Effectiveness of Superficial Temporal Artery–Middle Cerebral Artery Anastomosis in Adult Moyamoya Disease
Cerebral Hemodynamics and Clinical Course in Ischemic and Hemorrhagic Varieties

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Background and Purpose—The efficacy of superficial temporal artery–middle cerebral artery (STA-MCA) anastomosis in adult moyamoya disease was evaluated by clinicopathophysiological studies.

Methods—Fifteen patients with cerebral ischemic attacks (ischemia group) and 15 patients with intracranial hemorrhages (hemorrhage group) were investigated. Clinicoangiographic features and regional cerebral blood flow (rCBF) of the MCA territory were preoperatively and postoperatively investigated, and cortical arterial pressure (CAP) and anastomotic blood flow (AF) were intraoperatively measured.

Results—in the ischemia group, the preoperative rCBF of 38.4 mL/100 g per minute was significantly increased to 42.1 mL/100 g per minute with a diminution of angiographic moyamoya vessels in 67% of patients after surgery. The mean CAP and AF were 25.6 mm Hg and 34.7 mL/min, respectively. Proximal and distal cerebral vascular resistance (PCVR = [Mean Systemic Arterial Blood Pressure – Mean CAP]/rCBF and DCVR = [Mean CAP/rCBF]) were 1.78 and 0.68, respectively. One patient died perioperatively as a result of intracerebral hemorrhage. During follow-up (mean, 67 months), 12 of 14 patients recovered without neurological deficits, 1 was moderately disabled because of the initial insult, and another patient experienced an intracerebral hemorrhage but recovered fully. In the hemorrhage group, the preoperative rCBF of 38.0 mL/100 g per minute was significantly increased to 42.7 mL/100 g per minute with a diminution of moyamoya vessels in 60% after surgery. The mean CAP and AF were 29.1 mm Hg and 24.1 mL/min, respectively. PCVR and DCVR were 1.72 and 0.77, respectively. One patient became hemiparetic because of perioperative intracerebral hemorrhage. During follow-up (mean, 94 months), 3 patients had fatal intracranial hemorrhages, 10 had good recoveries, and 2 had moderate disabilities.

Conclusions—This study revealed a high PCVR and a very low DCVR in both the ischemia and hemorrhage groups of patients. STA-MCA anastomosis partially normalized cerebral circulation and decreased moyamoya vessels but did not completely prevent rebleeding. (Stroke. 1998;29:625–630.)

Key Words: bypass surgery ▪ cerebral blood flow ▪ cerebral hemorrhage ▪ moyamoya disease ▪ vascular resistance

Moyamoya disease is characterized angiographically by an abnormal network of fine “moyamoya” vessels at the base of the brain arising from the trunks of the main cerebral arteries in association with progressive occlusion of the distal portions of the ICA.1–5 In moyamoya disease, characteristic clinical presentations have been reported, including serious neurological deficits due to cerebral ischemic insults and/or brain hemorrhages.1,5 The age distribution of clinical presentation indicated two peaks, the first in childhood and the second in adulthood.1,5 Among pediatric patients the initial symptoms are mainly due to cerebral ischemia, but in adult patients intracranial hemorrhage is a more common clinical manifestation.1,5 The incidence of hemorrhage exceeds 60% in adult moyamoya disease and is only 10% among afflicted children.6 With regard to the treatment of moyamoya disease, revascularization surgeries have been among the more interesting methods used to decrease hemodynamic stress in the involved vessels.7–12 Such strategies have proven effective in decreasing deficits in cerebral ischemia. Karasawa et al9 demonstrated that surgical revascularization procedures for moyamoya disease could supply the territory of the MCA through the external carotid artery with measurable increases in CBF and result in a diminution of basal moyamoya vessels. Based on these observations, they suggested that surgical revascularization could protect the territory of the MCA from ischemia and might decrease the frequency of intracerebral hemorrhage in adult moyamoya disease. However, whether revascularization is useful in preventing rebleeding in the hemorrhagic group of adults with moyamoya disease remains controversial.12,14 Therefore, precise clinicopathophysiological studies with as-
Selected Abbreviations and Acronyms

