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Spatially separate cerebral infarction in the posterior cerebral artery territory after combined revascularization of the middle cerebral artery territory in an adult patient with moyamoya disease and fetal-type posterior communicating artery: illustrative case

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BACKGROUND Remote cerebral infarction after combined revascularization of the middle cerebral artery (MCA) territory is rare in patients with moyamoya disease (MMD) with a fetal-type posterior communicating artery (PCoA).

OBSERVATIONS A 57-year-old woman developed numbness in her right upper limb and transient motor weakness and was diagnosed with MMD. She also had a headache attack and a scintillating scotoma in the right visual field. Preoperative magnetic resonance angiography (MRA) showed stenosis of the left posterior cerebral artery (PCA). Combined revascularization was performed for the left MCA territory. No new neurological deficits were observed for 2 days after the operation, but right hemianopia, alexia, and agraphia appeared on postoperative day (POD) 4. Magnetic resonance imaging showed a new left occipitoparietal lobe infarction, and MRA showed occlusion of the distal left PCA. After that point, the alexia and agraphia gradually improved, but right hemianopia remained at the time of discharge on POD 18.

LESSONS Cerebral ischemia in the PCA territory may occur after combined revascularization of the MCA territory in patients with fetal-type PCoA. For these cases, a double-barrel bypass or indirect revascularization to induce a slow conversion could be considered on its own as a treatment option.

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KEYWORDS combined revascularization; fetal-type posterior communicating artery; moyamoya disease; remote cerebral infarction

Moyamoya disease (MMD) is characterized by stenotic obstructive changes at the ends of the bilateral internal carotid arteries (ICAs) and the development of a basal collateral network called “moyamoya vessels.”[1,2] Direct and indirect combined revascularization has been established for effective surgical treatment of MMD.[3–6] The procedure consists of a superficial temporal artery (STA)–middle cerebral artery (MCA) bypass for direct bypass and an indirect bypass where a vascularized pedicle of the temporal muscle, dura mater, and periosteum is placed on the brain surface.[7,8] Cerebral infarction is a characteristic complication that occurs after surgery, and its risk factors have been investigated.[9–13] However, no cases of remote cerebral infarction of the posterior cerebral artery (PCA) territory after revascularization surgery of the MCA territory in a patient with fetal-type posterior communicating artery (PCoA) have yet been reported. Furthermore, the pathophysiology of this rare entity has not been elucidated.

We describe this rare phenomenon and discuss its potential cause, focusing on changes in the diameter of the vascular lumen before and after surgery. This perspective could advance our understanding of this disease, which in this case presents with unique cerebral hemodynamics in the postoperative acute phase.

ABBREVIATIONS ACA = anterior cerebral artery; CBF = cerebral blood flow; CT = computed tomography; DSA = digital subtraction angiography; EC = external carotid; IC = internal carotid; ICA = internal carotid artery; MCA = middle cerebral artery; MMD = moyamoya disease; MRA = magnetic resonance angiography; MRI = magnetic resonance imaging; PCA = posterior cerebral artery; PCoA = posterior communicating artery; POD = postoperative day; SPECT = single-photon emission computed tomography; STA = superficial temporal artery; TOF = time of flight.

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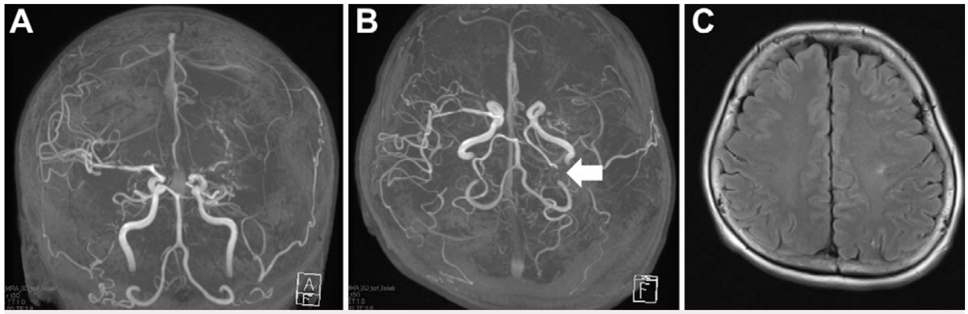

FIG. 1. Preoperative imaging findings. MRA showed severe stenosis of the left ICA terminal, ACA, and MCA and mild stenosis of the right ICA terminal and ACA/MCA (**A**). The left P1 was not developed even in the MRA TOF source image, and the PCoA was judged to be of the fetal type. The distal part of the left PCA was accompanied by stenotic findings (**B**, *white arrow*). On fluid-attenuated inversion recovery, a slight ischemic change in deep white matter was observed (**C**).

