Internal maxillary artery bypass for the treatment of complex middle cerebral artery aneurysms

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OBJECTIVE The rapid innovation of the endovascular armamentarium results in a decreased number of indications for a classic surgical approach. However, a middle cerebral artery (MCA) aneurysm remains the best example of one for which results have favored microsurgery over endovascular intervention. In this study, the authors aimed to evaluate the experience and efficacy regarding surgical outcomes after applying internal maxillary artery (IMA) bypass for complex MCA aneurysms (CMCAAs).

METHODS All IMA bypasses performed between January 2010 and July 2018 in a single-center, single-surgeon practice were screened.

RESULTS In total, 12 patients (9 males, 3 females) with CMCAAs managed by high-flow IMA bypass were identified. The mean size of CMCAAs was 23.7 mm (range 10–37 mm), and the patients had a mean age of 31.7 years (range 14–56 years). The aneurysms were proximally occluded in 8 cases, completely trapped in 3 cases, and completely resected in 1 case. The radial artery was used as the graft vessel in all cases. At discharge, the graft patency rate was 83.3% (n = 10), and all aneurysms were completely eliminated (83.3%, n = 10) or greatly diminished (16.7%, n = 2) from the circulation. Postoperative ischemia was detected in 2 patients as a result of graft occlusion, and 1 patient presenting with subarachnoid hemorrhage achieved improved modified Rankin Scale scores compared to the preoperative status but retained some neurological deficits. Therefore, neurological assessment at discharge showed that 9 of the 12 patients experienced unremarkable outcomes. The mean interval time from bypass to angiographic and clinical follow-up was 28.7 months (range 2–74 months) and 53.1 months (range 19–82 months), respectively. Although 2 grafts remained occluded, all aneurysms were isolated from the circulation, and no patient had an unfavorable outcome.

CONCLUSIONS The satisfactory result in the present study demonstrated that IMA bypass is a promising method for the treatment of CMCAAs and should be maintained in the neurosurgical armamentarium. However, cases with intraoperative radical resection or inappropriate bypass recipient selection such as aneurysmal wall should be meticulously chosen with respect to the subtype of MCA aneurysm.

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KEYWORDS complex middle cerebral artery aneurysm; internal maxillary artery; high-flow bypass

THE innovation of endovascular tools in clinical practice has put the indications for microsurgical repair in a constant state of ebb and flow. Although the treatment algorithm for intracranial aneurysms has been changed, microsurgery remains superior to endovascular therapy in the territory of the middle cerebral artery

(MCA),²⁶ which is frequently involved with perforating lenticulostriate arteries (LSAs), coursing in a curved morphology and situated peripherally.^{11,17,20} In selected cases, direct clipping across the aneurysm neck without blood flow impairment may pose a technical challenge by virtue of the complex angioarchitecture. In such cases, complex

ABBREVIATIONS AR = aneurysmorrhaphy; CMCAA = complex MCA aneurysm; CTA = CT angiography; ECB = early cortical branch; EC-IC = extracranial-intracranial; FDD = flow diversion device; IMA = internal maxillary artery; I₂ = pterygoid segment of the IMA; LSA = lenticulostriate artery; MCA = middle cerebral artery; mRS = modified Rankin Scale; M₁ = sphenoidal segment of the MCA; M₂ = insular segment of the MCA; M₃ = opercular segment of the MCA; RA = radial artery; SAH = subarachnoid hemorrhage; STA = superficial temporal artery.

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MCA aneurysms (CMCAAs) continue to require bypasses as part of a curative treatment strategy with deliberate occlusion.

Recently, the internal maxillary artery (IMA) bypass, the only substantive modification of cerebral revascularization techniques, has gained momentum.^{24,25,32–34,36} This technique was heralded as a new “workhorse” in the field of high-flow bypass to replace conventional cervical artery bypass.^{14,29} However, very limited data exist regarding the experiences with using this novel extracranial artery as a donor, especially in the territory of the MCA. In the present study, we aimed to investigate the surgical outcomes of IMA bypass in the treatment of CMCAAs.

