Modified pedicled temporoparietal fascial flap combined revascularization in adult moyamoya angiopathy

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Background: Pedicled temporoparietal fascial flaps (TPFF), which are flexible, thin, and highly vascularized, have been tried for the moyamoya angiopathy (MMA) treatment. To reduce postoperative complications and improve prognosis, we performed surgical modification and followed up to observe the efficacy.

Methods: From February 2018 and June 2022, the clinical data of 31 adult MMA patients who underwent the modified TPFF combined revascularization were collected. The clinical outcomes and complications of the patients were recorded until the cut-off date of follow-up. The primary endpoints were the magnetic resonance perfusion (MRP), modified Rankin Scale (mRS) scores, and Matsushima Grade; the secondary endpoints were the clinical symptom outcome and Postoperative complications. Descriptive statistics and rank sum test to assess the therapeutic effect of the modified TPFF combined revascularization for adult MMA treatment.

Results: The clinical symptoms of MMA were alleviated in 26 patients and disappeared in five. In all patients, MRP showed improvement in cerebral perfusion on the operated side, and no deterioration or new cerebral infarction occurred during follow-up. Postoperative digital subtraction angiography (DSA) showed that the anastomotic site was patent, and the MMA collateral was decreased in all patients. Only 1 case (3%) of Matsushima grade C showed poor collateral compensation. The admission mRS score (1.54±0.66) of the ischemic MMA was significantly reduced compared with ≥6 months postoperatively (0.54±0.72, $P<0.01$). The admission mRS score (0.57±0.53) of the hemorrhagic MMA was reduced compared with ≥6 months postoperatively (0, $P<0.05$). Postoperative complications included epileptic seizures in 2 cases, a cerebral hyper-perfusion syndrome in 2 cases, intracranial rebleeding in 2 cases, skin necrosis in 1 case, and skin maceration in 1 case.

Conclusions: Modified TPFF combined revascularization might be a feasible and safe surgical technique for MMA, but it is still necessary to increase the sample size and extend the follow-up time to evaluate its efficacy. Ischemic MMA may have a more significant prognostic benefit than hemorrhagic MMA by this surgery.

Keywords: Moyamoya; revascularization; pedicled temporoparietal fascial flap (TPFF); surgery

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Introduction

Moyamoya angiopathy (MMA) is a rare progressive cerebrovascular disease and a major cause of stroke, which leads to neurological and cognitive dysfunction (1,2). Many studies have shown that direct or combined revascularization reduces the incidence of stroke and improves prognosis in MMA patients (1-6). Microscopic anastomosis is challenging in pediatric patients due to the small diameter of blood vessels. These two bypass methods are only suitable for adult patients. Statistical analysis of the large sample showed that combined bypass could improve cerebral blood flow reserve and long-term prognosis (2-5).

The temporal muscle is often used for indirect bypass combined with revascularization (4,6), but postoperative soft tissue collapse can cause cosmetic failure in the temporal region. In addition, cerebral ischemia caused by the intracranial mass effect during follow-up has been reported (7,8). Pedicled temporoparietal fascial flap (TPFF) has been widely used for head and neck flap reconstruction in plastic surgery, due to its free, flexible, thin, and highly vascularized characteristics (9). In view of the above characteristics of the TPFF, some neurosurgeons have tried to replace the TPFF in the revascularization in MMA and succeeded (10-12). However, few reports have been published, as the technique is still in the exploratory stage.

Highlight box

Key findings

- This modified surgery is feasible and increases the treatment options for adult moyamoya angiopathy (MMA) patients. Ischemic MMA may have a more significant prognostic benefit than hemorrhagic MMA by this surgery.

What is known and what is new?

- The improved fan-shaped temporoparietal fascial flap (TPFF) contains branches of the superficial temporal artery (STA) and superficial temporal vein (STV), which avoid the swelling and necrosis of the TPFF.
- The vascular network of the STA can reduce the pulsating pressure at the anastomotic stoma and form extensive collateral anastomoses with cerebral cortical arteries. The inverted L-shaped incision has lower cutaneous tension, less arterial collateral damage, and fewer postoperative wound complications. Ischemic MMA can effectively improve on modified Rankin Scale (mRS) scores by this bypass.

What is the implication, and what should change now?

- Because it is a new surgical method, the selected cases are few, so it is necessary to increase the number of cases and follow-up time to demonstrate the efficacy of this surgical method.

Due to the small number of the reported cases, more poor collateral compensation and postoperative complications, further improvement is needed. In this retrospective study, we summarized the clinical data, surgical process, and postoperative follow-up of adult patients with MMA who underwent revascularization using modified TPFF to verify the efficacy and safety of the operation. We present the following article in accordance with the STROBE reporting checklist (available at https://atm.amegroups.com/article/view/10.21037/atm-22-5281/rc).

Methods

Study design and patients

MMA is common in Asian countries, but its incidence (≤0.94/100,000) is low (4). The most reported cases of MMA treated with TPFF were only 14 cases in 3 years (1). Although the study of Ravina *et al.* confirmed the feasibility of TPFF for MMA (11), the criteria for inclusion was not rigorous. Compared with the previous study (1), our selected cases were more cautious, the mRS Score was ≤3, and the digital subtraction angiography (DSA) examination showed Suzuki angiographic III/IV stage, where smoke phenomenon was most obvious. We modified the surgical incision and designed the fan-shaped TPFF to preserve the frontoparietal branch of the superficial temporal artery (STA) and its intervascular network. In this study, we retrospectively reviewed the clinical records of patients with MMA who underwent modified TPFF for combined revascularization at the Department of Neurosurgery at Tianjin Huanhu Hospital between February 2018 and June 2022. Patients younger than 18 years or with hematological disorders, congenital abnormal diseases, metabolic disorders, autoimmune diseases or modified Rankin Scale (mRS) score >3 were excluded. The enrolled patients were evaluated neurological function by two senior neurosurgeons. The ethical approval was waived by the institutional review board of Tianjin Huanhu Hospital. All patients provided signed informed consent. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013).

