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EC-IC Bypass: "Learning Curve" Experiences of Initial 100 Bypasses in Bangladesh

Bypass EC-CI: Experiências de "curva de aprendizado" de desvios iniciais em Bangladesh

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Abstract

Objectives Extracranial to intracranial (EC-IC) bypass is an important part of the armamentarium of a neurosurgeon in managing different vascular and neoplastic pathologies. Here, we report our initial experiences of EC-IC bypasses as experiences in the 'learning curve', including preparation and training of the surgeon, getting cases, patient selection, imaging, operative skills and microtechniques, complications, follow-up, and outcome. Lessons learned from the 'learning curve experiences' can be very useful for young vascular neurosurgeons who are going to start EC-IC bypass or have already started to perform and find themselves in the learning curve.

Methods From July 2009 to September 2018, 100 EC-IC bypasses were performed. We looked back to these cases of EC-IC bypass as our initial or 'learning curve' experiences. The recorded data of patient management (EC-IC bypass patient) were reviewed retrogradely. Our preparation for EC-IC bypass was described briefly. Case selection, indications, preparation of the patient for operation, techniques and technical experiences, preoperative difficulties and challenges, postoperative follow-up, complications, patency status of the bypass, and ultimate results were reviewed and studied.

Result A total of 100 bypasses were performed in 83 patients, of which 43 were male and 40 were female. The age range was from 04 to 72 years old (average 32 years old). Eleven patients were lost to follow-up postoperatively after 3 months and they were not even available for telephone follow-up. The follow-up period ranged from 3 to 120 months (average of18.4 months). Eight bypasses were high flow bypasses, whereas the number of low flow STA-MCA bypasses was 92. Indication of bypass were (in 83 cases):**1.** Arterial stenosis/occlusion/dissection causing cerebral ischemia (middle cerebral artery [MCA] stenosis/occlusion-05, MCA dissection-04, internal carotid artery [ICA] occlusion-19); **2.** Intracranial aneurysm-30; **3.** Moya-Moya disease-21; and **4.** Direct carotid cavernous fistula

Keywords
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- ► learning curve
- ► experiences
- ► bangladesh
- ► STA-MCA bypass
- ► high flow bypass

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[CCF]-04. Common clinical presentation was hemiparesis & dysphasia in ischemic group with history of transient ischemic attack (H/O TIA) (including Moya Moya disease). Features of subarachnoid hemorrhage (SAH) were the presenting symptoms in intracranial aneurysm group. The average ischemic time, due to clamping of recipient artery, was 28 minutes (range: 20–60 minutes). There was no clamp-related infarction. Two anastomoses were found thrombosed intraoperatively.
One preoperatively ambulant patient deteriorated neurologically in the postoperative period. She developed hemiplegia but improved later. Here, the cause seemed to be hyperperfusion. Headache resolved in all cases. TIA and seizures were also gone postoperatively. Ophthalmoplegia recovered in all cases in which it was present, except in one CCF, in which abducent nerve palsy persisted. Complete unilateral total blindness developed in one patient postoperatively (due to ophthalmic artery occlusion), where high flow bypass with ICA occlusion were performed. Red eye and proptosis were cured in CCF cases. Motor and sensory dysphasia improved in all cases in which it was present, except for one case in which preoperative global aphasia converted to sensory aphasia in the postoperative period. Three patients died in the postoperative period. The rest of the patients improved postoperatively. All patients were ambulant with static neurostatus and without new stroke/TIA until the last follow-up. All bypasses were patent until the last follow-up.
Conclusion The initial experiences of 100 cases of EC-IC bypass revealed even in inexperienced hand mortality and morbidity in properly indicated cases were low and result were impressive according to the pathological group and aim of bypass. Lessons learned from these experiences can be very helpful for new and beginner bypass neurosurgeons

Introduction

The first vascular anastomosis in history was described by Eck in 1877 with his operation on dogs to make a side-to-side anastomosis between the hepatic vein and the inferior vena cava.[1–3] French surgeon Alexis Carrel published the first arterial end-to-end anastomosis in 1902[1,4] and received the Nobel Prize in 1912. Kredel[5] attempted encephalomyosynangiosis in humans in 1942, but it was later abandoned due to an increased prevalence of postoperative seizures. Then, in 1949, Beck et al.[6] published their revascularization technique of a carotidjugular fistula. Jacobson et al. reported the first human microneurosurgical procedure in 1962: an middle cerebral artery [MCA] endarterectomy.[1,2,7–9]

Pool et al.,[1,10,11] in 1961, first adventured into cerebral revascularization with a synthetic material using a plastic tube to make a superficial temporal artery (STA) to anterior cerebral artery bypass, but an angiogram showed that the tube was thrombosed, although the patient recovered and survived. Woringer et al.[12] did the first extracranial to intracranial (EC-IC) bypass of the common carotid artery (CCA) – intracranial (IC) internal carotid artery (ICA) using a saphenous vein (SV) graft in 1963, but the patient died, although the graft was patent on autopsy.[1,2]

The first successful EC-IC bypass was performed by Prof. Yaşargil in 1967 in a patient with occluded ICA and, since then, it has become an essential way for managing patients with hemodynamic cerebral ischemia, complex intracranial aneurysms or skull base neoplasms.[13–15] The cases with cerebral hemodynamic ischemia have an annual stroke rate of 25%, which increases by 2% per year.[13] They can have a fatal ischemic stroke. Moyamoya disease is also included in this category.[13,16]

Yaşargil also did STA-middle cerebral artery (MCA) bypass for moyamoya disease in 1972. In 1971, Lougheed made the first EC-IC bypass using an SV graft. Ausman performed an EC-IC bypass using a radial artery (RA) graft in 1978. In the 1970s, Sundt et al.[17] and others performed posterior circulation revascularization for the management of steno-occlusive disease, vertebrobasilar insufficiency, and unclippable complex aneurysms.[1]

In ischemic stroke, after the failure of an EC-IC bypass trial in 1985,[1,2] neurovascular surgeons were looking for cases in which an EC- IC bypass would help the patients in neurological recovery and prevent future ischemic stroke. Moreover, EC-IC bypass is also used for the treatment of moyamoya disease, complex aneurysm, arterial dissection, and complex skullbase tumor. Here, we report our initial experiences of the first 100 bypasses as experiences in 'learning curve' covering the preparation and training of the surgeon, getting cases, patient selection, imaging, operative skills and microtechniques, complications, follow-up, and outcome. Lessons learned from the 'learning curve experiences' can be very useful for young vascular neurosurgeons who are going to start EC-IC bypass or have already started it and are in the learning curve.

Methods

We started EC-IC bypass in 2009. Patients who underwent EC-IC bypass from July 2009 to September 2018 were included in the present study. In this time frame, we performed 100 EC-IC bypasses. We looked back to these cases of EC-IC bypass as our initial or ‘learning curve’ experiences. The recorded data of patient management (EC-IC bypass patients) were reviewed retrogradely. Our preparation for EC-IC bypass was described briefly. Case selection, indications, preparation of the patient for operation, techniques and technical experiences, preoperative difficulties and challenges, postoperative follow-up, complications, patency status of the bypass, and ultimate results were reviewed and studied.

After undergoing the bypass, all patients were followed-up regularly (clinically and radiologically).

Representative Cases

Case 1 (►Figure 1a & 1b)

A 27-year-old male young doctor presented with right sided hemiplegia, aphasia, and visual field defect. His hemiplegia improved from initial Medical Research Council [MRC] grade 0/5 to 3+/5 in the right lower limb and 2/5 in the right upper limb 1 day after admission. His perception and comprehension of speech were normal, but he had motor aphasia and right homonymous hemianopia. Computed tomography (CT) scan and magnetic resonance imaging (MRI) of the head showed left-sided patchy infarcts and ischemic zones in left parieto-temporo-occipital zones. Digital subtraction angiography (DSA) and CT angiography (CTA) of the brain showed left M1 stenosis with scarcity of left MCA vessel (►**Figure 1a** & **1b** [B, C and D). Perfusion weighted (PW) images showed perfusion mismatch.

On an urgent basis, the patient underwent left-sided STA-MCA bypass.

Operation

Under general anesthesia (GA), the patient was placed on the supine position with the head turned $> 60°$. At this point, we used digital palpation technique and a handheld Doppler probe to map out the course of both the frontal and parietal branches of the STA.

The incision was started at the level of the zygoma and extended up to the near midline behind the hairline. Both branches were procured up to the superior temporal line very carefully (to avoid thermal damage or avulsion injury). Papaverine solution and plain local anesthetic agent (2% lidocaine) was used to irrigate the STA for vasospasm prevention. A mini pterional craniotomy was performed very carefully (so as to not damage the procured STA). After durotomy, a small posterior Sylvian fissure split was done to find out a suitable M3 as a recipient vessel for the bypass. Among the frontal and parietal branches, the suitable and larger frontal branch was used to make a STA-MCA anastomosis. After the bypass (►**Figure 1B**[A]), patency was checked clinically and with microdoppler. The dura was loosely closed around the STA (not watertight). Along the temporal margin of the bone flap, a portion was removed so that the STA would not be kinked or compressed by the bone. Mini plates and screws were used to fix the bone flap. The rest of the wound was closed accordingly without drain.