Methods

Data Collection

This study retrospectively evaluates our experience using an IMA bypass to treat CMCAAs between January 2010 and July 2018. The protocol was approved by the institutional review board and ethics committee of SanBo Brain Hospital, Capital Medical University. An informed consent form was signed by all patients and documented in each case. The patient demographic and clinical data were extracted from our electronic medical record system. The following data were collected: demographic information; clinical parameters (aneurysm characteristics, antiplatelet and anticoagulation regimens, and operative reports); radiographic studies; intraoperative measurement data and images; and outpatient clinical data. An experienced investigator who was blinded to the patients’ clinical characteristics independently reviewed all the data. The patients’ characteristics are given in Table 1.

IMA Bypass Decision-Making

The treatment strategy is tailored on a case-by-case basis by multiple considerations, including patient age, family history of subarachnoid hemorrhage (SAH), medical comorbidities, and psychological impact of aneurysm (morphology, location, size, rupture status). The MCA aneurysms that related to at least 2 of the following features were defined as complex in character: 1) size > 2.5 cm; 2) aneurysm angioanatomy (involvement of critical perforating or branch vessels); 3) previous treatment (endovascular or surgical); 4) complex morphology (fusiform, dissecting, serpentine, and dolichoectatic); 5) intraluminal thrombosis; or 6) atherosclerotic plaques and calcifications of the aneurysm wall and/or neck. Both surgical and endovascular treatment options are offered.

Therapeutic alternatives were discussed after diagnostic angiography among neurosurgeons, neurointerventionalists, and neurovascular neurologists in a multidisciplinary decision-making process. Patients and families had the freedom to choose a therapy. However, if direct clipping/clip reconstruction or neurointerventional treatment was deemed futile on the basis of preoperative imaging findings, patients were directly recommended for cerebral bypass.

The type of bypass performed in the MCA territory depended on the aneurysm origin, LSA involvement, caliber and location of the occluded artery, viability of the collat-

eral circulation, and the potential graft flow. The high-flow extracranial-intracranial (EC-IC) bypass was preferred to achieve the deliberate occlusion of large-diameter arteries (prebifurcation or bifurcation lesions), whereas low-flow bypass was first considered for distal MCA lesions. The cervical high-flow bypass has been replaced by the novel IMA bypass due to the avoidance of a second incision, short graft, and well-matched caliber. Considering many false-negative results, the balloon temporary occlusion test was rarely used in our series and did not affect our strategies.

MCA Aneurysm Location

The aneurysm location was divided into 4 subtypes according to a new classification:^{7,11} 1) sphenoidal segment of the MCA (M_1)–LSA; 2) M_1 –early cortical branch (ECB) (i.e., M_1 aneurysms arising on M_1 at the origin of early frontal or temporal ECB); 3) MCA bifurcation or trifurcation aneurysm; and 4) distal MCA aneurysms that arise on the insular, opercular, or cortical segments of the MCA. However, in our series, a majority of cases manifested with complex characteristics, and specific location was determined in a setting of multidisciplinary discussion.

Bypass Technique and Perioperative Management

The techniques of performing IMA bypass have been described in our previous articles.^{24,25,29,32–34,36} Briefly, we approached the aneurysms using a frontotemporal craniotomy with zygomatic osteotomy. The radial artery (RA) was harvested and prepared before being anastomosed in an end-to-end fashion to the pterygoid segment of the IMA (I_2) by using 9-0 prolene. The free end of the RA was then brought to the sylvian fissure and anastomosed to the insular segment of the MCA (M_2) by using 9-0 sutures in an end-to-side manner. The aneurysm located after the bypass takeoff was then resected or trapped with a permanent aneurysm clip or ligation.

For patients without a history of SAH, 300 mg of aspirin was given 3 days prior to the procedure. During the procedure, neurophysiological monitoring was used to identify cerebral ischemia during temporary occlusion of the parent artery. Doppler flow measurements (PRO Focus 2202, BK Medical) and indocyanine green videoangiography were used to analyze the adequacy of treatment and patency of parent vessels. After the procedure, all patients were monitored overnight in a neurointensive care unit under the supervision of neurosurgeons, and blood pressure was kept 10%–20% higher than the baseline. On postoperative day 2, subcutaneous anticoagulation with low-molecular-weight heparin was prescribed for 3 consecutive days, and then patients were kept on 300 mg of aspirin per day as in the preoperative algorithm. Three months after the procedure, each patient was maintained on a 100-mg single daily dose of aspirin. Patients were loaded with 1.0 mg/hr nimodipine for 7–10 days after the intervention.

