Chapter 8
Complex Intracranial Aneurysms: Strategies for Surgical Trapping and Cerebral Revascularization

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Background: The "Complex" Aneurysm

The majority of intracranial aneurysms can be successfully treated using standard reconstructive microsurgical or endovascular techniques, such as simple clip ligation or coil embolization. For ruptured aneurysms, early treatment is essential to eliminate the risk of rebleeding and allow aggressive medical and/or endovascular management of delayed cerebral ischemia (DCI), which typically occurs in the first 2 weeks after subarachnoid hemorrhage (SAH). However, there is a subset of "complex" aneurysms that do not lend themselves to simple reconstructive procedures and require more technically elaborate management strategies. Non-saccular lesions, including dissecting/blister, mycotic, and fusiform/serpentine aneurysms, have no clearly identifiable neck and are thus inherently classified as "complex." Likewise, saccular aneurysms may present certain morphological and angio-anatomic characteristics that make their treatment more challenging. Such characteristics include large (>10 mm) or giant (>24 mm) size, wide neck (>4 mm) or low dome/neck ratio (<2), presence of intraluminal thrombus, calcified or atherosclerotic neck, arterial branches or perforators originating from the aneurysmal dome or neck, and recurrent aneurysms after clipping or coiling [1–3]. While some of these complex aneurysms may still be amenable to reconstructive procedures, such as

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clipping or clip-wrapping for blister aneurysms, stent- or balloon-assisted embolization for large and wide-necked aneurysms, and flow diverter embolization for non-saccular lesions, many ultimately require a deconstructive procedure, i.e., occlusion of the parent artery or its branches along with the aneurysm. While this can be achieved either microsurgically or endovascularly, it typically mandates microsurgical cerebral revascularization, i.e., bypass surgery, to replace flow in the occluded vascular territory, particularly in the setting of SAH. In this chapter, we will focus on deconstructive microsurgical techniques and bypass surgery for complex intracranial aneurysms.

How Often Are Aneurysm Trapping and Bypass Required in the Real World?

In large microsurgical series, the proportion of intracranial aneurysms that are deemed complex, requiring microsurgical deconstruction and bypass, varies considerably according to the location of the aneurysm. For instance, while anterior cerebral artery (ACA) aneurysms only rarely require bypass surgery (<1%), the rate of bypass may reach 3–4% for middle cerebral artery (MCA) aneurysms and can be as high as 25–30% for posterior inferior cerebellar artery (PICA) aneurysms [1, 3–6]. This high variability is related to major differences in aneurysm morphology and arterial branch anatomy among various aneurysm locations. The rate of bypass surgery for ruptured blister or dissecting aneurysms also appears to be higher than for saccular aneurysms, ranging from 18% to as high as 95%, likely related to the absence of a clippable healthy wall in the aneurysm-bearing portion of the parent artery [7–9].

Deconstructive Microsurgery: Complete Versus Partial Trapping

When feasible, complete aneurysm trapping, i.e., occlusion of both its proximal inflow and distal outflow, usually with clips, is the most definitive treatment for unclippable complex aneurysms. Thus, it is the preferred treatment modality whenever it can be safely achieved. However, this requires that both its inflow (parent vessel) and outflow (distal portion of parent vessel or proximal portion of branches) are surgically accessible for clip placement. Likewise, the absence of vital perforators arising from the aneurysmal portion of the vessel is an absolute prerequisite for complete aneurysm trapping. In some cases, aneurysm trapping can allow aneurysm excision and in situ microsurgical reconstruction of the parent artery. For instance, if the aneurysm is excised from a non-branching linear segment of artery, end-to-end anastomosis of the cut vessel edges can be performed to restore flow. Alternatively, if the aneurysm is excised from an arterial bifurcation, direct branch reimplantation onto the parent artery can be performed via end-to-side anastomosis, end-to-end anastomosis, or a combination thereof. In situ microsurgical reconstruction of the parent artery may be the most physiological flow replacement technique when a deconstructive procedure is indicated, since it precludes the need for additional bypass procedures. Moreover, both parent artery reanastomosis and branch reimplantation require only a single end-to-end or end-to-side anastomosis and are therefore relatively quick. However, a tension-free anastomosis is essential to avoid suture pullout or breakage. Therefore, some degree of tortuosity or redundancy of the parent artery and extensive dissection prior to vessel reconstruction are mandatory to provide long enough and freely mobilizable vessel segments. It is also imperative for aneurysm excision to be complete, with no pathological arterial wall remaining in the transected ends. Unfortunately, this is not always possible, particularly in perforator-rich zones, where the ability to mobilize vessels can be extremely limited. Likewise, excision of aneurysms involving long arterial segments can result in large gaps that are impossible to repair primarily. In such cases, consideration may be given for an interposition venous or arterial graft. Ideally, the latter should be harvested and ready to implant before aneurysm excision to minimize ischemia time. Likewise, if needed, an extracranial-intracranial (EC-IC) bypass should also be ideally performed, for the same reason, before aneurysm excision. Therefore, before committing to a strategy of aneurysm excision and in situ microsurgical reconstruction, careful preoperative angiographic assessment is mandatory to ensure a high likelihood of technical success and minimize the risk of ischemic complications [3].

