

Clinical implications of intraoperative infrared brain surface monitoring during superficial temporal artery–middle cerebral artery anastomosis in patients with moyamoya disease

Clinical article

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Object. Surgical revascularization for moyamoya disease prevents cerebral ischemic attacks by improving cerebral blood flow (CBF). Symptomatic cerebral hyperperfusion is a potential complication of this procedure, but its treatment is contradictory to that for ischemia. Because intraoperative techniques to detect hyperperfusion are still lacking, the authors performed intraoperative infrared monitoring in moyamoya disease using a novel infrared imaging system.

Methods. During superficial temporal artery–middle cerebral artery anastomosis in 25 patients (26 hemispheres) with moyamoya disease, the authors monitored the brain surface temperature intraoperatively with the IRIS-V infrared imaging system. The average gradation value change (indicating temperature change) was calculated using commercial software. Magnetic resonance imaging, MR angiography, and *N*-isopropyl-*p*-[¹²³I]iodoamphetamine SPECT studies were performed routinely before and within 10 days after surgery.

Results. Patency of bypass, detailed local hemodynamics, and changes in cortical surface temperature around the anastomosis site were well recognized by the IRIS-V infrared imaging system in all cases. In the present study, 10 patients suffered transient neurological symptoms accompanied by an increase in CBF around the anastomosis site, recognized as symptomatic hyperperfusion. The increase in temperature was significantly higher in these patients. Intensive blood pressure control was undertaken, and free-radical scavengers were administered. No patient in the present study suffered a permanent neurological deficit.

Conclusions. Although the present method does not directly monitor surface CBF, temperature rise around the anastomosis site during surgery might be an indicator of postoperative hyperperfusion. Prospective evaluation with a larger number of patients is necessary to validate this technique. (DOI: 10.3171/2009.4.JNS08585)

KEY WORDS • extracranial-intracranial bypass • thermal artery imaging •
intraoperative monitoring • minimally invasive neurosurgery • neurocritical care

MOYAMOYA disease is a chronic, occlusive cerebrovascular disease with unknown etiology and is characterized by bilateral stenooclusive changes at the terminal portion of the internal carotid artery and an abnormal vascular network at the base of the brain.²² Surgical revascularization for moyamoya disease is believed to be beneficial to prevent cerebral ischemic attacks by improving CBF, and STA-MCA anastomosis with or without indirect bypass is generally used as

the standard surgical treatment.^{11,12} On the other hand, several lines of evidence support that not only ischemia but symptomatic cerebral hyperperfusion is a potential complication of this procedure in the acute stage.^{5–8,16} Accurate and early diagnosis of postoperative hyperperfusion is important because its treatment is contradictory to that for ischemia. Because intraoperative techniques to estimate subsequent occurrence of symptomatic hyperperfusion are still lacking, we performed intraoperative infrared monitoring of the surface brain temperature by using a novel infrared imaging system in the hope that we can indirectly evaluate changes in surface CBF. We also evaluated the clinical impact of temperature change on occurrence of symptomatic hyperperfusion during the acute stage after revascularization.

Abbreviations used in this paper: CBF = cerebral blood flow; DW = diffusion weighted; EDMS = encephaloduro-myosynangiosis; ¹²³I-IMP = *N*-isopropyl-*p*-[¹²³I]iodoamphetamine; MCA = middle cerebral artery; ROI = region of interest; STA = superficial temporal artery; TIA = transient ischemic attack.

