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Side-to-side reverse superficial temporal artery to M4 middle cerebral artery bypass for common carotid artery occlusion with bonnet collaterals: illustrative case

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BACKGROUND The bonnet bypass was initially described for common carotid artery occlusion. Considered a second-generation bypass, it augments intracranial perfusion with contralateral external carotid artery flow through an interposition graft running over the scalp vertex. However, the traditional first-generation low-flow superficial temporal artery (STA)-M4 middle cerebral artery (MCA) bypass may be enhanced by performing a side-to-side (S-S) bypass with an intraluminal suture technique (fourth-generation bypass) to increase perfusion through antegrade and retrograde flow.

OBSERVATIONS The authors present a reimagined S-S STA-M4 bypass in the case of a patient with symptomatic common carotid occlusion, in which the ipsilateral STA filled in a reverse fashion from the contralateral external carotid branches over the scalp vertex (bonnet collaterals). By performing an S-S anastomosis, the authors were able to improve cerebral perfusion and avoid the multiple anastomosis sites of the bonnet bypass.

LESSONS The patient had a good recovery with resolution of his preoperative symptoms. Follow-up angiography showed a patent bypass supplying the MCA territory through retrograde flow in the frontal and parietal limbs of the STA, converging at the anastomosis site. In this report, the authors present a new fourth-generation bypass dubbed the "S-S reverse STA-M4 MCA bypass."

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KEYWORDS bonnet bypass; carotid occlusion; cerebral bypass; cerebral revascularization; extracranial-intracranial bypass; side-to-side bypass

Common carotid artery (CCA) occlusion is a rare cause of ipsilateral cerebral hypoperfusion, ischemia, and hemorrhage. Risk factors include hypertension, hyperlipidemia, diabetes, ischemic heart disease, and smoking. Rarely, erosion of the cervical vasculature from head and neck cancer may result in carotid blowout syndrome and subsequent occlusion. The incidence of carotid blowout due to head and neck cancer with radiation is 4.5%–21.1%.[1] Treatments include covered stent placement and open surgical or endovascular occlusion with or without cerebral bypass.

The risk of stroke in surgical carotid occlusion is as high as 30% in unselected patients.[2] In those with inadequate collateral blood supply, bypass surgery may be considered. Extracranial-intracranial (EC-IC) bypass is a reperfusion surgery designed to improve cerebral blood flow with direct supply from an EC source. However, the traditional first-generation EC-IC bypass operation, the end-to-side (E-S) superficial temporal artery (STA) to M4 middle cerebral artery (MCA) bypass, is not an option in CCA occlusion since the external carotid artery (ECA) branches have been compromised. In this case, a second-generation bypass using saphenous vein or radial artery interposition graft from the ipsilateral subclavian artery is an option. When the subclavian artery is unavailable, the contralateral ECA may be used as the donor in the so-called bonnet bypass.[3,4]

In patients with an occluded CCA, ECA branches may fill in a reverse fashion through collaterals across the scalp vertex. These collaterals may be so robust that they may serve as the donor in a low-flow bypass.[5] We have come to term these vertex collaterals the "bonnet collaterals." A recent report described a side-to-side (S-S) modification of the traditional STA-M4 MCA bypass, including several advantages of this technique, such as capitalizing on the antegrade and retrograde flow in scalp vessels.[6] We applied these observations in a case of CCA occlusion due to neck cancer with carotid blowout in which the ipsilateral subclavian artery was

ABBREVIATIONS CCA = common carotid artery; EC-IC = extracranial-intracranial; ECA = external carotid artery; E-S = end to side; ICG = indocyanine green; MCA = middle cerebral artery; S-S = side to side; STA = superficial temporal artery; TIA = transient ischemic attack.