Illustrative Case

A 57-year-old female patient developed numbness in her right hand and transient motor weakness. The patient also had a headache attack and a scintillating scotoma in the right visual field. Magnetic resonance angiography (MRA) showed severe stenosis of the left ICA terminal and anterior cerebral artery (ACA) and middle cerebral artery (MCA) and mild stenosis of the right ICA terminal and ACA/MCA (Fig. 1A). The left P1 was not developed even in the MRA time-of-flight (TOF) source image, and PCoA was judged to be of the fetal type. The distal part of the left PCA was accompanied by stenotic findings (Fig. 1B). Magnetic resonance imaging (MRI) showed the development of two or more abnormal vascular networks in the basal ganglia, so the patient was diagnosed with MMD on the basis of diagnostic criteria of the Research Committee on the Pathology and Treatment of Spontaneous Occlusion of the Circle of Willis.[14] On fluid-attenuated inversion recovery, a slight ischemic change in deep white matter was observed (Fig. 1C). In preoperative resting-state single-photon emission computed tomography (SPECT), the cerebral blood flow (CBF) in the left MCA territory decreased to less than 80% of the ipsilateral cerebellum, whereas that in the PCA territory was maintained at approximately 90% (Fig. 2). On the basis of the above conditions, oral treatment

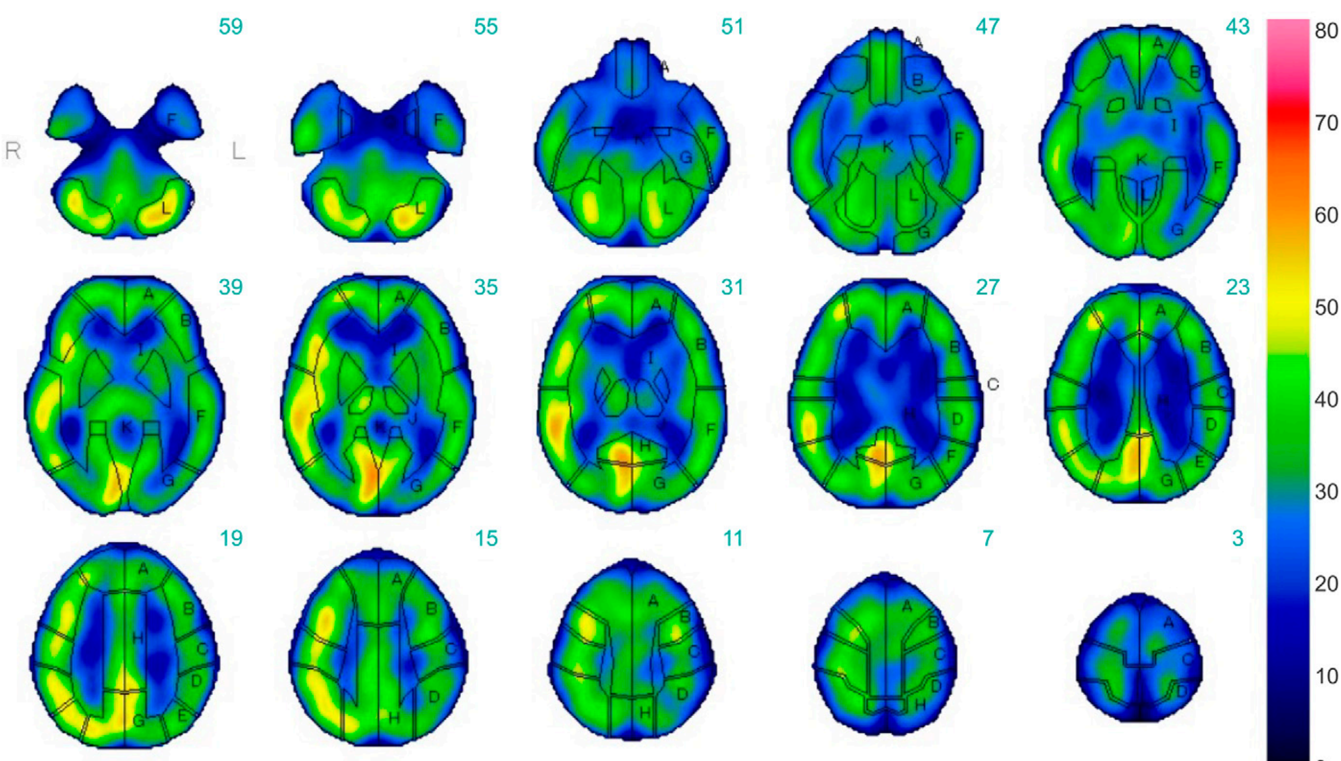

FIG. 2. In the preoperative resting-state SPECT, the CBF in the left MCA territory decreased to less than 80% of the ipsilateral cerebellum, whereas that in the PCA territory was maintained at approximately 90%.

with aspirin 100 mg daily as an antiplatelet regimen was initiated and continued until 3 days before surgery.

STA–MCA single bypass and indirect revascularization using the temporal muscle and periosteum for the left MCA territory were performed. The recipient artery was a precentral artery, and the bypass flow was patent on intraoperative indocyanine green video angiography. The intraoperative in–out balance was +2,104 ml, the countable bleeding volume was 56 ml, and no blood transfusion was performed. Postoperative blood pressure was maintained at the same level as the preoperative value (systole 110–130 mm Hg) by continuous intravenous infusion of antihypertensive drugs.

No new stroke event was observed on computed tomography (CT) images obtained on postoperative day (POD) 1, and the bypass graft was clearly visible on CT angiography (Fig. 3). No new neurological deficits occurred immediately after the operation until POD 3.