AF = anastomotic blood flow
CAP = cortical arterial pressure
CBF = cerebral blood flow
DCVR = distal cerebral vascular resistance
ICA = internal carotid artery
MCA = middle cerebral artery
PCVR = proximal cerebral vascular resistance
rCBF = regional cerebral blood flow
SABP = systemic arterial blood pressure
STA = superficial temporal artery

Assessment of angiographic changes in moyamoya vessels, rCBF, and hemodynamic stress on the collateral blood vessels will be necessary to determine the efficacy of surgical treatments.

In this study 30 consecutive patients with adult moyamoya disease who successfully underwent STA-MCA anastomosis were analyzed by means of the following methods: (1) measurements of preoperative and postoperative rCBF; (2) intraoperative measurement of CAP and AF; and (3) angiographic changes and clinical course in the perioperative and long-term follow-up periods.

Subjects and Methods

Patients and Clinical Features

In this study, moyamoya disease was defined as adult type if a patient had the initial attack of moyamoya disease after age 17 years. We treated 30 patients with STA-MCA anastomosis at Chugoku Rousai Hospital between 1984 and 1994. All patients were examined angiographically and were diagnosed with moyamoya disease. Fifteen patients had ischemic attacks (ischemia group), and the remaining 15 had hemorrhagic attacks (hemorrhage group). In the ischemia group, 11 patients were female and 4 were male. They ranged in age from 17 to 56 years (mean, 39 years). Ten of the 15 patients experienced transient ischemic attacks, 3 had reversible ischemic neurological deficits, and the remaining 2 had minor completed strokes. On CT scans, ischemic lesions characterized by low-density areas were observed in 7 patients, but no lesion was seen in the other 8 patients. In the hemorrhage group, 8 patients were female and 7 were male, ranging in age from 25 to 57 years (mean, 42 years). Fourteen of these patients presented with complaints of severe headache and disturbances of consciousness due to intracranial hemorrhage. CT scans revealed intraventricular hemorrhage in 12 patients, intracerebral hemorrhage in 3 patients, and subarachnoid hemorrhage in 3 patients.

The clinical course of each patient was followed for at least 2 years. Clinical results were evaluated with regard to recurrence of ischemic and/or hemorrhagic attacks and adaptation to daily living. Angiographic examination was performed 2 to 6 months after surgery to assess the patency of the anastomosis, the area perfused through the anastomosed STA, and any changes in the moyamoya vessels at the base of the brain.

Our criteria for direct revascularization in adult moyamoya disease were as follows: (1) Patients in the ischemia group did not present a major completed stroke, and those in the hemorrhage group recovered fully without serious neurological deficits. (2) On CT scans, low-density areas due to ischemic insults were less than 2 cm in diameter, and intraventricular, intracerebral, and/or subarachnoid hemorrhages had completely resolved. (3) The angiographic stage of the moyamoya disease according to the Kodama and Suzuki classification was II to IV. (4) The timing of the operation was at least 2 months after the most recent prior attack.

Angiographic Investigation

Conventional angiography was performed preoperatively to diagnose moyamoya disease and postoperatively to assess the contribution of the STA-MCA anastomosis to cerebral circulation. The anastomosis was evaluated as follows: 0 = no evidence of patency; 1 = bypass was patent, and the STA only perfused the recipient artery without significant changes in basal moyamoya vessels; and 2 = bypass was patent, and the STA widely perfused the MCA territory with evidence of a diminution of basal moyamoya vessels.

Measurements of rCBF

rCBF maps were obtained preoperatively and postoperatively with single-photon emission CT (Tomomatic 32) by the $^{133}$Xe inhalation method. Imaging was directed at a point 5 cm above the orbitomeatal line, from which we calculated the flow value in the MCA territory on the anastomosed side. Preoperative rCBF studies were performed within the 2 weeks before surgery, and postoperative studies were done 6 to 12 months after surgery. In these rCBF measurements, we monitored end-tidal CO$_2$ concentration to approximate the arterial PCO$_2$.