Postoperative Course

The patient recovered well from anesthesia. In the postoperative days, the patient recovered quickly from hemiparesis and aphasia. By the end of the 7^{th} postoperative day (POD), the patient became ambulant, but his visual field remained as preoperatively. By the end of 4 weeks after the operation, he returned to his professional work and muscle power on right side of the body was improved (MRC grade 4+/5). A postoperative CT scan showed no hematoma or new infarct. The CTA showed a patent STA-MCA bypass on the left side.

Case 2 - High Flow Bypass (CCA-RA-MCA bypass) (►Figure 2a-2f)

A 55-year-old right-handed man presented with clinical features of recurrent subarachnoid hemorrhage (SAH), that is, sudden severe headache and vomiting. His Hunt and Hess grade was G-1. He was a smoker but nondiabetic and non-hypertensive. A CT scan showed SAH in the carotid, the basal and both Sylvian fissures. A computed tomography angiography of the brain showed a left-sided supraclinoidal large fusiform ICA aneurysm (►**Figure 2a**). He was counselled for urgent operation. We decided to do a left sided CCA-RA-MCA (M2) high flow bypass with occlusion of the left ICA at the neck. The Allen test was done bilaterally and it showed that the ulnar arterial flow was adequate for hand circulation in the absence of the radial artery.

Operation (►Figure 2c-2e)

Under general anesthesia with endotracheal intubation, the patient was placed in the supine position. His head was fixed with a 3-pin head holder with neck extension and head turning to the opposite (right) side (30°). The head end of the table was elevated (20°). Eyes, ears, pressure points, and nerve areas were protected. The left upper limb was placed on a side ‘limb rest’ with extended elbow, 30° abducted from the trunk in supine for radial artery procurement. After preparation, the front of the left forearm, the left side of the neck, and the left pterional areas were draped properly.

With a longitudinal incision, the radial artery was harvested from the brachial bifurcation at the elbow to the wrist (20 cm). The artery was distended with intraluminal injection of heparin and papaverine mixed with normal saline. Then, the artery was kept in heparin and papaverine mixed with normal saline. The forearm wound was closed with a drain.

A curved incision on the left side of the neck was made from the tip of the mastoid process and extended downwards and medially 2 cm posterior to the angle of the mandible to the midline. After cutting the platysma and investing deep fascia the sternocleidomastoid muscle was retracted laterally. With further dissection of the posterior belly of the digastric muscle, the hypoglossal nerve, the internal jugular

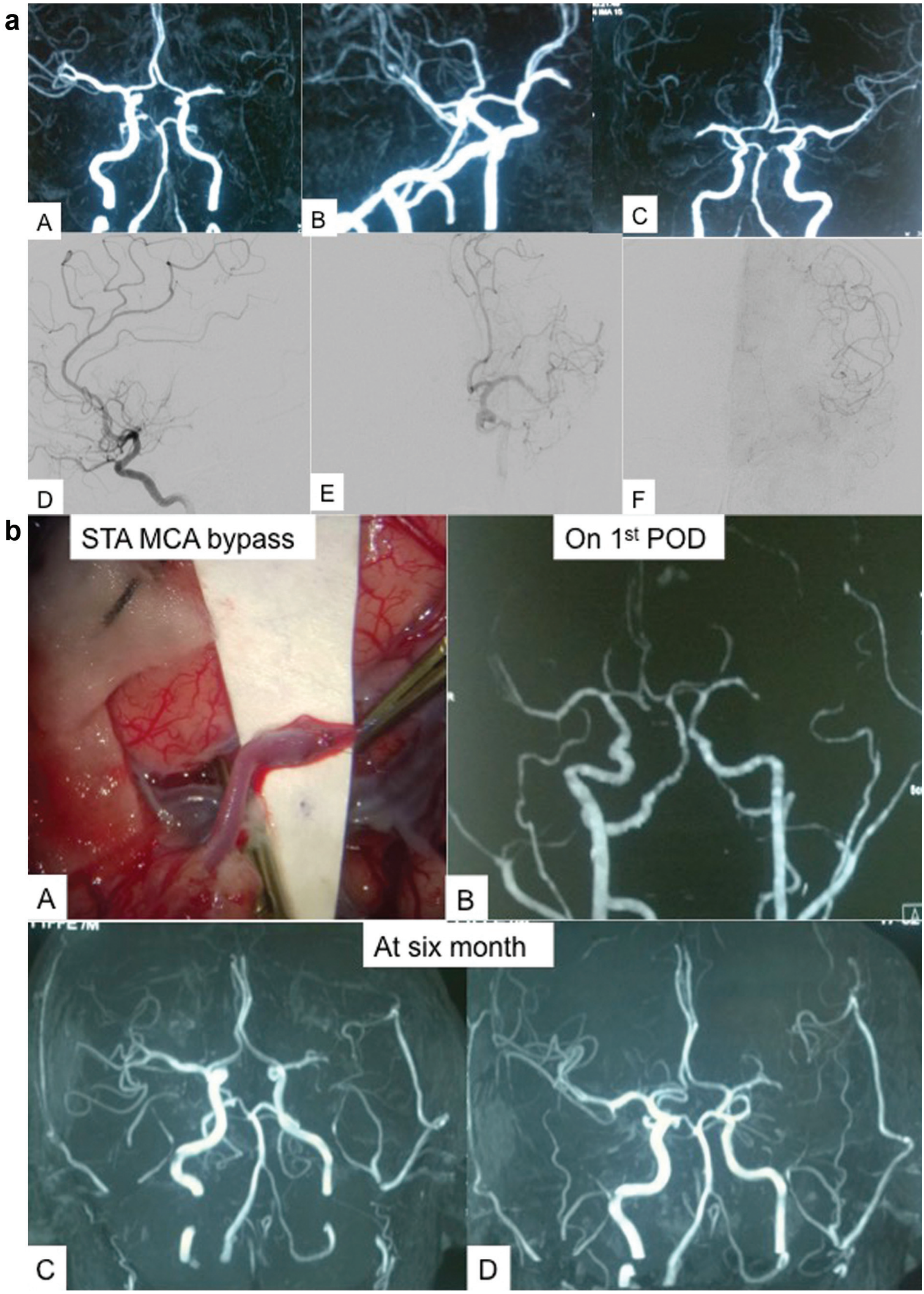

Fig. 1 (**a**): (**A, B & C**) CTA of the brain showing severe stenosis of the left MCA. (**E, F & G**) Cerebral DSA showing left MCA stenosis with delayed filling of the MCA territory. (**b**) (**A**) Preoperative picture of STA-MCA bypass. (**B**) CTA of the brain on the 1st POD showing left STA-MCA bypass. (**C & D**) CTA of the brain 6 months after the operation showing patent STA-MCA bypass.

