Intraoperative middle cerebral artery pressure measurements during superficial temporal artery to middle cerebral artery bypass procedures in patients with cerebral atherosclerotic disease

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OBJECTIVE No previous study has monitored middle cerebral artery (MCA) pressure during the superficial temporal artery (STA)-MCA bypass procedure for cerebral atherosclerotic disease. In this paper, the authors describe their method of monitoring MCA pressure and report their initial data on intraoperative MCA pressure and its relationship with hemodynamics prior to and after the bypass procedures.

METHODS The results from a total of 39 revascularization procedures performed between 2004 and 2014 were analyzed. The patient group included 27 men and 12 women, and their mean age at surgery was 67.6 years (range 39–83 years). The authors investigated the MCA pressure via the STA during STA-MCA bypass procedures. After one branch of the STA was anastomosed to the MCA, the other branch was connected to an arterial line, and a clip was placed temporally on the main STA trunk to monitor the pre-anastomosis MCA pressure. Simultaneously, the radial artery (RA) pressure was determined before removing the temporal clip to measure the post-anastomosis MCA pressure. The relationship between MCA pressures and single photon emission computed tomography findings and the risk factors for hyperperfusion after STA-MCA bypass were analyzed.

RESULTS The MCA/RA (%) pressure was significantly correlated with that of the resting stenotic/normal side cerebral blood flow (CBF) ratio (%) in the linear regression analysis (slope 1.200, $r^2 = 0.3564$, $F = 20.49$, $p < 0.0001$). The intraoperative MCA pressure was 39.3% of RA pressure in patients with Powers' Stage 2 cerebral atherosclerotic disease. After 1 branch of the STA was anastomosed, the intraoperative MCA pressure increased to 75.3% of the RA pressure. The rate of increase in pressure was significantly correlated with the increase in the STA diameter in the linear regression analysis (slope 2.59, $r^2 = 0.205$, $F = 9.549$, $p = 0.0038$). Hyperperfusion occurred in 2 cases. When mean values for these 2 patients were compared with those for the 37 patients without hyperperfusion, significant differences were found in the stenotic/normal side CBF ratio ($p = 0.0001$), pre-anastomosis MCA pressure ($p = 0.02$), rate of increase in pressure ($p = 0.02$), pre-anastomotic MCA/RA pressure ratio ($p = 0.01$), vascular reserve ($p = 0.0489$), and STA diameter ($p = 0.0002$).

CONCLUSIONS The measurement of intraoperative MCA pressure may be a useful technique to assess cerebral perfusion and for predicting the risk of hyperperfusion. Monitoring MCA pressure is recommended during STA-MCA bypass procedures for atherosclerotic disease.

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KEY WORDS SPECT; cerebral blood flow; middle cerebral artery; superficial temporal artery; vascular disorders

ABBREVIATIONS 3D-SSP = 3D stereotactic surface projection; CBF = cerebral blood flow; CPP = cerebral perfusion pressure; ICA = internal carotid artery; ¹²³I-IMP = *N*-isopropyl [¹²³I]-*p*-iodoamphetamine; JET = Japan Extracranial-Intracranial Bypass Trial; MCA = middle cerebral artery; RA = radial artery; rCBF = regional CBF; ROI = region of interest; SPECT = single photon emission computed tomography; STA = superficial temporal artery.

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THE role of superficial temporal artery (STA) to middle cerebral artery (MCA) bypass procedures has not been broadly established in adult intracranial vascular pathologies.^{4,13} However, there is supporting evidence for STA-MCA bypass surgery in cases of recurrent transient ischemic attacks with Powers' Stage 2 cerebrovascular reserve capacity.^{9,12,16,19,26,27,29}

The main diagnostic tools for cerebral atherosclerotic disease are *N*-isopropyl [¹²³I]-p-iodoamphetamine (¹²³I-IMP)–single photon emission computed tomography (SPECT) (¹²³I-IMP-SPECT) and cerebral blood flow (CBF) and vascular reserve studies.^{23,29}

To date, no study has monitored MCA pressure to assess hemodynamic change during an STA-MCA bypass procedure in patients with cerebral atherosclerotic disease. In this retrospective study, we investigated MCA pressure via the STA during STA-MCA bypass procedures.

