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РЕВАСКУЛЯРИЗАЦИЯ ГОЛОВНОГО МОЗГА ПУТЕМ СОЗДАНИЯ АНАСТОМОЗА МЕЖДУ ПОВЕРХНОСТНОЙ ВИСОЧНОЙ АРТЕРИЕЙ И СРЕДНЕЙ МОЗГОВОЙ АРТЕРИЕЙ

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В настоящей статье подробно рассмотрена методика реваскуляризации артерий головного мозга с помощью создания анастомоза между поверхностной височной артерией (ПВА) и средней мозговой артерией (СМА). Представлен краткий обзор 2 категорий церебральных шунтов, а также патологий, которые могут быть скорректированы с помощью этих методик. Обсуждены важные исследования, посвященные изучению шунтирования ПВА-СМА. Также описан процесс отбора пациентов, акцентируется внимание на необходимости оценки их гемодинамических показателей с помощью неинвазивных количественных методов визуализации. Подробно описана техника реваскуляризации на соответствующем клиническом примере с последующим обсуждением возможных осложнений и будущих направлений развития методики.

Ключевые слова: шунтирование, церебральная реваскуляризация, увеличение кровотока, экстра-интракраниальный микроанастомоз

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Superficial temporal artery to middle cerebral artery bypass for flow augmentation

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> In the lecture to follow, we provide an in-depth review of superficial temporal artery to middle cerebral artery (STA-MCA) bypass for flow augmentation. We begin with a brief review of the two broad categories of cerebral bypasses as well and the relevant pathologies treated. We then discuss some important landmark trials on the subject of STA-MCA bypass. Next, we focus on patient selection with an emphasis on hemodynamic assessment using non-invasive quantitative imaging methods. Revascularization technique is then described with a corresponding case example and a subsequent discussion on complications and future directions.

Key words: bypass, cerebral revascularization, flow augmentation, extracranial-intracranial microanastomosis

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Лекция

«Кровь будет течь туда, где это необходимо» "Blood will flow where it is needed"

INTRODUCTION AND HISTORICAL BACKGROUND

Stroke represents the fifth leading cause of death in the United States and is a major cause of mortality and morbidity worldwide [1, 2]. Large artery atherosclerosis is responsible for a significant proportion of ischemic stroke and most commonly involves the carotid artery. In a large population-based epidemiological study, atherosclerotic occlusion of the internal carotid artery (ICA) was found to cause 10 % of transient ischemic attacks (TIA) and 15-25 % of ischemic strokes in the carotid artery territory. Even with medical therapy, the 2-year risk of recurrent stroke was found to be 10–15 %. Annual stroke rates have been calculated at 5.5 % and at least 7 % in nonpopulation based studies examining over 1000 patients [3, 4]. The etiology of recurrent stroke in this subset of patients can be subdivided into that of atheroembolic origin as well as that related to hemodynamic compromise. Clearly, ICA occlusion is not a stable pathology. As such, much attention has been focused on interventional therapy for preventing recurrent events, especially in the case of hemodynamic failure.

In 1912, Alexis Carrell was awarded the Nobel Prize in Physiology and Medicine for his work on suturing blood vessels and pioneered the way for future work in vascular anastomosis and solid organ transplantation [5]. In the years to follow, techniques for vascular anastomosis were further expanded upon to the point where the first successful common carotid artery – internal carotid artery bypass was performed in 1963 by E. Woringer and J. Kunlin using a saphenous vein graft [6]. Gazi Yasargil performed the first superficial temporal artery (STA) to middle cerebral artery (MCA) (STA-MCA) bypass on October 30, 1967 in Zurich for a patient with MCA occlusion [7]. In the 1970s and 1980s, microsurgical techniques were further applied to increase the repertoire of donor and recipient vessels: R. Spetzler and N. Chater described the first occipital artery to MCA bypass, J. Ausman et al. described the first occipital artery to posterior inferior cerebellar artery and STA to superior cerebellar artery bypass, and T.M. Sundt et al. described superior cerebellar artery to posterior cerebral artery and external carotid artery to posterior cerebral artery bypass [8-11].

With standardization of microsurgical technique, cerebral bypass procedures were performed with increasing frequency among practicing neurosurgeons. In 2006, F.T. Charbel et al. dichotomized the bypass surgeries based on the indication: flow augmentation or flow replacement [12]. This then ushered in an era of surgeries based on the conceptual understanding of the procedure.