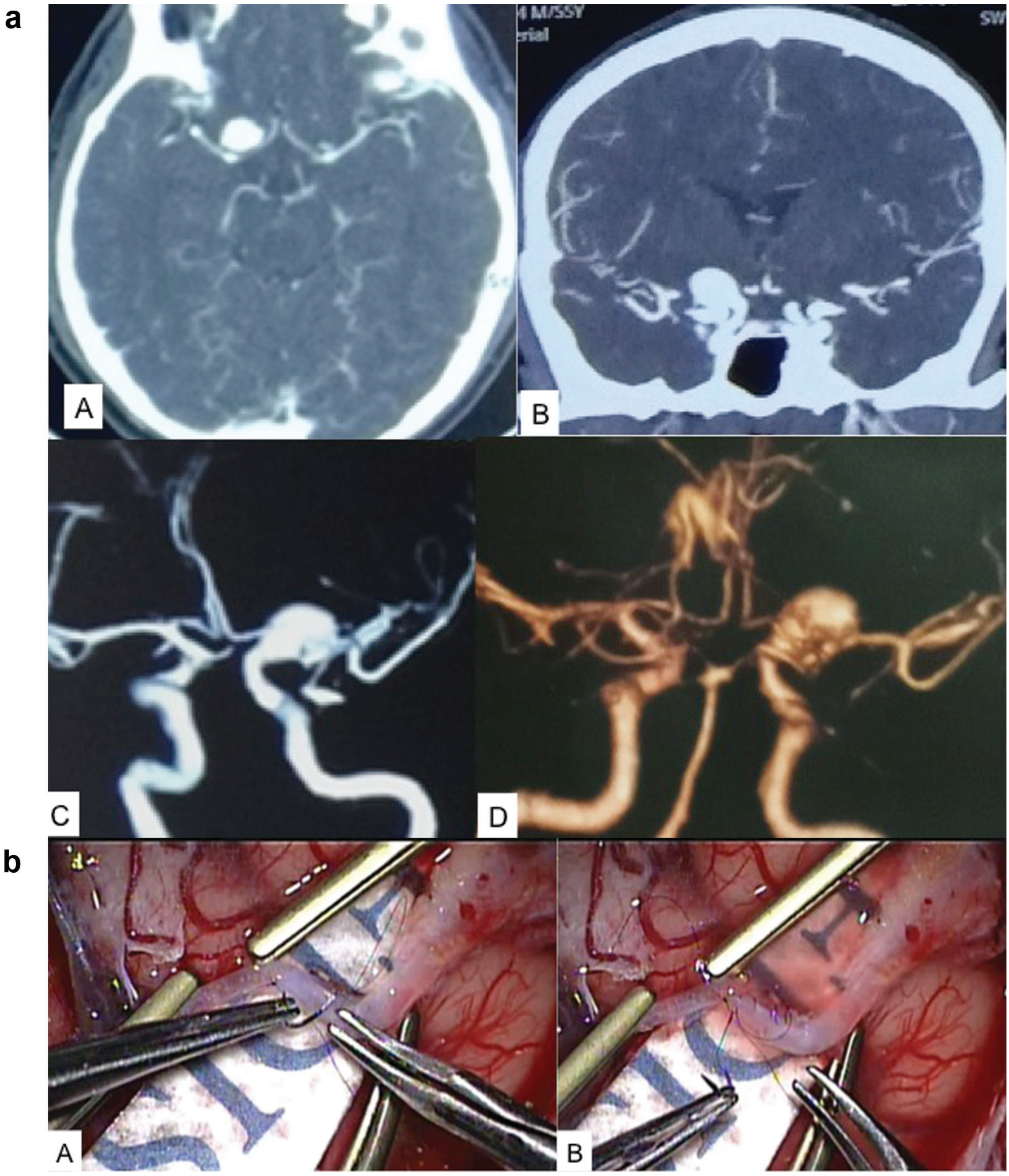

Fig. 2 (**a**)**:** (**A, B, C & D**) CTA of the brain showing a large fusiform aneurysm involving the left supraclinoidal ICA. (**b**)**:** (**A & B**) preoperative pictures of insurance STA-MCA bypass before performance of EC-IC high flow bypass. (**c**)**:** (**A & B**) preoperative pictures; sylvian dissection, identification and preparation of the temporal M2 as recipient artery for anastomosis with radial artery (RA) graft. RA, radial artery; M2 (MCA). (**d**): **A & B**-preoperative pictures of RA and M2 anastomosis. (**e**)**: A & B** preoperative pictures of RA and CCA anastomosis. (**f**)**:** Postoperative CTA of the brain and neck vessel on the 2nd POD showing CCA-RA-M2 high flow EC-IC bypass and nonvisualization of the left supraclinoidal ICA aneurysm.

vein, the common carotid, the internal carotid, and the external carotid artery with its branches were identified.

A left-sided precoronal posthairline curvilinear incision was made and the superficial temporal artery (STA) with its parietal branch was procured and prepared for STA-MCA protective bypass as donor artery. A temporally extended pterional craniotomy was performed. The temporal bone was removed down to the middle fossa floor. In the cervical wound, a blunt index finger dissection was made in between the digastric muscle and the hypoglossal nerve upward and superiorly to the styloid process, and then the finger dissection was continued upward, medially, and anteriorly to the lateral pterygoid plate. A curved medium-sized artery forceps was passed from the middle fossa floor to the fingertip, and, with finger guidance, the arterial tip was brought out into the cervical wound, and then a 26Fr thoracostomy tube

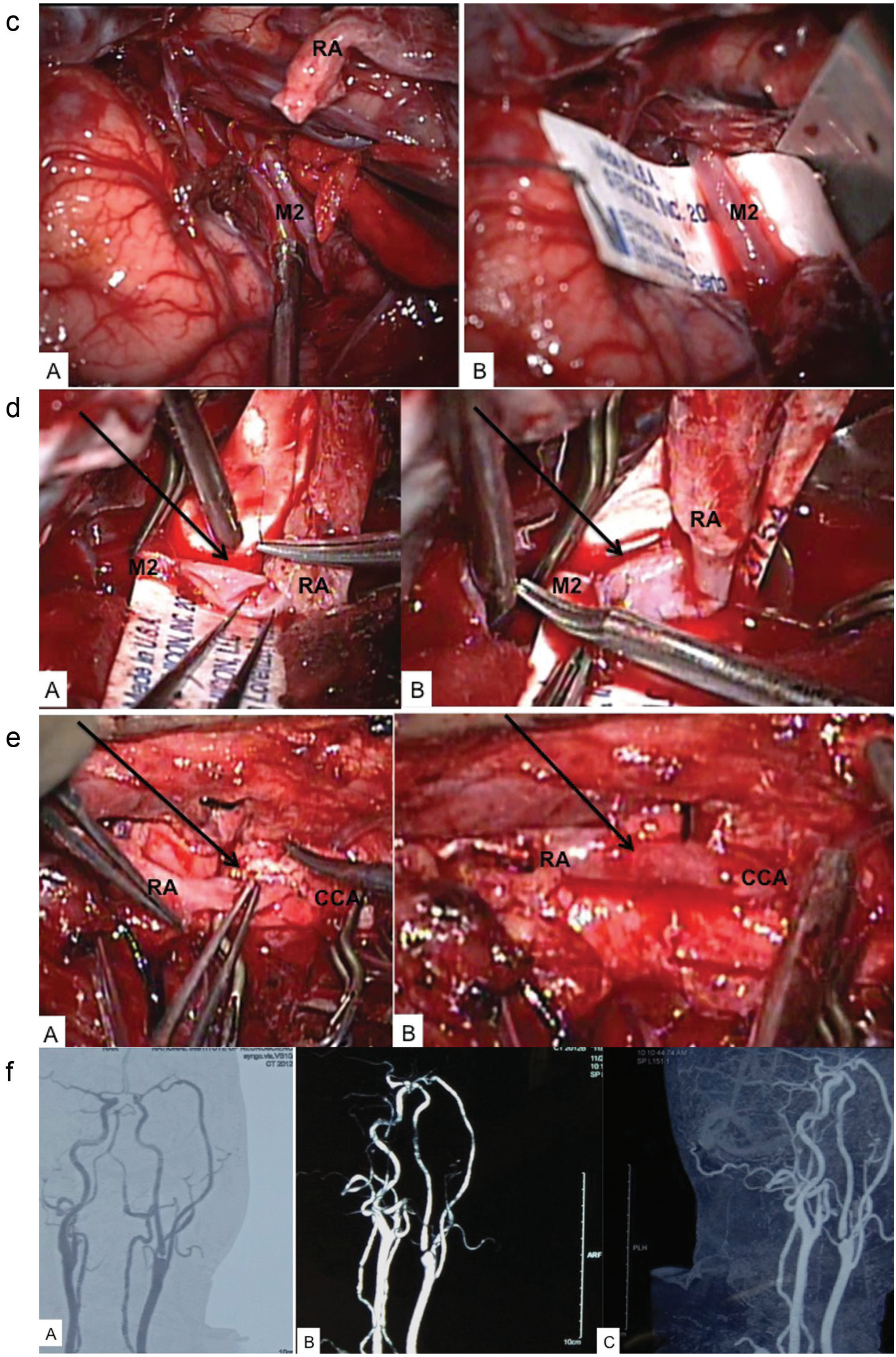

Fig. 2 (*Continued*)

was passed from the cervical wound to the middle fossa floor. The radial artery (RA) graft was passed from the middle fossa floor to the cervical wound through the tube. With stabilization of both ends of the RA graft, the thoracostomy tube was removed. The RA graft was made twist-free by injecting heparinized solution into the lumen.

After durotomy, a STA–MCA (Temporal M4) 'insurance bypass' was done with 10/0 nylon and checked for patency and function with micro Doppler (►**Figure 2b**). After Sylvian dissection, the temporal M2 was identified and prepared for bypass (►**Figure 2c**). The cranial end of the RA graft was also prepared for bypass, and the RA graft and temporal M2 bypass was made (►**Figure 2d**) after systemic heparinization with 3,000 units of heparin. The patency of anastomosis was checked by retrograde flow of blood through the caudal end of the RA graft in the cervical wound.

With the control of the common carotid artery (CCA), an anastomosis was made between the caudal end of the RA graft and the CCA (►**Figure 2e**). The patency and flow through the anastomoses and RA graft were checked with micro Doppler. The left ICA was identified as well as dissected to ligate it at its origin with 1-0 silk. The cervical wound and the craniotomy wound were closed with drains.

Postoperative Course

Postoperatively, the patient was on tab. Aspirin (75 mg daily). A CT scan on the 1st POD showed no infarct or any gross hematoma. A CT angiogram on the 2nd POD showed left external carotid artery (ECA)-radial artery graft (RAG)-M2 bypass with regression of the ICA fusiform aneurysm, but the ICA was visualized completely up to the ligation point at the neck. The patient made an uneventful recovery and was discharged on the 8th POD. Thirteen months after the operation, he returned with clinical features of SAH. A CTA showed a left ICA bifurcation aneurysm that had ruptured. But the bypass was patent and the ICA was again visualized up to its ligation at neck (►**Figure2f**). We decided to reoperate the patient, but he did not agree with any kind of further intervention. After the last SAH, he is under regular follow-up for the last 7 months, without further bleeding.