Unfortunately, complete trapping may not be always safe or feasible. Occasionally, surgical access to either the afferent or efferent vessel can be technically challenging or risky, thus precluding complete aneurysm trapping. Likewise, the presence of vital perforators arising from the aneurysm itself constitutes a contraindication to complete trapping. In such cases, consideration should be given to partial trapping, i.e., intraaneurysmal flow reduction and/or reversal by either proximal or distal parent vessel occlusion. By reducing and/or reversing flow through the aneurysmal portion of the vessel, partial trapping can lead to gradual intraaneurysmal thrombosis with concomitant vascular remodeling. Perforator patency is usually preserved as a result of continuous flow demand. Unfortunately, however, this is not always the case, since rapid complete intraaneurysmal thrombosis may unpredictably occur, leading to occlusion of perforators and cerebral infarction. Another infrequent but unpredictable potential hazard with this treatment strategy, particularly in the setting of SAH, is aneurysm rupture precipitated by intraaneurysmal thrombosis. To ensure adequate flow in the distal cerebral vasculature, an EC-IC or intracranial-intracranial (IC-IC) bypass is often performed prior to partial aneurysm trapping. The decision to add a distal bypass depends on the size of the vessel being occluded and its vascular territory, as well as the status of circle of Willis (CoW) and leptomeningeal collaterals. Given its preservation of a physiological anterograde flow into the trapped perforators, distal outflow occlusion may be particularly advantageous for aneurysms arising from perforator-rich vessels, such as the proximal MCA and PICA. In fact, good clinical outcomes after distal occlusion, with fairly low rates (0–12.5%) of aneurysm rupture and perforator infarct, have been well documented by a handful of small microsurgical series [2, 10, 11].

To Bypass or Not to Bypass?

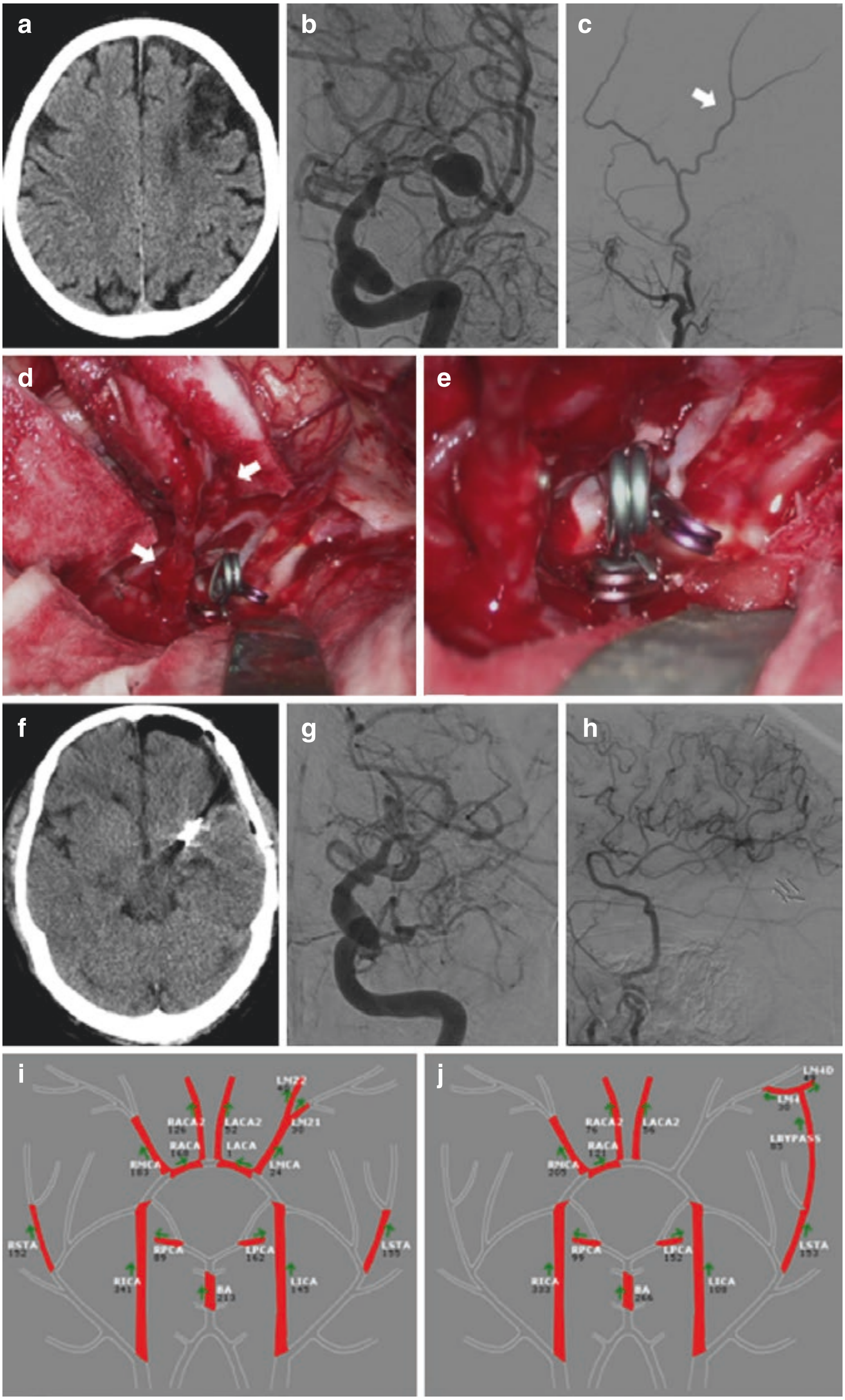
Whenever complete or partial aneurysm trapping is being contemplated, a decision whether or not to replace flow in the distal vascular territory, with either an EC-IC or IC-IC bypass, should be made preoperatively. For unruptured aneurysms, this decision largely relies on the size of the vessel being sacrificed, the extent of its vascular territory, and whether sufficient CoW and leptomeningeal collaterals exist to maintain distal flow after aneurysm trapping. For this reason, the importance of a careful preoperative review of angiographic studies and a balloon test occlusion (BTO) of the parent artery cannot be overemphasized in this setting. In our practice, we also routinely assess the intracranial flow map in each patient preoperatively, using the technique of quantitative magnetic resonance imaging via noninvasive optimal vessel analysis (NOVA qMRA®, VasSol Inc., River Forest, IL, USA). Understanding baseline intracranial flow dynamics is essential, as it allows us to tailor a bypass strategy individually for each patient [12–14]. Patient age is another factor many surgeons take into consideration when making the decision to bypass. In fact, occlusion of a major cerebral artery has been associated with an increased risk of de novo aneurysm formation, likely resulting from increased hemodynamic stress in the collateral circulation [15–18]. Given a longer remaining life expectancy, younger patients would theoretically be at greater risk for de novo aneurysm formation. For this reason, many surgeons advocate routine flow replacement bypass for young patients, irrespective of the extent of angiographic collateral flow and results of BTO. However, a flow replacement bypass performed in the setting of little or no flow demand in the cerebral vasculature is at risk of failure, irrespective of the surgeon's level of technical proficiency. Thus, in our practice, we do not endorse the policy of universal flow replacement bypass for young patients but rather rely in our decision-making on objective anatomic and physiologic data provided by preoperative angiographic studies, BTO, and qMRA.