In the lecture to follow, we provide an in-depth review of STA-MCA bypass for flow augmentation. We begin with a brief review of the two broad categories of cerebral bypasses as well and the relevant pathologies treated. We then discuss some important landmark trials on the subject of STA-MCA bypass. Next, we focus on patient selection with an emphasis on hemodynamic assessment using non-invasive quantitative imaging methods. Revascularization technique is then described with a corresponding case example and a subsequent discussion on complications and future directions.

INDICATIONS FOR CEREBRAL BYPASS-FLOW REPLACEMENT VS. FLOW AUGMENTATION

Flow replacement. A cerebral bypass in the context of flow replacement functions to serve as a channel to replace and preserve blood flow that is lost intentionally during definitive treatment of select neurosurgical pathologies. In current neurosurgical practice, this primarily involves giant aneurysms and skull base tumors. In the former, an intracranial aneurysm may not be amenable to simple clipping or endovascular coil embolization and therefore requires parent vessel sacrifice. Many giant proximal ICA aneurysms and fusiform aneurysms in the more distal vasculature may be treated by trapping and bypass. In such a procedure, it is paramount to assess the vascular flow deficit such that the bypass flow can appropriately match the corresponding metabolic demand of the vascular territory. Our group has previously described this decision-making algorithm for flow replacement bypass in intracranial aneurysm surgery [13]. Although newer endovascular techniques are now used to treat many of these aneurysms, surgical revascularization remains an important tool in the management of this pathology.

In the case of skull base tumors (typically meningiomas) and some head and neck cancers, firm adherence to or invasion of the ICA may necessitate a flow replacement bypass. Although some benign tumors will encase rather than invade the ICA, previous radiation will often render these tumors more adherent to critical vascular structures. Options for resection include carotid sacrifice without bypass, bypass in selected patients, or bypass in all cases. In general, the benefit of a gross total resection needs to be weighed against the risks associated with carotid sacrifice as well as cranial neuropathies. Although a balloon occlusion test has been established as a reliable method in predicting stroke risk, false negative rates have been reported at 13-15 % using neurological examination alone and 3-10 % with the addition of cerebral blood flow assessment with neuroimaging [14, 15]. In more recent years, bypass for these tumors has decreased in popularity in favor of less aggressive resection strategies combined with adjuvant therapy.

Flow augmentation. Flow augmentation bypass supplements blood flow in patients with symptomatic steno-occlusive cerebrovascular disease. In contrast to flow preservation bypass where a direct anastomosis is used, bypass techniques for flow augmentation include direct, indirect or both. While pathologies treated by flow replacement bypass are rare, those treated with flow augmentation bypass are more commonly encountered. For this reason, flow

augmentation bypass has been more critically studied in larger scale clinical trials. Broadly speaking, flow augmentation is used in treatment of moyamoya vasculopathy which represents an idiopathic progressive steno-occlusive disease as well as atherosclerotic steno-occlusive disease. Indications for flow augmentation bypass are further discussed and expanded upon in the sections to follow.

LANDMARK TRIALS

Theoretically, augmenting blood flow in patients with carotid stenosis or occlusion would provide collateral circulation and decrease recurrent stroke rates. However, some practitioners questioned the efficacy of this technically demanding procedure. This speculation paved the way for the international extracranial-intracranial (EC-IC) bypass trial which commenced in 1977 [16]. This trial enrolled 1377 patients with recent stroke or TIA and concurrent ipsilateral ICA or MCA stenosis or occlusion. Patients assigned to best medical care with STA-MCA bypass failed to demonstrate a benefit with respect to rates of major stroke and death when compared to patients treated with best medical therapy alone at a mean follow-up of 55.8 months. Although support for this procedure heavily declined following the publication of these results in 1985, select practitioners emphasized the benefit of STA-MCA bypass in more carefully selected patients.

Criticism of the EC-IC bypass trial primarily centered on inadequate patient selection especially with respect to lack of hemodynamic criteria [17–19]. More specifically, critics suggested that there were insufficient means of assessing preoperative blood flow to the cerebral vasculature as well a lack of proper patient selection. In the many years between the initiation of the trial and the publication of the final results, the understanding of cerebral ischemia was further expanded upon and neuroimaging techniques continued to improve. Many practicing neurosurgeons still performed the procedure with the understanding that there existed a subset of patients who would continue to receive benefit. Excluding cerebral bypass for flow replacement in cases of giant aneurysms and/or intracranial tumors, cerebral bypass for flow augmentation was performed in patients failing best medical therapy as well as those with documented hemodynamic compromise.

