Lessons Learned from the Initial Experience with Pedicled Temporoparietal Fascial Flap for Combined Revascularization In Moyamoya Angiopathy: A Case Series

Kristine Ravina[1], Paul E. Kim[2], Robert C. Rennert[5], Erik M. Wolfswinkel[4], Ben A. Strickland[3], Joseph N. Carey[4], Jonathan J. Russin[1,3]

■ BACKGROUND: **The pedicled temporoparietal fascial flap (TPFF) with a direct superficial temporal (STA) artery to middle cerebral artery (MCA) bypass is a novel combined revascularization approach for moyamoya angiopathy (MMA). With this case series, we aim to report the initial experience with pedicled TPFF combined revascularization for MMA treatment.**

■ METHODS: **Data from 14 consecutive patients undergoing pedicled TPFF combined revascularization for MMA between May 2016 and December 2018 were retrospectively reviewed. Patients admitted with acute ischemia or a modified Rankin Scale (mRS) score >3 were considered high risk.**

■ RESULTS: **Mean ± standard deviation age on surgery was 41.9 ± 15.4 years. Three of 14 patients (21.4%) presented with an mRS score >3. Nine of 14 patients (64.3%) presented with ischemic stroke, 4 of whom (44.4%) had acute ischemia. Direct anastomosis patency was confirmed in all cases postoperatively. Mean hospitalization time was 13 ± 9.3 days and mean follow-up time was 14.1 ± 9.3 months. From admission to follow-up, neurologic status improved in 8 patients (57.1%) and stabilized in 6 patients (42.9%). Overall, 11/14 patients (78.6%) achieved good functional outcome (mRS score ≤2). All patients achieved some radiographic collateral development, with 5 (71.5%) graded as Matsushima A and B. Three patients developed new radiographic ischemia and 3 experienced wound complications, all in the high-risk group.**

■ CONCLUSIONS: **The TPFF combined approach is a viable strategy for revascularization in MMA. This technique may be suboptimal in patients presenting with acute ischemia and/or mRS score >3.**

INTRODUCTION

Moyamoya angiopathy (MMA) is a rare progressive cerebrovascular disease characterized by steno-occlusive changes in the intracranial internal carotid arteries and their main branches and development of an abnormal collateral vascular network.[1-4] MMA can be isolated (moyamoya disease) or can occur in association with hereditary or acquired conditions such as trisomy 21 or after radiotherapy (moyamoya syndrome).[2] MMA progression is associated with a high risk of recurrent ischemic and hemorrhagic events leading to functional and cognitive disability.[1,2,4] Surgical treatment using direct, indirect, or combined revascularization is an established approach for providing supplemental blood flow to the cerebral territories at risk[5,6] and can reduce the risk of MMA-associated recurrent ischemic and hemorrhagic events.[7,8] Recently, favorable outcomes of combined and isolated direct over isolated indirect revascularization approaches have been increasingly reported, especially in the adult population.[8-14] A synergistic, reciprocal relationship observed between the direct and indirect components in

Key words
- Cerebral revascularization
- Combined bypass
- Moyamoya angiopathy
- Temporoparietal pedicled flap

Abbreviations and Acronyms
MCA: Middle cerebral artery
MMA: Moyamoya angiopathy
MRI: Magnetic resonance imaging
mRS: Modified Rankin Scale
POD: Postoperative day
STA: Superficial temporal artery
TIA: Transient ischemic attack
TPFF: Temporoparietal fascial flap

From the [1]Neurorestoration Center, Departments of [2]Radiology and [3]Neurological Surgery, and [4]Division of Plastic and Reconstructive Surgery, Department of Surgery, Keck School of Medicine, University of Southern California, Los Angeles, California; and [5]Department of Neurosurgery, University of California at San Diego, San Diego, California, USA

To whom correspondence should be addressed: Jonathan J. Russin, M.D. [E-mail: jonathan.russin@med.usc.edu]

Citation: World Neurosurg. (2019) 132:e259-e273.
https://doi.org/10.1016/j.wneu.2019.08.182

Journal homepage: www.journals.elsevier.com/world-neurosurgery

Available online: www.sciencedirect.com

combined approaches may nonetheless offer the most comprehensive revascularization strategy.[9,11,15]

The novel combined revascularization approach for adult MMA using a direct superficial temporal artery (STA) to middle cerebral artery (MCA) bypass in conjunction with a pedicled temporoparietal fascial flap (TPFF) for indirect revascularization has been recently reported.[16] The TPFF is harvested from temporal galea[17,18] and provides a cosmetically favorable, sizable, and highly vascularized alternative source for indirect revascularization (with preserved venous drainage through the superficial temporal vein).[16] We report our initial experience with the pedicled TPFF combined revascularization technique in 14 MMA cases between May 2016 and December 2018. Clinical characteristics, angiographic findings, clinical outcomes, and complications are summarized and discussed.

METHODS

This study was conducted in compliance with the Health Insurance Portability and Accountability Act regulations. A retrospective review of a prospectively maintained database was conducted to identify all patients with MMA treated with pedicled TPFF combined revascularization.

