



Superficial Temporal Artery Trunk-to-Middle Cerebral Artery Bypass with Short Radial Artery Interposition Graft for Symptomatic Internal Carotid Artery Occlusion

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■ **OBJECTIVE:** We investigated the use of high-flow superficial temporal artery trunk-to-radial artery-to-middle cerebral artery (STAT-RA-MCA) bypass to prevent ischemic stroke in patients with symptomatic internal carotid artery occlusion (SICAO).

■ **METHODS:** We retrospectively analyzed the data from patients with SICAO who had undergone high-flow STAT-RA-MCA bypass in our center from October 2014 to November 2017. The incidence of ischemic stroke, changes in cerebral blood flow, characteristics of perioperative complications, and related factors determining the blood flow rate in the graft were analyzed.

■ **RESULTS:** From October 2014 to November 2017, we treated 21 patients with SICAO using high-flow STAT-RA-MCA bypass. A total of 42 ischemic stroke events had been reported within 6 months before surgery. The ipsilateral/contralateral mean transit time (I/C MTT) ratio before surgery was 1.24 ± 0.10 (range, 1.14–1.51). During a median follow-up period of 692 days (range, 212–1114), 3 transient ischemic attacks occurred in 3 patients; 18 patients (85.7%) did not experience recurrent stroke. The patency rate of the bypass graft was 95.2% (20 of 21). The I/C MTT ratio was 1.06 ± 0.11 on postoperative day 1 in all patients and was significantly different from the preoperative I/C MTT ratio

($P < 0.001$). The surgical complication rate was 9.5% (2 of 21), and no reoperation was required.

■ **CONCLUSION:** Our results suggest that high-flow STAT-RA-MCA bypass can effectively reduce the risk of stroke in patients with SICAO. Moreover, the surgical procedure is a highly safe procedure. Further randomized controlled studies are required to draw more precise conclusions.

INTRODUCTION

Ten to fifteen percent of strokes or transient ischemic attacks (TIAs) related to the blood supply region of the internal carotid artery (ICA) are due to ICA occlusion (ICAO).¹ Although patients with ICAO receive active pharmacotherapy,^{2,3} the rate of annual recurrence of stroke has remained as high as 9%–18% because the hemodynamic state of the brain has been affected.

In theory, extracranial-to-intracranial (EC-IC) bypass can improve cerebral blood flow and the impaired cerebral hemodynamic state. Thus, this procedure can reduce the risk of stroke and benefit some patients with ICAO.^{4–6} However, the relatively authoritative EC-IC bypass trial and the Carotid Occlusion Surgery Study (COSS) reported suboptimal results^{7,8} that limited the use of

Key words

- High-flow bypass
- Interposition graft
- Ischemic stroke
- Radial artery
- Superficial temporal artery trunk
- Symptomatic internal carotid artery occlusion

Abbreviations and Acronyms

- COSS:** Carotid Occlusion Surgery Study
CTP: Computed tomography perfusion
DSA: Digital subtraction angiography
EC-IC: Extracranial-to-intracranial
ICA: Internal carotid artery
ICAO: Internal carotid artery occlusion
I/C MTT: Ipsilateral/contralateral mean transit time
MCA: Middle cerebral artery
mRS: Modified Rankin scale
RA: Radial artery

RAG: Radial artery graft

SICAO: Symptomatic internal carotid artery occlusion

STA-MCA: Superficial temporal artery-to-middle cerebral artery

STAT: Superficial temporal artery trunk

SVG: Saphenous vein graft

TIA: Transient ischemia attack

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bypass surgery for patients with ICAO.⁶ However, the EC-IC bypass trial (reported in 1985) had 2 disadvantages: 1) the hemodynamic factors were overlooked; and 2) the flow rate of the bypass graft was too low to prevent the occurrence of stroke.^{2,5} The subsequent COSS only addressed the first drawback in the trial design but not the problem of insufficient flow. Thus, in terms of the flow rate of a bypass graft, the COSS and EC-IC bypass trial focused on low-flow bypass. Many investigators believed that the insufficient blood flow induced by the conventional low-flow superficial temporal artery-to-middle cerebral artery (STA-MCA) bypass is a major reason for the unfavorable results obtained in authoritative, randomized controlled trials.^{4,5} Therefore, increasing the flow rate of the bypass graft to significantly improve the impaired cerebral blood perfusion is an approach that could be used to determine whether EC-IC bypass is effective in patients with ICAO.^{5,6}

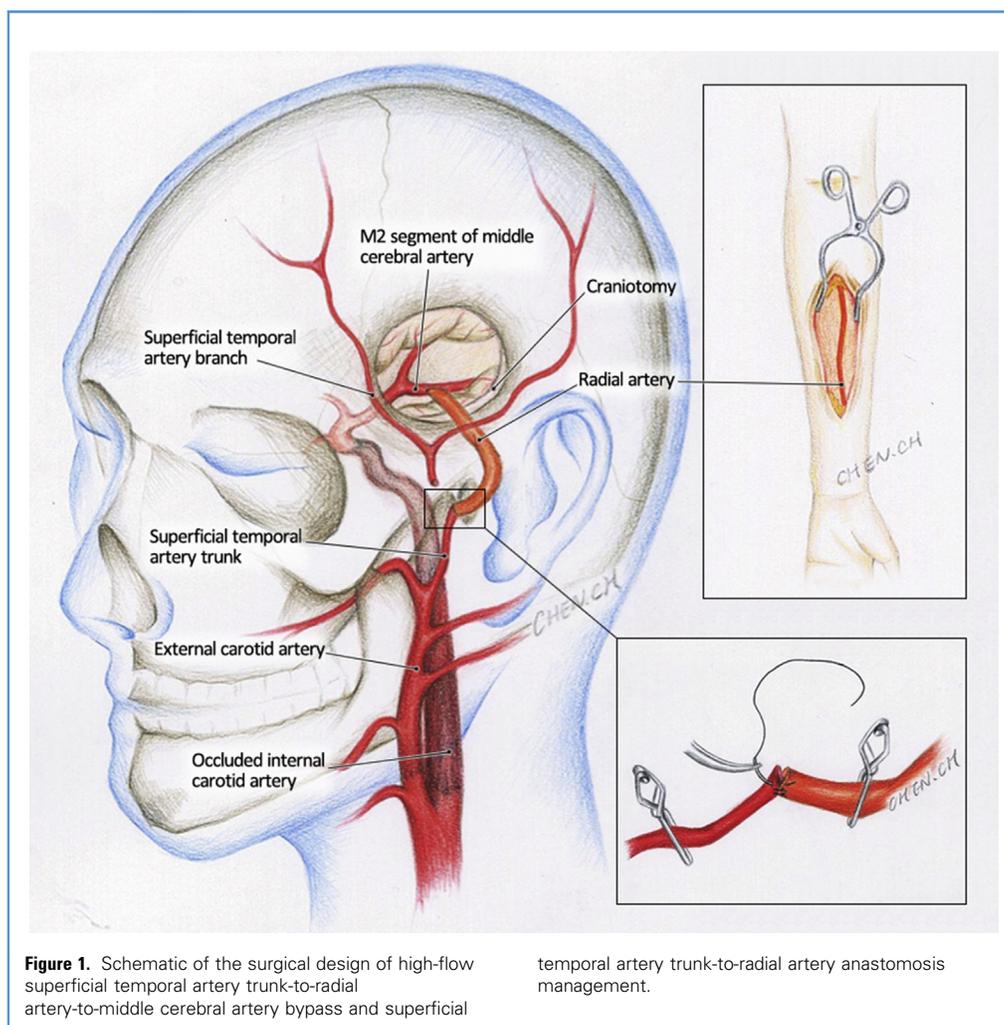
According to Poiseuille's law, the use of a larger superficial temporal artery trunk (STAt) as a feeding artery and a radial artery (RA) in a bypass graft can significantly increase the blood flow (≤ 54 –100 mL/min) compared with the use of the STA branch.^{9,10}