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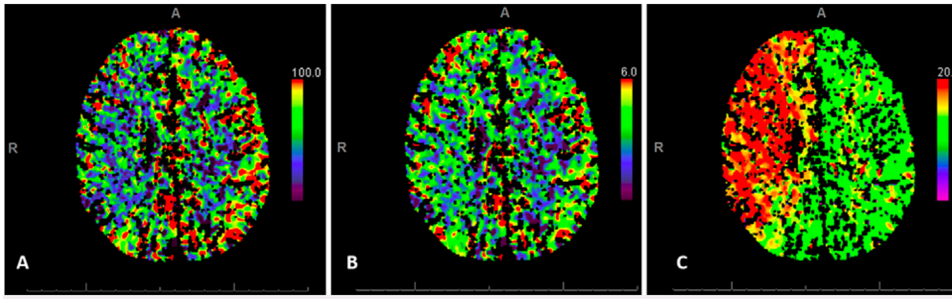

FIG. 1. A and B: Preoperative computed tomography perfusion scans showed diminished cerebral blood flow in the right hemisphere with preserved cerebral blood volume, indicating the brain was at risk. **C:** The time to peak was dramatically elevated on the right.

unavailable as the donor. In this patient, the ipsilateral ECA branches, including frontal and parietal STA branches, filled in a retrograde fashion from the contralateral ECA through the bonnet collaterals over the scalp vertex. By performing an S-S reverse STA-M4 MCA bypass, we were able to take advantage of the blood flow in both limbs of the STA.

Illustrative Case

History and Preoperative Evaluation

A 59-year-old man with a 7-year history of tonsillar squamous cell carcinoma status post radiation and chemotherapy presented with chronic ulceration and an exposed right carotid sheath. He had a pectoral flap reconstruction performed by our otorhinolaryngology team. He developed a ruptured pseudoaneurysm at the carotid bulb and underwent emergency ligation of the CCA.

In the days that followed, the patient experienced repeated episodes of perfusion-related weakness in his left extremities when mobilizing, thought to be limb-shaking transient ischemic attacks (TIAs). Medical treatments were maximized, but he remained bedridden. A perfusion scan showed poor perfusion in the right cerebral hemisphere with preserved cerebral blood volume, indicating significant risk to the brain (Fig. 1). The various cerebral revascularization options were considered. However, the right subclavian artery was not accessible as a donor because of oncological disease and treatments in the neck.

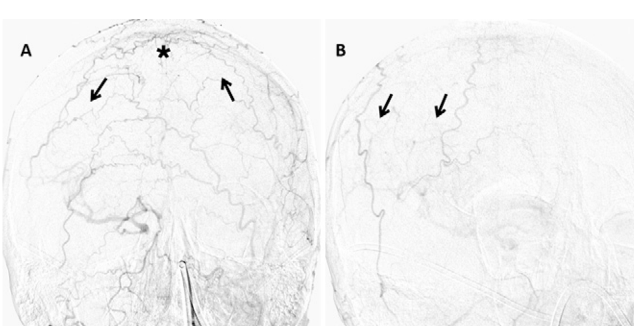

FIG. 2. Preoperative angiograms showed reverse flow in the right STA branches (*arrows*). **A:** An anteroposterior view of mid-phase left ECA injection revealed blood flow across the vertex through bonnet collaterals (*asterisk*). **B:** A transorbital oblique late-phase left ECA injection showed predominantly reverse flow in the right frontal and parietal STA branches.

A preoperative catheter cerebral angiogram revealed limited collateral flow to the right hemisphere through a small anterior communicating artery. A left ECA injection revealed collateral flow to the right ECA branches through robust collaterals in the vertex (bonnet collaterals). The right frontal and parietal STA branches as well as the right occipital artery were supplied in a retrograde fashion across the scalp vertex from contralateral ECA branches (Fig. 2). This robust retrograde filling of the right ECA branches provided an opportunity to perform a reverse STA-M4 MCA direct bypass. We also considered an S-S anastomosis in order to take advantage of retrograde flow in both the frontal and parietal STA branches.