Results

Dreaming Through: Brain Thought to Hand Skill (►Figure3)

When the main author was a 3rd year MBBS student, he became interested in neurosurgery after watching a video of the removal of an intracranial meningioma in the college library (the operation was done by late professor Rashid Uddin Ahmed). At that time, he was firmly motivated to be a neurosurgeon. During his intern period, when he was placed in the neurosurgery department, he presented on surgical management of intracranial hemorrhages on a clinical meeting and, at that time, he first knew about the EC-IC bypass for

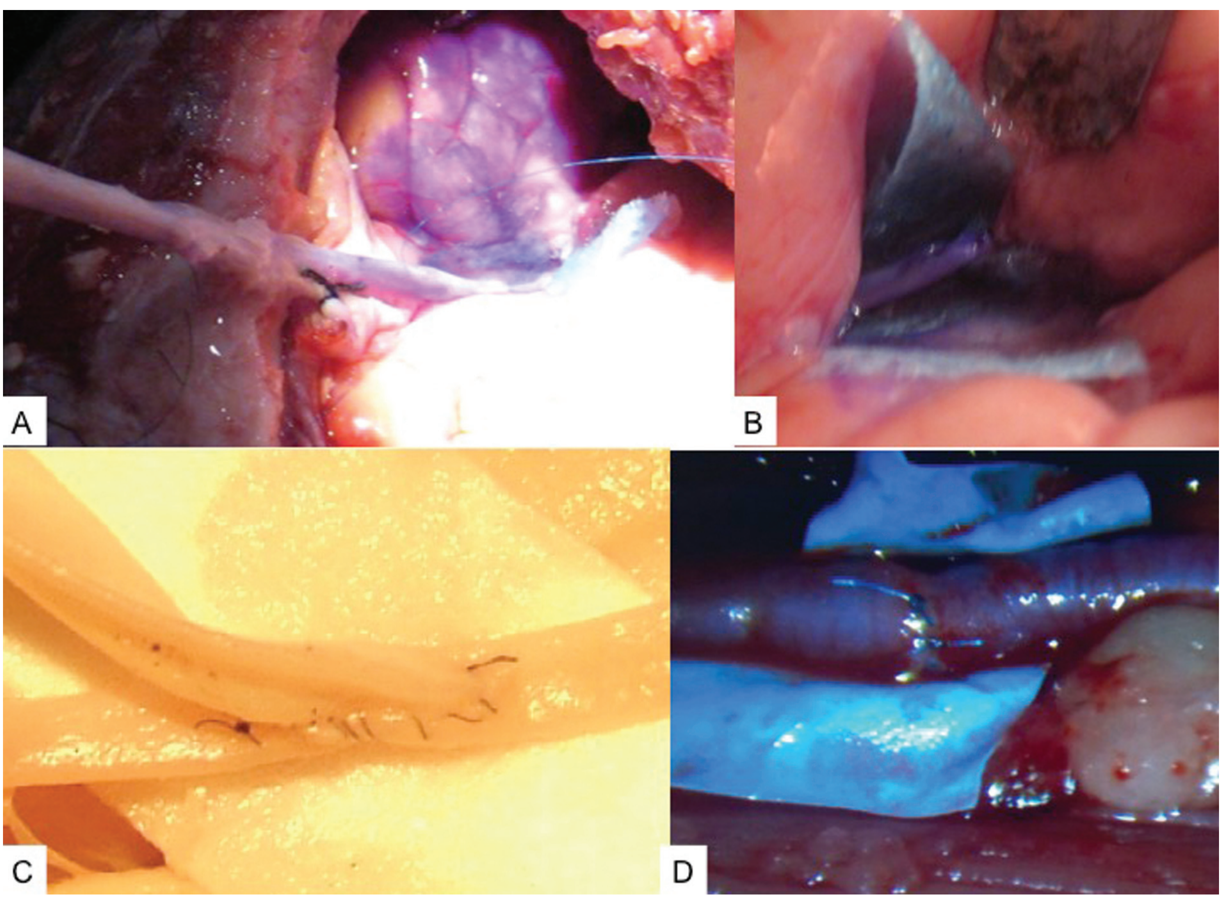

Fig. 3 Practices of microvascular anastomosis before clinical application. (A & B) Radial artery graft anastomosis with M2 in Sylvian fissure of fresh cadaveric brain. (C) Microvascular anastomosis practice on formalinized dry brain. (D) Microvascular anastomosis practice on live hen.

the management of various intracranial vascular lesions. Brain bypass!!! Is it really possible, who used to do it? Is there anyone in Bangladesh who practices brain bypass? The answer was no.

In 2001, in a neurosurgical meeting, a Japanese neurosurgeon showed a very brief video on petrous to supraclinoidal ICA bypass. In the World Federation of Neurosurgical Societies (WFNS) meeting in 2007 in Nagoya, Japan, a few lectures on vascular surgery really inspired us on focusing on EC-IC bypass. We started to practice anastomosis on fresh cadaveric brains [radial artery-MCA (M2)] in the forensic department, which was very poorly equipped.

During a fellowship (2009) in the department of neurosurgery, KEM Hospital, Mumbai, India, under professor Atul Goel, the main author took the opportunity to practice microvascular anastomosis on formalinized brain surfaces in his microneurosurgery lab under operating microscope. There, the main author practiced more than 50 times. Some Italian fellow (who was also visiting at the same time) told the main author to practice it on live rats or Guinea pigs. But that was not possible there. Then, we practiced on live hen and rats several times in the microvascular lab of the department of plastic surgery, Dhaka Medical College and Hospital, Dhaka (►**Figure 3**).

Getting the Clinical Cases

After achieving adequate motor skills and background knowledge, we were looking for cases that were appropriately indicated for EC-IC bypass, but we were not getting any cases. Finally, we got a case of M1 giant aneurysm. We decided to do an EC-IC bypass in this case, but when the relatives of the patient heard that it would be our first case and no one had performed this operation before in this country, they left the hospital to go outside the country. In this way, we failed to operate on our first case for another 4 or 5 cases for which bypass was indicated. Ultimately, we could convince our first case to undergo EC-IC bypass, a 14-year-old girl with M2-M3 dissection.

It took one and a half year more to get the second case. After starting bypass, we did only four cases in first 3 years and 7 cases in the next 2 years. Then, we got cases more frequently.

Preoperative Assessment of the Patients

In ischemia

Patients in this case series with transient ischemic attack (TIA)/stroke/recurrent stroke were evaluated clinically for history of TIA or recurrent/hemodynamic TIA (in rest or during work) or progressive hemiparesis/aphasia/visual disturbances or sudden hemiplegia/hemiparesis/aphasia with subsequent significant recovery (in days to in a week). Permanent hemiplegia cases were not considered for EC-IC bypass. Then the cases were evaluated radiologically for ischemia with or without infarcts and possible revascularization by EC-IC bypass. Computed tomography scan of the brain was done to exclude hemorrhage and other pathologies, such as tumors. Magnetic resonance imaging of the brain was done in ischemic protocol (all images including diffusion weighted [DW], afferent diffusion coefficient [ADC], PW, DTI and magnetic resonance angiography [MRA] and MRV, including neck vessels) to see cerebral ischemic zones (DWand PW mismatch), the corticospinal tract and other major tracts and intracranial or extracranial arterial stenosis. To see the arterial pathology, dynamic CTA was also done in all cases. DSA was done in 36 cases. When clinical features, cerebral ischemia on MRI and arterial stenosis/occlusion on angiogram were concordant with each other, only then cerebral revascularization by EC-IC bypass was done.

In other Indications

1. Moyamoya disease
2. As replacement: Intracranial giant fusiform ICA aneurysm or caroticocavernous fistula (CCF) where ICA ligation at neck and EC-IC bypass was planned.
3. Protective bypass in skullbase tumor where ICA was encased by tumor and the chance of injury or occlusion of ICA or ICA had to be removed with the tumor.
4. Protective bypass in giant MCA or ICA aneurysm where the trunk of the MCA or of the ICA occlusion/compromise was a possibility.
5. Protective bypass in aneurysm with proximal stenosis.
6. Insurance bypass during high flow EC-EC bypass.
7. Treatment of CCF.
8. Arterial dissection.

Preoperative Patient Preparation

Counselling and other preoperative preparations were as usual except in cerebral ischemic patients, in whom preoperative antiplatelet drugs were continued. In these cases, platelet concentrates were made available preoperatively, but were not required in any case.

Preoperative Assessment of Donor Artery

Preoperatively, the STA was assessed with digital palpation and Doppler in all cases for its presence and rough estimation of caliber and flow. Preoperatively, the STA was also assessed with angiogram (external carotid angiogram: DSA, CTA and MRA).

The Allen test was performed in cases where the RA was planned to procure as conduit for high flow EC-IC bypass.

Procurement of Donor Artery; STA/RA

In initial cases, we did Donor arterty procurement without microscope, but later we found that it is more comfortable with a microscope. Now, we routinely use a microscope in the procurement of the donor vessel. We procure the STA and its frontal and parietal branches up to the superior temporal line (length between 7 and 9 cm) (►**Figure 4**). Initially, we used 2% plain lignocaine instillation on the STA to avoid vasospasm, but in the later part of our experiences, we used papaverine solution along with lignocaine. After application of a temporary clip on the STA, we routinely irrigated its lumen with heparin solution several times.

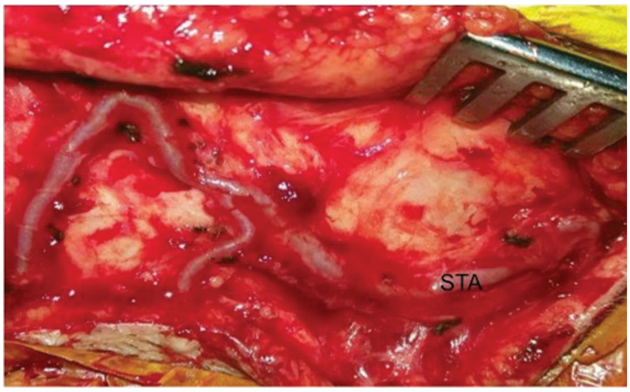

Fig. 4 Preoperative picture of procurement of the right STA and its branches.

