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Bypass surgery for ischemic stroke caused by intracranial artery stenosis or occlusion

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KEYWORDS
revascularization, anastomosis, ischemic stroke, stenosis, occlusion

ABSTRACT
Surgical revascularization may be beneficial in patients with ischemic stroke caused by intracranial stenosis or occlusion who are ineligible for thrombolysis.

Objective: To evaluate the outcome of superficial temporal artery to middle cerebral artery (STA-MCA) bypass in ischemic stroke caused by intracranial artery stenosis or occlusion.

Methods: We retrospectively studied successive case series of 19 patients who underwent surgical treatment between 2013–2017 of STA-MCA bypass. Surgical procedure was performed for the patients with acute ischemic stroke who were ineligible for thrombolysis.

Results: Of the 19 patients enrolled, symptom aggravation occurred during medical treatment, the patients were ineligible for thrombolysis despite being within 8 hours of symptom onset. Bypass significantly improved National Institutes of Health Stroke Scale scores, mean patient age was 78.05 years (range, 39-78 y). However, male 11 (57.95%) out of nineteen patients were presented with left-sided lesions while female 8 (42%) had right-sided lesions with significant infarction growth by diffusion weighted imaging achieved, after surgical maneuver. No major complications occurred intraoperatively, in contrast to 2 (10.5%) minor manifestation were suffering minor complications probably they included the remote infarction (posterior cerebral artery territory). Pooled analysis with our patients showed a significant neurological improvement and a good outcome in 13 (68.4%) patients without hemorrhage or any other complication, 6 (31.6%) patients with unfavorable outcome (severe disability 2; vegetative state 4, none of them are died 0).

Conclusion: STA-MCA bypass may be beneficial to patients with acute stroke or stenosis in progress who are ineligible for medical therapy. Furthermore, it appears safe when the infarction is small. These findings indicate that STA-MCA bypass could be considered as a treatment option in selected patients with ischemic stroke caused by intracranial stenosis or occlusion.
1 Introduction

In developed countries the third mortality and disability cause is Ischemic stroke [1–4]. Majority of ischemic strokes are thromboembolic originally, due to an intracranial artery stenosis or occlusion cloting, blocking blood flow to the brain. Those patients who are suffering from ischemic stroke can be treated pharmacologically with intravenous tissue plasminogen activator (tPA) if patients present within 4.5 hours of symptom onset [5]. Labeling of subtypes of ischemic stroke has had significant studies, but characterizations are difficult to verbalize and their presentation for conclusion in an individual patient is frequently difficult. In the past, categorizations have been based on risk factor profiles primarily, clinical manifestation of the stroke, and findings on brain imaging studies (computed tomography (CT) or magnetic resonance imaging (MRI)) [6]. However, clinical and brain imaging overlap features are not specific for any particular subtype of ischemic stroke. Bamford et al. [7] newly reported the results and probability of recurrent stroke varied significantly by stroke subtype; enormous hemispheric infarcts, mostly ensuing from occlusion of the internal carotid artery or proximal middle cerebral artery, had the worst prognosis. Based on clinical features investigators classified the strokes which forecasted the site and size of the ischemic lesion, but potentially they didn’t consider etiology of the stroke. Other researchers have noticed that the etiology of stroke can effect prognosis. Sacco et al. [8] point that higher mortality was among patients with large-artery atherosclerotic lesions than among patients with lacunar stroke. Recurrent strokes are more probable among patients with cardioembolic stroke than patients among with stroke of other causes [9]. Mortality rate is higher after cardioembolic stroke during period of 1-month than that with strokes of other etiologies [10, 11]. The Stroke patients with large artery occlusions can be treated with a variety of endovascular techniques in addition to intravenous thrombolysis. Recently several options including intra-arterial thrombolytic, mechanical thrombolysis, and/or embolectomy with devices such as the Merci retrieval system or the Penumbra device are available [12, 13]. Therefore, the main management of ischemic stroke is endovascular or medical, rather than surgical. Ischemic stroke caused by thromboembolism due to atherosclerotic plaque in a symptomatic cervical internal carotid artery is surgically treated by carotid endarterectomy.

But there are some ischemic strokes due to vast chronic circumstances that gradually reduce cerebral blood flow in the lack of compensatory indemnity circulation. Bypass surgery, first bypass is done by Yasargil, in 1967, succeeded for an embolism of the middle cerebral artery by means of a superficial temporal artery to middle cerebral artery anastomosis (STA-MCA anastomosis) [14]. Thereafter it has been called extracranial to intracranial bypass (EC-IC bypass). Although bypass moderations have resolved the majority of the occlusion, therefore, we have brought alteration.