Imaging Analysis and Follow-Up

Postoperative and 3D CT angiography (CTA), which was evaluated independently by neuroradiologists, was scheduled at 6–8 hours after treatment to confirm the

TABLE 1. Clinical characteristics of 12 patients with CMCAAs treated by IMA bypass

Case No.	Age (yrs)/ Sex	Initial Presentation	Aneurysm Location, Morphology	Size (mm)	Aneurysm Treatment	mRS Score			Bypass Patency		Aneurysm Outcome		Complications
						Preop	Postop	At FU (mos)	Postop	At FU (mos)	Postop	At FU (mos)	
1	44/M	FN	M ₁ -LSA, fusiform	13	PO + AR	1	2	0 (82)	Pa	Pa (74)	TE	TE (74)	No
2	40/F	Headache	MCA bifurcation, fusiform	12	PO	1	3	1 (75)	Oc	Oc (58)	TE	TE (58)	Cerebral ischemia
3	56/F	SAH (H & H II)	M ₁ -ECB, fusiform	10	PO + AR	4	3	0 (70)	Pa	Pa (43)	TE	TE (43)	No
4	33/M	SAH (H & H III)	M ₁ -M ₂ , thrombosed	26	Trapping	4	2	0 (63)	Pa	Pa (48)	TE	TE (48)	No
5	21/M	Headache	M ₁ -M ₃ , thrombosed	29	PO	1	0	0 (61)	Pa	Pa (5)	GD	TE (5)	No
6	22/M	Headache	M ₁ -M ₂ , fusiform	22	Trapping	1	2	1 (55)	Pa	Pa (3)	TE	TE (3)	No
7	23/M	Headache	M ₁ -ECB, recurrent	33	Trapping + AR	1	0	0 (53)	Pa	Pa (25)	TE	TE (25)	No
8	30/M	Headache	MCA bifurcation, thrombosed	26	Resection	1	4	0 (52)	Oc	Oc (50)	TE	TE (50)	Cerebral ischemia
9	29/M	SAH (H & H II)	M ₁ -ECB, fusiform, thrombosed	17	PO	3	2	1 (47)	Pa	Pa (20)	TE	TE (20)	No
10	31/M	Dizziness	M ₂ , serpentine	37	PO	1	1	0 (35)	Pa	Pa (11)	GD	TE (11)	No
11	14/M	Seizure	M ₁ -LSA, fusiform, thrombosed	23	PO	0	0	0 (25)	Pa	Pa (5)	TE	TE (5)	No
12	37/F	Headache	M ₁ -M ₂ , fusiform, thrombosed	36	PO	1	2	0 (19)	Pa	Pa (2)	TE	TE (2)	No

FN = facial numbness; FU = follow-up; GD = greatly diminished; H & H = Hunt and Hess; Oc = occlusion; Pa = patent; PO = proximal occlusion; TE = total elimination.

patency of the graft conduit and to look for hemorrhagic complications. If worsening neurological function was observed, multimodal MRI was performed immediately to identify territorial ischemia. The aneurysm stability was classified as complete occlusion/obliteration (no residual aneurysm), greatly diminished (residual neck), or incomplete occlusion (aneurysm lumen remaining). The follow-up cerebral angiogram was performed after 3 months, and then yearly thereafter.

The neurological outcomes were assessed using a modified Rankin Scale (mRS) by one of the authors (S.L.) in a blinded fashion, and the scores were recorded. Follow-up functional outcome was measured based on telephone interviews with the patient or, if the patients were unable to participate, their relatives or primary caregivers were asked to provide information. If complications occurred, mRS scores were determined on an outpatient visit with physical examination.

Results

Patients and Aneurysm Characteristics

During an 8-year period, 12 consecutive patients harboring CMCAAs were treated by IMA bypass; the group included 9 males and 3 females. The average age of patients was 31.7 years, with a range of 14–56 years. The most common presentation that led to the diagnosis was headache. Other presenting symptoms varied, and included facial numbness, dizziness, and seizure. SAH was observed in 3 patients, of which 2 were Hunt and Hess grade II and 1 was Hunt and Hess grade III. One patient had a thrombosed giant aneurysm following a first attempt at

treatment. The pretreatment mRS score (mean 1.6; range 0–4) was 0–1 for 9 patients and 3–4 for 3 patients.

