an arterial interpositional graft. It has the advantages of being readily available and requiring only 1 anastomosis when used as a pedicled graft. The main drawback, however, is the low flow rate, which precludes its use for bypass when larger flow rates are needed. The graft patency rate can be well estimated from the EC-IC bypass trial¹⁷ conducted in 1985. This study involved 663 STA-MCA bypass procedures performed for symptomatic ICA or MCA narrowing/occlusion. The graft patency was 96%, and the mean patient follow-up was 55.8 months. Morbidity from major stroke and mortality rates following surgery were 2.5 and 0.6%, respectively, at 30 days.¹⁷

The OA Bypass

The OA diameter and flow rates are similar to those of the STA. Recipient arteries may be the PICA or AICA.

The OA-PICA bypass has been extensively used for posterior circulation revascularization.^{5,38,45} The advantages here are the close caliber match between donor and recipient arteries and the wide and superficial surgical field, which renders the procedure less complicated.³⁴ The major disadvantage is dissection of the OA, which is usually challenging due to early branching and thus reduction in caliber and flow at the site of selection for harvest and anastomosis. In one small series, graft patency in OA-PICA bypass to treat symptomatic posterior circulation insufficiency has been reported to be 94% at 6–8 weeks postoperatively; no permanent morbidity or deaths were noted.⁷⁰ In another series on EC-IC bypass for symptomatic vertebrobasilar insufficiency, postoperative angiography showed that 73% of OA-PICA anastomoses were patent; moreover, the morbidity rate was 20% and mortality was 7%.⁵ On the other hand, the OA-AICA bypass is a more challenging procedure with few reports in the literature; this is due to the fact that the caliber of the AICA is smaller and the surgical field is deeper and narrower.³⁴ Graft patencies for OA-AICA bypasses as evidenced by postoperative angiography findings have been reported to be 94% in a small group of patients, with morbidity and mortality rates of 5 and 10%, respectively.⁵

The RA Graft

The RA is a medium-caliber artery with a diameter measuring ~ 3.5 mm⁴⁰ and a flow rate ranging between 40 and 70 ml/minute.^{40,57} It is categorized as a high-flow bypass graft. With the moderate volume of blood flow it provides, it is mainly used when the ICA needs to be sacrificed and the patient has some collateral flow. It can also be used when the STA and OA are not available, as in patients with prior craniotomy.³³ Its larger caliber (when compared with STA) allows it to be anastomosed to larger, more proximal donor arteries, such as the ICA or ECA. Moreover, it closely matches the luminal diameter of the M₂ segment of the MCA and the P₁ segment of the PCA.^{40,58} Before harvesting the RA graft, an Allen test should be performed to confirm an intact palmar arch and adequate hand perfusion despite occlusion of the RA. An ultrasound can also be obtained to assess the caliber of the RA and ulnar artery as well as the patency of the palmar arcade. Advantages related to its use include the fact that it is originally a conduit that conveys arterial blood, and therefore is equipped with arterial endothelium that may better handle arterial flow.⁵⁷ Moreover, unlike SV grafts, RA grafts are characterized by a homogeneous lumen that lacks valves and varices. These features may prevent graft thrombosis in cases of low flow rates or if temporary occlusion is necessary during aneurysm surgery.

Additionally, the RA graft is easy to harvest due to its unvarying anatomical location, and it is less prone to kinking when compared with the SV graft.^{40,58} The main disadvantage of RA grafts is the potential for vasospasm following harvest, which may lead to total occlusion of the vessel. Nevertheless, this can be circumvented by placing the graft in a calcium channel blocker solution until ready for suturing, or if spasm has already occurred, it can be remedied by using the pressure distension technique.^{57,59} Another disadvantage is the fact that RA grafts

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TABLE 1: Literature review of graft options and characteristics*

Authors & Year	Graft	Caliber	Flow Rate	Donor	Recipient	Patency Rate (FU)	% Morbidity	% Mortality
The EC/IC Bypass Study Group, 1985	STA	2 mm	15–30 ml/min	NA	MCA, ACA, PCA, SCA	STA-MCA: >95% (55.8 mos)	2.5	0.6
Streefkerk et al., 2004; Ausman et al., 1990; Ausman et al., 1990	OA	2 mm	15–30 ml/min	NA	AICA, PICA	OA-PICA: 94% (6–8 wks) OA-PICA: 73% (periop) OA-AICA: 94% (periop)	0 20 5	0 7 10
Hillen et al., 1991; Reinert et al., 2006	RA	3.5 mm	40–70 ml/min	ICA, ECA, OA	ICA, MCA, PCA, VA, SCA	ICA-MCA: 95% (3 wks) CABG: 92% (5 yrs)	2.3	0
Raaymakers et al., 1998	SV	5 mm	70–140 ml/min	ICA, ECA, OA	ICA, MCA, PCA, VA, SCA	multiple bypass combinations: 86% (30 days–1 yr) 73% (13 yrs)	6.5	15

* CABG = coronary artery bypass graft; FU = follow-up; NA = not applicable.

are free arterial grafts. It is speculated that total disruption of the vasa vasorum following harvest might lead to arterial wall degeneration over time, thus explaining the lower long-term patency rates when compared with pedicled grafts.¹⁵ As a way to avoid that, we usually preserve a draining vein that originates from the RA graft and connect it to the internal jugular vein to preserve normal drainage of the vasa vasorum and increase graft viability. Other drawbacks are the need to harvest an additional vessel from a separate site, the need for 2 anastomoses, and limited graft length when compared with SV grafts. In a study of 43 patients treated for giant paraclinoid and intracavernous aneurysms with reconstruction of the ICA by using RA grafts, the graft patency was reported to be 95% at 3 weeks; permanent morbidity from cerebral infarction was 2.3%, and there were no deaths.²⁷ In a coronary bypass series in which RA grafts were used for myocardial revascularization, the patency rate was 92% at 5 years.⁵¹