In the case of carotid artery occlusion, the cerebral vasculature acts to keep a constant cerebral blood flow by way of arteriolar vasodilation. Eventually, the vasodilatory ability of these arterioles is exceeded and compensatory autoregulation fails. This inability of cerebral blood flow to meet the metabolic demand of cerebral tissue is deemed "misery perfusion" [20]. The prognosis of patients with carotid occlusion and impaired hemodynamic reserve has been well studied. In 1995, M.W. Webster et al. showed that patients with carotid occlusion who had an impaired cerebral vasodilatory response with compromise of collaterals suffered a new stroke at a rate of 26 % compared to 0 % in those with preserved autoregulation at a mean follow-up

of 19.6 months [21]. R.L. Grubb et al. conducted a similar study where patients with misery perfusion as evidenced by high oxygen extraction fraction (OEF) on positron emission tomography suffered an ischemic stroke at a rate of 31 % compared to only 10 % in those with preserved hemodynamic reserve at a mean follow-up of 31.5 months [22]. The significance of increased OEF was re-demonstrated by H. Yamauchi et al. who showed that patients with increased OEF suffered recurrent ipsilateral strokes at a rate significantly higher than patients with a normal OEF (4/7 vs. 2/33) [23]. The work of the aforementioned authors highlighted the fact that patient selection was key to performing a successful bypass.

In the years to follow, the STA-MCA bypass procedure experienced a rebirth and the number of bypasses performed increased substantially in the late 1990s with the majority performed for the purpose of flow augmentation [24]. The Carotid Occlusion Surgery Study (COSS) addressed a major criticism of the EC-IC bypass study by focusing on patients who may derive the greatest benefit from STA-MCA bypass: those with hemodynamic cerebral ischemia [25]. The COSS trial randomized 97 patients to the surgical group of which 93 underwent surgery and 98 to the medical group. Patient were included if they had complete occlusion of the ICA and TIA or ischemic stroke in the corresponding hemisphere in the preceding 120 days. Furthermore, an ipsilateral to contralateral OEF ratio of 1.13 or greater was required prior to randomization. The trial was stopped early due to futility as 2-year ipsilateral stroke rates were 21 % for the surgical group and 22.7 % for the medical group. Perioperative stroke rates were 12.4 % higher in the surgical group. Of note, the medical group's ipsilateral stroke rate was much lower than that predicted by historical controls, perhaps due to improved medical management. The results of this trial put into question the role of STA-MCA bypass for flow augmentation in carotid occlusion.

After the publication of the COSS trial results in 2011, the role of and indications for the STA-MCA bypass procedure once again fell into question [26]. In the current era, indications for STA-MCA bypass have been significantly narrowed. Although the trial failed to show a benefit of surgery, certain key points are worth mentioning. First, 86 % of patients in COSS who suffered an ipsilateral perioperative stroke had a mechanism that was not related to the bypass itself. Moreover, the surgical group had a significantly lower rate of recurrent ipsilateral ischemic stroke after postoperative day 2 (9 % vs. 22.7 %). Currently, one may justify an STA-MCA bypass for atherosclerotic carotid disease if the perioperative complication rate can be made lower than that reported in the COSS trial. This may involve specialized neuroanesthesia and perioperative management protocols. In addition, specific subsets of patients not studied in the COSS trial may benefit. These include those with multiple stroke or TIAs failing maximum medical therapy, unstable patients with crescendo TIAs, as well as patients with ischemic symptoms during postural changes or limb-shaking TIAs.

Indications for flow-augmentation bypass: moyamoya vasculopathy and cerebrovascular atherosclerotic disease

Moyamoya disease and moyamoya syndrome. Moyamoya disease is an idiopathic steno-occlusive disease characterized by progressive intimal hyperplasia of the proximal anterior circulation vessels with a bimodal distribution in both childhood and adulthood. Patients ultimately develop an anastomotic network of perforating vessels resembling a puff of smoke on angiographic imaging, moyamoya vasculopathy in the absence of risk factors is termed "moyamoya disease" whereas that along with associated conditions such as sickle cell anemia or neurofibromatosis 1 is termed "moyamoya syndrome" [27]. Moyamoya can present with ischemic symptoms from progressive luminal occlusion as well as intracranial hemorrhage from rupture of fragile collateral blood vessels. Inevitably, moyamoya represents a progressive condition with a natural history characterized by continuous neurological decline. Unfortunately, medical therapy has not been shown to be particularly effective in halting this decline [27].

