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ORIGINAL ARTICLE

# Efficacy of superficial temporal artery-middle cerebral artery bypass in cerebrovascular steno-occlusive diseases: Hemodynamics assessed by perfusion computed tomography

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## ABSTRACT

**Objectives:** Our purpose of this study was to assess the cerebral hemodynamic improvement with perfusion computed tomography (CT), before and after superficial temporal artery (STA) to middle cerebral artery (MCA) bypass surgery in patients with cerebrovascular steno-occlusive diseases including both moyamoya disease and nonmoyamoya steno-occlusions.

**Materials and Methods:** Twenty-four STA-MCA bypasses were performed to 22 patients with symptomatic cerebrovascular steno-occlusive diseases, including both moyamoya disease and nonmoyamoya steno-occlusive diseases. Brain perfusion CT images were obtained before and after the bypass surgery. The relative parameters such as cerebral blood volume (CBV), cerebral blood flow (CBF), and mean transit time (MTT) derived from the perfusion CT were collected and analyzed to assess the efficacy of STA-MCA bypass.

**Results:** The CBF increased, and MTT decreased after the bypass surgery in both moyamoya group and nonmoyamoya group. The increase of CBF in nonmoyamoya group and the decrease of MTT delay in moyamoya group, overall group were statistically significant ($P < 0.05$). No significant postoperative change in CBV was noted. During the postoperative follow-up period, none of the 22 patients experienced any repeated ischemic/hemorrhagic attacks nor any newly developed neurologic deficits.

**Conclusion:** The STA-MCA bypass is an effective surgical management for patients with cerebrovascular steno-occlusive diseases, such as moyamoya disease and internal carotid artery/MCA steno-occlusion. And perfusion CT can be used as an effective quantitative modality to assess the cerebral perfusion before and after the STA-MCA bypass surgery.

**Key words:** Cerebrovascular steno-occlusive disease, perfusion computed tomography, superficial temporal artery - middle cerebral artery bypass

## Introduction

Cerebrovascular steno-occlusive diseases are known to decrease the cerebral blood flow (CBF) and cerebral perfusion reserve. In such patients, medical treatment is insufficient, and superficial temporal artery (STA) to middle cerebral artery (MCA) bypass surgery has been performed in many centers to treat these diseases and to prevent ischemic episodes.[1-4]

In patients with cerebrovascular steno-occlusive diseases, varying degrees of hemodynamic insufficiency exists, and they tend to experience cerebral ischemic insults and/or cerebral hemorrhages, both of which could result in neurologic deficits.[5,6] The STA-MCA bypass surgery is known to prevent brain infarction and decrease the risk of hemorrhage by improving cerebral hemodynamics in patients with steno-occlusive cerebrovascular diseases.[7-10] Although some studies reporting that STA-MCA bypass surgery does not significantly reduce the rates of re-infarction has been published,[11] in well-selected patients with ischemic cerebrovascular steno-occlusive diseases such as moyamoya

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disease and other carotid artery or cerebral artery steno-occlusive diseases, it still remains as an important and effective treatment option and does benefit.[12-16]

Therefore, assessing the hemodynamics of cerebrovascular steno-occlusive diseases would be a key point before and after performing STA-MCA bypass surgery, not only to assess the efficacy of the treatment, but also to estimate the long-term outcome. Although no golden standard method has been established in assessing the changes in cerebral perfusion following the STA-MCA bypass, as medical imaging techniques develop, there are a variety of modalities to study the hemodynamics of these patients, as follows: Xenon-computed tomography (CT),[17,18] perfusion CT,[19] perfusion magnetic resonance (MR),[20] positron emission tomography (PET)[21] or single photon emission computed tomography (SPECT).[4,17,18,22,23] Perfusion CT is a noninvasive, cost-effective, and accurate imaging technique that can measure the most important parameters of cerebral hemodynamics, including CBF, cerebral blood volume (CBV), and mean transit time (MTT).[24-26]

In the present study, we retrospectively studied the patients who underwent STA-MCA bypass to treat symptomatic cerebrovascular steno-occlusive diseases, such as moyamoya disease and nonmoyamoya steno-occlusions. We used the perfusion CT as an imaging tool to assess the cerebral hemodynamic status pre and postoperatively and evaluate the efficacy of STA-MCA bypass on those diseases.