Moreover, this approach significantly improved the blood flow in the impaired cerebral region in patients with ICAO and, thus, reduced the risk of stroke. However, only 6 cases of ICAO treated with STAT-RA-MCA bypass have been reported,^{5,11} and a study specifically designed to investigate the use of STAT-RA-MCA bypass has not been performed. To this end, this relatively simple high-flow bypass technique was called "The Forgotten Bypass" by Abla and Lawton.¹⁰ In the present study, we report the cases of 21 patients with symptomatic ICAO (SICAO) who had specifically been treated with high-flow STAT-RA-MCA bypass at our center (Figure 1). To the best of our knowledge, our report represents the first study to specifically evaluate this surgical approach.

METHODS

Surgical Indications for High-Flow STAt-RA-MCA Bypass

We retrospectively analyzed the data from 21 patients with SICAO who had undergone high-flow STAt-RA-MCA bypass in our center from October 2014 to November 2017. The surgical indications were as follows:



1. Age <75 years
2. Symptoms of cerebral ischemia during the previous 6 months (not only retinal symptoms but also TIAs or minor ischemic stroke defined as persistent focal neurological deficit with a baseline National Institute of Health stroke scale score ≤ 3)¹² considered to be caused by ICAO, despite antiplatelet or anticoagulation treatment
3. A modified Rankin scale (mRS) score ≤ 2 on admission¹³
4. Computed tomography perfusion (CTP) showing ipsilateral/contralateral mean transit time (I/C MTT) ratios in the posterior part of the inferior frontal gyrus > 1.13 (determined by referring to the ipsilateral/contralateral oxygen extraction fraction according to the COSS inclusion criteria⁸)
5. Computed tomography angiogram showing the STAT caliber at the level of the zygoma was > 2 mm^{5,14}

The contraindications for surgery were as follows:

1. Presence of a major infarction⁵ or a major disabling stroke (mRS score grade 4 or 5)¹⁵
2. Occlusion of the ipsilateral MCA
3. Positive Allen test in both forearms¹⁶
4. A contraindication for the use of antiplatelet drugs

The regional ethics committee of our hospital approved the present study, and all the patients provided written informed consent.

Surgical Procedures

The procedures were performed in a hybrid operating room. The patient was placed in the supine position under general anesthesia with tracheal intubation. The surgical procedure was as follows. First, the STAT was located with Doppler ultrasonography, and then the incision was made ~ 3 cm in front of the tragus, and the STAT was dissected under a microscope. To avoid damage to the STAT during the subsequent craniotomy, once the STAT had been successfully dissected, the STAT was cut and maintained at ~ 2 cm. Distal bleeding was controlled with bipolar cautery, and the proximal segment was temporarily clamped with a clip. Gauze moistened with papaverine saline was wrapped around the stump of the STA. After that, a frontotemporal craniotomy was performed to separate the Sylvian fissure and to expose the M2 segment of the MCA by 2 of us (C.C., W.H.). The inferior trunk of the M2 segment was the preferred vessel for grafting. Concurrently, another group of us (L.L., L.Z.) harvested the RA (10–11 cm) in the nondominant forearm. We preferred to harvest the RA, together with its bilateral parallel veins, under direct vision to ensure that the RA was not irritated and to effectively avoid its contraction from spasms. The RA graft was stored in heparin–papaverine solution. An end-to-side anastomosis of the RA-MCA was performed first. A temporary clip was used to occlude the MCA. The anastomosis between the RA and MCA was performed using an interrupted suture with a 9–0 Prolene suture (10 stitches in total). After anastomosis, the RA was temporarily occluded, and

MCA blood flow was restored. The end-to-end anastomoses of the STAT and RA were completed with interrupted sutures (8–0 Prolene sutures; 10 stitches in total). Care should be taken to avoid kinking the RA. The STAT should be trimmed to ensure that its caliber matches the RA caliber for easy end-to-end anastomosis (Figure 2). Before completion of the last stitch, the temporary clip on the RA was removed to expel air from the vessel. After bypass grafting, digital subtraction angiography (DSA) was performed immediately to verify the patency of the graft. The Matsushima classification was used to assess the extent of intracerebral perfusion induced by the graft. The Matsushima classification uses DSA to evaluate the formation of the collateral circulation induced by vascular anastomosis: grade A, more than two thirds of the MCA anastomosis-induced circulation is fulfilled; grade B, one-third to two-thirds fulfillment; and grade C, less than one-third fulfillment.¹⁷

Antiplatelet and Anticoagulation Therapy

The oral administration of aspirin (100 mg/day [Bayer, Berlin, Germany]) was started ≥ 5 days before surgery (including the day of surgery). The administration of aspirin (100 mg/day) should be maintained for the patient's lifetime after surgery. Before the MCA