The SV Graft

The SV graft has a diameter of ~ 5 mm⁴ and a flow rate ranging between 70 and 140 ml/minute.⁴⁰ Flow rate has also been reported to exceed 250 ml/minute in some cases.²⁹ This graft allows for high-volume collateral circulation in patients in whom other collateral channels are inadequate. In fact, to maintain SV graft patency, it is necessary that the recipient vessel be of large enough caliber and have considerable hemodynamic demand.²⁹ Some positive aspects of using this graft include its accessibility and ease of harvest, absence of atherosclerosis, and its large caliber (and therefore high flow rate when needed). Drawbacks are the reduced patency rates with such grafts, probably due to the venous endothelium, and the caliber mismatch often encountered between graft

and recipient vessel, which may lead to turbulent flow and thrombosis. Of note, one should make sure that the vein is grafted in the proper direction so that the valves do not oppose blood flow; this is performed by transferring the SV graft cranially and confirming flow prior to anastomosis by using a heparinized saline flush.⁴³ Alternatively, a reversed SV graft may be used, but this requires a valvectomy.¹⁴ Another drawback is the risk of kinking at the donor or recipient anastomosis site because of the SV graft's thicker wall composition.^{43,57} In fact, the thick SV graft muscular wall and adventitia increase the technical difficulty of anastomosis: sutures can get embedded in the wall and fine needles can be bent. Other disadvantages are the need to harvest an additional vessel with a separate incision at a different site and the need for 2 anastomoses. Patency rates for SV grafts have been well studied.^{29,54,57} In a study by Regli et al.⁵⁴ involving 201 patients with 202 SV graft bypasses, the patency rate was 86% at 30 days; morbidity related to occlusion was 6.5%, and the overall mortality rate was 15% (27% of those who died had early graft occlusion) at 30 days. This study involved multiple combination bypasses from donor to recipient vessels and targeted both the anterior and posterior cerebral circulation. The cumulative patency rate was 86 ± 3% at 1 year, 82 ± 4% at 5 years, and 73 ± 19% at 13 years. The mean graft failure rate per year was 1–1.5% after the 1st year. The 5-year cumulative survival rate was 78 ± 4% in patients with patent grafts and 49 ± 13% in patients with graft occlusion.

Side-to-Side Revascularization Within the Circle of Willis

These bypass procedures can be used creatively to revascularize the territory or branch that must be sacrificed to treat an aneurysm. These procedures include MCA-MCA, ACA-ACA, and PICA-PICA anastomo-

ses.^{33,34} Other combinations may also be used.⁷ The advantage of these grafts is that they avoid the need for graft harvest and they involve a single anastomotic site. In some cases, such as a PICA-PICA bypass, the surgery is superficial at the cistern magna. The disadvantage of this bypass strategy is that it puts the territories of both branches at risk for ischemia during temporary trapping. Technologies that may allow for bypass without temporary occlusion may make this type of bypass more desirable in the future.

Please refer to Table 1 for a summary of graft options and characteristics.

Role of Extra- and Intracranial BTO in Decision Analysis

The safe treatment of unclippable complex aneurysms and those that are not amenable to endovascular therapy requires parent vessel sacrifice to exclude the lesion. Although 80% of patients might tolerate ICA occlusion or nondominant or codominant VA sacrifice,^{13,18} the remainder are at high risk for ischemic complications and therefore require revascularization. In an effort to determine which patient group can safely tolerate permanent vessel occlusion, preprocedural BTO has evolved as a useful tool to test the cerebrovascular reserve^{47,49} and hence answer 2 important questions. First, is a bypass needed, and if so, which flow rate is appropriate? This approach is referred to as a selective revascularization approach. Certain institutions are keen advocates of the selective approach.^{16,25,29,47,49,63} On the other hand, some support a universal approach, whereby revascularization is systematically performed on all cases requiring vessel sacrifice.^{36,43,48,64} Second, some studies have suggested high rates of morbidity and mortality related to stroke, despite passing the occlusion test.^{36,48,60} Our experience, however, suggests that BTO can be performed with lower morbidity than in the quoted studies. Nonetheless, in patients < 18 years of age, we often favor bypass even when the BTO is passed, because of the issues of delayed aneurysm formation that may result from hemodynamic stress in areas such as the anterior communicating artery; another reason for this is the rare but real risk of delayed ischemia after vessel sacrifice, even when the balloon test suggests no need for a bypass.

In general, we use a selective revascularization protocol in most patients. To predict tolerance to vessel sacrifice safely, we use a specific testing paradigm that is composed of 4 modalities: neuroclinical, hemodynamic, neurophysiological, and provocative (Table 2).^{47,49,63} Cerebrovascular reserve testing prior to vessel occlusion or sacrifice at our institution has been previously described.⁴⁷ Briefly, in neuroclinical assessment, the patient is examined while awake for any deficit occurring as a result of BTO. During hemodynamic evaluation, blood flow from the contralateral to the ipsilateral hemisphere is studied with DS angiography and radionuclide CBF (this is done afterward) imaging studies while performing balloon occlusion and maintaining normal blood pressure. Neurophysiological EEG readings are monitored throughout to detect any changes during temporary occlusion. Provoca-

TABLE 2: Indications and institutional protocol for bypass from temporary BTO

Clinical	EEG	SPECT	Hypotension	Intervention
pass	pass	pass	pass	permanent occlusion
pass	fail	fail	fail	permanent occlusion + low-flow bypass (STA-MCA)
fail	fail	fail	fail	permanent occlusion + high-flow bypass (venous/RA bypass)
pass	pass	fail	fail	permanent occlusion + low-flow bypass (STA-MCA)

tive testing entails pharmacologically induced hypotension to two-thirds of the baseline blood pressure during BTO, and neuroclinical reevaluation. Following cerebrovascular reserve testing, these 4 modalities are evaluated collectively. The results allow an assessment of vessel sacrifice tolerance, temporary occlusion tolerance, and most suitable bypass type. Based on the testing results, patients are stratified into 3 groups: Group 1, all 4 modalities passed; Group 2, passed only neuroclinically; and Group 3, failed neuroclinically. Group 1 patients usually do not require revascularization, Group 2 typically undergoes a low-flow bypass procedure, and Group 3 typically requires a high-flow bypass procedure (Table 2).

