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Ultrasonographically Predicting the Extent of Collateral Flow through Superficial Temporal Artery-to-Middle Cerebral Artery Anastomosis

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BACKGROUND AND PURPOSE: This study was performed to elucidate whether the extent of bypass flow through superficial temporal artery-to-middle cerebral artery (STA-MCA) anastomosis could be indirectly estimated by measuring the blood flow velocity in the superficial temporal artery (STA) by using duplex ultrasonography.

METHODS: We analyzed 29 patients (31 sides) who underwent STA-MCA bypass surgery for occlusive cerebrovascular disease (28 sides) or unclippable cerebral aneurysm that required therapeutic occlusion of the internal carotid artery (three sides). The flow velocities of the STA were measured by using ultrasonography. For patients who underwent the surgery unilaterally, the flow velocity ratios of the operated side to the contralateral side for the individual arteries were calculated. The correlation between these flow velocity parameters and the extent of bypass flow, which was graded based on the findings of cerebral angiography, was investigated.

RESULTS: Both the affected STA flow velocity and the STA flow velocity ratio, particularly those in the end diastole, increased in patients with more extensive bypass flow. In patients with extensive, moderate, and poor bypass flow, the end diastolic flow velocities of the operated STA were 27.4 ± 8.8 , 23.0 ± 7.8 , and 13.5 ± 7.5 cm/s, respectively and the end diastolic flow velocity ratios of the STA were 3.4 ± 0.8 , 2.1 ± 0.5 and 1.3 ± 0.4 , respectively. The pulsatility index and resistance index of the affected STA were significantly lower in the patients with more extensive bypass flow. The optimal threshold value of the end diastolic flow velocity ratio of STA for the group with extensive bypass flow was 2.75, whereas that for the group with poor bypass flow was 1.60. With the obtained values, the sensitivity and specificity were 87.5% and 93.9% for the group with extensive bypass flow and 95.2% and 95.0% for the group with poor bypass flow, respectively.

CONCLUSION: The blood flow velocity in the operated STA seems to be a highly sensitive parameter for predicting the extent of bypass flow in patients undergoing STA-MCA anastomosis.

Superficial temporal artery-to-middle cerebral artery (STA-MCA) bypass is a direct type of revasculariza-

tion surgery that was pioneered by Yasargil et al (1) and has been applied to moyamoya disease (2). It is now generally accepted that this direct revascularization surgery seems to provide a remarkable improvement in cerebral blood flow and a better prognosis than that associated with conservative treatment. This procedure has also been used in patients who require therapeutic occlusion of the internal carotid artery for unclippable cerebral aneurysms or certain skull base tumors (3, 4). In patients with atherosclerotic arterial disease in the carotid arteries and middle cerebral arteries (MCAs), however, a 1985 Cooperative Study reported an extracranial-intracranial bypass to be ineffective in preventing cerebral ischemia (5). Although the results of this trial caused many physicians to abandon the procedure, additional studies indicate that this technique may improve the effect of surgical therapy for internal carotid artery occlusion (6–9).

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Clinical characteristics of the patients and controls

	Patient	Control
No. of cases (sides)	29 (31)	15
Mean age, y	64.4 $\pm$ 9.9	68.6 $\pm$ 8.7
Sex, M/F	23/6	9/6
Clinical diagnosis		
ICA/MCA occlusive disease	26 (28)	
Unclippable cerebral aneurysm	3 (3)	

Note.—ICA indicates internal carotid artery; MCA, middle cerebral artery.

Recently, Grubb et al (10) indicated that stage II hemodynamic failure defines a subgroup of patients with symptomatic carotid occlusion who are at high risk for subsequent stroke when treated medically. Considering that the Cooperative EC/IC Bypass Study lacked an assessment of the collateral circulation and cerebrovascular reserve, a randomized trial evaluating surgical revascularization in this high risk subgroup seems called for. In Japan, a multicenter randomized re-trial including strictly selected patients is currently in progress (Japan EC-IC Bypass Trial: JET Study) (11, 12).

