

Indications and Outcomes of Prophylactic and Therapeutic Extracranial-to-intracranial Arterial Bypass for Cerebral Revascularization

Emre Gazyakan, MD, MSc*
 Ching-Yi Lee, MD†
 Chieh-Tsai Wu, MD†‡
 Chung-Kan Tsao, MD‡§
 Randall Craft, MD¶
 Steven L. Henry, MD||
 Ming-Huei Cheng, MD,
 MBA‡§
 Shih-Tseng Lee, MD†

Background: Extracranial-to-intracranial (EC-IC) arterial bypass is a technically demanding procedure used to treat complex cerebral artery diseases. The indications, proper surgical techniques, and outcomes of this procedure have been under debate over the recent decades.

Methods: Between January 2004 and December 2012, 28 patients, including patients with cerebral artery occlusion, intracranial aneurysm, cranial base tumor, and Moyamoya disease, underwent EC-IC bypass. Patients' records were retrospectively reviewed for demography, indications, complications, high-flow versus low-flow bypass, patency rate of bypass, and neurological outcome. The patients were sorted into prophylactic ($n = 16$) and therapeutic ($n = 12$) groups based on the preoperative presentation of their neurological symptoms. Follow-up evaluation was performed at a mean of 32.7 ± 24.3 months.

Results: The overall patency rate of bypass was 100%, the postoperative stroke rate was zero, and the surgical complication rate was 14.3%. There was no significant difference in the bypass patency rate between the 2 groups or between the high-flow and low-flow bypass patients. Patients who underwent prophylactic bypass had minimal surgical and total complications ($P = 0.03$ and $P < 0.01$, respectively) and a better neurological outcome. Surgical complications were more common in patients who underwent therapeutic bypass (25%).

Conclusions: The collaboration of neurosurgeons and plastic surgeons in performing EC-IC bypass can result in excellent outcomes with a high bypass patency rate and few complications, particularly for prophylactic EC-IC bypass. (*Plast Reconstr Surg Glob Open* 2015;3:e372; doi: 10.1097/GOX.0000000000000339; Published online 10 April 2015.)

In 1970, Yasargil et al¹ reported the first extracranial-to-intracranial (EC-IC) arterial bypass, in which the superficial temporal artery (STA) was

anastomosed to the middle cerebral artery (MCA) as a treatment for an occluded internal carotid artery

From the *Department of Hand, Plastic and Reconstructive Surgery, BG Trauma Center Ludwigshafen, University of Heidelberg, Ludwigshafen, Germany; †Department of Neurosurgery, Chang Gung Memorial Hospital, College of Medicine, Chang Gung University, Taoyuan, Taiwan; ‡Center for Tissue Engineering, Chang Gung Memorial Hospital, Taoyuan, Taiwan; §Division of Reconstructive Microsurgery, Department of Plastic and Reconstructive Surgery, Chang Gung Memorial Hospital, College of Medicine, Chang Gung University, Taoyuan, Taiwan; ¶Plastic and Reconstructive Surgery, Banner MD Anderson Cancer Center, Gilbert, Ariz.; and ||Institute of Reconstructive Plastic Surgery, Seton Institute of Reconstructive Plastic Surgery, Austin, Tex.

Drs. Gazyakan and Lee contributed equally to this work.

Received for publication September 23, 2014; accepted February 9, 2015.

Disclosure: The authors have no financial interest to declare in relation to the content of this article. The Article Processing Charge was paid for by the authors.

Presented at the 2013 Annual Meeting of American Society of Plastic Surgeons, October 11–15, 2013, San Diego, Calif., and 2014 Annual Meeting of American Society for Reconstructive Microsurgery, January 11–14, 2014, Kauai, Hawaii.

Copyright © 2015 The Authors. Published by Wolters Kluwer Health, Inc. on behalf of The American Society of Plastic Surgeons. All rights reserved. This is an open-access article distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 3.0 License, where it is permissible to download and share the work provided it is properly cited. The work cannot be changed in any way or used commercially.

DOI: 10.1097/GOX.0000000000000339

(ICA). The procedure gained some popularity, and the indications have recently expanded to include not only cerebral ischemia but also Moyamoya disease (MMD, which is marked by the gradual stenosis of bilateral internal carotid arteries, typically affects teenagers and young adults, and is largely resistant to medical treatment),²⁻⁵ intracranial aneurysms, and intracranial tumors.⁶

In 1985, a randomized trial failed to demonstrate the superiority of EC-IC bypass to the best medical treatments available for reducing the risk of ischemic stroke.⁷ As a consequence, the frequency of these operations declined sharply.^{8,9} However, this study was later criticized for several design flaws, including inappropriate cohort assignments and the involvement of mostly low-volume centers and surgeons.¹⁰ A post hoc analysis confirmed that EC-IC bypass is indeed an effective treatment for MMD and for atherosclerotic disease, particularly for those with poor cerebrovascular reserve, inadequate collateral flow, and posterior circulation disease,¹¹ and Schaller¹² later demonstrated that neurologic function and stroke risk can be significantly improved by EC-IC bypass.¹⁰ Currently, there are many conditions for which EC-IC bypass is becoming the standard therapy, including MMD, certain tumors encasing the branches of the ICA in the skull base,^{13,14} and giant aneurysms that require ligation or the clipping of the ICA or its branches.^{14,15}

Its resurgence in popularity notwithstanding, EC-IC bypass remains a technically demanding procedure that requires considerable microvascular skill and experience. In this light, we have previously described a beneficial collaboration between neurosurgeons and reconstructive microsurgions performing EC-IC bypass, reporting 3 successful cases.¹⁶ This study was performed to investigate the indications, technical considerations, complications, and clinical outcomes for both prophylactic and therapeutic EC-IC bypass.

PATIENTS AND METHODS

A retrospective review of 28 consecutive patients who underwent EC-IC bypass at the Chang Gung Memorial Hospital between January 2004 and December 2012 was conducted after Institutional Review Board approval (# IRB-103-4535B) (Table 1). To be clear, EC-IC bypass has been performed by neurosurgeons around the world and at our institution for many years, and the clinical decision to perform this procedure was made according to the judgment of the attending neurosurgeon(s). This series of patients differs only in that the procedure was performed in conjunction with a plastic surgeon with microvascular expertise. This retrospective study therefore served primarily to highlight the out-

comes of this collaboration between neurosurgeons and microsurgions. Secondarily, we explored whether outcomes were different in patients undergoing the procedure because they had had episode(s) of cerebral ischemia/infarction (ie, therapeutic intervention) or because they had been found to be at high risk of ischemia/infarction (ie, prophylactic intervention). As such, patients were retrospectively categorized into prophylactic (group A; Table 1) and therapeutic (group B; Table 2) groups.