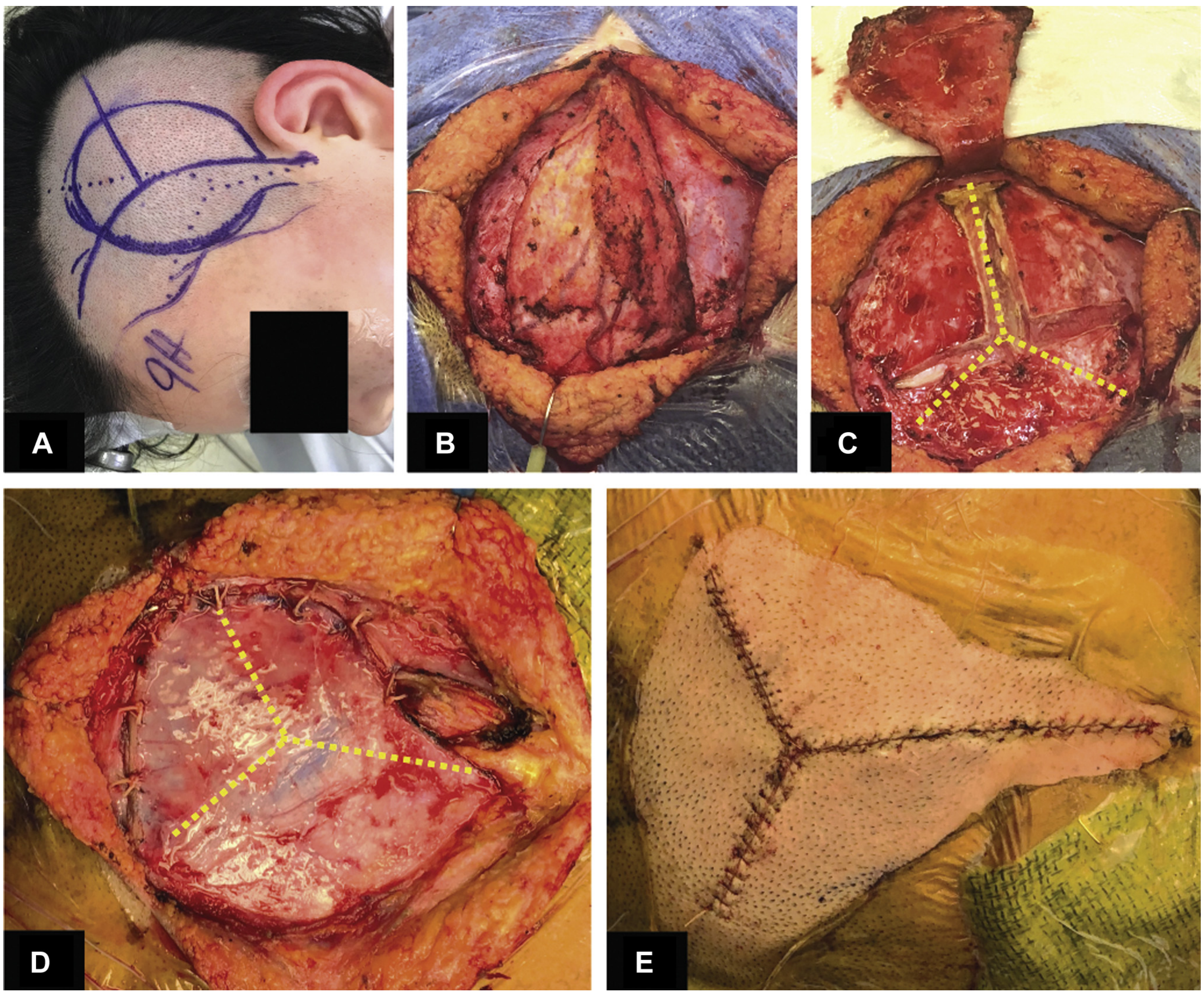


Figure 1. Pedicled temporoparietal fascial flap (TPFF) preparation and wound closure surgical steps. The location of the superficial temporal artery is marked using Doppler ultrasound followed by the Y-shaped incision and TPFF outline marking (**A**). The TPFF is dissected (**B**) and a T-shaped temporalis muscle incision made (**C**). Modified approach involves an eccentric, curved temporalis muscle incision (**D**) located remotely from the skin incision closure lines (**E**). Dotted line indicates the location of the skin incision relative to the temporalis muscle incision.

Study Population and Case Clinical Evaluation

Between May 2016 and December 2018, 14 patients who underwent pedicled TPFF combined revascularization for MMA were identified. Case clinical features; angiographic characteristics; surgical details; Glasgow Coma Scale scores on admission; modified Rankin Scale (mRS) scores on admission, discharge, and follow-up; as well as detailed information about complications were collected and analyzed. Functional outcome measures were independently evaluated by an investigator not involved in patient clinical management. A patient was deemed high risk if they were admitted with acute ischemic stroke or with mRS score >3.

Surgical Technique

Combined revascularization using a pedicled TPFF has been previously described.[16] The patient's blood pressure was maintained approximately 20 points above baseline intraoperatively. Neuromonitoring was performed throughout the procedure. The STA branches were marked with Doppler ultrasound (Figure 1A). Once the TPFF flap was dissected (Figure 1B), the distal portion of the STA frontal or parietal branch was divided. After splitting and dissecting the temporalis fascia and muscle, a frontotemporal craniotomy was performed (Figure 1C–E). A segment of a cortical MCA branch was then dissected free (Figure 2A). After completion of the end-to-side STA-MCA anastomosis (Figure 2B and C), patency was evaluated using intraoperative indocyanine green video angiography (Figure 2D). The TPFF was then laid intracranially (Figure 2E and F), and the dural leaflets were reapproximated with a nylon suture. Patency of the direct anastomosis was angiographically confirmed postoperatively and at follow-up.

Angiographic Evaluation

Angiographic evaluations were performed by an experienced neuroradiologist. The extent of preoperative MMA changes was

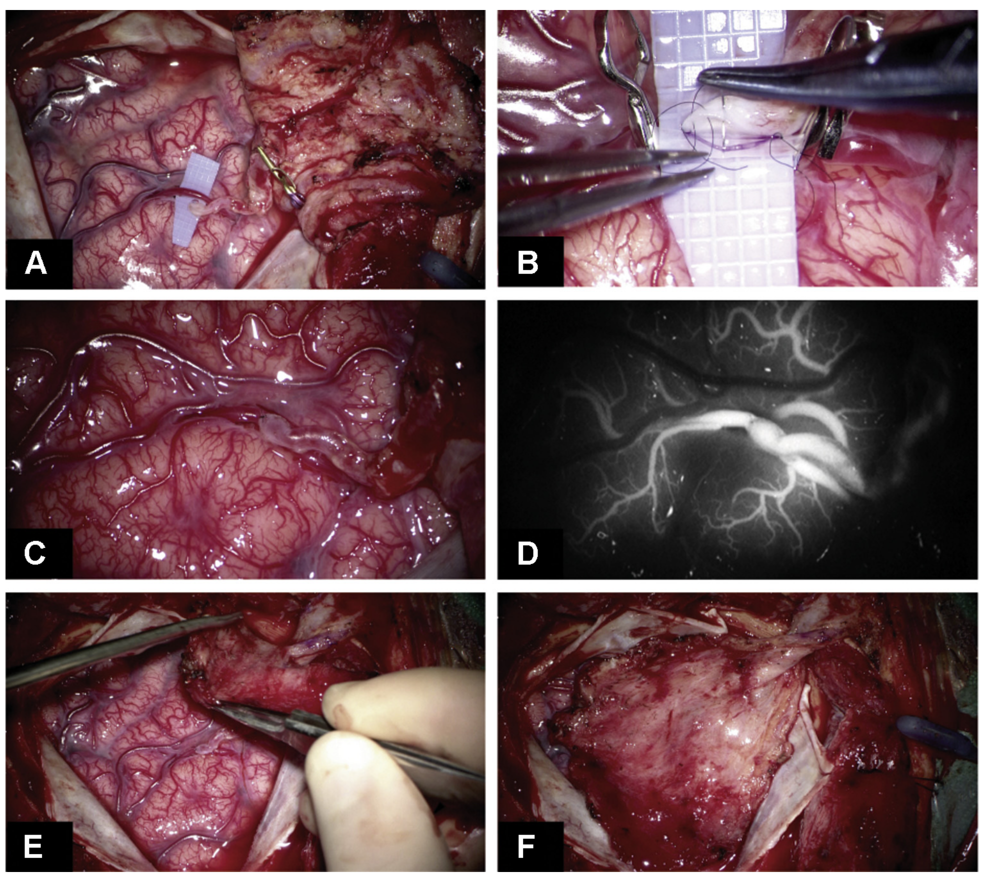


Figure 2. Major intracranial surgical steps of the combined pedicled temporoparietal fascial flap and superficial temporal artery to middle cerebral artery bypass combined revascularization. A segment of cortical middle cerebral artery recipient is circumferentially dissected and prepared for anastomosis with the superficial temporal artery donor (**A**). End-to-side microvascular anastomosis is performed (**B**). Once the anastomosis is completed (**C**), its patency is confirmed using indocyanine green intraoperative video angiography (**D**). Pedicled temporoparietal fascial flap is then laid intracranially (**E, F**).