While it may not reverse the disease process, surgical revascularization is the mainstay of treatment of moyamoya. Flow augmentation serves to prevent future ischemic symptoms and can theoretically reduce the incidence of hemorrhagic complication indirectly by reducing the number of fragile collateral blood vessels formed. There is a wide body of literature in support of surgical revascularization techniques for moyamoya vasculopathy in both children and adults. Without treatment, annual stroke and hemorrhage are cited at 13.3 % and 7.1 % respectively [28]. Progression of disease was found to occur in 23.8 % of adults in cerebral hemispheres lacking surgical treatment [29]. With respect the frequency of ischemic symptoms, hemorrhagic events and overall quality of life, patients undergoing surgical revascularization fare better compared to non-treated patients [30–34]. The type of surgical revascularization performed for moyamoya still remains a point of controversy.

Direct, indirect and combined bypass all remain treatment options for moyamoya. The most common type of direct bypass used is the STA-MCA bypass and provides immediate flow augmentation. Indirect bypass uses vascularized tissue such as the temporalis muscle, dura mater or other along with the STA and places it directly onto the cortical surface. Neoangiogenesis occurs over time and flow augmentation is achieved in a delayed fashion. Direct bypass is typically used in adult patients whereas indirect bypass is used in the pediatric population [26, 27]. In addition, techniques exist which combine both direct and indirect bypass into one surgery. Although more complex and time-consuming, this combined procedure can offer patients the benefit of both immediate and delayed flow augmentation.

Cerebrovascular atherosclerotic disease. Stenosis or occlusion of one of the major arteries supplying the brain leads to ischemic stroke. Similarly, patients suffering from ischemic stroke or TIA are often found to have cerebrovascular atherosclerotic disease and are prone to recurrent

events. Not surprisingly, in the early stages of bypass surgery, the operation was most commonly performed for symptomatic atherosclerotic disease of both the ICA and MCA. However, there existed other indications including acute ischemic stroke as well as cerebral vasospasm related to subarachnoid hemorrhage which eventually fell out of favor and are now treated with more modern endovascular techniques [35, 36]. By far, the most common indication was atherosclerotic disease not amenable to endarterectomy and this was the basis for the EC-IC bypass study.

The EC-IC bypass study included patients with recent TIA or minor stroke and concomitant ICA stenosis, occlusion or proximal MCA stenosis. 714 patients were randomized to best medical treatment and 663 to best medical treatment plus STA-MCA bypass. Despite an excellent bypass patency rate of 96 %, major perioperative stroke rates occurred at a rate of 4.5 % compared to a spontaneous-stroke rate of 1.3 % in the medical group. At a mean follow-up of 55.8 months, 205/715 or 29 % of patients in the medical group and 205/663 or 31 % of patients in the surgical group experienced fatal and nonfatal strokes leading to the conclusion that STA-MCA bypass was ineffective in this group of patients. The prevailing theory at the time suggested that recurrent ischemic events in patients with steno-occlusive cerebrovascular disease were embolic in origin from atherosclerotic plaques [37]. However, after the publication of the EC-IC bypass trial, a large body of evidence suggested hemodynamic compromise as the etiology of stroke in these patients [4]. As imaging techniques developed to identify this subgroup of patients, the stage was set for a new trial to test EC-IC bypass surgery in patients with impaired hemodynamic reserve.

As previously mentioned, the COSS trial focused specifically on a patient cohort with hemodynamic cerebral ischemia using a predefined OEF ratio and failed to demonstrate a benefit of surgery. As such, there is currently Level 1 evidence from two landmark clinical trials failing to support STA-MCA bypass for symptomatic carotid artery occlusion. Advances in lifestyle modification and conservative medical therapy have indeed demonstrated a benefit with respect to stroke risk, thereby rendering an advantage of surgery more difficult to demonstrate. Pursuing medical treatment with antithrombotic therapy such as aspirin, strictly controlling blood pressure to a goal systolic blood pressure <140 mmHg, and targeting an low-density lipoprotein < 70 mg/dL with statin medications are all means to reduce stroke risk. Moreover, aggressive lifestyle modification targeting secondary risk factors such as diabetes mellitus, obesity, inactivity, and tobacco use can work synergistically in this patient population. In fact, these are the aggressive treatments that helped demonstrate significantly lower stroke rates in patients with intracranial stenosis in the Stenting and Aggressive Medical Management for Preventing Recurrent Stroke in Intracranial Stenosis Trial [38].