Methods

Between March 2005 and December 2006 at Tohoku University Hospital, we conducted intraoperative monitoring of brain surface blood flow by using the IRIS-V infrared imaging system (Sparkling Photon, Inc.) during STA-MCA anastomosis on 26 hemispheres in 25 patients with moyamoya disease (female/male ratio 16:9; age range 7–63 years, mean age 33.4 years). All patients met the criteria of the Research Committee on Spontaneous Occlusion of the Circle of Willis, of the Ministry of Health, Labor, and Welfare, Japan. Standard angiography was performed preoperatively in all adult patients and whenever possible in pediatric patients. All patients underwent STA-MCA anastomosis consisting of EDMS and dural pedicle insertion.²⁰ During surgery the patients were kept normotensive with normocapnia and a rectal temperature of 36°C. The room temperature was maintained at 23°C to keep the background cortical surface temperature as constant as possible. After completion of anastomosis, the high-resolution infrared camera of the IRIS-V infrared imaging system was set 30 cm above the brain, and blood flow was continuously monitored for as long as 3 minutes, including time for placement and release of the temporary clip (Fig. 1). We used this method instead of monitoring before and after the surgical procedure because the cortical temperature before starting the surgical procedure would have been recorded long before completion of the bypass procedure, and thus might not have been as accurate as the baseline value because of temperature changes from the time of craniotomy until the end of the bypass procedure.¹⁷

The IRIS-V infrared imaging system is composed of 3 parts: a main computer, a camera head, and a display monitor. The size of the camera head is 14 × 16 × 19 cm. The camera is connected to the main computer part by folded 5-joint arms (maximum horizontal distance: 80 cm, possible vertical motorized distance 125–155 cm above floor) so that surgeons can bring the camera head over the operative field whenever necessary. The infrared focal plane array detector (barium strontium titanate, 320 × 240 pixels) shows an area of 110 × 82 mm using an F50 infrared lens. The detectable temperature is limited to 35 ± 10°C. Temperatures > 45°C are shown in black, whereas those < 25°C are shown in white and are presented as 8-bit black-and-white images in each pixel. The detectable wavelength band is 7–14 μm. No contrast medium or radiation was used to obtain the images. The recording speed was 30 frames/second. All of the images were stored in the installed computer and recorded with a digital video device. Obtained images were analyzed with imaging software by changes in gradation value.^{13,17,24} In addition, the ROI was set around the anastomosis site (diameter 100 pixels), and the average gradation value within the ROI was calculated by Matrox Inspector software (version 8.0, Matrox Electronics Systems, Ltd.). Probability values < 0.05 were considered to be statistically significant.

In all cases, preoperative CBF was measured using ¹²³I-IMP-SPECT. The ¹²³I-IMP-SPECT studies were routinely performed before surgery and 1 and 7 days after

surgery in all cases. Before surgery and within 10 days of surgery, 1.5-T MR imaging and MR angiography were routinely performed. Standard angiography was not performed postoperatively.⁶ The MR imaging studies included DW images, FLAIR images, T1- and T2-weighted images, and T2*-weighted images.

Results

Patency of bypass could be evaluated in all cases attempted, and it was also confirmed by conventional Doppler ultrasonography during the operation and by postoperative MR angiography during the follow-up period. Information regarding local hemodynamics, which includes flow direction and distribution, could also be evaluated in all cases by the IRIS-V infrared imaging system throughout the craniotomy. Among the 25 patients who underwent 26 surgeries, 10 suffered transient postoperative neurological deterioration. These patients exhibited an intense increase in CBF around the anastomosis site as detected by ¹²³I-IMP-SPECT and a thick STA on MR angiography.^{5–7} Intensive blood pressure control with administration of oxygen radical scavengers was performed, and no patient suffered permanent neurological deterioration compared with his or her preoperative neurological status. Transient ischemic attacks disappeared or improved in all cases during the follow-up period.

Representative Cases

Case 1

Presentation. This 54-year-old man presented with frequent TIAs (transient weakness in the left extremity). Stage III moyamoya disease was identified, and ¹²³I-IMP-SPECT showed that his right CBF and cerebrovascular reserve capacities were markedly impaired. Therefore, STA-MCA anastomosis with EDMS was performed in the right hemisphere.