The mean size of the CMCAA was 23.7 mm (range 10–37 mm), and all the aneurysms were large ($n = 6$) or giant ($n = 6$). Two aneurysms were located at the M₁-LSA segment, 3 at the M₁-ECB segment, 2 at the MCA bifurcation, 1 at the distal MCA segment, and 4 extensively involved the MCA. Treated lesions presented with fusiform morphology in 7 patients, thrombotic in 6 patients, serpentine in 1 patient, and recurrent after a primary attempt in 1 patient. The baseline patient and aneurysm characteristics are summarized in Table 2.

Immediate and Long-Term Outcomes of IMA Bypass Surgery

The proximal occlusion of the parent artery following IMA bypass was attained in 8 cases (75%) with ($n = 2$) or without ($n = 6$) aneurysmorrhaphy (AR). The remaining aneurysms were completely trapped with ($n = 1$) or without ($n = 2$) AR or completely resected ($n = 1$). Intraoperative complications, such as unexpected rupture, were not observed. Of the 12 patients who were initially included in this study, 10 (83.3%) achieved complete aneurysm elimination on immediate angiographic results, and the aneurysms of the other 2 (16.7%) were greatly diminished. Postoperative angiograms documented graft patency in 10 of 12 patients (83.3%). Surgery-related deaths did not occur in the perioperative period. The mRS score (mean 1.7; range 0–4) at discharge was 0–2 in 9 patients and 3–4 in 3 patients, which was equal to the preoperative status. Three patients had unfavorable outcomes, of whom 2 had

TABLE 2. Summary of baseline patient and aneurysm characteristics in 12 patients with CMCAAs

Variable	Value
Background characteristics	
Sex	
Male	9
Female	3
Mean age, yrs (range)	31.7 (14–56)
Mean size, mm (range)	23.7 (10–37)
Location	
M ₁ –LSA	2
M ₁ –ECB	3
Bifurcation	2
Distal	1
Extended involvement	4
Presenting aneurysm characteristic	
Size	
Large	6
Giant	6
Complexity	
Fusiform	7
Thrombotic	6
Serpentine	1
Recurrent	1
History of SAH	
H & H II	2
H & H III	1
Mean mRS score (range)	1.6 (0–4)

new permanent neurological deficits by virtue of the graft occlusion and 1 was slightly disabled as reflected in the poor Hunt and Hess status. The angiographic and clinical outcomes after the procedure are summarized in Table 3.

No adverse events (patient death, posttreatment rupture, or aneurysm recurrence) were observed during hospitalization and follow-up. In the angiographic follow-up study (mean 28.7 months; range 2–74 months), patent RA was found in 83.3% (n = 10) of patients, and the complete occlusion rate of aneurysms was 100%. The median duration of follow-up focusing on neurological functions was 53.1 months (range 19–82 months), and excellent outcomes were achieved in all patients (mRS score: mean 0.3; range 0–1). Regarding the cosmetic issue in the region of the temporalis muscle, no patient complained of fullness and discomfort at a level that was bothersome enough to merit intervention. The outcomes at long-term follow-up are summarized in Table 4.

Illustrative Cases

A 37-year-old woman (case 12) was admitted to our department with a 1-month history of severe headache, and a mass lesion in the sylvian fissure was detected. Her past medical history was unremarkable, and neurological examination on admission revealed no focal deficits. Pre-

TABLE 3. Postoperative results of IMA bypass surgery in 12 patients with CMCAAs

Description	No. (%)
Aneurysm manipulation	
Parent artery occlusion	8
w/ AR	2
w/o AR	6
Trapping	3
w/ AR	1
w/o AR	2
Resection	1
Graft patency	
Pa	10 (83.3)
Occluded	2 (16.7)
Aneurysmal morphology	
TE	10 (83.3)
GD	2 (16.7)
Clinical outcomes	
Mean mRS score	1.7, range 0–4
0–2; favorable	9 (75.0)
3–5; poor	3 (25.0)
6; died	0 (0)
Surgery-related complication	
Cerebral ischemia	2 (16.7)

operative CTA (Fig. 1) was performed and confirmed a giant, fusiform, thrombosed aneurysm that involved the M₁–M₂ segment of the MCA. Following a multidisciplinary discussion, microsurgical repair or endovascular treatment modalities were deemed likely to fail. Therefore, a high-flow IMA bypass was considered, followed by parent artery occlusion to preserve the perforators arising from the aneurysm wall. The RA was harvested and prepared after confirmation of the Allen test, and the