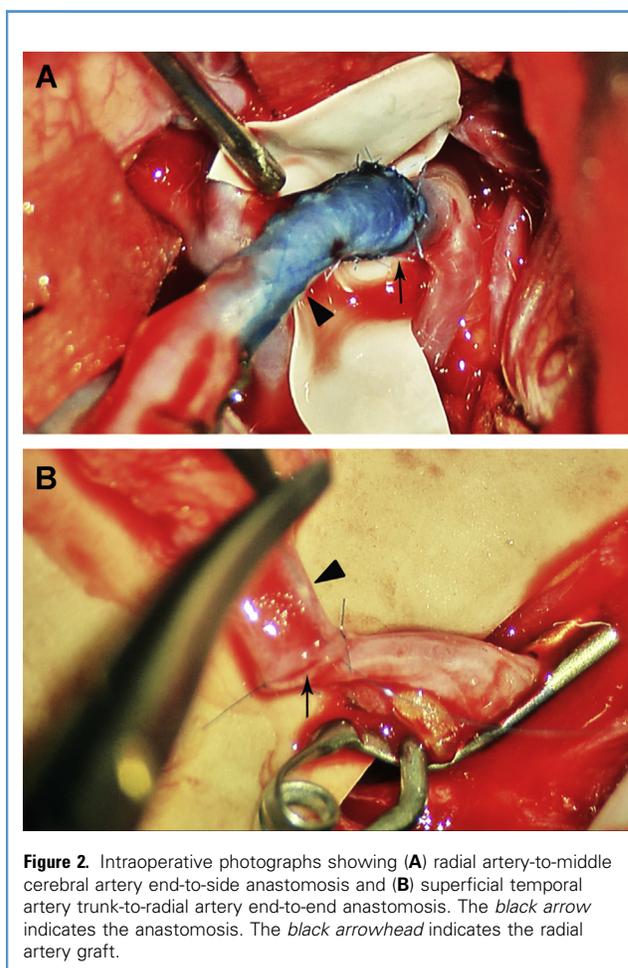


Figure 2. Intraoperative photographs showing (A) radial artery-to-middle cerebral artery end-to-side anastomosis and (B) superficial temporal artery trunk-to-radial artery end-to-end anastomosis. The black arrow indicates the anastomosis. The black arrowhead indicates the radial artery graft.

was temporarily occluded during surgery, 3000 IU of heparin was administered intravenously. Heparin was not neutralized or continued after surgery. If cerebral hemorrhage is present after surgery, aspirin should be discontinued for 1 week.

Follow-Up Protocol

Doppler ultrasonography (MyLab Twice, Florence, Italy) was performed at the end of the surgery (day 1) and 6 months after surgery (day 180) to view the changes in RA caliber and flow rate (at the level of the zygoma). On postoperative days 2 and 180, computed tomography angiography and CTP (Aquilion One [Canon, Tokyo, Japan]) of the head were performed to determine the improvement in cerebral blood perfusion (I/C MTT ratio) by 1 of us (Y.G.). Six months after surgery, a telephone follow-up interview was conducted for all patients by 2 of us (L.W., C.L.). During the follow-up period, the occurrence of TIAs and stroke were recorded. The mRS score was used to assess the neurological state of the patients.

Statistical Analysis

The paired *t* test was used to compare the differences in the caliber and flow rate of the RA at the different follow-up points after

surgery and the changes in the I/C MTT ratio preoperatively and immediately and 6 months postoperatively. The Pearson correlation analysis was used to assess the correlations among different continuous variables. $P < 0.05$ was considered to indicate statistical significance. The data were analyzed using SPSS, version 22.0 (IBM Corp., Armonk, New York, USA).

RESULTS

From October 2014 to November 2017, we treated 21 patients with SICAO using a high-flow STAT-RA-MCA bypass according to the inclusion criteria. The demographic data for all patients are shown in **Table 1**. The patients included 12 men and 9 women, with an average age of 62.8 ± 7.8 years. The onset symptoms included TIAs, amaurosis fugax, hemiplegia, limb numbness, anomic aphasia, and minor stroke. The number of episodes of these symptoms was 1–4 within the previous 6 months. Left ICAO was identified in 11 patients and right ICAO in 10 patients. The preoperative mRS score was ≤ 2 points for all patients. The I/C MTT ratio ranged from 1.14 to 1.51 (average, 1.24 ± 0.10) in 21 patients. Preoperative Doppler ultrasonography showed that the

Table 1. Patient Characteristics

Pt. No.	Age (years); Gender	HTN	T2DM	Symptoms	Episodes ≤ 6 Months	Side of SICAO	mRS Score	I/C MTT Ratio	Caliber of STAT (mm)	Flow Rate of STAT (mL/min)
1	52/M	Yes	No	TIA, amaurosis fugax	1	Left	1	1.21	2.0	34
2	68/F	Yes	Yes	TIA	1	Right	1	1.19	2.1	32
3	47/F	Yes	No	Stroke, hemiplegia	2	Right	2	1.18	2.1	47
4	53/F	No	Yes	TIA	2	Left	0	1.26	2.1	50
5	67/M	Yes	Yes	Stroke, limb numb	1	Right	1	1.20	2.4	68
6	69/M	No	No	Stroke, limb numb	2	Left	1	1.15	2.1	54
7	70/F	Yes	No	TIA	3	Right	1	1.18	2.0	32
8	55/M	Yes	No	TIA, amaurosis fugax	4	Left	1	1.30	2.1	34
9	64/F	No	Yes	TIA	2	Right	1	1.23	2.0	30
10	52/M	Yes	No	Stroke, hemiplegia	3	Left	2	1.51	2.0	33
11	71/M	Yes	No	TIA	3	Left	1	1.27	2.1	35
12	69/M	Yes	Yes	Stroke, anomic aphasia	1	Left	2	1.43	2.2	46
13	64/M	No	No	TIA	2	Right	0	1.17	2.2	48
14	61/F	No	Yes	TIA	1	Right	1	1.28	2.0	38
15	68/F	Yes	No	TIA	2	Left	1	1.14	2.0	31
16	54/M	Yes	No	Stroke, hemiplegia	2	Right	1	1.19	2.1	46
17	72/F	Yes	Yes	TIA	4	Left	1	1.37	2.0	32
18	70/M	No	No	TIA	1	Left	0	1.22	2.3	68
19	71/M	Yes	Yes	TIA, amaurosis fugax	2	Right	1	1.15	2.1	48
20	63/M	Yes	No	TIA	2	Left	1	1.19	2.0	37
21	58/F	Yes	No	Stroke, hemiplegia	1	Right	2	1.30	2.0	31

Pt. No., patient number; HTN, hypertension; T2DM, type 2 diabetes mellitus; SICAO, symptomatic internal carotid artery occlusion; mRS, modified Rankin scale; I/C MTT, ipsilateral-to-contralateral mean transit time; STAT, superficial temporal artery trunk; M, male; TIA, transient ischemia attack; F, female.

mean STAt caliber and flow rate were 2.09 ± 0.11 mm and 41.6 ± 11.6 mL/min, respectively.