## Materials and Methods

### Patients and clinical process

The subjects that were included in this study were patients with cerebrovascular steno-occlusive diseases who underwent STA-MCA bypass surgery from April 2012 to June 2013 at Korea University Guro Hospital, Seoul. Patients were selected for STA-MCA bypass surgery if they matched the indication criteria below: History of clinical ischemic and/or hemorrhagic attack with (i) an occlusion of the internal carotid artery (ICA) or proximal segment of the MCA (ii) high-grade stenosis on those intracerebral vessels (iii) moyamoya disease or unilateral moyamoya syndrome. The confirmative diagnosis of moyamoya disease or ICA/MCA steno-occlusion was both established by the findings of ICAs and anterior cerebral artery (ACA), MCAs on conventional cerebral angiograms. Preoperative perfusion CT images were obtained for all the 22 patients, and the postoperative perfusion CT images were taken at the 3rd month after surgery. Patients who did not follow this follow-up protocol were excluded.

### Our surgical technique

- Stage 1 - Positioning: The patient is positioned supine on the operative table with a roll under his/her shoulder. The head is then rotated about 60° to the opposite side and fixed by mayfield fixators in order to provide a horizontal surface for the bypass. The course of the frontal and parietal branch of the STA is previously identified with a Doppler probe and marked on the scalp. Local anesthesia should not be injected to avoid STA injury
- Stage 2 - Scalp incision and STA dissection: An inverted U-shaped scalp incision is made on the temporal area including the parietal branch within the scalp flap, being careful not to injure the frontal branch of STA. The cut end of STA parietal branch is temporarily holding by a Raney clip. Under the microscope, STA dissection beginning from the lowest margin of the scalp flap up to the cut end is performed. (The STA pedicle should be longer than 10 cm in length.) Branches emanating from its trunk are coagulated or tied. The parietal branch of STA is occluded proximally by a temporary aneurysm clip. Vessel patency and flow are verified by opening the temporary clip. The distal end is cut in an oblique plane to match the length of the opening on the recipient M4
- Stage 3 - Craniotomy and dura incision: Then, the temporalis muscle is divided and reflected to expose the skull. An approximately 5 cm in diameter craniotomy is done, and the dura is opened in a semilunar type, and the brain cortex is exposed
- Stage 4 - The Recipient branch dissection: Under the microscope, arachnoid membrane over a recipient M4 branch is opened. After dissecting the vessel circumferentially by coagulating tiny branches with a micro bipolar cautery, a small piece of the rubber glove is placed underneath the vessel
- Stage 5 - Direct anastomosis: The M4 recipient artery is trapped by two temporary clips both on the proximal and distal end, and a linear arteriotomy is made with a sharp blade. The length of the arteriotomy is made at least twice the diameter of the recipient M4. Both the donor and recipient vessels are flushed with heparinized saline, and the incision line is marked with a marker. The distal end of the donor STA is sutured to the arteriotomy site on the recipient vessel with 10–0 nylon sutures. Stitching in done from the outside to inside of the STA, and then from the inside to outside of the M4. The temporary clips are then removed, and if bleeding occurs along the anastomosis site, additional sutures are done. Indocyanine green dye is administered intravenously to check the patency and flow in the bypass.

### Perfusion computed tomography imaging protocol

All the patients underwent a perfusion CT before the bypass surgery to measure the hemodynamic impairment of the affected hemisphere. The postoperative perfusion CT images were taken 3 months after the surgery. The perfusion CT imaging was performed using a 320-row multi-detector CT (Aquilion ONE, Toshiba Medical Systems, Otawara, Tochiki-ken, Japan) scanner. Acquired perfusion CT data were analyzed by semi-automated postprocessing commercial software (Vitrea 6.3, Vital Images, Minnetonka, MN, USA).