This method of testing was highly correlated with tolerance to vessel sacrifice in 95% of patients in one study.⁶⁵ Several other studies have also contributed to further validation of the safety and efficacy of BTO.^{16,23,42,47,63,77} In fact, Mathis et al.⁴² reported a 0.4% permanent neurological complication rate in a large series of 500 temporary ICA and common carotid artery occlusions. Van Rooij and colleagues⁷⁷ demonstrated that none of their 17 patients who had undergone successful and uncomplicated BTO of the ICA performed using neurological and neurophysiological monitoring followed by permanent ICA occlusion had experienced an ischemic event at 21 months of follow-up. Moreover, based exclusively on unpublished institutional experience, we estimate the BTO-related risk of serious complications to be ~ 1.5%.

Neuroanesthesia Considerations in Bypass Surgery

The anesthetic goals for intracranial neurovascular procedures are to maintain cerebral perfusion; optimize brain relaxation, thus reducing tissue retraction; promote cerebral protection; and provide rapid recovery to facilitate neurological examination.⁸¹ With careful preoperative planning, it is possible to obtain all of these goals while minimizing postoperative cardiovascular and neurological morbidity and mortality levels.²¹

To prevent cerebral ischemia from hypoperfusion and inadvertent aneurysm rupture from hypertension, minute-to-minute control of mean arterial pressure within 10–15% of baseline levels is targeted.¹² Unfortunately,

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there are many causes of hypotension in the perioperative period. As a result of recent osmotic diuresis used to treat elevated intracranial pressure, the osmotic diuresis that is induced by contrast agents used for angiography, and the sympathetic response to SAH, patients may be in a state of volume contraction on arrival in the operating room.³² With the use of motor evoked potentials to monitor for intraoperative cerebral ischemia, higher concentrations of opioids and hypnotics, which are potent systemic vasodilators, are necessary to prevent movement responses to noxious stimulation than if neuromuscular blockade was allowed. In addition, the use of high concentrations of propofol to induce a burst suppression ratio of 70–80% to prolong the tolerance of temporary arterial occlusion can induce hypotension in some patients.⁶⁷ Fortunately, the adrenergic agonists can maintain systemic perfusion pressure without directly affecting cerebrovascular resistance.⁴¹

The combination of low-dose, low-solubility volatile anesthetics (for example, desflurane or sevoflurane), short-acting opioids (for example, remifentanyl), and the short-acting intravenous hypnotic propofol, provides amnesia and immobility to surgical stimulation while preventing sympathetic responses to surgical stimulation and facilitating a predictable, rapid return of consciousness.¹⁹ When osmotic diuresis and CSF drainage cannot achieve adequate brain relaxation, discontinuing the cerebral arterial dilating volatile anesthetic and increasing the propofol concentration will decrease the cerebral metabolic rate and reflexively decrease CBF and cerebral blood volume.^{12,24} Besides decreasing brain bulk, this anesthetic-induced cerebral metabolic depression may increase the tolerance of ischemia. However, this protection may be in the form of prolonging the time before irreversible ischemia and apoptosis are induced, rather than preventing ischemia-induced infarction and apoptosis.⁷⁸ Additional cerebral metabolic depression can be achieved by inducing mild hypothermia (34.5–35.5°C). Along with decreasing brain bulk, mild hypothermia has prolonged the time of ischemia tolerance and inhibited ischemia-induced infarction and apoptosis in animal models.⁷² However, mild hypothermia has not been shown to improve neurological outcome after craniotomy for good-grade patients with aneurysmal SAH.⁷¹ Therefore, the risks of mild hypothermia (for example, coagulopathy, arrhythmia, and immunosuppression)⁶² have to be weighed against the potential theoretical benefits in high-risk neurovascular patients. Unfortunately, additional strategies for pharmacological neuroprotection have had limited success when translated from animal models to humans.^{22,28} Therefore, focusing on prevention of secondary injury from inadequate cerebral perfusion, hyperglycemia, and hyperthermia are the most effective strategies to minimize neurological morbidity.²²

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Cavernous Carotid Aneurysms

Although most cavernous carotid aneurysms are benign, asymptomatic lesions, some may become symp-

tomatic, due to either progressive mass effect from enlargement or from spontaneous rupture that often leads to a carotid cavernous fistula, thus requiring treatment. Although coil insertion maybe suitable for smaller lesions and for ruptured lesions without mass effect, coil embolization of cavernous carotid aneurysms with symptomatic mass effect may result in worsening acute or delayed (if recurrence occurs) mass effect in the cavernous sinus. To avoid this concern, proximal parent artery ligation with or without bypass has proven highly effective at treating cavernous carotid aneurysms with mass effect.

A significant majority of patients who present with larger, symptomatic cavernous carotid aneurysms are female, > 50 years old, Caucasian, and present with clinical symptoms of mass effect. The most common results of progressive mass effect at presentation are diplopia and pain.

The main indications for treatment, as described by Linskey et al.,³⁹ include progressive ophthalmoplegia or visual loss, severe ipsilateral facial or orbital pain, or progressive aneurysmal enlargement. Treatment strategies of symptomatic cavernous carotid aneurysms include coil embolization, with or without stent assistance, and parent artery ligation, with or without a revascularization procedure. In symptomatic cavernous carotid aneurysms with significant mass effect, coil embolization may actually worsen or cause delayed mass effect, thus worsening the symptomatology. Stiebel-Kalish et al.⁶⁶ reported that 2 coil-occluded cavernous carotid aneurysms resulted in delayed cranial neuropathy. To avoid such potential complications in the treatment of these lesions, especially in larger cavernous carotid aneurysms, proximal CA occlusion with or without cerebral revascularization can be used. Historically, without the availability of preoperative BTO, patients who underwent open CA occlusion suffered mortality rates of 0–11% and morbidity rates of 2.9–36%.⁵⁶ Niiro et al.⁴⁶ reported that 8 of 11 patients with symptomatic cavernous carotid aneurysms improved or had resolved pain or ocular symptoms after CA occlusion but that 9.1% had permanent morbidity from ischemic complications.