In the setting of SAH, the decision process described above becomes less relevant given the high risk of DCI. In our practice, flow replacement bypass is typically performed whenever trapping of a ruptured aneurysm is expected to occlude a major cerebral artery, apart from a nondominant vertebral artery (VA), irrespective of the preoperative angiographic findings and extent of collateral circulation. Likewise, although preoperative BTO can help assess the quality of collateral flow and cerebrovascular reserve, its results seldom impact our decision to perform a bypass in this setting. The only exception to this rule is in patients who present late, beyond the time window for DCI, i.e., after the second week post-SAH. Early therapeutic ICA sacrifice in the setting of SAH has been associated with very high rates of cerebral ischemia and mortality, both acutely and in a delayed fashion, as a result of DCI [19]. In contrast, the outcomes after aneurysm trapping and bypass have been generally shown to be favorable, essentially paralleling those observed in patients after simple aneurysm clipping [1, 3, 5, 7, 8, 11, 20]. In fact, flow replacement bypass surgery has been shown to preserve cerebral blood flow (CBF) during the second week after SAH, at a time when the risk of DCI is maximal [20]. Moreover, when cerebral vasospasm occurs, it tends to spare the bypass graft, which allows the latter to be used as an endovascular conduit to treat DCI [20]. In experienced hands, the technical bypass success rates are very high, ranging from 80% to 100% [1, 3, 5–8, 11, 20].

Timing of Bypass: Before or After Attacking the Aneurysm?

There is no doubt that a thoroughly planned bypass strategy ahead of the actual surgical procedure allows the surgeon and operating room personnel to be well prepared in advance, which in turn helps optimize intraoperative efficiency and minimize complications. The determination as to whether an aneurysm is safely clippable can often be made preoperatively, after careful review of angiographic studies (Fig. 8.1). For instance, angiographically large or giant-sized aneurysms that incorporate branching arteries are often associated with a greater difficulty at direct clipping. In cases where simple clip reconstruction is unlikely to succeed, an EC-IC or IC-IC bypass should be given consideration prior to attacking the aneurysm, thus providing the surgeon with more options in terms of parent artery occlusion and aneurysm trapping should the need arise. This extra degree of freedom becomes particularly important when tackling lesions with a notoriously high risk of intraoperative rupture, such as dissecting and blister aneurysms. However, in many cases, the determination that an aneurysm is unclippable can only be made after the parent artery and aneurysm neck have been fully dissected and the local microvascular anatomy has been directly assessed. For instance, dense calcifications or atheroma in the aneurysm neck, which are not always obvious on preoperative angiographic studies, may impede the ability of clip blades to fully close onto the aneurysm neck. In such cases, aneurysm manipulation should be halted and the bypass procedure performed prior to permanently securing the aneurysm. For this reason, it is always advisable to assume the worst-case scenario when surgically approaching complex intracranial aneurysms and prepare for a potential bypass procedure, even when the latter is unlikely to be required. In other words, the potential donor and recipient vessels should be dissected out and prepared for a possible bypass before the aneurysm is approached. Specifically, the superficial temporal artery (STA) should always be preserved when it is of suitable size in the event that it may serve as a donor vessel, even when the use of a high-flow transplanted conduit had been planned. Having a multitude of options intraoperatively is paramount when tackling these challenging lesions and increases the likelihood of a good outcome.

In contrast to the scenario of planned revascularization described above, a rescue bypass procedure may be occasionally required after an unsuccessful clipping attempt. When permanent clip application leads to partial or complete occlusion of the parent artery or a major branch of it, clip repositioning should be performed to deobstruct the normal vessels while keeping the aneurysm neck occluded. However, clip repositioning may not be always possible, particularly when intraoperative aneurysm rupture has occurred within or close to its neck. Any attempts to reposition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the clip in that setting would lead to profuse intraoperative bleeding from the rupture site. In such instances, a rescue EC-IC or IC-IC bypass becomes indicated to supplement or replace flow in the distal territory of the occluded vessel. Needless to say, a rescue bypass needs to be performed rapidly and efficiently to minimize ischemia time, especially in the setting of marginal CoW and leptomeningeal collaterals.