Operation

The patient was continued on aspirin 81 mg daily through the surgery. His mean arterial pressures were maintained at 90–100 mm Hg during the operation. He was positioned supine with his head turned to the left in rigid fixation. Doppler ultrasound was used to outline the arterial vessels across the vertex. The ultrasound confirmed that the majority of the flow was retrograde from distal to proximal, although there was some degree of antegrade flow as well.

The parietal STA was dissected using the operative microscope. Its diameter was 2 mm. A standard 6-cm craniotomy was fashioned, and the dura was opened. A vertically oriented M4 recipient was selected to decrease rotational forces on the graft. It measured 1.1 mm in diameter. The arachnoid covering the recipient M4 was opened widely. An indocyanine green (ICG) angiogram with the FLOW 800 software analysis tool (Carl Zeiss Meditec) and flow probe testing confirmed dominant retrograde flow and a small amount of antegrade flow in the parietal STA. Our S-S anastomosis approach was designed to take advantage of both the retrograde and antegrade flow.

Temporary anastomosis clips were placed on the parietal STA and M4 MCA. The vessels were opened with a 27-gauge microneedle and Potts microdissecting scissors. The lumens were washed with heparinized saline. Indigo carmine was used to define the vessel edges. The anastomosis was performed with two running 10-0 nylon sutures with an intraluminal suturing technique along the back wall. Anchoring stitches were placed at the distal and proximal aspects of the arteriotomies. An entry stitch brought the distal suture into the intraluminal space. The back wall was sewn using a running technique, placing loose stitches first and tightening them as a

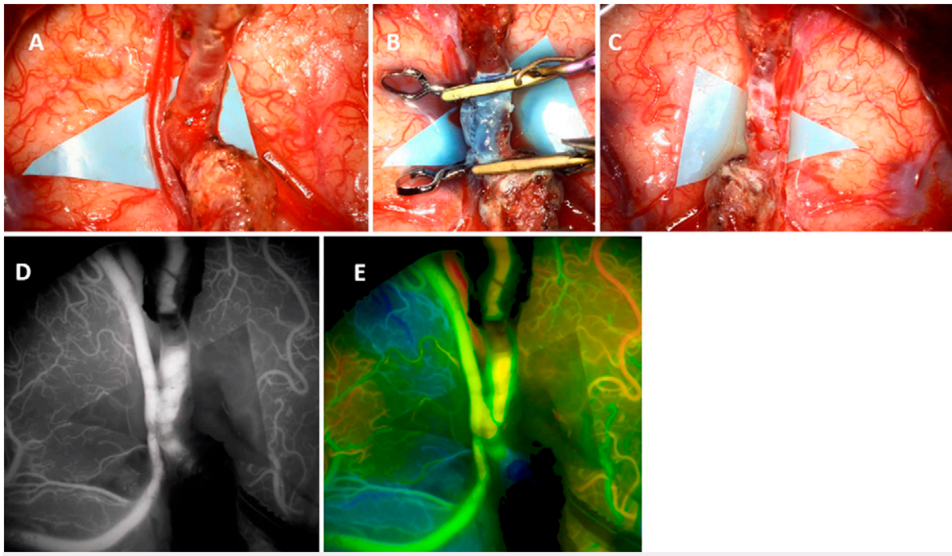

FIG. 3. Intraoperative images of the S-S STA-M4 MCA bypass. **A:** Preoperative ICG angiogram (not pictured) showed delayed antegrade flow in the M4 branch and mostly retrograde, but some late-phase antegrade, flow in the STA. A vertically oriented M4 recipient was selected. **B and C:** The S-S bypass was completed using an intraluminal suture technique on the back suture line and extraluminal sewing on the front suture line. **D:** Intraoperative ICG angiogram showed filling of all four bypass limbs. **E:** FLOW 800 analysis showed uniform flow in the STA and M4 branch.

final step. An exit stitch brought the suture to the extraluminal space, where it was tied to the tail of the second anchoring stitch. The extraluminal suture line was then completed (Fig. 3).