After STA-MCA anastomosis, the patients were required to undergo postoperative selective angiography to confirm the patency and extent of improved filling of the affected MCA branches. The luxuriance of the bypass could be directly evaluated by the number and size of the branches opacified from the donor STA compared with the preoperative appearance. However, angiography is an invasive procedure associated with non-negligible complications and should not be repeatedly performed as a follow-up study. Because of these limitations, noninvasive and easily repeatable techniques are preferable. The present study was thus designed to examine whether the extent of bypass flow could be estimated by duplex ultrasonography. We measured the postoperative flow velocities of STA and compared them with the findings of cerebral angiography. We herein present the first report of the predictable value of ultrasonography in clarifying the extent of the collateral flow through the bypass.

Methods

Participants

The study participants consisted of 29 consecutive patients (31 sides) who underwent STA-MCA anastomosis and were examined with the use of postoperative cerebral angiography and duplex ultrasonography. Both tests were performed simultaneously 1 month after surgery. The average age of the patients (23 men, six women) was 64.4 years. STA-MCA anastomosis was performed for 26 patients (28 sides) with internal carotid artery/MCA occlusive disease and three patients (three sides) each with an unclippable cerebral aneurysm that required therapeutic occlusion of the internal carotid artery. The clinical characteristics of the patients and control participants are summarized in the Table. The selection criteria for STA-MCA anastomosis in the patients with internal carotid artery/MCA occlusive disease was identical to that used in a JET

study (11, 12). All patients with atherosclerotic internal carotid artery/MCA occlusive disease underwent stimulated cerebral blood flow study preoperatively and all showed impairment of the perfusion reserve. Surgery was performed with the patients under general anesthesia. Blood pressure, heart rate, blood gas, and an electric potentials of the brain were continuously monitored during the procedure. All patients provided informed consent to be treated with this surgical method and to be examined by these tests.

Techniques

Ultrasonography was performed by a neurosonographer, who was blinded to the angiographic information, using a color-coded duplex ultrasonographic device (LOGIQ500MD; GE Yokogawa Medical Systems Ltd., Tokyo, Japan). A 5.0- to 10.0-MHz and a 5.0-MHz sonography beam were used for imaging and pulsed Doppler sonography, respectively. For the examinations of STA, each patient was examined in a supine position with his or her head turned away from the side undergoing imaging. The transducer was placed in the temporal region before the external opening of the acoustic canal, and STA underwent color imaging. On the longitudinal images, the sample volume was set within the STA at the point proximal to its bifurcation. Particular care was taken to keep the incident angle between the beam and the STA at ≤ 60 degrees. The peak systolic velocity (PSV), end diastolic velocity (EDV), and time-averaged mean velocity (TMV) were measured in both STAs and were then corrected with the incident angle. The flow velocities of the external carotid artery (ECA) were also measured. The pulsatility index (PI) and resistance index (RI) for the individual arteries were calculated by using the following formulae: $PI = (PSV-EDV)/TMV$ and $RI = (PSV-EDV)/PSV$.

To obtain normal values, 15 age-matched control participants who had never suffered a stroke and had no major cerebral artery occlusive disease underwent ultrasonographic examinations (nine men, six women; average age at examination, 68.6 years). To avoid any influence of systemic factors, we calculated the flow velocity parameter ratios of the operated side to the contralateral side for the patients who underwent the surgery unilaterally. For the control participants, the flow velocity parameter ratio of the higher side in EDV of the STA to the contralateral side was obtained.

Conventional selective angiography was performed by a neuroradiologist. The pattern of the collateral circulation through the bypass was categorized based on postoperative external carotid angiograms. We graded the extent of bypass flow without any knowledge of ultrasonographic findings. Three categories were determined based on postoperative angiograms as follows: extensive, antegrade and retrograde filling of the entire MCA system; moderate, filling of two or more MCA branches; and poor, filling of only the anastomosed MCA branch.