Table 1. Case Clinical Characteristics, Outcomes, and Complications

Case No.	Age (Years)/ Sex	Presentation	Diagnosis	Comorbidities	Risk Group	Suzuki Grade	TPFF Revascular-ization Side	Temporary Occlusion Time (Minutes)	Direct Bypass Patency	mRS Score on Admission
1	49/F	Recurrent TIAs	MMD	DM, HT, HL, chronic kidney disease	Low	VI	L	35	Patent	0
2	63/M	Recurrent TIAs	MMD	HT, hypercholesterolemia	Low	III	L	35	Patent	0
3	56/F	Chronic ischemic R-sided stroke, recurrent TIAs with mild L-sided weakness and fine motor difficulties	MMD	HT, HL	Low	—	R	36	Patent	1
4	29/F	Chronic L occipital infarct, small, acute R thalamic hemorrhage, L-sided weakness	MMD	HT, DM	Low	III/IV	R	30	Patent	2
5	30/F	Chronic ischemic L-sided stroke, mixed aphasia, right upper extremity weakness	MMD	DM	Low	II	R	40	Patent	2
6	62/M	Chronic ischemic stroke, L-sided weakness	MMD	HT, DM, HL, s/p prostate cancer resection and radio tx	Low	II	R	30	Patent	1
7	58/F	Acute L ischemic stroke, mixed aphasia, R-sided weakness	MMS	HT, Graves disease, depression	High	—	L	40	Patent	4
8	46/M	Chronic ischemic R-sided stroke, L-sided hemiplegia	MMD	S/p ruptured moyamoya pseudoaneurysm, intraventricular hemorrhage, ischemic stroke	High	III	L	26	Patent	4
9	26/F	Acute ischemic R-sided stroke, L-sided weakness	MMD	HT, hyperthyroidism, s/p menorrhagia after myomectomy	High	III	L	35	Patent	5
10	30/F	Acute L-sided ischemic stroke, right lower extremity weakness	MMS	Trisomy 21, celiac disease, hypothyroidism	High	II	L	40	Patent	3
11	45/M	Chronic ischemic R-sided strokes	MMS	Obesity, s/p cerebellar arteriovenous malformation resection, ruptured posterior inferior cerebellar artery aneurysm embolization	Low	—	R	38	Occluded (asymptomatic at 2 months f/u)	1
12	14/F	Recurrent TIAs	MMS	S/p craniopharyngioma resection and radio tx, hydrocephalus, hypothyroidism	Low	IV	L	35	Patent	2
13	49/M	Acute R-sided ischemic stroke, left-sided weakness	MMD	HT, DM	High	—	R	40	Patent	2
14	29/M	Recurrent TIAs	MMD	None	Low	II	R	34	Patent	0

TPFF, temporoparietal fascial flap; mRS, modified Rankin Scale; f/u, follow-up; F, female; TIA, transient ischemic attack; MMD, moyamoya disease; DM, diabetes mellitus; HT, hypertension; HL, hyperlipidemia; L, left; M, male; R, right; STA-MCA, superficial temporal artery—middle cerebral artery bypass; S/p, status post; tx, therapy; MMS, moyamoya syndrome; *E coli*, *Escherichia coli*; UTI, urinary tract infection.

Table 1. Continued

mRS Score on Discharge	Latest f/u (Approximate Months)	mRS Score f/u (Status from Admission to f/u)	Perioperative Stroke	Wound Complications	Alopecia	Other Complications	Matsushima Grade	Other Moyamoya Treatment
0	12	0 (stable)	None	None	None	None	A	None
0	18	0 (stable)	None	None	Minimal	None	—	None
1	15	1 (stable)	None	None	None	Postoperative seizure	—	None
1	34	0 (improved)	None	None	Minimal	None	A	Contralateral STA-MCA approximately 18 months later
2	11	1 (improved)	None	Mild (superficial wound breakdown)	None	None	B	Contralateral STA-MCA approximately 13 months earlier
1	11	0 (improved)	None	None	None	Pseudomeningocele	C	Contralateral STA-MCA approximately 9 months later
4	8	3 (improved)	Yes (new and worsening L>R watershed frontoparietal infarcts)	Severe (wound dehiscence with subdural empyema)	None	deep venous thrombosis, *E coli* UTI	B	None
4	25	4 (stable)	None	Severe (subgaleal hematoma, wound necrosis, epidural abscess)	None	Low pressure hydrocephalus, epileptic seizures, sinking skin flap syndrome	—	None
4	11	1 (improved)	None	Mild (superficial wound breakdown)	None	None	—	None
4	20	3 (stable)	Yes (hemorrhagic conversion of L frontoparietal existing infarct, new R intracerebral hemorrhage, and a new R frontal watershed infarcts)	Moderate (wound dehiscence and necrosis, healed secondarily)	Minimal	*E coli* UTI	A	None
1	24	0 (improved)	None	None	None	Asymptomatic direct bypass occlusion	C (only indirect collaterals)	None
0	1	0 (improved)	None	None	None	Asymptomatic left Anterior cerebral artery distribution stroke at 2 weeks f/u	—	Contralateral encephaloduroarteriomyosynangiosis approximately 3 years earlier
2	7	1 (improved)	Yes (hemorrhagic conversion of R existing infarct, new R frontal watershed infarct)	None	None	None	—	None
0	1	0 (stable)	None	None	None	None	—	None

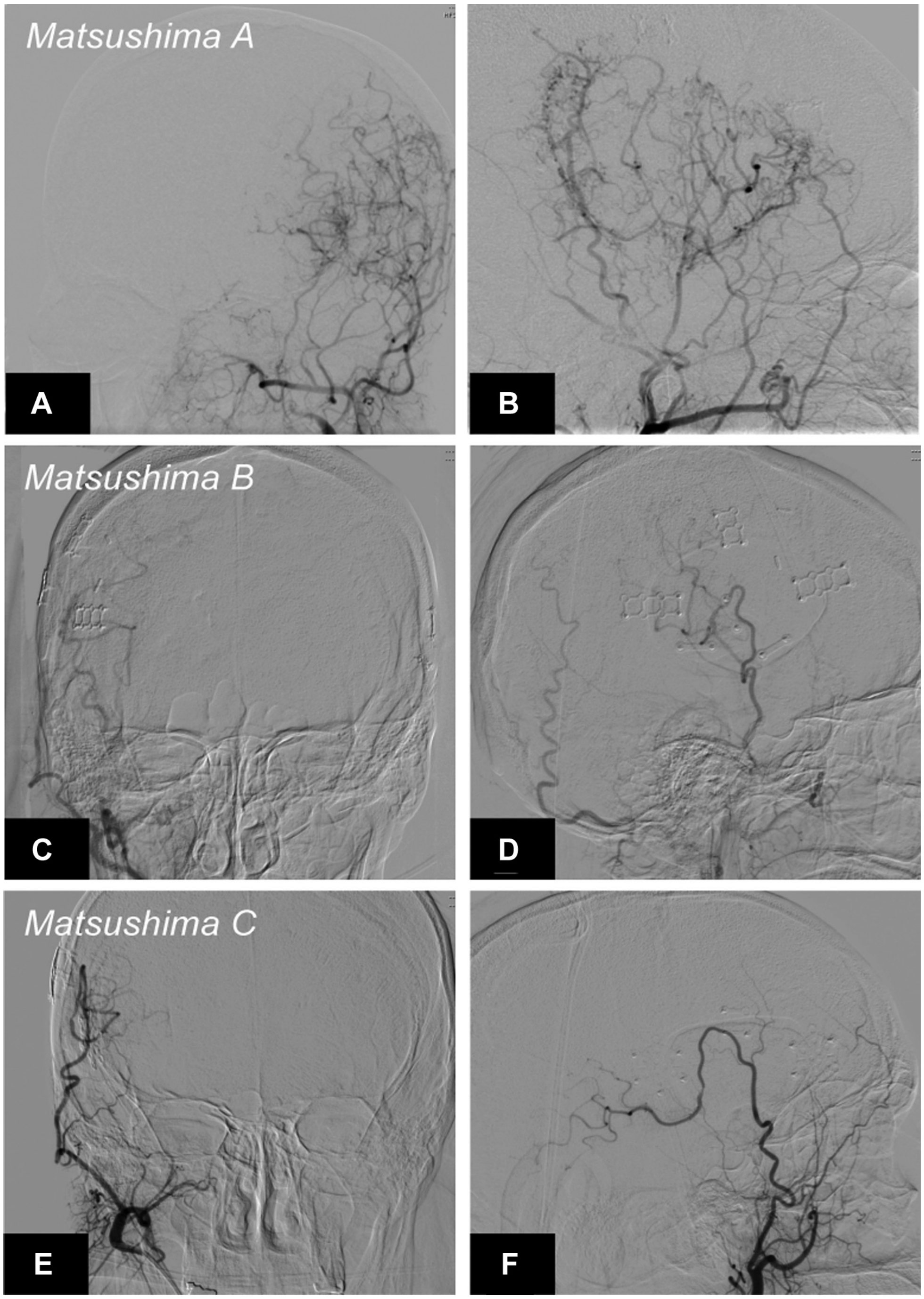


Figure 3. Matsushima grade A–C collateral development after combined revascularization with pedicled temporoparietal fascial flap and superficial temporal artery to middle cerebral artery bypass. Catheter angiogram external carotid artery injection anteroposterior and lateral projections showing Matsushima grade A revascularization in case 1 (**A, B**), grade B in case 5 (**C, D**) and grade C in case 6 (**E, F**).