On POD 4, the patient exhibited symptoms of right hemianopia, alexia, and agraphia. Diffusion-weighted imaging showed acute cerebral infarction in the left occipitoparietal lobe. Simultaneous MRA showed that the bypass patency was preserved, but the distal portion of the left PCA was obstructed (Fig. 4). After that, no new sign of neurological deficits occurred, and no new stroke event was confirmed by MRI on POD 11. Eventually, the alexia and agraphia gradually improved, but right hemianopia remained at the time of discharge on POD 18.

Discussion

Observations

We report here an adult patient with MMD with fetal-type PCoA who experienced a remote cerebral infarction that occurred in the PCA territory after combined revascularization of the MCA territory. After cerebral revascularization, ischemic stroke occurs in patients with MMD with some frequency. Extensive research has been reported on the predictors of its occurrence.[9–13,15–18] However, there have been no reports of cases of ipsilateral PCA territory cerebral infarction after combined revascularization to the MCA territory, as in this case.

At our facility, digital subtraction angiography (DSA) is usually not performed if the MRA results fulfill the diagnostic criteria for MMD. Therefore, DSA was not performed in this patient. However, DSA may provide additional information about moyamoya vessels and pial collaterals that are not detected by MRA. In the present case, on the one hand, changes in hemodynamics after bypass surgery could have been dynamically recorded. Furthermore, if DSA had been performed both preoperatively and postoperatively, the changes might have provided new evidence for this rare condition. On the other hand, DSA carries a risk, albeit a low risk, of catheter-related and ischemic complications. Normally, it is often uneventful even if the DSA before and after surgery is not evaluated. Therefore, in future practice, it will be important to decide which types of cases should have hemodynamic changes assessed by DSA.

First, postoperative anemia, dehydration, hyperventilation, and hypotension should be verified because they are risk factors for postoperative cerebral infarction.[19–22] In this case, the amount of bleeding during the operation was very small, and no anemia was observed in the postoperative blood count data. In addition, postoperative water intake was controlled to balance the daily infusion volume, oral drinking volume, and urine volume. Intraoperative and postoperative target blood pressures were as tightly controlled as preoperative values. Thus, the influence of inappropriate intraoperative and postoperative management on the cause of this cerebral infarction was small. Moreover, further factors that predict the occurrence of postoperative stroke should be evaluated, including the development of collaterals and leptomeningeal anastomosis on DSA, cerebrovascular reserve on acetazolamide-enhanced SPECT, and metabolism on positron emission tomography.