Intraoperative Measurements of CAP and AF

Surgery was performed under general anesthesia with the use of neuroleptanalgesia (patients were intubated with fentanyl, thiopental, and pancuronium bromide and were maintained with oxygen plus nitrous oxide). All patients underwent STA-MCA anastomosis more than 2 months after either ischemic or hemorrhagic attacks. In moyamoya disease, the STA-MCA anastomosis is quite challenging because the recipient artery is very small in diameter and the arterial wall is thin and translucent. We inserted our designed silicone stent (400 μm in diameter, 3 to 4 mm in length; Xanthopren Byern) into the recipient artery through an arteriotomy to facilitate surgical preparation. A polyethylene tube was cannulated into a branch of the STA, and CAP was defined as the back pressure measured during recording of CAP and AF. CAP is obtained by temporary clipping of the proximal STA, resulting in an abrupt decrease in the anastomotic blood pressure (ABP) recorded from the cannula.
In the ischemia group, 4 patients underwent bilateral STA-MCA anastomoses, and the remaining 11 patients had a unilateral STA-MCA anastomosis on the affected side. In the hemorrhage group, 7 patients underwent bilateral STA-MCA anastomoses, and 8 had a unilateral STA-MCA anastomosis on the affected side.

During the operation, arterial blood gases were monitored to ensure normocapnia and normoxia.

Statistical Analysis
Statistical analyses were performed with the use of Student’s paired or unpaired t test, and statistical significance was determined by P < .05. All values shown are mean ± SD.

Results
Intraoperative Measurements of CAP and AF
Figure 1, bottom panel, shows a representative recording of CAP and AF in moyamoya disease. CAP is extremely low and anastomotic flow is relatively high despite the small recipient artery. All anastomoses were confirmed to be patent by the intraoperative measurements of CAP and AF. Figure 2 shows CAP and AF measured intraoperatively in both groups. In the ischemia group, mean SABP was 95.5 ± 13.1 mm Hg (range, 74 to 118 mm Hg), mean CAP was 25.6 ± 7.7 mm Hg (range, 15 to 50 mm Hg), and mean AF was 34.7 ± 21.3 mL/min (range, 10 to 110 mL/min). The ratio of mean CAP to mean SABP was 0.27 ± 0.08. In the hemorrhage group, mean SABP was 94.5 ± 14.5 mm Hg (range, 65 to 123 mm Hg), mean CAP was 29.1 ± 8.4 mm Hg (range, 15 to 45 mm Hg), and mean AF was 24.1 ± 10.9 mL/min (range, 10 to 55 mL/min). The ratio of mean CAP to mean SABP was 0.31 ± 0.09. The mean SABP of the ischemia group was similar to that of the hemorrhage group. There were no significant differences in either CAP or AF between the ischemia and hemorrhage groups or in the ratio of mean CAP to mean SABP.

Preoperative and Postoperative rCBF Measurements
In our previous rCBF studies, the mean rCBF value in normal control subjects in the MCA territory was 48.4 ± 4.6 mL/100 g per minute (mean age, 39 years; mean SABP, 91 ± 15 mm Hg). Figure 3 shows preoperative and postoperative rCBF in the ischemia and hemorrhage groups. Preoperative rCBF was obtained from 19 hemispheres (14 patients) in the ischemia group and from 21 hemispheres (14 patients) in the hemorrhage group.

The mean rCBF was 38.4 ± 4.8 mL/100 g per minute in the ischemia group and 38.0 ± 4.5 mL/100 g per minute in the hemorrhage group. These rCBF values were significantly low compared with those in the control subjects (P < .001).

Postoperative rCBF in the ischemia group was 42.1 ± 4.5 mL/100 g per minute, and that in the hemorrhage group was 42.7 ± 5.2 mL/100 g per minute. These postoperative rCBF values were significantly increased in both groups (P < .001) but were still significantly low compared with those in the control subjects (P < .001).