evaluated using the Suzuki grading system, as previously described.[3] Postoperatively, the assessment of revascularization (direct and indirect collaterals) was performed using the previously reported Matsushima grading system.[19] The extent of collateral formation was graded as follows: grade A, whole MCA territory; grade B, more than two thirds of the MCA territory;

Table 2. Comparison Between Low-Risk and High-Risk Cases

Variable	Low-Risk (N = 9)	High-Risk (N = 5)	*P* Value
Clinical parameters			
Age on surgery (years), mean ± SD	41.9 ± 17.2	41.8 ± 13.4	0.99
Hospitalization time (days), mean ± SD	8 ± 5.7	22 ± 7.8	<0.01
Admission Glasgow Coma Scale score, median (range)	15 (14–15)	15 (7–15)	0.34
Admission mRS score, median (range)	1 (0–2)	4 (2–5)	<0.01
Discharge mRS score, median (range)	1 (0–2)	4 (2–4)	<0.01
Follow-up mRS score, median (range)	0 (0–1)	3 (1–4)	<0.01
Previous major cranial surgery (excluding revascularization)	2 (22.2)	1 (20)	>0.99
Previous contralateral hemisphere revascularization	2 (22.2)	0 (0)	0.51
Complications			
Perioperative stroke	0 (0)	3 (60)	0.03
Wound complications	1 (11.1)	4 (80)	0.02
Other complications	4 (44.4)	3 (60)	>0.99
Comorbidities			
Diabetes	4 (44.4)	1 (20)	0.58
Thyroid disease	1 (11.1)	3 (60)	0.1
Hypertension	5 (55.6)	3 (60)	>0.99
Hyperlipidemia	3 (33.3)	0 (0)	0.26
Hypercholesterolemia	1 (11.1)	0 (0)	>0.99

Values are number (%) except where indicated otherwise.
SD, standard deviation; mRS, modified Rankin Scale.

and grade C, more than one third of the MCA territory and none of the MCA territory.

Statistical Analysis

Categorical and ordinal variables are reported as frequency (percentage) or median (range) where appropriate. Continuous variables are reported as mean ± standard deviation or median (range) where appropriate. A Shapiro-Wilk test was used to assess normality of data distribution. A multiple unpaired t tests method with Holm-Sidak multiple comparison corrections was used to compare continuous variables. A Mann-Whitney U test was used to compare ordinal variables between low-risk and high-risk patient groups. Contingency table analysis with a Fisher exact test was used to compare frequency of categorical variables between low-risk and high-risk patient groups. Statistical significance was set at a P value <0.05. Statistical analyses were performed using GraphPad Prism 8 for MacOS (GraphPad Software, Inc., San Diego, California, USA).

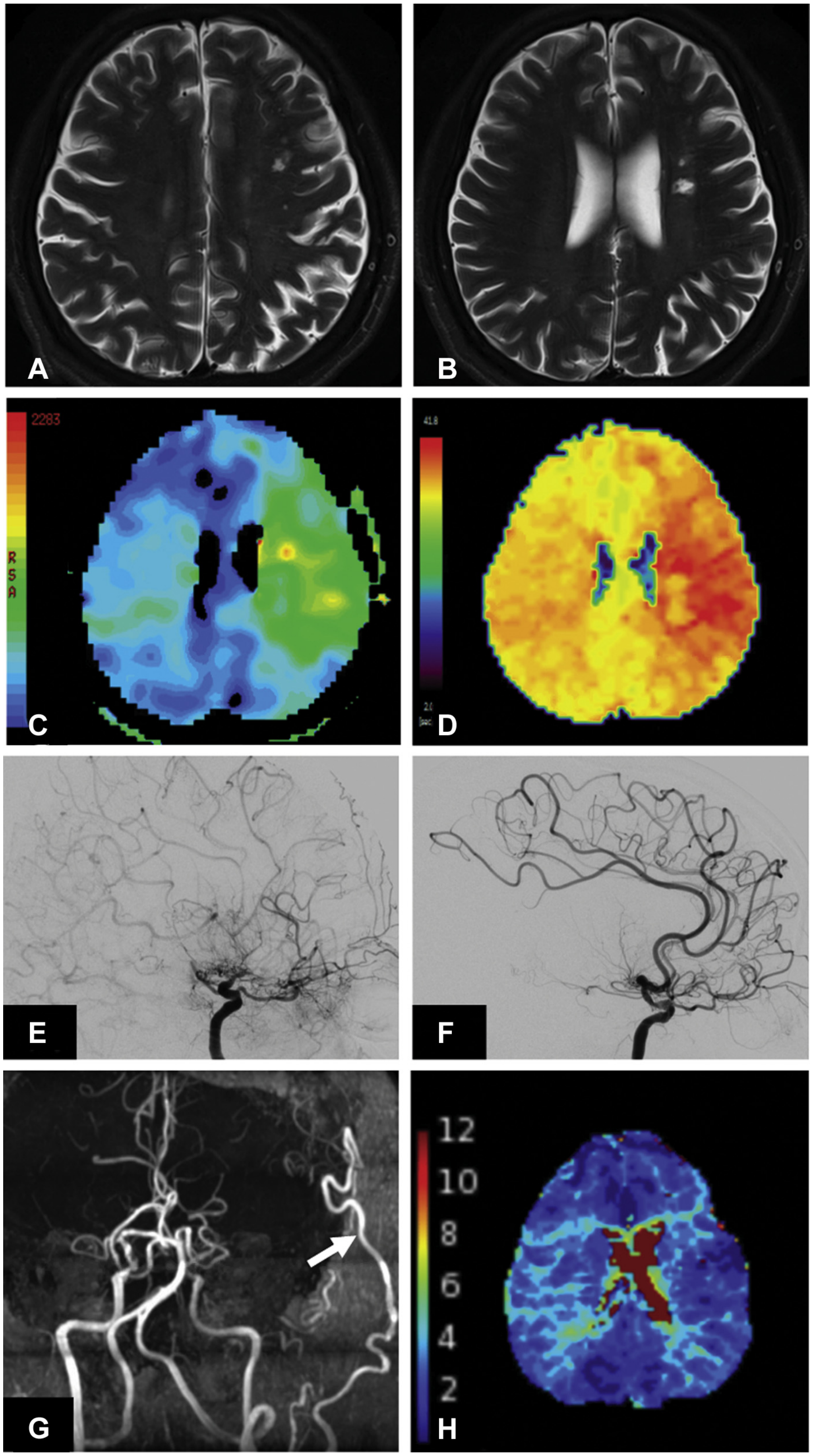
RESULTS

Summary of Clinical Data and Outcomes

Patient characteristics and surgical outcomes/complications are summarized in Table 1. Mean ± standard deviation patient age was 41.9 ± 15.4 years (8 women, 6 men). Four patients (28.6%) presented with recurrent transient ischemic attacks (TIAs) and 9 (64.3%) presented with ischemic strokes, 4 (44.4%) of whom had an acute ischemia. One patient (7.1%) presented with a hemorrhagic stroke. On admission, 3/14 patients (21.4%) had an mRS score >3, 1/14 (7.1%) had an mRS score of 3, 4/14 (28.6%) had an mRS score of 2, and 6/14 (42.9%) had an mRS score <2. Two patients with an acute ischemia also had an mRS score >3.