Second, there are disagreements about aspirin administration in patients with MMD, especially for Asian versus non-Asian populations.[23] However, a large-scale study has confirmed the effectiveness of aspirin in preventing further ischemic attacks after adult ischemic MMD.[24] There have also been a few reports testing the outcomes of perioperative aspirin administration.[25–27] Rashad et al.[26] reported that strict blood pressure control and aspirin administration can reduce the potential risk of surgical complications in combined revascularization for pediatric patients with MMD. On the one hand, their use of aspirin was in close agreement with the regimen used in our case, with administration stopping 3 days before surgery and starting the day after surgery. On the other hand, according to a report from China, there was no statistically significant difference in the incidence of major stroke after direct or combined surgery for MMD in adults with ischemic onset between the groups that received aspirin from POD 1 and those that did not.[27] We examined this issue in patients with MMD who underwent combined surgery at our institution. We found a significant difference in the postsurgical incidence of ischemic and hemorrhagic stroke among the group in which aspirin was continued, the group in which it was discontinued only on the day of surgery, the group in which it was discontinued 3 days before surgery, and the group in which it was not used.[25] The case in the present report belonged to the group in which aspirin administration was discontinued 3 days before surgery. However, the study found that the appearance of white thrombi during the bypass procedure was significantly reduced in the aspirin-treated group. Eventually, there may not be sufficient evidence to justify continued administration of aspirin during the perioperative period. In

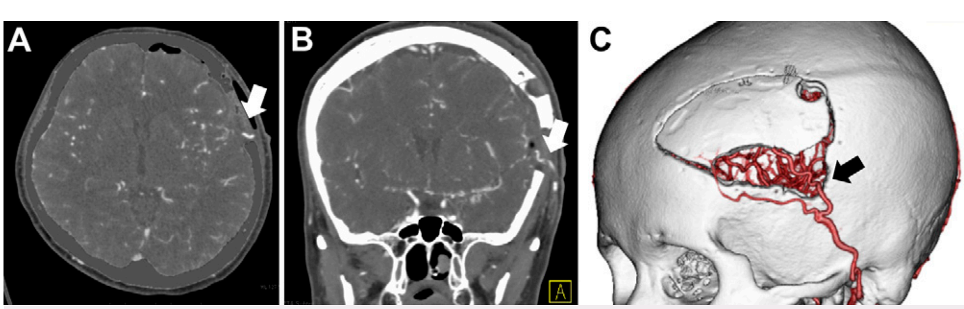

FIG. 3. CT angiography on POD 1 (**A**, axial image; **B**, coronal image; **C**, three-dimensional reconstructed image). The *white* and *black arrows* indicate a clearly visible bypass graft. No new stroke event was observed.

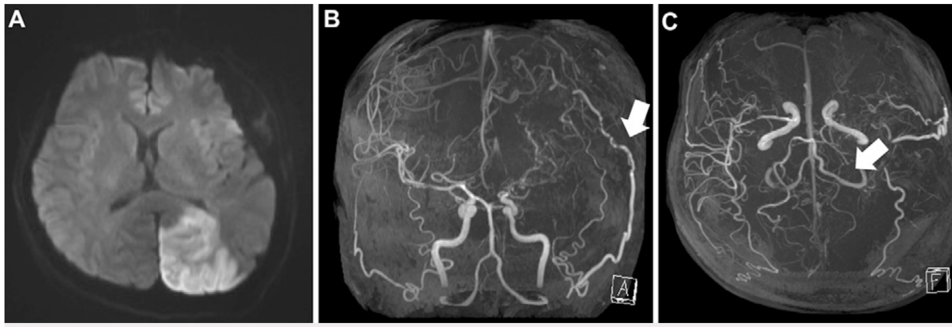

FIG. 4. MRI/MRA on POD 4. Diffusion-weighted imaging on MRI showed acute cerebral infarction in the left occipitoparietal lobe (**A**). Simultaneously, MRA showed that the bypass patency was preserved (**B**, *white arrow*), but the distal portion of the left PCA was obstructed (**C**, *white arrow*).

particular, the risk of hemorrhagic complications, including subdural hematoma due to bleeding from vascularized pedicles used in combined surgery and intracerebral hemorrhage associated with hyperperfusion after direct bypass, may be increased by continuous administration of aspirin. It may be necessary to adjust the administration of aspirin in order to balance the risks with the benefit of continuous administration to avoid postoperative ischemic complications, inferred from the degree of preoperative cerebral ischemia. Consequently, in this case, continued aspirin administration may have been justified.

