Bypass surgery for complex middle cerebral artery aneurysms: an algorithmic approach to revascularization

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OBJECTIVE Management of complex aneurysms of the middle cerebral artery (MCA) can be challenging. Lesions not amenable to endovascular techniques or direct clipping might require a bypass procedure with aneurysm obliteration. Various bypass techniques are available, but an algorithmic approach to classifying these lesions and determining the optimal bypass strategy has not been developed. The objective of this study was to propose a comprehensive and flexible algorithm based on MCA aneurysm location for selecting the best of multiple bypass options.

METHODS Aneurysms of the MCA that required bypass as part of treatment were identified from a large prospectively maintained database of vascular neurosurgeries. According to its location relative to the bifurcation, each aneurysm was classified as a prebifurcation, bifurcation, or postbifurcation aneurysm.

RESULTS Between 1998 and 2015, 30 patients were treated for 30 complex MCA aneurysms in 8 (27%) prebifurcation, 5 (17%) bifurcation, and 17 (56%) postbifurcation locations. Bypasses included 8 superficial temporal artery–MCA bypasses, 4 high-flow extracranial-to-intracranial (EC-IC) bypasses, 13 IC-IC bypasses (6 reanastomoses, 3 reimplantations, 3 interpositional grafts, and 1 in situ bypass), and 5 combination bypasses. The bypass strategy for prebifurcation aneurysms was determined by the involvement of lenticulostriate arteries, whereas the bypass strategy for bifurcation aneurysms was determined by rupture status. The location of the MCA aneurysm in the candelabra (Sylvian, insular, or opercular) determined the bypass strategy for postbifurcation aneurysms. No deaths that resulted from surgery were found, bypass patency was 90%, and the condition of 90% of the patients was improved or unchanged at the most recent follow-up.

CONCLUSIONS The bypass strategy used for an MCA aneurysm depends on the aneurysm location, lenticulostriate anatomy, and rupture status. A uniform bypass strategy for all MCA aneurysms does not exist, but the algorithm proposed here might guide selection of the optimal EC-IC or IC-IC bypass technique.

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KEY WORDS giant aneurysm; complex aneurysm; extracranial–intracranial bypass; intracranial–intracranial bypass; pterional craniotomy; orbitozygomatic craniotomy; vascular disorders

MIDDLE cerebral artery (MCA) aneurysms have long been considered amenable to microsurgical clipping because they are easily accessible through miniaturized craniotomies, can be visualized and manipulated safely after splitting the Sylvian fissure, and have broad necks that can be reconstructed with numerous direct clipping techniques that use intersecting or overlapping clips, “picket-fence” configurations, tandem clipping,

or fenestration tubes.^{7,20,49} The MCA aneurysm is the best example of an aneurysm for which results of microsurgery remain superior to those of endovascular therapy; as a consequence, it remains an aneurysm managed preferentially with direct clipping.^{2,9,42} These aneurysms are relatively less amenable to endovascular therapy because coiling is associated with a higher risk of recurrence, retreatment, and rehemorrhage,^{25,35,36} flow diverters often cover len-

ABBREVIATIONS ACA = anterior cerebral artery; ATA = anterior temporal artery; CCA = common carotid artery; EC = extracranial; ECA = external carotid artery; IC = intracranial; ICA = internal carotid artery; LSA = lenticulostriate artery; MCA = middle cerebral artery; mRS = modified Rankin Scale; RAG = radial artery graft; SAH = subarachnoid hemorrhage; STA = superficial temporal artery; SVG = saphenous vein graft.

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ticulostriate arteries (LSAs) or other arterial trunks, which can cause unintended occlusions and ischemic complications,^{10,16,40,41,46,47} and devices such as intraaneurysmal flow diverters or bifurcation stents are new and unproven and have not been compared rigorously with the microsurgical standard.^{5,27}

Complex MCA aneurysms can be managed with bypass procedures when conventional clipping fails and a parent artery requires deliberate occlusion.^{11,31,38,45} In a previously published 13-year experience with 543 patients with an MCA aneurysm, bypass was performed in 21 (4%) patients, which provided a trapping or proximal occlusion option for some of the more difficult aneurysms in that series.³² A wide variety of bypass techniques for MCA aneurysms exist because they are so amenable to both traditional extracranial-to-intracranial (EC-IC) bypasses, such as superficial temporal artery (STA) bypass and high-flow interpositional bypass to the cervical carotid artery, and reconstructive IC-IC bypasses, such as the end-to-end reanastomosis and the double-reimplantation technique.^{4,6,8,11–14,17–19,22,25,28,30–34,37,39,43,50,51} The pathological spectrum of MCA aneurysms combined with the variety of applicable bypasses makes it challenging to select the optimal bypass, particularly when these decisions must be made intraoperatively in response to unexpected anatomy or technical complications. To our knowledge, no algorithm to guide these decisions or surgical plans exists. In this report, we review our experience with MCA bypass for complex aneurysms and our patients' results to develop such an algorithm.

Methods

Study Design

This study was approved by the institutional review board of University of California, San Francisco, and performed in compliance with Health Insurance Portability and Accountability Act regulations. The prospective database of the University of California, San Francisco, Vascular Neurosurgery Service was queried for patients who required a bypass for an MCA aneurysm. Medical and operative records, preoperative and postoperative images, angiographic data (including location, size, and type of aneurysm), and the hospital course were reviewed retrospectively.