Patients' records were reviewed for demography, indications, acute medical and surgical complications (especially postoperative stroke or neurological deterioration), high-flow versus low-flow bypass, patency rate of bypass, pre- and postintervention Glasgow Coma Scores, and the Medical Research Council grading of muscle power (Table 1).

Ligation of aneurysms, application of the adjustable clamp to the aneurysm, and excision of the skull base tumor were performed by the neurosurgeon, whereas the plastic surgeon focused on microvascular anastomoses and the harvest of the bypass graft when used. Postoperatively, all patients were observed in the intensive care unit under the supervision of the neurosurgeons. Graft flow was monitored using a handheld Doppler probe every hour for 24 hours and then every 2 hours for the following 3 days. No systemic anticoagulation was administered routinely, out of concern for intracranial hemorrhage. Graft patency was assessed upon discharge using angiography or magnetic resonance angiography if indicated. The length of the hospital stay was typically 1 week. Comprehensive follow-up evaluation was performed at a mean of 32.7 ± 24.3 months (range, 1–67 months).

Surgical Technique

Preoperative planning was guided by arteriography or magnetic resonance angiography. In the majority of cases, the targeted recipient artery was the insular segment of the MCA, and the donor vessel was usually the distal STA. However, the vascular imaging results and/or the intracranial pathology occasionally dictated the use of other arteries, including the anterior cerebral artery (ACA), posterior cerebral artery, and posterior inferior cerebellar artery as recipient arteries and the external carotid artery (ECA) and occipital artery as donor arteries. The different locations of the MCAs, ranging from M2 to M5, were also documented (Table 3).

The procedure began with craniotomy/intracranial exposure (and tumor extirpation or aneurysmal clipping). The dura was then incised, and the sylvian fissure was exposed for the identification of the intracranial recipient artery by the neurosurgeons.¹⁶ The target recipient site of the

Table 1. Demography, Type of Procedure, and Functional Outcome of 28 Consecutive Patients Who Underwent Extracranial-to-intracranial Arterial Bypass

Case No.	Age (y)	Sex	Site	Indication	Treatment Category	Procedure	Graft	Graft Length (cm)	Bypass Patency	Glasgow Coma Scores		Muscle Power (Upper/Lower Limb)	
										Pre-op	Post-op	Pre-op	Post-op
1	75	F	L	Giant cavernous ICA aneurysm	Prophylactic	ECA-MCA M3 bypass	GSV	20	Patent	E4V5M6	E4V5M6	L: G5/G5 R: G5/G5	L: G5/G5 R: G5/G5
2	60	F	L	ICA occlusion	Prophylactic	ECA-MCA M2 bypass	GSV	20	Patent	E4V5M6	E4V5M6	L: G5/G5 R: G5/G5	L: G5/G5 R: G5/G5
3	35	F	R	Moyamoya disease	Prophylactic	STA-MCA M4 bypass	cephalic vein	13	Patent	E4V5M6	E4V5M6	L: G3/G4 R: G5/G5	L: G4/G4 R: G5/G5
4	40	F	R	MCA occlusion	Prophylactic	STA-MCA M3 bypass			Patent	E4V5M6	E4V5M6	L: G4/G4 R: G5/G4	L: G5/G4 R: G5/G5
5	67	M	R	ICA occlusion	Prophylactic	ECA-MCA M3 bypass	GSV	23	Patent	E4V5M6	E4V5M6	L: G4/G4 R: G4/G4	L: G4/G4 R: G4/G4
6	76	F	R	ICA occlusion, MCA stenosis	Prophylactic	ECA-MCA M3 bypass	GSV	11	Patent	E4V5M6	E4V5M6	L: G4/G4 R: G5/G5	L: G4/G4 R: G4/G4
7	57	M	L	ICA occlusion	Prophylactic	STA-MCA M5 bypass	LSV	7	Patent	E4V5M6	E3V5M6	L: G5/G5 R: G4/G4	L: G4/G4 R: G4/G4
8	57	M	L	MCA occlusion	Prophylactic	STA-MCA M2 bypass	GSV	7	Patent	E4V5M6	E4V5M6	L: G5/G5 R: G5/G5	L: G5/G5 R: G5/G5
9	56	F	R	ACA aneurysm	Prophylactic	STA-ACA bypass			Patent	E4V5M6	E4V5M6	L: G3/G2 R: G4/G4	L: G4/G4 R: G5/G5
10	15	F	R	Moyamoya disease	Prophylactic	STA-MCA M4 bypass			Patent	E4V5M6	E4V5M6	L: G4/G4 R: G4/G4	L: G4/G4 R: G4/G4
11	16	F	L	Moyamoya disease	Prophylactic	STA-MCA M4 bypass			Patent	E4V5M6	E4V5M6	L: G5/G5 R: G5/G5	L: G5/G5 R: G5/G5
12	69	M	L	MCA occlusion	Prophylactic	STA-MCA M4 bypass			Patent	E4V5M6	E4V5M6	L: G5/G5 R: G5/G5	L: G5/G5 R: G5/G5
13	68	M	Bl	ICA stenosis	Prophylactic	STA-L: MCA M3 bypass			Patent	E4V5M6	E4V5M6	L: G5/G5 R: G5/G5	L: G5/G5 R: G5/G5
14	12	M	L	Moyamoya disease	Prophylactic	STA-MCA M4 bypass			Patent	E4V5M6	E4V5M6	L: G5/G5 R: G5/G5	L: G5/G5 R: G5/G5
15	30	M	L	Moyamoya disease	Prophylactic	STA-MCA M4 bypass			Patent	E4V5M6	E4V5M6	L: G5/G5 R: G5/G5	L: G5/G5 R: G5/G5
16	5	M	R	Moyamoya disease	Prophylactic	STA-MCA M4 bypass			Patent	E4V5M6	E4V5M6	L: G5/G5 R: G5/G5	L: G5/G5 R: G5/G5
17	71	F	L	Giant basilar trunk dissection aneurysm, SAH	Therapeutic	ECA-PCA P2 bypass	GSV	18	First occluded, second patent	E1V1M4	E1V1M4	L: G2/G1 R: G3/G2	L: G1/G1 R: G1/G1
18	55	F	R	ICA aneurysm, SAH	Therapeutic	STA-MCA M3 bypass			Patent	E4V5M6	E4V5M6	L: G5/G5 R: G5/G5	L: G4/G4 R: G4/G3
19	69	F	R	ICA occlusion, SAH	Therapeutic	STA-MCA M4 bypass			Patent	E4V5M6	E4V5M6	L: G3/G4 R: G5/G5	L: G4/G4 R: G5/G5
20	60	F	L	PCOMA aneurysm, SAH	Therapeutic	OA-PICA bypass			Patent	E3VeM5	E4V5M6	L: G4/G4 R: G4/G4	L: G3/G3 R: G3/G3
21	48	M	R	Giant basilar aneurysm, SAH	Therapeutic	STA-MCA M3 bypass	GSV	10	Patent	E4V5M6	E4V5M6	L: G5/G5 R: G5/G5	L: G4/G4 R: G4/G4
22	61	M	L	Cranial base meningioma	Therapeutic	STA-MCA M3 bypass	GSV	12	Patent	E4V5M6	E1V1M4	L: G5/G5 R: G5/G5	L: G1/G1 R: G1/G1