In the current era, flow-augmentation bypass for symptomatic carotid occlusion may still be considered if perioperative

stroke rates can be significantly reduced and if proper patient selection is applied. Patients with hemodynamic cerebral ischemia represent one of the most unstable patient cohorts and the requirement for specialized neuroanesthesia and perioperative neurointensive care cannot be understated. In addition, there exist several subgroups of patients who were not examined in the COSS trial. Although the mere existence of these patient cohorts does not provide justification for operative intervention, these subgroups may serve as a basis for further clinical trials [39]. This includes patients with limb-shaking TIAs, patient with hemodynamic impairment greater than those of patients studied in COSS, patients with chronic retinal ischemia, as well as patients with persistent symptoms despite maximum medical therapy. STAMCAR is an ongoing prospective EC-IC bypass registry focusing on these subgroups.

PATIENT SELECTION WITH FLOW-ASSISTED HEMODYNAMIC ASSESSMENT

Non-invasive flow measurement imaging and intraoperative flow-measuring devices have allowed for a flow-based approach to STA-MCA bypass. This allows integration of quantitative flow measurements into pre-operative planning, intraoperative assessment, and post-operative surveillance. A successful bypass begins with proper patient selection which can be optimized with flow measurement technology. Moreover, intraoperative flow measurement can alter surgical technique and intraoperative decision making. Lastly, our knowledge of hemodynamics helps to quantify post-operative outcomes in terms of graft patency and hemodynamic improvement over time [40].

Pre-operative assessment is aided by non-invasive quantitative MR imaging (QMRA). In this manner, blood vessel flow rate can be quantified noninvasively using phase-contrast MR imaging. Using NOVA (Noninvasive Optimal Vessel Analysis; VasSol, Inc, Chicago, IL) software, a 3D surface rendering of the cerebral vasculature is generated and a flow report is created which provides mean volumetric flow rate [41]. QMRA in a healthy population differs than that of patients suffering from cerebrovascular disease and can serve as a benchmark to gauge cerebrovascular flow impairment [42, 43]. QMRA NOVA scans can be augmented by the use of acetazolamide to test hemodynamic reserve. Flows are calculated before and after acetazolamide challenge which can provide valuable information in addition to standard functional and perfusion MR imaging.

Intraoperative flow-measurement devices can also be used to guide intraoperative decision making. The microvascular ultrasonic flow probe (Charbel Micro-flowprobe; Transonic Systems, Inc., Ithaca, NY) uses the principle of transit time to derive blood flow in vessels of interest. Donor or recipient vessels 1.5 to 3 mm in diameter are placed into the probe and the field is irrigated generously with saline. An ultrasound wave is emitted from the transducers and transit time is calculated from which flow is derived in mL/min. Our group has previously described the utility

flow-assisted surgical technique in cerebrovascular neurosurgery, most notably with cerebral aneurysm clipping and STA-MCA bypass for both flow augmentation and flow replacement [44].

In the case of STA-MCA bypass, two values are of utmost importance: the cut-flow and the bypass flow. The flow of the STA in situ is low at roughly 5–10 ml/min secondary to the downstream resistance provided by the scalp vasculature. However, once the distal end is cut open, the flow dramatically increases. This unobstructed blood flow is termed the "cut flow" and is approximately 10-fold higher than in-situ flow. The "bypass flow" represents the flow in the STA donor after the anastomosis and remains high owing to the low resistance provided by the cerebral cortex with hemodynamic impairment. The "cut flow index" (CFI) defined as bypass flow divided by cut flow can be used to gauge the success of a bypass. In a series describing 51 separate bypass operations, bypasses with a CFI > 0.5 had a 92 % patency rate whereas those with a CFI <0.5 had a 50 % patency rate, demonstrating with statistical significance that CFI was a predictor of bypass patency [45]. This observation was more recently validated in a larger cohort of 278 patients with intracranial bypasses [46]. In this way, intraoperative flow measurements can alert the surgeon to a technical issue with the bypass itself.

Traditionally, invasive diagnostic cerebral angiography has been used to assess STA-MCA bypass graft patency over time. However, NOVA has proven to be a promising non-invasive alternative. Not only can QMRA NOVA determine whether or not the bypass is patent but it can provide more descriptive information related to bypass function. Our group has previously demonstrated correlation between post-operative QMRA findings and those on angiographic surveillance [47]. Notably, occluded bypasses were found to be absent on QMRA and absolute flows of less than 20 mL/min or a reduction greater than 30 % in a 3-month period were correlated with stenotic bypasses or those with reduced caliber. For this reason, QMRA can supplement or even provide an alternative to conventional catheter angiogram.