Data collection

Clinical data were collected, including sex, age, cerebral infarct, transient ischemic attack (TIA), intracranial bleeding, clinical symptoms, the interval between onset and admission, hospital admission, Suzuki stage, and surgical side. All patients were followed up at the outpatient clinic or by telephone up to June 2022.

mRS scores on admission, 1 month postoperatively, and ≥6 months postoperatively by an independent neurologist to evaluate the recovery of neurological function after treatment and to assess surgery efficacy. Computed tomography angiography (CTA) was performed within 1 month after surgery to determine the scope of craniotomy and the patency of the anastomotic site. DSA and magnetic resonance perfusion (MRP) were used to evaluate intracranial cerebral blood flow and perfusion changes. The Matsushima grading system was used to evaluate direct and indirect collateral compensation. The postoperative collateral formation was graded as follows: grade A, >2/3 of the middle cerebral artery (MCA) territory; grade B, between 1/3 and 2/3 of the MCA territory; and grade C, <1/3 of the MCA territory (1,12). Radiological examinations were performed on admission, 1 month postoperatively, and ≥6 months postoperatively.

Typical surgical procedures

Preoperative Doppler ultrasound was used to locate and mark the STA and its branches in the scalp. The patient was placed in the supine position, with the Sugita head holder fixed and the head turned to the opposite side of the surgery with the zygoma positioned at the highest point.

Centering on the main trunk of the STA, an arc (parietal STA takes shape in front of the ear) or an inverted L-shaped incision (the distal end of parietal STA extends to the epiotic region) was used around all branches of the STA (Figure S1A,S1B). Microdissection of the parietal STA could be started in the temporoparietal fascia at the level of the superficial temporal line (Figure S1C) and proceed toward the zygoma, exposing the STA trunk and the beginning of the frontal STA, then proceed to the distal and leading edge of the frontal STA (Figure S1D). Separating the temporal-parietal fascia and loose connective tissue under the superficial temporal line, a fan-shaped TPFF (about 8×6 cm) was dissected on the superficial surface of the temporal muscle fascia, with a 3-cm wide pedicle of STA (Figure S1E). The distal ends of the frontal STA and parietal STA in TPFF were temporarily blocked and cut off (Figure S1F), and the TPFF was turned over and wrapped in wet gauze containing heparin papaverine.

Attention was paid to the anatomical relationships of the STA, the superficial temporal vein (STV) (Figure S2A), the frontal branch of the facial nerve, and the TPFF (Figure S2B) to avoid related injuries. A "C"-type incision of the temporal muscle fascia and temporal muscle was performed with monopolar coagulation (Figure S3A). If the temporal muscle was excessively hypertrophic, an "H"-type incision was performed (Figure S3B). Craniotomy centered over the Sylvian fissure was performed, and a 2×4-cm skull defect was left 2 cm above the zygomatic arch, allowing the TPFF pedicle to pass through freely. The dura was cut around the Sylvian fissure in an arc.

The arachnoid was extensively opened along the M4 branch of the MCA around the Sylvian fissure. The recipient's vessels were selected. MCA M4 segment with a diameter of ≥1 mm and the angular gyrus branch, posterior temporal branch, or posterior parietal branch was preferred. STA–MCA end-to-side vascular anastomosis was performed with a 10-0 nylon suture line (Figure S3C). The recipient vessel occlusion time was about 20 min. Indocyanine green angiography was used to evaluate the patency of the anastomosis (Figure S3D). TPFF was applied to the surface of the cerebral cortex and loosely sutured with the surrounding dura. The dura was applied to the top of the TPFF (Figure S3E). The bone flap was reset and fixed (Figure S3F), and the incision of the temporal muscle above the zygomatic arch was loosely sutured to avoid compression at the pedicle of the TPFF.

Statistical analysis

SPSS 24.0 (IBM Corporation, NY, USA) was used for data analysis. The descriptive statistics were used for clinical characteristics, outcomes and complications of patients. The comparison of the MRS scores in different periods of MMA and subtypes was made using the rank sum test. Significance was set at $P<0.05$.

Results

Thirty-one patients (24 with ischemic MMA and 7 with hemorrhagic MMA) were involved. There were 12 males and 19 females. The patients were aged 21–63 years. The nidus location was on the left side in 23 patients and on the right in 8 patients. Among them, 21 patients suffered cerebral infarction, 3 had TIA, and 7 suffered intracranial bleeding (5 had intracranial hemorrhage with intraventricular hemorrhage). The clinical presentation included limb weakness (68%), aphasia (48%), blurred vision (13%), dizziness (10%), seizure (3%), calculation