(Continued)

Table 1. (Continued)

Case No.	Age (y)	Sex	Site	Indication	Treatment Category	Procedure	Graft	Graft Length (cm)	Bypass Patency	Glasgow Coma Scores		Muscle Power (Upper/Lower Limb)	
										Pre-op	Post-op	Pre-op	Post-op
23	32	M	L	Cranial base paraganglioma	Therapeutic	STA-MCA M2 bypass	GSV	10	Patent	E4V5M6	E4V5M6	L: G3/G3 R: G4/G4	L: G5/G5 R: G5/G5
24	48	F	R	ICA occlusion, cerebral infarction	Therapeutic	STA-MCA M3 bypass	LSV	8	Patent	E4V5M6	E4V5M6	L: G4/G4 R: G5/G5	L: G4/G4 R: G5/G5
25	93	F	L	ICA occlusion, cerebral infarction	Therapeutic	STA-MCA M2 bypass			Patent	E4V5M6	E4V5M6	L: G5/G5 R: G5/G5	L: G5/G5 R: G5/G5
26	54	M	R	ECA occlusion	Therapeutic	STA-MCA M4 bypass			Patent	E4V5M6	E4V5M6	L: G4/G4 R: G5/G5	L: G4/G4 R: G5/G5
27	7	F	R	Moyamoya disease	Therapeutic	STA-MCA M4 bypass			Patent	E4V5M6	E4V5M6	L: G5/G4 R: G5/G5	L: G5/G5 R: G5/G5
28	17	F	R	Moyamoya disease	Therapeutic	STA-MCA M4 bypass			Patent	E4V5M6	E4V5M6	L: G4/G5 R: G4/G5	L: G5/G5 R: G5/G5

ACA, anterior cerebral artery; E, eyes opening; F, female; G, grade; L, left; M, male; M, motor response; MCA, medial cerebral artery; OA, occipital artery; PCA, posterior cerebral artery; PCOMA, posterior communicating artery; PICA, posterior inferior cerebellar artery; R, right; SAH, subarachnoid hemorrhage; GSV, great saphenous vein graft; LSV, lesser saphenous vein V, verbal response.

Table 2. Preoperative Neurological Symptoms in 12 Patients Who Underwent Therapeutic Extracranial-to-intracranial Arterial Bypass

Neurological Symptoms	No. Patients (%)
Limb weakness	6 (50)
Dysarthria	5 (41.7)
Ataxia	4 (33.3)
Excruciating headache	3 (25)
Paresthesia	3 (25)
Facial palsy	2 (16.7)
Somnolence	2 (16.7)
Syncope	2 (16.7)
Dysphasia	1 (8.3)
Coma	1 (8.3)
Diplopia	1 (8.3)
Disorientation	1 (8.3)
Dysphagia	1 (8.3)
Global aphasia	1 (8.3)
Mild mental retardation	1 (8.3)
Transcortical motor aphasia	1 (8.3)
Vertigo	1 (8.3)
Visual acuity loss	1 (8.3)

MCA (or alternate recipient artery) was dissected. The STA (or alternate donor artery) was prepared and dissected; a length of approximately 2–8 cm was mobilized. If the need for a vein graft was anticipated, a segment of the greater saphenous, lesser saphenous, or cephalic vein of 7–23 cm in length was harvested, marking the proximal (outflow) end of the graft. The donor artery was transected distally, and vigorous pulsatile bleeding was confirmed before flushing was performed with heparinized saline and a microvascular clamp was applied.

In the high-flow setting, the initial anastomosis was performed distally between the intracranial recipient artery and the outflow end of the vein graft in an end-to-side fashion. Two single vascular microclamps (S&T, Neuhausen, Switzerland) were applied to either end because there was rarely sufficient space to apply a double microclamp. Elliptical arteriotomy was performed to match the diameter of the vein graft, and the lumen was flushed with heparinized solution. End-to-side anastomosis began on the posterior wall followed by the anterior wall of the recipient vessel, using interrupted 11-0 nylon sutures. Blood flow through the recipient artery after anastomosis served to untwist the vein graft and allow for the better assessment of the vein graft length required to reach the donor artery. Standard end-to-end anastomosis was performed using a double clamp and interrupted 9-0 or 10-0 nylon sutures between the vein graft and the donor artery. The adventitia was routinely stripped from the vein graft, allowing for adequate pulsatile flow and facilitating flow from the STA through the graft.

Table 3. Detailed Surgical Procedure Performed on Donor and Recipient Vessels with or without Vein Grafts and Location of Middle Cerebral Artery Used according to Availability

Group	No. Cases	Bypass Procedure						Recipient Vessel Segment					
		STA-MCA	ECA-MCA	STA-ACA	OA-ACA	OA-PICA	ECA-PCA	M2	M3	M4	M5	Others	Vein Graft
		N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)
A. Prophylactic	16	11 (68.8)	4 (25)	1 (6.3)	0	0	0	2 (12.5)	5 (31.3)	7 (43.8)	1 (6.3)	1 (6.3)	7 (43.8)
B. Therapeutic	12	10 (83.3)	0	0	1 (8.3)	1 (8.3)	1 (8.3)	2 (16.7)	4 (33.3)	4 (33.3)	0	2 (16.7)	5 (41.7)
Total	28	21 (75)	4 (14.3)	1 (3.6)	1 (3.6)	1 (3.6)	1 (3.6)	4 (14.3)	9 (32.1)	11 (39.3)	1 (3.6)	3 (10.7)	12 (42.9)
P		1	0.03*	1	1	1	1	0.05*	1	1	1	1	1

ACA, anterior cerebral artery; OA, occipital artery; PCA, posterior cerebral artery; PICA, posterior inferior cerebellar artery.
*Statistically significant.