Nevertheless, hyperperfusion and hypoperfusion can occur in patients with MMD after revascularization.[28–33] It would be reasonable for local changes in CBF to cause symptoms around where the direct bypass was performed. However, it has been reported that cerebral ischemia occurs at a site distant from direct bypass.[34] This pathological condition is thought to be caused by the conflict between the flow from the direct bypass and the flow of the ICA system, which is called the "watershed shift phenomenon."[34–36] Alternatively, cerebral ischemia in the contralateral hemisphere away from the anastomotic site can occur if the unintervened side exhibits unstable cerebral hemodynamics.[17,37] However, among remote cerebral infarctions, the pathophysiology observed in cases with fetal-type PCoA and distal PCA stenosis is expected to be unique. Therefore, we focused on the blood vessel lumen diameter measurement data of the ICA and PCoA from the preoperative to postoperative periods and verified the cause of this rare pathological condition. In this study, we used MRA TOF source images to estimate the blood flow in each vessel by measuring the lumens of the ICA (just proximal to the origin of the PCoA), the origin of the PCoA, and the STA (anterior part of the auricle). Serial images were taken preoperatively on POD 4 (at the onset of cerebral infarction), POD 5, and POD 11. The data showed that the ICA diameters (in millimeters) were 3.23, 2.28, 2.43, and 2.14; the PCoA diameters (in millimeters) were 1.74, 1.71, 1.62, and 1.49; and the STA diameters

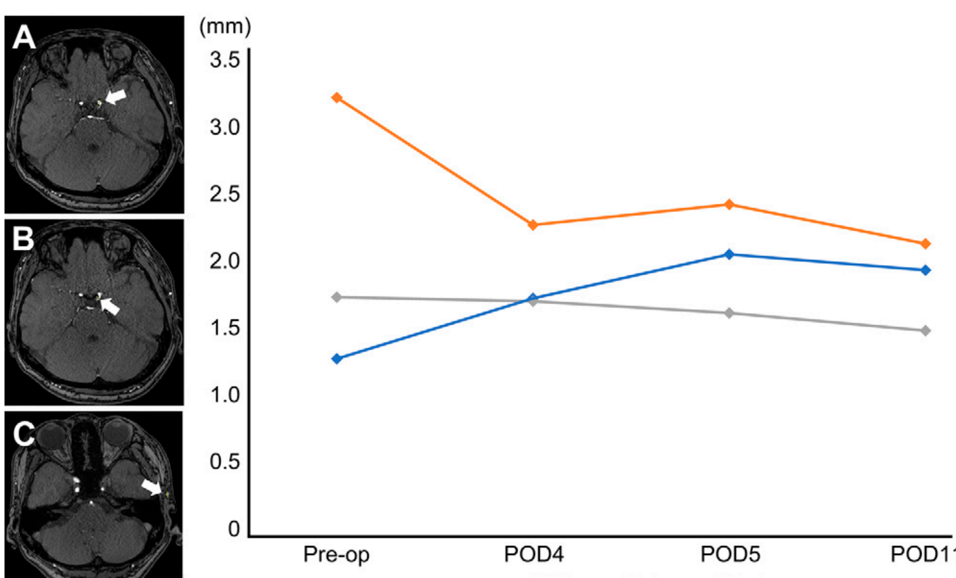

FIG. 5. MRA TOF source images were used to estimate the blood flow in each vessel by measuring the lumens of the ICA (just proximal to the origin of the PCoA, **A**, *white arrow*), the origin of the PCoA (**B**, *white arrow*), and the STA (anterior part of the auricle, **C**, *white arrow*). Serial images were taken preoperatively on POD 4 (at the onset of cerebral infarction), POD 5, and POD 11. The STA lumen diameter increased approximately 1.6 times by POD 5 compared with that before surgery. Simultaneously, the lumen diameters of the ICA and PCoA were reduced by 0.75 times and 0.93 times, respectively.

(in millimeters) were 1.28, 1.73, 2.06, and 1.94 for preoperative, POD 4, POD 5, and POD 11, respectively (Fig. 5).

These findings indicate that the STA lumen diameter increased approximately 1.6 times by POD 5 compared with that before surgery. Simultaneously, the lumen diameters of the ICA and PCoA were reduced by 0.75 times and 0.93 times, respectively. Thus, it was inferred that the increase in the STA lumen diameter increased the perfusion pressure from the external carotid (EC) artery system to the internal carotid (IC) artery system via bypass. Subsequently, it was speculated that the blood flow from the fetal-type PCoA to the PCA via the ICA decreased. Furthermore, obstruction of the PCA on POD 4 may be due to the hypercoagulation state associated with surgical invasion in addition to the decrease in blood flow. Scintillation in the right visual field was observed as a preoperative symptom because the perfusion pressure in the left PCA territory was reduced, as was also found in the CBF study. This could be a symptomatically important finding indicative of an increased risk of postoperative cerebral ischemia.[38] However, we recognize that changes in the vessel lumen diameter alone are insufficient to support this hypothesis. Evaluation of CBF and perfusion time by quantitative MRA, intraoperative flow measurement using indocyanine green, and measurement of the change in mean transit time on cerebral angiography will also be needed.[33,39,40] In addition, repeated SPECT and blood oxygenation level–dependent MRI assessments should be considered for hemodynamic reserve follow-up.[41,42] This limitation may be resolved by accumulating and analyzing further data on similar cases in the future.