Definitions and Classifications

Although an accepted standardized definition does not exist in the literature, previous reports have identified the following features of a "complex" MCA aneurysm: intraluminal thrombus; mycotic or infectious etiology; atherosclerotic thickening of the neck or calcification; giant size (≥ 25 mm in diameter); fusiform or dolichoectatic morphology; serpentine shape; aberrant branch arteries that originate from the sidewall of the aneurysm or at an obtuse angle from the base; and/or involvement of the LSAs.^{1,12,23,26,29,39,51} Any one or a combination of these features can prevent conventional clipping and necessitate bypass, and they were recorded specifically for each aneurysm in this study.

The algorithmic approach was based on the location

of the MCA aneurysm relative to the point of bifurcation (or trifurcation, quadrifurcation, etc.), and the aneurysms were categorized into 1 of 3 groups: 1) prebifurcation, 2) bifurcation, or 3) postbifurcation aneurysms (Fig. 1).

MCA bypasses were classified as 1 of 7 types.^{1,37} EC-IC bypasses involve an EC donor artery, either 1) a scalp artery such as the STA, which creates a low-flow bypass, or 2) the cervical carotid artery (external [ECA], internal [ICA], or common [CCA] carotid artery), which requires an interpositional graft (radial artery graft [RAG] or saphenous vein graft [SVG]) and creates a high-flow bypass. IC-IC bypasses involve an IC donor artery and 1 or more of the following reconstructive anastomoses: 3) reanastomosis, in which the aneurysm is excised and 2 transected arterial ends are sutured together end to end; 4) in situ bypass, which uses a side-to-side anastomosis between the efferent artery of the aneurysm and an adjacent parallel donor artery; 5) reimplantation, which uses an end-to-side anastomosis between the transected end of the efferent artery and the side of an adjacent donor artery; 6) interpositional bypass, which joins the donor and recipient arteries with a harvested arterial or venous graft; and 7) combination bypass, which uses any 2 or more of the aforementioned bypass techniques, with 2 or more anastomoses. The double-reimplantation²² technique is an example of a combination bypass, as is an EC-IC plus IC-IC bypass.

Bypass Indications

When an aneurysm could not be treated with conventional clip reconstruction, it was treated as follows: 1) trapped, 2) trapped and excised, or 3) partially occluded by proximal or distal occlusion of the parent artery. A bypass procedure was performed whenever a parent artery was deliberately sacrificed to re-perfuse the involved territory and prevent cerebral ischemia or infarction. Although we use preoperative balloon-test occlusion and routinely monitor patients intraoperatively with somatosensory and motor evoked potentials, these tests result in significant false-negative rates and inconsistencies, and we prefer not to rely on them when deciding on the type of bypass to use.^{15,17,25,48}

Results

Microsurgical Management

During a 17-year period between January 1998 and March 2015, 30 patients with an MCA aneurysm required a bypass as part of the treatment for their aneurysm. Giant size (16 [53%] aneurysms), fusiform/dolichoectatic morphology (18 [60%] aneurysms), and a thrombotic lumen (12 [40%] aneurysms) were the most common features of these complex MCA aneurysms (Table 1). Fewer than one-third of the patients presented with a ruptured aneurysm. These aneurysms were classified as prebifurcation in 8 patients (27%), bifurcation in 5 (17%), and postbifurcation in 17 (56%) (Table 1).

All aneurysms were exposed through pterional (24 [80%]) or orbitozygomatic-pterial (6 [20%]) craniotomy and a transsylvian approach. Overall, 10 (33%) MCA aneurysms were obliterated by trapping, 11 (37%) by trapping and excision, 8 (27%) by proximal occlusion, and 1

FIG. 1. A: Aneurysms of the MCA were classified according to their location relative to the MCA bifurcation as a prebifurcation (PreBif), bifurcation (Bif), or postbifurcation (PostBif) aneurysm, as seen from an anterior oblique view with the frontal lobe sectioned down to the insula. Postbifurcation aneurysms were located in the Sylvian fissure (Sylv), insular recess (Ins), or operculum (Oper). Bypasses were performed through standard pterional (**B** and **C**, surgeon views) or orbitozygomatic craniotomy and wide opening of the Sylvian fissure (**D**, surgeon view). Copyright Michael Lawton. Published with permission. Figure is available in color online only.

(3%) by distal occlusion of the parent artery (Table 2). Bifurcation aneurysms had the highest frequency of trapping (80%), whereas postbifurcation aneurysms had the highest frequency of trapping with excision (47%).

Bypasses performed in treatment of these 30 aneurysms included 12 (40%) EC-IC bypasses and 13 (43%) IC-IC bypasses, and 5 (17%) combination bypasses, 1 of which was entirely intracranial (Table 3). The EC-IC bypasses included 8 STA-MCA bypasses and 4 high-flow interpositional bypasses. The IC-IC bypasses included 6 reanastomoses, 3 reimplantations, 1 M₃-M₃ segment in situ bypass, and 3 IC interpositional bypasses. The combination bypasses included 2 double reimplantations (ECA-SVG-MCA-MCA and A₁-anterior cerebral artery [ACA]-RAG-MCA-MCA), 2 STA-MCA bypasses performed together with separate IC-IC bypasses (1 reanastomosis and 1 anterior temporal artery [ATA]-MCA in situ bypass), and a reanastomosis, reimplantation, and STA-MCA bypass (Table 3).