1) Direct Bypass (Direct anastomosis) in which donor artery and an intracranial recipient artery delivering blood flow to the brain (Fig. 1), it’s is further categorized into: EC-IC Bypass (None Graft interposition) which can describe Single bypass and Double bypass. IC-IC (Single bypass) is divided into three-parts, (a) Graft interposition (long graft), (b) Graft interposition (short graft), (c) No graft interposition (“in situ”) Bypass (Fig. 2).

2) Indirect Bypass (Combined procedure).

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2 Material and methods

We retrospectively studied successive case series of 19 patients who underwent surgical treatment between 2013–2017 of STA-MCA bypass. Surgical procedures were performed for the patients with acute ischemic stroke who were ineligible for thrombolysis. To evaluate the outcome of superficial temporal artery to middle cerebral artery (STA-MCA) bypass in acute stroke and stroke in progress, with cortical selective-targeted EC-IC bypasses is presented. All patients were operated on by the senior Doctor Prof. Lukui Chen in Zhongda Hospital Medical Center, affiliated with Southeast University, Nanjing China, over a period of 48-month. The characteristics of patients and treatments are detailed in Table 1.

Selected patients underwent preoperative computed tomography angiography (CTA) and/or digital subtraction angiography (DSA) with 3-D reconstructions to optimally define the anatomy. Control angiography (CTA or DSA) was performed in the first 12th hours after surgery and follow-up (CTA) was done at 3 months (except in case 5). Functional health of all patients was assessed preoperatively and at 3-month follow-up by modified Rankin Scale (mRS).

2.1 Surgical procedure and technique

The most common operative technique described in the literature is the STA-MCA anastomosis [16–21]. Variations of the EC-IC bypass procedure have also utilized the occipital, auricular, middle meningeal, common carotid, external carotid, and subclavian arteries as donor vessels and the anterior cerebral, posterior cerebral, posterior

Table 1 Demographic data of 19 patients underwent cerebral bypass.

| Characteristic                  | Value (%) | Characteristic                  | Value (%) |
|--------------------------------|-----------|--------------------------------|-----------|
| Age (Years)                    | 39–78     | M2                              | 3 (15.8)  |
| Sex                            |           | Procedures                      |           |
| Female                         | 8 (42)    | Single bypass                   | 17 (89.5) |
| Male                           | 11 (57.9) | Double bypasses                 | 2 (10.5)  |
| Left-sided lesions             | 11 (57.9) | Postoperative state             | 10 (52.6) |
| Right-sided lesions            | 8 (42)    | Improved                        |           |
| Preoperative symptoms          |           | Unchanged                       | 3 (31.6)  |
| Disturbance of consciousness   | 4 (21.1)  | Worsened                        | 3 (15.8)  |
| Motor weakness                 | 16 (84.2) | Preventing new infarction by surgery | 12 (63.2) |
| Aphasia                        | 5 (26.3)  | Yes                             |           |
| Cognitive disturbance          | 3 (15.8)  | No                              | 7 (36.8)  |
| Crescendo TIA                  | 3 (15.8)  | Surgical complication           |           |
| Affected arteries              |           | Major                           | 0         |
| Cervical ICA                   | 0         | Minor (remote infection)        | 2 (10.5)  |
| Intradural ICA                 | 4 (21.1)  | Outcome at discharge            |           |
| Proximal M1                    | 7 (36.8)  | Favorable (GR, MD)              | 13 (68.4) |
| Distal M1                      | 5 (26.3)  | Unfavorable (SD, VS, D)         | 6 (31.6)  |