The anastomosis clips were removed, and there was good blood flow in all four limbs of the anastomosis. A postanastomosis ICG angiogram with FLOW 800 analysis revealed a patent bypass (Fig. 3). The total clamp time was 65 minutes. The bone flap was thinned to accommodate the graft. During each stage of closure, STA flow was confirmed with Doppler imaging.

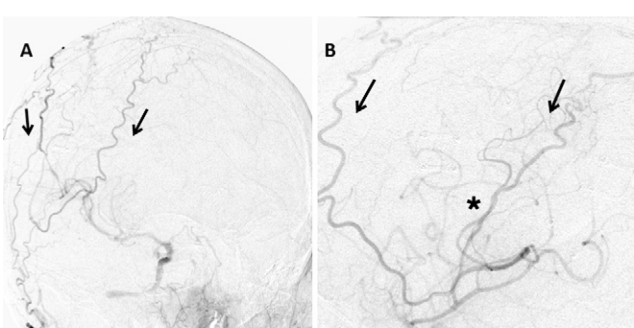

FIG. 4. The postoperative angiogram showed filling of the right MCA by way of reverse flow (*arrows*) in the right frontal and parietal branches of the right STA. **A:** A transorbital oblique late-phase left ECA injection showed robust flow across the scalp vertex through the bonnet collaterals, with filling of the right MCA territory through a patent bypass fed by reverse flow in the frontal and parietal branches of the right STA. **B:** A magnified lateral view shows filling of the MCA territory through an S-S reverse STA-M4 MCA bypass (*asterisk*).

Postoperative Care

The patient was extubated in our neuroscience intensive care unit. He was mobilized slowly with a goal systolic blood pressure $>$ 140 mm Hg. He had several minor limb-shaking TIA events, but these were dramatically reduced compared with the preoperative period. He was able to be discharged to rehabilitation.

At discharge from rehabilitation, he was able to ambulate 1000 feet without assistance. He had a good recovery at home. At the time of his 30-day postoperative visit, he was able to ambulate around his house without assistance. By 90 days, he was doing work around the house, including mowing the lawn.

A 2-month postoperative outpatient catheter angiogram was obtained. This showed a patent S-S reverse STA-M4 bypass with retrograde flow in both the parietal and frontal branches of the right STA, converging on the bypass site and supplying nearly the entire right MCA distribution (Fig. 4). The patient provided his written consent for this report, and institutional review board approval was waived.

Discussion

Observations

The aim of cerebral revascularization surgery is to restore perfusion to the brain and prevent future stroke. Indications include moyamoya disease,[7,8] IC atherosclerosis,[9] carotid compromise,[10] and complex aneurysm treatment.[11,12] Direct and indirect bypass approaches have been described, although the direct approach offers the advantage of immediately improved perfusion and perhaps better bypass graft durability.[13–15] There does not appear to be a difference in complication rate between the direct and indirect approaches.[13–15]