In this paper, we first describe our technique of measuring MCA pressure and present the initial intraoperative MCA pressure data for patients with cerebral atherosclerotic disease. We then examine the relationship between MCA pressure and SPECT findings to understand the significance of MCA pressure in STA-MCA bypass surgery. In addition, we analyze the risk factors for hyperperfusion after STA-MCA bypass.

Methods

The study is reported based on criteria from the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) statement. The study protocol was approved by the Nippon Medical School Hospital Research Ethics Committee, and written informed consent was obtained from all patients.

Patient Characteristics

We retrospectively analyzed the results from a total of 39 revascularization procedures performed in patients at our hospitals and associated institutions between 2004 and 2014. The patient group comprised 27 men and 12 women, and the patients' mean age at the time of surgery was 67.6 years (range 39–83 years). We included patients with atherosclerosis and internal carotid artery (ICA) or MCA lesions undergoing either single- or double-bypass procedures. We excluded the patients with bilateral intracranial stenotic lesions. All patients underwent bypass surgery approximately 3 months after the last ischemic event, and the procedure was performed by 1 of 3 surgeons (Y.M., R.T., H.K.), each of whom had more than 15 years of experience in neurological surgery.

Analysis of SPECT Study and Surgical Indication

The indications for the use of STA-MCA anastomosis for cerebral atherosclerotic disease in our study were based on those detailed in the Japan Extracranial-Intracranial Bypass Trial (JET) protocol.¹⁸ A preoperative CBF study was performed using ¹²³I-IMP-SPECT in all patients. The SPECT study was evaluated by autoradiography¹⁷ in 21 patients and by the microsphere method²¹ in 18 patients.

The CBF image set was quantified using autoradiography with 222 MBq of ¹²³I-IMP administered intravenously

at a constant rate over a 1-minute period. SPECT data were acquired 20 minutes after the injection, and blood samples were taken from the antecubital artery 7 minutes before the administration of ¹²³I-IMP and 10 minutes after the injection. The SPECT system had a full-width, half-maximum resolution of 10.4 mm, and used a 3-headed gamma camera (GCA-9300A/HG, Toshiba Co.) equipped with low-energy, high-resolution fan beam collimators and a GMS-5500A/DI processing computer (Toshiba Co.). For the microsphere methods, patients were administered 222 MBq of ¹²³I-IMP intravenously at a constant rate over a 45-second period. SPECT data were acquired 26–50 minutes after the injection, and blood samples were taken from the antecubital artery continuously 5 minutes after the injection of ¹²³I-IMP. The full-width, half-maximum resolution of the SPECT system was 10.0 mm, and it had a 2-headed gamma camera (Millennium MG, GE Healthcare Japan) equipped with low-energy, general-purpose collimators and a GENIE Xeleris processing computer (AGE Healthcare Japan). We conducted a paired CBF study with an acetazolamide challenge according to the JET study protocol, which corresponded to the 3D stereotactic surface projection (3D-SSP).²⁶ In addition to obtaining mean counts of isotope in the region of interest (ROI) on axial images, brain surface images were obtained using the 3D-SSP program. The 3D-SSP method offers quantitative information and 3D displays of CBF at rest and after an acetazolamide challenge. It also provides information about the vascular reserve and the severity of the hemodynamic brain ischemia. The maximum count data correlated closely with the ROI data at rest and with the acetazolamide SPECT images ($p < 0.0001$ for both). The results of this method indicated that 3D-SSP could simply and objectively evaluate the severity of impaired brain circulation. The cerebrovascular reserve capacity was classified into 3 stages (Stages 0–2) on the basis of vascular reserve capacity calculated from the regional CBF (rCBF) values at rest and during the acetazolamide challenge. Vascular reserve was defined as follows: $[(\text{CBF under acetazolamide} - \text{rCBF})/\text{rCBF}] \times 100 (\%)$. Each of the 15,965 coordinates of the brain surface image were classified as Stage 0 (rCBF is greater than 15 ml/100 g/min and vascular reserve is greater than 30%); Stage 1 (rCBF is less than 34 ml/100 g/min [80% normal CBF] but greater than 15 ml/100 g/min and vascular reserve is less than 30% but greater than 10% or rCBF is greater than 34 ml/100 g/min and vascular reserve is less than 30% but greater than –30%); and Stage 2 (rCBF is less than 34 ml/100 g/min but greater than 15 ml/100 g/min and vascular reserve is less than 10% but greater than –30%). We investigated the normal and stenotic side for CBF at rest, CBF with an acetazolamide challenge test, and the acetazolamide reactivity. Postoperative hyperperfusion was defined as CBF greater than 150% of the CBF value for the normal side.