REVASCULARIZATION TECHNIQUE

A successful STA-MCA bypass surgery begins with a comprehensive pre-operative assessment. As previously mentioned, several imaging studies are particularly useful in cerebral revascularization procedures. A diagnostic cerebral angiogram provides high-resolution images of both the diseased intracranial vasculature as well as potential STA donors vessels. Parenchymal imaging in the form of MRI assists with identifying prior strokes while QMRA NOVA provides quantitative data on blood flow. SPECT as well as functional and perfusion-weighted MR images with and without acetazolamide are means of examining cerebrovascular reserve. We also highly recommend baseline neuropsychological testing in the preoperative assessment of patients.

If the patient is not already taking aspirin 325 mg daily, he/she is instructed to take 325 mg the night before surgery

and will continue it perioperatively. We routinely use invasive blood pressure monitoring with an arterial line to achieve normotension and to avoid hypotension upon anesthetic induction. Normotension, normocapnia and normovolemia are maintained throughout the procedure. At the time of vessel occlusion with temporary clips, we ensure that the patient is in metabolic burst suppression by bispectral index monitoring and raise mean arterial pressure 25 % above baseline. Post-operatively, all patient are monitored in a neurosciences ICU and blood pressure management is guided by intraoperative cut flow and bypass flow measurements.

After the induction of general anesthesia, the patient is placed supine with the head fixed in a lateral position using either a Sugita (Mizuho America, Inc., Beverly, MA) or Mayfield (Integra LifeSciences, Plainsboro Township, NJ) clamp. A shoulder roll may occasionally be used to achieve a higher degree of rotation. After fixation, the STA is marked out using doppler ultrasonography. STA dissection is begun by gently scoring the skin with a skin knife. The epidermis and dermis is then incised with a Colorado monopolar cautery device (Stryker Leibinger, Kalamazoo, MI) at a setting of 8. We then use a curved snap to bluntly dissect down to the STA. The loose areolar plane above the vessel can be mobilized with this snap, allowing for protection of the underlying vessel during electrocautery. This process is continued towards the main trunk of the STA and along both frontal and parietal branches. Once 8–10 cm of STA is exposed, Bovie electrocautery (Bovie Medical Corp., St. Petersburg, FL) is used to further free the tissue around the STA. The STA is then wrapped in a papaverine-soaked cottonoid and is placed to the side.

After STA dissection, the temporalis muscle and fascia are incised with bovie electrocautery. Hooks are used to retract both skin flaps as well as the temporalis muscle to each respective side. An acorn drill bit (Medtronic Midas Rex, Fort Worth, TX) is used to fashion either one or two burr holes at the proximal aspect of the vessel or at both proximal and distal aspects. A circular craniotomy flap is then drilled and elevated. Hemostasis is obtained using Gelfoam (Pharmacia & Upjohn, Kalamazoo, MI) or Surgicel (Johnson & Johnson Products, Chicago, IL) and dural tack-up sutures are used to prevent epidural collections from forming. The dura can then be opened in a cruciate fashion to expose the underlying cortex. A suitable recipient vessel, preferably greater than 1.5 mm is then identified and dissected free.

Arachnoid bands encasing the recipient vessel are gently opened using an arachnoid knife, forceps and microscissors. At least 1 cm of the recipient vessel is freed and mobilized such that a rubber dam can be placed underneath. A papaverine-soaked cotton ball can be placed on the vessel surface to prevent iatrogenic vasospasm. After preparation of the recipient vessel, the donor STA is brought back into the field. The curved snap is once again used to bluntly dissect soft tissue off of the proximal vessel to create an area for a Sugita temporary clip (Mizuho America, Inc.). The same

process is performed at a more distal location along the vessel, preferably distal to the takeoff of the unused branch such that forward flow is preserved into the branch of interest. After placement of proximal and distal clips, the distal STA is coagulated. The distal temporary clip is then removed and a blunt-tip needle is used to flush the vessel with heparinized saline (10 U heparin/mL) while the proximal clip is briefly opened.

