Cerebral revascularization for ischemic disease in the 21st century

Nicholas C Bambakidis, Shakeel A Chowdry

ABSTRACT

Shortly after the first extracranial to intracranial (EC–IC) carotid artery bypass was performed by Yasargil in 1967 for internal carotid artery occlusion, cerebral revascularization became widely accepted in the neurosurgical field, and the procedures became increasingly used as practitioners began to master the technical aspects of the surgery. The procedures were performed for intracranial arterial stenosis and occlusion and used as an adjunct in the treatment of large aneurysms and skull base tumors. The results of the EC–IC bypass group trial in 1985 were surprising to many and sobering to all; EC–IC bypass for stenosis or occlusion of the high internal carotid artery or middle cerebral artery did not decrease the risk of subsequent stroke compared with medical management. Rather, the incidence of stroke increased, and the events were noted to occur sooner than with medical therapy alone. Despite the known limitations of this landmark study, the number of EC–IC bypass procedures fell precipitously over the ensuing decades. Despite this significant setback, cerebral revascularization is not obsolete. This article revisits the sequence of events leading to the rise of revascularization surgery and recaps the impact of the EC–IC bypass trial. The limitations of the trial are discussed, as are current studies evaluating the efficacy of cerebrovascular bypass procedures for symptomatic carotid occlusive disease. The authors review the accepted indications for bypass surgery in the early 21st century.

INTRODUCTION

Extracranial to intracranial (EC–IC) bypass for treatment of cerebrovascular pathology remains an elegant microsurgical procedure for which multiple, sometimes controversial, indications exist. Despite recent continuous technical advances in endovascular therapy, bypass procedures remain an important tool in the armamentarium of cerebrovascular surgeons. This article reviews the history of the development of bypass procedures throughout the microsurgical era and applies an historical perspective to present and future indications for its continued application in the treatment of neurovascular disorders.

CEREBRAL REvascularization: THE EARLY YEARS

French surgeon Alexis Carrel (1875–1944) pioneered revascularization surgery at the turn of the 20th century (table 1). He was awarded the Nobel Prize in Physiology and Medicine in 1912 for his work in this field and organ transplantation. In 1902, he performed the first arterial end to end anastomosis. His work was preceded by NV Eck, who in 1877 performed the first venous side to side anastomosis in dogs. German and Taffel introduced the indirect bypass by performing the first encephalomyosangiosis in animals in 1959. E Kredel was the first to perform an encephalomyosangiosis in humans but he later abandoned the procedure due to a high incidence of postoperative epilepsy. Beck (1894–1971) performed the first carotid–jugular fistula in 1949.

In the first half of the 20th century, it was believed that the majority of strokes were the result of vasospasm. Fisher challenged this notion and promoted the theory that stroke was associated with carotid artery disease.

Independent advancements in surgical magnification and the advent of microsurgery were occurring simultaneously (table 2). Ophthalmologist Edwin Theodore Saemisch of Bonn introduced the first binocular magnifying device to the operating room in 1876. Surgical microscopes and teleloupes were incorporated into the medical laboratories in the early 20th century and used in medical experiments. Theodore Kurze at the University of Southern California was the first to use an operating microscope for a neurosurgical procedure when he removed a benign tumor from the seventh nerve of a 5-year-old patient in 1957. Working in the lab of RMP Donaghy at the University of Vermont in 1961, general vascular surgeon Julius Jacobsen and Ernesto Suarez described the technique for performing a vascular anastomosis using the operative microscope. Jacobsen subsequently performed the first human microneurosurgical procedure with Donaghy in 1962. The procedure, an endarterectomy of the middle cerebral artery (MCA), failed. Donaghy went on to perform nine MCA endarterectomies and embolectomies; only two were noted to remain patent. Donaghy worked with Hans Littman of Zeiss to develop microsurgical instruments, and Donaghy noted a 66% revascularization patency rate for microvascular anastomotic techniques in his laboratory in 1965.

In 1961, Pool and Potts reported the first documented EC–IC bypass. They performed a superficial temporal artery (STA) to anterior cerebral artery bypass using a plastic tube as the conduit. The patient recovered well following the surgery and returned to work. However, an angiogram performed within the first 2 weeks following surgery demonstrated complete occlusion of the graft. Woringer and Kunlin performed a common carotid artery (CCA) to internal carotid artery (ICA) bypass using a saphenous vein graft in 1963. Yasargil worked in Donaghy’s laboratory.