In two cases STA length was short up to suitable recipient artery on temporal surface due to less available length of STA and also due to falling of brain in deep as a result of cerebro spinal fluid (CSF) drainage. Extra dissection at the root of the zygoma, flushing of the temporal bone and assistant ‘holding of donor artery’ near the recipient artery helped to make anastomosis with some difficulty.

We procured both branches of the STA and the relatively larger branch was used as donor artery where the other branch was ligated. Where needed, both branches were used as donors in double barrel bypass. In moyamoya disease, we used the frontal branch of the STA for direct STA-MCA bypass, where the parietal branch was used for indirect revascularization (as in EDAS) and the distal end was kept in continuity with the scalp.

Radial artery (RA) Procurement (in High Flow Bypass)

In all cases of high flow bypasses, the left RA was procured after performing the Allen test with a radially placed longitudinal incision from wrist to elbow (20 to 22 cm). We used papaverine solution along with lignocaine solution on the artery during procurement. After procurement, the RA graft was distended with heparin and papaverine solution and then it was suspended in heparin and papaverine mixed solution.

Craniotomy

In most of the cases pterional craniotomy was used for EC-IC bypass. In two cases of moyamoya disease, a suitable recipient artery was found near the bony margin and was prepared for anastomosis, but there were a lot of difficulties (for example, in instrumental movements during stitching) faced by the surgeons due to the bony margin. In the later part of our experiences, when such situations occurred, we cut more bone so that the bony margin did not interfere during instrumental movements

In high flow bypasses, pterional craniotomy was extended down until the root of the pterygoid by removing bone with a rongeur or a drill, so that the RA graft could be brought to the middle fossa through the infratemporal fossa from the cervical wound.

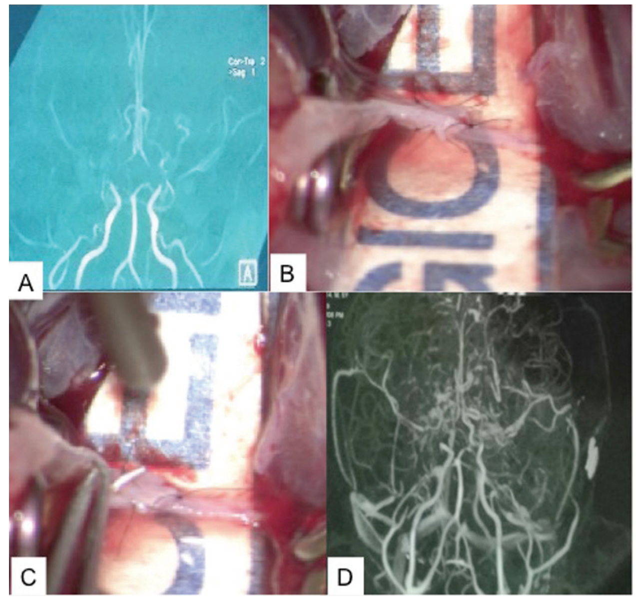

Fig. 5 (A) preoperative MRA of the brain showing bilateral Moyamoya disease. (B & C) Preoperative picture of direct STA-MCA bypass. (D) Postoperative CTA on the 1st POD showing patent STA-MCA anastomosis with increased vascularity.

Recipient Selection

In most of the STA-MCA bypasses, the temporal M4 or M3 were used as recipient arteries, which were easy to find and easy to prepare. Finding a suitable recipient artery in moyamoya disease, especially in children, was very challenging. In some cases, deep Sylvian dissection was needed to get a suitable artery. In children, the recipient artery was very thin and fragile, which made anastomosis more difficult. With patience and skill, anastomosis was successfully done in all cases (even in a 4-year-old boy) (►**Figure 5**). In all cases, we had to make the anastomosis with 10/0 nylon with cutting body needle, since there was no alternative suture. The unavailability of appropriate/alternative suture material made anastomosis more complex and difficult.

In high flow bypasses, we did insurance bypass by STA-MCA bypass at first. Then, the temporal M2 was dissected out for quite a distance up to its cortical branches with deep Sylvian dissection. Then deep to the artery triangular background paper (prepared from surgice a package covering) was passed. Both end of background paper was tied with suture to bring the M2 superficially; so that anastomosis became easier. Spongostan was put deep to the background to prevent blood collection in Sylvian fissure from anastomotic leak after release of temporary clips.

The M3/M4 branches of the upper trunk of the MCA were used in 9 cases of double barrel bypasses.

Why the temporal trunk of the MCA and its branches were preferable than the frontoparietal trunk and its branches as recipient artery?

1. The upper trunk supplies more eloquent and important areas (Broca area, primary motor, and primary sensory areas) than the temporal trunk (primary auditory areas

and lower part of the Wernicke area on the left side only, which has overlapping supply from the upper trunk).
2. Occlusion of the upper M2 has more chances of infarction compared with the lower trunk.
3. Infarction of lower trunk areas produce less severe deficits than upper trunk areas.
4. In some cases, the upper trunk supplies the corona radiata.
5. Use of the lower trunk and its branches as recipient arteries is technically easier.

Ischemic Time

From the beginning, we were afraid of infarction of the brain during performance of anastomosis in clinical cases. When we talked to experts (including Prof. Atul Goel) regarding ischemic time, all of them said ischemic time is not a major issue in bypass. But it was our major concern even when we were practicing anastomosis on hen in < 20 minutes.

Realization regarding Ischemic Time

In the first 100 clinical bypasses, we faced no infarction related to temporary occlusion of brain arteries. In the earlier cases, we did not take any protecting measures for the brain parenchyma against ischemia or any talk with anesthesiologist regarding ischemic time. Initially, we took 35 minutes to 40 minutes in STA-M4 anastomosis and 35 to 60 minutes in STA-M3 anastomosis, but, surprisingly, we found no infarct in temporarily occluded arterial territory. In one case, we found infarct that was not related to temporary clamping [►**Figure 6**]. Now, we used to talk regularly with anesthesiologist to keep BP at upper normal level and high dose inj. propofol in high dose. Now, we require 20 to 30 minutes to performing STA-M4 or STA-M3 bypass.

In the later part of our learning curve, we used to take heel and toe suture bites on Donor arteriotomy before applying cross clamps on the recipient artery. This practice decreases ischemic time to some extent.

Preoperative Use of Systemic Heparin

During high flow bypass inj. Heparin 3000 U i.v was used a single dose just before putting a cross clamp 9 on M2. In STA-MCA bypass, no systemic heparin was used.

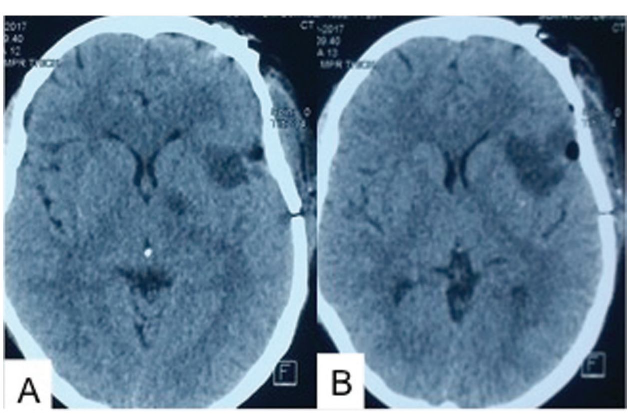

Fig. 6 (A & B) Postoperative CT scan on the 1st POD showing a fronto-insulo-caudate infarct that was not related to cross clamping of the temporal M3-M4 junction.

Hematoma in Sylvian Fissure

In the initial 3 to 4 cases in which STA-M3 bypass was performed, we found postoperatively hematoma in the sylvian fissure, which was due to initial leaking through anastomotic sites after removal of temporary clips. Later, to prevent this hematoma, we routinely place Spongostan pieces deep to the anastomotic site so that leaking blood should not spread into deep Sylvian spaces.

Common Leaking Sites (►Figure 7a-7c)

Leaking is near the heel or toe stitches. To prevent this, we use 'right angle needle pricking direction on recipient' to the needle pricking direction on donor in first stitch near the toe or heel stitch. Anastomotic leaking after removal of temporary clips usually stops spontaneously within 5 minutes; if not, it should stop with round Surgicel packing within the next 5 to 10 minutes. Even with Surgicel, if leaking persists, a temporary clip should be applied on the donor artery for 3 to 5 minutes. If temporary clipping of the donor artery fails to stop leaking, an additional microanastomotic suture will be needed to stop leaking.

In these first 100 EC-IC bypasses, only 3 cases needed additional stiching after removal of the temporary clips and their location was near to toe (anchoring) stich.