Surgical Treatment and MCA Pressure

We dissected 2 branches of the STA, placed a clip proximally on each branch, and then cut the STA diagonally, creating a wide cross-sectional opening to increase the stitching length. We then anastomosed one branch of the STA to the MCA in an end-to-side fashion with 10-0

nylon thread. The other branch of the STA was then connected to an arterial line, and a clip was placed temporally on the main STA trunk to monitor the pre-anastomosis MCA pressure before completing the second bypass. At the same time, we checked the radial artery (RA) pressure (Fig. 1), and then removed the temporal clip and measured the post-anastomosis MCA pressure.

Statistical Analysis

The correlations between arterial MCA/RA pressure ratio (%) and resting stenotic/normal side CBF pressure ratio (%) were calculated using linear regression models. The correlation between rate of increase in pressure and STA diameter were also calculated using linear regression models. The relationship between hyperperfusion and these parameters was investigated. Student t-tests were used to assess age, sex, and CBF ratios (stenotic-side MCA territory and normal-side MCA territory), vascular reserve and RA pressures, pre-anastomosis MCA pressure, post-anastomosis MCA pressure, pre-anastomosis MCA/RA pressure ratio, STA diameter, and the increase in MCA pressure. Differences were considered significant when $p < 0.05$. All statistical analyses were performed using GraphPad Prism (version 5.0 software package, GraphPad Software).

Results

On retrospectively analyzing the results from 39 revascularization procedures, we found that ICA and MCA lesions accounted for 22 and 17 cases, respectively, while single bypass was performed in 7 cases and double bypass

in 32 cases. Table 1 summarizes the results of SPECT, with intraoperative MCA pressure measurements. The MCA/RA (%) pressure was significantly correlated with that of the resting stenotic/normal side CBF ratio (%) in the linear regression analysis (slope 1.200, $r^2 = 0.3564$, $F = 20.49$, $p < 0.0001$; Fig. 2 left). When the cases were stratified on the basis of method (autoradiography vs microsphere), the correlations were still significant (for the autoradiography method, slope 1.121, $r^2 = 0.3569$, $F = 10.55$, $p = 0.0042$; for the microsphere method, slope 1.121, $r^2 = 0.2934$, $F = 6.644$, $p = 0.020$). There was no statistically significant difference between the MCA/RA pressure ratios (%) for the ICA lesions and those for the MCA lesions (95% CI -0.21 to 0.03 , $p = 0.1589$). The intraoperative MCA pressure was 39.3% of the RA pressure in patients with Stage 2 cerebral atherosclerotic disease. The intraoperative STA pressure was very similar to the RA pressure ($p = 0.69$). After 1 branch of the STA was anastomosed, the intraoperative MCA pressure increased to 75.3% of RA pressure. Therefore, the increase in the intraoperative MCA pressure was 36.0% (29.2 mm Hg) following the anastomosis of 1 branch of the STA. Moreover, the rate of increase in pressure was significantly correlated with the increase in the STA diameter in the linear regression analysis (slope 2.59, $r^2 = 0.205$, $F = 9.549$, $p = 0.0038$; Fig. 2 right). Hyperperfusion was observed in 2 of 39 cases. Table 2 provides the results of statistical analysis for the risk of hyperperfusion after STA-MCA bypass. Using the Student t-test, we found significant differences in the risk of hyperperfusion for the stenotic/normal side CBF ratio (range 0.18–0.5; mean 0.53 ± 0.1 for the hyperperfusion

FIG. 1. Illustration showing intraoperative monitoring of MCA and RA pressure. Copyright Fumihiro Matano. Published with permission.