Perfusion deficits were detected first visually using three perfusion color maps; CBF as mL per 100 g brain tissue per min, CBV as mL per 100 g of brain tissue and MTT in seconds. Quantitative measurements were also done by the software, after dividing the brain parenchyma into several regions. From each perfusion CT study, we selected a region of interest (ROI) which is located on the most affected region of the symptomatic hemisphere. The selected ROI was where the CBF was most significantly decreased, and definite hypoperfusion was noted. The CBV and MTT were measured at the same region as CBF.

### Statistical analysis

All values shown in this article are the mean ± standard deviation. Statistical analyses were performed with a paired-sample *t*-test, and $P < 0.05$ was considered statistically significant in this study.

## Results

### Patients and the clinical progress

The demographics and the clinical data of the patients involved in this study are shown on Table 1.

Twenty-four STA-MCA bypass surgeries were performed to 22 patients. Totally, 16 of the 22 patients were diagnosed as moyamoya disease while 6 were nonmoyamoya cerebrovascular steno-occlusive disease patients diagnosed as ICA or proximal MCA steno-occlusion. Two patients who were diagnosed as moyamoya disease underwent bilateral STA-MCA bypass, with a time interval of >2 months between surgeries, while the other 20 patients had a unilateral STA-MCA bypass only on the symptomatic hemisphere. In the moyamoya group, 12 of the 16 patients (75%) were females while only 33.3% of the nonmoyamoya group were females (2 out of the 6). The mean age of the moyamoya group was 43.9 years old ranging from 14 to 69 years old. In contrast, the mean age of the nonmoyamoya steno-occlusive disease group was 60.8 years old ranging from 47 to 74 years old, which was significantly older than the moyamoya group ($P = 0.01$).

All 22 patients suffered from ischemic events, including transient ischemic attack (TIA) and/or hemorrhagic attacks. All six patients in the nonmoyamoya group suffered from ischemic symptoms while 25% of the moyamoya group patients had a hemorrhagic attack with definite neurologic deficits.

The moyamoya group had no dominancy in the side of surgery; however, five out of six patients in the nonmoyamoya group had a right-sided lesion.

All 24 bypass surgeries were successfully performed without any severe acute complications in this series. Three patients in the moyamoya group suffered new infarctions during the early postoperative in-hospital period, but fully recovered after fluid therapy, and were neurologically free at discharge. None of the nonmoyamoya group showed any infarctions. Those who had TIAs without any changes in postoperative imaging studies were not considered as postoperative acute complications. All the 22 patients were followed-up postoperatively for 4–18 months after the bypass surgery, and none of them experienced repeated ischemic/hemorrhagic attacks or any newly developed neurologic deficits.

### Results of perfusion computed tomography image analysis

Table 2 provides an overview of the perfusion CT data analysis before and after the bypass surgery. Preoperatively, all patients showed clinically significant hypoperfusion and

**Table 1: Demographics and clinical data of the patients**

| Characteristics | Moyamoya group (%) | Nonmoyamoya group* (%) | Overall (%) |
|---|---|---|---|
| Number of patients | 16 | 6 | 22 |
| Sex | | | |
| Male | 4 (25) | 4 (67) | 8 (36) |
| Female | 12 (75) | 2 (33) | 14 (64) |
| Mean age (range) | 43.9 (14-69)** | 60.8 (47-74)** | 48.6 (14-74) |
| Clinical events | | | |
| Ischemic only | 12 (75) | 6 (100) | 18 (82) |
| Hemorrhagic | 4 (25) | 0 (0) | 4 (18) |
| Operated side | | | |
| Right | 7 (44) | 5 (83) | 12 (55) |
| Left | 7 (44) | 1 (17) | 8 (36) |
| Bilat§ | 2 (12) | 0 (0) | 2 (10) |

*Nonmoyamoyagroup, nonmoyamoya cerebrovascular steno-occlusive disease group; ***P*=0.01; §One side at a time, with a time interval of >2 months between bypass surgeries