The detailed intraoperative data for all patients are shown in **Table 2**. The M2 segment of the MCA on the affected side was selected as the recipient vessel. The inferior trunk was chosen in 18 patients (85.7%). When end-to-side anastomosis of the RA-MCA was performed, the mean clamping time of the M2 segment was 31.4 ± 3.7 minutes (range, 24–37). The average length of the RA selected to connect the STAt and MCA was 8.2 ± 0.6 cm. At completion of the anastomosis, the intraoperative DSA showed that the graft was patent in 21 patients. Assessment of the bypass graft using the Matsushima classification scores showed grade A revascularization in 17 of 21 patients (81.0%) and grade B revascularization in 4 of 21 patients (19.0%). No patient had grade C revascularization (**Figure 3**).

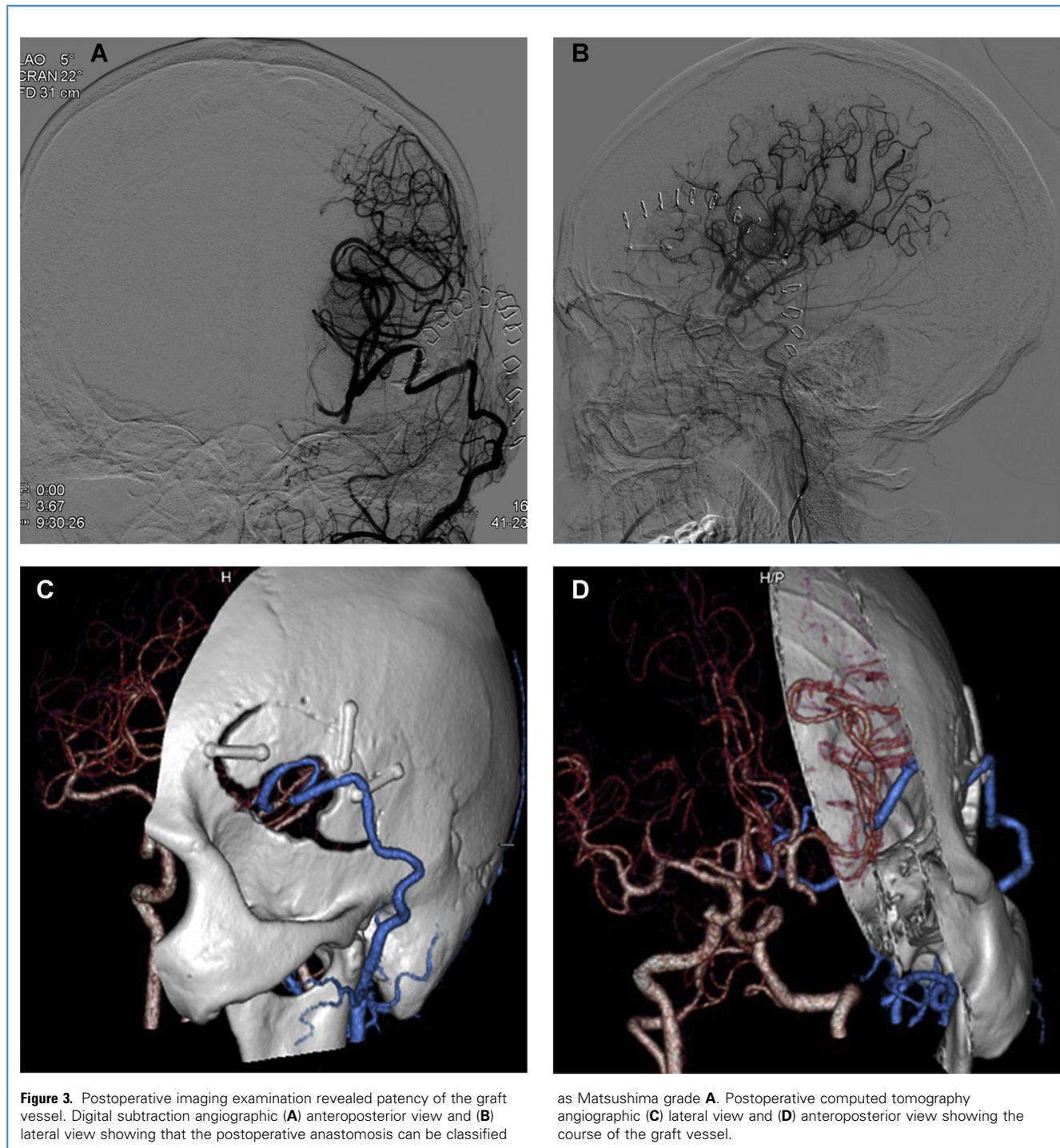
The detailed postoperative and follow-up data for all patients are shown in **Table 3**. The follow-up period ranged from 212 to 1114 days (median, 692). A TIA occurred in only 1 patient (4.8%) within 30 days after surgery. During the follow-up period >30 days after surgery, another 2 patients experienced recurrent TIAs.

Therefore, during a median of 692 days of follow-up, only 3 of 21 patients experienced TIAs (patients 10, 15 and 17), and the recurrence rate for stroke was 14.3% (3 of 21). The surgical complication rate was 9.5% (2 of 21). The complication was subdural hemorrhage in both patients (patients 7 and 17) in the operative area and led to seizures or RA spasms. These 2 patients received conservative therapy. All these postoperative ischemic events and surgical complications resulted in a prognosis with a mRS of ≤ 1 (**Table 3**). One patient (patient 17) had a patent graft after surgery (spasms occurred later); however, Doppler ultrasonography showed graft occlusion 6 months after surgery. The remaining 20 patients (95.2%) had patent grafts during the 6-month follow-up period. DSA showed anastomotic stenosis of the RA-MCA in 1 patient (patient 15) at 6 months after surgery (**Figure 4**). In the 20 patients with patent grafts, Doppler ultrasonography on days 1 and 180 showed that the mean RA caliber was 2.92 ± 0.27 mm and 3.11 ± 0.27 mm, respectively, a statistically significant difference ($P < 0.001$). Additionally, the mean RA flow rates were 68.9 ± 11.3 mL/min and 81.5 ± 13.5 mL/min, respectively, with statistically significant differences