MMD is characterized by a pathological condition in which the main source of blood flow to the brain slowly shifts from the IC system to the EC system, which is called "IC-EC conversion."[41,43] In this case, though, the ICA diameter decreased, and the STA diameter, which is the ECA system, increased within a few days after surgery. Normally, IC-EC conversion is induced slowly, triggered by cerebral revascularization, but it occurred over a short period of time in this case. The occurrence of conversion in this short time span has not been reported thus far, but it is suggestive of a watershed shift, which causes a decrease in CBF at a site distant from the direct bypass site.[34–36,44] The lesson learned from this case is that after direct bypass to the MCA territory, cerebral ischemia in the PCA territory can occur due to the watershed shift phenomenon, especially in patients with fetal-type PCoA. An aggressive strategy for patients with preoperatively recognized regions of vulnerable CBF is to perform a double-barrel bypass, with a direct bypass to that territory in addition to the planned direct bypass.[34,35] However, based on the hypothesis that this rare condition was caused by rapid EC-IC conversion, direct revascularization to induce a slow conversion may be considered as a treatment option on its own. To resolve this important issue, more cases of this rare pathology need to be evaluated.

Lessons

Cerebral ischemia in the PCA territory may occur after revascularization of the MCA territory in patients with MMD with fetal-type PCoA. The risk of cerebral ischemia in the PCA territory may be increased in patients with advanced-stage MMD with PCA involvement; therefore, careful postoperative management should be considered. For cases in which a region with vulnerable CBF has been identified preoperatively, a double-barrel bypass, with a direct bypass to the territory in addition to the planned direct bypass, may be considered as a surgical strategy. Alternatively, indirect revascularization to induce a slow conversion could be considered on its own as a treatment option.

References

1. Kuroda S, Houkin K. Moyamoya disease: current concepts and future perspectives. *Lancet Neurol.* 2008;7(11):1056–1066.
2. Suzuki J, Takaku A. Cerebrovascular "moyamoya" disease. Disease showing abnormal net-like vessels in base of brain. *Arch Neurol.* 1969;20(3):288–299.
3. Kim T, Oh CW, Bang JS, Kim JE, Cho WS. Moyamoya disease: treatment and outcomes. *J Stroke.* 2016;18(1):21–30.
4. Kuroda S, Nakayama N, Yamamoto S, et al. Late (5-20 years) outcomes after STA-MCA anastomosis and encephalo-duro-myo-arterio-pericranial synangiosis in patients with moyamoya disease. *J Neurosurg.* 2020;134(3):909–916.
5. 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.
6. Zheng J, Yu LB, Dai KF, Zhang Y, Wang R, Zhang D. Clinical features, surgical treatment, and long-term outcome of a multicenter cohort of pediatric moyamoya. *Front Neurol.* 2019;10:14.
7. Araki Y, Uda K, Yokoyama K, et al. Surgical designs of revascularization for moyamoya disease: 15 years of experience in a single center. *World Neurosurg.* 2020;139:e325–e334.
8. Kuroda S, Houkin K, Ishikawa T, Nakayama N, Iwasaki Y. Novel bypass surgery for moyamoya disease using pericranial flap: its impacts on cerebral hemodynamics and long-term outcome. *Neurosurgery.* 2010;66(6):1093- 1101.
9. Araki Y, Yokoyama K, Uda K, et al. Postoperative stroke and neurological outcomes in the early phase after revascularization surgeries for moyamoya disease: an age-stratified comparative analysis. *Neurosurg Rev.* 2021;44(5):2785–2795.
10. Kim SH, Choi JU, Yang KH, Kim TG, Kim DS. Risk factors for postoperative ischemic complications in patients with moyamoya disease. *J Neurosurg.* 2005;103(5 suppl):433–438.
11. Muraoka S, Araki Y, Kondo G, et al. Postoperative cerebral infarction risk factors and postoperative management of pediatric patients with moyamoya disease. *World Neurosurg.* 2018;113:e190–e199.
12. Park W, Ahn JS, Lee HS, Park JC, Kwun BD. Risk factors for newly developed cerebral infarction after surgical revascularization for adults with moyamoya disease. *World Neurosurg.* 2016;92: 65–73.
13. Wei W, Chen X, Yu J, Li XQ. Risk factors for postoperative stroke in adults patients with moyamoya disease: a systematic review with meta-analysis. *BMC Neurol.* 2019;19(1):98.
14. Research Committee on the Pathology and Treatment of Spontaneous Occlusion of the Circle of Willis. Guidelines for diagnosis and treatment of moyamoya disease (spontaneous occlusion of the circle of Willis). *Neurol Med Chir (Tokyo).* 2012;52(5):245–266.
15. Choi JW, Chong S, Phi JH, et al. Postoperative symptomatic cerebral infarction in pediatric moyamoya disease: risk factors and clinical outcome. *World Neurosurg.* 2020;136:e158–e164.
16. Fujimura M, Tominaga T. Lessons learned from moyamoya disease: outcome of direct/indirect revascularization surgery for 150 affected hemispheres. *Neurol Med Chir (Tokyo).* 2012;52(5):327–332.
17. Funaki T, Takahashi JC, Takagi Y, et al. Unstable moyamoya disease: clinical features and impact on perioperative ischemic complications. *J Neurosurg.* 2015;122(2):400–407.
18. Kazumata K, Ito M, Tokairin K, et al. The frequency of postoperative stroke in moyamoya disease following combined revascularization: a single-university series and systematic review. *J Neurosurg.* 2014;121(2):432–440.
19. Lee JK, Williams M, Reyes M, Ahn ES. Cerebrovascular blood pressure autoregulation monitoring and postoperative transient ischemic attack in pediatric moyamoya vasculopathy. *Paediatr Anaesth.* 2018;28(2):94–102.