Operation. After exploration of the parietal branch of the right STA, a frontotemporoparietal craniotomy was performed. The recipient artery at the M₄ segment of the anterior parietal branch of the MCA was explored, and anastomosis was performed between the stump of the STA (2.0 mm in diameter) and the M₄ segment (1.0 mm in diameter). Then, EDMS and dural pedicle insertion were performed. Intraoperative infrared monitoring disclosed changes in the color of the bypass to white after the temporary occlusion (indicating decrease in temperature) (Fig. 2 upper left), and then a change to black (indicating increase in temperature) 2 seconds after removal of the clip (Fig. 2 lower left), indicating presence of blood flow and patency of the bypass. During the color change, the cooled blood was shown to be pushed away toward the cranial artery, in both proximal and distal directions of the M₄ segment at 1.00 second (Fig. 2 upper right), indicating the presence of a perfusion pressure gradient (Fig. 2 upper right). The patency of the bypass was also confirmed by intraoperative Doppler ultrasonography. The color of the exposed brain around the anastomosis site did

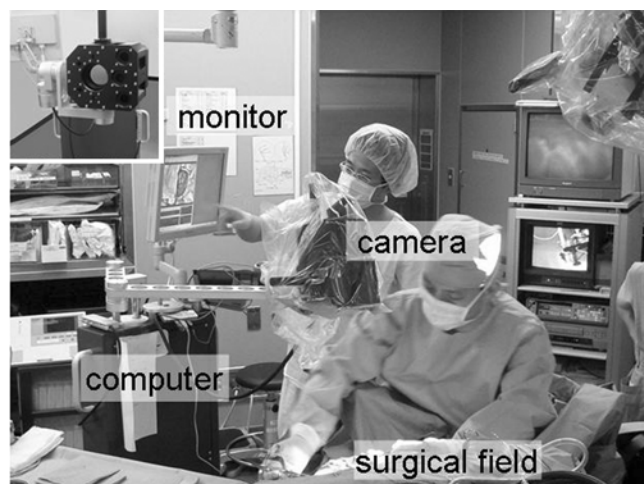


FIG. 1. Photograph of the IRIS-V infrared imaging system in the operating theater. *Inset*: The infrared and charge-coupled device camera.

not show significant change before and after removal of the temporary clip (Fig. 2). The change in average gradation value within the ROI was within 5 points, indicating no significant increase in temperature after release of the temporary clip (Fig. 3).

Postoperative Course. The patient's postoperative course was uneventful. Patency of the bypass was also confirmed by MR angiography. The ^{123}I -IMP-SPECT studies performed 1 and 7 days after surgery showed a slight increase in CBF in the right hemisphere compared with the preoperative findings. Postoperative DW MR imaging showed no evidence of ischemic change, and MR angiography demonstrated the apparently patent STA-MCA bypass as a higher intensity signal than the opposite side STA. The patient did not experience neurological deterioration during the follow-up period.

Case 2

Presentation. This 26-year-old woman presented with a TIA (transient weakness in the left upper extremity). Stage III moyamoya disease was identified, and ^{123}I -IMP-SPECT showed that her bilateral CBF and cerebrovascular reserve capacities were markedly impaired. Therefore, bilateral bypass surgery was planned.

Operation. An STA-MCA anastomosis with EDMS was performed in the right hemisphere. After exploration of the parietal branch of the right STA, a frontotemporoparietal craniotomy was performed. The recipient artery at the M_4 segment of the anterior parietal branch of the MCA was explored, and anastomosis was performed between the stump of the STA (1.0 mm in diameter) and the M_4 segment (0.8 mm in diameter). Then an EDMS procedure and dural pedicle insertion were performed. Intraoperative infrared monitoring disclosed changes in the color of the bypass to white after the temporary occlusion (indicating a decrease in temperature) (Fig. 4 *upper left*), and a change to black (indicating an increase in temperature) after removal of the clip, indicating presence of