TABLE 4. Long-term outcomes of IMA bypass surgery in 12 patients with CMCAAs

Long-Term Outcome	No. (%)
Angiographic	
Mean time in mos, range	28.7, 2–74
Graft patency	
Pa	10 (83.3)
Occluded	2 (16.7)
Aneurysm morphology	
TE	12 (100)
Clinical	
Mean time in mos, range	53.1, 19–82
Mean mRS score, range	0.3, 0–1
Favorable	12
mRS 0	9 (75)
mRS 1	3 (25)

FIG. 1. Preoperative axial (A), coronal (B), and sagittal (C) CTA demonstrated a giant (36 × 25 × 25 mm), thrombosed, fusiform MCA aneurysm. 3D CTA (D–F) images were then reconstructed to identify the specific location of the aneurysm involving the M₁–M₂ MCA segment.

aneurysm was approached using a frontotemporal craniotomy with zygomatic osteotomy to expose the I₂. The extracranial IMA-RA bypass was initially performed in an end-to-end manner, and then the free end of the RA was anastomosed to the M₂ in an end-to-side manner. Following the bypass, patency was confirmed by intraoperative Doppler ultrasonography and indocyanine green, and the proximal part of M₁ was occluded with a permanent aneurysm clip (Aesculap Instruments Corp.) (Fig. 2). Complete elimination of the aneurysm with a patent graft artery was confirmed by postoperative angiography (Fig. 3), and the patient was discharged, having attained independent status (mRS score of 2). She underwent follow-up evaluation at 19 months after surgery through an outpatient visit without exhibiting any functional neurological limitations (mRS score of 0).

Complications and Clinical Impact

Two patients experienced permanent neurological worsening after IMA bypass. The first patient (case 2) had an MCA bifurcation aneurysm (Fig. 4A and B), and the atherosclerotic nature of the lesion was noted intraoperatively (Fig. 4C). Following the primary attempt at arterial reconstruction between RA and temporal M₂, stenosis of the anastomosis site was detected immediately. The by-

pass was disassembled and the opening of temporal M₂ was sutured. The M₂ segment of the aneurysm wall was then chosen as a recipient, and microsurgical anastomosis was performed uneventfully in an end-to-side fashion. Neurophysiological monitoring showed no change during the bypass, and Doppler imaging identified patency of the graft with abundant distal flow. However, the patient's functions gradually decreased, and neuroimaging demonstrated left frontotemporal ischemia with severe vasospasm of the RA (Fig. 4D–F). Mannitol and nimodipine were then prescribed for conservative management. Although the patient had weakness of the right extremity (muscle strength grade 2) at discharge with moderate disability (mRS score of 3), her symptoms were completely resolved without neurological deficits (mRS score of 1) at the last follow-up.

In the second patient (case 8), a giant MCA bifurcation aneurysm was resected following IMA-RA–temporal M₂ bypass. Although the perforators that arose from the aneurysm wall were not observed, the proximal M₁ segment that was involved in the lesion was partially sacrificed intraoperatively. Postoperative CTA revealed graft occlusion, and the patient experienced left hemiparesis on postoperative day 7. The basal ganglia infarction was verified by neuroimaging with the suspicion of M₁ perforating

FIG. 2. IMA-RA-M₂ bypass was performed followed by proximal occlusion of the aneurysm. An intraoperative picture (left) showing 2 anastomosis sites (white asterisks) and clip ligation of proximal M₁ (black asterisk). Artist's rendering (right) of the patient's microsurgical treatment with IMA bypass for the management of CMCAA. An = aneurysm; Ant. = anterior; Max. A = maxillary artery; O.N = optic nerve; Pcom = posterior communicating artery; RAG = right arterial graft; Temp. A = temporal artery. Copyright Li Cai (right panel). Published with permission.

artery thrombosis. The patient was discharged with severe disability (mRS score of 4) but recovered uneventfully during the 4-year follow-up.

These 2 occlusion cases that resulted in temporary neurological deficits could be explained by the perforator sacrifice and inappropriate recipient site selection.

Discussion

This study of 12 patients with IMA bypasses for the CMCAAs observed on immediate angiographic sequences showed that the patency rate was 83.3% and that all the aneurysms were removed from the circulation. In 2 cases (16.7%) our patients experienced ischemic events that resulted in new permanent neurological deficits. In one case the surgeon had used the aneurysm wall as the recipient, and the other aneurysm was resected intraoperatively, which may compromise the surrounding perforators. However, over a long-term follow-up, all patients experienced unremarkable outcomes, and negative events (aneurysm recurrence or late-phase bleeding) were not encountered. We emphasize that radical aneurysm resection or using the aneurysm wall as a recipient should be avoided. To our knowledge, this represents the largest case series reported to date, and no previous study has attempted to describe

the failed experience with IMA bypass. Our results predict that, even in the endovascular era, high-flow bypass retains an essential role for complex cerebrovascular disorders.