TIA—transient ischemic attack, ICA—internal carotid artery, MCA—middle cerebral artery, GR—good recovery, MD—moderate disability, SD—severe disability, VS—vegetative state, D—dead.
inferior cerebellar, and superior cerebellar arteries as recipient vessels [16, 18, 22, 23]. The operative procedure used for the bypass is essentially unchanged since reported by Donaghy et al. [24]. Prior to intubation, an arterial line was inserted for general anesthesia constantly monitor blood pressure. Swan-Ganz flow-directed balloon-tipped catheter was placed percutaneously in neurological unstable patients, to monitor and maintain fluid balance within cardiovascular function closely during and after the operation. Usually the catheter was placed just before the operation in those patients whose heparin anticoagulation had been discontinued several hours prior to surgery. A Foley catheter was inserted to monitor urinary output and to allow the use of osmotic diuretics during the surgery. A lumbar catheter was inserted for intraoperative cerebrospinal fluid (CSF) drainage. It is critical that the CSF drainage should be functional because of the necessity for retraction and elevation of the temporal lobe in order to reach the tentorial incisura. The patients were placed supine with the right shoulder and hip elevated and the head horizontal, hyperextended, and the left side down. The right side was always used to avoid retraction of the temporal lobe on the dominant side. Both anterior and posterior branches of the STA were traced on the scalp with the use of a directional flow Doppler probe. The anterior branch was preferred for use in the anastomosis. It was traced from the area anterior to the pinna to the most distal portion visualized on the angiogram, usually for 8 to 10 cm or more. The scalp was shaved and prepared with povidone-iodine solution in the usual manner. A direct incision was made over the STA (Fig. 1), and approximately 10 cm of the vessel was dissected under the microscope, from its most distal to its most proximal location. All side branches were individually cauterized and transected. Anatomical continuity is maintained only at the proximal and distal ends of the vessel. The incision was then extended posteriorly from the pinna above the ear in a parieto-occipital direction so that the incision from anterior limb to posterior limb represents a V, with the apex of the V at the pinna (Fig. 2). The flap was reflected and retracted superiorly. The temporalis muscle was incised in a cross-bow fashion and

| FLOW-PRESERVATION |
|-------------------|
| EC-IC bypass      |
| IC-IC bypass      |
| No graft interposition | Graft interposition (long graft) | Graft interposition (short graft) | No graft interposition (“in situ” bypass) |
| Single-bypass     | Double-bypass    |

*Figure 2* Illustration of flow preservation bypasses. EC–IC indicates extracranial-intracranial; IC–IC indicates intracranial-to-intracranial [15].
the flaps were retracted laterally. A free bone flap was raised by placing a single burr hole on the anterior inferior temporal region just above the ear at the point through which the STA would enter (Fig. 3). With the electrical drill, a quadrangular free bone flap was elevated. The inferior portion of the flap was brought down to the base of the middle fossa by extending the craniectomy with a Leksell rongeur. After hemostasis was achieved, the dura was tacked to the bone to prevent intraoperative bleeding. The spinal drain was opened at this time, and the patient was given 40 mg of furosemide intravenously, followed 10 to 15 minutes later by a 50-gm bolus of intravenous mannitol. A dural incision was made at the base of the craniotomy and the dura was reflected superiorly (Fig. 4). The temporal lobe was elevated until the tentorial incisura is identified. Take care do not to compromise the vein of Labbé or posterior temporal veins as they enter the sigmoid sinus. Self-retaining retractors were placed. The edge of the tentorium were elevated, cauterized, and transected to provide more exposure. The microscope was used to utilized and the arachnoid over the brain occluded or ischemic area is picked up and opened, revealing the ICA. The operation involved the dissection of the superficial temporal artery from a small temporal scalp flap. Then a small craniectomy was placed over the middle cerebral artery territory. Preoperative rCBF measurements were used to localize the ischemic area for correct placement of the bone flap. After the dura was opened, a suitable cortical artery was identified with the use of the operating microscope. The arachnoid around the vessel was removed. A rubber dam was placed under the free segment of the artery to avoid any damage of the underlying cortex. After the application of two temporary vessel clips, the superficial temporal artery was anastomosed end-to-side to the temporarily occluded segment of the cortical artery (Fig. 5). Ten to 12 single sutures of 10/0 mono-filament nylon were required. To minimize thrombotic complications, all patients received an intravenous infusion of