Bypass Strategy According to MCA Aneurysm Classification

The management of prebifurcation MCA aneurysms was determined by LSA involvement (Fig. 2). These arteries were displaced by aneurysms in 6 of 8 patients (Table 4), and these 6 aneurysms were trapped or excised. Of these aneurysms, 2 were excised and reanastomosed primarily (Fig. 3), and 1 required an interpositional graft. A high-flow EC-IC interpositional grafting was performed in 4 patients. In 1 patient with a mycotic aneurysm, 1 of the bifurcation's trunks was already occluded, and only an STA-MCA bypass was needed. When LSA branches originated from the aneurysm and it could not be trapped, the aneurysm was occluded proximally and bypassed distally with a high-flow EC-IC interpositional graft (2 patients), enabling some retrograde filling of the aneurysm to supply all efferents with a single bypass.

The management of bifurcation MCA aneurysms was determined by their rupture status (Fig. 2). Of 5 patients

TABLE 1. Clinical and angiographic features of 30 patients with a complex MCA aneurysm

Feature	Value
Mean age in yrs (range)	47 (7–80)
Sex (no. [%])	
Male	13 (43)
Female	17 (57)
Presentation (no. [%])	
SAH	8 (27)
Focal deficit	12 (40)
Headache	7 (23)
Seizure	2 (7)
Incidental	1 (3)
Aneurysm feature/morphology (no. [%])	
Dolichoectatic	7 (23)
Thrombotic	12 (40)
Fusiform	11 (37)
Mycotic	4 (13)
Serpentine	2 (7)
Aneurysm size (no. [%])	
Giant (≥ 25 mm)	16 (53)
Large (10–24 mm)	9 (23)
Small (< 10 mm)	5 (27)

TABLE 2. Aneurysm obliteration techniques used in 30 patients

Aneurysm Location	Trapping	Excision	Proximal Occlusion	Distal Occlusion	Total
Prebifurcation	3	3	2	0	8
Bifurcation	4	0	0	1	5
Postbifurcation	3	8	6	0	17
Total	10	11	8	1	30

with a bifurcation aneurysm, 4 presented with subarachnoid hemorrhage (SAH), necessitating complete aneurysm exclusion (Table 5). Conventional clipping was not possible because of recurrence after coiling in 2 patients, mycotic aneurysm in 2 patients, and giant calcified thrombotic aneurysm in 1 patient. In 3 patients, the bifurcations were reconstructed with a combination bypass (a double reimplantation with an EC donor, a double reimplantation

with an IC donor, and an ATA-MCA plus an STA-MCA bypass). Two other patients with a mycotic aneurysm had only 1 viable trunk, and their aneurysms were managed with trapping and revascularization with MCA-ATA reimplantation or an STA-MCA bypass. Figure 4 shows an example of a double-reimplantation technique used for a complex MCA bifurcation aneurysm.

The management of postbifurcation MCA aneurysms was determined by their location in the candelabra (Fig. 2). Postbifurcation MCA aneurysms were treated with all of the bypass types except the EC-IC interpositional bypass, because the flow requirements of a distal efferent artery do not call for high flow (Table 6). The most common bypasses were the STA-MCA bypass and primary reanastomosis. The STA-MCA bypass to a cortical M₄ recipient was ideal for a postbifurcation MCA aneurysm located on the remote insular segments in the distal Sylvian fissure. The flash fluorescence technique identified the efferent artery on the cortical surface, and the superficial STA-MCA bypass was followed by proximal aneurysm occlusion (5 patients) or trapping (1 patient). Simple distal aneurysms with a single afferent and efferent artery were reanastomosed primarily, without needing another donor artery or harvesting a scalp artery (4 patients). Reanastomoses were performed in the Sylvian fissure (early M₂ insular segment), where a wide Sylvian fissure split created working space, or distally in the operculum (M₃ segment), where the field was superficial and shallow. Other IC-IC options required an adjacent donor artery. Reimplantation and interpositional bypass were each performed in 2 patients, and in situ bypass was performed in 1 patient (Fig. 5). Two postbifurcation MCA aneurysms were observed at significant branch points with 2 efferent arteries requiring a combination bypass (reanastomosis-reimplantation plus STA-MCA bypass in 1 patient and reanastomosis plus STA-MCA bypass in another patient).

Surgical Results

Overall, 29 of 30 treated MCA aneurysms were occluded completely, as confirmed angiographically. In 1 case (Case 8), a small residual aneurysm segment was left deliberately for postoperative coiling. Twenty-seven bypasses were patent according to postoperative angiography. Of the 3 patients with an occluded bypass, 2 had postoperative neurological deficits, and 1 did not have complications related to the occlusion. Two of the 3 bypass occlusions occurred with a prebifurcation MCA aneurysm, and 2 of the 3 occlusions occurred with the excision-reanastomosis

TABLE 3. Bypass techniques used in 30 patients with a complex MCA aneurysm

Aneurysm Location	EC-IC Bypass		IC-IC Bypass				Combination Bypass	Total
	Low Flow	High Flow	Reanastomosis	Reimplantation	In Situ Bypass	Interposition		
Prebifurcation	1	4	2	0	0	1	0	8 (27)
Bifurcation	1	0	0	1	0	0	3	5 (17)
Postbifurcation	6	0	4	2	1	2	2	17 (56)
Total	8 (27)	4 (13)	6 (20)	3 (10)	1 (3)	3 (10)	5 (17)	30

Values are expressed as number (percent).

FIG. 2. Algorithm for treatment and bypass strategy for complex MCA aneurysms. D.O. = distal occlusion; P.O. = proximal occlusion. Figure is available in color online only.