Patency Test after Anastomosis

After cessation of leaking through the anastomosis, the anastomotic patency and functionality were checked by inspection, palpation, test occlusion of the donor artery by microforceps or temporary clip and by micro-doppler. We found that the anastomosis was functioning in all cases after completion, except in two cases in which the pathology was giant supraclinoidal ICA aneurysm, and the anastomoses were found occluded after completion of clip reconstruction of the aneurysm. Then, we opened the donor artery just proximal to the anastomotic line with a small arteriotomy and found thrombus at the anastomotic site. Then, we removed it and irrigated with heparinized solution along with systemic heparinization. Blood flow was re-established through the anastomosis. In one case in which the ICA lumen was compromised by aneurysm clips, the total MCA territory was infarcted due to rethrombosis of the STA-MCA bypass (►**Figure 8**). When we reviewed the operating videos, in this case we found that there was overstaining of the endothelial surface of the donor artery at the anastomotic end with 'gentian violet', and we think this might be the cause of thrombosis. Therefore, in subsequent cases, the anastomotic margins of the donor artery were stained carefully after apposing margins, so that the stain should not enter into the luminal surface, and staining of the recipient artery was done before arteriotomy. In another case, we did not find any definitive cause of thrombotic occlusion of the anastomotic site on reviewing the operating video.

In high flow bypasses, we did not face any preoperative or postoperative graft spasm or occlusion.

Dural Closure

In all cases, watertight dural closure was not performed (actually, it was not possible). The wound was closed with

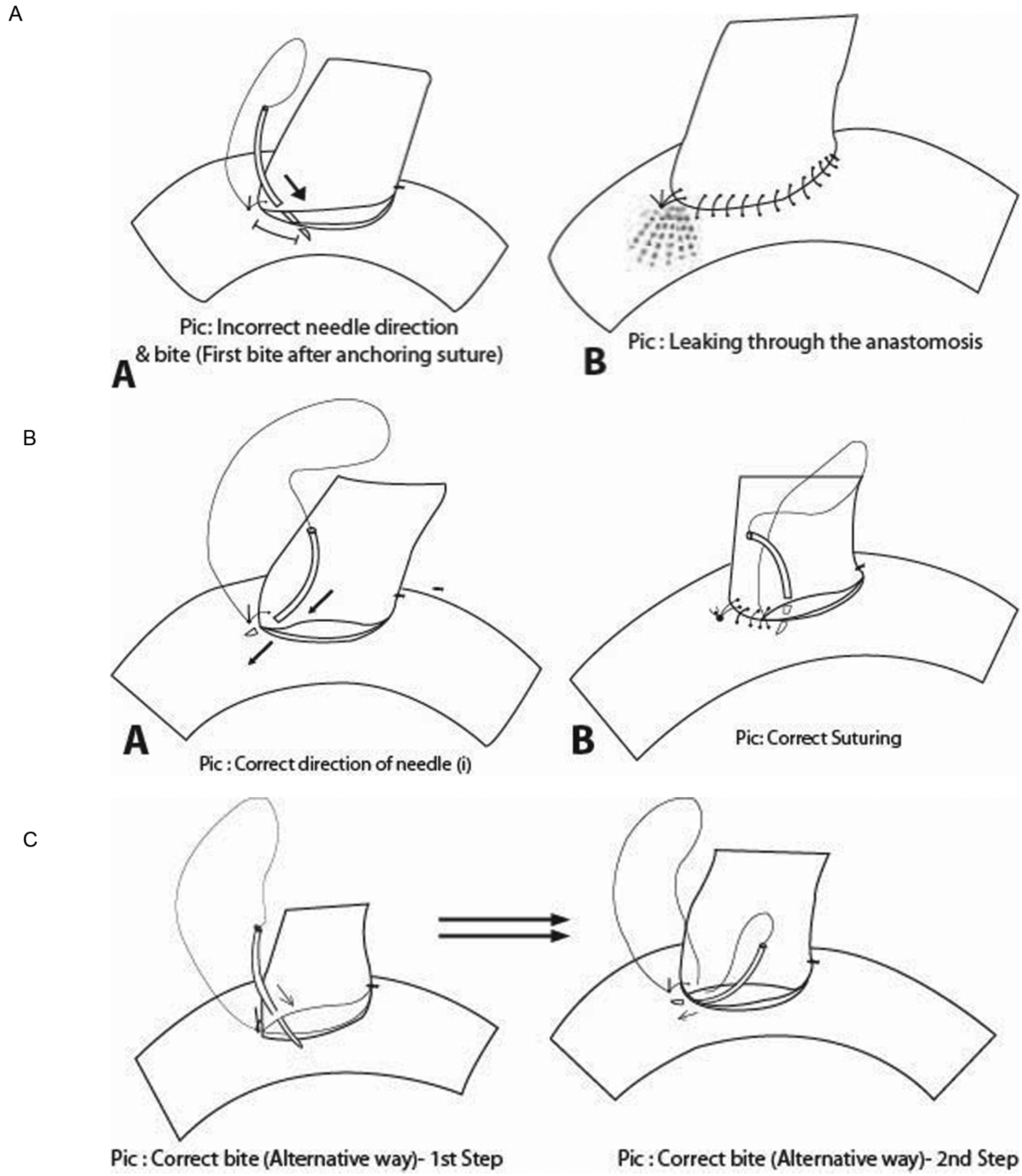

Fig. 7 (**A**) Schematic drawing showing “incorrect” techniques of 1st bites, needle direction, and suturing after the anchoring suture that results in anastomotic leak after removal of cross clamps. (B) anastomotic leak through the anastomosis (at the 1st suture site) after removal of cross clamps. (**B**) Schematic drawing showing “correct” techniques of 1st bites, needle direction, and suturing after the anchoring suture that prevents anastomotic leak after removal of cross clamps. (**C**) Schematic drawing showing alternative two-step correct techniques of the 1st bites, needle direction, and suturing after the anchoring suture that also prevents anastomotic leak after removal of cross clamps.

drain at the upper end of the wound. In most of the cases, the drain was removed on the 3rd or 4th POD if drain collection was minimum. In only 9 cases in which CSF was coming through the drain after the 4th POD, we continued the drain up to the 8th day and then removed the drain with stitching of the drain site. In four cases, there was subcutaneous collection of CSF that was resolved within 3 weeks in 3 cases; in 1 case, repeated tapping failed to stop collection of CSF and the patient needed readmission followed by lumbar CSF drainage to stop CSF collection at the end of 8 weeks postoperatively.

Patency of Anastomosis on Follow-up (►Figure1b,2f,5 and 9f)

Digital palpation of the STA, doppler checking, CT scan, and CTA of the brain including neck vessels were performed in all

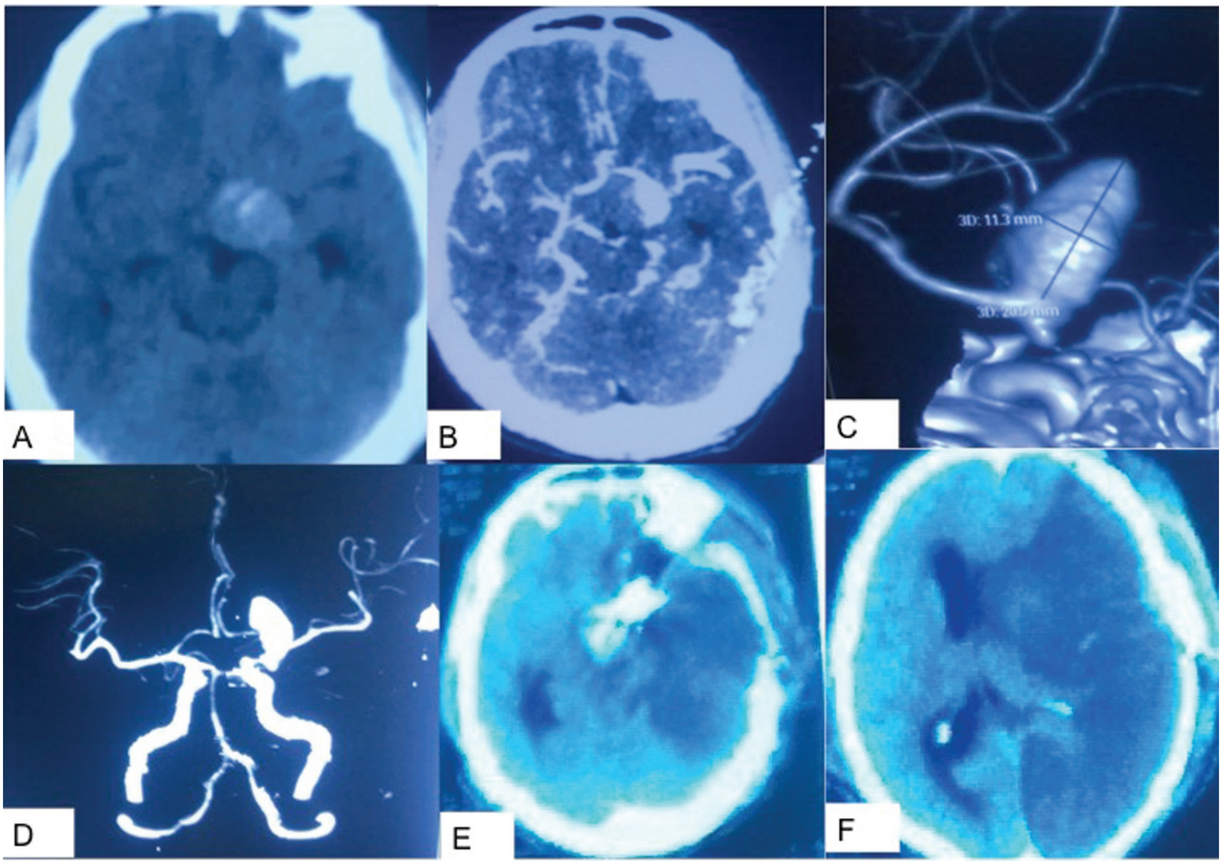

Fig. 8 (**A**) Preoperative CT scan showing suspected giant left ICA aneurysm. (**B, C and D**) CTA of the brain showing a giant partially thrombosed left ICA aneurysm. (**E and F**) Postoperative CT scan on the 1st POD showing massive left MCA infarct (clip reconstruction of the aneurysm was done with protective STA-MCA bypass, but the bypass was thrombosed preoperatively and it was rescued).

cases on the 1st POD to check anastomotic patency. Computed tomography scan also detects hematomas and infarcts. In one case, infarcts in the caudate nucleus head and in the anterior insula were found, which were not due to cross clamping. Sylvian fissure hematoma was found in two cases on CT scan. In two cases, there were no flows through the STA.