Table 2. Surgery-Related Information of Patients with Symptomatic Internal Carotid Artery Occlusion

Pt. No.	Recipient Vessel (M2)	M2 Temporary Clamping Time (minutes)	RA Length (cm)	Intraoperative DSA	
				Graft Patency	Matsushima Grade
1	Lower trunk	29	8.4	Yes	A
2	Lower trunk	37	9	Yes	A
3	Lower trunk	24	7.4	Yes	A
4	Lower trunk	34	8.5	Yes	A
5	Upper trunk	30	9.1	Yes	A
6	Lower trunk	34	7.6	Yes	A
7	Lower trunk	37	7	Yes	B
8	Lower trunk	36	8.4	Yes	A
9	Lower trunk	34	8.3	Yes	A
10	Lower trunk	35	7.6	Yes	B
11	Lower trunk	29	7.9	Yes	A
12	Upper trunk	30	8	Yes	A
13	Lower trunk	34	8.7	Yes	A
14	Upper trunk	32	9.1	Yes	A
15	Lower trunk	27	7.6	Yes	B
16	Lower trunk	31	7.4	Yes	A
17	Lower trunk	25	8.7	Yes	A
18	Lower trunk	33	8.8	Yes	A
19	Lower trunk	28	8.5	Yes	A
20	Lower trunk	30	8.1	Yes	A
21	Lower trunk	31	7.9	Yes	B

Pt. No., patient number; M2, segment 2 of middle cerebral artery; RA, radial artery; DSA, digital subtraction angiography.



($P < 0.001$). In the 21 patients, the mean I/C MTT ratios before and after surgery were 1.24 ± 0.10 and 1.06 ± 0.11 , respectively, with statistically significant difference ($P < 0.001$). In the 20 patients with patent bypass grafts, the I/C MTT ratios were 1.06 ± 0.11 and 1.02 ± 0.06 on postoperative days 1 and 180, respectively, and were significantly different from the

preoperative I/C MTT ratio of 1.24 ± 0.09 ($P < 0.001$ and $P < 0.001$, respectively). However, the difference between these 2 postoperative ratios was not statistically significant ($P = 0.059$). The correlation analysis showed that the RA flow on the day of surgery (day 1) was significantly associated with the RA caliber ($r = 0.762$; $P < 0.001$) and the preoperative SAt flow

Table 3. Follow-Up Information for Patients with Symptomatic Internal Carotid Artery Occlusion after High-Flow Superficial Temporal Artery Trunk-to-Radial Artery-to-Middle Cerebral Artery Bypass

Pt. No.	Caliber of RA Graft (mm)		Flow Rate of RA Graft (mL/min)		I/C MTT Ratio		Complications	Follow-Up Period (days)	Ischemic Events <30 Days	Ischemic Events >30 Days	Graft Patency on Day 180	mRS Score on Day 180
	D1	D180	D1	D180	D2	D180						
1	3.1	3.4	68	92	1.07	1.05	None	1114	None	None	Yes	0
2	2.5	2.8	74	79	0.97	1.01	None	1056	None	None	Yes	1
3	2.9	3.0	63	89	1.09	0.94	None	1022	None	None	Yes	2
4	3.1	3.1	74	79	0.94	0.93	None	931	None	None	Yes	0
5	3.0	3.4	70	99	1.02	1.03	None	963	None	None	Yes	0
6	3.5	3.6	88	102	1.04	1.01	None	810	None	None	Yes	1
7	2.9	3.1	73	86	1.06	1.08	Subdural hemorrhage, seizure	877	None	None	Yes	1
8	2.6	2.9	48	59	1.21	1.16	None	781	None	TIA	Yes	1
9	2.8	3.0	55	64	0.97	1.01	None	721	None	None	Yes	1
10	2.7	3.1	61	80	1.34	1.02	None	783	TIA	None	Yes	1
11	3.0	3.2	67	78	1.10	1.04	None	692	None	None	Yes	1
12	2.7	3.2	73	94	1.24	1.07	None	631	None	None	Yes	2
13	3.4	3.3	88	92	0.97	0.98	None	549	None	None	Yes	0
14	2.9	3.1	63	87	1.06	1.05	None	487	None	None	Yes	0
15	2.5	2.5	48	54	0.88	0.90	None	428	None	None	Yes	1
16	2.8	3.0	62	66	1.05	1.07	None	396	None	None	Yes	1
17	2.7	NA	49	NA	1.11	1.30	Subdural hemorrhage, RA spasm	421	None	TIA	No	1
18	3.1	3.2	80	79	1.01	1.02	None	332	None	None	Yes	0
19	2.7	2.6	64	68	0.96	0.95	None	245	None	None	Yes	1
20	3.0	3.3	79	94	1.04	1.02	None	277	None	None	Yes	0
21	3.1	3.3	80	89	1.19	1.08	None	212	None	None	Yes	2

Pt. No., patient number; RA, radial artery; I/C MTT, ipsilateral/contralateral mean transit time; mRS, modified Rankin scale; D1, day of surgery; D180, 6 months after surgery; D2, first day after surgery; TIA, transient ischemia attack; NA, not applicable.

($r = 0.451$; $P = 0.04$) but not with the preoperative I/C MTT ratio ($r = -0.245$; $P = 0.285$) or the STAt caliber ($r = 0.351$; $P = 0.119$). Six months after surgery (day 180), the RA flow was related only to the RA caliber ($r = 0.828$; $P < 0.001$) and was not related to the other variables (Figure 5).

DISCUSSION

To the best of our knowledge, the present study was the first specific study with the largest sample size of 21 patients with SICA0 who had undergone high-flow STAt-RA-MCA bypass in our center. Our retrospective study showed that the patency rate of the

bypass graft for all 21 patients with SICA0 was 95.2%. During a median follow-up period of 692 days after surgery, 18 patients had not have recurrent ischemic events, and the improvement rate in the symptoms was 85.7% (18 of 21). Only 3 patients (14.3%; patients 10, 15, and 17) experienced recurrent TIAs (once for each patient). The operative complication rate was 9.5% (2 of 21). The complication was subdural hematoma in the operative area that did not require reoperation. All of these postoperative ischemic events or surgical complications resulted in a mRS of ≤ 1 . Therefore, the results from the present study might suggest that high-flow STAt-RA-MCA bypass can effectively and safely reduce the risk of stroke in patients with SICA0.