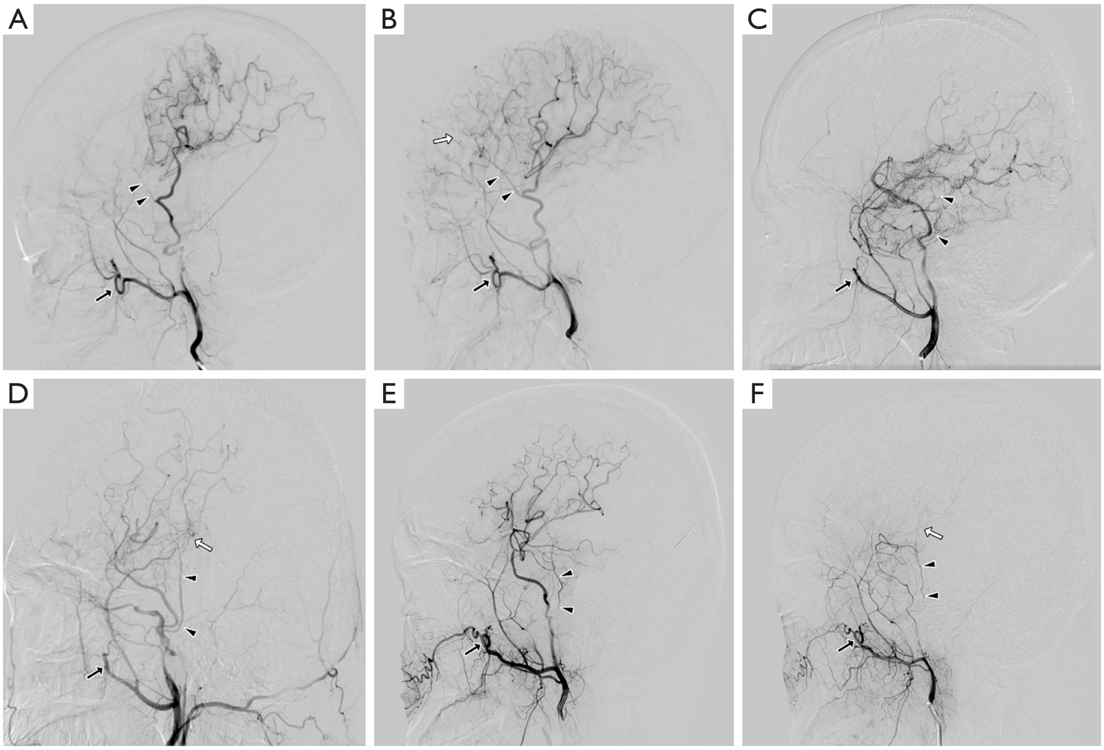

Figure 1 External carotid arteriography shows postoperative and long-term collateral compensation changes in different patients, and long-term angiography shows Matsushima grading A-C. The terminal caliber of the internal maxillary artery is used as the reference standard (black arrows). Pedicled TPFF forms a neovascularization network with the cortex (white arrow). (A,B) Postoperative angiography shows the case is a STA parietal branch bypass, long-term angiography shows STA frontal branch diameter increase, regarded as Matsushima grade A. (C,D) Postoperative angiography shows the case is an STA frontal branch bypass, long-term angiography shows STA parietal branch diameter increase, regarded as Matsushima grade B. (E,F) Postoperative angiography shows the case is an STA frontal branch bypass, long-term angiography shows STA parietal branch diameter remains unchanged (black arrowheads), regarded as Matsushima grade C. TPFF, temporoparietal fascial flap; STA, superficial temporal artery.

and memory loss (3%), and headache (3%); 6% were and asymptomatic. The time interval between symptom presentation and admission ranged from 1 to 84 months. All patients presented different Suzuki stages as follows: stage III in 20 cases and stage IV in 11 cases (Table S1).

After treatment, the mean follow-up duration was 21.1 ± 10.3 months (6–38 months) (Table S1). The clinical symptoms of MMA were alleviated in 26 patients and disappeared in five. In all patients, MRP showed improvement in cerebral perfusion on the operated side, no apparent soft-tissue collapse was observed in the temporal region after surgery, and no deterioration or new cerebral infarction occurred during follow-up (Table S2). Postoperative DSA showed that the anastomotic site was patent, and the MMA collateral was decreased in all patients. The caliber before the terminal bifurcation of the internal maxillary artery was taken as the reference standard. The DSA of all patients showed new collateral angiogenesis between the TPFF and the cerebral cortex in the long-term follow-up examination. Moreover, in the long-term follow-up, 10 cases (32%) with a Matsushima grade A and 20 cases (65%) with grade B (Table S2 and *Figure 1A-1D*), and the range of long-term collateral compensation were greater than that after surgery. The caliber of the STA indirect bypass branch in the TPFF was enlarged. Only 1 case (3%) of Matsushima grade C showed poor collateral compensation, and the caliber of the STA indirect bypass branch in the TPFF remained unchanged (*Figure 1E,1F*). Compared with the preoperative state, postoperative cerebral perfusion improved significantly, as well as $\geq$6 months postoperatively.

However, complications, such as cerebral hyperperfusion syndrome (n=2), epileptic seizures (n=2), and intracranial rebleeding (n=2), were observed. In addition, wound complications included 1 case of skin necrosis and 1 case of skin maceration (Table S2).

The results of the mRS score showed that the long-term prognosis improved ($P<0.01$) (Table S2), demonstrating the effectiveness of surgery. The clinical symptoms of patients with ischemic MMA were gradually alleviated with the prolongation of 1 month postoperatively, and ≥6 months postoperatively prognosis was significantly improved ($P<0.01$). Patients with hemorrhagic MMA had relatively mild or asymptomatic preoperative symptoms, with the highest mRS score of 1 point, and the long-term improvement degree was not as obvious as that in ischemic patients ($P<0.05$) (Table S3).

Typical cases

Case 1

A 28-year-old female experienced a left thalamic hemorrhage in the ventricles 4 years ago (Figure S4A). She was admitted to Tianjin Huanhu Hospital and had no neurological dysfunction on physical examination. DSA demonstrated symptomatic carotid atherosclerosis, occlusion of the anterior cerebral arteries (ACAs) and MCAs, and loss of the posterior communicating artery. Subsequently, the development of MMA vessels was marked on both sides under Suzuki stage IV (Figure S4B). Postoperative DSA demonstrated that the anastomotic stoma was patent (Figure S4C). At 12 months postoperatively, DSA demonstrated that the temporoparietal fascia formed extensive collateral neovascularization with the cerebral cortex, and Matsushima grade reached grade A (Figure S4D). CTA showed that the scope of the bone window and the skull defect above the zygomatic arch could prevent compression at the pedicle of the TPFF (Figure S4E). MRP showed that the mean transit time (MTT) and time to peak (TTP) of the left cerebral hemisphere were significantly shortened after surgery than before surgery (Figure S4F-S4I). Left STA–MCA anastomosis combined with TPFF was then performed. The scalp wound healed satisfactorily, no hair loss was observed, the patient had no clinical symptoms, and no stroke occurred during the follow-up.

Case 2

A 36-year-old female, who complained of frequent left limb weakness for 4 months, was admitted to Tianjin Huanhu Hospital. MRP showed right frontal-parietal lobe infarction (Figure S5A,S5B). DSA demonstrated extensive moyamoya vessels of the skull base and occlusion at the proximal portion of the ACA and MCA. The posterior communication artery was dilated, and the posterior lateral choroidal artery was anastomosed with the pericallosal artery through the ventricle system to compensate for blood flow to the cortex, which was consistent with Suzuki grade III (Figure S5C). Right STA-MCA anastomosis combined with TPFF was applied. Postoperative DSA demonstrated that the anastomotic stoma was patent, and the caliber of the STA parietal branch became enlarged (Figure S5D).