Preoperative Suzuki grades could be assigned in 10/14 (71.4%) patients (Table 1). Preoperative Suzuki grade could not be assigned in the remaining 4 patients because of limited microvascular visualization offered by computed tomography or magnetic resonance imaging (MRI) angiogram. Four patients (40%) presented with Suzuki grade II, 3 patients (30%) with grade III, 1 patient (10%) with a grade between III and IV, 1 patient (10%) with grade IV, and 1 patient (10%) with grade VI.

All patients underwent combined revascularization with a pedicled TPFF coupled with an STA-MCA direct bypass. Mean temporary occlusion time for direct anastomosis was 35.3 ± 4.3 minutes. Bypass patency was confirmed in all cases intraoperatively using indocyanine green video angiography. Mean hospitalization time was 13 ± 9.3 days. On discharge, 10/14 patients (71.4%) achieved good functional outcome (mRS score ≤2). Postoperative Matsushima grades were assigned in 7/14 patients (50%) (Table 1) at a mean postoperative time of 11.1 ± 10.4 months. Matsushima grades could not be assigned in the


A
B
2283
C
D
E
F
12
10
8
6
4
2
G
H

remaining 7 patients because they had not undergone a postoperative catheter angiogram necessary to perform a detailed microvasculature assessment. Matsushima grade A was achieved in 3 patients (42.9%) (Figure 3A and B), grade B in 2 patients (28.6%) (Figure 3C and D), and grade C in 2 patients (28.6%) (Figure 3E and F). Mean follow-up time was 14.1 ± 9.3 months. On follow-up, 11/14 of the patients (78.6%) achieved good functional outcome. Compared with admission, functional status on follow-up had improved in 8/14 patients (57.1%) and stabilized in 6/14 patients (42.9%).

Complications

There were no mortalities or technical complications. New perioperative ischemic stroke occurred in 3/14 patients (21.4%), all in the high-risk group. All 3 of these infarcts were located in the anterior cerebral artery/MCA watershed area, 2 of which were ipsilateral (cases 7 and 13) and 1 contralateral (case 10) to the revascularization site. In addition, in 2 of these cases, a hemorrhagic conversion of a preexisting ischemic stroke occurred intraoperatively after anesthesia-related blood pressure fluctuations (cases 10 and 13). In case 13, the ischemic stroke on postoperative day (POD) 3 occurred after several relative hypotension episodes when restarting blood-pressure-lowering medications. One patient (7.1%) (case 12) experienced small asymptomatic ischemic stroke on follow-up. There were no hemorrhagic complications on follow-up. Patency of the direct anastomosis was confirmed on follow-up imaging in all but 1 case (case 11), in which asymptomatic direct bypass occlusion was found on 2-month follow-up.

Overall, 5/14 patients (35.7%) experienced wound complications, with 2 (high-risk group) being severe and requiring surgical wound washout and bone flap removal (cases 7 and 8). The pedicled TPFF was preserved in both of these cases. In case 7, a patient with a past medical history of hypertension and Graves disease experienced a wound dehiscence with subdural empyema. In case 8, a patient with a past medical history of a ruptured moyamoya pseudoaneurysm, intraventricular hemorrhage, ischemic strokes, poor wound hygiene, and malnutrition developed a subgaleal hematoma postoperatively and had subsequent wound necrosis with an epidural abscess. Three other patients developed mild or moderate wound complications classified as superficial wound breakdown or wound dehiscence and necrosis, respectively, which healed without infection or need for surgical intervention besides in-clinic debridement. Three patients (21.4%) experienced mild peri-incisional alopecia.

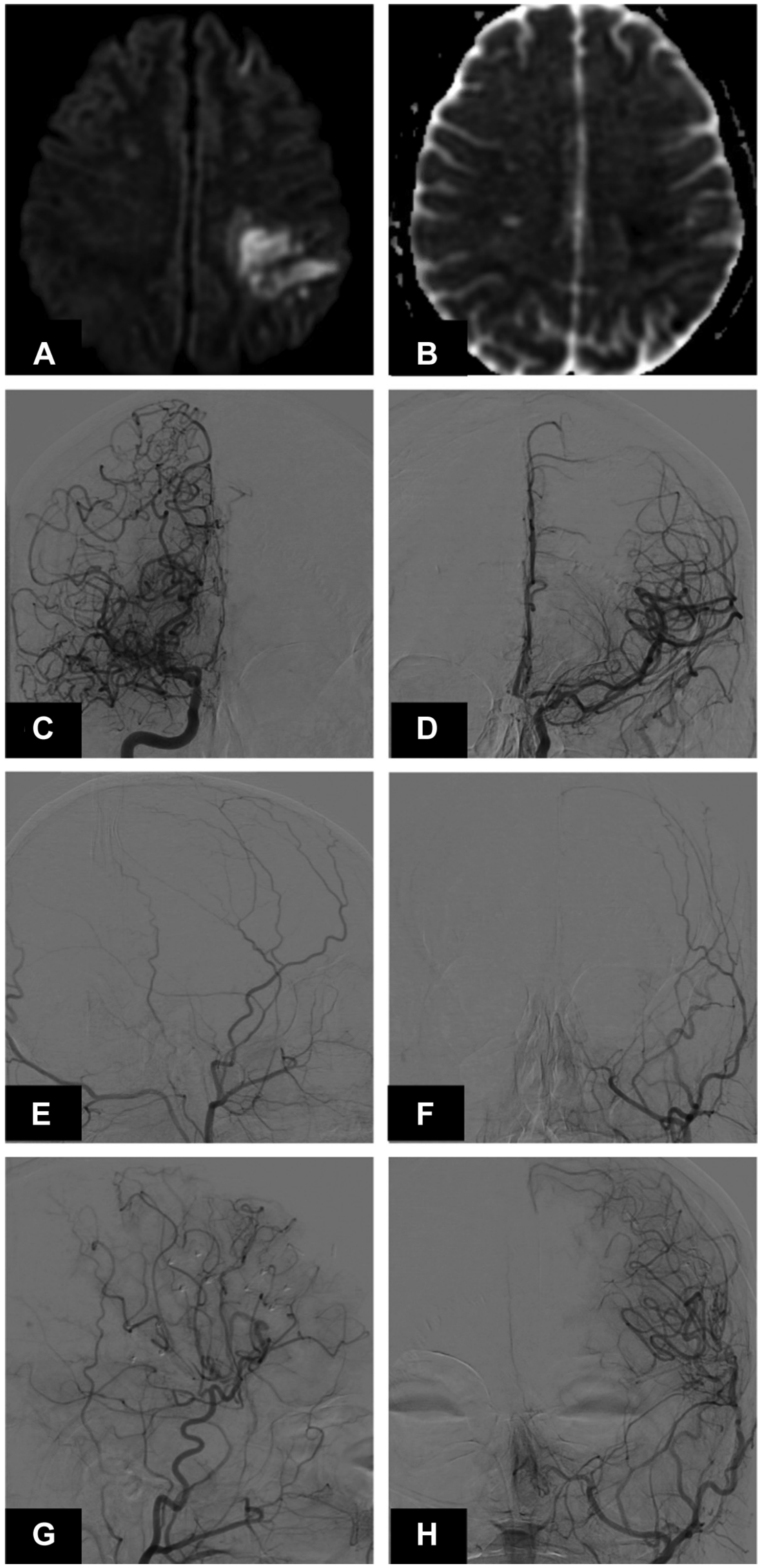
Five patients (35.7%) met high-risk criteria and 9 (64.3%) were deemed as low-risk (Table 2). High-risk patients showed significantly higher discharge and follow-up mRS scores ($P < 0.01$ and $P < 0.01$, respectively) compared with low-risk patients. In the high-risk patient group, the incidence of perioperative ischemic stroke and wound complications was also significantly higher ($P = 0.03$ and $P = 0.02$, respectively) compared with the low-risk patient group. Hospitalization time was also significantly longer for high-risk patients ($P < 0.01$). The prevalence of major comorbidities was not significantly different between the 2 groups. Patients who developed wound complications typically had a worse admission functional status (median mRS score 4 vs. 1 in the without wound complication group), which led to worse outcomes on discharge and at follow-up (median mRS score 4 and 3 vs. 1 and 0 in the without wound complication group, respectively).