**Table 2: Perfusion CT data (mean±SD and *P* values) for ROI on the affected hemisphere**

| Groups | CBV (mL/100 g) | CBF (mL/100 g/min) | MTT (s) |
|---|---|---|---|
| Overall | | | |
| Preoperative | 3.75±1.04 | 42.66±10.27 | 5.23±1.32 |
| Postoperative (3 months) | 3.33±1.31 | 48.78±22.41 | 4.29±0.59 |
| *P* | 0.09 | 0.10 | 0.00* |
| Moyamoya group | | | |
| Preoperative | 4.03±0.95 | 44.89±10.62 | 5.41±1.24 |
| Postoperative (3 months) | 3.45±1.31 | 51.09±22.96 | 4.25±0.69 |
| *P* | 0.07 | 0.15 | 0.00* |
| Nonmoyamoya group | | | |
| Preoperative | 2.93±0.64 | 35.97±5.65 | 4.70±0.77 |
| Postoperative (3 months) | 2.97±0.33 | 42.00±5.43 | 4.40±0.61 |
| *P* | 0.46 | 0.04* | 0.24 |

**P*<0.05. CT – Computed tomography; ROI – Region of interest; SD – Standard deviation; CBV – Cerebral blood volume; CBF – Cerebral blood flow; MTT – Mean transit time decreased reserve in the ROI of the affected hemisphere. In the moyamoya group, the CBV decreased from 4.03 ± 0.95 to 3.45 ± 1.31 mL/100 g while the CBF increased from 44.89 ± 10.62 to 51.09 ± 22.96 mL/100 g/min after the bypass surgery, however, this change was not statistically significant ($P > 0.05$). On the other hand, the MTT in moyamoya group decreased from 5.41 ± 1.24 before to 4.25 ± 0.69 after surgical revascularization, which was statistically significant ($P = 0.00$). The result was not different in the overall group including all the 22 patients included in this series.

The nonmoyamoya group showed a similar result. The CBF increased from 35.97 ± 5.65 to 42.00 ± 5.43 mL/100 g/min ($P = 0.04$), and the MTT decreased from 4.70 s ± 0.77 s to 4.40 s ± 0.61 s ($P > 0.05$) after the STA-MCA bypass.

Although the increase of CBF was statistically significant only in the nonmoyamoya group and the decrease of MTT was significant only in the moyamoya group, the CBF and MTT showed a tendency to increase and decrease respectively in both groups. However, the CBV did not show any significant difference before and after the bypass surgery in any of the groups.

These changes of perfusion CT parameters after direct revascularization suggest that significant improvement of cerebral perfusion in the operated hemisphere could be expected following the surgery.

### A representative case

A 14-year-old girl visited our center presenting with headache and repeated TIAs in her left upper and lower extremities. A magnetic resonance imaging (MRI) scan on admission demonstrated multiple T2 high signal intensities on deep white matter of the left posterior watershed zone [Figure 1a], suggesting previous ischemic insults. However, she was neurologically free on the initial neurologic examination. Preoperative imaging studies including MR angiography and 6-vessel conventional angiography were obtained, and advanced moyamoya disease was confirmed. Occlusion on both distal ICAs was noted as well as severe steno-occlusive changes on both ACAs and MCAs. Moyamoya vessels were developed at the bilateral bases of the brain [Figure 1b and c]. Preoperative perfusion CT revealed perfusion deficit on both hemispheres represented by diminished CBF and prolonged MTT [Figure 2a and b]. Successful STA-MCA bypass was performed on the right hemisphere first [Figure 1d], as left sided symptoms were dominant, and another bypass surgery was performed on the left side 3 months later. After bilateral STA-MCA bypass, marked an increase in CBF on both hemispheres were noted as well as a significant decrease of MTT on both sides, compared to preoperative perfusion CT images [Figure 2c and d]. The patient showed several TIA symptoms immediately after the surgery but recovered and did not experience any complications or further ischemic episodes.

## Discussion

There are still controversies in surgical managements like direct revascularization for cerebrovascular steno-occlusive diseases as not only moyamoya disease but also nonmoyamoya carotid steno-occlusions.[27-29] However, many neurosurgical centers including our center, still perform this procedure for well-selected cerebrovascular steno-occlusive disease patients.