TABLE 1. Data for preoperative SPECT and intraoperative MCA and RA pressure*

Study	Mean (SD)
SPECT	
Stenotic side CBF, ml/100 g/min	32.1 (8.6)
Normal side CBF, ml/100 g/min	37.5 (8.1)
Vascular reserve, %	1.19 (6.7)
MCA & RA pressure	
RA, mm Hg	80.2 (14.6)
MCA, mm Hg	
Pre-anastomosis	31.2 (15.5)
Post-anastomosis	60.4 (16.5)
MCA/RA, %	
Pre-anastomosis	39.3 (18.6)
Post-anastomosis	75.30 (19)
Rate of increase of MCA pressure, %	36.00 (22.5)

group vs 0.87 ± 0.2 for the no-hyperperfusion group; $p = 0.0001$), pre-anastomosis MCA pressure (range 4.0–46.9 mm Hg; mean 7 ± 4 vs 32.5 ± 15 mm Hg; $p = 0.02$), rate of increase in pressure (range 0.08–0.7; 0.85 ± 0.2 vs 0.46 ± 0.1 ; $p = 0.02$), pre-anastomotic MCA/RA pressure ratio (range 0.07–0.59; mean 0.07 ± 0.02 vs 0.41 ± 0.06 ; $p = 0.01$), vascular reserve (range -13%–9.2%; mean $-8\% \pm 7.1$ vs $1.45\% \pm 6.4$; $p = 0.0489$), and STA diameter (range 0.8–2.3; mean 2.01 ± 0.3 vs 1.34 ± 0.2 ; $p = 0.0002$).

Discussion

In this report, we have presented the technique and initial data relevant for intraoperative MCA pressure measurements via the STA in patients with cerebral atherosclerotic disease. We can conclude that because these pressure measurements were related to the preoperative CBF results obtained by SPECT and were lower than the lower limit of CBF autoregulation, they may reflect cerebral perfusion in the patients with Stage 2 cerebral atherosclerotic disease. Moreover, intraoperative monitoring

of MCA pressure and preoperative checking of the STA diameter may aid in the prediction of cerebral hyperperfusion syndrome.

The Carotid Occlusion Surgery Study (COSS), which examined the prevention of cerebral ischemia in patients with atherosclerotic disease, concluded that the indications for STA-MCA bypass required reconsideration because of the number of perioperative ischemic complications.^{4,31} However, improved hemodynamics in study participants who survived STA-MCA bypass surgery without perioperative stroke were associated with lower risk of recurrent stroke compared with the risk for patients receiving medical therapy in the nonsurgical group. Therefore, if we can reduce the rate of perioperative complications, STA-MCA bypass has the potential to reduce the cerebral infarction rate. To prevent perioperative ischemic complications, a favorable blood supply may be required. However, vascular reconstructions can occasionally cause a rapid increase in CBF, resulting in cerebral hyperperfusion syndrome.^{14,15} Because hyperperfusion syndrome is associated with worse outcomes,^{7,32} it is important that it be avoided following the STA-MCA bypass procedure. Although we know that patients with poorer cerebrovascular reactivity have a higher risk for hyperperfusion syndrome,³⁴ other predictive factors have not been adequately reported; therefore, we investigated MCA pressure calculated through a single anastomosed branch of the STA during the STA-MCA bypass procedure. To the best of our knowledge, no reports have described a technique for calculating the intraoperative MCA pressure to date.

Lee et al.²⁵ reported on intraoperative MCA and STA flow in patients with high-volume moyamoya disease. The authors successfully showed that intraoperative flow data aid in the understanding of the complex hemodynamic pathology of the vasculopathy and of the mechanism by which STA-MCA bypass surgery changed the hemodynamics. However, as predicted by Bernoulli's principle,¹⁰ the blood flow in the distal stenosis was faster than that in the proximal stenosis. Therefore, it is thought that cerebral arterial pressure evaluation is more appropriate than cerebral arterial flow evaluation for analyzing cerebral

FIG. 2. Left: Scatterplot showing that the MCA/RA pressure (%) was significantly correlated with the resting CBF stenosis side/normal side (%) in linear regression analysis (slope 1.200, $r^2 = 0.3564$, $F = 20.49$, $p < 0.0001$). **Right:** Scatterplot showing that the rate of increased pressure was significantly correlated with that of STA diameter in linear regression analysis (slope 2.59, $r^2 = 0.205$, $F = 9.549$, $p = 0.0038$). Dotted lines denote the 95% CIs.