Revascularization procedures are intended for patients who cannot tolerate abrupt CA occlusion. Therefore, the determination of CA occlusion tolerance is paramount in the assessment of treatment strategies, which should always include the possibility of CA sacrifice with or without revascularization with a bypass graft. However, the benefit of cerebral revascularization in patients requiring CA occlusion remains controversial. Sen and Sekhar⁶¹ presented 30 patients with skull base lesions, all of whom underwent a revascularization procedure, with 12 patients eventually experiencing ischemic events. However, Regli et al.⁵⁴ only reported an ischemic complication rate of 12% (25 of 202 patients) over a 13-year period in patients treated with vein bypass grafts for various pathological conditions requiring revascularization. The discrepancy of these reports probably rests on several factors, namely patient selection, treatment strategies, and outcome measures. With more strenuous testing criteria, which included BTO and quantitative CBF analyses (Xe-enhanced CT scans), Field et al.²⁰ reported on 26 patients

with symptomatic cavernous carotid aneurysms, of which 8 patients were considered at high or moderate risk of delayed ischemia and underwent STA-MCA bypass and the other 18 patients were determined to be at low risk for delayed ischemic complications and underwent CA occlusion alone. Only 1 of the 8 bypass patients developed delayed symptomatology from an ischemic event. None of the low-risk patients, who were treated with CA occlusion alone, developed delayed symptomatology. Stiebel-Kalish et al.⁶⁶ showed that in 64 of 67 symptomatic cavernous carotid aneurysms treated with bypass and CA occlusion, ophthalmic pain improved or resolved, whereas diplopia improved or resolved in 39 of 64 patients treated. However, only 31 of 51 patients had improvement or resolution of symptoms without therapy.

In addition to determining via BTO whether a revascularization procedure is necessary before occlusion of the CA when treating a symptomatic cavernous carotid aneurysm, the type of bypass necessary may also be determined, as discussed in an earlier section. With respect to bypass procedures in patients with giant cavernous carotid aneurysms, Kai et al.³¹ reported no ischemic complications in patients needing a bypass procedure in their series of 19 individuals, 10 of whom underwent revascularization procedures based on poor perfusion on BTO, SPECT scans, and physiological testing. The variant bypass strategies used in this series were STA-MCA for low-flow, RA for medium-flow, and vein grafts for high-flow needs, as discussed earlier.

When treating symptomatic cavernous carotid aneurysms at our institution, we initially determine the need for a bypass procedure and the type of bypass by using BTO as described previously. For patients in need of a low-flow bypass, that is, STA-MCA, the patient is taken to the interventional suite for endovascular CA occlusion 2–3 days after the bypass procedure. However, if the patient needs a high-flow bypass, the patient is taken immediately after the bypass procedure for endovascular CA occlusion due to the high risk of graft thrombosis if competitive flow from the parent vessel persists.

Giant MCA and Other Anterior Circulation Aneurysms

The International Study of Unruptured Intracranial Aneurysms investigators found that the 5-year cumulative rupture rate for giant (≥ 25 mm) anterior circulation aneurysms (ACA, anterior communicating artery, ICA, and MCA aneurysms) was 40%.⁷⁹ The high rupture risk and the morbidity and mortality levels intimately associated with rupture necessitate treatment in most patients. In addition to the risk of SAH, giant intracranial aneurysms often present with symptoms of mass effect or cerebral ischemia.⁴⁷

When examining parent vessel preservation strategies, the literature suggests the superiority of microsurgical clip placement to primary coil insertion. Our recent review of the literature on endovascular coil occlusion of giant aneurysms suggests that the mean complete occlusion rate is $\sim 57\%$, with an associated 7.7% mortality and 17.2% major morbidity rate.⁵⁰ In their meta-analysis of unruptured aneurysms, Raaymakers et al.⁵³ reported a 7.4% mortality and 26.9% morbidity rate in patients with surgi-

cal treatment of anterior circulation giant aneurysms. Due to the comparable morbidity and mortality levels and the high percentage of incompletely treated aneurysms with an endovascular approach, an open surgical approach is often selected in these cases over endovascular treatment if possible.⁵⁰ Endovascular parent artery occlusion with or without bypass, on the other hand, is highly effective at treating select giant aneurysms that are not amenable to strategies that preserve that parent artery.

Direct clipping (reconstructive strategy) of the neck is possible in many giant aneurysms and is considered to be the best surgical treatment. Endovascular strategies can complement surgical treatments to enable direct clipping of large or giant aneurysms.⁵⁰ The use of suction decompression for the treatment of giant paraclinoid aneurysms by using a guide catheter with balloon placed in the ICA, described above, can help facilitate the treatment of giant aneurysms near the clinoid to allow direct clip application with or without bypass. However, some aneurysms, especially fusiform lesions, are not amenable to clip ligation strategies. Therefore, alternative strategies must be used (deconstructive strategy), and these involve proximal ligation (Hunterian) or trapping with or without bypass. Additionally, a bypass can be used to revascularize a problematic branch or branches arising from the dome to render an “unclippable” aneurysm amenable to clip application.

When surgery is considered, a carefully planned and clearly defined strategy is paramount to a successful outcome in the treatment of giant aneurysms. In most cases a BTO is performed as outlined earlier in this manuscript. Not only can the ECA be assessed with BTO, but selective BTO can be performed in the intracranial vessel of interest to improve the accuracy of the information gained from the procedure. This is important when assessing the value of collateral blood flow if a targeted vessel is to be sacrificed. For example, a patient with a giant ICA aneurysm may pass a BTO of the cervical ICA due to robust collateral flow through ECA anastomosis with the ophthalmic artery that may be eliminated by surgical trapping. Therefore, the selective BTO may improve the sensitivity of this test. In our experience, BTO performed intracranially has been safe.

Patients who pass the BTO clinically but in whom failure is shown by radiographic perfusion or EEG studies (Group 2) are candidates for bypass strategies and are generally considered for “low-flow” bypass, for example STA-MCA/ACA. Other examples of low-flow bypasses are MMA-MCA, side-to-side (MCA-MCA and ACA-ACA), and arterial and venous short interpositional graft anastomosis (STA, OA, or superficial temporal vein).³³ When needed, a “double-barrel” STA-MCA bypass can be used to connect 2 branches of the recipient vessels to increase flow from the bypass, which can be necessary in giant aneurysms with 2 branches emerging from the dome of the lesion.³⁷ Also, a double-barrel bypass may allow for further augmentation of flow.

Patients who have neurological symptoms during BTO prior to or during provocative hypotension (Group 3) are candidates for “high-flow” bypass procedures. These include the ECA/ICA-MCA and ICA-ICA anasto-

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mosis.³³ These bypass procedures are performed through a conduit created from the RA or the SV. The M₂ branches are the favored target for high-flow bypass. Consideration must be given to the diameter, the length of the artery available on the cortical surface, and the perforating arteries of the segment that supply the basal ganglia, whereas M₄ branches are more suitable for the “low-flow” STA bypass target.