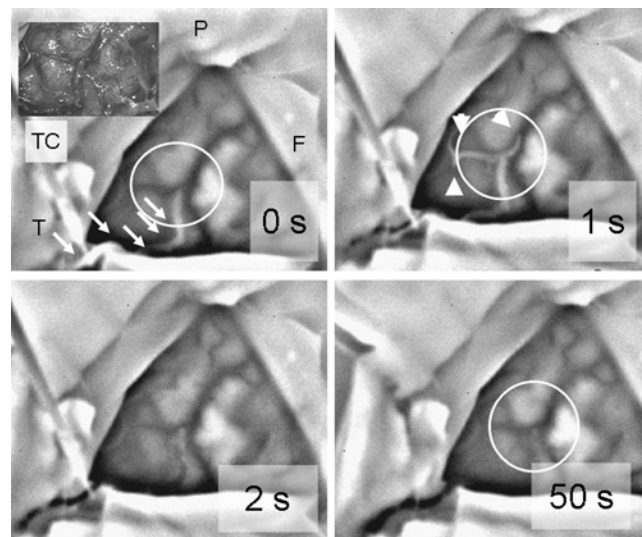


FIG. 2. Case 1. Microscopic views of the surgical field around the anastomosis (*inset, upper left*) and intraoperative infrared monitoring showing changes in color of the STA (*arrows*) to white after temporary occlusion, indicating decrease in temperature (*upper left*) due to the absence of blood flow. Right after removal of the clip at 1 second, the color of the bypass transiently changed to white by cooled blood flow (*upper right, arrowheads*) and then changed to black (indicating an increase in temperature) at 2 seconds (*lower left*), indicating patency of the bypass. Note that the brain surface color around the anastomosis site (*circle, lower right*) did not significantly change throughout the process. F = frontal lobe; P = parietal lobe; T = temporal lobe; TC = temporary clip.

blood flow and patency of the bypass (Fig. 4 *upper right* and *lower left*). Patency of the bypass was also confirmed by intraoperative Doppler ultrasonography. The images also disclosed that the color of the brain surface around the anastomosis changed significantly to black after removal of the temporary clip until the end of monitoring (Fig. 4 *lower right*). The change of average gradation value within the ROI increased 15–20 points, indicating a significant increase of temperature after release of the temporary clip (Fig. 5).

Operation. The patient showed no evidence of neu-

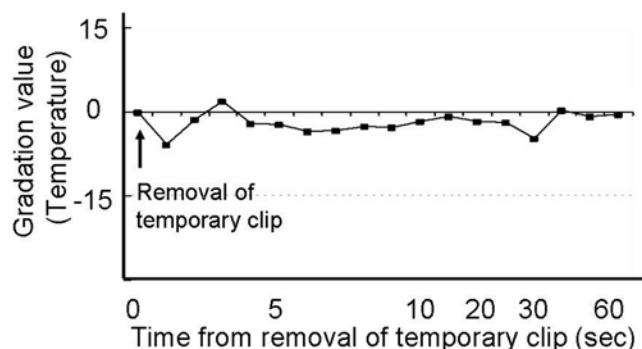


FIG. 3. Graph showing the relationship between time after removal of the temporary clip and changes of the average gradation value within the ROI around the anastomosis site as evaluated using imaging software in Case 1. The increase of gradation value after removal of the temporary clip was within 5 points, indicating no significant change in surface temperature.