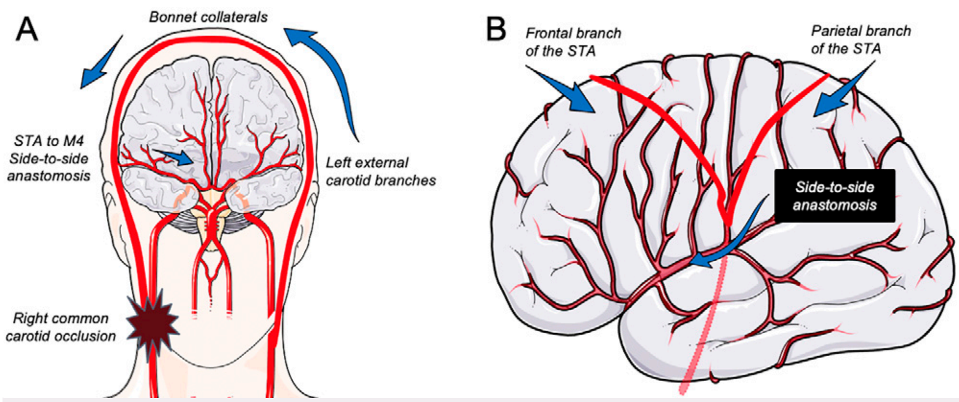

FIG. 5. Schematic maps of the S-S reverse STA-M4 MCA bypass. The *arrows* indicate direction of blood flow. **A:** Coronal view. **B:** Sagittal view of the bypass hemisphere. Figures were generated with images from Servier Medical Art licensed under a Creative Commons Attribution 3.0 Unported License.

Limb-shaking TIA represents a unique situation in which reduced cerebral reperfusion causes significant TIAs when the patient mobilizes. As seen in our case, this can be a disabling condition. Our patient remained bed bound prior to the bypass operation. Direct cerebral bypass has been described for limb-shaking TIA, and the most common approach is STA-MCA direct cerebral bypass.[16] With cerebral revascularization, patients may have recovery of function and reduced risk of stroke.[16]

In the case of CCA occlusion, STA-MCA bypass may not be an option because ECA vessels may have been occluded. However, these branches may fill in a retrograde fashion from contralateral ECA branches across the scalp vertex and may provide an excellent source for revascularization.[5,17–19] We have come to term these vessels "bonnet collaterals." A second innovation in this case is the S-S anastomosis approach, which allowed us to take advantage of retrograde flow in both the frontal and parietal branches of the STA. This flow converged on the bypass site, potentially increasing blood supply.

The traditional bypass options for CCA occlusion include direct bypass with an interposition graft from the ipsilateral subclavian artery and bonnet bypass from the contralateral ECA with interposition.[3,4,10] Retrograde flow in ECA branches along with an S-S anastomosis together provide a third option, the S-S reverse STA-M4 MCA bypass. These observations underscore the importance of studying collateral flow and direction of flow in ipsilateral ECA branches in CCA occlusion.

Interposition Graft in Bypass Surgery

One advantage of our approach in this case was avoiding the need for interposition graft. The subclavian to CCA, subclavian to internal carotid artery, and subclavian to MCA bypasses have been described.[10] These require neck dissection and at least two anastomosis sites. In our case, previous neck radiation and a pectoral flap precluded this approach. The bonnet operation also involves at least two anastomosis sites and multiple incisions.[3,4] While cerebral bypass anastomosis patency is generally $> 90\%$, it stands to reason that multiple anastomosis sites may increase the risk of graft failure. Moreover, graft site infections may be as high as 10%.[20,21]

Several generations of cerebral bypass have been described.[11] The first generation is the low-flow EC-IC bypass, and second-generation approaches involve interposition graft with saphenous vein or radial artery graft. The third- and fourth-generation approaches use nearby vessels and innovation in suture technique (e.g., intraluminal suture technique) to decrease incisions and anastomosis sites in an effort to create increasingly elegant, efficient bypass constructs.[11] Our reimagined bonnet bypass is an example of this effort. The S-S reverse STA-M4 MCA bypass is a fourth-generation bypass approach for CCA occlusion that avoids several of the limitations of previous bypasses for CCA occlusion.

S-S Anastomosis

S-S anastomosis offers the advantage of preserving flow in both limbs of the bypass graft. It allows the recipient vessel to receive antegrade and retrograde flow. This was recently demonstrated in EC-IC bypass for moyamoya disease in which the distal STA supplied natural transosseous collaterals and could not be cut and used in the normal E-S configuration.[6] Our group has also used an S-S approach in moyamoya disease with natural transosseous collaterals from the STA with good results (personal communication, E. W. Church, MD, February 1, 2021).