Statistical Analysis

All data were expressed means $\pm$ SD. Statistical comparisons between the groups were performed with analysis of variance and then Scheffe's multiple comparison test. The cutoff values of the STA flow velocity parameters for predicting each group were analyzed with a sensitivity-specificity curve analysis. A value of $P < .05$ was considered to indicate a statistically significant difference.

Results

Postoperative Angiographic Findings

The patients were divided into three groups based on the pattern of the collateral circulation through the bypass, which was determined based on the angiographic findings. They consisted of an extensive

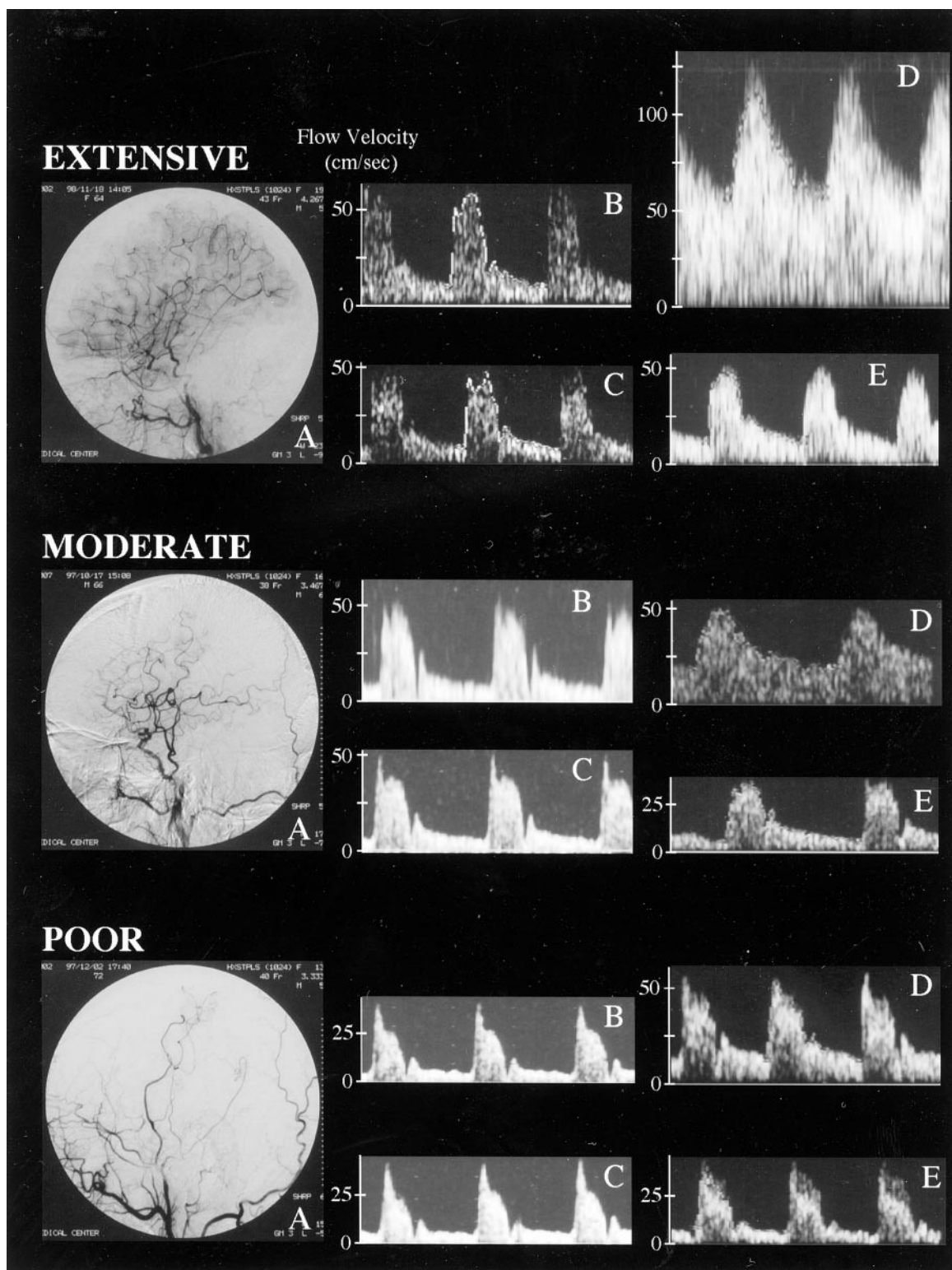


FIG 1. Postoperative digital subtraction angiograms and changes in pulsed Doppler ultrasonographic images of STA.