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and improved the original microsurgical techniques of Suarez and Jacobsen.\textsuperscript{15} Yasargil refined his techniques in a canine model prior to performing the first successful EC-IC bypass in Zurich in 1967 for an occluded ICA.\textsuperscript{20, 21} Later in 1972, Yasargil performed the first STA–MCA bypass for moyamoya in a 4-year-old patient with right hemiplegia and anarthria. His contributions to the field included his role in assisting Littman in developing a counterbalanced microscope as well as designing novel microsurgical instruments, aneurysm clips and clip applicers.\textsuperscript{22} An additional significant advancement was introduced with the development of bipolar cautery, which Yasargil incorporated in his microneurosurgical work.

Numerous other surgeons made significant contributions to further the field of cerebral revascularization (Table 3). The first successful EC–IC bypass using a saphenous vein graft (common carotid artery to intracranial ICA) was performed in 1971 by William Loughseed in Toronto, Canada.\textsuperscript{23} Sundt introduced the use of EC–IC bypass for treatment of unclippable aneurysms.\textsuperscript{24} Robert Spetzler performed the first bonnet bypass in which an extracranial graft is passed from one side of the head to the other for anastomosis. Spetzler also pioneered the use of barbiturates for metabolic protection during temporary clipping as well as using heparin for graft and parent vessel protection during vascular occlusion.\textsuperscript{25} Sekhar and Ausman made numerous contributions as well.\textsuperscript{26} Sekhar and Spetzler independently described the use of vascular bypass for use in cranial base tumors while Morimoto pioneered the use of radial artery grafts for aneurysm bypass. With the advent of these techniques, patency rates greater than 95% were seen.\textsuperscript{27} Others have described the use of the internal maxillary artery as a donor.\textsuperscript{28}

Recent advances in cerebral revascularization include the use of ultrasonic perivascular flow probe (flow assisted surgical technique) and magnetic resonance flow quantification to assess the need for bypass and to aid in selecting an appropriate conduit for grafting.\textsuperscript{29–31} The intracranial Excimer Laser Assisted Non-occlusive Anastomosis (ELENA) and recently introduced Sutureless Excimer Laser Assisted Non-occlusive Anastomosis (SELENA) allow for bypass without occlusion of the parent vessel.\textsuperscript{32, 33} Dacey recently introduced the Cardica C-Port xA device for automated anastomosis.\textsuperscript{34} The micro Doppler probe and indocyanine green have also contributed to surgical efficacy.

### Table 1: History of surgical revascularization

<table>
<thead>
<tr>
<th>Surgeon and year pioneered</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alexis Carrel, 1902\textsuperscript{2}</td>
<td>First arterial end to end anastomosis (utilizing fine suture material and triangulation)</td>
</tr>
<tr>
<td>German and Taffel, 1939\textsuperscript{4}</td>
<td>First encephalomyosynangiosis (transposition of a vascular muscle flap onto the cortex in dogs and primates)</td>
</tr>
<tr>
<td>Kredel, 1942\textsuperscript{5}</td>
<td>First encephalomyosynangiosis in humans (later abandoned due to high incidence of seizures)</td>
</tr>
<tr>
<td>Beck, 1949\textsuperscript{6}</td>
<td>Carotid–jugular fistula</td>
</tr>
<tr>
<td>Henschel, 1950\textsuperscript{7}</td>
<td>First encephalomyosynangiosis for carotid occlusion and seizure</td>
</tr>
<tr>
<td>Eck, 1877\textsuperscript{3}</td>
<td>First vascular anastomosis (side to side: hepatic vein to inferior vena cava in dogs) ‘Eck fistula’</td>
</tr>
</tbody>
</table>

### Table 2: History of magnification/microscope

<table>
<thead>
<tr>
<th>Surgeon and year pioneered</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saemisch, 1876\textsuperscript{26}</td>
<td>First binocular magnifying device for surgery Built and used first surgical microscope (chronic otitis media)</td>
</tr>
<tr>
<td>Nylen, 1921\textsuperscript{27}</td>
<td>Operating microscope for neurosurgical procedure</td>
</tr>
<tr>
<td>Kurz, 1957\textsuperscript{18} (University of Southern California)</td>
<td>First human microsurgical procedure in neurosurgery (MCA endarterectomy) failed; only two of nine MCA endarterectomies/ embolectomies remained patent.</td>
</tr>
<tr>
<td>Jacobsen, 1962\textsuperscript{14} (with Donaghy)</td>
<td></td>
</tr>
</tbody>
</table>

MCA, middle cerebral artery.