20. Li C, Zhang N, Yu S, et al. Individualized perioperative blood pressure management for adult moyamoya disease: experience from 186 consecutive procedures. *J Stroke Cerebrovasc Dis.* 2021;30(1):105413.
21. Ogawa A, Nakamura N, Yoshimoto T, Suzuki J. Cerebral blood flow in moyamoya disease. Part 2: autoregulation and CO_2 response. *Acta Neurochir (Wien).* 1990;105(3-4):107–111.
22. Smith ER, Scott RM. Surgical management of moyamoya syndrome. *Skull Base.* 2005;15(1):15–26.
23. Kraemer M, Berlit P, Diesner F, Khan N. What is the expert's option on antiplatelet therapy in moyamoya disease? Results of a worldwide survey. *Eur J Neurol.* 2012;19(1):163–167.
24. Ye F, Li J, Wang T, et al. Efficacy and safety of antiplatelet agents for adult patients with ischemic moyamoya disease. *Front Neurol.* 2021;11:608000.
25. Kanamori F, Araki Y, Yokoyama K, et al. Effects of aspirin and heparin treatment on perioperative outcomes in patients with moyamoya disease. *Acta Neurochir (Wien).* 2021;163(5):1485–1491.
26. Rashad S, Fujimura M, Niizuma K, Endo H, Tominaga T. Long-term follow-up of pediatric moyamoya disease treated by combined direct-indirect revascularization surgery: single institute experience with surgical and perioperative management. *Neurosurg Rev.* 2016;39(4):615–623.
27. Zhao Y, Zhang Q, Zhang D, Zhao Y. Effect of aspirin in postoperative management of adult ischemic moyamoya disease. *World Neurosurg.* 2017;105:728–731.
28. Fujimura M, Kaneta T, Mugikura S, Shimizu H, Tominaga T. Temporary neurologic deterioration due to cerebral hyperperfusion after superficial temporal artery-middle cerebral artery anastomosis in patients with adult-onset moyamoya disease. *Surg Neurol.* 2007;67(3):273–282.
29. Fujimura M, Shimizu H, Inoue T, Mugikura S, Saito A, Tominaga T. Significance of focal cerebral hyperperfusion as a cause of transient neurologic deterioration after extracranial-intracranial bypass for moyamoya disease: comparative study with non-moyamoya patients using *N*-isopropyl-*p*-[^{123}I]iodoamphetamine single-photon emission computed tomography. *Neurosurgery.* 2011;68(4):957–965.
30. Hamano E, Kataoka H, Morita N, et al. Clinical implications of the cortical hyperintensity belt sign in fluid-attenuated inversion recovery images after bypass surgery for moyamoya disease. *J Neurosurg.* 2017;126(1):1–7.
31. Mukerji N, Cook DJ, Steinberg GK. Is local hypoperfusion the reason for transient neurological deficits after STA-MCA bypass for moyamoya disease? *J Neurosurg.* 2015;122(1):90–94.
32. Uchino H, Kuroda S, Hirata K, Shiga T, Houkin K, Tamaki N. Predictors and clinical features of postoperative hyperperfusion after surgical revascularization for moyamoya disease: a serial single photon emission CT/positron emission tomography study. *Stroke.* 2012;43(10):2610–2616.
33. Uda K, Araki Y, Muraoka S, et al. Intraoperative evaluation of local cerebral hemodynamic change by indocyanine green videoangiography: prediction of incidence and duration of postoperative transient neurological events in patients with moyamoya disease. *J Neurosurg.* 2019;130(4):1367–1375.