Illustrative Cases

Case 2. A 63-year-old man presented with recurrent TIAs consisting of lip numbness, expressive aphasia, and right-hand weakness. MRI showed multiple small chronic ischemic infarcts in the left MCA territory (Figure 4A and B). MRI perfusion showed increased time to enhance and time to peak values in the left MCA territory (Figure 4C and D). Catheter angiogram showed bilateral carotid terminus and proximal MCA stenosis with moyamoya vessel development (Figure 4E and F) consistent with Suzuki grade III, more prominent on the left side. Collateral development from the right anterior cerebral artery supplementing the left MCA territory was also evident. Given the patient's progressive right-sided symptoms, evidence of left MCA territory ischemia, and prominent left-sided angiographic changes consistent with moyamoya disease, a combined left MCA revascularization using a pedicled TPFF combined approach was recommended. Magnetic resonance angiography on POD 1 showed patent direct anastomosis (Figure 4G). MRI showed no new ischemia. Postoperatively, the patient remained functionally intact and was discharged on POD 3. At 3 weeks follow-up, the patient's symptoms had completely resolved, and he was performing all activities of daily living independently. He experienced no wound issues or significant alopecia. He remained neurologically stable at 18 months follow-up, when direct bypass patency and improved left hemisphere perfusion (Figure 4H) were shown.

Case 10. A 30-year-old woman with a past medical history of trisomy 21, celiac disease, and hypothyroidism was evaluated for moyamoya syndrome after 3 weeks of progressive right hemibody weakness and MRI showing acute ischemic infarcts in the left MCA territory (Figure 5A) and several old punctate infarcts in the right MCA territory (Figure 5B). A catheter angiogram showed bilateral moyamoya changes consistent with Suzuki grade II disease (Figure 5C and D). Prominent carotid terminus narrowing and moyamoya vessels with collaterals from the external carotid circulation were present on the right side. The left side showed less prominent moyamoya vessels with sparse collaterals (Figure 5D). Catheter angiogram was significant for a

Figure 4. Imaging findings in case 2. Preoperative magnetic resonance imaging (MRI) showing chronic ischemic infarcts in left middle cerebral artery (MCA) territory (**A, B**). MRI perfusion imaging showing increased time to enhance (**C**) and time to peak (**D**) in the left MCA territory. Preoperative catheter angiogram internal carotid artery injection lateral projection showing bilateral carotid terminus and proximal MCA stenosis with moyamoya vessel development more prominent on the left (**E**) than right (**F**), consistent with Suzuki grade III. Postoperative computed tomography angiogram showing patent direct bypass (*arrow*) (**G**). On follow-up, improved MRI perfusion of the left hemisphere was shown (**H**).


A
B
C
D
E
F
G
H

good-caliber left STA (**Figure 5E** and **F**). A left-sided combined revascularization with a pedicled TPFF combined approach was recommended. During the procedure, the patient developed a hypertensive episode. Postoperatively, the patient had worsened right-sided weakness and new aphasia. A postoperative head computed tomography scan showed hemorrhagic conversion of her left-sided ischemic infarct, as well as a new intracerebral hemorrhage in the right lentiform nucleus. The patient slowly improved with physical and occupational therapy. She was discharged to acute rehabilitation on POD 25. At 2 months follow-up, a small wound dehiscence was noted requiring in-clinic debridement. At 5 months follow-up, catheter angiography showed a patent direct anastomosis and indirect neovascularization from the TPFF (Matsushima grade A) (**Figure 5G** and **H**). At 20 months follow-up, the patient had made a significant recovery with only a mild residual weakness of her right lower extremity and a well-healed incision.

DISCUSSION

Surgical revascularization is the mainstay treatment for adult and pediatric MMA and has been shown to significantly reduce the risk of recurrent ischemic and hemorrhagic events.[5,6,20] Although there remains controversy regarding the most efficient surgical revascularization approach, the superiority of isolated direct and combined revascularization approaches over isolated indirect revascularization in adults is being increasingly reported (**Table 3**).[8-13] The use of a combined revascularization technique with an STA-MCA bypass and pedicled TPFF offers a cosmetically favorable sizable indirect component without significant mass effect and spares the temporalis muscle.[16]

It has been described that after combined revascularization, the direct component provides early augmentation of blood flow to at-risk cerebral regions. This direct flow may then decrease over time, because the indirect component provides a robust, complementary, and progressive long-term revascularization.[9,11,15] Specifically, Amin-Hanjani et al.[9] have shown that the indirect component provides reciprocal long-term benefit to the direct anastomosis using quantitative magnetic resonance angiography measurements. Uchino et al.[11] studied MMA cases treated with STA-MCA anastomosis and encephaloduromyoarteriopericranial synangiosis. These investigators found that although indirect collateralization developed in 95% and 78% of pediatric and adult cases, respectively, complementary direct flow remained in 56% and 47% of cases. More recently, Zhao et al.[15] studied 64 adult patients with MMA undergoing combined revascularization with STA-MCA anastomosis and encephaloduromyosynangiosis and also found that dominant collateral revascularization developed from the indirect component only or from both bypasses simultaneously more commonly than from the direct bypass only. Although isolated indirect bypass can yield good revascularization results in adult MMA, with collaterals forming as early as 2 months postoperatively,[21] in patients with hemodynamically unstable and symptomatic MMA, direct or combined bypass has been suggested to be superior to isolated indirect revascularization.[22] Extending this reasoning, the TPFF combined technique maximizes tissue area for indirect revascularization, with our results showing indirect collateral development in all patients assessed (**Table 1**), and most patients having indirect collaterals covering more than two thirds of the MCA territory at a median follow-up time of 10 months (range, 4–34 months).

Despite increased technical difficulty, most studies have found no significant differences in perioperative complication rates with combined or direct versus indirect revascularization techniques.[6,13,22,23] The overall reported perioperative complication rate in combined bypass procedures ranges between 1.6% and 15.6%.[22] The postoperative ischemic complication rate after combined and direct bypass ranges between 1.5% and 11.4%.[24] Wound complications, on the other hand, are inherent in procedures involving scalp vessel harvest. The incidence of postoperative wound complications after extracranial-intracranial bypass ranges from 1.8% to 31.7%,[25-29] whereas the rate of wound complications after craniotomies without scalp vessel harvest is markedly lower at 5%–10%.[28,29] In the current series, new perioperative ischemia occurred in 3/14 patients (21.4%), whereas mild to moderate and severe wound complications occurred in 3/14 patients (21.4%) and 2/14 patients (14.3%), respectively. In the current series, the overall rate of wound complications was relatively high at 35.7%. Nonetheless, the rate of severe wound complications requiring return to the operating room was markedly lower, at 14.3%. Although the blood supply to the scalp is redundant, the STA (located within the temporoparietal fascia) is a major supplier covering the temporoparietal region.[28,30] During combined revascularization with pedicled TPFF combined technique, the TPFF along with one of the STA branches and the superficial temporal vein are dissected and translated intracranially.[16] The remaining scalp layer for closure is thus relatively thin, with the Y-shaped skin incision leaving an ischemia-vulnerable wound edge trifurcation.[16,31] If the underlying temporalis muscle incision is made in either a T-shaped or a Y-shaped fashion (as was initially performed) (**Figure 1C**) and superficial breakdown occurs, it can easily affect the muscle underneath and result in full thickness wound necrosis. To overcome this issue, we introduced an eccentric, curved temporalis muscle incision (**Figure 1D** and **E**), and are working

Figure 5. Imaging findings in case 10. Preoperative magnetic resonance imaging (MRI) showing new ischemic infarct in the left middle cerebral artery (MCA) territory (**A**) and old punctate infarcts in the right MCA territory (**B**). Preoperative catheter angiogram right (**C**) and left (**D**) internal carotid artery injections in anteroposterior projection showing moyamoya changes consistent with Suzuki grade II. Left external carotid artery injection in lateral (**E**) and anteroposterior projection (**F**) showing good-caliber left superficial temporal artery. Five months follow-up catheter angiogram left external carotid artery injection in lateral (**G**) and anteroposterior (**H**) projection showing Matsushima grade A revascularization.