In the present case, the retrograde flow in the parietal and frontal branches of the STA converged at the STA common trunk. This allowed us to take advantage of flow in both limbs of the STA, converging at the anastomosis site following bypass. We were able to confirm this with an intraoperative ICG angiogram and postoperative angiogram. The retrograde flow in both limbs of the STA converged at the anastomosis site. The S-S configuration potentially increases blood flow to a blood-starved cerebral hemisphere, although this remains to be proven definitively. The S-S anastomosis configuration will probably play an increasingly important role in cerebral bypass and may be practiced in a live rat model.[22]

Innovation in Cerebrovascular Bypass Neurosurgery

From its earliest days, cerebrovascular neurosurgery has been a field of creativity and innovation. Despite the disappointing bypass trials in 1985 and 2013, bypass technique continues to evolve.[23,24] A MEDLINE search combining the terms "cerebral," "bypass," "revascularization," and "EC-IC" shows an early rise in the number of references in the mid-1980s, followed by a modest decrease in

1990. Since that time, there has been a dramatic increase in writing on cerebral bypass. Over 1000 references were published in 2020.

The present case represents a small example of how we may continue to move our field forward by combining new techniques and observations. As we share these experiences, we can create new bypass approaches, future cerebrovascular bypass neurosurgeons may be encouraged, and we may improve patient care. This process calls for courage and creativity as well as honesty when approaches do not work. Although we saw some success in this single case, it remains to be seen whether our approach will be useful for other similar patients.

Lessons

We present a direct cerebral bypass for common carotid occlusion, dubbed "S-S reverse STA-M4 MCA bypass" (Fig. 5). This bypass takes advantage of natural bonnet collaterals in the scalp vertex that may fill the STA in a reverse fashion from the contralateral STA in the case of common carotid occlusion. An S-S anastomosis allows the bypass to fill from both directions and offers potentially increased cerebral perfusion in the short and long terms. This reimagined bonnet bypass is an example of continued innovation in cerebrovascular bypass neurosurgery.