EC-IC Versus IC-IC Bypass: Which Is Better?

When feasible, an IC-IC bypass constitutes an elegant alternative to EC-IC bypass for several reasons. First, it obviates the need for donor vessel harvesting, additional neck incisions, or cervical carotid artery manipulation. Second, it requires no graft or a short graft, which may translate into a higher long-term patency rate. Third, the bypass graft is less vulnerable to accidental injury, kinking, or compression, given its exclusively intracranial location [21]. However, IC-IC bypasses are generally technically challenging considering the smaller vessel size and the often deep and narrow surgical corridors. More importantly, they require dissection and temporary occlusion of an uninvolved intracranial donor artery, which leads to an additional risk of arterial injury and/or cerebral ischemia, particularly in the setting of SAH [3].

Compared with either IC-IC bypass or aneurysm excision with local reconstruction, EC-IC bypass does not often require interruption of flow in a major cerebral artery, which translates into a lower risk of cerebral infarction. This is especially true when the external carotid artery (ECA) or one of its branches is used as donor vessel and a distal cerebral artery as recipient vessel, as in the case of the very commonly performed STA-MCA bypass. Likewise, the excimer laser-assisted

Fig. 8.1 A 71-year-old diabetic and hypertensive man presented with mild aphasia secondary to a recent left MCA territory stroke. (**a**) Head CT shows a small left frontal infarct. (**b**) Left ICA angiogram reveals an 8-mm saccular aneurysm of the left MCA bifurcation with a 2-mm neck. There is an associated high-grade, flow-limiting stenosis of the M1 segment, which makes endovascular access particularly challenging and risky. Although the aneurysm's narrow neck makes it potentially clippable, the presence of significant atherosclerotic disease in the MCA puts the patient at imminent risk of perioperative stroke. We elected to proceed with surgical revascularization of the left MCA territory followed by clip deconstruction of the MCA bifurcation and aneurysm. (**c**) Left ECA angiogram demonstrates a well-sized parietal branch of the STA, which divides into two equally sizeable branches (white arrow). A "Y" bypass making use of these two donor vessels was thus planned. (**d**, **e**) Intraoperative microphotographs show a successful "Y" bypass to both M2 trunks (**d**, white arrows), followed by complete clip deconstruction of the MCA bifurcation and aneurysm (**e**). (**f**) Postoperative head CT. (**g**) Postoperative left ICA angiogram reveals successful occlusion of the MCA bifurcation and aneurysm, with preservation of the lenticulostriate arteries along the M1 segment. (**h**) Postoperative left ECA angiogram demonstrates a patent "Y" bypass supplied solely by the parietal branch of the STA, with robust opacification of the distal left MCA territory. (**i**) Preoperative NOVA qMRA shows markedly reduced flow (20–40 mL/min) in the left MCA territory. (**j**) Postoperative NOVA qMRA demonstrates high flow (85 mL/min) in the bypass graft non-occlusive anastomosis (ELANA) technique can be employed to obviate the need for intracranial flow interruption when a high-flow bypass to a large intracranial artery, such as the ICA or proximal MCA, is required [22, 23].

In light of these considerations, we generally favor EC-IC bypass in most cases, except when a side-to-side in situ IC-IC bypass constitutes a more straightforward alternative. This is usually the case when the distal portion of the occluded vessel travels close and parallel to its contralateral counterpart in the midline or to a similarly sized artery, as is the case with distal PICA-PICA, ACA-ACA, and MCA-MCA bypasses [5, 6, 21]. Our general policy is to favor a side-to-side strategy for PICA preservation whenever the local anatomy is deemed appropriate. While equally feasible, an occipital artery (OA) to PICA bypass can be problematic, given that the OA is typically tortuous, which makes it difficult to dissect and makes the graft length somewhat unpredictable until all of the dissection has been carried out. For this reason, we reserve the OA-PICA bypass solely for cases where the PICA-PICA option is deemed unsuitable and where the OA is angiographically robust. Likewise, we find the MCA-MCA bypass, either M2-M2 or M3-M3, to be extremely valuable in managing complex MCA bifurcation aneurysms (Figs. 8.2 and 8.3). By practically converting the MCA bifurcation into a single M2 vessel, MCA-MCA bypass tremendously simplifies clip reconstruction at the MCA bifurcation, allowing to safely deconstruct any of the two M2 branches along with the aneurysm. Moreover, in cases where a complete takedown of the MCA bifurcation is necessary, a side-to-side M2-M2 or M3-M3 bypass allows a single EC-IC bypass graft to perfuse the entire MCA territory. However, if an MCA-MCA bypass is not feasible, consideration may be given, for unruptured aneurysms, to partial trapping via proximal parent vessel occlusion. By preserving patency of the MCA bifurcation, this relatively simple option allows both M2 vessels to be perfused via a single distal EC-IC bypass graft. Alternatively, complete aneurysm trapping requiring takedown of the MCA bifurcation with two distal EC-IC bypass procedures, one for each M2 vessel, may become necessary, particularly in the setting of a ruptured aneurysm.