### Table 3: History of microsurgical cerebral revascularization

<table>
<thead>
<tr>
<th>Surgeon and year pioneered</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pool and Potts, 1961\textsuperscript{17}</td>
<td>STA–ACA bypass with plastic tube; first attempted revascularization; patient recovered well and returned to work; angio less than 2 weeks following procedure showed occlusion of graft</td>
</tr>
<tr>
<td>Worringer and Kunlin, 1963\textsuperscript{19}</td>
<td>First EC–IC bypass (CCA–ICA w/saphenous vein); patient did not survive but graft patent on autopsy</td>
</tr>
<tr>
<td>Jacobson and Suarez, 1960\textsuperscript{12} (in Donaghy’s lab)</td>
<td>Described technique of vascular anastomosis using operative microscope</td>
</tr>
<tr>
<td>Yasargil, 1967\textsuperscript{20} (in Donaghy’s lab)</td>
<td>First EC–IC bypass; STA–MCA in a dog</td>
</tr>
<tr>
<td>Yasargil, 1967\textsuperscript{20} (in Zurich; in Vermont, June 7)</td>
<td>Ec–IC bypass of occluded ICA</td>
</tr>
<tr>
<td>Loughseed, 1971\textsuperscript{21}</td>
<td>First EC–IC bypass with saphenous vein graft</td>
</tr>
<tr>
<td>Yasargil, 1972\textsuperscript{22}</td>
<td>Occipital artery to MCA bypass</td>
</tr>
<tr>
<td>Spetzler and Charter, 1974\textsuperscript{25}</td>
<td>CCA–ICA bypass</td>
</tr>
<tr>
<td>Tew, 1975\textsuperscript{23}</td>
<td>Occipital artery–PICA bypass</td>
</tr>
<tr>
<td>Ausman, 1976\textsuperscript{24}</td>
<td>First EC–IC bypass with radial artery graft</td>
</tr>
<tr>
<td>Ausman, 1978\textsuperscript{24}</td>
<td>STA–SCA bypass</td>
</tr>
<tr>
<td>Sundt and colleagues, 1970s\textsuperscript{24}</td>
<td>Posterior fossa revascularization for occlusive disease, vertebrobasilar insufficiency, and unclippable aneurysms</td>
</tr>
<tr>
<td>Nishikawa, 1979\textsuperscript{27}</td>
<td>MMA–MCA bypass</td>
</tr>
<tr>
<td>Spetzler and Matusushima, 1980\textsuperscript{27, 30}</td>
<td>Encephaloduroarteriovenangiosis</td>
</tr>
<tr>
<td>Sundt, 1981\textsuperscript{24}</td>
<td>SCA–PCA bypass</td>
</tr>
<tr>
<td>Sundt, 1982\textsuperscript{24}</td>
<td>ECA–PCA bypass</td>
</tr>
<tr>
<td>Morimoto, 1988\textsuperscript{31}</td>
<td>Bypass with radial artery</td>
</tr>
<tr>
<td>Charbel, 2007\textsuperscript{27}</td>
<td>FAST</td>
</tr>
</tbody>
</table>

ACA, anterior cerebral artery; CCA, common carotid artery; ECA, extracranial carotid artery; EC–IC, extracranial to intracranial; FAST, flow assisted surgical technique; ICA, internal carotid artery; MCA, middle cerebral artery; MMA, middle meningeal artery; PCA, posterior cerebral artery; PI, posterior inferior cerebellar artery; SC, superficial cerebellar artery; STA, superficial temporal artery.

Anastomosis (SELENA) allow for bypass without occlusion of the parent vessel.\textsuperscript{32, 33} Dacey recently introduced the Cardica C-Port xA device for automated anastomosis.\textsuperscript{34} The micro Doppler probe and indocyanine green have also contributed to surgical efficacy.