When dealing with anterior circulation giant aneurysms that are not amenable to direct clip ligation strategies or clip reconstruction, and require a bypass, we first consider a strategy in which the bypass to a vessel would allow direct clip occlusion. Mohit et al.⁴³ describes a case in which a large MCA bifurcation aneurysm with an adherent superior branch was bypassed, allowing direct clip ligation of the neck, which included the portion of the bypassed superior branch proximal to the bypass. This is a clear example in which bypass allowed an aneurysm to be clipped that would otherwise not have been treatable in this manner. Unfortunately, this is not always possible. We primarily use Hunterian strategies with bypass in patients who did not tolerate the BTO and in whom perforating vessels arise from the aneurysm, precluding us from safely sacrificing these vessels by trapping. If possible, especially with giant fusiform aneurysms, we prefer to trap the vessel and place the bypass based on the BTO as described previously. Finally, on rare occasions, the vessel that harbors the giant aneurysm can be sacrificed and the aneurysm removed and replaced with a graft. On a different note, in cases in which sacrifice of an MCA trunk is required for aneurysm treatment, a bypass will be performed even if the BTO is passed. As specified previously, BTO testing not only assesses tolerance to vessel sacrifice but also allows the surgeon to tailor the size of the donor vessel on a more physiological and less empirical basis: high-, intermediate-, or low-flow bypass. The BTO is also helpful in giving the surgeon information as to the available time for temporary arterial occlusion in the more complex lesions requiring reimplantation. Therefore, in this particular case, BTO would be used for these ends. For an aneurysm located on a more distal MCA branch, however, one could contemplate vessel sacrifice alone if the BTO is passed.

Sekhar and Kalavakonda⁵⁹ reported their 15-year experience with cerebral revascularization for tumor or aneurysm. During this time these authors performed 24 RA grafts, 105 SV grafts, and 8 other revascularization procedures. Fifty patients were treated for aneurysms with cerebral revascularization and 83 patients for cranial base tumors. The overall patency rate was 95.6%. They reported that 23 patients experienced a cerebral infarction; among those patients, 17 (12.5%) exhibited symptoms, but the majority demonstrated considerable recovery during the follow-up period. Additionally, 101 patients recovered to an excellent (GOS score of 5) or good (GOS score of 4) condition. Lawton et al.³⁷ reported a 9-year experience of cerebral revascularization for the treatment of intracranial aneurysms. Of the 61 patients treated, 63 revascularization procedures were performed. The postoperative patency rate was 92% at 5 months. They reported 1 death during the perioperative

period (2% mortality); 93% had a good outcome (GOS score of 1 or 2) and 5% had a fair or poor outcome (GOS score of 3 or 4). Finally, these authors reported an 8% neurological morbidity. Jafar et al.²⁹ reported their experience treating specifically giant intracranial aneurysms with cerebral revascularization by using an SV graft. They reported on their 9-year experience treating 29 patients with 30 SV bypass grafts. They found that 28 vein grafts remained patent, 1 death occurred from a cerebral infarction, 1 patient had a homonymous hemianopia, and another patient had a temporary hemiparesis. Although not all of these series report solely on treatment of giant aneurysms, they do illustrate a high graft patency rate. This supports cerebral revascularization for select aneurysms and skull base tumors.

Further consideration must be given to various in situ bypass strategies that were alluded to briefly earlier. In situ bypass requires that donor and recipient arteries lie parallel and in close proximity.⁵² Quinones-Hinojosa and Lawton⁵² described their experience with in situ bypass in 13 patients. They reported at least 4 sites where this requirement is met: the ACAs (A₂ and A₃ segments), MCA branches (including the anterior temporal artery branches as they course through the sylvian fissure), the PCA and SCA (as they course through the ambient cistern), and the PICAs (as they course around the posterior medulla and tonsils in the cisterna magna). Included in their series were aneurysms that were excised, with primary end-to-end reanastomosis. Although these were not all giant aneurysms, they found no adverse ischemic complications, and only 1 of the 13 bypasses became occluded (the MCA-STA-MCA graft). Additionally, 7 of the 13 aneurysms involved the anterior circulation. These authors do emphasize the importance of a long arteriotomy (3 times the diameter of the arteries) to avoid occlusion that could affect 2 vascular territories.

Posterior Circulation Aneurysms

Cerebral revascularization in the posterior circulation is well recognized as a key component in the treatment of complex and giant intracranial aneurysms.³⁴ Common revascularization techniques in the posterior circulation involve STA-PCA anastomosis, ECA-PCA via SV or RA, STA-SCA anastomosis, OA-AICA anastomosis (rare due to small vessel size and the deep operative field), OA-PICA anastomosis, interpositional graft anastomosis with OA or STA, and side-to-side or end-to-end PICA anastomosis. Revascularization of the posterior circulation is unique when compared with the anterior circulation because the surgical corridors are narrow, with many critical structures including the brainstem, and the recipient vessels are smaller in diameter; therefore, the SV is seldom used (although it can be used in PCA/ECA anastomosis). Four arteries are recipient vessels: PCA, SCA, AICA, and PICA. An RA graft may be ideal for bypass into the PCA in the treatment of aneurysms beyond the middle or upper BA.⁶⁰ An STA-SCA anastomosis may be a necessary option if both PCA are severely diseased or atretic.

Ausman et al.⁶ were the first to report an intracranial posterior circulation bypass (OA-PICA). They chose the

FIG. 1. Case 1. A: Preoperative DS angiography study in anteroposterior (AP) view obtained in a 60-year-old woman treated for a large paraclinoid aneurysm with STA-MCA (M_3) bypass followed by endovascular parent vessel occlusion. B: Postoperative DS angiography study in AP view demonstrating coil occlusion (arrow) of the parent artery with good collateral flow. C: Postoperative CT angiography study demonstrating a patent bypass graft (arrows).

OA, and there are specific advantages to this choice: the recipient vessel is relatively large, the lumen of donor OA approximates that of the distal PICA, and the bypass location is rather shallow.³⁴ Bypass strategies involving the posterior circulation have naturally progressed during the past few decades and have gone from inferior and superficial to superior and deep.