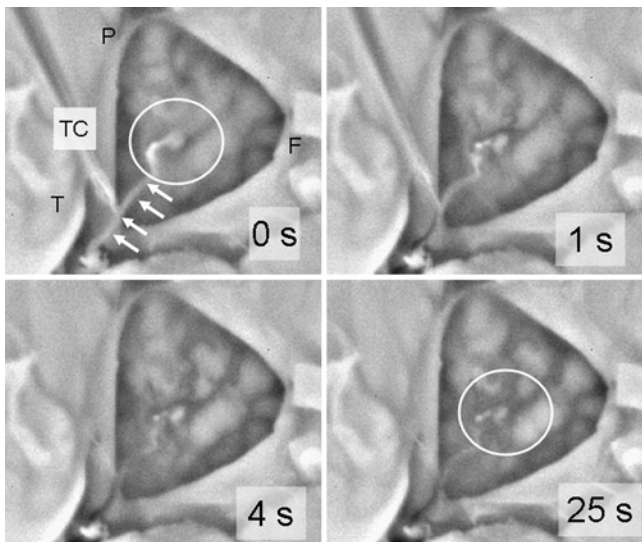


FIG. 4. Case 2. Images obtained during intraoperative infrared monitoring disclosing changes in color in the color in the STA (arrows) to white after temporary occlusion (indicating decrease in temperature; upper left) due to the absence of blood flow. Immediately after removal of clip at 1 second, the color of the bypass changes to black (upper right), indicating the presence of blood flow. The area is even darker after 4 seconds (lower left). Note that the color of the brain surface around the anastomosis site (circle, lower right) gradually changes to black (indicating an increase in temperature).

rological deficit immediately after surgery. The ^{123}I -IMP-SPECT studies obtained 1 day after surgery showed a slight increase in CBF in the right hemisphere (Fig. 6 center) compared with the preoperative findings (Fig. 6 upper). Postoperative DW MR imaging showed no evidence of ischemic change, and MR angiography demonstrated the apparently patent STA-MCA bypass as a higher intensity signal than the contralateral STA (Fig. 7 arrowhead). One day later, she suffered from fluctuating dysarthria, left facial palsy, and numbness in the left upper limb. A ^{123}I -IMP-SPECT study showed a focal intense increase in CBF at the site of anastomosis 7 days after surgery (Fig. 7 lower). A diagnosis of hyperperfusion was thus made based on neurological symptoms along with ^{123}I -IMP

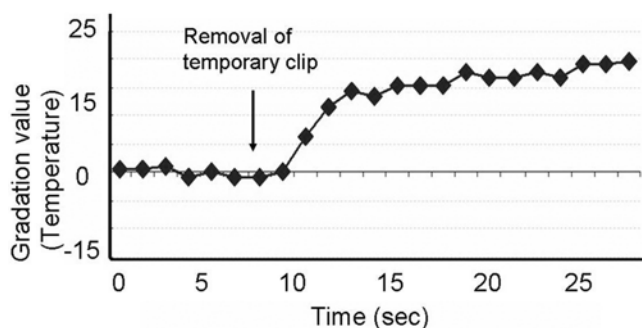


FIG. 5. Graph showing the relationship between time after removal of the temporary clip and changes in average gradation value within the ROI around the anastomosis site as evaluated by imaging software in Case 2. There was a significant rise of gradation value after removal of the temporary clip, indicating significant change in surface temperature.