### THE UTILITY OF THE EC–IC BYPASS

Although initially envisioned as an analogous procedure to coronary artery bypass as a treatment option for cerebrovascular ischemic and occlusive disease, cerebrovascular bypass is rarely performed for this reason today. Instead, the most common use of cerebrovascular bypass is for treatment of moyamoya disease, aneurysm trapping and vessel sacrifice.

### Moyamoya disease

Moyamoya disease was first described by Takeuchi and Shimizu in 1957, and the term ‘moyamoya’ was coined by Suzuki and Takaku in 1969.\textsuperscript{35} The word moyamoya translates to ‘puff of smoke’ and describes the angiographic picture of the abnormal vasculature at the carotid terminus and proximal MCA and anterior cerebral artery. The disease involves a narrowing of the intracranial vessels, usually involving the distal ICA or proximal anterior cerebral artery and MCA, resulting in an oligemic state; parenchymal perfusion relies on the development of collateral circulation. The cause of moyamoya disease is unknown but moyamoya variants may be secondary to numerous disease processes, including fibromuscular dysplasia, collagen vascular disease and radiation induced arteriopathy. Medical therapies including steroids, antiplatelet medications and vasodilatory
medications may be utilized. Nevertheless, in the presence of documented symptomatic reduction of cerebrovascular blood flow and diminished cerebral perfusion reserve, surgical revascularization has been shown to significantly reduce the long term incidence of ischemic events (figure 1) (see video 1 available online). In general, direct revascularization via STA—MCA bypass is reserved for late adolescent or adult patients while symptomatic children are generally offered encephaloduroarteriosynangiosis or another form of indirect revascularization. The benefit of surgery for patients who present with hemorrhage is less clear. The Japan Adult Moyamoya (JAM) trial is currently underway to evaluate whether revascularization provides a benefit for patients that present with hemorrhage.

Intracranial aneurysms

Vascular bypass for the management of difficult aneurysms is a relatively common indication. EC–IC bypass is considered either when sacrifice of the parent vessel or a major branch vessel is anticipated or as a prophylactic measure when parent vessel sacrifice may be necessary during aneurysm clipping (figure 2, figure 3, and see video 2 available online). Generally, such aneurysms are fusiform in shape and giant in size and may have critical branches emanating from the neck or dome. In addition to utilization of the STA, the increased blood flow requirements caused by major branch occlusion required in the treatment of some giant aneurysms necessitate the use of more than one donor STA branch or other donor grafts, such as radial artery (figure 4). In the posterior fossa, alternatives include use of the occipital artery (figure 5). Some surgeons have recently begun to employ in situ IC–IC bypass in the setting of complex aneurysm surgery. Continued advances in endovascular treatment methods may result in additional treatment options in the future, flow diverting stents holding particular promise. Nevertheless, the use of revascularization for the treatment of complex aneurysms will continue to be a necessary tool in a significant number of cases.

Other indications

Intracranial bypass has been used by a number of skull base surgeons when resecting tumors that enace the ICA. Advocates cite that bypass facilitates resection of the tumor and thus helps to improve overall patient outcome. Others have cited that preservation of the normal vessel should be attempted, if possible. With certain tumors, such as slow growing malignant tumors and even some meningiomas, complete dissection away from the carotid artery is impossible as the tumors invade the wall of the vessel. In practice, the use of bypass in the treatment of tumors is rarely indicated or

Figure 1  Left internal carotid artery injection in a woman in her 30s with ischemic symptoms referable to the left hemisphere demonstrates the classic moyamoya pattern of internal carotid artery occlusion, with reconstitution of small diffuse arterial branches (A). Following revascularization via double barrel bypass of the superficial temporal artery and middle cerebral artery (MCA) (see video 1 available online; ©University Hospitals Case Medical Center), there is filling of the intracranial circulation in the MCA distribution as seen on an external carotid artery injection (B, arrows).