References

1. Suárez C, Fernández-Alvarez V, Hamoir M, et al. Carotid blowout syndrome: modern trends in management. *Cancer Manag Res.* 2018;10:5617–5628.
2. American Society of Interventional and Therapeutic Neuroradiology. Carotid artery balloon test occlusion. *AJNR Am J Neuroradiol.* 2001;22(8 suppl):S8–S9.
3. Spetzler RF, Roski RA, Rhodes RS, Modic MT. The "bonnet bypass." Case report. *J Neurosurg.* 1980;53(5):707–709.
4. Deshmukh VR, Porter RW, Spetzler RF. Use of "bonnet" bypass with radial artery interposition graft in a patient with recurrent cranial base carcinoma: technical report of two cases and review of the literature. *Neurosurgery.* 2005;56(1 suppl):E202.
5. Aso K, Ogasawara K, Kobayashi M, Yoshida K. Arterial bypass surgery using a spontaneously formed "bonnet" superficial temporal artery in a patient with symptomatic common carotid artery occlusion: case report. *Neurosurgery.* 2010;67(3 suppl operative): onsE316–onsE317.
6. Lang MJ, Kan P, Baranoski JF, Lawton MT. Side-to-side superficial temporal artery to middle cerebral artery bypass technique: application of fourth generation bypass in a case of adult moyamoya disease. *Oper Neurosurg (Hagerstown).* 2020;18(5):480–486.
7. Guzman R, Lee M, Achrol A, et al. Clinical outcome after 450 revascularization procedures for moyamoya disease. Clinical article. *J Neurosurg.* 2009;111(5):927–935.
8. Miyamoto S, Yoshimoto T, Hashimoto N, et al. Effects of extracranial-intracranial bypass for patients with hemorrhagic moyamoya disease: results of the Japan Adult Moyamoya Trial. *Stroke.* 2014;45(5):1415–1421.
9. Ilyas A, Chen CJ, Ironside N, et al. Medical management versus surgical bypass for symptomatic intracranial atherosclerotic disease: a systematic review. *World Neurosurg.* 2019;129:62–71.
10. Martin RS III, Edwards WH, Mulherin JL Jr, Edwards WH Jr. Surgical treatment of common carotid artery occlusion. *Am J Surg.* 1993;165(3):302–306.
11. Lawton MT, Lang MJ. The future of open vascular neurosurgery: perspectives on cavernous malformations, AVMs, and bypasses for complex aneurysms. *J Neurosurg.* 2019;130(5):1409–1425.
12. Ramanathan D, Temkin N, Kim LJ, et al. Cerebral bypasses for complex aneurysms and tumors: long-term results and graft management strategies. *Neurosurgery.* 2012;70(6):1442–1457.
13. Deng X, Gao F, Zhang D, et al. Direct versus indirect bypasses for adult ischemic-type moyamoya disease: a propensity score–matched analysis. *J Neurosurg.* 2018;128(6):1785–1791.
14. Kim H, Jang DK, Han YM, et al. Direct bypass versus indirect bypass in adult moyamoya angiopathy with symptoms or hemodynamic instability: a meta-analysis of comparative studies. *World Neurosurg.* 2016;94:273–284.
15. Liu JJ, Steinberg GK. Direct versus indirect bypass for moyamoya disease. *Neurosurg Clin N Am.* 2017;28(3):361–374.
16. Baquis GD, Pessin MS, Scott RM. Limb shaking—a carotid TIA. *Stroke.* 1985;16(3):444–448.
17. Nagm A, Horiuchi T, Hasegawa T, Hongo K. Intraoperative evaluation of reverse bypass using a naturally formed "bonnet" superficial temporal artery: technical note. *World Neurosurg.* 2016; 88:603–608.
18. Nussbaum ES, Paranjape GS, Lowary J, Nussbaum LA. Superficial temporal artery to middle cerebral artery (STA-MCA) bypass via retrograde arterial anastomosis in a patient with common carotid artery occlusion: a case report. *Acta Neurochir (Wien).* 2020;162(1): 183–186.
19. Otani N, Wada K, Sakakibara F, et al. "Reverse" bypass using a naturally formed "bonnet" superficial temporal artery in symptomatic common carotid artery occlusion: a case report. *Neurol Med Chir (Tokyo).* 2014;54(10):851–853.
20. Sia SF, Davidson AS, Assaad NN, et al. Comparative patency between intracranial arterial pedicle and vein bypass surgery. *Neurosurgery.* 2011;69(2):308–314.
21. Trick WE, Scheckler WE, Tokars JI, et al. Risk factors for radial artery harvest site infection following coronary artery bypass graft surgery. *Clin Infect Dis.* 2000;30(2):270–275.
22. Tayebi Meybodi A, Aklinski J, Gandhi S, et al. Side-to-side anastomosis training model using rat common carotid arteries. *Oper Neurosurg (Hagerstown).* 2019;16(3):345–350.
23. EC/IC Bypass Study Group. Failure of extracranial-intracranial arterial bypass to reduce the risk of ischemic stroke. Results of an international randomized trial. *N Engl J Med.* 1985;313(19):1191–1200.
24. Powers WJ, Clarke WR, Grubb RL Jr, et al. Extracranial-intracranial bypass surgery for stroke prevention in hemodynamic cerebral ischemia: the Carotid Occlusion Surgery Study randomized trial. *JAMA.* 2011;306(18):1983–1992.

Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: Church, Daggubati. Acquisition of data: all authors. Analysis and interpretation of data: Church, Daggubati. Drafting the article: all authors. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Church. Statistical analysis: Daggubati. Administrative/technical/material support: Daggubati. Study supervision: Church, Daggubati.

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