Video Graphic 1. See video, Supplemental Digital Content 1, which displays how an indocyanine green (25 mg in 5 mL) was intravenously injected after the completion of anastomosis during the end-to-side EC-IC arterial bypass. The video angiography was recorded by the infrared lens of the Leica Microscope FL720 (Wetzlar, Germany) with a 820-nm filter. Fluorescence began at the superficial temporal artery at 10 seconds post indocyanine green injection and then traveled through the EC-IC arterial bypass to perfuse the ischemic middle cerebral artery territory, <http://links.lww.com/PRSGO/A95>.

In the case of low-flow bypass, the plastic surgeon performed a direct bypass between the donor artery and recipient intracranial vessel using end-to-side anastomosis as described above. The dura was repaired and tented, the calvaria was fixed with miniplates, and the burr holes were enlarged to accommodate the bypass and to prevent any compression. The scalp was closed over a suction drain without causing excessive tension.

Statistical Analysis

Statistical analysis was performed using the SPSS version 18.0 statistical software (SPSS, Chicago, Ill.). The significance was tested using Pearson’s chi-square test. A P value of < 0.05 was considered statistically significant.

RESULTS

The patients included 12 men and 16 women, with an average age of 48.3 ± 23.7 years (range, 5–93 years). Twelve patients underwent EC-IC bypass for vascular occlusion/stenosis, 8 for MMD, 6 for an aneurysm, and 2 for a tumor (Table 1). There were 21 STA-MCA and 4 ECA-MCA bypasses and 1 STA-ACA, 1 ECA-posterior cerebral artery, and 1 occipital artery-posterior inferior cerebellar artery bypass. Vein graft was used in 12 cases, with a mean graft length of 12.8 ± 5.9 cm (range, 7–23 cm) (Table 1). The ECA was significantly preferred as the donor artery in group A rather than in group B (P = 0.03), and MCA M4 was more frequently used as the recipient vessel

in group A ($P = 0.05$) (Table 3). Postoperative cerebral angiography demonstrated a complete bypass patency rate of 100% (28 of 28). There were no occurrences of postoperative stroke or surgical-related mortality during follow-up.

Sixteen patients underwent prophylactic EC-IC bypass (group A), including 2 patients with aneurysms, 6 patients with MMD, 3 patients with ICA occlusion, 3 patients with MCA occlusion, 1 patient with bilateral ICA stenosis, and 1 patient with ICA occlusion and MCA stenosis. Seven patients in group A used a vein graft as a bypass conduit (Table 3). There were no bypass failures or neurologic deterioration observed in group A (Table 1). The Glasgow Coma Scale and muscle power scores also showed improvement or remained constant (Table 1). At a mean follow-up of 30.1 ± 22.4 months, there was one complication involving a persisting hydrocephalus that occurred in 16 patients (8.3%) (Table 4).

Group B included 2 patients with cranial base tumors, 2 patients with ICA aneurysms and subarachnoid hemorrhage (SAH), 2 patients with ICA occlusion and cerebral infarction, 1 patient with a posterior communicating artery aneurysm and SAH, 1 patient with a giant basilar aneurysm and SAH, 1 patient with a giant basilar trunk dissection, 1 patient with ECA occlusion, and 2 patients with MMD (Table 1). Seven of the 12 patients (58.3%) had associated SAH or cerebral infarction. Five of the 12 patients used a vein graft as a high-flow conduit (Table 1). The average graft length in group B was 11.6 ± 3.8 cm. Seven of the 12 patients (58.3%) showed improved clinical symptoms and a stable neurological status after therapeutic EC-IC bypass (Table 1). One patient (case no. 17) with a symptomatic giant basilar trunk dissection aneurysm had neurological deterioration after a failed first EC-IC bypass and underwent a second revisional bypass on post-op day 4, which remained patent (Table 1). The clinical course was further impaired by respiratory failure, pneumonia, and meningitis. However, with appropriate medical care, the patient's symptoms remained stable.

Twelve of the 28 patients (42.9%) were treated with a high-flow bypass (9 great saphenous veins, two lesser saphenous and one cephalic vein). There were no significant differences in bypass patency, surgical complications, and total complications between the groups with and without vein grafts (Table 5).

In total, 11 complications developed in 28 patients (39.3%) (Table 4). One patient with cranial base meningioma died at 6 months after surgery from tumor progression after being discharged to

Table 4. Outcome Analysis of 28 Consecutive Patients Who Underwent Either Prophylactic or Therapeutic Extracranial-to-intracranial Arterial Bypass

Group	No. Cases	Age (y/o)	Mean \pm SD	Low-Flow EC/IC	High-Flow EC/IC	Vein Graft	Vein graft Length (cm)	Bypass Patency	Complications				Follow-up Mean \pm SD (mo)
									Surgical Complications	Medical Complications	Other Complications	Total Complications	
A. Prophylactic	16	48.8 \pm 22.6	9 (56.3)	7 (43.8)	13.6 \pm 7.2	16 (100)	0	1 (8.3)	0	1 (8.3)	1 (8.3)	30.1 \pm 22.4	
B. Therapeutic	12	47.7 \pm 26.2	7 (58.3)	5 (41.7)	11.6 \pm 3.8	12 (91.7)	4 (25)	4 (25)	2 (12.5)	10 (62.5)	10 (62.5)	36.2 \pm 27.1	
Total	28	48.3 \pm 23.7	16 (57.1)	12 (42.9)	12.8 \pm 5.9	28 (100)	4 (14.3)	5 (17.9)	2 (7.1)	11 (39.3)	11 (39.3)	32.7 \pm 24.3	
P		0.9	1	1	1	1	0.03*	0.4	0.5	<0.01*	<0.01*	0.5	

*Statistically significant.