Seven months after the bypass, DSA showed that the anastomosis was patent, the caliber of the STA parietal branch was increased, TPFF formed extensive collateral anastomosis with the cerebral cortex, and Matsushima grade reached A (Figure S5E). Moyamoya vessels on the skull base were reduced, and the scope of collateral compensations of the posterior lateral choroidal artery to the cortex was significantly reduced (Figure S5F). Preoperative MRP showed prolonged TTP and MTT in the bilateral frontotemporal cortex and right basal ganglia (Figure S6A-S6C). During the long-term follow-up, MRP showed shortened TTP and MTT in the right frontotemporal region and increased cerebral blood flow (CBF) in the ACA region (Figure S6D-S6F). The head wound healed well, the clinical symptoms were completely relieved, and no stroke occurred during the follow-up.

Discussion

The findings of the present study indicated that modified TPFF for combined revascularization is a feasible surgical approach with clinical improvement in patients with MMA, preserving the frontoparietal branch of the STA that provides cortical collateral compensation.

In a previously published study, Kim *et al.* reported that in adult patients with MMA and cerebral perfusion damage and clinical symptoms, direct or combined bypass is superior to indirect bypass in blood flow reconstruction (13). However, several studies have found that combined revascularization improves cerebrovascular storage capacity (3,4). Since hemodynamic damage can induce collateral compensation, combined bypass can generate more collateral vessels than indirect bypass, depending on the need to replenish blood flow in the ischemic area. Therefore, the opening degree of the anastomotic stoma of the direct bypass is based on forming new vessels of indirect bypass, making revascularization a dynamic and self-remodeling process (14). Our findings confirmed the above theory based on the short- and long-term changes in the caliber of the branch and the compensatory range of the STA after the bypass.

Chen *et al.* reported that the anastomotic patency rate of 30 patients after STA–MCA bypass was 93.3% (6). In the present study, the short- and long-term patency rate was 100%. We speculated that, in the microstructure, the recipient's vessels were cut into a triangle using a T-shaped incision, and the terminal orifice of the bypass vessel was cut into an inclined plane. The 3D anastomosis after the suture was conducive to the blood flow patency and proximal MCA blood flow supplementation.

Ravina *et al.* separated the STA from the TPFF and then disassociated the TPFF in a butterfly-like morphology (11). Matsushima grade A and B ratio was regarded as good long-term collateral circulation (71.5%), but the rate was inferior to the 97% observed in the present study. Furthermore, clinical symptoms were alleviated in our 29 (93.5%) cases, and 1 case with an mRS score of 3 in our series did not show any improvement in symptoms during follow-up. MRI showed multiple cerebral infarctions in the frontotemporal and parietal lobes.

An anatomical study by David *et al.* found that when the TPFF is raised without damaging the nerves and vessels, the pedicle width of 66% of specimens is >3.5 cm above the superior aspect of the helix (15). Demirdover *et al.* reported that in head and neck reconstruction, the preauricular width of the TPFF pedicle is at least 2–3 cm (16). The TPFF isolated in our study was fan-shaped, including the frontal and parietal branches of STA. The pedicle width was 3 cm intraoperatively, and no swelling or necrosis of the TPFF was detected after bypass.

Cerebral hyperperfusion can occur in about 30% of patients with adult-onset MMA (2,17,18). Only 2 (6.5%) patients in our study experienced postoperative hyperperfusion. The vascular network of STA and TPFF comprised the blood flow reconstruction without damaging the collateral vessels between the frontoparietal branches of the STA. The regulation of blood pressure at the end of bypass vessels might meet the needs of the cerebral cortex for blood flow.

In the present study, 2 cases of intracranial hemorrhage were observed after the operation, and no new cerebral infarction occurred. The annual re-hemorrhage rate was 0.46%, similar to the annual stroke rate of 0.4% reported by Kuroda *et al.* after combined bypass surgery for MMA (19). Of the 2 cases, 1 was an ischemic MMA patient with contralateral hemorrhage 3 months post-surgery, accounting for 4.2% of the ischemia group. Hemorrhagic transformation (HT) in ischemic MMA is a rare phenomenon. In their study, Lu *et al.* analyzed 29 cases (4.3%) of HT after revascularization surgery in 683 patients with ischemic MMA and speculated that normal cerebral perfusion might be a risk factor for HT (20). The Japan Adult Moyamoya (JAM) trial divided hemorrhagic MMA into anterior and posterior hemorrhage according to region. The re-hemorrhage rate in the posterior region was significantly higher than in the anterior region, with an annual rate of 17.1%. This phenotype could be attributed to the abnormal anastomosis of the choroid artery, which manifests as dilatation and extension of the choroid artery and sudden anastomosis with the medulla artery outward from the track of the ventricular wall, and is considered a dangerous cause of re-hemorrhage (3,21). The re-hemorrhage rate in the current study was 1.98%, which was lower than that reported by the JAM trial, and closer to 1.87% reported by Jiang *et al.* and 1.9% reported by Abhinav *et al.* (22,23).

Acker *et al.* conducted a comparative analysis of 236 skin incisions after revascularization for MMA vasculopathy and found that, in the combined bypass group, the probability of impaired healing was 14.3% for Y-shaped incisions (24). Ravina *et al.* used a Y-type incision, and 5/14 (35.7%) of patients exhibited postoperative incision complications (1). In the present study, we did not use a Y-shaped incision, and 2/31 (6.5%) cases of incision complications were recorded, all of which were inverted L-shaped incisions along the parietal branch of the STA. Excessive electrocoagulation in the process of skin flap separation and postoperative suture tension might affect the local blood circulation of the skin. Compared with the curved incision, the probability of STV damage behind the parietal of the STA was higher. It is important to be mindful of patients with diabetes because their microcirculation is damaged, which is a risk factor for wound-related complications (24).

The incidence of postoperative complications decreased through the modified approach, and Suzuki stage III-IV patients were suitable for this operation. An arc-shaped skin incision avoids superficial temporal vein injury, and a fan-shaped TTPF retaining the STA frontoparietal branch is beneficial in the long term.

Limitations of the study

We started carrying out this type of bypass in 2018.