Endovascular Treatment of CMCAAs

Recently, techniques in which flow diversion devices (FDDs) are used to treat complex cerebrovascular diseases have documented acceptable safety profiles, which result in a decrease in the number of indications for a classic surgical approach.¹¹ However, the treatment results remain suboptimal in the territory of the MCA, which should be evaluated as a separate entity for the following reasons.^{3,4,40} First, the estimated proportion of MCA aneurysms that are amenable to treatment with the FDD was only 5%.² Moreover, this device is not currently indicated for aneurysms on tortuous sidewall or end-wall bifurcations,^{2,3,5} and those arising from bifurcation represent 85% of all MCA aneurysms.⁴⁰ Even with the latest-generation devices, there is in vitro and in vivo experimental evidence that FDDs are more prone to fail.^{5,6} As for MCA aneurysms, perforator injury is another potential concern.^{3,40} FDDs often cover or “jail” side branches, which can cause unintended occlusions and ischemic complications.^{20,22,26,40} The rate of side-branch occlusion was strongly associated with bi-

FIG. 3. Postoperative axial (A), coronal (B), and sagittal (C) CTA confirmed the total elimination of the aneurysm, and 3D CTA (D–F) illustrated the patent status of the graft vessel, with robust distal flow.

furcation aneurysms.²⁸ In addition, delayed hemorrhage and aneurysm rupture are complications that must be factored into the treatment algorithm.³ The requirement for antiplatelet agents also limits their application in patients with a history of rupture.²⁰ Another major concern is the high recanalization and retreatment rates,^{5,6} as well as the high risk of incomplete occlusion,^{11,40} which may render the endovascular method ineffective. Therefore, we should also remind ourselves that the clinical course after FDD placement is not inevitably benign or without risk, and the morbidity and mortality rates associated with these endovascular series consistently exceeded those reported by experienced microneurosurgeons.¹⁷

Microsurgical Selection for CMCAAs

The primary treatment strategy for MCA aneurysms remains microsurgical repair.²⁰ However, when an aneurysm presents complex characteristics, such as an intraluminal thrombus, mycotic or infectious etiology, atherosclerotic or calcified neck, nonsaccular morphology, and incorporation of perforators, complete surgical clipping is infeasible or at least notoriously difficult.²⁶ In those circumstances, cerebral revascularization must be considered as an al-

ternative method that depends on the aneurysm location, LSA anatomy, and rupture status.

Recently, intracranial-to-intracranial bypass has been widely used for its simpler and less invasive characteristic.^{18,30,31} At the same time, several potential shortcomings including anatomical constraints and technical demands should be considered. Besides, the frequent involvement of perforators, as in most cases in this study, may prohibit this technique from being indicated for proximal MCA aneurysms. However, in situ side-to-side bypass is particularly attractive for arterial reconstruction of distal MCA (M_2 or M_3 [opercular segment of the MCA]) arborization because this technique eliminates the need for graft harvesting or the further dissection of extracranial donor vessels. Meanwhile, the low flow volume is adequate for the blood replacement of distal vasculatures.³⁰

The EC-IC bypass is a well-established method for treating complex aneurysms and is often performed in combination with a trapping strategy. Proximal occlusion, as a subtype of partial trapping, is preferred for producing a retrograde flow from the distal part of the aneurysm and facilitating intraaneurysmal thrombosis. Complete trapping may be the best alternative for aneurysms free of

FIG. 4. Preoperative axial (A) and coronal (B) CTA illustrated an MCA bifurcation aneurysm. Intraoperative photograph showing atherosclerotic characteristics of the lesion (C). The patent graft was not observed on postoperative angiography (D and E) studies, and left frontotemporal ischemia was detected (F).

perforating vessels. In rare cases, efferent outflow occlusion may be preferable when the afferent artery is difficult to reach and sacrifice,^{8,15,16} although negative results have been documented in the literature.²³ In addition, AR may be implemented following vascular reconstruction for debulking purposes.¹⁰

The Role of IMA Bypass in Cerebral Revascularization

Superficial temporal artery (STA)–MCA bypass is the standard type of cerebral revascularization. However, insufficient blood flow may result in negative events following therapeutic occlusion of the main trunk arteries that should be replaced by high-flow revascularization. Recently, the IMA bypass was redefined as a new “workhorse” in the field of high-flow bypass to replace conventional cervical artery bypass,^{14,29} in which long-term grafts are prone to kink subcutaneously and second-site incision is mandatory.