TABLE 2. Statistical analysis of the risk factors for hyperperfusion*

Variable	Hyperperfusion		p Value
	Present (n = 2)	Absent (n = 37)	
Age in yrs	70.5 (11)	67.3 (4.9)	0.69
Male sex, no.	2 (5%)	25 (64%)	>0.99
Stenotic/normal side CBF ratio	0.53 (0.1)	0.87 (0.2)	0.0001
Vascular reserve, %	-8 (7.1)	1.45 (6.4)	0.0489
RA pressure, mm Hg	94 (14)	79.4 (17)	0.17
Pre-anastomosis MCA pressure, mm Hg	7 (4)	32.5 (15)	0.02
Post-anastomosis MCA pressure, mm Hg	59.5 (16)	60.4 (28)	0.94
Pre-anastomosis MCA pressure/RA pressure ratio	0.07 (0.2)	0.41 (0.06)	0.01
STA diameter, mm	2.01 (0.3)	1.34 (0.2)	0.0002
Rate of increase in MCA pressure	0.85 (0.2)	0.46 (0.1)	0.02

* Values are mean (SD) unless otherwise indicated.

perfusion. Furthermore, there are no reports concerning cerebral flow and pressure in patients with cerebral atherosclerotic disease.

We found that the intraoperative pre-anastomosed MCA pressure obtained via the STA statistically correlated with the preoperative CBF as determined by SPECT. CBF is relatively independent of changes in mean arterial pressure within a certain range.^{22,30} The lower limit of CBF autoregulation corresponds to mean arterial pressures of approximately 50–60 mm Hg.^{1,20,24,30} Stump pressure provides an objective measurement of collateral cerebral circulation. The patients with a stump pressure less than 25 mm Hg and contralateral carotid occlusion have been found to exhibit electroencephalographic changes.⁵ AbuRahma et al.² reported that stump pressure and retrograde internal flow were statistically significant and predict cerebral hypoperfusion. They concluded that in patients with a stump pressure greater than 40 mm Hg, carotid shunting during carotid endarterectomy is not always necessary.³ In the present study, the mean pressures of the pre- and post-anastomosed MCAs were 31.2 mm Hg (SD 15.47 mm Hg) and 60.4 mm Hg (SD 16.54 mm Hg), respectively. Provisionally, using the intraoperative pre-anastomosed MCA pressure to approximate the cerebral perfusion pressure (CPP) and RA pressure to approximate the mean arterial pressure, the CPP was 39.3% of the mean arterial pressure in patients with Stage 2 cerebral atherosclerotic disease.¹² After one branch of the STA had been anastomosed, the CPP increased to 75.3% of the mean arterial pressure, with an increase in the CPP of 36.0% (29.2 mm Hg). Collectively, the pre-anastomosed MCA pressure was lower than the lower limits of CBF autoregulation, and MCA pressure was up to the threshold of CBF autoregulation after one branch of the STA had been anastomosed (Fig. 3). Thus, the present study showed that intraoperative pre-anastomosed MCA pressure may reflect cerebral perfusion.