Therefore, the longest follow-up was 3 years, which is relatively short. In the present study, we aimed to report the feasibility of the technique itself. As follow-up is still ongoing, a future study will report the long-term follow-up outcomes of these patients. Because there were only 7 cases of hemorrhagic MMA, the statistical power would be too low to have any useful meaning. This technique is still used at our center, and the sample size is also increasing. A future study could be used for comparison.

Conclusions

Based on this study, it can be concluded that the technique minimizes the arteriovenous branch damage of PTFF. The modified surgery reported in this study is feasible and increases the treatment options for adult MMA patients. Ischemic MMA may have a more significant prognostic benefit than hemorrhagic MMA by this surgery. Taken together, the significant outcomes of all cases are supported by this modified technique and are applicable to larger sample sizes.

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Footnote

Reporting Checklist: The authors have completed the STROBE reporting checklist. Available at https://atm.amegroups.com/article/view/10.21037/atm-22-5281/rc

Data Sharing Statement: Available at https://atm.amegroups.com/article/view/10.21037/atm-22-5281/dss

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at https://atm.amegroups.com/article/view/10.21037/atm-22-5281/coif). The authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The ethical approval was waived by the institutional review board of Tianjin Huanhu Hospital. All patients provided signed informed consent.

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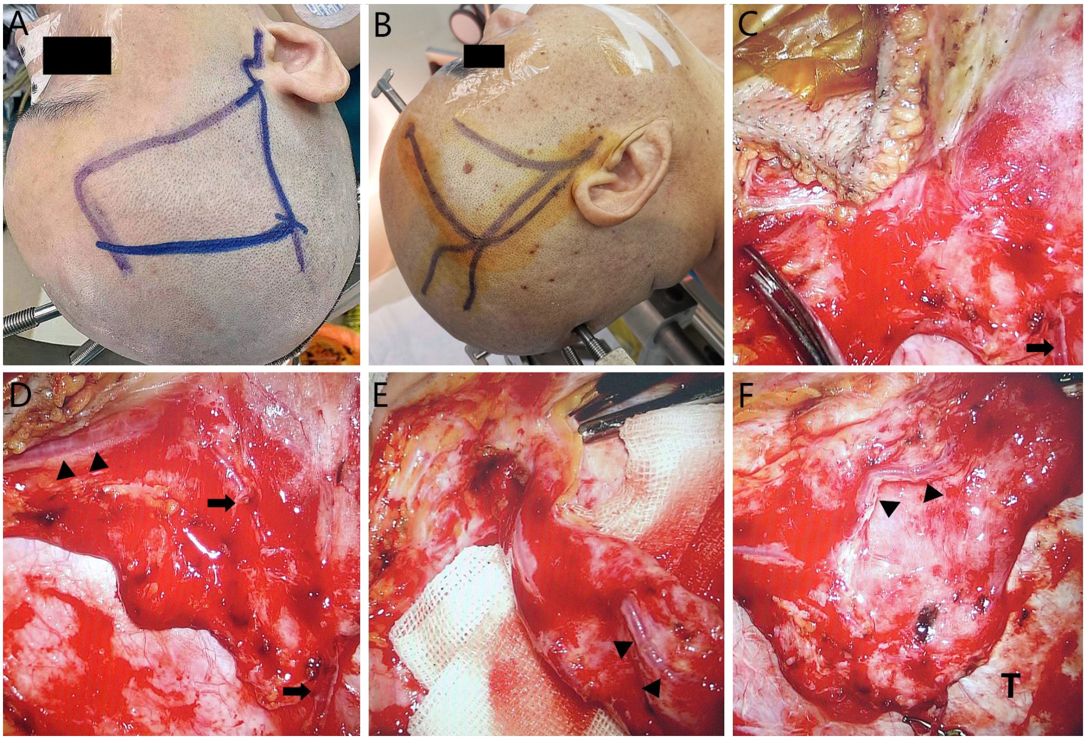

Figure S1 Intraoperative photographs showing the skin incision and step-by-step procedures of the TPFF acquisition. (A) An inverted L-shaped incision was formed by extending along the parietal branch of the STA to the supratemporal line and then curling toward the forehead hairline. (B) A curved incision which shape behind the parietal branch of the STA. (C) The distal end of the STA parietal branch (arrow) below the subcutaneous fat layer was dissociated. (D) The STA trunk (triangles) was separated above the zygomatic arch along the parietal branch of the STA (arrows). Separation was made forward to the distal of the frontal branch of STA around the pterion of the skull. (E) The TPFF was separated along the leading edge of the frontal branch of the STA (arrowhead), and attention was given to avoid facial nerve injury. (F) The Fan-shaped TPFF was completely separated on the temporal myofascial (T) surface, and the frontal branch of the STA (triangles) within the TPFF was intact. These images are published with the patient's consent. TPFF, temporoparietal fascial flap; STA, superficial temporal artery; T, temporal myofascial.

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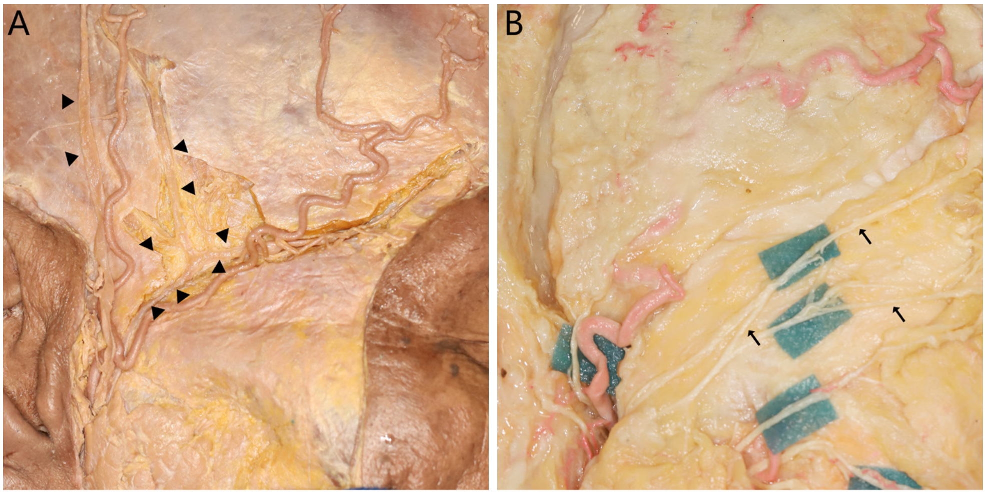

Figure S2 Anatomical photographs show the relationship between STA, STV, and facial nerve. (A) STV (triangles) rises along the posterior edge of the parietal branch of the STA, and the STV receives reflux from the internal branch of TPFF on the upper zygomatic arch. (B) Temporal branch of the facial nerve is shaped in front of the TPFF (arrows). STA, superficial temporal artery; STV, superficial temporal vein; TPFF, temporoparietal fascial flap.