A, Postoperative digital subtraction angiograms. Pattern of collateral circulation through bypass was graded based on the findings of a postoperative angiogram of the external carotid artery.

B, Preoperative images of affected side.

C, Preoperative images of nonaffected side.

D, Postoperative images of affected side.

E, Postoperative images of nonaffected side.

Doppler wave forms of STA in a patient with extensive (*top*), moderate (*middle*), and poor (*bottom*) bypass flow are also shown. The vertical axis represents the flow velocity (in cm/s). Note that the postoperative EDV of the affected STA increased in patients with more extensive bypass flow. The postoperative EDV ratios of the anastomosed STA to the contralateral one was 3.9 (*top*), 2.1 (*middle*), and 1.5 (*bottom*), respectively.

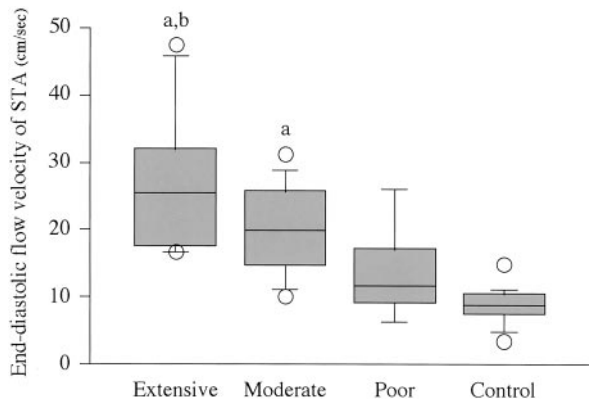


Fig 2. EDV of anastomosed STA after STA-MCA bypass surgery. Patients were divided into three subgroups according to the extent of bypass flow based on angiograms of the external carotid artery. Values of EDV were compared among groups. EDV was significantly higher in patients with more extensive bypass flow. *a*, $P < .0001$ versus control group; *b*, $P < .01$ versus poor group.

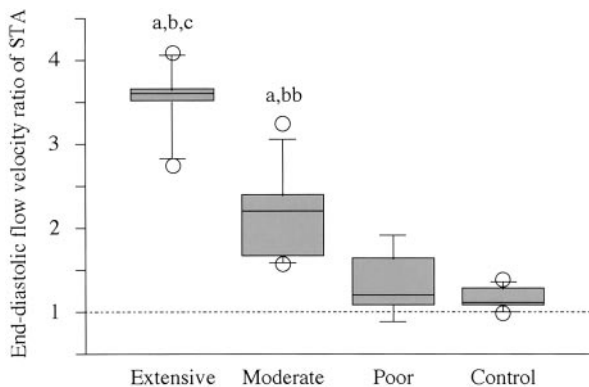


Fig 3. Ratios of EDV of affected STA to contralateral STA after STA-MCA bypass surgery in each group. Ratio of EDV was significantly higher in patients with more extensive bypass flow, and significant differences were observed between each group, except between the poor and control groups. *a*, $P < .0001$ versus control group; *b*, $P < .0001$ versus poor group. *c*, $P < .0001$ versus moderate group; *bb*, $P < .05$ versus poor group.

group (10 sides), a moderate group (16 sides), and a poor group (five sides). No patient was found to have an occluded bypass. Figure 1A shows the typical angiographic findings for each group.