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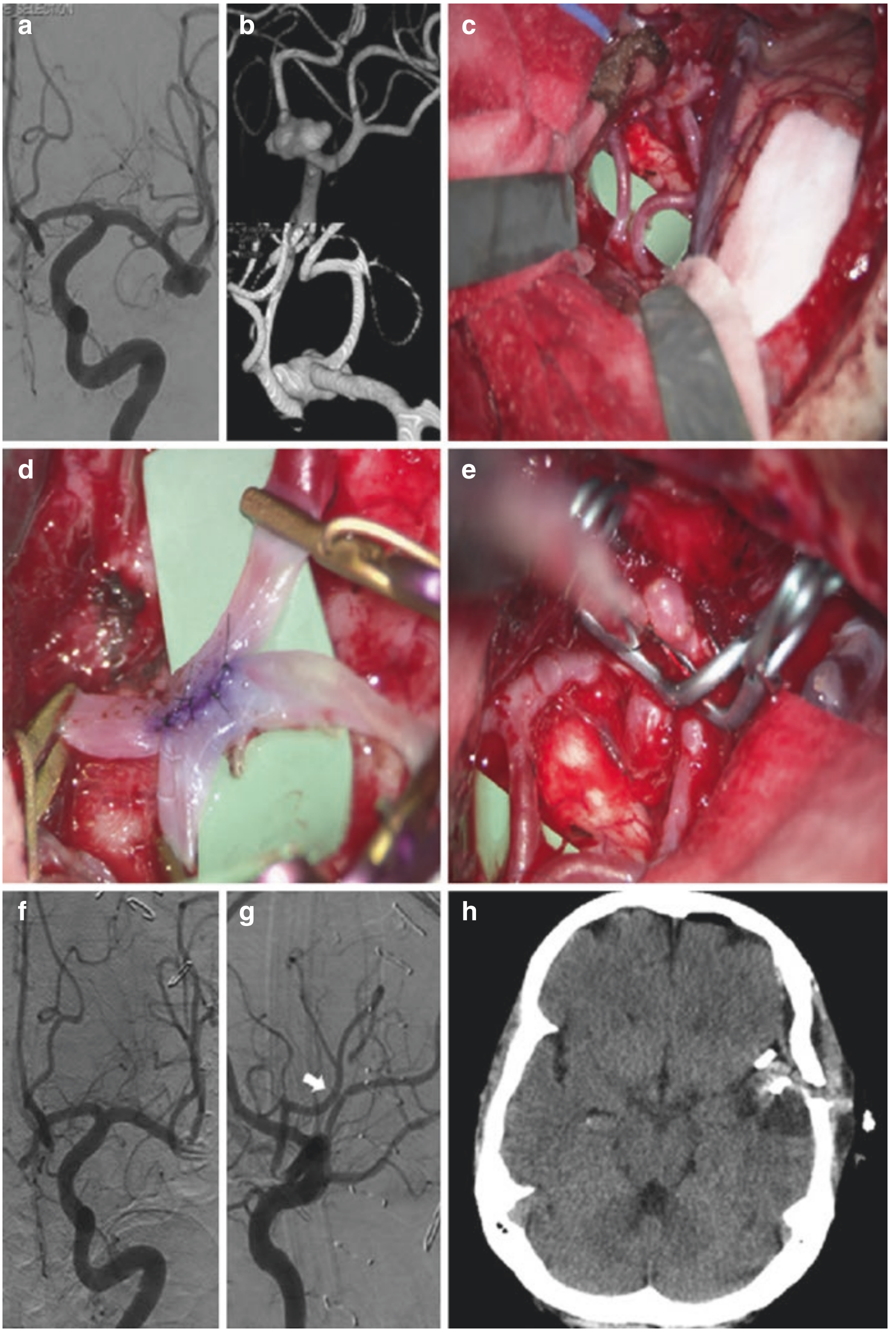
Fig. 8.2 A 65-year-old woman presented with an incidental left MCA aneurysm. (**a**, **b**) Left ICA angiogram reveals a 10-mm, wide-necked saccular aneurysm of the MCA bifurcation, which incorporates one of the two M2 branches. Note the proximity of the two M2 trunks on 3D angiography (**b**), making them suitable for a side-to-side anastomosis. (**c**–**e**) Intraoperative microphotographs demonstrate a global view of the MCA bifurcation, aneurysm, and M2 trunks (**c**). An in situ M2-M2 bypass was successfully performed (**d**), followed by clip deconstruction of the aneurysm and the incorporated M2 branch (**e**). (**f**, **g**) Postoperative left ICA angiogram shows complete aneurysm obliteration with robust opacification of the entire MCA territory via the widely patent in situ M2-M2 bypass (**g**, white arrow). Following surgery, the patient developed expressive aphasia, which resolved spontaneously over a period of 1 week. (**h**) Postoperative head CT reveals a small infarct in the vicinity of the aneurysm clips, likely secondary to inadvertent occlusion of a cortical MCA branch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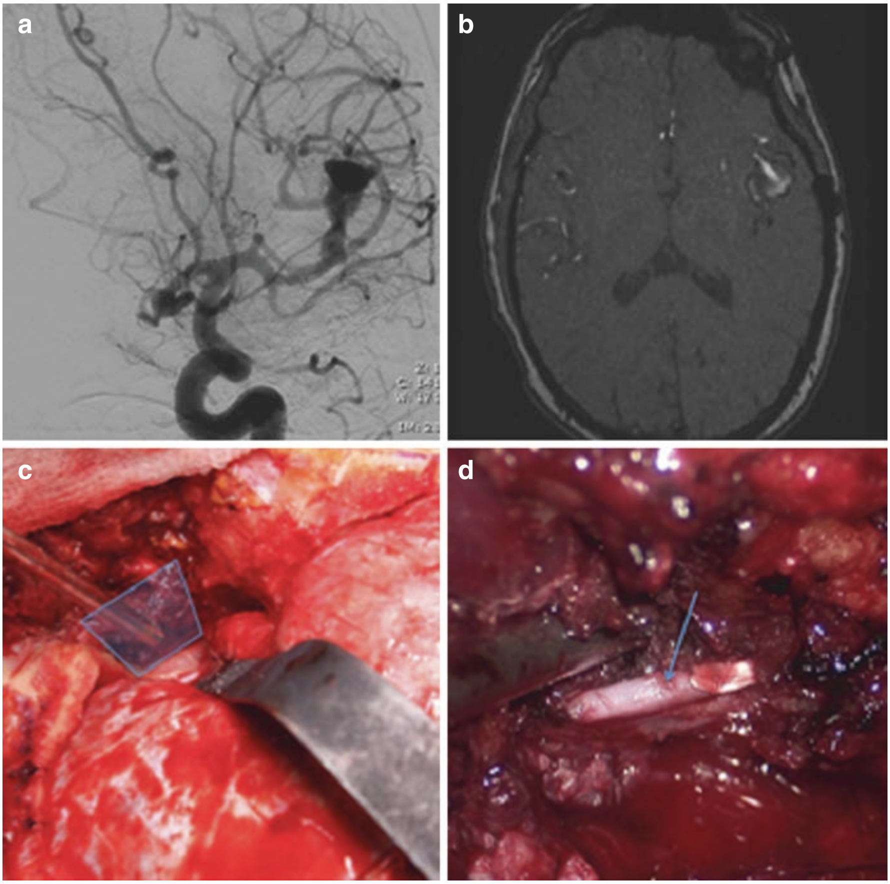