Figure 2  Three-dimensional angiogram showing a giant partially thrombosed right internal carotid artery (ICA) aneurysm in a man in his 40s (A). He also had an 8 mm anterior communicating (ACOMM) artery aneurysm (not shown). Treatment consisted of a superficial temporal artery (STA) and middle cerebral artery (MCA) bypass followed by clipping the ACOMM artery aneurysm and trapping the ICA aneurysm. Postoperative angiography confirms occlusion of the giant aneurysm (B) and filling of the MCA territory via the STA (C). A video of the surgical procedure is available online (see video 2 online; ©University Hospitals Case Medical Center.)
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Figure 3  Angiogram demonstrating a giant right middle cerebral artery (MCA) aneurysm in a teenage boy (A). This aneurysm arises at the take-off of the anterior temporal artery (B). Following a double barrel bypass from the superficial temporal artery (STA) to the MCA distal branches, a resulting pattern of competing flow leads to the aneurysm thrombosis (C). Postoperative angiography at 6 months demonstrates thrombosis of the aneurysm (D) and maturation of the bypass, with early arterial filling of the STA (E, arrows). A late phase image confirms flow in the distal MCA distribution (F).

Figure 4  Left internal carotid artery injection demonstrating a fusiform internal carotid artery aneurysm in a woman in her 30s. Following balloon test occlusion, she developed ischemic symptoms and evidence of diminished left cerebral perfusion. Subsequently, she was treated by surgical trapping following bypass to the middle cerebral artery (MCA) with a radial artery graft, which was well tolerated and supplied the MCA circulation (B).

utilized with the advent of radiosurgical treatment options, such as Gamma Knife or CyberKnife.

THE EC–IC BYPASS TRIAL

In the 1970s, the majority of bypasses were performed for vascular stenosis or occlusion. The EC–IC Bypass Study Group began a trial in 1977 to test the benefit of STA–MCA bypass for stroke prevention. The results were published in 1985.45 46 A total of 1577 patients were randomized to either the medical arm, which included blood pressure control and aspirin, or the surgical arm, which consisted of the same medical therapy plus surgical bypass. Patients with strokes prior to randomization were included in an intent to treat analysis. After randomization, 118 patients were excluded. The trial included patients with stenosis or occlusion in the ICA above the level of C2 or in the MCA. Additionally, patients with a transient ischemic attack or cerebrovascular accident in the anterior circulation within the past 3 months were included. The primary end points were fatal and non-fatal strokes. The average study follow-up was more than 55 months, and no patient had less than a 35 month follow-up. No patients were lost to follow-up. The patients had a graft patency greater than 96%.

The final results of the trial indicated that surgery did not improve outcome. Indeed, patients who underwent surgery had increased incidence and earlier timing of non-fatal and fatal strokes compared with the medical arm. Secondary survival analyses were commiserative. The findings of the study came as a surprise to many. Patients with symptomatic ICA occlusions with stenosis or occlusion in the ICA above the level of C2 or in the MCA. Additionally, patients with a transient ischemic attack or cerebrovascular accident in the anterior circulation within the past 3 months were included. The primary end points were fatal and non-fatal strokes. The average study follow-up was more than 55 months, and no patient had less than a 35 month follow-up. No patients were lost to follow-up. The patients had a graft patency greater than 96%.

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Conversely, they noted that hospitals with higher
In constructing a logistic
A stronger criticism of the EC
Increased OEF measured by PET in the hemisphere
or lack of autoregulatory failure.48
trial was that it did not segregate patients based on the presence
throughout the 1990s, the mortality rates from bypass surgery
vascular disease and aneurysms from 1992 to 2001 and found that,
the rate of bypass surgical procedures for occlusive cerebrovas-
procedures for ischemia. Amin-Hanjani and colleagues looked at
insurance companies began to reject claims for revascularization
was conducted.2
investigators, such a method of subdividing patients by the
angiographic criteria alone for inclusion. In fairness to the trial
presence or absence of reserve did not exist at the time the trial
In the setting of severe stenosis or vessel occlusion, perfusion
pressure beyond the site of blockage is diminished. In compen-
sated or stage I hemodynamic failure, vasodilation of arterioles
and leptomeningeal collaterals allow for maintenance of cerebral
hemodynamic impairment (stage II failure) or even paradoxical decrease in blood flow as blood is shunted into other dilated vessels (‘steal phenomenon,’ severe stage I failure). In decompensated or stage II hemody-
namic failure, the compensatory measures become insufficient, and cerebral blood flow begins to decline. In this scenario, cerebral metabolic requirements are attempted to be met by an increased oxygen extraction fraction (OEF) which may be measured by ^15^O positron emission tomography (PET).56–60
Additional methods for assessing cerebral hemodynamics include the following: xenon-CT,61–63 single photon emission CT,64 65 CT angiography and perfusion, MR angiography and perfusion,66 67 and transcranial Doppler.68–70 Each of these modalities has advantages and limitations.