Doppler Flow Velocity of STA and ECA

Various parameters in the flow velocity of bilateral STA and ECA were measured in the patients and control participants. The flow velocities measured in each artery were then compared according to the grades of the collateral pattern.

STA. The values of the PSV, EDV, and TMV of the anastomosed STA were 67.0 ± 12.0 , 27.4 ± 8.8 , and 41.7 ± 9.6 cm/s in the extensive group ($n = 10$), 53.8 ± 14.2 , 23.0 ± 7.8 , and 34.3 ± 10.2 cm/s in the moderate group ($n = 16$), and 46.6 ± 21.3 , 13.5 ± 7.5 , and 24.7 ± 11.2 cm/s in the poor group ($n = 5$), respectively. Those in the control group ($n = 15$) were 44.7 ± 8.7 , 8.8 ± 2.8 , and 18.9 ± 5.2 cm/s,

respectively. The values of the PSV, EDV, and TMV of the anastomosed STA were significantly different among the groups ($P < .01$ for PSV, $P < .0001$ for both EDV and TMV by analysis of variance). The values tended to be higher in patients with more extensive bypass flow. This tendency was most evident in EDV (Fig 2). The values of the PI and RI of the anastomosed STA were 0.98 ± 0.26 and 0.59 ± 0.09 in the extensive group ($n = 10$), 0.93 ± 0.29 and 0.57 ± 0.09 in the moderate group ($n = 16$), and 1.33 ± 0.35 and 0.70 ± 0.09 in the poor group ($n = 5$), respectively. The values in the control group ($n = 15$) were 2.02 ± 0.64 and 0.81 ± 0.05 , respectively. The values of the PI and RI of the anastomosed STA were significantly different among the groups ($P < .0001$ for both PI and RI by analysis of variance). The values of PI were significantly lower in the three patient groups than in the control group ($P < .0001$ for the extensive/moderate group versus control, $P < .05$ for the poor group versus control by Scheffe's multiple comparison test). The values of RI were significantly lower in the extensive and moderate groups than in the control group (both $P < .0001$ by Scheffe's multiple comparison test).

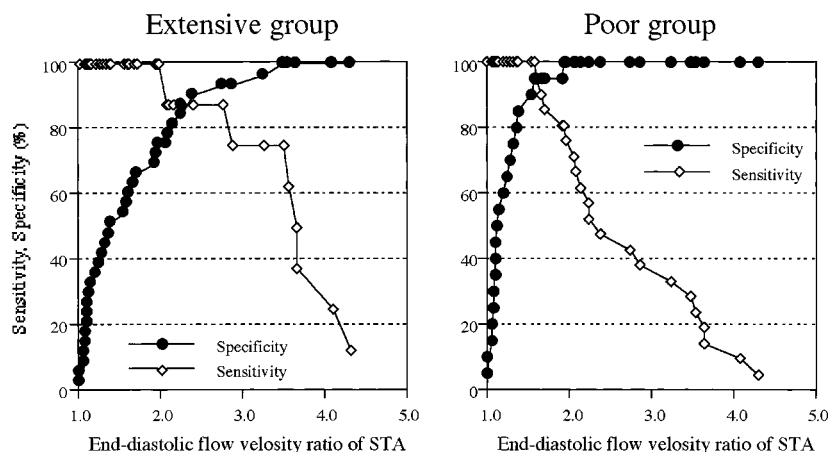
ECA. The values of PSV, EDV, and TMV of the affected ECA were 96.4 ± 32.1 , 19.5 ± 10.6 , and 41.3 ± 15.1 cm/s in the extensive group ($n = 9$), 91.0 ± 46.6 , 17.6 ± 6.0 , and 36.8 ± 14.7 cm/s in the moderate group ($n = 16$), and 96.4 ± 32.5 , 15.0 ± 3.5 , and 33.3 ± 6.3 cm/s in the poor group ($n = 5$), respectively. In one patient from the extensive group, the ECA flow velocity could not be measured because of the high position of the carotid bifurcation. The values in the control group ($n = 15$) were 73.8 ± 15.7 , 10.0 ± 3.7 , and 25.9 ± 7.1 cm/s, respectively. Concerning the affected ECA flow velocity, not PSV but EDV and TMV were significantly different among the groups ($P < .01$ for EDV and $P < .05$ for TMV by analysis of variance), thus indicating that the EDV and TMV of the affected ECA in the extensive and moderate groups were higher than those in the control group. However, no significant differences were observed among the patient groups. The values of the PI and RI of the affected ECA were significantly different among the groups ($P < .05$ for both PI and RI by analysis of variance, data not shown). Those in the extensive and moderate groups tended to be lower than those in the control group, although the differences were not significant.