Table 5. Comparisons of Outcomes and Complications for Extracranial-to-intracranial Arterial Bypass with and without the Use of Vein Grafts

Group	No. Cases	Age Mean ± SD (y/o)	Low-Flow EC/IC N (%)	High-Flow EC/IC N (%)	Bypass Patency N (%)	Complications				Follow-up Mean ± SD (mo)
						Surgical Complications N (%)	Medical Complications N (%)	Other Complications N (%)	Total Complications N (%)	
Vein graft	12	58.9 ± 12.6	0 (0)	12 (100)	12 (91.7)	2 (16.7)	3 (25)	0 (0)	6 (50)	50.8 ± 21.3
Nonvein graft	16	40.4 ± 27.2	16 (100)	0 (0)	16 (100)	2 (12.5)	2 (12.5)	2 (12.5)	5 (31.3)	19.2 ± 16.4
Total	28	48.3 ± 23.7	16 (57.1)	12 (42.9)	28 (100)	4 (14.3)	5 (17.9)	2 (7.1)	11 (39.3)	32.7 ± 24.3
P		0.03*	<0.01*	<0.01*	1	1	0.6	0.5	0.4	<0.01*

*Statistically significant.

a nursing facility. One patient had a residual tumor after resection of the cranial base paraganglioma at 14-month follow-up. Outcome analysis between the prophylactic (group A) and therapeutic (group B) groups is summarized in Table 4. The surgical and total complications in group B were 25% and 62.5%, respectively, which were significantly greater than those in group A ($P = 0.03$ and $P < 0.01$, respectively) (Table 4). Although the overall complication rate was fairly high, it must be remembered that these were very morbid patients with a life-threatening condition in whom the risk of doing nothing was extremely high. Furthermore, as many complications were medical and not surgical, and hence attributable largely to the patients' comorbidities rather than to the procedure, the risk-to-benefit ratio, in our opinion, was therefore favorable.

Case Presentations

A 48-year-old woman presented with symptoms of acute cerebral infarction with acute onset of limb weakness and moderate dysarthria and dysphagia. Emergent preoperative computed tomographic angiography demonstrated right temporal infarction with right MCA occlusion (Fig. 1). Right STA-MCA bypass (M3 segment) was performed with an 8-cm great saphenous vein graft (Fig. 2). Perioperative indocyanine green video angiography provided imaging of the patent anastomosis and the restoration of brain perfusion [See Video 1, Supplemental Digital Content 1, which displays how an indocyanine green (25 mg in 5 mL) was intravenously injected after the completion of anastomosis during the end-to-side EC-IC arterial bypass, <http://links.lww.com/PRSGO/A95>]. Postoperatively, the patient was neurologically stable, and the remaining hospital stay was uneventful. At the 8-month follow-up evaluation, the patient had resumed her normal lifestyle, and angiography showed collateral perfusion to the right MCA via the right thyrocervical trunk, deep cervical artery, right ECA, right STA, and EC-IC bypass and then to the right MCA, intracranial ICA, and ACA (Fig. 3).

A 54-year-old man with right neck internal carotid dissection experiencing nearly total MCA occlusion for 1 month underwent EC-IC bypass (Fig. 4). A right STA of 2 mm in diameter was prepared with good sprouting and was directly anastomosed to the MCA M4, which was 1.2 mm in diameter (Fig. 5). At the 6-month follow-up evaluation, magnetic resonance angiography revealed collateral perfusion to the right MCA via the right ECA, right STA, and EC-IC bypass and then to the right MCA (Fig. 6).

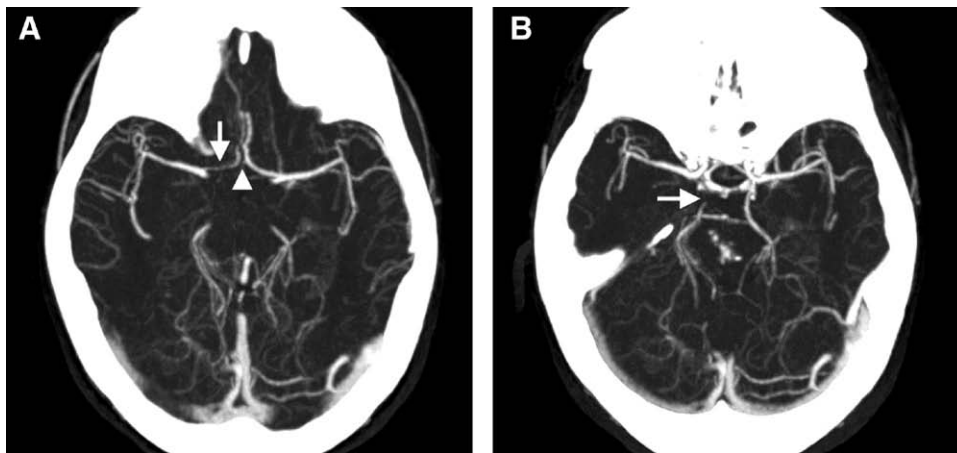


Fig. 1. A, Preoperative CT angiography of a 48-year-old woman with infarction in right middle cerebral arterial territory. Note tiny right anterior cerebral artery A1 segment (arrow) and significant focal stenosis of tiny anterior communicating artery (arrowhead). B, Preoperative CT angiography of a 46-year-old woman with infarction in right middle cerebral arterial territory. Note significant focal stenosis of tiny right posterior communicating artery (arrow). CT indicates computed tomography.

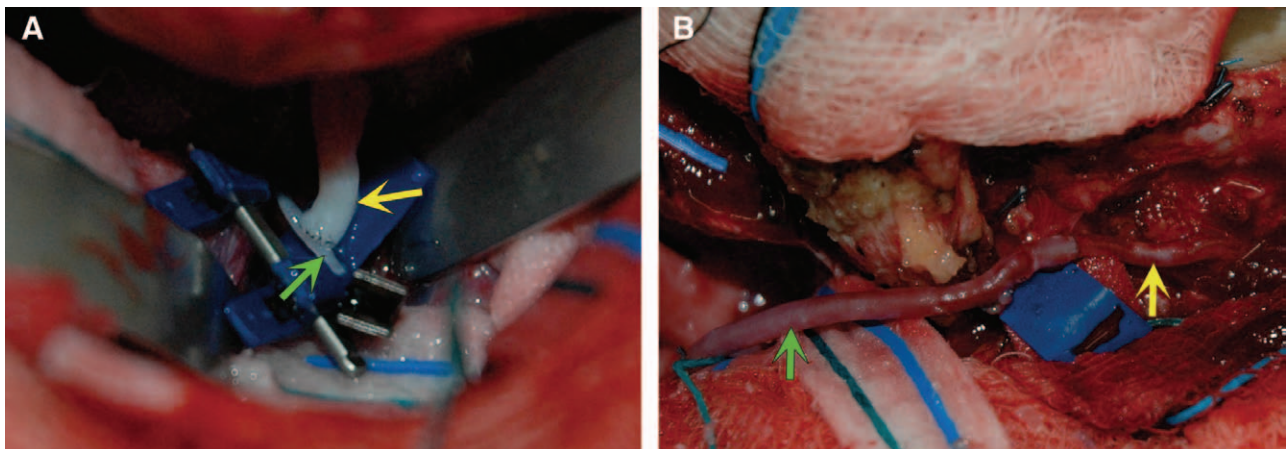


Fig. 2. A, Vein graft from right lesser saphenous vein (yellow arrow), which was 8 cm in length and 3 mm in diameter, was anastomosed to the MCA M3 (green arrow), which was 1 mm in diameter, with 10-0 nylon in an end-to-side fashion. B, Right superficial temporal artery (green arrow), which was 2.5 mm in diameter, was anastomosed to the vein graft (yellow arrow) in an end-to-end fashion.