Fig. 8.3 A 36-year-old man presented with a gradually enlarging, dysplastic aneurysm of the left MCA. (**a**) Left ICA angiogram shows a complex fusiform aneurysm of the bifurcation of the superior M2 division of the left MCA (M2-M3 junction). (**b**) Brain MRA demonstrates the presence of an intraaneurysmal thrombus. We elected to proceed with surgical revascularization of the superior M2 trunk followed by aneurysm deconstruction. The patient had a prior history of left craniotomy for meningioma resection, during which the left STA was sacrificed. The left IMax was thus selected as an alternative donor vessel. (**c**–**e**) Intraoperative microphotographs illustrate the surgical approach: extradural subtemporal drilling of the floor of the middle cranial fossa (**c**, shaded blue area), dissection of the IMax in the infratemporal fossa (**d**, blue arrow), and use of a SVG (**e**, blue arrow) connected proximally to the IMax via an end-to-end anastomosis in the infratemporal fossa (**e**, black arrow) and distally to an M3 vessel via an end-to-side anastomosis in the distal Sylvian fissure (**e**, green arrow). (**f**) Postoperative head CTA reveals the SVG course (black arrow) from infratemporal fossa to intracranial space. Following the bypass procedure, the patient was taken immediately to the angiography suite, where proximal coil deconstruction of the aneurysm and parent vessel was performed. A small portion of the aneurysmal dome was intentionally left open to preserve patency of the bifurcation. (**g**) Postoperative left ICA angiogram demonstrates complete obliteration of the aneurysm and parent artery. (**h**) Left ECA angiogram at 2 years shows a patent and mature IMax-SVG-M3 bypass graft, providing robust opacification of the distal MCA territory. Note the persistently open M2 bifurcation, which allows perfusion of both M3 branches via a single distal bypass graft (Parts from Nossek et al. [30], with permission)