Giant, dissecting, and fusiform aneurysms involving the posterior circulation may need to be treated with Hunterian occlusion or trapping. Depending on the patient's specific anatomy, revascularization may be necessary. There are some specific vascular lesions in the posterior circulation that can be managed by creative revascularization and clip ligation strategies. Fusiform and giant thrombotic BA aneurysms often need to be treated with revascularization. Kai et al.³⁰ reported on the treatment of an enlarging nongiant basilar trunk dissecting aneurysm treated with Hunterian ligation and RA bypass from the VA to the P_2 segment. This treatment involved proximal ligation and flow reversal, with complete resolution of the dissecting BA aneurysm distal to the AICA at the 1-year follow-up angiogram. This case example illustrates how this strategy can be used for a variety of complex posterior circulation aneurysms. Giant PICA aneurysms often need to be treated by bypass (OA-PICA or PICA-PICA bypass) and trapping.³⁴

Not only giant aneurysms but often dissecting aneurysms need to be cared for in a deconstructive manner (proximal occlusion or trapping), necessitating revascularization in many cases. The management of dissecting PICA aneurysms causing SAH remains challenging and controversial.² Either PICA-PICA or OA-PICA bypass may be used successfully in the management of these lesions to eliminate the aneurysm and preserve cerebral perfusion. When dealing with PICA aneurysms, bypass strategies are generally considered when the lesion involves the PICA in the proximal 3 segments; distal to the third segment, sacrifice is generally considered safe without revascularization. Finally, giant or fusiform VA aneurysms proximal to the PICA may need to be treated

with an RA or SV “jump” graft to facilitate resection and reperfusion.

Sundt and Piepgras⁷⁰ reported on 16 patients treated with OA-PICA bypass for ischemic symptomatology. They found that 15 of 16 grafts were patent at the 6- to 8-week follow-up interval and that the 3 patients with 3 months–1 year of follow-up all had patent grafts. There was only 1 patient with a small cerebellar infarct postoperatively. Ausman et al.⁵ reported their experience treating 83 patients with 85 bypass procedures for vertebrobasilar insufficiency by using STA and OA grafts. They found that 8 (73%) of 11 OA-PICA anastomoses were patent at an average follow-up duration of 25 months. In the group with OA-AICA bypasses, postoperative angiograms demonstrated patency in 15 (94%) of 16 angiograms. Finally, STA-SCA bypasses remained patent in 48 (98%) of 49 patients. The overall mortality rate was 7%. Although these series represent treatment for ischemic disease, similar outcomes could be expected when using similar techniques for posterior circulation bypass for aneurysms.

Patients who have undergone cerebral bypass procedures are placed on aspirin postoperatively. The patient is kept well hydrated for further prevention of graft occlusion and monitored in the neurosurgical intensive care unit, where the graft is monitored hourly with Doppler ultrasonography. The patients routinely undergo postoperative angiography when assessing occlusion of giant aneurysms.

Illustrative Cases

Case 1

This 60-year-old woman was found to have an incidental 13 × 11-mm left paraclinoid aneurysm (Fig. 1A) during workup of ear pain. She also had an earlier history of blurred vision but none on presentation. The patient underwent BTO and clinically passed, with no electrophysiological deficit. However, SPECT scans showed asymmetry in the basal ganglia. The patient underwent

Fig. 2. Case 2. *Left:* Preoperative DS angiography study revealing the giant MCA aneurysm in an 11-year-old girl. The patient tolerated a BTO; however, given her young age, flow augmentation with STA-MCA bypass was chosen. *Right:* Postoperative DS angiography image demonstrating elimination of the aneurysm and a patent bypass graft (arrows).

an STA-MCA bypass followed on postoperative Day 2 by endovascular occlusion of the parent artery (Fig. 1B). Postoperatively, the patient was discharged in stable neurological condition when compared with baseline and remained intact at her 4-year follow-up visit (Fig. 1C).

Case 2

This 11-year-old right-handed girl presented to another institution with progressive headache and seizure. Workup led to the discovery of an unruptured giant fusiform left MCA aneurysm (Fig. 2 *left*). Due to the aggressive nature of these lesions, a discussion was held with the parents and a decision to treat surgically was made. The patient underwent a BTO and she passed with evidence of good pial collateral flow; however, she had some slight increase in the transit time when the balloon was inflated, along with hypotension. It was believed that we would plan on open surgical treatment with STA-MCA bypass, after which we would trap the aneurysm. A low-flow bypass was thought to be adequate because the patient had good collateral circulation and favorable BTO results. We therefore chose to bypass into the frontal branch that was 1 of 2 main branches that came off a common trunk exiting the aneurysm. Choosing this vessel allowed us to maintain outflow from the aneurysm during temporary occlusion for the bypass. Once the bypass was sewn in place, the proximal MCA (M_1) was temporarily clipped, the distal common outflow trunk was clipped, and the anterior temporal branch was temporarily clipped. The aneurysm was deflated and there were lenticulostriate perforating vessels arising from it. We created a conduit for flow into these perforating vessels with large straight fenestrated aneurysm clips, and placed a straight clip distal to the lesion. The intention of this strategy was to allow inflow into the aneurysm neck to perfuse the perforating vessels. We were able to preserve the anterior temporal branch of the MCA. Our bypass was perfusing the superior division of the MCA supplying the frontal lobe. Our hope was that

this would allow flow also into the common trunk of the MCA; however, despite the robust pulsation of the frontal MCA branch and the appearance of the bypass at the time of surgery, there appeared to be competitive flow at the MCA. The bypass was patent postoperatively (Fig. 2 *right*), but the patient was left with a right hemiparesis and expressive dysphasia that had almost completely resolved at the 2-month follow-up visit.

Case 3

This 39-year-old man was found to have a large cavernous aneurysm resulting in intermittent double vision (Fig. 3 *left*). Progressive growth of the aneurysm was noted on yearly serial imaging. After careful review of options with the patient, he elected to proceed with EC-IC bypass followed by endovascular parent artery sacrifice. The patient underwent BTO, showing stability on clinical and EEG measures; however, a SPECT study showed asymmetry therefore the patient underwent STA-MCA bypass prior to endovascular occlusion (Fig. 3 *right*).