34. Tu XK, Fujimura M, Rashad S, et al. Uneven cerebral hemodynamic change as a cause of neurological deterioration in the acute stage after direct revascularization for moyamoya disease: cerebral hyperperfusion and remote ischemia caused by the 'watershed shift'. *Neurosurg Rev.* 2017;40(3):507–512.
35. Hayashi T, Shirane R, Fujimura M, Tominaga T. Postoperative neurological deterioration in pediatric moyamoya disease: watershed shift and hyperperfusion. *J Neurosurg Pediatr.* 2010;6(1):73–81.
36. Yu J, Hu M, Yi L, Zhou K, Zhang J, Chen J. Paradoxical association of symptomatic cerebral edema with local hypoperfusion caused by the 'watershed shift' after revascularization surgery for adult moyamoya disease: a case report. *Ther Adv Neurol Disord.* 2019;12:1756286419878343.
37. Araki Y, Yokoyama K, Uda K, et al. Ipsilateral late stroke after revascularization surgery for patients with moyamoya disease. *Acta Neurochir (Wien).* 2021;163(5):1493–1502.
38. Miyamoto S, Kikuchi H, Karasawa J, Nagata I, Ihara I, Yamagata S. Study of the posterior circulation in moyamoya disease. Part 2: visual disturbances and surgical treatment. *J Neurosurg.* 1986;65(4):454–460.
39. Chen L, Mossa-Basha M, Balu N, et al. Development of a quantitative intracranial vascular features extraction tool on 3D MRA using semiautomated open-curve active contour vessel tracing. *Magn Reson Med.* 2018;79(6):3229–3238.
40. Chen Y, Ma L, Yang S, et al. Quantitative angiographic hemodynamic evaluation after revascularization surgery for moyamoya disease. *Transl Stroke Res.* 2020;11(5):871–881.
41. Fujimura M, Tominaga T. Significance of cerebral blood flow analysis in the acute stage after revascularization surgery for moyamoya disease. *Neurol Med Chir (Tokyo).* 2015;55(10):775–781.
42. Roder C, Klose U, Hurth H, et al. Longitudinal reproducibility of CO_2-triggered BOLD MRI for the hemodynamic evaluation of adult patients with moyamoya angiopathy. *Cerebrovasc Dis.* 2021;50(3):332–338.
43. Fujimura M, Tominaga T. Current status of revascularization surgery for moyamoya disease: special consideration for its 'internal carotid-external carotid (IC-EC) conversion' as the physiological reorganization system. *Tohoku J Exp Med.* 2015;236(1):45–53.
44. Kim HG, Lee SK, Lee JD. Characteristics of infarction after encephaloduroarteriosynangiosis in young patients with moyamoya disease. *J Neurosurg Pediatr.* 2017;19(1):1–7.

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: Araki, Takayanagi, Nishihori, Tanei. Acquisition of data: Araki, Yokoyama, Uda, Kanamori, Mamiya, Takayanagi, Takeuchi, Nagata, Tanei. Analysis and interpretation of data: Araki, Takayanagi, Tanahashi. Drafting the article: Araki, Takayanagi. Critically revising the article: Tanahashi, Nishimura, Saito. Reviewed submitted version of manuscript: Yokoyama, Uda, Ishii, Nishihori, Tanahashi, Nishimura, Saito. Approved the final version of the manuscript on behalf of all authors: Araki. Administrative/technical/material support: Uda, Mamiya. Study supervision: Nishihori, Tanei, Izumi, Saito.

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