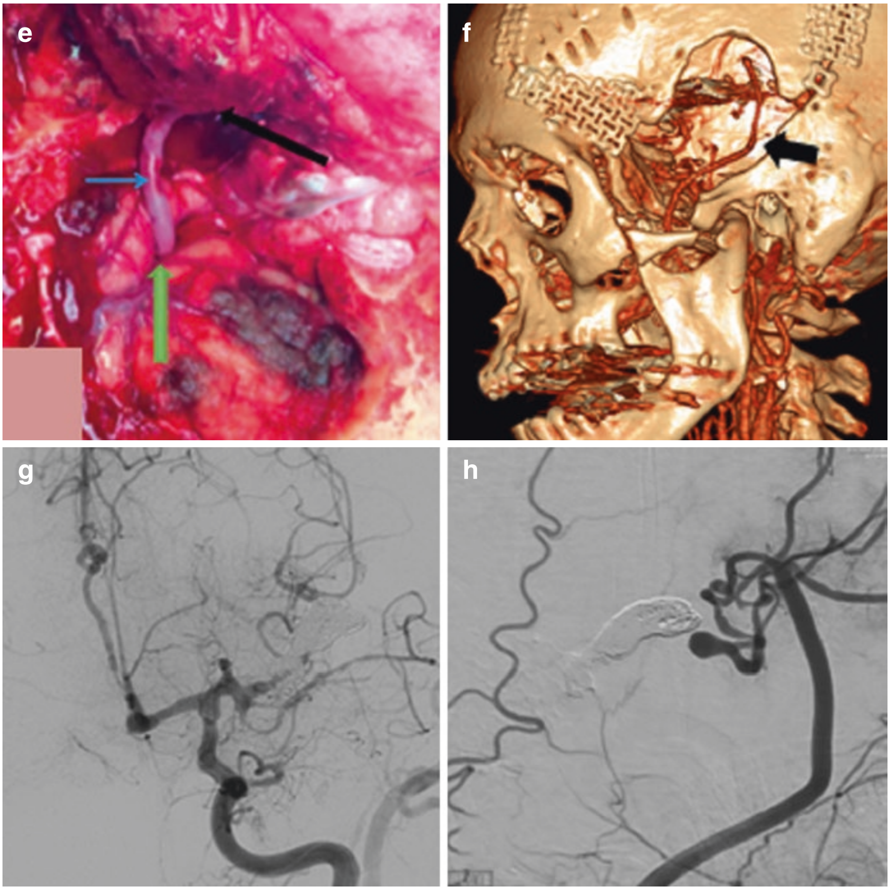

Fig. 8.3 (continued)

Planning the EC-IC Bypass: Donor, Recipient, and Graft Vessels

When planning an EC-IC bypass, it is first essential to determine the amount of blood flow that needs to be replaced, since this will often dictate the type of bypass needed and the choice of donor, recipient, and graft vessels. Depending on the blood flow provided, EC-IC bypass can be grossly classified into low-flow (20–30 mL/min), intermediate-flow (40–60 mL/min), and high-flow (70–140 mL/min). Amin-Hanjani and Charbel [24, 25] advocate the use of flow-assisted surgical technique (FAST), i.e., measuring the flow in the vessel to be replaced and choosing a suitable donor vessel accordingly. Cut-flow measurements of the STA using a micro-flow probe (Intracranial Charbel Micro-Flow Probe®, Transonic Systems Inc., Ithaca, NY, USA) can be extremely useful when planning a flow replacement bypass, particularly in the MCA territory.

A standard STA-MCA bypass typically provides 20–30 mL/min via the M3 or M4 segment of the MCA [26–28] and is best indicated when either the superior or inferior division of the MCA is sacrificed. STA grafts can, however, provide flows in the intermediate- or even high-flow range. This is especially true as the graft gradually matures over time to match flow demand in a chronically ischemic MCA territory [29]. Other types of low-flow bypass can also be performed using either the STA or occipital artery (OA) as donor vessel, to provide flow to the distal portion of a cerebral or cerebellar artery, such as the posterior cerebral artery (PCA), superior cerebellar artery (SCA), and PICA. Such bypasses only require donor vessel dissection and preparation, followed by a single end-to-side intracranial anastomosis. There is no need for additional graft harvesting or neck incisions. They are generally less technically challenging and quicker to perform than other types of EC-IC bypass. Moreover, in contrast to transplanted conduit high-flow bypass, they do not require wide Sylvian fissure dissection or a deep microsurgical field, which can be problematic in patients with high-grade SAH and substantial cerebral edema. Finally, in experienced hands, excellent long-term patency rates in the range of 95–100% are the norm.

When occlusion of the proximal MCA, basilar artery (BA), or a largely dominant VA is being contemplated, either an intermediate- or a high-flow bypass becomes indicated, depending on the extent and quality of CoW and leptomeningeal collaterals. A double-barrel STA-MCA bypass makes use of both the parietal and frontal branches of the STA to replace flow in both the superior and inferior divisions of the MCA, thus providing 50 mL/min or more blood flow in the MCA territory [28]. Another technique of intermediate-flow bypass using the main trunk of the STA as donor vessel, the MCA as recipient, and a short interposition saphenous vein graft (SVG) was recently shown to provide blood flow in the range of 20–100 mL/min [29]. However, we feel that extreme caution should be exercised when selecting an appropriate donor vessel for flow replacement in the MCA and that the STA, given its variable size and flow-carrying capacity, may not be the best option for this purpose. In our practice, we favor the use of a modified technique of intermediate-flow EC-IC bypass, which we term subcranial-intracranial (SC-IC) bypass, using the internal maxillary (IMax) trunk as donor vessel, the M2 or M3 segment of the MCA as recipient, and a short cephalic vein graft (CVG). This SC-IC bypass requires only 8–10 cm of graft length and has been shown to provide blood flow in the range of 30–60 mL/min [30, 31]. The CVG has a diameter ranging from 1.5 to 2 mm, which is very well matched with the size of the MCA. It has little to no valves and very few branches, which makes harvesting easier than that of the SVG. Finally, in contrast to the radial artery graft (RAG), the use of the CVG is not associated with any risk of ischemic complications in the upper extremity. For these reasons, we favor the use of a CVG whenever a short interposition graft is indicated [31]. We generally consider the STA-MCA bypass as a second-line option after either an IMax-MCA or a standard EC-IC bypass using a transplanted arterial or venous graft. An advantage of intermediate-flow bypass techniques that make use of the STA and IMax is that they usually involve a single cranial incision, thus obviating the need for additional neck incisions, cervical carotid artery manipulation, or long EC-IC bypass grafts [29–32].