Subsequent follow-up was made by digital palpation and doppler routinely. Computed tomography angiography/ magnetic research angiography [MRA] were performed after 3 months, 9 months, and then at 12-month intervals. No DSA was done in the postoperative follow-up.

At the end of 12 months (69 cases were available for follow-up), all anastomoses were functioning on digital palpation and doppler examination. But CTA/MRA failed to show the anastomosis in 11 cases. All high flow anastomosis were patent on CTA/MRA at the end of 12 months after the operation.

A total of 100 bypasses were done in 83 patients, of which 43 were male and 40 were female. The age range was from 04 to 72 years old (average 32 years old). Eleven patients were lost to follow-up postoperatively after 3 months and they were not even available for telephone follow-up. The follow-up period was from 03 to 120 months (average 18.4 months).

Total number of EC-IC bypasses:100

- High flow bypasses: 08
- Ischemia/infarct (both with ICA occlusion): 02
- Giant ICA aneurysm

  □ Cavernous ICA: 02
  □ Supraclinoidal ICA: 04
- Low flow STA-MCA bypass:
- Single barrel:

  □ Replacement:
- Ischemia/infarct:17
- MCA dissection: 04
- CCF-04:

  ■ Protective/Insurance:

- With high flow bypass: 08
- With aneurysm:

♦ With proximal stenosis: 08
♦ Protective: 16

- Skullbase tumor: 05
- Moya moya: 21
- Double barrel: 08
- MCA stenosis: 05
- Moya moya: 03
- Double barrel (+A3-A3 bypass) [Figure 9a-9f]: 01

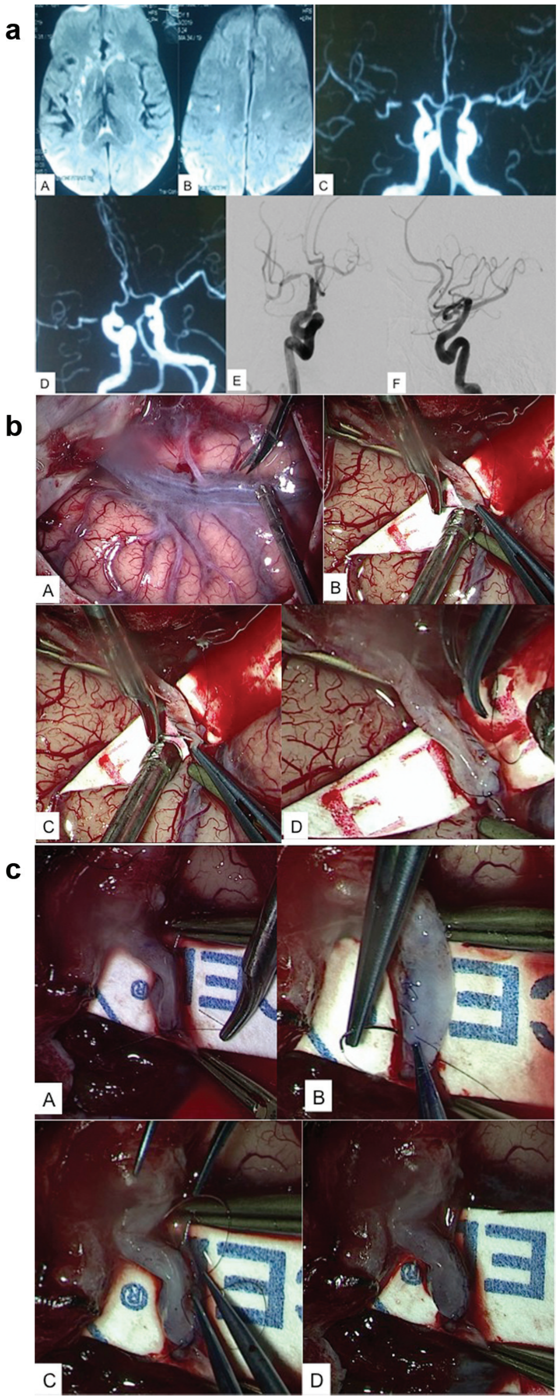

Fig. 9 (a) (**A and B**) MRI of the brain DW images showing the right MCA territory and left ACA ischemia and patchy infarcts. (**C and D**) CTA of the brain showing right M1 stenosis (severe) and left A2 stenosis. (**E and F**) Cerebral DSA showing right M1 stenosis (severe) and left A2 stenosis. (**b**)**:** (**A, B, C, and D**) Preoperative pictures of anastomosis for temporal STA-MCA bypass as a part of double barrel bypass. (**c**) (**A, B, C, and D**) Preoperative pictures of anastomosis for frontal STA-MCA bypass as a part of double barrel bypass. (**d**)**:** (**A, B, C, and D**) Preoperative sequential picture of A3-A3 bypass in the frontal interhemispheric fissure; (**A and B**) Durotomy and interhemispheric dissection. (**C and D**) Identification and preparation of left and right A3 after removal of a small part of the falx. (**e**)**:** (**A, B, C, and D**) Preoperative sequential pictures of A3-A3 side to side anastomosis. (**f**) (**A and B**) Postoperative CTA of the brain showing patent double barrel STA-MCA bypass and A3-A3 bypass (yellow circles indicate anastomosis). Privacy Policy | Disclaimer | Site Map.

Indication of Bypass (83 Cases)

1. Arterial stenosis/occlusion/dissection causing cerebral ischemia:
   - MCA stenosis/occlusion: 05
   - MCA dissection: 04
   - ICA occlusion: 19

   – ICA dissection: 04
   – Thrombotic occlusion of ICA with giant aneurysm: 02
   – Sinonasal infection-induced ICA occlusion: 02
   – Atherosclerotic: 11
2. Intracranial aneurysms: 30
3. Moyamoya disease: 21
   – Ischemia/infarction: 16
   – Haemorrhage: 05
4. Direct CCF- 04 (►**Tables 1** and **2**)

The most common presentation was hemiparesis and dysphasia in the ischemic group with history of transient ischemic attack (H/O TIA). Features of SAH (that is, headache, vomiting and loss of consciousness [LOC]) were the presenting symptoms of the intracranial aneurysm group. Eight cases of intracranial aneurysm had stenosis just proximal to the aneurysm. Middle cerebral stenosis cases presented with TIA and ischemic stroke. In MCA dissection, both ischemic clinical picture and SAH picture were present. All CCF cases were direct and had H/O head injury. Most cases of moyamoya disease presented with symptoms of ischemia. Infection was the etiology of thrombosis in cavernous ICA, in two cases. In one case, orbital cellulitis spread in the CS and caused thrombosis of the ICA (with aneurysm). In the other cases, panrhinosinusitis (by MRSA) spread to both cavernous sinuses (CSs) and both ICAs were occluded. In one interesting case, a giant partially thrombosed ICA bifurcation aneurysm thrombosed totally with distal ICA, A1 and M1. Acute thrombosis of the ICA with aneurysm in CS occurred in 4 cases, one of whom was a 3-month pregnant woman. In one case, there was intractable TIA with impending major stroke in which the whole brain was supplied only by the right-sided ICA, and the patient developed posterior inferior cerebellar artery (PICA) infarct 12 hours before the ‘scheduled urgent’

Table 1 Clinical Presentation of the patients ($n = 83$)

Features	Number	Percentage
Features of SAH (Headache, vomiting, LOC)	33	39.8%
Hemiparesis	36	43.4%
Ophthalmoplegia	06	7.2%
Dysphasia	18	21.7%
Visual disturbance	06	7.2%
Seizure	02	2.4%
H/O TIA	31	37.3%
Red eye and proptosis	04	4.8%

Abbreviations: LOC, loss of consciousness, SAH, subarachnoid hemorrhage; H/O TIA, history of transient ischemic attack.