Case 4

This 60-year-old man presented with progressing neurological deficits and rapidly progressing headaches. On DS angiography, the patient was found to have a dolichoectatic aneurysm involving both VAs and the proximal BA, compressing the brainstem, with a dominant left VA (Fig. 4A). However, the disease was worst on the left side. The patient underwent BTO for possible left VA occlusion, and passed the test. He then underwent successful trapping of the lesion, which decompressed his brainstem. The patient presented 9 months later with incrementally worsening spasticity, and DS angiography showed a massive expansion of the residual ectatic distal right VA (Fig. 4B). He underwent a BTO, which failed profoundly due to poor remaining collateral circulation. An STA-PCA bypass was therefore performed and the graft was left to mature (Fig. 4C). A BTO done at that

FIG. 3. Case 3. *Left:* Preoperative DS angiography study in oblique view of the large 15-mm cavernous carotid aneurysm. *Right:* Postoperative DS angiography study of an ECA injection in lateral view, after treatment of a cavernous carotid aneurysm; the patent graft is visible (arrows).

time was tolerated. The patient was followed up for 1 year and showed a downhill neurological course with a relentlessly enlarging giant aneurysm. He underwent endovascular coil occlusion of his right cervical VA, but substantial BA flow and aneurysm filling were still noted through several arterial collateral vessels (Fig. 4D). The patient then underwent trapping of his BA aneurysm with clip placement. Nevertheless, the patient did not tolerate the procedure due to loss of perforating vessels in the trapped segment and subsequently died.

Technologies to Assess Bypass Results

Intraprocedural assessment of bypass grafts has historically been crude and nonquantitative. Frustrations with unexplained postprocedural graft occlusion and insufficiency led to the development of more quantitative intraprocedural instruments. Postprocedural assessment has relied on cerebral angiography as the gold standard. This technique, however, carries risk and does not convey quantitative information. Therefore, noninvasive, more quantitative techniques that afford little or no risk to the patient have been desired. Current technological developments have led to a multitude of noninvasive techniques to determine accurately the graft patency and hemodynamic information that may be used to predict the risk of graft occlusion. Herein, we review several useful technologies for intra- and postprocedural assessment of bypass graft patency.

Intraprocedural Assessment

Intraoperative determination of bypass graft patency and functionality may also avoid future complications from either premature graft stenosis or occlusion. Several

techniques to determine graft patency intraoperatively are available. Intraoperative determination of graft patency has involved independent pulsatile motion of the donor vessel after anastomosis, the use of microvascular Doppler ultrasonography, and the use of intraoperative cerebral angiography. Despite the direct nature of these techniques, each modality carries inherent disadvantages and inaccuracies, mainly based on the subjective and qualitative nature of flow determination. Recently, however, Charbel and colleagues¹¹ developed an intraoperative technique for assessing graft blood flow measurements, namely the Charbel Micro-Flowprobe, which provides flow quantification in arteries with diameters ranging from 1 to 3 mm. This technique determines vessel blood flow independent of the flow velocity profile, turbulence, or hematocrit, and merely relies on the principle of ultrasonic transit time. Amin-Hanjani et al.³ reported on the use of the Charbel flow probe and quantified bypass blood flow by calculating the cut flow index, which is obtained by dividing the measured bypass flow rate by the cut flow of the donor artery, as follows: $\text{cut flow index} = \text{bypass flow (ml/minute)} / \text{cut flow (ml/minute)}$. The cut flow index is a measure of the full carrying capacity of the donor vessel in the absence of downstream resistance. Using this novel index measure, Amin-Hanjani et al. determined a probability value of < 0.5 to be predictive of the risk of graft occlusion or poor functioning. Intraoperative determination of potential graft failure would allow the surgeon to consider alternative means of revascularization.

A recent development for intraoperative assessment of bypass graft patency has been intraoperative video fluorescence angiography, which involves a fluorescent tracer (indocyanine green) and specially equipped surgical microscopes that are able to view light in the near-infrared spectra. Woitzik et al.⁸⁰ demonstrated that in-

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FIG. 4. Case 4. A: Preoperative DS angiography study of a left VA injection in lateral view revealing a dolichoectatic aneurysm involving the distal left VA and the proximal BA. The PICA is seen originating proximal to the lesion. B: Postoperative DS angiography study of a right VA injection in AP view demonstrating massive expansion of the residual ectatic distal right VA and proximal BA. The PICA is seen originating proximal to the lesion. C: Postoperative DS angiography study of an ECA injection in lateral view after an STA-PCA bypass, demonstrating a patent bypass graft (arrows). D: In this oblique view of a DS angiography study, despite coil occlusion of the proximal right VA, increased blood flow through the distal right VA, the BA, and the aneurysm is still observed due to several arterial collateral vessels (arrows).

traoperative video angiography was useful in identifying both nonfunctioning and stenotic bypass grafts, which were successfully revised at the time of identification. This intraoperative technology is in its infancy and will most certainly prove to be a highly useful technique in identifying bypass graft patency. Early results from our institution are very encouraging, and we have been able to determine the direction of flow in complex situations due to the dynamic nature of the video angiogram.

Many modalities for noninvasive assessment of bypass graft patency and functionality are currently available. These noninvasive modalities not only avoid the potential complications of cerebral angiography, but also provide important hemodynamic information that can be used to assess the potential risk of bypass graft failure,

thus potentially avoiding unnecessary ischemic complications.

Postprocedural Assessment

Multislice contrast-enhanced CT angiography has been developed over the last several years and allows a multitude of parameters that can be determined with regard to bypass graft patency and functionality. With the development of 32- and 64-slice CT angiography, direct visualization of patent bypass grafts with submillimeter resolution can be performed. Furthermore, in combination with CT perfusion studies and CBF analyses, the patency and functionality can be quantitated and assessed over time, giving the surgeon a measurement of cerebral revascularization. However, contrast-enhanced CT an-

giography requires the use of iodinated contrast agents as well as exposure to radiation, which confers some risk to the procedure, especially in patients with compromised renal function. An alternative to contrast-enhanced CT angiographic assessment of bypass graft patency has been quantitative contrast-enhanced MR angiography. Quantitative contrast-enhanced MR angiography allows the direct measure of blood flow through the bypass graft, thus providing valuable hemodynamic information. The combination of contrast-enhanced MR angiography with MR perfusion allows a complete assessment of bypass patency, functionality, and effect on CBF. Finally, quantitative MR angiographic imaging based on time-of-flight MR datasets can be reconstructed into 3D datasets by using commercially available software (NOVA [Noninvasive Optimal Vessel Analysis], VasSol Inc.), with which CBF quantification can be rendered, making blood flow assessment in individual vessels possible, thus allowing the determination of the patency and hemodynamic behavior of a bypass graft. Unfortunately, imaging of bypass graft patency near any surgical clips (aneurysm or parent artery) is often difficult due to the often significant signal scattering afforded by the clips. The CT images can be processed so that the clip artifact is minimal, but MR images with significant clip artifact are more difficult to render due to the significant paramagnetic effect. As a result, postoperative noninvasive imaging of bypass graft patency needs to be tailored so that the clip artifact, if any, can be minimized.