Flow Velocity Ratio of STA and ECA

We next calculated the laterality ratio of the parameters of STA and ECA for the patients who underwent the bypass surgery unilaterally and compared them in each group.

STA. The PSV, EDV, and TMV ratios of STA were 1.7 ± 0.3 , 3.4 ± 0.8 , and 2.4 ± 0.5 in the extensive group ($n = 8$), 1.0 ± 0.3 , 2.1 ± 0.5 , and 1.5 ± 0.4 in the moderate group ($n = 13$), and 0.9 ± 0.3 , 1.3 ± 0.4 , and 1.2 ± 0.4 in the poor group ($n = 5$), respectively. Those in the control group ($n = 15$) were 1.0 ± 0.2 ,

FIG 4. Sensitivity-specificity curve based on EDV ratio of affected STA to contralateral STA. Optimal threshold value of ratio for extensive group was 2.75 (left); that for poor group was 1.60 (right).



1.2 ± 0.1 , and 1.0 ± 0.1 , respectively. The PSV, EDV, and TMV ratios of STA were significantly different among the groups (all $P < .0001$ by analysis of variance), and they also tended to be higher in patients with a more extensive bypass flow. This tendency was most evident regarding the EDV ratio (Fig 3). The PI ratio was significantly lower in the three patient groups than in the control group ($P < .0001$ for extensive/moderate group versus control group, $P < .01$ for poor group versus control group by Scheffe's multiple comparison test, data not shown).

The RI ratio was significantly lower in the extensive and moderate groups than in the poor and control groups ($P < .0001$ for extensive/moderate group versus control group, $P < .05$ for extensive/moderate group versus poor group by Scheffe's multiple comparison test, data not shown).

ECA. Concerning the ECA, the flow velocity ratios were not different among the groups ($P = .6$ for PSV ratio and $P = .1$ for both EDV and TMV ratios by analysis of variance). On the other hand, the PI and RI ratios were significantly different among the groups ($P < .01$ for both PI and RI ratios by analysis of variance) and were lower in the extensive and moderate groups than in the control group ($P < .05$ for both the PI and RI ratios by Scheffe's multiple comparison test, data not shown).

Predictive Value for Detecting the Extent of Postoperative Bypass Flow

We analyzed the sensitivity-specificity curve for the relationship between the flow velocity ratio of EDV in STA and the grades of collateral circulation through the bypass. With this analysis, the optimal threshold value of this ratio between the extensive group and moderate group could be obtained as 2.75 and that between the moderate group and poor group as 1.60 (Fig 4). When the obtained values were applied, the sensitivity and specificity were 87.5% and 93.9% for the extensive group and 95.2% and 95.0% for the poor group, respectively.

Discussion

The extent of collateral flow through the anastomosed graft is not determined by the success of the procedure but rather by the preoperative hemodynamic state. Iwama et al (13) reported that the extent of bypass flow could be predicted from the preoperative hemodynamic status. They concluded that postoperative bypass function is expected only in patients with spontaneously developed leptomeningeal anastomoses and decreased reactivity to acetazolamide. In patients with lower perfusion pressure due to hemodynamically significant stenosis or occlusion, the stimulus for a good flow from an anastomosed graft tends to increase. On the other hand, those with preserved vasodilatory capacity have sufficient blood supply and, accordingly, a lesser demand for the additional flow via bypass. Yamashita et al (14) proposed that a reduced cerebrovascular reserve capacity or a reduced cerebral blood flow with a reduced cerebrovascular reserve capacity are the basic criteria for selecting candidates for bypass surgery. At present, a randomized controlled trial for EC/IC bypass is in progress to elucidate whether bypass surgery can effectively prevent ischemic stroke and impairment in the cognitive function in selected patients with decreased vasodilatory reserve (11, 12). Although the present study was performed based on this trial, its purpose was not to make any definitive conclusion but to provide new insight into the noninvasive assessment of bypass flow after surgery.