Figure 3  Flow intensification strategies. Left, Direct (superficial temporal artery to middle cerebral artery “STA–MCA”) bypass. Right, Combined revascularization consisting of unilateral “STA–MCA” bypass plus encephalo-duro-myo-synangiosis and bifrontalencephaloduro- periosteal-synangiosis [15].
Dextran 40 intraoperatively and for several days post-operatively. In three patients, two branches of the superficial temporal artery were used as donor vessels. All patients, however, had protracted wound healing as a result of an insufficient blood supply of the temporal skin flap postoperatively. A major portion of the dura was closed and the bone flap was replaced. The skin and muscle were closed in a routine manner. One patient with occlusions of bilateral internal carotid arteries and ischemic cortical regions in both hemispheres had a bilateral anastomosis bypass. In the patients with recurrent TIA, the operation was performed during an asymptomatic interval. In three patients the operation was done as an emergency procedure, that is, within 4, 6, and 16 hours respectively following onset of acute cerebral ischemic event. In most cases, however, an interval of 1 to 12 months elapsed between the last ischemic event and surgery. Sometimes a saphenous vein, radial artery or synthetic graft was interposed between the donor and recipient vessels. Besides the variety of indications and operative techniques,
previous EC-IC bypass studies have entailed various preoperative and postoperative tests in the workup of patients for EC-IC bypass, some of which may not have included conventional arteriography. With such a diversity of indications and techniques as well as preoperative and postoperative studies, Samson and Boone commented that evaluation of the efficacy of EC-IC bypass was obscured and that the natural history of cerebrovascular disease and more conventional forms of medical and surgical therapies may need reexamination vis-a-vis cerebrovascular bypass procedures [25]. Besides the preliminary medical and neurological evaluations in the workup of patients with symptoms of cerebrovascular ischemia, conventional arteriography alone is incomplete and digital vascular imaging in place of conventional arteriography can be misleading. In spite of the diversity of preoperative studies available, we emphasize the importance of selective angiography and computed tomographic (CT) scanning with or without contrast infusion, in the preoperative assessment of patients with symptoms of cerebrovascular ischemia by presenting two unusual cases.

### 3 Results

Clinical and demographic data of 19 patients were summarized in Table 1. Mean patient age was 78.05 years (range, 39–78 years). However, male 11 (57.95%) out of nineteen patients were presented with left-sided-lesions while female 8 (42%) had right-sided-lesions. On physical examination, 4 (21.1%) patients had disturbance of consciousness, motor weakness was seen in 16 (84.2%) patients, 5 (26.3%) cases were aphasic, 3 (15.8) patients had symptoms of cognitive disturbance, only 3 (15.8%) patients were detected with crescendo TIA. There was no evidence of cervical ICA stenosis, 4 (21.1%) patients were registered with progressive intra-dural ICA occlusion respectively. 7 (36.8%) patients had proximal M1 blockage, compared with 5 (26.3%) patients with completely distal M1 occluded, and 3 (15.8%) patients diagnosed with M2 arterial stenosis. High number of patients 17 (90%) underwent single bypass surgery, while only 2 (10%) were operated by double bypass procedure Postoperatively neurological symptoms were improved in 10 (52.6%) patients and 6 (31.6%) cases were unchanged apparently, whereas, 3 (15.8%) patients had worsened neurological conditions. No infarction was observed in 12 (63.2%) patients but 7 (36.8%) were infarcted after surgical maneuver. No major complications occurred intraoperatively, in contrast to 2 (10.5%) minor manifestation.

Complications during periods of perioperative are presented in Table 1. Nomajor complication was reported in any case, 2 (10.5%) patients were suffering minor complications probably they included the remote infarction (posterior cerebral artery territory). 13 (68.4%) patients had favorable outcome (good recovery, moderate disability), while 6 (31.6%) with unfavorable outcome (severe disability 2; vegetative state 4, non of them are died 0).
The surgical effectiveness of endeavor is judged by its ability to favorably influence the natural history of a given disease. Thus, the merit of the cerebral bypass procedure in the treatment of cerebral ischemia must be determined by a comparison with the natural history of cerebrovascular disease. The most important findings of the present study are twofold. First, in patients with ICA occlusion, the flow territory of the EC-IC bypass is smaller compared with the flow territory of the ICA on the contralateral side. Second, cerebral perfusion of the brain tissue supplied by the EC-IC bypass is unchanged compared with tissue perfusion of the contralateral hemisphere and tissue perfusion of control participants.