Table 3. A Summary of Recent Studies Comparing Combined with Direct and/or Indirect Revascularization Approaches for Moyamoya Angiopathy Treatment

Reference	Moyamoya Presentation Type	Number of Patients	Number of Treated Hemispheres	Mean Patient Age (years)	Mean Follow-Up Period (months)	Angiographic Response to Revascularization	Functional Outcome	Recurrent Ischemic or Hemorrhagic Events Postoperatively, n (%)	Other Complications
Zhao et al., 2018[20]									
Direct bypass	Hemorrhagic	68	17	39	Angiographic: 10.2 Clinical: 21.8	Good outcome* in 10 (21.7%)	mRS score 0—2 in 13 (81.3%)	2 (12.5)	0
Combined bypass			54			Good outcome* in 36 (78.3%)	mRS score 0—2 in 52 (100%)	5 (9.6)	Transient neurologic events in 2 (3.8%), wound infection in 1 (1.9%), perioperative hemorrhage in 3 (5.8%)
Lee et al., 2012[8]									
Direct bypass	Ischemic and hemorrhagic	27	30	NR	Angiographic: 6—12 Clinical: 54.5	Good response† in 7 patients (23.3%)	Improved functional status (based on mRS score) in 19 patients (70.4%)	3 (11.1)	NR
Indirect bypass		68	77			Good response† in 8 patients (10.4%)	Improved functional status (based on mRS score) in 40 patients (58.8%)	18 (26.5)	NR
Combined bypass		29	31			Good response† in 9 patients (29.9%)	Improved functional status (based on mRS score) in 20 patients (69%)	2 (6.9)	NR
Kim et al., 2012[10]									
Indirect bypass	Ischemic	45	NR (reported 61 procedures)	36.2	Angiographic: 8 Clinical: 46	Good response† in 46 procedures (75.4%)	Excellent‡ in 37 procedures (59.7%) Good in 13 procedures (21%)	Perioperative stroke overall in 7 procedures (5.3). No significant difference reported between indirect and combined bypass	Overall neurologic complications except ischemic stroke in 22 procedures (16.7%). Perioperative wound complications in 3 combined (4.2%) and 2 indirect (3.3%) procedures
Combined bypass		51	NR (reported 71 procedures)	41.1	Angiographic: 6 Clinical: 38	Good response† in 67 (80.3%) procedures	Excellent‡ in 42 (59.2%) Good in 17 (23.9%)		

Choi et al., 2012[14]									
Indirect bypass	Ischemic and hemorrhagic	43	33	42.3	23 (angiogram $\geq$6 months after surgery)	Good response† in 9 (27.3%)	NR	2 (6.1)	NR
Combined bypass			25			Good response† in 12 (48%)	NR	4 (16)	NR
Bang et al., 2011[12]		65	75						
Direct bypass	Ischemic and hemorrhagic	NR	11	35	Angiographic: 6 Clinical: 63.8	Mean extent of revascularization‡: 57.4%	Permanent neurologic deficits after 1 procedure (9.1%), transient neurologic deficits after 5 (45.5%) procedures	1 (9.1)	0
Indirect bypass		11	14			Mean extent of revascularization§: 32.4%	Permanent neurologic deficits after 1 (7.1%) procedure, transient neurologic deficits after 5 (35.7%) procedures	1 (7.1)	Subdural hematoma/ICH in 2 (14.3%)
Combined bypass		NR	50			Mean extent of revascularization§: 58.4%—70.8%	Permanent neurologic deficits after 4 procedures (8%), transient neurologic deficits after 11 procedures (22%)	4 (8)	Overall complications in 9 (18%): epidural hematoma/ICH in 3 (6%), intraventricular hematoma in 1 (2%), subdural fluid collection in 2 (4%), infection in 3 (6%)

mRS, modified Rankin Scale; NR, not reported; ICH, intracerebral hematoma.
*Good revascularization outcome defined as neoangiogenesis from external carotid artery covering more than one third of the middle cerebral artery territory.
†Good response defined as an extent of the revascularization area supplied by bypass more than two thirds of the middle cerebral artery territory.
‡Excellent outcome defined as preoperative symptoms completely disappeared with no fixed neurologic deficits and good as preoperative neurologic symptoms completely disappeared, but neurologic deficit remained.
§Extent of revascularization reported as a % of revascularized area from whole supratentorial hemisphere area.

with our plastic surgery colleagues to use other skin incisions, such as a lazy S, inverted T, or linear variations, which may help reduce the risk of wound complications.[32]

Various preoperative factors including multiple recurrent TIAs, acute ischemic lesions in imaging, posterior cerebral artery involvement, and older age of symptom onset have been significantly associated with postoperative ischemia.[33,34] To better evaluate the effects of clinical and hemodynamic factors on surgical outcomes in our patient cohort, we separated them into high-risk and low-risk groups based on the presence versus absence of preoperative acute ischemia or mRS score >3 versus 1–3 (Table 2). The high-risk patient group showed a significantly higher incidence of perioperative stroke and wound complications. This patient group also required significantly longer hospitalization times and showed significantly worse functional outcomes on discharge and at follow-up compared with the low-risk group. In the current series, new perioperative ischemic stroke occurred in 3/14 cases (21.4%). All 3 patients (cases 7, 10, and 13) had presented with acute stroke and functional deficits indicating labile hemodynamic status and were deemed as high-risk patients in this study. Two of them developed new watershed ischemic lesions in the revascularized hemisphere, which was also the hemisphere affected by their initial acute infarct. Two of the 3 patients also developed hemorrhagic transformation of their acute infarct intraoperatively. Although efforts were made to maintain blood pressure at approximately 20 points above the baseline level in the perioperative period, intraoperative blood pressure fluctuations in cases 10 and 13 were likely associated with hemorrhagic transformation. Postoperative hypotensive episodes after restarting antihypertensive medications in case 13 were followed by an ischemic stroke in the revascularized territory. These complications are nonetheless in line with the heightened risk of postoperative ischemic complications in patients presenting with a preoperative stroke and/or more advanced disease because of their inability to compensate for sudden hemodynamic changes.[24]

Although limited by a small sample size, single-institution design, and retrospective nature, this study represents the first single-surgeon experience with a series of patients with MMA treated using the novel combined STA-MCA bypass and pedicled TPFF revascularization technique. Our experience emphasizes the importance of careful patient selection for this combined approach given the added wound complication risks from the procedure itself. This revascularization approach may be suboptimal for patients with acute ischemia and/or mRS score >3. Comorbidities that may increase risk of wound complications could also be considered a contraindication for this approach. Risk/benefit ratio should be carefully weighed on a case-by-case basis. Postoperatively, great care should be taken to educate patients regarding wound hygiene and signs of wound infection and confirm that the incision is entirely healed on the first follow-up 3 weeks after surgery. Long-term angiographic follow-up is necessary to assess the development and relationship of the direct and indirect bypasses over time. The effect of optimized skin and muscle incision techniques on wound outcomes remains to be further elucidated in larger patient cohorts.

CONCLUSIONS

Combined revascularization with an STA-MCA bypass and a pedicled TPFF is a viable strategy for the management of MMA. This technique can fulfill the primary goal of improving or stabilizing disease symptoms and provide an alternative to other combined revascularization approaches in selected patients. Careful patient selection and recognizing, monitoring, and managing wound complication risk factors and perioperative hemodynamic fragility are imperative to reduce the risk of complications. This revascularization approach may be suboptimal for patients at high surgical risk presenting with acute ischemia and/or mRS score >3.