Final preparation of the STA donor involves using a marking pen to mark the estimated length of vessel required to reach the recipient. Any remaining adventitia is then bluntly dissected off the vessel using curved microscissors and side branches are carefully coagulated. Temporarily releasing the proximal clip allows for recording of cut flow with a flow probe. The vessel is then once again flushed with heparinized saline before replacement of the proximal clip. The STA is then cut at a 45-degree angle with microscissors such that a "fish-mouth" is created. This distal end is marked with a marking pen as is the recipient vessel. Temporary clips must be placed on the recipient vessel and the STA donor is placed alongside in order to gauge the length of arteriotomy required.

We use an ophthalmic blade to incise the recipient vessel and a 10–0 nylon suture for the anastomosis. The suture is passed outside-in from the donor and inside-out through the recipient vessel. After anchoring, interrupted sutures are placed on each side of the anastomosis and sutures are tied with three knots. Before the final suture, the arterial lumen must once again be flushed with heparinized saline. The temporary clips of the recipient vessel are then removed followed by that of the proximal donor vessel. Oozing can be controlled by gentle pressure and if necessary, additional sutures may be placed at this time. The bypass flow can then be measured. The dura is then left open and the burr hole defect in the craniotomy flap is enlarged so as not to inadvertently kink the STA donor. Post-operatively, patients are cared for in a dedicated neurosciences ICU on a continued regimen of aspirin 325 mg daily. Angiography and QMRA are performed shortly after surgery. Patients are often discharged on post-operative day one or two.

CASE REPORT

Fig. 1 and 2 illustrate a case example of STA-MCA bypass for flow-augmentation in a patient with moyamoya disease.

The patient in question was a 37-year-old male with no significant past medical history and was diagnosed during workup of episodic numbness in the upper extremities in the setting of a first degree relative with a recent diagnosis of moyamoya disease. At that time, MRI & MRA of the brain were performed which were notable for severe stenosis of the anterior circulation. A diagnostic cerebral angiogram revealed severe steno-occlusive disease of the anterior circulation bilaterally with development of a basal collateral network of vessels, confirming the diagnosis of moyamoya disease. Functional MR-imaging T2 BOLD sequences

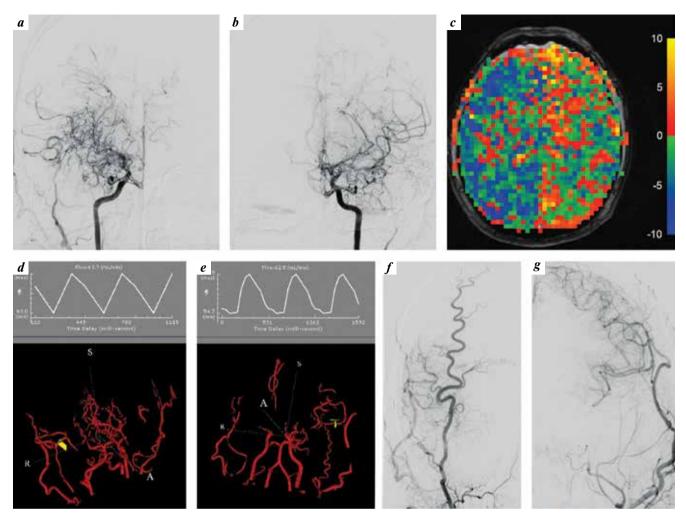


Fig. 1. Preoperative and post-operative assessment. AP view of right and left internal carotid injections of digital subtraction angiogram show occlusion of the supraclinoid internal carotid artery bilaterally with the development of a characteristic moyamoya collateral network of vessels (a & b respectively). T2 BOLD MR-imaging performed during functional provocation demonstrates diminished cerebrovascular reserve bilaterally with a more prominent decrease in the right hemisphere (c). Post-operative quantitative MR imaging (QMRA) NOVA and AP view of right external carotid injection of digital subtraction angiogram show a patent right STA-MCA bypass (d & f respectively). Post-operative QMRA NOVA and AP view of left external carotid injection of digital subtraction angiogram show a patent left STA-MCA bypass (e & g respectively)

demonstrated decreased cerebrovascular reserve in both hemispheres (right greater than left) on functional provocation using audiovisual bilateral hand movement and ${\rm CO}_2$ rebreathing. The patient was started on aspirin and after a discussion of treatment options, he elected to undergo a direct STA-MCA bypass.

Initially, a right sided end-to-side anastomosis was performed using a the frontal STA branch with a CFI of 1.1. The parietal branch was kept in continuity to be used as an indirect bypass. Post-operative diagnostic cerebral angiogram and QMRA NOVA showed a patent bypass. Three months later, he subsequently underwent a left end-to-side anastomosis using the parietal STA branch with CFI of 1.0. Post-operative diagnostic cerebral angiogram and QMRA NOVA confirmed patency of the bypass. The patient was discharged on post-operative day two. During the most recent follow-up visit, the patient denied any further episodes of numbness and remained neurologically intact.