The end-tidal CO₂ concentration of the ischemia group was 39.7 ± 4.3 mm Hg preoperatively and 38.6 ± 4.3 mm Hg postoperatively. In the hemorrhage group, the end-tidal CO₂ concentration was 42.4 ± 4.4 mm Hg preoperatively and 40.5 ± 5.0 mm Hg postoperatively. No significant changes in preoperative and postoperative end-tidal CO₂ concentrations were observed in either the ischemia group or the hemorrhage group.

Vascular Resistance in the MCA Territory
Intraoperative CAP and preoperative rCBF in the MCA territory were used to evaluate cerebral vascular resistance in all patients with moyamoya disease (Fig 4). We calculated PCVR and DCVR using the following equations: (1) $\text{PCVR} = (\text{Mean SABP} - \text{CAP}) / \text{rCBF}$, and (2) $\text{DCVR} = (\text{PCVR} / 2) + \text{CAP}$.
SABP = Mean CAP/rCBF, and (2) DCVR = Mean CAP/rCBF. In these analyses, venous pressure was assumed to be zero. Mean PCVR and mean DCVR in the ischemic group were 1.78 ± 0.44 and 0.68 ± 0.28, respectively. Mean PCVR and mean DCVR in the hemorrhage group were 1.72 ± 0.36 and 0.77 ± 0.24, respectively. There was a significant difference between mean PCVR and mean DCVR in both groups (P < .001), but there were no significant differences in mean PCVR and mean DCVR between the ischemia and the hemorrhage groups.

Angiographic Changes
Eighteen anastomosed hemispheres (14 patients) in the ischemia group and 20 anastomosed hemispheres (13 patients) in the hemorrhage group were angiographically investigated. An angiographic score of 2 (bypass was patent and the STA widely perfused the MCA territory with a diminution of basal moyamoya vessels, as shown in Fig 5) was observed in 12 of 18 anastomosed sites (67%) in the ischemia group and in 12 of 20 anastomosed sites (60%) in the hemorrhage group. In the remaining patients of both groups, carotid angiography showed that the STA only perfused the recipient cortical artery without changes in basal moyamoya vessels.

Clinical Course
Perioperatively complicated cases are shown in the Table (cases 1 and 2). Intracerebral hemorrhage was observed on the second day in 2 patients who showed hypertension (>200 mm Hg systolic pressure). One patient (from the ischemia group) died as a result, and the other patient (from the hemorrhage group) developed hemiparesis. The remaining 28 patients, including 2 who were moderately disabled as a result of their primary insults, returned to their previous occupations after discharge.

Complicated cases during the follow-up periods are also shown in the Table (cases 3 through 6). In the ischemic group, patients were followed up for an average of 67 months. During follow-up, 1 patient with an angiographic score of 2, who had been working as a housewife without any problems, had an intracerebral hemorrhage of the left frontal lobe 5 years after bilateral STA-MCA anastomosis (Table, case 3). Her initial attack had been a transient ischemic attack with a right hemiparesis without lesions on CT scans. Fortunately, she recovered almost completely. The remaining 12 patients of the ischemia group had good recoveries, and 1 patient had moderate disability due to her initial attack. All these patients had uneventful courses without recurrence of ischemic attacks. In the hemorrhage group, the patients were followed up for an average of 94 months. Three patients died during the follow-up period. In each case the patient had fully recovered without deficits until the fatal second attack (Table, cases 4 through 6). The first patient with an angiographic score of 2, who had been an engineer, died as the result of a serious intraventricular hemorrhage 4 years after unilateral bypass surgery. The second patient with an angiographic score of 2, who had been engaged in the Self-Defense Force of Japan, died 2 years after bilateral STA-MCA anastomosis. He also sustained a serious intraventricular hemorrhage. The third patient with an angiographic score of 1, who had been a public official, died 3 years after unilateral STA-MCA anastomosis. He developed alcoholic hepatic cirrhosis and experienced a massive cerebral hemorrhage on the operated side. In the remaining 12 patients, 10 maintained a good level of recovery and 2 were moderately disabled during the follow-up period. Moderate disability in 1 patient was due to perioperative intracerebral hemorrhages and in the other was due to her initial attack. No ischemic attacks were observed in the hemorrhage group, but a total of 4 patients presented rebleeding during the follow-up period. The hemodynamic variables in these patients are summarized in the Table. No prominent differences in these variables were found when these patients were compared with the remaining patients in both groups.