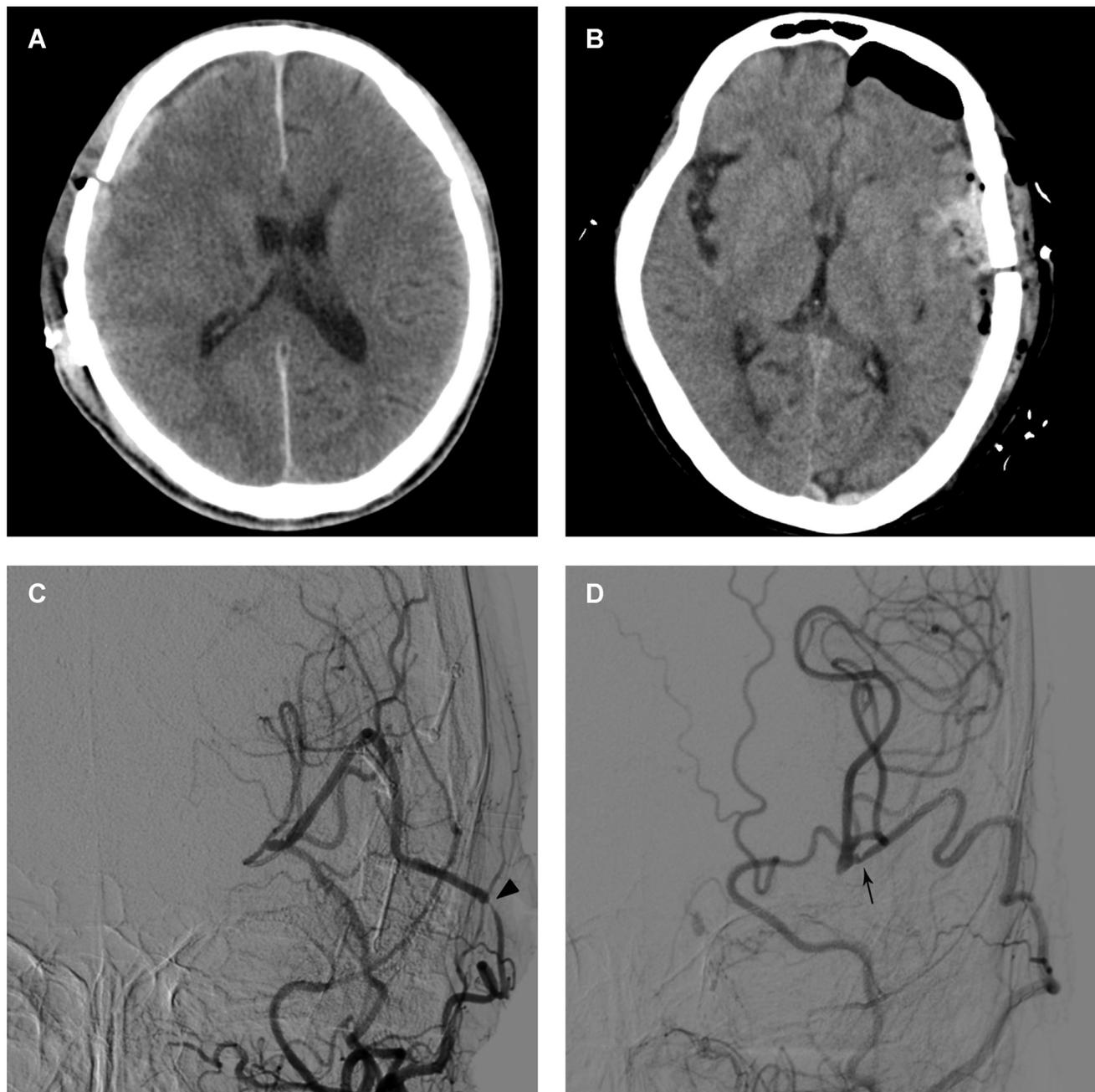


Figure 4. Postoperative imaging examination showing postoperative complications. **(A)** Postoperative hemorrhage, located only in the subdural region (patient 7). **(B)** Postoperative hemorrhage located in the subcutaneous and subdural regions and Sylvian fissures (patient 17),

resulting in vasospasm of the graft **(C)**. The *black arrowhead* indicates the vasospasm. **(D)** Anastomotic stenosis of radial artery-to-middle cerebral artery occurred 6 months after surgery (patient 15). The *black arrow* indicates the stenosis.

Effectiveness of High-Flow STA_t-RA-MCA Bypass

The follow-up period ranged from 212 to 1114 days (median, 692), which was close to the follow-up period (median, 723 days; interquartile range, 288–730) for the surgical group in the COSS. During the follow-up period, the ischemic events of the brain

included 3 episodes of TIAs (14.3%; 3 of 21), lower than the 21.0% and 22.7% stroke recurrence rates during the follow-up period in the COSS surgical and nonsurgical groups, respectively. One patient (4.8%; patient 10) experienced a TIA within 30 days after surgery. The recurrence rate was also lower than the 15%