TABLE 4. Clinical, angiographic, and surgical characteristics of 8 patients with a prebifurcation MCA aneurysm

Case No.	Age (yrs), Sex	Presentation	Aneurysm Location/Segment & Size (mm)	Complex Aneurysm Feature(s)	Aneurysm Treatment	Bypass Performed	Preop mRS Score	Late mRS Score	Aneurysm Occlusion	Bypass Patency
1	27, F	HA, recurrence after clipping	Lt M ₁ , 42	G, D	Tr	ECA-RAG-M ₂	4	4	Complete	Patent
2	58, F	Enlarging aneurysm, progressive dysphasia, lt hemiparesis	Rt M ₁ , 53	G, D, T	Tr	ECA-SVG-M ₂	2	1	Complete	Patent
3	12, M	SAH	Lt M ₁ , 32	G, Fu, Myc	Tr	STA-M ₂	1	0	Complete	Patent
4	63, F	HA	Rt M ₁ , 18	T	Ex	M ₁ -M ₁ reanastomosis	0	3	Complete	Occluded
5	66, F	Szs	Lt M ₁ , 26	G, D	PO	ECA-SVG-M ₂	1	3	Complete	Occluded
6	7, M	SAH	Rt M ₁ , 29	G, D	Ex	M ₁ -RAG-M ₁	5	3	Complete	Patent
7	73, M	Difficulty finding words	Lt M ₁ , 46	G, S, T	Ex	M ₁ -M ₁ reanastomosis	1	1	Complete	Patent
8	47, M	Lt hemiparesis	Rt M ₁ , 27	G, D	PO	CCA-SVG-M ₂	3	5	Residual	Patent

D = dolichoectatic; Ex = excision; Fu = fusiform; G = giant (≥ 25 mm); HA = headache; Myc = mycotic; PO = proximal occlusion; S = serpentine; Szs = seizures; T = thrombotic; Tr = trapping.

technique. In 1 of these cases, the M₁ segment thrombosed after clipping the aneurysm, and the bypass was performed in part to reopen the parent artery, which suggests an underlying hypercoagulable state.

No deaths that resulted from surgery were found. Figure 6 summarizes preoperative and postoperative modi-

fied Rankin Scale (mRS) scores. The median postoperative mRS score was 1 (range 0–5). The conditions of 27 patients (90%) either improved or were unchanged neurologically. Good outcomes (mRS score ≤ 2) were observed in 24 patients (80%) at the last follow-up (mean duration 2.37 years). Poor neurological outcomes were caused by

FIG. 3. Case 7. Prebifurcation MCA aneurysm. **A:** Axial CT image of a 73-year-old man who presented with difficulty finding words and was found to have a giant thrombotic left MCA aneurysm. **B:** Digital subtraction angiography (DSA) image (left ICA injection, lateral view) revealed a small luminal component arising from the M₁ segment proximal to the MCA bifurcation. **C:** After splitting the Sylvian fissure, the greenish-colored thrombotic aneurysm was found to separate the proximal and distal M₁ segments. **D:** The reconstructed M₁ segment was located proximal to the MCA bifurcation. **E:** Postoperative angiogram (left ICA injection, lateral view) revealed complete elimination of the aneurysm and excellent MCA revascularization. Dist. = distal; Prox. = proximal. Figure is available in color online only.

TABLE 5. Clinical, angiographic, and surgical characteristics of 5 patients with a bifurcation MCA aneurysm

Case No.	Age (yrs), Sex	Presentation	Aneurysm Location & Size (mm)	Complex Aneurysm Feature(s)	Aneurysm Treatment	Bypass Performed	Preop mRS Score	Late mRS Score	Aneurysm Occlusion	Bypass Patency
9	74, F	SAH	Lt M ₁ -M ₂ , 26	G, T	Tr	ECA-SVG-M ₂ +M ₂ (double reimplantation)	1	1	Complete	Patent
10	17, F	SAH, Lt hemiparesis	Rt M ₁ -M ₂ , 9	Myc	Tr	STA-M ₂	4	0	Complete	Patent
11	24, M	SAH, Lt hemiparesis	Rt M ₁ -M ₂ , 10	Myc	Tr	ATA-M ₂ reimplantation	4	3	Complete	Patent
12	20, F	HA, Rec	Lt M ₁ -M ₂ , 26	G, Rec	DO	ATA-M ₂ + STA-M ₂	1	1	Complete	Patent
13	48, F	SAH, Rec	Rt M ₁ -M ₂ , 4	Rec	Tr	A1-RAG-M ₂ +M ₂ (double reimplantation)	0	0	Complete	Patent

DO = distal occlusion; Rec = recurrence after coiling.

bypass occlusion in 2 patients (Cases 4 and 5) with a prebifurcation aneurysm (Table 4). Also, a patient with a giant dolichoectatic prebifurcation aneurysm that also involved the carotid terminus and supraclinoid carotid artery and MCAs and extended from the origin of the ophthalmic aneurysms to the MCA bifurcation suffered a postoperative epidural hematoma and impending herniation. The bleeding source was the STA, and the bypass was patent (Table 4) (Case 8). No other postoperative complication was found.