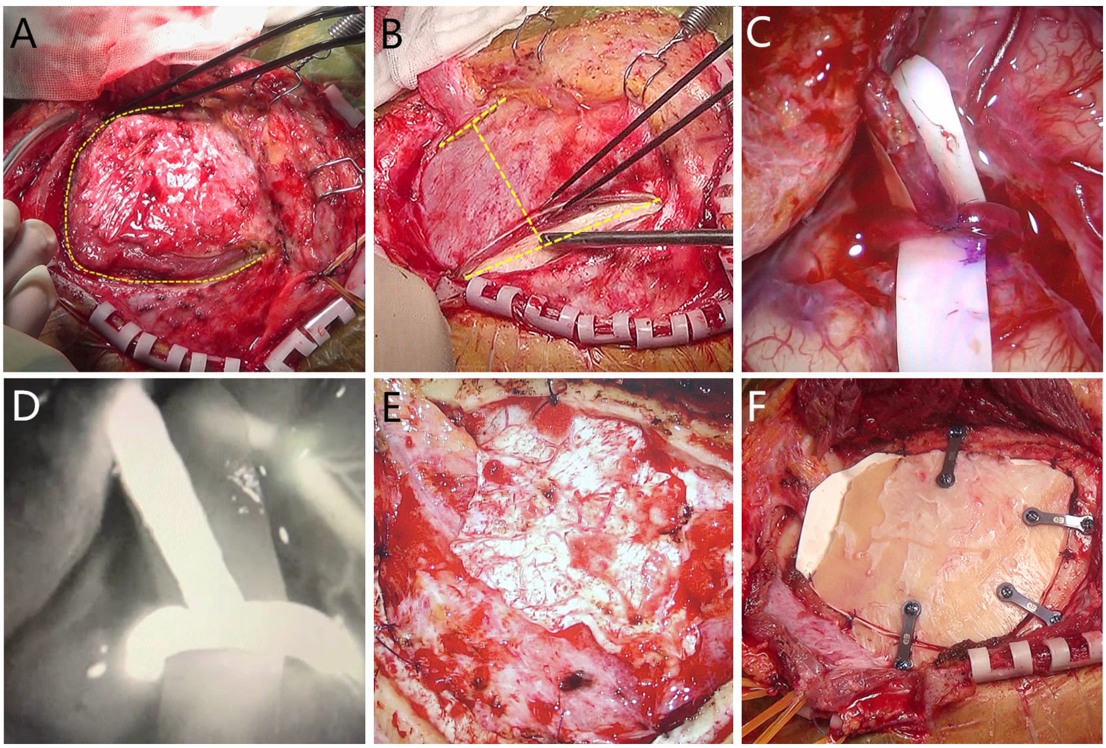

Figure S3 Intraoperative photographs show intraoperative vascular anastomosis and skull opening and closing procedures. (A) The C-type incision for normal temporal muscle (yellow dotted line). (B) The h-type incision for hypertrophic temporal muscle (yellow dotted line). (C) The end-to-side anastomosis was completed without blood leakage at the anastomotic site. (D) Intraoperative fluorescence contrast was used to verify the patency of the anastomotic site. (E) TPFF was loosely sutured to the peripheral dura, and the curved dura flap was located above the TPFF. (F) The bone flap around the root of the TPFF was removed to avoid compression. TPFF, temporoparietal fascial flap.

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Table S1 Clinical characteristics (n=31)

Variables	Mumeric data
Ischemic MMA	24
Hemorrhagic MMA	7
Female:male	19:12
Admission age, years	
Mean ± SD	40.5±10.6
Range	21–63
Nidus location, n	
Left side	23
Right side	8
Indications for revascularization, n	
TIA	3
Cerebral infarction	21
ICH	2
IVH with ICH	5
Clinical presentation, %	
Limb weakness	68%
Aphasia	48%
Blurred vision	13%
Dizziness	10%
Seizure	3%
Calculation and memory loss	3%
Headache	3%
Asymptom	6%
Suzuki angiographic stage, n	
III	20
IV	11
Time interval between symptom presentation and admission, months	
Mean ± SD	9.4±16.2
Range	1–84
Duration of follow-up, months	
Mean ± SD	21.1±10.3
Range	6–38

MMA, moyamoya angiopathy; TIA, transient ischemic attack; ICH, intracranial hemorrhage; IVH, intraventricular hemorrhage.

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Table S2 Outcomes and complications

Variables	Mumeric data
mRS score, n=31	
Admission, mean	1.00; ref.
One month after surgery, mean	0.74; P1=0.125
Latest follow-up, mean	0.42; P2=0.004, P3=0.002
Clinical symptoms of MMA, n=31	
Improvement	26
Disappearance	5
Deterioration	0
Complications, n=6	
Epileptic seizures	2
Cerebral hyper-perfusion syndrome	2
Intracranial rebleeding	2
Wound complications, n=2	
Skin necrosis	1
Skin maceration	1
Matsushima grade of synangiosis collaterals, n=31	
A	10
B	20
C	1

mRS, modified Rankin scale; MMA, moyamoya angiopathy; P1, admission *vs.* one month; P2, one month *vs.* latest follow-up; P3, admission *vs.* latest follow-up.