We found that the risk of hyperperfusion was associated with the stenotic/normal side CBF ratio ($p = 0.0001$), vascular reserve ($p = 0.0489$), pre-anastomosis MCA pressure ($p = 0.02$), pre-anastomotic MCA/RA pressure ratio ($p = 0.01$), rate of increase in pressure ($p = 0.02$), and STA diameter ($p = 0.0002$) in this study. The finding that low perfusion and poorer cerebrovascular reactivity were as-

sociated with the risk of hyperperfusion is consistent with findings of previous studies.^{6,34} There are few reports of the diameter of the donor vessel and the blood supply as risk factors for hyperperfusion. When we analyzed the STA diameter at 2 cm from the bifurcation, the intraoperative STA pressure was almost the same as the RA pressure ($p = 0.69$; data not shown). The increased MCA pressure correlated positively with the STA diameter. However, our technique requires the sacrifice of both STA branches, which has been shown to be associated with a higher incidence of wound complications than the single bypass procedure.³³ Therefore, we must take precautions to protect the skin while performing our methods. To prevent impaired blood flow to the skin, we cut the frontal branch of the STA distal to the bifurcation to retain retrograde blood flow; resutured the branch of the STA, when possible; debrided the wound margin of the parietal part of the scalp, about 2 mm; and loosely sutured with 4-0 nylon thread.

FIG. 3. Illustrative graph showing the relationship between the lower limits of CBF autoregulation and the intraoperative MCA pressure. MAP = mean arterial pressure.

In addition, arterial line cannulation was carefully carried out using a microscope to prevent dissection of the STA and air embolism. No complications related to this procedure, such as wound complication, STA dissection, air embolism, or ischemic lesion as evaluated by MRI and MR angiography, were encountered within postoperative Day 3.

With respect to blood supply, we consider double anastomoses to be more effective for preventing perioperative ischemia than single bypass.^{8,23} However, in patients with low preoperative CBF, low pre-anastomosed MCA pressure, wide STA diameter, and increased MCA pressures after the initial bypass, double anastomoses may induce excessive flow and a single bypass should be appropriate.

In addition, special attention should be focused on postoperative hyperperfusion in high-risk cases, as established from intraoperative data using our methods. We can prevent postoperative hyperperfusion with aggressive blood pressure control measures, such as the administration of edaravone, which lowered the incidence of post-carotid endarterectomy hyperperfusion in treated patients (7%) compared with controls (67%),²⁸ or minocycline, which lowered the incidence of post-bypass hyperperfusion in the treated group (0 of 60 cases) compared with the control group (4 of 49 cases, 8.16%) of patients with moyamoya disease.¹¹ There have been no previous reports focusing on intraoperative MCA pressure in patients with atherosclerotic disease, and it would be helpful to further examine intraoperative MCA pressure results through additional study.

Limitations

This study is limited by the relatively small sample size, which precluded comprehensive statistical correlations. Therefore, we did not perform multivariate logistic regression analysis and were instead restricted to univariate analyses. Moreover, in the present study, postoperative hyperperfusion occurred in only 2 patients; additional cases are required to support our findings. STA-MCA bypass for atherosclerotic disease is uncommon. Although only 2 patients exhibited postoperative hyperperfusion in our study, this represents a complication rate of over 5%, a frequency that cannot be considered low; thus, consideration for preventing such complications is required. Judging from our statistical results, the combination of low cerebral perfusion with an abundant blood supply may be a risk factor for hyperperfusion. Finally, MCA pressure is not the best direct measure of CPP and does not always correlate with perfusion or clinical improvement/deterioration.

Conclusions

Intraoperative MCA pressure may be a useful technique for assessing cerebral perfusion and for predicting the risk of hyperperfusion. Monitoring MCA pressure is recommended during STA-MCA bypass procedures for atherosclerotic disease.

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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: Matano, Mizumura. Acquisition of data: Matano, Murai, Tanikawa, Kamiyama, Tateyama, Tamaki. Analysis and interpretation of data: Matano, Murai, Mizumura. Drafting the article: Matano, Murai, Mizumura. Critically revising the article: Murai, Tanikawa, Mizumura, Kobayashi, Teramoto, Morita. Reviewed submitted version of manuscript: Tanikawa, Kamiyama, Tateyama, Tamaki, Mizunari, Mizumura, Kobayashi, Teramoto, Morita. Statistical analysis: Matano, Morita. Administrative/technical/material support: Tanikawa, Kamiyama, Tateyama, Tamaki, Mizunari, Mizumura, Kobayashi, Morita. Study supervision: Murai, Kamiyama, Mizunari, Mizumura, Kobayashi, Teramoto, Morita.

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