However, complex and traumatic donor vessel harvesting that required zygomatic osteotomy or middle fossa removal during the IMA bypass discouraged broader acceptance of this technique into neurosurgical practice. Recently, a less invasive method without bone sacrifice to identify I_2 was proposed.^{19,21,39} Meanwhile, new bone landmarks to locate I_2 in a simpler and more efficient way were

also introduced by conducting surgical simulation in cadavers. However, we should keep in mind that the working space on a fixed cadaver head is wider than that of a live patient because cadaver tissue is stiff and atrophied.³⁸ Notably, the only clinical case presented by the investigators had received 2 previous procedures, and the middle fossa had been partially removed before IMA bypass.³⁹ Therefore, this is not the truly minimally invasive IMA bypass operation as defined. Meanwhile, regarding the issues of severe postoperative pain and chewing difficulties, no patient complained of fullness and discomfort of the temporal region in the current study. From our clinical experience after performing 130 cases of IMA bypass, exposing I_2 without bone sacrifice is not reasonable and is extremely difficult due to obstruction by the temporalis muscle. Our position is that a comparative study of the advantages and limitations of each exposure technique should be conducted in the near future.

As for the interposition graft of IMA bypass, the RA^{24,25,32–34,36} and forearm cephalic vein^{12,13} have been used in clinical settings. Recently, preclinical studies focusing on STA trunk grafts have been comprehensively reported in the literature.^{1,9,21,27} However, its diameter mismatch with donor vessels and the short length available for approaching EC-IC vessels make tension-free reconstruction

difficult.^{35,37} Notably, an article with “STA graft” in its title included the only case of IMA bypass with RA graft.⁹ We highly recommend that RA be used as the preferred graft in IMA bypass procedures by virtue of suitable arterial diameter and adequate graft length. Meanwhile, the synchronous performance of craniotomy and graft harvesting by 1 primary surgeon and 2 assistants makes the procedure less time-consuming. The forearm cephalic vein is another valid option for those who fail the Allen test. The STA trunk may only be considered when other reliable grafts are not available. Therefore, IMA bypass with RA following bone drilling remains the benchmark in this novel bypass surgery.

Limitations of the Study

The main inherent limitation of this study was the retrospective nature of the data analysis, which leads to potential ascertainment bias. Besides, the limited number of patients may have precluded a firm conclusion regarding the safety and efficacy of IMA bypass for treating CMCAAs. In addition, this study was not a randomized controlled trial, which is another limitation. Further studies with more cases and a control group are necessary to confirm our findings. Our results also reflected the experience of a single surgeon who used a defined set of protocols at a single center, which may not be representative of the neurosurgical cases in other large academic centers and may limit the generalizability of the data.

Conclusions

The satisfactory results in the present study demonstrate the feasibility of treating CMCAAs by using an IMA bypass procedure; the rates of periprocedural complications and morbidity were acceptable, and the efficacy of the surgery was high. This novel arterial reconstruction procedure is a promising method for complex cerebrovascular cases and should be kept in the armamentarium of neurosurgeons. However, intraoperative radical aneurysm resection or inappropriate recipient site selection should be avoided in this subtype of MCA aneurysm. Despite advances in endovascular and neurointerventional techniques, EC-IC bypass remains an essential solution and, indeed, the dominant option when performed by experienced hands.

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Disclosures

Dr. Tanikawa holds patents with Medical U & A and Takayama.

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Conception and design: Wang. Acquisition of data: Shi, Wang, Lu, Qian. Analysis and interpretation of data: Wang. Drafting the article: Wang, Cai. Critically revising the article: Wang. Reviewed submitted version of manuscript: Shi, Wang. Approved the final version of the manuscript on behalf of all authors: Shi. Statistical analysis: Shi, Wang. Administrative/technical/material support: Shi, Wang, Qian, Tanikawa. Study supervision: Shi, Tanikawa.

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