Discussion

The anterior and posterior cerebral arteries have communicating arteries that contribute collateral blood flow from left to right via the anterior communicating artery and from anterior to posterior via the posterior communicating artery. Communicating arteries protect distal territories from ischemic complications after natural or iatrogenic occlusions and decrease the need for microsurgical bypass after deliberate arterial sacrifice during complex aneurysm treatment. In contrast, the MCA lacks a communicating artery, is vulnerable to ischemic complications after therapeutic occlusions, and depends on microsurgical bypass with unclippable aneurysms. For example, the number of patients who underwent MCA bypass reported here is 3 times larger than the number of patients who underwent ACA bypass reported previously from our institution (10 patients).¹ Moreover, of the 3 main cerebral arteries, the MCA supplies the largest and most eloquent territories in the cerebral hemispheres. Therefore, complex MCA aneurysms not amenable to direct clipping require a reconstructive posture toward bypass that restores blood flow robustly to avoid neurological complications.

This experience with bypass surgery for 30 complex MCA aneurysms derives from a larger cohort of 1426 MCA aneurysms in 872 patients treated microsurgically over a 17-year period. Only 2.1% of the MCA aneurysms or 3.4% of the patients with an MCA aneurysm required an MCA bypass. Although the frequency of bypass seems low, it indicates that revascularization remains an essential part of the microsurgical armamentarium. This experience also shows the gamut of bypasses that are available for MCA aneurysms; 18 different bypasses were used in these 30 patients because of variations in reconstructive

technique, combination of bypasses, EC donor site, type of interpositional graft, or recipient site. Therefore, the spectrum of bypass options can be overwhelming and confusing. Our approach over this period was to individualize the bypass strategy for each patient based on pathology, afferent and efferent artery anatomy, and flow requirements. However, retrospective review of one of the largest MCA bypass experiences enabled us to distill our practices and formulate an overall strategy based on our classification of prebifurcation, bifurcation, and postbifurcation MCA aneurysms. An algorithmic approach is needed to guide MCA bypass planning and intraoperative decision-making (Figs. 2 and 7).

Prebifurcation MCA Aneurysms

The strategy for treating prebifurcation MCA aneurysms is dictated by the presence or absence of LSAs along the aneurysmal segment that supply vital basal ganglial structures (Fig. 2).^{3,18,24,39,45,51} It is fortunate that the majority (75%) of complex prebifurcation aneurysms displaced these perforators proximally or distally as they enlarged to a giant size or morphed into dolichoectatic lesions. Absence of LSAs along the aneurysmal segment enabled aneurysm trapping, which then creates an opportunity to excise the aneurysm and reconstruct the M₁ segment with primary reanastomosis, if the pathological segment is short (Fig. 8).⁵⁰ Primary reanastomosis requires a single end-to-end anastomosis and is therefore quick, but it also requires some tortuosity or redundancy of the parent artery and extensive dissection to mobilize the afferent and efferent arteries and bring the transected ends together without tension. Careful anatomical assessment and a high likelihood of success are needed before committing to primary reanastomosis, because failure requires either an interpositional graft or a change in strategy to an EC-IC high-flow bypass, which are both executed best before aneurysm trapping. Primary reanastomosis fails when a long segment of aneurysm is excised, pathological arterial wall remains at the transected ends, and/or the ends are approximated under tension with suture pullout or breakage. Complete aneurysm excision and the problem of an unbridgeable arterial gap are directly related; thorough excision increases the gap and failure rate of reanastomosis, whereas incomplete aneurysm excision decreases the gap

FIG. 4. Bifurcation MCA aneurysm. A 71-year-old woman presented with an SAH and was found to have a large calcified right MCA bifurcation aneurysm. **A:** DSA image (right ICA injection, anterior oblique view) revealed the inferior trunk originating from the base of the aneurysm and recurring along the course of the parent M₁ segment. **B:** 3D rotational angiogram revealing the superior trunk, also originating from the base of the aneurysm and coursing superiorly. The aneurysm was bypassed with a double-reimplantation technique to reimplant the superior trunk onto the graft with an end-to-side anastomosis (**C**) and connect the distal end of the graft to the inferior trunk with another end-to-side anastomosis (**D**). **E:** This atherosclerotic unclippable aneurysm was then trapped completely and deflated. Postoperative angiograms (right ICA injection, anteroposterior [**F**] and lateral [**G**] views) revealing complete elimination of the aneurysm, a patent bypass graft, and excellent MCA revascularization. *Solid arrows* point to the proximal anastomosis to the A₁ segment, and the *dashed arrow* points to the anastomosis with the superior M₂ trunk. Figure is available in color online only.

TABLE 6. Clinical, angiographic, and surgical characteristics of 17 patients with a postbifurcation MCA aneurysm