DISCUSSION

One currently accepted indication for EC-IC bypass is flow augmentation in the setting of chronic occlusive/stenotic cerebrovascular disease.¹⁷ Patients with untreated athero-occlusive disease have a 10–12% annual risk of stroke.¹⁸ Schaller,¹² in a systematic review, reported that the risk of stroke or death in selected patients with symptomatic inaccessible stenotic lesions of the ICA or MCA treated with EC-IC bypass is significantly less than that of medically treated patients (1.3% vs 3.6% per year, respectively). Neurological function was improved in 84% of the patients in the review by Schaller.¹² In our study, 12 patients were treated for ICA and/or MCA occlusion/stenosis. Eight of these patients in group A were asymptomatic and were treated

prophylactically; all fared well, with no stroke or neurologic deterioration and few complications observed. Of the 4 symptomatic patients (nos. 19, 24, 25, and 26) in group B, 3 improved neurologically, 1 remained stable, and none suffered a post-bypass stroke.

MMD is an additional indication for EC-IC bypass. In these patients, the frequency of transient ischemic attacks can be reduced, and strokes can be avoided, by creating an alternative circulatory pathway in the brain.¹⁹ The Japan Adult Moyamoya Trial is currently underway, prospectively examining the prognoses of patients treated with EC-IC bypass. Pending the publication of these results, most cerebrovascular surgeons recommend bypass surgery.²⁰ In our study, there were 8 patients with MMD; all

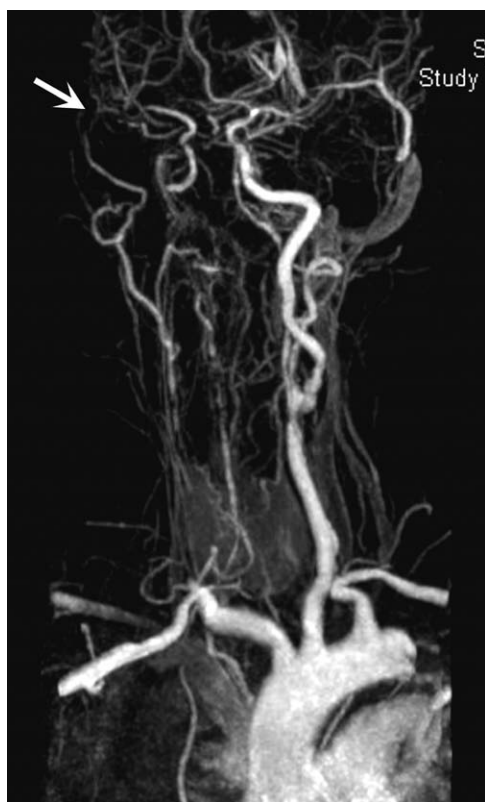


Fig. 3. Status of 48-year-old woman with prior left common carotid arterial stenting and infarction in right middle cerebral arterial territory post EC-IC bypass. Contrast-enhanced MRA showed total occlusion of right vertebral artery V4 segment, right common carotid artery and right cervical internal carotid artery, high grade stenosis of right middle cerebral artery distal M1 segment, and hypoplastic anterior communicating artery and right anterior cerebral artery A1 segment. Collateral perfusion to right middle cerebral artery is shown via right thyrocervical trunk, deep cervical artery, right external carotid artery, right superficial temporal artery, and EC-IC bypass (arrow) and then to right middle cerebral artery, intracranial internal carotid artery, and anterior cerebral artery. MRA indicates magnetic resonance angiography.

fared well, with no significant complications and no strokes observed.

An additional indication for EC-IC bypass is flow replacement in the context of therapy for complex aneurysms and skull base tumors.^{16,17} Clip application or coil placement for an intracranial aneurysm is not always feasible. In such cases, the parent artery can be obliterated to induce thrombosis of the aneurysm, but if this involves one of the major cerebral arteries, EC-IC bypass is indicated for ipsilateral revascularization. A recent meta-analysis of 20 studies has demonstrated that neurologic function and subsequent stroke risk in patients with otherwise untreatable intracranial aneurysm are significantly improved by EC-IC bypass.²¹

Our study included 6 patients with an aneurysm, including 4 with an associated SAH in group B. These 4 patients, along with 1 of the tumor patients, comprised the 5 total patients (nos. 17, 18, 20–22) in the study who demonstrated a postoperative diminution of muscle strength. These unfavorable outcomes likely reflect the grave nature of their neurologic condition rather than an untoward effect of the bypass procedure.

Prophylactic EC-IC bypass demonstrated a high patency rate and minimal complications in this study. However, therapeutic EC-IC bypass was associated with significantly greater surgical and total complications. It might be considered that there is a trade-off between the 100% patency rate and 25% surgical complication rate associated with therapeutic EC-IC bypass in this study and the gravity of the symptomatic cerebral artery disease present. The equally high successful patency rate of EC-IC bypass with or without vein graft indicated that a vein graft can be used safely depending on the availability of donor and recipient vessels.

The choice of revascularization conduit is dependent on the required amount of brain perfusion, the availability of the donor vessels, the availability of graft flow, and the size of the recipient vessel.⁶ The ICA can be used, provided that there is sufficient collateral flow to allow for temporary occlusion. The ECA or one of its branches is used if the ICA is not available or if collateral flow is insufficient (Table 3).⁶ Because of its good accessibility and close proximity, the STA is an ideal graft in patients with cerebro-occlusive disease, aneurysm, tumor, and MMD, ensuring that the low-flow volume is adequate for the recipient territory.²² The size of the STA should be at least 1 mm in caliber, and the recipient vessel can be the M2 or M3 segment of the MCA or the superior cerebellar artery.⁶ Patency rates of the STA were as high as 95%,^{22,23} and in our study, they reached 100%. However, in cases of large parent vessel sacrifice, the STA is inadequate. For high-flow conduits, the reverse great saphenous vein graft is preferred because of its robust flow (70–140 mL/min). We prefer end-to-side anastomosis because it has been demonstrated that for venous repairs with a size discrepancy, end-to-side repairs are significantly better.²⁴ The lesser saphenous vein, which is similar to the greater saphenous vein but is smaller in diameter, may be another good option for decreasing the size mismatch at the end-to-side anastomosis of the MCA insular segment. In this study, the cephalic vein was used in one case because it matched the recipient vessel in size.