The effectiveness of the procedure can be directly judged by the luxuriance of flow in the MCA, visualized by using angiography. To evaluate the patency and extent of bypass flow after STA-MCA anastomosis, cerebral angiography is the standard for such assessment. Although cerebral angiography provides detailed information, it is invasive, time consuming, and requires the use of ionizing radiation. Because of these limitations, a noninvasive, real time, and easily repeatable technique that provides information regarding flow dynamics through the graft is preferable as an adjunct to the extracranial-intracranial bypass procedure. MR angiography has been reported to be an alternative for the assessment of bypass patency

(15). However, the information obtained by MR angiography is still limited and the procedure is expensive and not available at bedside. Instead, the use of duplex ultrasonography might offer a new tool for evaluating the hemodynamic state after STA-MCA anastomosis. The intraoperative measurement of blood flow in the bypass, performed by placing the transducer directly on the graft vessel, was reported to be useful for the assessment of patency during STA-MCA bypass surgery (16). However, this method is valid only during surgery. No data concerning the postoperative assessment of STA-MCA anastomosis are yet available. In the present study, we measured the flow velocities of STA and showed the possibility that the extent of bypass flow could be predicted by duplex ultrasonography.

In this study, we showed that the flow velocity of the anastomosed STA, particularly that in the end diastole, increased in patients with more extensive collateral flow through the STA-MCA bypass. The increase in the flow velocity of the STA may have reflected the increase in the cerebral blood flow through the bypass. The PI and RI of operated STA and ECA were significantly lower in the patients with more extensive collateral flow via graft bypass. Decreased PI and RI indicated that the blood flow pattern in anastomosed STA and ECA changed from a high resistance pattern to a low resistance one. Moreover, the present study clearly indicated that the EDV ratio of the operated STA to the contralateral one was a highly sensitive parameter for evaluating the extent of bypass flow in patients who underwent this procedure unilaterally. EDV ratios of STA >2.75 and <1.60 were found to indicate extensive and poor bypass flow, respectively. When these values are used, the sensitivity for detecting extensive and poor bypass flow was 88% and 95%, respectively. The specificity for both groups was 94% and 95%, respectively. The absolute value of the STA flow velocity, unlike the STA flow velocity ratio, was not significantly different between the moderate group and the two other patient groups. As a result, it was therefore difficult to estimate the extent of bypass flow based on the absolute value of the STA flow velocity. This may be because of the influence of systemic factors, including blood pressure and severity of atherosclerosis. The flow velocity of CCA also varied because of a conflict between the cerebral blood flow decrease due to carotid artery occlusive disease and the cerebral blood flow increase due to the STA-MCA bypass, and no relationship was observed with the extent of bypass flow (data not shown). Although the flow velocity of the ECA tended to be higher in the patient groups than in the control group, it did not show any significant correlation with the extent of bypass flow. We therefore could not predict the extent of bypass flow based on the ECA flow velocity. Moreover, measurement of the ECA flow velocity is sometimes difficult in patients whose carotid bifurcation is located in a high position. On the other hand, the STA flow ve-

locity ratio clearly indicated the extent of bypass flow, because this ratio might correct for the influence of systemic factors.

Conclusion

We conclude that duplex ultrasonography is a potentially useful method for predicting the extent of collateral flow through an STA-MCA bypass. EDV ratios of STA >2.75 and <1.60 indicate extensive and poor bypass flow, respectively.

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