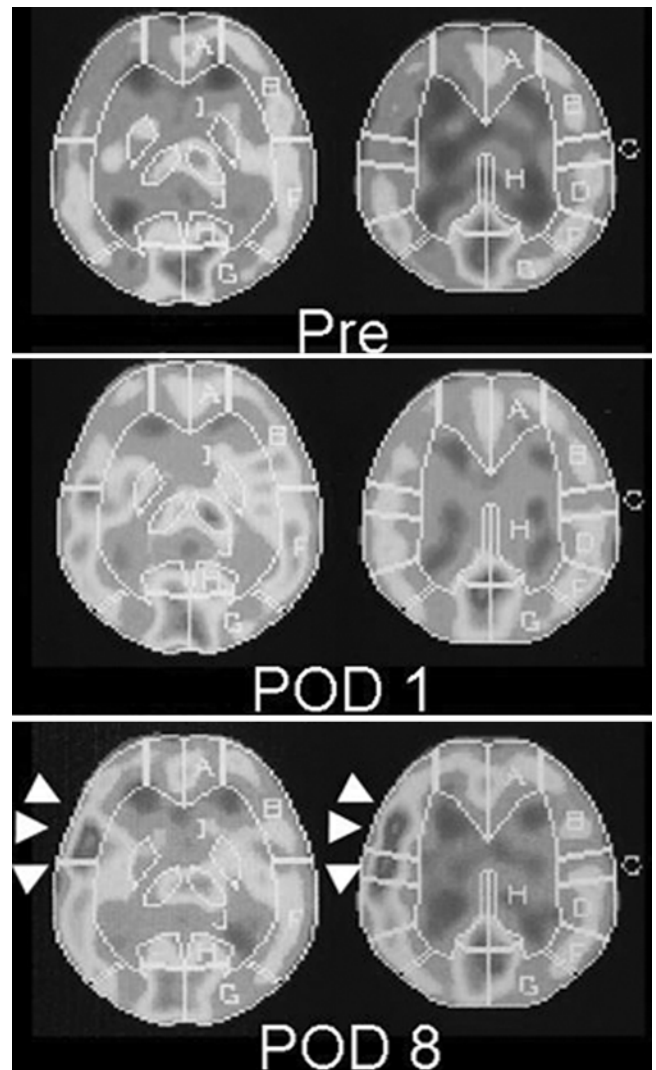


FIG. 6. The ^{123}I -IMP-SPECT studies obtained preoperatively (upper), 1 day after surgery (center) and 8 days after surgery (lower). Note the focal intense increase in the CBF at the site of anastomosis (arrowheads in lower).

SPECT and MR angiography findings. Intensive blood pressure control and the use of a free radical scavenger relieved her symptoms, which completely disappeared 13 days after surgery, at which time she was discharged from the hospital without neurological deficit. We performed second-stage surgery on the left side 1 month later.

Postoperative Course. She was discharged uneventfully after successful left STA-MCA anastomosis and EDMS, which resulted in disappearance of her ischemic attacks as well as a significant improvement in CBF on the bilateral cerebral hemisphere. She did not exhibit neurological deterioration during the follow-up period.

Neurological Deterioration

In all, 10 patients suffered from transient postoperative neurological deterioration, which were proved to be due to hyperperfusion in the present series. The aver-

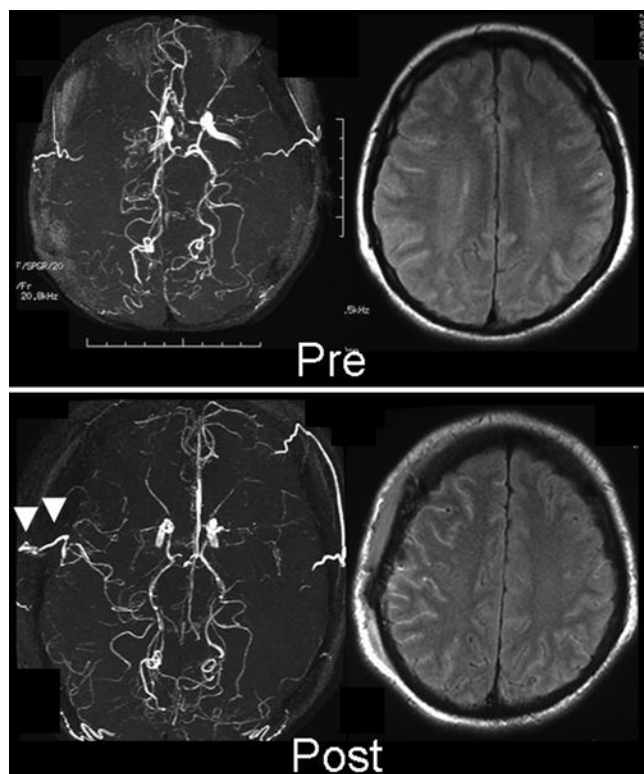


FIG. 7. Upper Left: Preoperative MR angiogram. Upper Right: Preoperative FLAIR study. Lower Left: Postoperative MR angiogram showing the apparently patent STA-MCA bypass (arrowheads). Lower Right: Postoperative FLAIR study showing high intensity signal around the site of anastomosis.

age gradation value change (representing temperature) was significantly higher in the patients who experienced symptomatic hyperperfusion (Fig. 8) immediately after and up to 60 seconds following removal of the temporary clip.

Discussion

In the present study, our novel infrared imaging system allowed us not only successful monitoring of the bypass patency and comprehensive visual evaluation of local hemodynamics, but also for the first time, it showed the possibility of estimating the risk of subsequent occurrence of postoperative symptomatic hyperperfusion by temperature rise around the anastomosis site during the operation.