In a study of 137 revascularizations, Sekhar and Kalavakonda²⁵ reported an overall graft patency

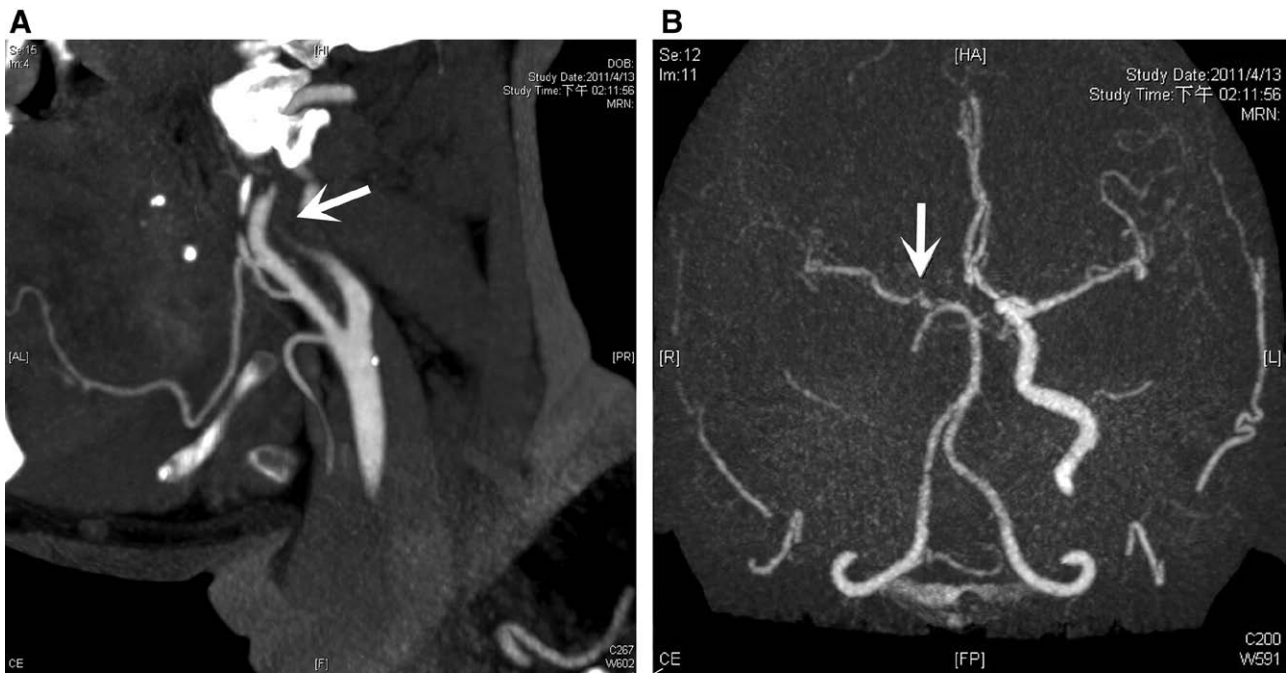


Fig. 4. A, A 54-year-old man with infarction in right middle cerebral arterial territory. CT angiography showed right cervical internal carotid artery dissection with nearly total occlusion (arrow). B, CT angiography showed total occlusion of right internal carotid artery. Vascular angulation with significant stenosis at right MCA origin is shown (arrow). CT indicates computed tomography.

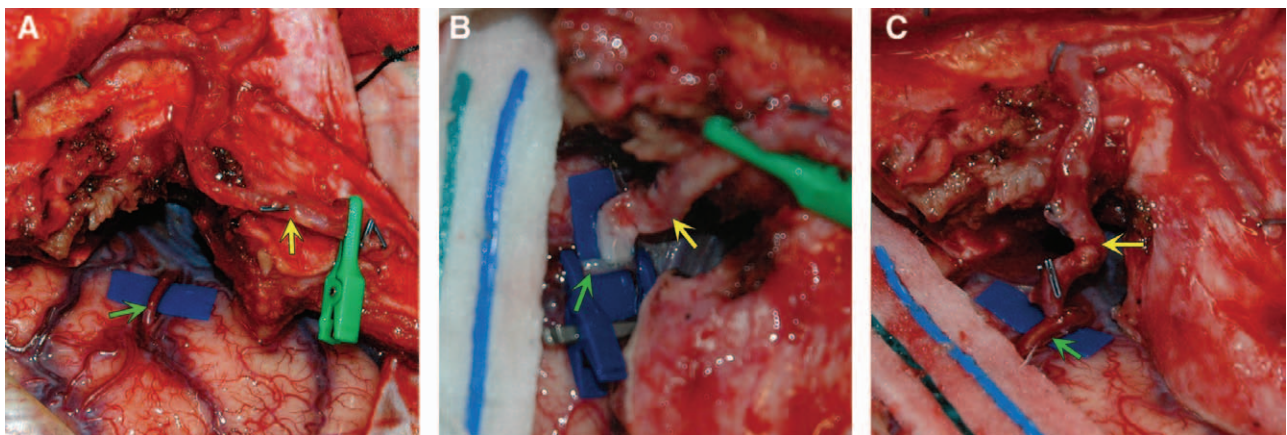


Fig. 5. A, The MCA M4 (green arrow), which was 1.2 mm in diameter, was used as the recipient vessel, and the superficial temporal artery with good sprouting (yellow arrow), which was 2 mm in diameter, was prepared as the donor vessel. B, The area immediately after microsurgical anastomosis was performed in an end-to-side fashion using double microclamp. C, Good perfusion of MCA M4 after anastomosis and the release of microclamp.

rate of 95.6% and an incidence of postoperative cerebral infarction of 16.8%. In addition to graft thrombosis, cerebral infarction can be caused by a prolonged ischemia time of the recipient segment of the MCA. Chazono et al²⁶ reported a case of intraoperative infarction with a clamping time of 65 minutes and no infarction in 3 identical cases with clamping times of 30–40 minutes. In partnership with neurosurgical colleagues, the plastic surgeon with well-honed microvascular skills is uniquely

poised to perform these anastomoses accurately and efficiently to maximize the outcomes in these patients.