Table S3 Comparison of mRS scores in different time periods of moyamoya disease and subtypes

Target	mRS Score, mean ± standard deviation			z-Score, P value		
Variable	Admission	One month	Latest follow-up	P1	P2	P3
MMA	1.00±0.68	0.74±0.86	0.42±0.86	−1.54, 0.125	−2.89, 0.004*	−3.05, 0.002*
Ischemic	1.54±0.66	0.92±0.88	0.54±0.72	−3.87, 0.000*	−2.71, 0.007*	−4.18, 0.000*
Hemorrhagic	0.57±0.53	0.14±0.38	0	−1.73, 0.083	−1.00, 0.317	−2.00, 0.046*

*, statistical significance (P<0.05). mRS, modified Rankin scale; MMA, moyamoya angiopathy; Ischemic, ischemic moyamoya disease; Hemorrhagic, hemorrhagic moyamoya disease; P1, admission versus one month; P2, one month *vs.* latest follow-up; P3, admission *vs.* latest follow-up.

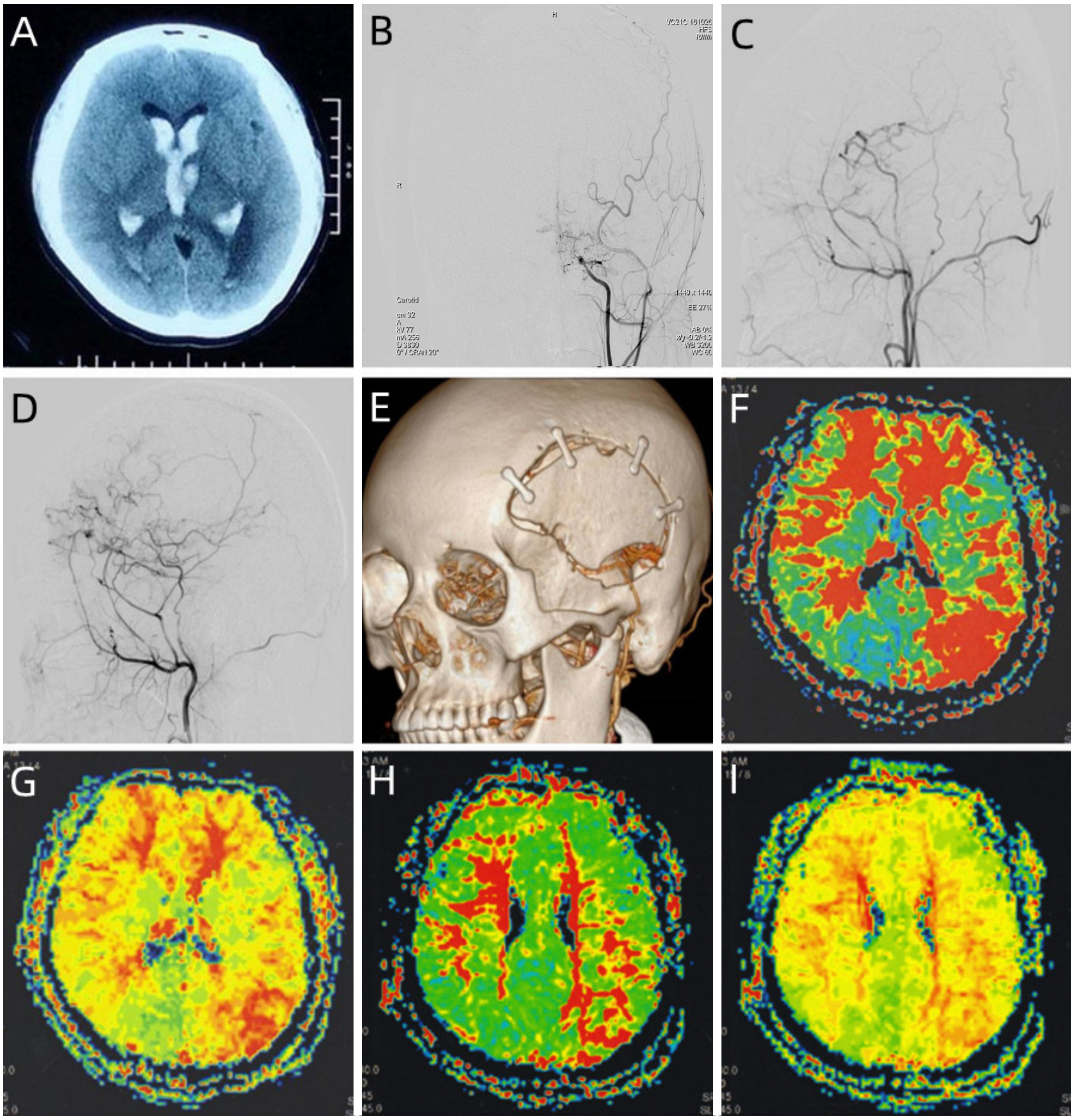

Figure S4 Preoperative and postoperative radiological findings of a 28-year-old woman. (A) Head computed tomography shows left thalamic hemorrhage broken into ventricles. (B) MMD Suzuki stage IV. (C,D) postoperative angiography shows a left STA frontal branch bypass. Long-term angiography shows extensive collateral anastomosis between STA and cerebral cortex, regarded as Matsushima grade A. (E) Postoperative 3D computed tomography scans of the skull. Note the cranial windows to prevent compression at the pedicle of TPFF for surgical revascularization. (F-H) MTT changes of MRP before and after surgery, and MTT of the left cerebral hemisphere is significantly shortened. (G-I) TTP changes of MRP before and after surgery, and TTP of the left cerebral hemisphere is significantly shortened too. MMD, moyamoya disease; STA, superficial temporal artery; TPFF, temporoparietal fascial flap; MRP, magnetic resonance perfusion; MTT, mean transit time; TTP, time to peak.