Current Advances and Future Directions

Although STA-MCA bypass procedures are correlated with a slight risk of intraoperative ischemic injury because temporary occlusion is applied to superficial, small, distal MCA branches, higher-flow bypasses such as the RA and SV grafts are associated with a higher risk of ischemic insult because temporary occlusion of the larger M₂ or M₃ branches is required. This in fact diminishes the time window of safe temporary occlusion and subjects the operating neurosurgeon to an increased component of stress.

The ELANA technique allows the construction of a high-flow bypass using SV or RA grafts without the need for temporary occlusion of the recipient artery. Grafting to larger, more proximal segments of the recipient arteries and deeper anastomoses are therefore possible without the risk of intraoperative ischemic injury. By allowing for a more proximal outflow anastomosis, this technique has raised the bar for previously established maximal graft flow, better approximating the physiological CBF. In fact, data suggesting that a higher flow can be achieved with a more proximal anastomosis on the recipient artery have previously been reported.^{11,26,75} Other advantages of performing bypasses using ELANA include no need for systemic heparin burst suppression to protect against cerebral ischemia,⁴⁴ therefore eliminating additional risks related to a conventional procedure. Moreover, an ELANA bypass necessitates less surgical exposure due to the fact that more space is available on the recipient artery, where a temporary clip is no longer needed.

Since its development by Tulleken and colleagues,⁷⁵ in Utrecht, there have been numerous reports regarding the safety and efficacy of ELANA in the literature.^{10,35,69,73,74,76} In 2002, Brilstra et al.¹⁰ published a retrospective series on 77 patients who were treated for intracranial aneurysms by using an ELANA bypass. A permanent neurological deficit related to the procedure was noted in 29%. At a median of 2.5 months of follow-up, 32% were dependent or had died. In 13% of patients, procedural complications were the sole cause of poor outcome. A multivariate analysis showed that the baseline clinical condition was the only factor significantly correlated to outcome. The authors concluded that ELANA should be considered in cases in which aneurysms cannot be occluded with coils or ligated with clips and in which the patients cannot tolerate parent vessel sacrifice. They also mentioned that although the procedure-related complication risk was substantial, it had to be weighed against the natural history of these aggressive lesions. In the same year, Klijn et al.³⁵ published a report on 15 patients treated with ELANA for symptomatic CA occlusion. In that series, 73% had an uncomplicated procedure, 7% had a severely disabling stroke and occluded bypass, 13% had a moderately disabling stroke, and 7% died. The median follow-up duration was 27 months. Of those in whom no complications occurred during the procedure, 9% suffered an ipsilateral new stroke at 10 months and 9% had died at 17 months postoperatively due to a brainstem stroke. The authors concluded that ELANA was a promising approach for the management of the condition in patients with symptomatic CA occlusion and a high risk of recurrent stroke. They also reported that the procedure-related risk was clearly evident; however the patient's baseline condition might also have contributed to this risk.

In 2005, Streefkerk and colleagues⁶⁸ experimented on pigs and showed that ELANA anastomoses were capable of long-term reendothelialization comparable to conventional anastomoses. In 2006, van Doormaal et al.⁷⁶ described 34 patients with an ICA aneurysm treated with ELANA. The mean follow-up period was 3.3 years. A bypass was constructed in 97% of cases. Occlusion of the ICA and subsequent aneurysm thrombosis was achieved in 94% of cases. Perioperative morbidity and death were noted in 21 and 6% of cases, respectively. At long-term follow-up, 74% had a favorable outcome and 79% were independent, with a modified Rankin Scale score of < 3. The authors concluded that the ELANA high-flow bypass provided maximal brain protection because temporary occlusion was not required and that it was an effective treatment modality in cases in which no other approach would be feasible. In the same year, Reinert et al.⁵⁵ demonstrated that ELANA could be used to perform end-to-side anastomoses with expanded polytetrafluoroethylene grafts in rabbits and that a bypass procedure using both may be a viable option.

In December 2007, Bremmer et al.⁹ published a laboratory investigation on the use of a sutureless (SELANA) technique to construct a high-flow bypass with an expanded polytetrafluoroethylene graft on the abdominal aorta in 18 rabbits (36 anastomoses). The authors found that a bypass using SELANA was easier and could be

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performed faster (15–25 minutes) when compared with ELANA, which requires > 90 minutes. Furthermore, when the animals were killed, 89% of bypasses were patent. Eighty-nine percent of the anastomoses could be completed without the need for temporary occlusion of the recipient vessel. In the rest, complicating factors necessitated temporary occlusion. In all 36 anastomoses, complete coverage with neointimal repair tissue was evident on electron microscopy at 10 days. The authors concluded that SELANA was easier and faster than ELANA and that further studies evaluating its safety and long-term patency were warranted.

Conclusions

Cerebral revascularization strategies are important in the armamentarium of the cerebrovascular neurosurgeon. These strategies are important in the treatment of complex and giant intracranial aneurysms. Through proper patient selection (often based on results of BTO) an appropriate graft can be chosen. Through creative strategies a bypass can facilitate clip ligation of a previously unclippable aneurysm, or it can allow for the exclusion of an aneurysm via Hunterian ligation or trapping. It is anticipated that revascularization procedures and reimplantations will be increasingly required in the future at the main treatment centers as the straightforward lesions are treated endovascularly and only the most severe are referred. Also, endovascular failures need substantial creativity to accomplish successful reconstruction.

Disclaimer

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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