Discussion
This study demonstrated that successful STA-MCA anastomosis in adult moyamoya disease partially normalized cerebral
circulation with a reduction of moyamoya vessels and helped prevent further ischemic attacks but did not ward off hemorrhagic attacks. Hemodynamic studies revealed markedly low CAP and moderately decreased rCBF due to occlusive changes in the ICA with high vascular resistant collaterals of the basal moyamoya vessels. However, no significant differences in these CAP, rCBF, and vascular resistance values were observed between patients with cerebral ischemic attacks at onset and those with cerebral hemorrhagic attacks.

Moyamoya disease has two primary clinical presentations, ischemic and hemorrhagic attacks. Additionally, the hemorrhagic attacks have rarely been described, but the main causes of death were massive intracranial hemorrhage. At present, some causes of the rupture of the vessels in moyamoya disease have been reported. Mauro et al suggested that lipohyalinosis and miliary aneurysms were the source of fatal intracerebral hemorrhage. Kodama and Suzuki reported that microaneurysms resulting from fragility and localized disruption of the vascular wall could cause an intracerebral hemorrhage. Although some reports have demonstrated ruptured aneurysms in cerebral hemorrhages seen in moyamoya disease, few cases have demonstrated small aneurysms on angiographic examination. Yamashita et al suggested that the rupture of the vessels in moyamoya disease could occur in the absence of microaneurysm or fibrinoid necrosis. In their meticulous morphological studies in moyamoya patients, elastic laminae were usually well preserved, and the wall of the vessels was ruptured without fibrinoid necrosis but was associated with fibrosis and attenuation of the medial smooth muscle cell. From these clinicopathological studies, hemorrhagic attacks in moyamoya disease were thought to be due to the existence of several vascular lesions and the severity of the lesions, which was closely related to the hemodynamic stress of basal moyamoya vessels and aging of the patients.

Several hemodynamic findings in moyamoya disease have been reported by measurements of rCBF and CAP. Yonekawa et al reported the hemodynamics of moyamoya disease in children before and after STA-MCA anastomoses. They found that the CAP measured in six children with moyamoya disease was below the level observed in most atherosclerotic occlusive cerebrovascular diseases and noted that rCBF increased in both the operated and contralateral hemispheres. Ogawa et al reported that CBF was significantly lower in moyamoya patients than in normal subjects of the same age and that the distribution of CBF showed a dominant posterior distribution in contrast to the dominant anterior distribution observed in normal control subjects. Taki et al investigated cerebral circulation and metabolism in patients with adult moyamoya disease using positron emission tomography and reported that the cerebral circulation in adult moyamoya disease appeared to be characterized by a mild decrease in perfusion pressure and prolonged circulation time. We observed a prominently reduced CAP, 25.6 mm Hg in the ischemia group and 29.1 mm Hg in the hemorrhage group, and moderately reduced rCBF in the MCA territory. From these findings, we demonstrated significantly higher PCVR (cerebral vascular resistance from the ICA to the cortical arteries of the MCA) than DCVR (cerebral vascular resistance from the cortical arteries of the MCA to the vein). In an experimental study, Symon demonstrated that normal CAP of the MCA territory in dogs and macaques was 80% to 95% of SABP obtained from the femoral artery. Additionally, our unpublished normal CAP in humans was 78 mm Hg in contrast to 93 mm Hg of SABP, which was obtained from four patients having vein graft bypass from the external carotid artery to the MCA to trap giant cavernous aneurysms (Y.O. et al, unpublished data, 1995). When these CAP and SABP data and our normal rCBF data were applied to calculate normal cerebral vascular resistance, PCVR and DCVR were 0.31 and 1.31, respectively. These calculated cerebrovascular resistance values clarified characteristics of cerebral circulation in moyamoya disease such as prominent high vascular resistance from the main cerebral arteries to the cortical arteries and remarkable dilatation of distal resistance vessels. It is well known that CBF itself is not a reliable indicator to assess the effectiveness of STA-MCA anastomosis for occlusive cerebrovascular diseases. Our hemodynamic studies suggested that the STA-MCA anastomosis could normalize not only rCBF but also cortical perfusion pressure in moyamoya disease.