Case No.	Age (yrs), Sex	Presentation	Aneurysm Location & Size (mm)	Complex Aneurysm Feature(s)	Aneurysm Treatment	Bypass Performed	Preop mRs Score	Late mRS Score	Aneurysm Occlusion	Bypass Patency
14	80, F	HA	Rt M ₃ , 13	Fu	Ex	M ₃ -M ₃ reanastomosis	1	0	Complete	Occluded
15	19, M	HA	Rt M ₃ , 15	D, T	Ex	M ₃ -M ₃ reanastomosis	1	1	Complete	Patent
16	40, M	TIA, Szs	Rt M ₂ , 8	Fu, T	Ex	M ₂ -M ₂ reimplantation	1	1	Complete	Patent
17	66, M	TIA (lt facial droop)	Rt M ₃ , 9	T	Ex	M ₂ -M ₂ reanastomosis	1	0	Complete	Patent
18	32, M	SAH	Lt M ₂ , 14	Fu	PO	STA-M ₄	1	0	Complete	Patent
19	64, F	TIA (lt hemiparesis)	Rt M ₃ , 12	Fu, T	PO	STA-M ₄	1	0	Complete	Patent
20	59, F	Dysarthria	Lt M ₂ , 8	Fu	PO	STA-M ₄	1	1	Complete	Patent
21	61, M	Lt sensory deficit	Rt M ₂ , 53	G, S	Tr	STA-M ₄	1	0	Complete	Patent
22	42, F	HA	Lt M ₂ , 31	G, T	PO	STA-M ₄	1	0	Complete	Patent
23	74, M	Progressive dysphasia, drop attack	Rt M ₃ , 10	Fu	PO	STA-M ₄	1	1	Complete	Patent
24	39, F	SAH	Lt M ₃ , 26	G, Fu, Myc	Ex	M ₃ -M ₃ reanastomosis	1	0	Complete	Patent
25	36, M	Szs	Rt M ₂ , 26	G, D, T	Ex	M ₂ -STA-M ₂ interposition	1	0	Complete	Patent
26	57, F	TIA (lt hemiparesis)	Rt M ₂ , 11	Fu, T	PO	M ₃ -M ₃ in situ bypass	3	0	Complete	Patent
27	68, F	HA	Rt M ₂ , 27	G, T	Ex	STA-M ₄ , M ₂ -M ₂ reanastomosis, M ₂ -M ₂ reimplantation	1	1	Complete	Patent
28	23, F	Rt hemiparesis & aphasia	Lt M ₂ , 38	G, Fu	Tr	M ₂ -M ₂ reimplantation	4	1	Complete	Patent
29	15, M	Recurrence after clipping, TIA (lt hemiparesis)	Rt M ₂ , 26	G	Tr	M ₂ -RAG-M ₂ interposition	1	1	Complete	Patent
30	37, F	Incidental	Rt M ₂ , 10	Fu	Ex	M ₂ -M ₂ reanastomosis, STA-M ₂	0	0	Complete	Patent

TIA = transient ischemic attack.

but might incorporate pathological tissues into the reanastomosis and occlude it.

With interpositional grafting, a graft must be harvested in advance and be ready to suture. The caliber of the RAG is well matched to the M₁ segment. Two end-to-end anastomoses are usually performed with short suture lines that are quicker than end-to-side anastomoses. However, the MCA territory cannot be reperfused until both anastomoses are completed. If reperfusion is needed between anastomoses, or if an LSA originates at one of the transected ends, an end-to-side anastomosis can be performed first, followed by reperfusion and an end-to-end anastomosis. With EC-IC high-flow bypass instead of an interpositional graft, the bypass is performed first, before trapping and excising the aneurysm. Like the IC-IC interpositional graft, this EC-IC interpositional bypass also requires 2 anastomoses, one to an efferent trunk and the other to the cervical ECA or CCA. The same EC-IC interpositional bypass is used when the prebifurcation MCA aneurysm involves the LSAs and the aneurysm cannot be trapped. Proximal occlusion is performed instead, and the bypass supplies anterograde flow to the recipient trunk, retrograde flow to the other trunks, and retrograde flow through the aneurysm to the LSAs. A single high-flow bypass is needed for prebifurcation aneurysms because a competent bifurcation allows 1 bypass to retrogradely fill the unbypassed efferent trunks. Exceptions to this algorithm occurred when a major trunk was already occluded with preexisting ischemic injury and the reduced revascularization requirements of

a single trunk were met with a single low-flow STA-MCA bypass.

Bifurcation MCA Aneurysms

The management of bifurcation MCA aneurysms is determined by the rupture status of the patient (Fig. 2). Bifurcation aneurysms in patients who present with SAH must be excluded completely, and when conventional clipping fails, the aneurysm is trapped and multiple trunks are revascularized. Combination bypasses use 2 or more bypasses to rebuild the bifurcation; examples include the double-reimplantation bypass (Fig. 9), EC-IC plus IC-IC bypasses, 2 IC-IC bypasses, and 2 EC-IC bypasses. The double-reimplantation technique²² is an ideal bypass because it delivers high flow through an RAG, and using the A₁ segment as an IC donor shortens the length of the graft and keeps it entirely intracranial. This bypass requires 3 end-to-side anastomoses, typically 2 at each end of the graft and 1 midgraft reimplantation. The successive reimplantation technique can be extended to reconstruct trifurcations with triple reimplantations or quadrifurcations with quadruple reimplantations. Other combination bypasses can be completed with 2 anastomoses when the EC-IC bypass is an STA-MCA bypass and the IC-IC bypass is either a reimplantation, reanastomosis, or an in situ bypass. EC-IC or IC-IC interpositional bypasses require 3 anastomoses.

Unruptured bifurcation MCA aneurysms can be managed with proximal occlusion, rather than trapping, and distal high-flow EC-IC bypass to a single efferent trunk,

FIG. 5. Case 26. Postbifurcation MCA aneurysm. **A:** Coronal T1-weighted Gd-enhanced MR image obtained in a 57-year-old woman who presented with an episode of left hemiparesis and was found to have a distal thrombotic right MCA aneurysm diagnosed with MRI. **B:** DSA image (right ICA injection, lateral view) revealing the aneurysm on the insular M_2 segment (red arrows). The aneurysm was proximally occluded and bypassed distally with an in situ M_3 - M_3 bypass. **C:** The flash fluorescence technique identified the posterior parietal artery as the efferent artery and the angular artery as an uninvolved adjacent artery. **D:** These 2 cortical arteries were joined with a side-to-side anastomosis, and the angular artery served as an in situ donor artery. **E:** Overview of the surgical field, showing that the flash fluorescence technique spares the additional dissection needed to trace the efferent arteries from the aneurysm to the cortical surface to determine the recipient site of the bypass (white arrow, permanent clip; dashed black arrow, in situ anastomosis). **F:** Postoperative angiogram (right ICA injection, anteroposterior view) demonstrating complete elimination of the aneurysm, a patent anastomosis (solid black arrow), and excellent MCA revascularization. Figure is available in color online only.