CONCLUSIONS

EC-IC bypass can be an effective procedure in the treatment of complex neurovascular conditions, including occlusive, stenotic, aneurysmal, and oncologic diseases. This study demonstrates that the collaboration of neurosurgeons and plastic surgeons in



Fig. 6. Status of 54-year-old man with infarction in right middle cerebral arterial territory post EC-IC bypass. Contrast-enhanced MR angiography showed total occlusion of right internal carotid artery and hypoplastic right anterior cerebral artery A1 segment. Collateral perfusion to right middle cerebral artery is shown via right external carotid artery, right superficial temporal artery, and EC-IC bypass (arrow) and then to right middle cerebral artery. MR indicates magnetic resonance.

performing EC-IC bypass can result in excellent outcomes with few complications. Therapeutic EC-IC bypass was associated with greater total and surgical complications compared with prophylactic bypass.

Ming-Huei Cheng, MD, MBA, FACS

Center for Tissue Engineering
Division of Reconstructive Microsurgery
Department of Plastic and Reconstructive Surgery
Chang Gung Memorial Hospital
College of Medicine, Chang Gung University
5, Fu-Hsing Street, Kweishan
Taoyuan 333, Taiwan
E-mail: minghuei@cgmh.org.tw

ACKNOWLEDGMENT

We thank Chia-Yu Lin, MSc, for her assistance in the preparation of this article, video, and figures.

REFERENCES

1. Yasargil MG, Kraysenbuhl HA, Jacobson JH II. Microsurgical arterial reconstruction. *Surgery* 1970;67:221–233.

2. Goda M, Isono M, Ishii K, et al. Long-term effects of indirect bypass surgery on collateral vessel formation in pediatric moyamoya disease. *J Neurosurg*. 2004;100(2 Suppl Pediatrics):156–162.
3. Choi IJ, Cho SJ, Chang JC, et al. Angiographic results of indirect and combined bypass surgery for adult moyamoya disease. *J Cerebrovasc Endovasc Neurosurg*. 2012;14:216–222.
4. Han DH, Nam DH, Oh CW. Moyamoya disease in adults: characteristics of clinical presentation and outcome after encephalo-duro-arterio-synangiosis. *Clin Neurol Neurosurg*. 1997;99(Suppl 2):S151–S155.
5. Kuroda S, Houkin K. Moyamoya disease: current concepts and future perspectives. *Lancet Neurol*. 2008;7:1056–1066.
6. Sekhar LN, Natarajan SK, Ellenbogen RG, et al. Cerebral revascularization for ischemia, aneurysms, and cranial base tumors. *Neurosurgery* 2008;62(6 Suppl 3):1373–1408; discussion 1408–1410.
7. Failure of extracranial-intracranial arterial bypass to reduce the risk of ischemic stroke. Results of an international randomized trial. The EC/IC Bypass Study Group. *N Engl J Med*. 1985;313:1191–1200.
8. Caplan LR, Piepgras DG, Quest DO, et al. EC-IC bypass 10 years later: is it valuable? *Surg Neurol*. 1996;46:416–423.
9. Amin-Hanjani S, Butler WE, Ogilvy CS, et al. Extracranial-intracranial bypass in the treatment of occlusive cerebrovascular disease and intracranial aneurysms in the United States between 1992 and 2001: a population-based study. *J Neurosurg*. 2005;103:794–804.
10. Crowley RW, Medel R, Dumont AS. Evolution of cerebral revascularization techniques. *Neurosurg Focus* 2008;24:E3.
11. Grubb RL Jr, Powers WJ, Derdeyn CP, et al. The Carotid Occlusion Surgery Study. *Neurosurg Focus* 2003;14:e9.
12. Schaller B. Extracranial-intracranial bypass surgery to reduce the risk of haemodynamic stroke in cerebroocclusive atherosclerotic disease of the anterior cerebral circulation—a systematic review. *Neurol Neurochir Pol*. 2007;41:457–471.
13. Feiz-Erfan I, Han PP, Spetzler RF, et al. Salvage of advanced squamous cell carcinomas of the head and neck: internal carotid artery sacrifice and extracranial-intracranial revascularization. *Neurosurg Focus* 2003;14:e6.
14. Numata T, Konno A, Takeuchi Y, et al. Contralateral external carotid-middle cerebral artery bypass for carotid artery resection. *Laryngoscope* 1997;107:665–670.
15. O’Shaughnessy BA, Salehi SA, Mindea SA, et al. Selective cerebral revascularization as an adjunct in the treatment of giant anterior circulation aneurysms. *Neurosurg Focus* 2003;14:e4.
16. Bernier C, Hsu YH, Ali R, et al. The plastic surgeon’s role in extracranial-to-intracranial bypass using a reverse great saphenous vein graft. *Plast Reconstr Surg*. 2009;123:517–523; discussion 524.
17. Vajkoczy P. Revival of extra-intracranial bypass surgery. *Curr Opin Neurol*. 2009;22:90–95.
18. Grubb RL Jr, Derdeyn CP, Fritsch SM, et al. Importance of hemodynamic factors in the prognosis of symptomatic carotid occlusion. *JAMA* 1998;280:1055–1060.
19. Vilela MD, Newell DW. Superficial temporal artery to middle cerebral artery bypass: past, present, and future. *Neurosurg Focus* 2008;24:E2.
20. Miyamoto S; Japan Adult Moyamoya Trial Group. Study design for a prospective randomized trial of extracranial-intracranial bypass surgery for adults with moyamoya disease and hemorrhagic onset—the Japan Adult Moyamoya Trial Group. *Neurol Med Chir (Tokyo)*. 2004;44:218–219.

21. Schaller B. Extracranial-intracranial bypass to reduce the risk of ischemic stroke in intracranial aneurysms of the anterior cerebral circulation: a systematic review. *J Stroke Cerebrovasc Dis.* 2008;17:287–298.
22. Baaj AA, Agazzi S, van Loveren H. Graft selection in cerebral revascularization. *Neurosurg Focus* 2009;26:E18.
23. Liu JK, Kan P, Karwande SV, et al. Conduits for cerebrovascular bypass and lessons learned from the cardiovascular experience. *Neurosurg Focus* 2003;14:e3.
24. Bas L, May JW Jr, Handren J, et al. End-to-end versus end-to-side microvascular anastomosis patency in experimental venous repairs. *Plast Reconstr Surg.* 1986;77:442–450.
25. Sekhar LN, Kalavakonda C. Cerebral revascularization for aneurysms and tumors. *Neurosurgery* 2002;50:321–331.
26. Chazono H, Okamoto Y, Matsuzaki Z, et al. Extracranial-intracranial bypass for reconstruction of internal carotid artery in the management of head and neck cancer. *Ann Vasc Surg.* 2003;17:260–265.