The St Louis Carotid Occlusion Study by Powers et al was a blinded prospective study demonstrating an association between cerebral hemodynamic impairment (stage II failure) and stroke.50 Increased OEF measured by PET in the hemisphere ipsilateral to the carotid occlusion was associated with an increased risk for ipsilateral stroke and all stroke. Other studies had similar findings, using a variety of methods for assessing cerebral hemodynamics.71

In light of these findings, many have argued that if the patients
in the original EC–IC bypass trial had been selected based on the
presence of vessel occlusion with stage II or decompensated hemodynamic failure, then perhaps a benefit for bypass would have been seen. In 2009, Garrett et al performed a systematic review of the literature for surgical revascularization to treat symptomatic hemodynamic failure secondary to athero-occlusive disease since the EC–IC bypass trial.72 In constructing a logistic regression of the pooled studies that have been performed, including six that report postoperative stroke rates in patients with hemodynamic failure undergoing EC–IC bypass, they found that patients with severe stage I hemodynamic failure have a significantly higher stroke rate than those with mild stage I hemodynamic failure. Patients with stage II hemodynamic failure

A fusiform ruptured aneurysm arising at the origin of the posterior inferior cerebellar artery (PICA) is shown in anterior-posterior (A) and
oblique views (B) in a man in his 40s. Following positioning for a far lateral craniotomy, the occipital artery is harvested (C) and utilized in an end to side bypass to the distal PICA with trapping of the aneurysm. Postoperative angiography demonstrates occlusion of the aneurysm (D) with filling of the PICA territory through the occipital artery via an external carotid artery injection (E).

Figure 5
trended toward a higher stroke rate than those with mild stage I failure but significance was not found, likely due to the small sample size. Patients with severe hemodynamic failure were found to respond better to surgery than those with mild disease. Therefore, patients with either severe stage I hemodynamic failure or stage II hemodynamic failure may benefit from revascularization. Clinically, it does seem that there exists a subset of patients in whom the progression of ischemic symptoms may be arrested following direct revascularization (figure 6).

Several important studies are currently underway to evaluate this hypothesis. The Carotid Occlusion Surgery Study (COSS) is an ongoing multicenter, randomized, controlled trial that seeks to demonstrate whether STA–MCA anastomosis for patients with symptomatic ICA occlusion and stage II hemodynamic failure (ipsilateral increased OEF) performed within 120 days of symptoms can reduce the rate of subsequent ipsilateral ischemic stroke by 40% at 2 years. Enrollment for COSS is expected to be completed in 2013 or 2014. PET determined OEF is used in this study as a key inclusion criterion. The ratio of the OEF on the side ipsilateral to the occlusion to that of the contralateral side must be greater than 1.130. Primary end points include all death and all strokes within 30 days. A follow-up of 2 years is planned. Randomized Evaluation of Carotid Occlusion and Neurocognition (RECON) is an ancillary trial that seeks to elucidate the relationship between cerebral hemodynamics and cognitive function in patients undergoing treatment for symptomatic ICA occlusion.

### Table 4
Consecutive bypass procedures by senior author (NCB) over a consecutive 12 month period. Overall graft patency was 90% at 30 days, with a 9% incidence of new stroke or disability.