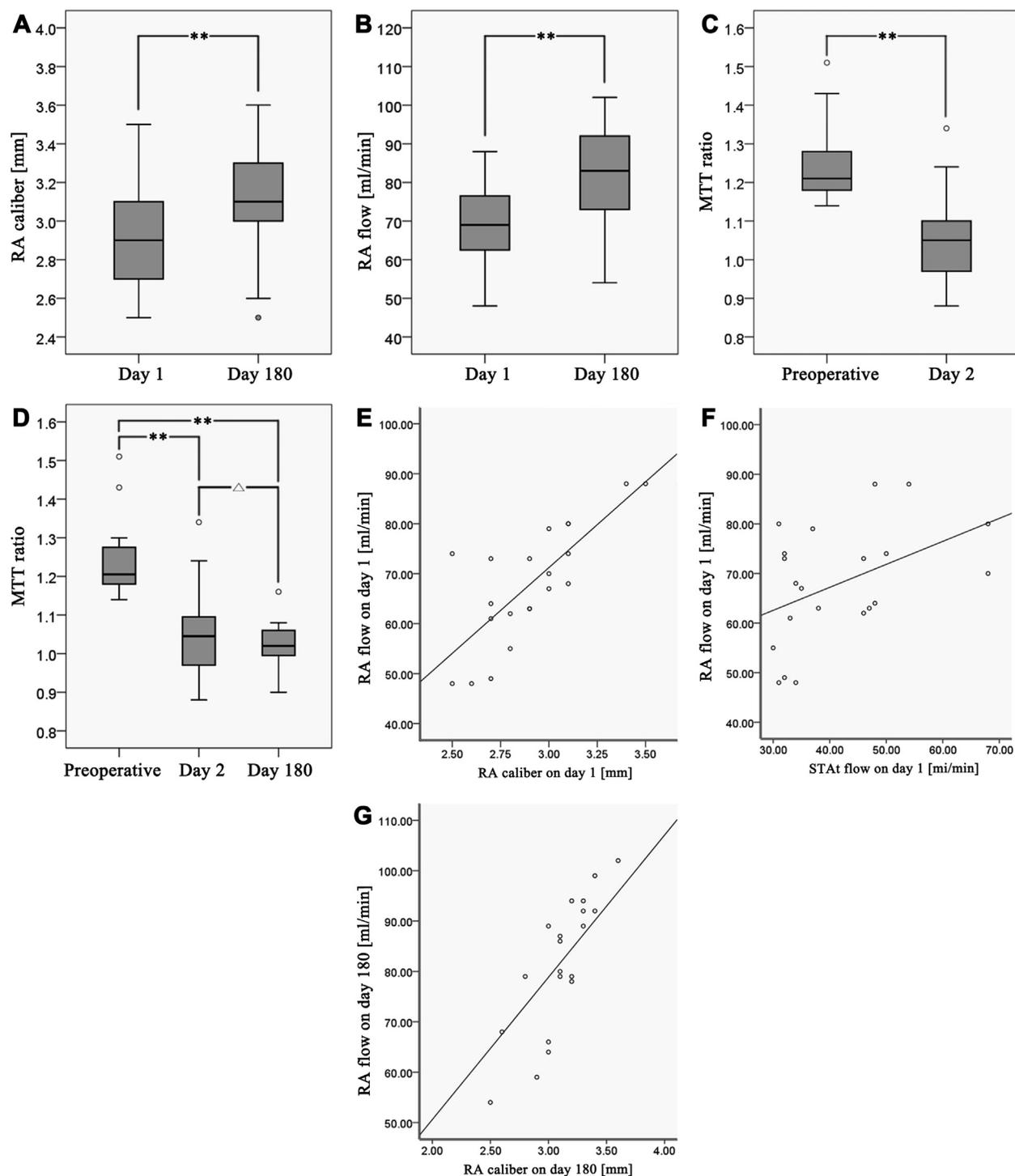


Figure 5. Box plot and scatter plot showing (A) significant differences in radial artery (RA) caliber between the day of surgery (day 1) and 6 months after surgery (day 180). (B) Significant differences in the RA flow rates between the day of surgery (day 1) and 6 months after surgery (day 180). (C) Significant difference in the ipsilateral/contralateral mean transit time ratio of all 21 patients between postoperative day 1 (day 2) and before surgery. (D) The ipsilateral/contralateral mean transit time ratio before surgery and at postoperative day 1 (day 2) and 6 months after

surgery (day 180) in 20 patients with patent grafts. (E) A significant correlation between the RA flow rate and RA caliber on the day of surgery (day 1). (F) A significant correlation was found between the RA flow rate on the day of surgery (day 1) and the preoperative superficial temporal artery trunk flow. (G) A significant correlation was found between the RA flow rate and RA caliber at 6 months after surgery (day 180). ** $P < 0.001$; $\Delta P > 0.05$.

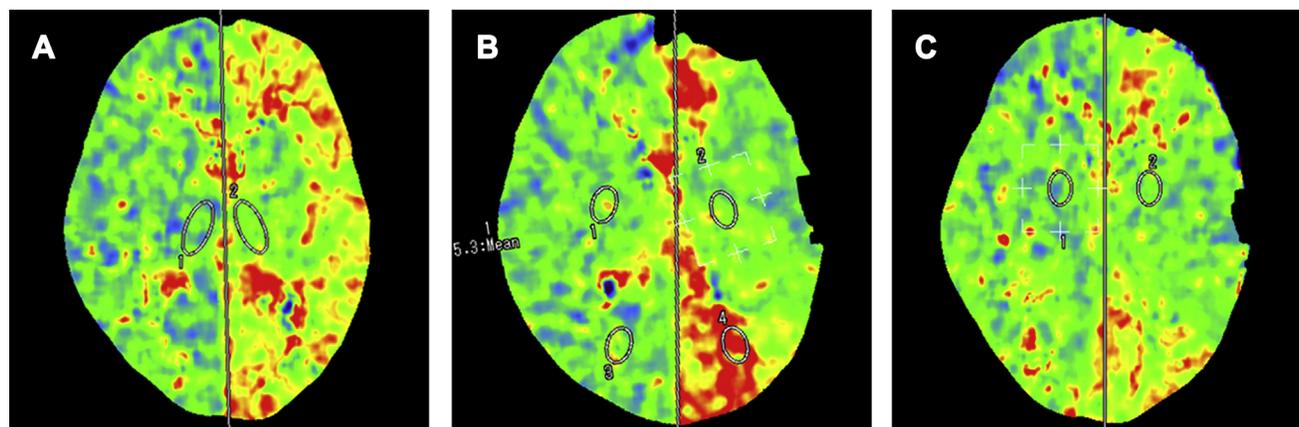


Figure 6. Progressive improvement in ipsilateral cerebral blood perfusion (ipsilateral/contralateral mean transit time) (A) preoperatively, (B) postoperative day 1, and (C) 6 months after surgery.

incidence of stroke within 30 days after surgery in the COSS group. A total of 18 patients had no postoperative ischemic events (i.e., the improvement rate of symptoms was 85.7%; 18 of 21). Compared with the occurrence of 42 ischemic stroke events in the 6 months before surgery (average, 2 episodes per person for 6 months), the occurrence of ischemic stroke was significantly lower after surgery. The results from the present study suggest that by strictly screening patients for surgery, high-flow STAT-RA-MCA bypass might be more effective than conventional STA-MCA bypass and might benefit patients with SICA0 by reducing the occurrence of cerebral ischemic events. Of the 3 patients with recurrent TIAs, 1 (patient 15) had anastomotic stenosis and a flow rate of only 54 mL/min within 6 months after surgery. Therefore, we considered that the recurrence of TIAs might be related to the development of anastomotic stenosis. In the case of another patient with severe atherosclerosis in the ipsilateral MCA (patient 10), the I/C MTT ratio on postoperative day 1 was still as high as 1.34. Such a poor cerebrovascular condition might be related to the recurrence of TIAs in this patient within 30 days of surgery. TIA recurrence in the remaining patient (patient 17) might have resulted from late occlusion of the graft.