FIG. 6. Graphs showing preoperative and postoperative mRS scores for the 30 patients with a complex MCA aneurysm. Figure is available in color online only.

which enables the 1 bypass to retrograde fill the aneurysm and supply the unbypassed efferent trunk or trunks. Retrograde filling of a ruptured aneurysm is not advisable, because the aneurysm can re-rupture even though the inflow is occluded and reversed flow through the aneurysm is reduced. Exceptions to this algorithm occurred when a major trunk was already occluded with preexisting ischemic injury, and the reduced revascularization requirements of a single trunk were met with a low-flow STA-MCA bypass or an IC-IC bypass (Fig. 7).

Postbifurcation MCA Aneurysms

The strategy for postbifurcation MCA aneurysms is determined by their location along the MCA circulation (Fig. 2). Proximal insular (M_2 segment) aneurysms are accessible through a transsylvian approach that splits the Sylvian fissure and exposes the limen insulae. Similarly, opercular (M_3 segment) aneurysms are accessible through a distal transsylvian approach that opens the operculum. The accessibility of the proximal Sylvian fissure and the superficiality of the operculum make proximal insular (Fig. 10) and opercular MCA (Fig. 11) aneurysms, respectively, amenable to trapping and to all of the different bypass types, with the exception of the EC-IC interpositional bypass, because a distal efferent artery does not require high flow (Table 6). Reanastomosis was the most common technique, used in more than one-third of these patients

by reconstructing the simple distal aneurysm with a single afferent and efferent artery without needing another donor artery or harvesting a scalp artery. Successful primary reanastomosis requires the same technical considerations discussed for prebifurcation aneurysms: redundancy of parent arteries, mobilization of the transected ends, complete excision of abnormal arterial tissues, and tension-free reanastomosis. Compared with prebifurcation aneurysms, postbifurcation aneurysms result in a higher success rate when primary reanastomosis is performed because these aneurysms tend to be smaller and have excisional gaps that are easier to bridge. Other IC-IC options involve an adjacent donor artery that makes for a more complex reconstruction. Reanastomoses were performed both deep in the Sylvian fissure and shallow in the operculum. In situ bypass, reimplantation, and interpositional bypass were used when aneurysm size or complexities prevented an easy end-to-end reanastomosis. Postbifurcation MCA aneurysms at significant branch points with 2 efferent arteries require a combination bypass.

In contrast to proximal insular and opercular MCA aneurysms, distal insular (M_2 segment) aneurysms are much less accessible and more difficult to visualize, because efferent arteries are buried deep in the insular recess. Instead of trapping/excision and IC-IC bypass, these aneurysms are treated with proximal occlusion and STA-MCA bypass (Fig. 12). These aneurysms were common, accounting for more than one-third of postbifurcation MCA an-

FIG. 7. Summary of bypass options according to 5 MCA aneurysm locations and 7 types of bypasses. M₁, M₂, and M₃ refer to the segmental anatomy of the MCA; 1st, 2nd, 3rd, and 4th refer to the preferred choices for bypass options. Figure is available in color online only.

eurysms. An STA-MCA bypass to a cortical M₄ recipient is ideal, because the distal Sylvian fissure can be difficult to split and is surrounded by Broca and Wernicke speech areas in the dominant hemisphere. A superficial bypass and proximal occlusion using the flash fluorescence technique to identify the efferent artery on the cortical surface provide a simple strategy for managing these aneurysms. Postbifurcation MCA aneurysms, unlike the other MCA aneurysms, are not associated with LSAs, which simplifies their management.

Strategic Planning

Our strategic algorithm is meant to be simple and efficient, using the minimum number of bypasses and anastomoses while avoiding unnecessary effort. We do not use prophylactic or protective bypasses, which typically are STA-MCA bypasses performed to support the MCA territory during the installation of a high-flow bypass or during temporary occlusion for the intervention of some aneurysms. These protective bypasses require extra time and effort for bypasses that ultimately become unneces-

sary. However, strategic planning should minimize overall ischemia time. The sequence and type (side to side, end to end, or end to side) of anastomoses can be modified to allow early reperfusion after completing an anastomosis (as with the double-reimplantation technique) or intermittent reperfusion between anastomoses (as with end-to-side or side-to-side rather than end-to-end anastomoses). Bypass selection should also be adapted to the surgical conditions. For example, a double-reimplantation bypass with an A₁ segment donor site might be inappropriate in a swollen brain after a high-grade SAH, and a simpler combination bypass might be better. Our published results of IC-IC bypasses are comparable with those of EC-IC bypasses.^{4,17,18,21,44} Although we favor IC reconstructive techniques, conventional low- and high-flow EC-IC bypasses are essential for complex MCA aneurysms for several reasons. First, the large hemispheric territory supplied by the MCA requires high-flow replacement with prebifurcation aneurysms and EC contributions to combination bypasses with bifurcation aneurysms. Second, IC bypasses are technically challenging, and EC-IC bypasses are a simpler

Prebifurcation - MCA Aneurysm

FIG. 8. Summary of bypass options for prebifurcation MCA aneurysms. As seen from an anterior oblique view (A) with the frontal lobe sectioned down to the insula. Reanastomosis (B), interpositional grafting (C), and EC-IC high-flow bypass (D) are shown in coronal cross-sectional views. CC = common carotid artery; Ins = insula. Copyright Michael Lawton. Published with permission. Figure is available in color online only.