<table>
<thead>
<tr>
<th>No</th>
<th>Indication for surgery</th>
<th>Type of anastomosis</th>
<th>Graft patency at 30 days with modality of verification</th>
<th>New disability or stroke at 30 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Aneurysm ICA</td>
<td>STA–MCA</td>
<td>Yes—CTA</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>Aneurysm MCA</td>
<td>MCA–MCA</td>
<td>Yes—CTA</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>Occlusive disease</td>
<td>STA–MCA</td>
<td>Yes—CTA</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>Occlusive disease</td>
<td>STA–MCA</td>
<td>Not verified</td>
<td>Died of disease post op day 4</td>
</tr>
<tr>
<td>5</td>
<td>Aneurysm ICA</td>
<td>Radial artery–MCA</td>
<td>Yes—CTA</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>Moyamoya</td>
<td>STA–MCA (bilateral; staged procedure)</td>
<td>Yes—angiogram</td>
<td>No</td>
</tr>
<tr>
<td>7</td>
<td>Moyamoya</td>
<td>STA–MCA</td>
<td>Yes—CTA</td>
<td>No</td>
</tr>
<tr>
<td>8</td>
<td>Aneurysm ICA</td>
<td>STA–MCA</td>
<td>Yes—CTA</td>
<td>No</td>
</tr>
<tr>
<td>9</td>
<td>Occlusive disease</td>
<td>ACA–ACA</td>
<td>Yes—angiogram</td>
<td>No</td>
</tr>
<tr>
<td>10</td>
<td>Traumatic cervical dislocation with vertebral artery injury</td>
<td>Occipital artery–vertebral artery</td>
<td>No—CTA</td>
<td>No</td>
</tr>
<tr>
<td>11</td>
<td>Moyamoya</td>
<td>STA–MCA</td>
<td>Yes—CTA</td>
<td>No</td>
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</tbody>
</table>

ACA, anterior cerebral artery; CTA, CT angiogram; ICA, internal carotid artery; MCA, middle cerebral artery; STA, superficial temporal artery.
unilateral carotid occlusion with EC–IC bypass in the COSS trial. The Japanese EC–IC bypass trial is a prospective multicenter trial to evaluate the benefit of bypass surgery for patients with symptomatic major cerebral occlusive disease and evidence of hemodynamic cerebral ischemia defined by cerebral blood flow measurements and neuropsychological function. A follow-up period of 2 years is planned.\textsuperscript{74} The second phase of the trial examines stroke recurrence rate on medical therapy for patients with stage I hemodynamic failure, as determined by cerebrovascular reserve and rest cerebral blood flow measurements gathered from paired blood flow studies after administration of a cerebral vasodilatory stimulus. The study seeks to identify a subgroup of patients with stage I hemodynamic failure that may benefit from bypass surgery. Finally, the JAM trial is a multicenter, randomized study seeking to determine the benefit of bypass revascularization for patients with moyamoya disease who present with hemorrhagic stroke.

**THE FUTURE OF EC–IC BYPASS**

Cerebral revascularization currently remains an important tool for the vascular neurosurgeon. Detractors of the procedure suggest that revascularization surgery will soon become nearly obsolete, relegated to limited practice at a limited number of highly specialized centers. These detractors point to the current trend towards fewer revascularization procedures as a sign of the times. They believe that the multicenter trials currently underway will not show a significant benefit for revascularization surgery in patients with stage II hemodynamic failure. They also note, with the further development of endovascular flow diverting stents and current use of adjunctive or primary radiosurgery for skull base tumors, indications for bypass surgery will continue to decline.

Supporters of the procedure see things quite differently. They anticipate resurgence of surgical bypass procedures for severe intracranial major vessel stenosis and/or occlusion after the current studies demonstrate a definite benefit for patients with evidence of decompensated cerebral hemodynamic failure that undergo bypass surgery. They point to continually improving techniques and methods and argue that, as the procedure volume increases, the associated surgical morbidity will decline. They also argue that, even with the advent of endovascular flow diversion, certain types of aneurysms may still be better treated with revascularization surgery, such as aneurysms in which branch vessels emanate from the neck or dome of the aneurysm and require transplantation prior to aneurysm occlusion.

**CONCLUSION**

The use of EC–IC bypass procedures remains an important therapeutic modality in the treatment of complex aneurysms when revascularization is required. Although overall its use is declining due to advances in endovascular techniques for the treatment of skull base tumors and endovascular technology in the treatment of aneurysms, it remains an elegant procedure necessary in certain cases and relatively common in specialized neurosurgical tertiary care centers (table 4). Its use in the treatment of ischemic occlusive disease continues to be refined and re-evaluated based on landmark studies currently underway.

**Competing interests None.**

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**REFERENCES**

Open surgery