Importance of Estimating Risk of Postoperative Symptomatic Hyperperfusion in Patients With Moyamoya Disease

Occurrence of transient postoperative neurological deficits due to hyperperfusion has been recently recognized as an important potential complication after revascularization surgery for moyamoya disease.^{5-8,16} It is important to recognize the pathology because strict control of blood pressure is mandatory in patients with hyperperfusion, whereas such treatment is contradictory to that in patients with ischemic episodes.⁵⁻⁷ In addition, from

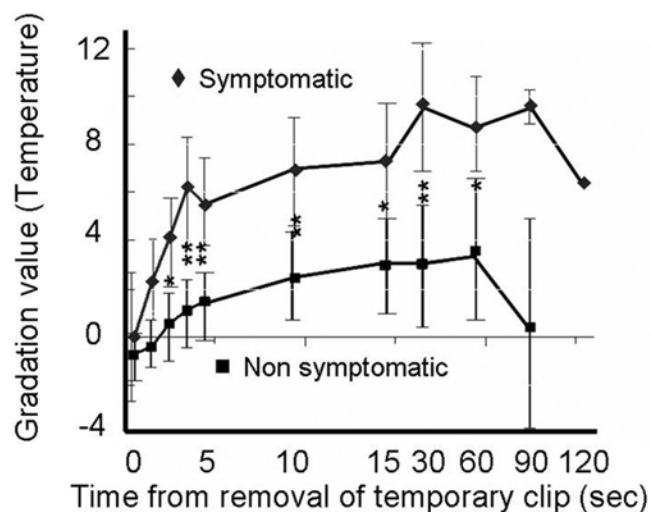


FIG. 8. Graph showing the differences in average gradation value within the ROI around the anastomosis site among 10 patients who had transient neurological deficits due to focal increase of CBF around the anastomosis site and 16 patients who did not, showing significant increase in gradation value (indirectly showing significant increase in surface cortical temperature) in the former group (up to 60 seconds after removal of the temporary clip). * $p < 0.05$; ** $p < 0.05$.

the viewpoint of cognitive functional impairment, the occurrence of hyperperfusion cannot be ignored.¹⁶ The rate of hyperperfusion in the present series was higher than that reported in the series dealing with STA-MCA anastomosis in chronic cerebral ischemia. Postoperative cerebral hyperperfusion syndrome has been considered to be less common in patients with moyamoya disease because of the relatively low-flow revascularization obtained through surgery for moyamoya disease. In our previous study involving 34 consecutive cases of moyamoya disease, we reported that STA-MCA anastomosis in patients with adult-onset moyamoya disease can result in a substantial rate (13 [38.2%] of 34) of temporary neurological deterioration due to transient focal intense increases in CBF at the site of anastomosis and that intensive blood pressure control can relieve this condition.⁵ However, the clinical manifestation is different from hyperperfusion syndrome after carotid endarterectomy; radical clinical presentation succeeding intracranial hemorrhage was observed in 1 case, but the majority were limited to subtle, transient focal neurological deficits mimicking ischemic attack, with no patient suffering a permanent neurological deficit. Identification of the predictors for cerebral hyperperfusion in patients with moyamoya disease is clinically important. Preoperative cerebrovascular reserve capacity, severity of ischemia during surgery, patients age, and anatomical vascular structures around the site of the anastomosis may affect postoperative cerebral hyperperfusion.^{5-8,10,16,19,25} In our study, most patients showed a preoperative cerebrovascular reserve capacity of $< 0\%$ (steal phenomenon), which may contribute to the high incidence of postoperative symptomatic hyperperfusion.