Table 2 Review of death cases (03) in EC-IC bypass

No.	Age, gender, and diagnosis	Preoperative	Postoperative CT	Time of death
1	31, M, Moyamoya disease	Smoothly functioning bypass	Distant parenchymal hemorrhage	8th POD
2	36, M, giant supraclinoidal aneurysm with atherosclerosis	Preoperative thrombosis of STA-MCA bypass with occlusion of ICA lumen after multiple clip reconstruction	LSA and total MCA infarct	1st POD
3	65, F, giant supraclinoidal aneurysm with atherosclerosis	Preoperative tear of aneurysm neck near bifurcation.	LSA and total MCA infarct	1st POD

Abbreviations: CT, computed tomography; F, female; LSA, lanticulo striate artery; M, male; MCA, middle cerebral artery; STA-MCA, superficial temporal artery-middle cerebral artery bypass; POD, postoperative day.

revascularization operation; high flow EC-IC bypass was done in this case. Postoperatively, the patient developed 'behavioural, intellectual, and psychogenic' symptoms that recovered slowly. The average ischemic time was 28 minutes (range: 20–60 minutes). There was no clamp-related infarction. In one case, the patient developed postoperative insulofrontal infarct unrelated to temporary clamping. One preoperative ambulant patient deteriorated neurologically in the postoperative period and developed hemiplegia. Six months after the operation, she was ambulant with support. In this case, the cause seemed to be hyperperfusion.

Headache resolved in all cases. Transient ischemic attack and seizures were also gone postoperatively. Ophthalmoplegia recovered in all cases in which it was present, except in one case, in which abducent nerve palsy persisted. In one girl, mono-ocular complete blindness developed postoperatively due to ophthalmic artery occlusion, in which high flow bypass with ICA occlusion were performed. Red eye and proptosis were cured in CCF cases. Motor and sensory dysphasia improved in all cases in which it was present, except for one case in which preoperative global aphasia converted to sensory aphasia in the postoperative period.

Three patients died in the postoperative period. The rest of the patients improved postoperatively. All patients were ambulant with static neurostatus without new stroke/TIA until the last follow-up. All bypasses were patent until the last follow-up (clinical, doppler/imaging).

Discussion

As microneurosurgery advanced tremendously, indications for cerebral revascularization expanded to include multi-infarct dementia, acute ischemic stroke, MCA stenosis, MCA dissection, and ischemic retinopathy. To recommend the indications and results of EC-IC bypass, the International Cooperative Study of Extracranial/Intracranial Arterial Anastomosis (EC/IC bypass study) was performed from 1977 to 1985.[18] However, the data of the study showed that EC-IC anastomosis was not superior in preventing stroke in patients with atherosclerotic arteriopathy of the ICA and MCA compared with best medical therapy.[18] The study identified two important subgroups that seemed to do particularly poorly: cases with severe MCA stenosis and those with persistence of TIA or of ischemic symptoms in known ICA occlusion.[19] The subgroups subsequently identified to potentially benefit from surgical cerebral revascularization were those in which hemodynamic changes play a primary role in the precipitation of ischemic stroke. Since then, recent technological advances that were not available at the time of the EC/IC bypass study have made it possible to better identify this potential subgroup of patients.[20–23] One of these parameters (the oxygen extraction fraction [OEF] as determined by positron emission tomography [PET]) identifies cases with hemodynamic susceptibility, which may then benefit from an EC-IC bypass procedure.[24–27]

Currently, EC-IC bypass is either done for cerebral blood flow (CBF) augmentation or replacement. Examples of the first one would be symptomatic cases with ICA occlusion and proven hemodynamic vulnerability or moyamoya disease. Extracranial to intracranial bypass surgery for CBF replacement is most commonly done in complex aneurysm management, such as when an aneurysm is trapped, or in skull base neoplasm surgery associated with arterial sacrifice or injury.[1,2,22,28]

In the following conditions, EC-IC bypass is usually considered:

- an aneurysm or atherosclerotic plaque that is not treatable endovascularly or by other means
- failure of medication to control TIA symptoms or stroke
- imaging tests (angiogram, CTA, MRA) that show arterial stenosis or occlusion
- cerebral blood flow (CBF) studies (CT perfusion, PET, single photon emission computed tomography [SPECT]) that show arterial stenosis is causing insufficient blood flow to the brain

Cerebral bypass may be helpful in restoring blood flow and reducing the risk of stroke in conditions such as:

- Moyamoya disease: a narrowing of the internal carotid arteries at the base of the brain that can cause multiple strokes or hemorrhages. To compensate for the narrowing arteries, the brain creates collateral blood vessels in an attempt to deliver oxygen-rich blood to deprived areas of

the brain. A bypass can restore blood flow to the brain and prevent future strokes.
- Aneurysm: a bulge or ballooning of an artery wall. Some giant, fusiform, or dissecting aneurysms cannot be treated with surgical clipping or endovascular coiling. In such cases, the parent artery must be sacrificed, and the blood flow bypassed for the aneurysm to be effectively treated.
- Skull base tumor: a tumor can grow where the major vessels enter the skull and surround or invade the artery. Removing the tumor may require sacrificing the encased artery and bypassing the blood flow.
- Carotid artery stenosis: a narrowing or blockage of the carotid artery in the neck caused by atherosclerotic plaque deposits in the vessel wall.
- Intracranial arterial stenosis: a narrowing or blockage of an artery inside the skull that supplies blood to specific areas within the brain.[1,2,22,28]

Several techniques for the creation of artificial CBF conduits are available in addition to the arterial graft of the STA-MCA anastomosis. A STA-MCA bypass has a luminal flow patency rate > 95%.[29] Since the first STA-MCA procedure was described by Yasargil,[11,16] many variations have been published, but STA-MCA bypass remains the main workhorse of a neurovascular surgeon. Many of these variations have been developed in dealing with complex intracranial aneurysms and skull base neoplasms. These variations include anastomoses between the bilateral anterior cerebral arteries, the occipital artery to the posterior inferior cerebellar artery (PICA), and the anterior inferior cerebellar artery (AICA). Others include PICA to PICA, vertebral artery (VA) to PICA, STA to SCA or to the posterior cerebral artery (PCA), subclavian artery to PCA, PCA to SCA, and even a tandem occipital artery to AICA and PICA anastomoses.[10]

Other common EC-IC bypasses for cerebral revascularization methods include venous interposition grafts, such as the great saphenous vein, free arterial conduits including the radial artery, and artificial grafts (with polytetrafluoroethylene ePTFE tubes).[30,31]

The great saphenous vein graft has been used in bypasses for giant intracranial aneurysms, skull base neoplasms requiring ICA sacrifice or involving the ICA, or VA occlusive disease.[32,33] Internal carotid artery bypasses include the cervical-supraclinoid ICA, the petrous-supraclinoid ICA, and the cervical–petrous ICA.[34] The radial artery bypass graft has been shown to have long-term patency when used for the management of giant aneurysms of the ICA.[35]

Intracranial-intracranial (IC-IC) bypasses are occasionally necessary (►**Figure9d** and **9e**). A short interposition graft such as the the saphenous vein of the patient can be used in IC-IC bypasses. Donor vessels in IC-IC bypasses are usually from the ICA, M_1 or A_1 arteries, and the recipients may include the ICA, M1–3, A1–2, P1–2, the basilar artery, and the superior cerebellar artery (SCA).[1]

Very useful and important advancements in monitoring intraoperative blood flow have also been developed. The use of micro-Doppler, and of transit time flowmetry, such as the Charbel microflow probes (Transonic), and indocyanine green (ICG) video angiography have all had a positive impact on cerebral revascularization by EC-IC bypass surgery by ensuring anastomotic and graft patency.[1]

Complications in STA-MCA bypass are limited and include early postoperative TIA, delayed stroke, development of a pseudoaneurysm, and wound dehiscence. High-flow bypass grafts are more prone to develop complications than low-flow STA-MCA bypass. Radial artery grafts may suffer vasospasm or intimal hyperplasia and, eventually, occlude. Proatherogenic changes can occur in SV grafts, which eventually leads to occlusion. After parent vessel occlusion, thromboembolic complications are common in high flow bypass, mainly due to the change in intracranial hemodynamics. Preoperative antiplatelet medications, as well as intraoperative anticoagulation, can prevent these thromboembolic events. In patients without vascular reserve, prolonged temporary occlusion times can lead to territory infarcts without changes in the neuromonitoring. So, it is important to minimize occlusion times in these patients. In longstanding perfusion deficiency, reperfusion hemorrhage may be problematic after revascularization, although its incidence is low. Other complications involve the site of graft harvests, such as infection, ischemic hand, or hematoma.[10]

Cerebral revascularization by EC-IC bypass has evolved from the culmination of several technologies, from the early dawn of vascular surgical techniques in animals to the development and utilization of the surgical microscope, of bipolar coagulation, and of suitable suture material. Major asking regarding the indications and benefits of cerebral revascularization are being addressed. Fascination in further development of this matter to make it safer for the patients remains strong and high. Advanced research into perioperative blood flow assessment will play a key role in determining the positive result of cerebral revascularization. It is logical to hope that, with better understanding of the pathophysiology of cerebral ischemia and better patient selection, cerebral revascularization by EC-IC bypass will remain an indispensable tool in microneurosurgery.[1]

Conclusion

Our initial experiences of 100 cases of EC-IC bypass showed that, even in inexperienced hands, the mortality and morbidity in properly indicated cases were low and that the results were impressive according to the pathology and the aim of the bypass. Lessons learned from these experiences can be very helpful for new and beginner bypass neurosurgeons.

Conflict of Interests
The authors have no conflict of interests to declare.

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