REFERENCES

1. Scott RM, Smith ER. Moyamoya disease and moyamoya syndrome. *N Engl J Med*. 2009;360:1226-1237.

2. Guey S, Tournier-Lasserve E, Herve D, Kossorotoff M. Moyamoya disease and syndromes: from genetics to clinical management. *Appl Clin Genet*. 2015;8:49-68.

3. Suzuki J, Takaku A. Cerebrovascular "moyamoya" disease. Disease showing abnormal net-like vessels in base of brain. *Arch Neurol*. 1969;20:288-299.

4. Kuroda S, Ishikawa T, Houkin K, Nanba R, Hokari M, Iwasaki Y. Incidence and clinical features of disease progression in adult moyamoya disease. *Stroke*. 2005;36:2148-2153.

5. Lee SU, Oh CW, Kwon OK, et al. Surgical treatment of adult moyamoya disease. *Curr Treat Options Neurol*. 2018;20:22.

6. Acker G, Fekonja L, Vajkoczy P. Surgical management of moyamoya disease. *Stroke*. 2018;49:476-482.

7. Kawaguchi S, Okuno S, Sakaki T. Effect of direct arterial bypass on the prevention of future stroke in patients with the hemorrhagic variety of moyamoya disease. *J Neurosurg*. 2000;93:397-401.

8. Lee SB, Kim DS, Huh PW, Yoo DS, Lee TG, Cho KS. Long-term follow-up results in 142 adult patients with moyamoya disease according to management modality. *Acta Neurochir (Wien)*. 2012;154:1179-1187.

9. Amin-Hanjani S, Singh A, Rifai H, et al. Combined direct and indirect bypass for moyamoya: quantitative assessment of direct bypass flow over time. *Neurosurgery*. 2013;73:962-967 [discussion: 967-968].

10. Kim DS, Huh PW, Kim HS, et al. Surgical treatment of moyamoya disease in adults: combined direct and indirect vs. indirect bypass surgery. *Neurol Med Chir (Tokyo)*. 2012;52:333-338.

11. Uchino H, Kim JH, Fujima N, et al. Synergistic interactions between direct and indirect bypasses in combined procedures: the significance of indirect bypasses in moyamoya disease. *Neurosurgery*. 2017;80:201-209.

12. Bang JS, Kwon OK, Kim JE, et al. Quantitative angiographic comparison with the OSIRIS program between the direct and indirect revascularization modalities in adult moyamoya disease. *Neurosurgery*. 2012;70:625-632 [discussion: 623-632].

13. Sun H, Wilson C, Ozpinar A, et al. Perioperative complications and long-term outcomes after bypasses in adults with moyamoya disease: a systematic review and meta-analysis. *World Neurosurg*. 2016;92:179-188.

14. Choi IJ, Cho SJ, Chang JC, Park SQ, Park HK. Angiographic results of indirect and combined bypass surgery for adult moyamoya disease. *J Cerebrovasc Endovasc Neurosurg*. 2012;14:216-222.

15. Zhao J, Liu H, Zou Y, Zhang W, He S. Clinical and angiographic outcomes after combined direct and indirect bypass in adult patients with moyamoya disease: a retrospective study of 76 procedures. *Exp Ther Med*. 2018;15:3570-3576.

16. Ravina K, Rennert RC, Strickland BA, Chien M, Carey JN, Russin JJ. Pedicled temporoparietal fascial flap for combined revascularization in adult moyamoya disease. *J Neurosurg*. 2018:1-7.

17. Demirdover C, Sahin B, Vayvada H, Oztan HY. The versatile use of temporoparietal fascial flap. *Int J Med Sci*. 2011;8:362-368.

18. David SK, Cheney ML. An anatomic study of the temporoparietal fascial flap. *Arch Otolaryngol Head Neck Surg*. 1995;121:1153-1156.

19. Matsushima T, Inoue T, Ikezaki K, et al. Multiple combined indirect procedure for the surgical treatment of children with moyamoya disease. A comparison with single indirect anastomosis and direct anastomosis. *Neurosurg Focus*. 1998;5:e4.

20. Zhao Y, Yu S, Lu J, et al. Direct bypass surgery vs. combined bypass surgery for hemorrhagic moyamoya disease: a comparison of angiographic outcomes. *Front Neurol*. 2018;9:1121.

21. Chou SC, Chen YF, Lee CW, et al. Improving indirect revascularization for effective treatment of adult moyamoya disease: a prospective clinical, cerebral angiographic, and perfusion study. *World Neurosurg*. 2018;119:e180-e191.

22. Kim H, Jang DK, Han YM, et al. Direct bypass versus indirect bypass in adult moyamoya angiopathy with symptoms or hemodynamic instability: a meta-analysis of comparative studies. *World Neurosurg*. 2016;94:273-284.

23. Deng X, Gao F, Zhang D, et al. Direct versus indirect bypasses for adult ischemic-type moyamoya disease: a propensity score-matched analysis. *J Neurosurg*. 2018;128:1785-1791.

24. Zhao M, Deng X, Zhang D, et al. Risk factors for and outcomes of postoperative complications in adult patients with moyamoya disease [e-pub ahead of print]. *J Neurosurg*. https://doi.org/10.3171/2017.10.JNS171749, accessed September 23, 2019.

25. Yokoyama R, Mikami T, Ukai R, et al. Interdisciplinary prevention and management of wound-related complications in extracranial-to-intracranial bypass surgery. *World Neurosurg*. 2018;115:247-253.

26. Houkin K, Ishikawa T, Yoshimoto T, Abe H. Direct and indirect revascularization for moyamoya disease surgical techniques and peri-operative complications. *Clin Neurol Neurosurg*. 1997;99(suppl 2):S142-S145.

27. Katsuta T, Inoue T, Arakawa S, Uda K. Cutaneous necrosis after superficial temporal artery-to-middle cerebral artery anastomosis: is it predictable or avoidable? *Neurosurgery*. 2001;49:879-882 [discussion: 874-882].

28. Takanari K, Araki Y, Okamoto S, et al. Operative wound-related complications after cranial revascularization surgeries. *J Neurosurg*. 2015;123:1145-1150.

29. Chung Y, Lee SH, Choi SK. Fundamental basis of scalp layering techniques to protect against wound infection: a comparative study between conventional and in-to-out dissection of the superficial temporal artery. *World Neurosurg*. 2017;97:304-311.

30. Wormald PJ, Alun-Jones T. Anatomy of the temporalis fascia. *J Laryngol Otol*. 1991;105:522-524.

31. Acker G, Schlinkmann N, Fekonja L, et al. Wound healing complications after revascularization for moyamoya vasculopathy with reference to different skin incisions. *Neurosurg Focus*. 2019;46:E12.

32. Mokal NJ, Ghalme AN, Kothari DS, Desai M. The use of the temporoparietal fascia flap in various clinical scenarios: a review of 71 cases. *Indian J Plast Surg*. 2013;46:493-501.

33. Hyun SJ, Kim JS, Hong SC. Prognostic factors associated with perioperative ischemic complications in adult-onset moyamoya disease. *Acta Neurochir (Wien)*. 2010;152:1181-1188.

34. Bao XY, Duan L, Yang WZ, et al. Clinical features, surgical treatment, and long-term outcome in pediatric patients with moyamoya disease in China. *Cerebrovasc Dis*. 2015;39:75-81.

Conflict of interest statement: The authors declare that the article content was composed in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Received 14 June 2019; accepted 22 August 2019

Citation: World Neurosurg. (2019) 132:e259-e273.
https://doi.org/10.1016/j.wneu.2019.08.182

Journal homepage: ***www.journals.elsevier.com/world-neurosurgery***

Available online: ***www.sciencedirect.com***