The theoretical basis for surgical revascularization in moyamoya disease is to decrease hemodynamic stress, thereby reducing moyamoya vessels. Currently three procedures are frequently used: STA-MCA anastomosis, encephaloduroarteriosynangiosis, and encephalomyosynangiosis. Most published reports support the efficacy of these procedures in children. Although these techniques have also been used in adults to prevent ischemic attacks as well as to decrease the risk of bleeding, the effectiveness of these techniques in preventing hemorrhagic attacks in adult moyamoya disease remains unproven. STA-MCA anastomosis is a rapid procedure and is a potential method for supplying blood with normal cortical arterial perfusion pressure. In this study
angiographic moyamoya vessels were reduced in over 60% of patients with excellent visualization of the MCA cortical arteries after STA-MCA anastomoses, but prevention of rebleeding was not accomplished in all of these cases. Wanifuchi et al.31 studied 59 adult moyamoya patients, 38 of whom were treated conservatively and 21 of whom were surgically treated. Their results suggested that hemorrhagic recurrence in the surgically treated group was less frequent than in the conservatively treated group. Suzuki et al.32 reviewed long-term clinical results in 28 adult moyamoya patients who had had ischemic symptoms in childhood. Fourteen percent of the patients who had not undergone bypass surgery had hemorrhagic attacks as adults. Conversely, 18 patients who had undergone bypass surgery in the pediatric period showed no hemorrhagic attacks later. In their results, bypass surgery performed in the pediatric period appeared to prevent later hemorrhage in adult moyamoya disease. Their results may indicate that STA-MCA anastomosis can halt progression of moyamoya vessels, in severity and distribution, by generating normal perfusion pressure and significant blood supply in the cortical artery in the early period of the disease. Houkin et al.33 studied 35 patients with adult moyamoya disease, 24 patients with intracerebral hemorrhage at onset, and 11 patients with cerebral ischemia at onset who underwent both STA-MCA anastomosis and indirect revascularization using encephaloduroarteriomyosynangiosis. Three of 24 patients with hemorrhagic-type onset showed rebleeding, and 2 of 11 patients with ischemic-type onset showed intracerebral hemorrhage after surgery. From these results they concluded that revascularization could not always prevent rebleeding in adult moyamoya disease but that moyamoya vessels were decreased only by direct revascularization surgery, which may ultimately reduce the risk of hemorrhage more effectively than conservative treatment.

The hemodynamics of cerebral circulation in moyamoya disease are characterized by low CBF with extremely high vascular resistance in the collaterals at the base of the brain, and therefore STA-MCA anastomosis has appeared to be a logical treatment for providing a readily accessible blood supply. However, certain disadvantages of STA-MCA anastomosis have been proposed. First, the anastomosis is difficult to accomplish because the recipient arteries are very small, thin, and fragile. In addition, the STA-MCA bypass may not have the potential to perfuse the territory of the anterior cerebral artery and posterior cerebral artery. Second, some bypass may not have the potential to perfuse the territory of the anterior cerebral artery and posterior cerebral artery. Therefore, it will be necessary to perform a randomized study with angiographic and CBF studies to test the efficacy of STA-MCA anastomosis in reducing the risk of cerebral ischemia and hemorrhage in adult moyamoya disease.

References
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