Regarding intraoperative ischemic insult during anastomosis, which may facilitate postischemic hyperperfusion, most of the cases were subjected to temporary

occlusion (30 minutes) at the distal M₄ segment. It is not clear how a rapid increase in CBF affects the ischemic brain in moyamoya disease, although a substantial number of patients may suffer transient neurological deterioration due to an unknown mechanism. As shown in the present study, the mean gradation value around the anastomosis site obtained from an infrared image showed a significant increase in temperature lasting up to 60 seconds in patients who suffer symptomatic hyperperfusion. According to the calibrated data from the manufacturer, the IRIS-V system demonstrates 20° of temperature difference between 25 and 45°C by 8-bit, or 256 gradation values. Therefore, a 1-point difference in gradation value is equivalent to 0.08°C. In the present study, the temperature difference between the 2 groups was calculated to be 0.28°C at 10 seconds, 0.42°C at 30 seconds, 0.41°C at 60 seconds, and 0.77°C at 90 seconds after removal of the temporary clip. However, whether this temperature increase is benign or a sign of abnormal overflow of CBF into a previously poorly perfused area, or merely a reaction unrelated to the postoperative phenomenon, is still uncertain. Even if it is a sign of abnormal overflow, the threshold remains unknown. Both issues are limitations of the present study and should be evaluated prospectively, and for a longer time after removal of the temporary clip. In light of the fact that STA-MCA anastomosis could result in postoperative symptomatic hyperperfusion in childhood⁷ as well as in adult-onset moyamoya disease,⁶ it is worth further studying the relationship between the pattern of intraoperative cerebral hemodynamics and postoperative neurological status.

Clinical Implications of Intraoperative Infrared Imaging

Infrared imaging is an established technique for studying the surface temperature of human organs.^{18,23} In the past, this technique has been applied in coronary artery bypass graft surgery to measure the cooling effect of cardioplegic solutions, or to evaluate coronary perfusion and graft patency.^{1,3,4} With advances in infrared technology, including detective wavelength, detective temperature range, cooling system, and filters, as well as data processing, it is now possible to observe surface blood flow with high spatial and time resolution without contact with blood vessels, radiation exposure, or injection of contrast medium.²¹

The relationship of infrared camera thermography and quantitative blood flow has been extensively investigated in the heart. Experimental cardiac studies demonstrated a quantitative correlation between blood flow and myocardial temperature.^{1,3} In the isolated pig heart, in which there is no metabolic contribution to temperature change, graft flow was found to correlate highly with a mathematical expression of the temperature change observed during thermography.³ In the brain literature, Watson et al.²⁴ applied high-resolution infrared imaging to the brain of *Cynomolgus* monkeys and reported that the cortical arterial temperature was related to blood flow and the temporal temperature profile was identical to that of blood flow measured by Doppler ultrasonography. Moreover, a recent study by Okada et al.¹⁷ showed linear relationships between cortical surface CBF and

temperature that were confirmed using a laser Doppler flowmeter. It is considered that cortical brain temperature is determined by metabolism and blood flow coupling^{2,9} and sensitive infrared imaging might be a useful measure provided that there is no significant metabolism change during monitoring.²⁴ Therefore, the increase in temperature around the anastomosis site in the present study was considered to be due to an increase in blood flow.

The IRIS-V is a new-generation infrared system with higher resolution at minimal temperature differences. In addition, by shifting the sensitive wavelength band up to 7–14 μm from 3–5 μm, it is possible to detect infrared rays from near the surface region. Using a previous prototype, we have evaluated patency of bypass in beagles (vessel diameter as small as 0.5 mm), and we have also reported that flow territory can be delineated by temperature difference.¹⁴ Infrared monitoring has also been useful for confirmation of venous drainage during surgical obliteration of a spinal perimedullary arteriovenous malformation.¹⁵ Including the novel infrared system presented in this report, future infrared monitoring will not only serve for intraoperative monitoring but may become a useful tool for estimation of postoperative risks, although further examination is necessary.

Conclusions

Temperature rise around an anastomosis site above a certain threshold during surgery as detected by intraoperative infrared monitoring might indicate the subsequent occurrence of postoperative symptomatic hyperperfusion. Prospective evaluation with a larger number of patients is necessary to validate this technique.

Disclosure

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