Therapeutic occlusion of the ICA generally requires a high-flow bypass for adequate flow replacement. However, it should be noted that, in the current era of endovascular flow diversion, ICA sacrifice and flow replacement are seldom required in the management of complex ICA aneurysms. In those rare cases, an EC-IC bypass with a transplanted conduit is indicated if the patient fails BTO preoperatively. For this purpose, the cervical carotid system is used as donor vessel and the M2 or M3 segment of the MCA as recipient, with either an arterial or venous interposition graft in between. We generally favor the use of the ECA as donor vessel over the common carotid artery (CCA) or internal carotid artery (ICA), since this would avoid any reduction of CBF as result of temporary clipping during the proximal anastomosis. Preservation of CBF throughout the procedure is particularly important in patients with SAH. In regard to the interposition graft, a minimum length of 18–20 cm is usually required to connect the cervical carotid system with the proximal MCA. For this reason, either a SVG or a radial artery graft (RAG) is usually preferred. The main advantage of a SVG is that very high flows can be achieved in the bypass, over 200 mL/min in some cases. However, this may lead to a potentially increased risk of hyperperfusion syndrome [20, 29]. Moreover, there is an abundance of unidirectional valves in the lumen of the SVG and frequent discrepancy between its size and that of the MCA, which could lead to excessive turbulence at the distal anastomosis site and an increased risk of delayed graft thrombosis [30]. Despite a somewhat lower flow-carrying capacity, the RAG tends to be well matched in caliber to the proximal MCA and has the advantage of being a normal physiological conduit for arterial blood, which could translate into a higher long-term patency rate. However, the RAG has an inherent risk of spasm and is not an option for patients with bilaterally poorly developed palmar arches [30]. For this reason, in our practice, we still consider the SVG as a first-line option for long EC-IC bypass grafts.

The Bypass Is In: Now What?

“The operation begins when the bypass is in” is a statement that summarizes our general philosophy and reflects the importance of assessing the entire case once again with the new graft in place. Following bypass construction and before any deconstructive procedure, we usually start by confirming patency and assessing flow in the bypass graft, using a combination of different modalities. While the micro-Doppler probe can provide a quick subjective assessment of graft patency, we generally rely on the Charbel micro-flow probe to quantitatively measure flows in the bypass construct. Indocyanine green (ICG) video-angiography is also frequently obtained to demonstrate anatomic patency of the bypass. Finally, an intraoperative angiogram is always performed prior to any deconstructive procedure, not only to confirm patency and study flow in the newly created bypass graft but also to reveal what cannot be readily seen with the microscope, specifically the status of CoW and leptomeningeal collaterals with the graft in place. At that point, the decision must be made on how best to deconstruct the aneurysm and parent artery. When readily achievable, complete or partial microsurgical trapping remains the preferred approach. However, we will often defer direct microsurgical attack on the aneurysm where the deconstruction puts perforators at risk, involves cranial nerve dissection, or requires significant brain retraction or manipulation, particularly in the setting of SAH. In such cases, to entertain flow demand and maintain graft patency, we typically occlude the parent artery using a permanent aneurysm clip placed on a surgically accessible, perforator-free portion of the vessel. We then transfer the patient directly to the angiography suite, where a high-quality angiogram is obtained to fully understand intracranial flow dynamics with the graft in place. Then, the aneurysm and parent artery can often be directly deconstructed using endovascular techniques. In fact, modern hybrid angiography suites should make the decision-making process much more streamlined and allow direct endovascular treatment when microsurgical deconstruction is deemed unsafe.

Principles of Postoperative Care

When a deconstructive procedure and bypass are being contemplated, patients are typically started on full-dose aspirin (e.g., 325 mg daily) preoperatively, which is continued for a minimum of 6 months after surgery. Postoperatively, patients are closely monitored in the neurointensive care unit (NICU) and are kept euvolemic and normotensive. Hypovolemia and hypotension should be avoided at all costs to prevent bypass graft thrombosis and, in the setting of SAH, minimize the risk of DCI. If the latter occurs, aggressive triple H therapy (hypertension-hypervolemia-hemodilution) should be instituted. As mentioned above, cerebral vasospasm generally spares the bypass graft, which allows the latter to be used as access route should endovascular treatment for DCI become indicated. Patients undergo head CT and cerebral catheter angiography on the first postoperative day to rule out ischemic complications and confirm bypass patency. NOVA qMRA is also routinely obtained postoperatively to assess flow through the graft, which helps us better understand flow demand and the relationship between conduit selection and flow. We believe this type of feedback is essential, as it helps surgeons match their preoperative bypass plans with desired postoperative results, based on objective quantitative data. For patients with unruptured aneurysms, the typical length of stay in the NICU is 48 h, following which they are gradually mobilized and transferred to the floor. They are typically discharged home on the fourth or fifth postoperative day. In contrast, patients with unruptured aneurysms undergo standard SAH management, including DCI watch which requires a longer stay in the NICU.

Conclusion

Complex intracranial aneurysms often require surgical or endovascular deconstruction to achieve complete obliteration and eliminate the risk of hemorrhage. A microsurgical bypass to replace flow in the parent artery may thus become necessary to prevent cerebral ischemia and, in the setting of aneurysmal SAH, DCI-related morbidity and mortality. Complete aneurysm trapping is always desirable if it can be achieved safely. Otherwise, partial trapping, either proximal or distal, can help prevent aneurysm rupture by reducing or reversing intraaneurysmal flow. The bypass procedure is best performed before exploring the aneurysm, hence the importance of meticulous preoperative planning. The vascular neurosurgeon has a variety of bypass options, donor and recipient vessels, and interposition grafts to choose from. While personal preference certainly matters, the specific type of bypass is often dictated by the aneurysm location, local microvascular anatomy, parent artery caliber, and quality of collateral flow. In experienced hands, microsurgical trapping and bypass have high technical success rates, with clinical outcomes essentially similar to those observed after simple clipping.

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