There are many other previous studies showing the efficacy of STA-MCA bypass,[7-10] however only few studies have assessed the hemodynamic changes of the affected area of the brain both pre- and post-operatively. And although few of them have evaluated the hemodynamics by other diagnostic modalities, fewer studies have used the perfusion CT as a tool to assess the hemodynamics. Our study shows favorable outcomes of STA-MCA bypass surgery with the evaluation of hemodynamics before and after the operation in cerebrovascular steno-occlusive disease patients. Hemodynamics which was assessed by perfusion CT revealed a marked improvement in cerebrovascular perfusion after STA-MCA bypass.

A successful bypass can prevent neurologic deficits and repeated TIAs that will burden moyamoya disease or other carotid steno-occlusive disease patients.[15,19,22,26] To assess the efficacy of STA-MCA bypass, postoperative evaluation including neurologic functional status and the status of cerebral hemodynamics in the patients has been considered important.[30] To determine the hemodynamic impairment in cerebrovascular steno-occlusive patients before the surgery, and to assess the improvement after the surgery, a quantitative assessment of the cerebrovascular perfusion and reserve is a key step. Previous studies have investigated that quantitative measurement of MTT using a deconvolution algorithm could act as a sensitive and reliable indicator of cerebral perfusion reserve capacity and provide useful information for the treatment of cerebrovascular steno-occlusive diseases.[15,31,32] In our study, all the patients underwent perfusion CT pre- and post-operatively. We found that the CBF had a tendency to increase after the surgery in both moyamoya and nonmoyamoya group, and the increase was statistically significant in the nonmoyamoya disease group [Table 2]. Regarding the MTT, it had a tendency to decrease postoperatively in both groups, being statistically significant in the overall group and moyamoya group [Table 2]. This significant increase in CBF and decrease of MTT seems to be a followed result of the increased blood flow produced by direct bypass from the STA.

As mentioned before, the cerebral perfusion is a key target for assessing the efficacy of STA-MCA bypass. Thanks to the advancing techniques in modern imaging modalities, we have many options to assess the cerebral hemodynamics both before and after revascularization surgeries for cerebrovascular vascular diseases. These include the perfusion

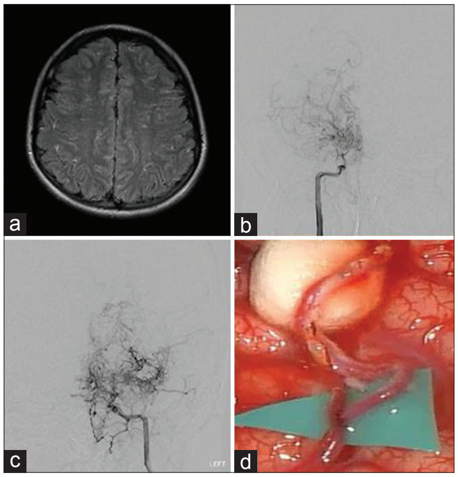

**Figure 1:** A representative case. Imaging studies of a representative case. (a) Initial brain magnetic resonance imaging showed multiple T2 high signal intensities on deep white matter of the left posterior watershed zone, suggesting previous ischemic insults. (b) Preoperative right internal carotid artery (ICA) angiography showed occlusion of the distal ICA and also steno-occlusive changes on the anterior cerebral artery (ACA), middle cerebral artery (MCA). Marked moyamoya vessels are noted. (c) Preoperative left ICA angiography showed occluded distal ICA like the right side, and severely narrowed ACA, MCA. Characteristic moyamoya vessels are noted on the base of the brain. (d) An intraoperative photograph of the patient showing successful superficial temporal artery-MCA end to side anastomosis

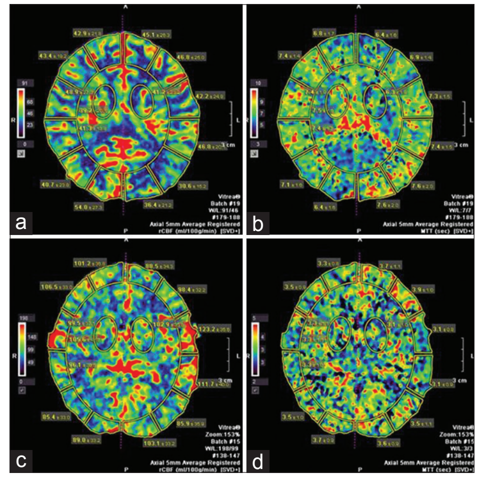

**Figure 2:** Perfusion computed tomography (CT) images the same patient Preoperative perfusion CT images and quantitative parameters showed diminished cerebral blood flow (CBF) (a) and prolonged mean transit time (MTT) (b) on both hemispheres, consistent with perfusion deficit due to moyamoya disease. Postoperative perfusion CT demonstrates a significant increase in CBF (c) and a significant decrease in MTT (d) on both hemispheres at the 3rd month after bypass