Several surgical reperfusion methods have been used to treat patients with acute ischemic stroke, or stroke in progress for many decades, but outcomes range from encouraging to disappointing [26]. The most important reason for these mixed results is that patients could not be selected for surgical treatment by multimodal MR or CT, which is usually performed nowadays. Today, using advanced imaging techniques, we can understand the mechanisms of symptom development or fluctuation and select candidates likely to benefit from urgent reperfusion. Efforts to identify potentially salvageable brain tissues using advanced imaging techniques and to increase the proportion of patients with acute ischemic stroke that receive treatment are not limited to endovascular treatment, but are applicable to all types of reperfusion methods, including surgical revascularization. Therefore, we think that the patient selection using multimodal MRI for STA-MCA bypass was the most important factor to achieve the good outcome in our study. The first notable finding of our study and of the pooled analysis is the effect of STA-MCA bypass. Because STA-MCA bypass cannot improve perfusion status in the entire affected area to the previous status immediately after surgery, its main role is to maintain cerebral blood flow in the ischemic region above the level of the threshold of pump failure, which can prevent irreversible damage until sufficient collaterals have been established after major arterial occlusion, and sometimes restore the neurological status. Practically, CT perfusion imaging at 7 days postoperatively showed relatively large areas with MTT prolongation compared with contralateral sides, but tissues at risk (the region with a relative MTT of 145% of that of the contralateral side) were much reduced after STA-MCA bypass. Accordingly, in the present study, ENI was observed in patients within 3 days of bypass surgery, and all patients with ENI that benefited from STA-MCA bypass achieved a good functional outcome. Furthermore, no significant growth in infarction size was observed by follow-up DWI. In our pooled analysis, neurological status was found to be significantly improved by bypass and a good functional outcome was achieved by 83.3% of patients. These findings suggest that STA-MCA bypass may be beneficial to patients with acute stroke or stroke in progress. The second finding of note is the lack of a reperfusion-induced complication of STA-MCA bypass. In the late period beyond the standard time window, high-flow antegrade reperfusion may induce hemorrhage in brain tissue with EIC. Endovascular recanalization showed a high rate of hemorrhage, up to 33.3% in a report for delayed procedures [27]. Compared with blood flow furnished by endovascular recanalization (about 150 mL/min for M1), STA-MCA bypass provides less amount of blood flow (20.60 mL/min), and such a relatively small amount of flow augmentation seems to have less risk for reperfusion-induced hemorrhage. Following STA-MCA bypass in acute stroke,
there has been no reperfusion-induced complica-
tion in most previous reports [28, 29], although one
CT-based study reported asymptomatic brain edema and hemorrhage associated with
STA-MCA bypass in low-density lesions on
preoperative CT scan in 3 and 1 of 19 patients,
respectively [30]. We also encountered no surgical
complication or hemorrhage in the present study
and collective analysis, especially including
patients with ischemic stroke outside of the 6 to
8-hour time frame. Therefore, STA-MCA bypass
appears to be safe in carefully selected patients
with acute stroke or stroke in progress beyond
the standard time frame. The infarction volumes
for our 5 patients were small, and thus, their
natural courses may have been benign. However,
all patients showed a moderate to severe
neurological severity just before surgery and,
especially, no patients with mild severity in
the acute stage showed symptom aggravation
and infarction progression, despite maximum
medical therapy. Several authors concluded
that this stroke in progress is associated with a
poor outcome [31]. The European Progressing
Stroke Study Group reported that patients with
neurological deterioration showed a significantly
higher rate of poor outcome (77%) than patients
without neurological deterioration (30%) [32].
Additionally, one prospective study demonstrated
that for each 10 cm³ of infarction volume
growth, the odds ratio for achieving an excellent
outcome by mRS and the Barthel Index was
0.52 and 0.64, respectively [31]. These results
indicate that stroke progression worsens the
prognosis of patients with ischemic stroke.
Therefore, we believe that reperfusion treatment
was urgently needed to prevent more aggravation
and impact on recovery in patients enrolled
in our study. The present study has several
limitations. Its major limitations are its retro-
spective nature, and the lack of a control group.
According to the treatment protocol at our
institute, patients with acute stroke or stenosis
in progress are considered for revascularization
treatment. Few patients did not undergo any
type of reperfusion therapy at our institute and,
therefore, it was not possible to recruit controls.
In addition, we used MR perfusion for initial
evaluations, but during follow-up, CTA was
used to check revascularization status, and thus,
revascularization improvements observed after
surgery were not the result of direct quantitative
comparisons. Finally, this study is limited by the
small number of patients recruited, and for this
reason, the sample size limitation prevents our
drawing firm conclusions, thus, we propose that
a large prospective study be conducted to confirm
the effectiveness and safety of STA-MCA bypass
in acute ischemic stroke.

5 Conclusions

Because cerebral bypass surgery is one of the
best selective revascularization method used
in acute ischemic stroke caused by intracranial
artery stenosis or occlusion, it should be con-
sidered as the first treatment technique in cases
which require urgent revascularization. However,
our series of 19 patients and our pooled analysis
demonstrate that STA-MCA bypass may be
beneficial to patients with acute ischemic stroke
or occlusions in progress in whom medical
therapy failed. Additionally, the low flow pro-
vided by STA-MCA bypass appears safe in cases
with a small infarction. Accordingly, our findings
indicate that STA-MCA bypass could be con-
sidered a treatment option in selected patients
with acute ischemic stroke or stenosis in progress.

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**Conflict of interests**

The authors have no conflicts of interest to declare.

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