COMPLICATIONS

Post-operative complications of STA-MCA bypass can be separated into those related to the anastomosis itself and other external factors. As with any surgery, superficial or deep wound infection is a potential complication. Hyperperfusion hemorrhage, although rare may also occur. As previously mentioned, a low CFI may lead to bypass stenosis or occlusion. We have previously explored reasons for low CFI which can be further subdivided into several types of errors [45]. A type 1 error represents a case in which there is a poor indication for revascularization, resulting in less demand by the ischemic cortex. Thankfully, with non-invasive flow-measurement technology, this type of error has been significantly reduced. Type 2 errors represent issues with the donor, anastomosis, or recipient bed. In type 2a, atherosclerotic disease of the donor vessel or iatrogenic injury lead to a poor-functioning bypass. In type 2b, there is a problem with the anastomosis itself such as thrombosis.

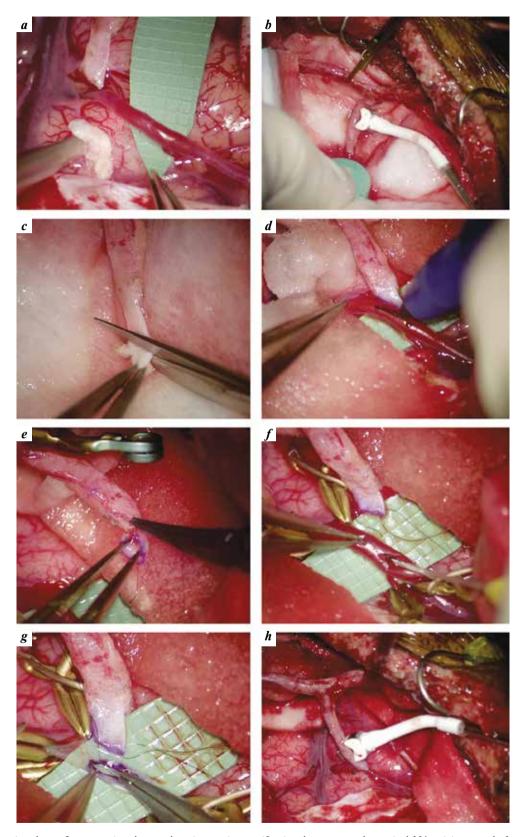


Fig. 2. Intraoperative photos. Intraoperative photo under microscopic magnification demonstrates the cortical M4 recipient vessel after detachment from neighboring arachnoid bands (a). The cut-flow of the parietal superficial temporal artery donor is measured using a Charbel Micro-flowprobe (b). The donor vessel is then cut with microscissors in an oblique fashion (c). The donor branch is laid alongside the cortical recipient vessel which is marked with a marking pen (d). 10-0 nylon sutures are placed into the heel and toe of the donor vessel (e). Temporary clips are placed on the recipient vessel which is then cut with an ophthalmic blade (f). The donor vessel is flushed with heparinized saline and the anastomosis is performed (g). After completion of the anastomosis, the bypass flow is measured (h)

Lastly, type 2c represents a situation in which the recipient vessel was of either small caliber or quality to support the outflow of the graft.

CONCLUSION AND FUTURE DIRECTIONS

The STA-MCA bypass remains one of the most technically challenging and intricate procedures within the scope of neurosurgical practice. In recent years, the medical community has seen significant progress with respect to the techniques of cerebral revascularization as well as the hemodynamic assessment of patients. Flow-measurement strategies are particularly useful in the pre-operative assessment, intra-operative decision-making and post-operative surveillance

of these patients. In current practice, STA-MCA bypass is used for flow replacement in complex aneurysms and skull base tumors as well as flow augmentation. Surgical flow-augmentation bypass is the most effective and enduring treatment for moyamoya vasculopathy but is met with skepticism in the context of atherosclerotic ICA occlusion with hemodynamic compromise. Although the EC-IC bypass and COSS trials have narrowed the indications for STA-MCA bypass, patients with progressive atherosclerotic disease will not stop suffering from ischemic events. As our ability to decrease perioperative event rates increases, more prospective randomized control trials will be needed to study this procedure in a select group of patients with hemodynamic cerebral ischemia.

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