MR, PET, SPECT, Xenon-CT, and perfusion CT which we used as a modality of choice in this study. The PET and SPECT have been widely used to assess cerebral perfusion,[4,23] but they have some disadvantages. PET and SPECT requires delivery of ionizing radiation and is relatively more costly compared to other modalities, and in case of PET the availability of a cyclotron is required to produce PET tracers because they are very short-lived radiopharmaceutical materials.[17,18] Furthermore, SPECT is not strictly quantitative and has a poor spatial resolution.[18] Xenon-CT technique has also been used to evaluate hemodynamics after bypass surgeries,[17,18] but has some disadvantages as well. It has a relatively long acquisition time, it is prone to motion artifacts and most critically, some patients cannot tolerate the inhalation of Xenon due to complications such as nausea, vomiting, headache, and occasionally, respiratory failures.[17,18] Perfusion MR is a noninvasive modality that can provide many parameters including CBF, CBV, and MTT with a high spatial resolution.[20] However, the relatively high cost and relatively long procedure time is known to be the disadvantages of perfusion MR, and quantification of the CBF is more complex than perfusion CT because of the mismatch between gadolinium concentration and the signal intensity.[25,26] The perfusion CT scanning, which is the modality we used in this study as well, is a relatively new technique that measures cerebral hemodynamics and has several advantages compared to other imaging modalities. The CBV, CBF, and MTT maps can easily be generated in a relatively short time of the procedure and with lower costs.[25,26] Moreover, several studies have shown good correlation of the data generated by perfusion CT and the data provided by imaging modalities we have mentioned before.[19,26] Finally, the number of available CT scanners are far more larger than the number of PET, SPECT, or MRI scanners, which is a very large advantage to other modalities.[17,18] In this present report, we used perfusion CT to evaluate brain perfusion and cerebral reserve before and after STA-MCA bypass for 24 hemispheres in 22 patients who suffered from cerebrovascular steno-occlusive diseases. The CBV, CBF, and MTT were measured by perfusion CT in all those patients pre- and post-operatively. Unlike many other previous studies, we evaluated the change in hemodynamics after STA-MCA bypass not only in moyamoya disease patients but also in nonmoyamoya steno-occlusive disease patients. The CBF in the affected region significantly increased in nonmoyamoya group, and the MTT decreased significantly in the moyamoya group as well as the overall group. Although the increase of CBF in moyamoya group and the decrease of MTT in nonmoyamoya group were not statistically significant, they showed a tendency to increase and decrease, respectively. These results revealed that the remarkable improvement in cerebral perfusion was noted in the affected region of the brain after STA-MCA bypass. Furthermore, it revealed that perfusion CT is a fast and cheap, but accurate tool to assess the efficacy of STA-MCA by measuring the hemodynamic parameters of brain.

However, there are some limitations in our study. Our study included a small number of patients, especially nonmoyamoya cerebrovascular steno-occlusion patients. Thus, there may probably be some statistical errors. Further study with a larger number of patients and the larger set of clinical data, as well as more individual perfusion CT imaging analyses would be required for more accurate knowledge in assessing the efficacy of STA-MCA bypass.

## Conclusion

This study shows that STA-MCA bypass is an effective surgical treatment for patients with cerebrovascular steno-occlusive diseases which improves the patient not only clinically, but also the hemodynamics, in both the moyamoya disease and nonmoyamoya cerebrovascular steno-occlusions. And perfusion CT can be used as a noninvasive sufficient quantitative modality to evaluate the cerebral hemodynamics such as CBF and MTT before and after the STA-MCA bypass surgery.

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