Bifurcation - MCA Aneurysm

FIG. 9. Summary of bypass options for bifurcation MCA aneurysms. As seen from an anterior-oblique view (A) with the frontal lobe sectioned down to the insula. EC-IC high-flow bypass (B) and combination bypass (A-M₂-M₂ double-reimplantation technique) (C) are shown in coronal cross-sectional views. Copyright Michael Lawton. Published with permission. Figure is available in color online only.

Postbifurcation (Sylvian) - MCA Aneurysm

FIG. 10. Summary of bypass options for postbifurcation MCA aneurysms in the proximal insula or Sylvian fissure. As seen from an anterior oblique view (A) with the frontal lobe sectioned down to the insula. Reanastomosis (B), reimplantation (C), in situ bypass (D), interpositional bypass (E), and combination bypasses (F–H) are shown in coronal cross-sectional views. Copyright Michael Lawton. Published with permission. Figure is available in color online only.

alternative. Third, anatomical constraints, such as those in the insular recess or when the ATA is not available as an IC donor, can limit IC-IC bypass options. Fourth, IC-IC bypass can require temporary occlusion of an uninvolved donor artery and confer additional ischemic risk, which might not be advisable for patients in critical condition.

Many of our reconstructive designs were based on arterial anatomy rather than quantitative blood flow measurements. Bypasses were selected to replace flow after deliberate arterial sacrifice based on the caliber of the occluded artery and the size of the associated territory. High-flow bypasses were selected for proximal arteries with large diameters, whereas low-flow bypasses were selected for distal arteries with small diameters. In addition, single

high-flow bypasses were selected to revascularize multiple distal branches, such as after obliteration of a prebifurcation or bifurcation aneurysm. We did not use quantitative Doppler ultrasonography intraoperatively as part of our bypass selection, and balloon temporary occlusion did not affect our strategies. Our results with this anatomical approach compare favorably to those of other series in which quantitative techniques were used.^{4,51}

Limitations

The algorithm discussed here is proposed as a guide for surgical planning and decision-making, but it is no substitute for individualized management and creative innovation. Some aneurysms might not fit our classification or

Postbifurcation (Opercular) - MCA Aneurysm

FIG. 11. Summary of bypass options for postbifurcation MCA aneurysms in the operculum. As seen from an anterior oblique view (A) with the frontal lobe sectioned down to the insula. Reanastomosis (B), reimplantation (C), in situ bypass (D), and interpositional bypass (E) are shown in coronal cross-sectional views. Copyright Michael Lawton. Published with permission. Figure is available in color online only.

Postbifurcation (Insular) - MCA Aneurysm

FIG. 12. Summary of bypass options for postbifurcation MCA aneurysms in the distal insula. **A:** As seen from an anterior oblique view with the frontal lobe sectioned down to the insula. **B:** An STA-MCA bypass is shown in a coronal cross-sectional view. Copyright Michael Lawton. Published with permission. Figure is available in color online only.

might not be treated best with our approach. These strategies are based on a small cohort of patients with inherent referral and selection biases. The algorithm embodies our preference for IC-IC bypasses, which we like for their el-

egance, their prevention of additional cervical incisions, their shorter graft lengths and higher patency in the long term, and less vulnerability and for their lack of requirement for harvesting an EC donor artery. Figure 7 shows a

comprehensive summary of available bypass options, and the preferred choices reflect the thinking of our team and our experiences over many years. However, these choices are not absolute recommendations, and those who make final decisions must account for patient presentation, specific aneurysm anatomy, relative risks, and surgeon ability. For example, we prefer reanastomosis (first choice) for a prebifurcation MCA aneurysm that does not incorporate perforators, because it reconstructs the parent artery with a single short suture line, but a simple STA-MCA bypass (fourth choice) might also work well. Future studies with more patients are needed to define the best choice of bypass for each pathological entity.

Conclusions

The management of complex MCA aneurysms can be challenging. Many of these aneurysms cannot be clipped and require exclusion from the circulation in combination with a revascularization strategy to re-perfuse the territory supplied by the excluded parent artery. Variations in segmental MCA anatomy preclude a uniform bypass strategy for all MCA aneurysms. Prebifurcation, bifurcation, and postbifurcation MCA aneurysms present different surgical challenges that must be individualized to specific patient anatomy and clinical status. Our proposed algorithm might assist in surgical planning for complex MCA aneurysms by providing a comprehensive yet flexible strategy for selecting the optimal bypass and occlusion technique according to aneurysm location relative to the MCA bifurcation. The proposed algorithm is intended only as a guide for surgical therapy and will need to be adapted as novel endovascular treatments become available.

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Disclosures

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

Author Contributions

Conception and design: Lawton. Acquisition of data: Lawton, Tayebi Meybodi, Huang. Analysis and interpretation of data: all authors. Drafting the article: Lawton, Tayebi Meybodi. Critically revising the article: Lawton, Tayebi Meybodi, Huang, Benet. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Lawton. Statistical analysis: Lawton, Tayebi Meybodi, Huang. Administrative/technical/material support: Lawton. Study supervision: Lawton.

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