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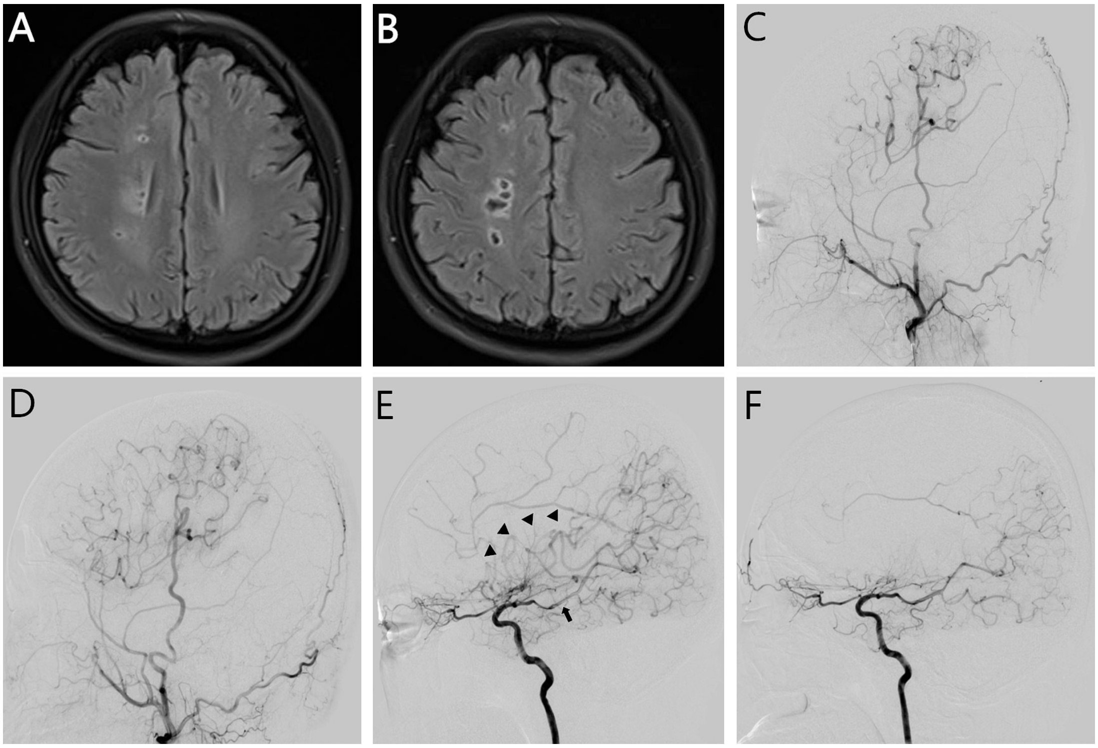

Figure S5 Preoperative and postoperative radiological findings of a 36-year-old woman. (A,B) Flare magnetic resonance imaging showing right frontal-parietal and periventricular infarction. (C,D) Postoperative angiography shows a right STA parietal branch bypass. Long-term angiography shows extensive collateral anastomosis between STA and cerebral cortex, regarded as Matsushima grade A. (E) Preoperative carotid angiography showed the formation of moyamoya vessels on the skull base (arrowheads), and anastomosis is formed between the posterior lateral choroidal artery (arrow) and pericallosal artery. (F) Long-term angiography showing the extensive disappearance of moyamoya vessels in the skull. STA, superficial temporal artery.

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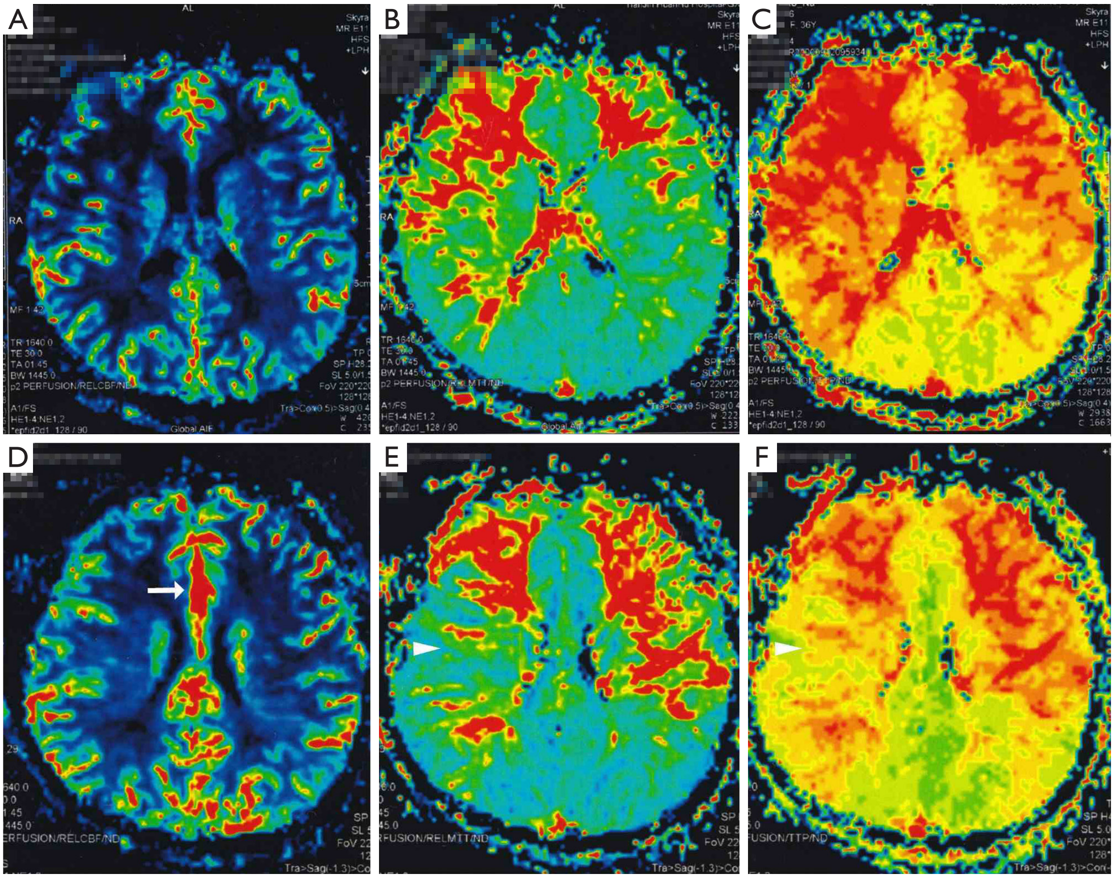

Figure S6 Preoperative, and long-term changes in MRP (A,D), TTP (B,E), and MTT (C,F) in a 36-year-old woman. CBF in the distribution of the anterior cerebral artery was increased (arrow), and TTP and MTT in the right frontal-parietal region were shortened (arrowhead). MRP, magnetic resonance perfusion; TTP, time to peak; MTT, mean transit time; CBF, cerebral blood flow.

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