Relationship Between RA Flow Rate and I/C MTT Ratio

Compared with the Doppler ultrasound results on the day of surgery, the RA caliber in this group of patients was significantly enlarged (from 2.92 ± 0.27 mm to 3.11 ± 0.27 mm; $P < 0.001$) after 6 months, and the RA flow rate was significantly increased (from 68.9 ± 11.3 mL/min to 81.5 ± 13.5 mL/min; $P < 0.001$). This conformity to blood flow in the caliber of the graft has been previously reported by several investigators^{16,18,19} and is one of the advantages of the RA compared with the saphenous vein. However, what was not comparable to the significant change in the RA flow rate and caliber is that, although the I/C MTT ratio on the second day after grafting decreased significantly (from 1.24 ± 0.10 to 1.06 ± 0.11 ; $P < 0.001$), the I/C MTT ratio after 6 months did not further decrease (from 1.06 ± 0.11 to 1.02 ± 0.06 ; $P = 0.059$)

with the continued increase in RA flow rate. We speculated that this discrepancy was the result of redistribution of the bilateral cerebral blood flow after grafting (both sides of the cerebral perfusion will tend to be balanced; Figure 6). Intuitively, the greater flow of the graft will be associated with obvious improvement in the ischemic symptoms.⁶ The RA flow rate (40–100 mL/min)^{9,20} reported in published studies and the average of 81.5 ± 13.5 mL/min reported in the present study were still lower than the ICA flow rate in the physiological state (~ 250 mL/min).⁴ However, because the caliber and flow rate of the RA gradually increased over time and the compensated blood supply was established from the anterior or posterior communicating artery, the blood flow of the RA might have been sufficient to significantly reduce the risk of ischemic events.

Rationality of Application of STAT-RA-MCA for Patients with SICA0

Despite the unfavorable results of the EC-IC bypass trial and COSS, improving the symptoms and prognosis of patients with ICA0 by increasing blood perfusion remains an area that has been unremittingly explored by neurosurgeons. The conventional STA-MCA bypass is a low-flow bypass (20–40 mL/min), and the STA branch with a 1-mm diameter cannot provide sufficient blood flow to prevent the occurrence of stroke, especially when the compensation blood flow from the anterior and posterior communicating arteries is limited. We learned that the incidence of stroke after high-flow bypass surgery was lower than that after low-flow bypass surgery.¹¹ According to the Hagen-Poiseuille equation (flow = Δ pressure $\pi r^4/8 \times$ length \times viscosity),^{6,9} an RA with a 3-mm diameter can provide a blood flow rate that is 81-fold greater than that provided by the 1-mm STA branch. Therefore, in theory, the high-flow STAT-RA-MCA bypass can prevent the occurrence of stroke more efficiently than the conventional STA-MCA and is more suitable for patients with SICA0.

However, the question remains whether this finding suggest that an external carotid artery-graft-MCA bypass that provides

greater blood flow might be more beneficial to patients with SICA0 than a STAT-RA-MCA bypass. We believe that, in addition to the differences in flow rates, the high-flow STAT-RA-MCA bypass should be more suitable for patients with SICA0 than the external carotid artery-graft-MCA bypass for the following reasons. First, the compensation of ipsilateral cerebral blood flow in patients with chronic SICA0 has been established as coming from the anterior communicating artery, posterior communicating artery, or leptomeningeal anastomoses before surgery. Therefore, the flow rate of the STAT-RA-MCA will be sufficient. Second, the graft vessel is short and does not travel through the neck; therefore, the chance of kinking and compression is low and the bypass patency rate greater.¹⁴ Third, the risk of overperfusion will be lower. Fourth, a neck incision is not needed and the related complications are, thus, avoidable. Fifth, the incision for RA harvest in the forearm is shorter (the average length of the RA in this group was 8.20 ± 0.61 cm).

Graft Selection

During graft vessel selection, we prefer a RA graft (RAG) to a saphenous vein graft (SVG), although spasm of the RAG can cause occlusion of the graft vessels (patient 17). The main reason is because a RAG has greater short- and long-term patency rates. The patency rate of the RAG has been reported to be 91%–100%. In contrast, the rate of the SVG has been 73%–93%.^{16,21–23} Ishishita et al.²⁴ reported 38 cases of high-flow EC-IC bypass (mean, 46.7 months), and graft occlusion occurred in only 2 cases in which an SVG was used.²⁴ Matsukawa et al.¹⁶ reported 75 cases of high-flow EC-IC bypass (mean 26.2 months), in which 4 cases of occlusion were reported among 20 cases using an SVG (patency rate, 80%). No occlusion was reported in the remaining 55 cases using an RAG (patency rate, 100%).¹⁶ In addition to the greater patency rate, the reasons for choosing an RAG also included the following. First, the RAG caliber will gradually increase over time owing to RAG denervation,²⁵ and the blood flow rate will increase accordingly. However, the caliber of an SVG will rarely change.¹⁶ Second, the wound on the forearm will not prevent the patient from early ambulation. Finally, the SVG can be easily

damaged during harvesting.¹¹ Finally, if the Allen test result is positive in both forearms, a STAT-SV-MCA bypass will still be a good choice.^{20,26}

Study Limitations

First, our study had a retrospective design with the inherent limitations that led to a potential ascertainment bias. Second, the sample size in the present study was small. Moreover, multivariate analysis could not be performed because only a few patients had developed postoperative bleeding and graft occlusion. Third, considering the convenience, economic burden, and radiation exposure, we prefer the use of CTP (MTT ratio) to evaluate the changes in cerebral blood flow. However, this measure is only a relative indicator comparing the bilateral cerebral hemispheres and an increased I/C MTT (>1.13) might not correspond to the increased oxygen extraction fraction in the COSS. To understand the absolute changes in the metabolic index of the ipsilateral hemisphere, the use of the regional oxygen extraction fraction might be better, because the latter is more precise. Finally, our study lacked a control group; thus, further randomized controlled studies are needed to compare the efficacy of high-flow STAT-RA-MCA bypass and conventional STA-MCA bypass.

CONCLUSIONS

The results from our study suggest that high-flow STAT-RA-MCA bypass can effectively reduce the risk of stroke in patients with SICA0 through the strict screening of surgical candidates. Moreover, the surgical procedure itself is a highly safe procedure. Further randomized controlled studies are needed to draw more precise conclusions. The high-flow STAT-RA-MCA bypass is a simple and effective approach for high-flow grafting that should be considered by neurosurgeons.

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