Changes in Computed Tomography Perfusion Parameters after Superficial Temporal Artery to Middle Cerebral Artery Bypass: An Analysis of 29 Cases

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Abstract

Introduction Analysis of computed tomography perfusion (CTP) studies before and after superficial temporal artery to middle cerebral artery (STA-MCA) bypass is warranted to better understand cerebral steno-occlusive pathology.

Methods Retrospective review was performed of STA-MCA bypass patients with steno-occlusive disease with CTP before and after surgery. CTP parameters were evaluated for change after STA-MCA bypass.

Results A total of 29 hemispheres were bypassed in 23 patients. After STA-MCA bypass, mean transit time (MTT) and time to peak (TTP) improved. When analyzed as a ratio to the contralateral hemisphere, MTT, TTP, and cerebral blood flow (CBF) improved. There was no effect of gender, double vessel versus single vessel bypass, or time until postoperative CTP study to changes in CTP parameters after bypass.

Conclusions Blood flow augmentation after STA-MCA bypass may best be assessed by CTP using baseline MTT or TTP and ratios of MTT, TTP, or CBF to the contralateral hemisphere. The failure of cerebrovascular reserve to improve after cerebral bypass may indicate irreversible loss of autoregulation with chronic cerebral vasodilation or the inability of CTP to detect these improvements.

Keywords

- cerebral bypass
- Moyamoya
- computed tomography
- perfusion

Introduction

Superficial temporal artery to middle cerebral artery (STA-MCA) bypass surgery has been performed since 1967 for cerebral steno-occlusive disease.^{1,2} In the last 3 decades,

inconsistent results have been found from multiple cerebral bypass trials as well as individual case series.^{3–6} Current debate exists over (1) the efficacy of surgical management versus medical management in the modern era (specifically with the addition of statins and Plavix), and

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(2) the optimal perfusion study for selection of patients for cerebral bypass.

Although medical management has undoubtedly improved outcomes in patients with athero-occlusive pathology, patients with Moyamoya arteriopathy, radiation-induced arteriopathy, traumatic steno-occlusive lesions, and other vasculopathies do not have equivalent medical treatment and still require STA-MCA bypass in many cases. In the Carotid Occlusion Surgery Study, which selected patients with athero-occlusive disease, 22.7% still had an ipsilateral ischemic stroke despite maximum medical therapy.⁵ This clinical scenario may be due to resistance of antiplatelet agents, but it still suggests that even in the athero-occlusive population, a large group exists that may benefit from STA-MCA bypass.^{7,8} For these reasons, the cerebrovascular surgeon is still faced with patient populations that may benefit from STA-MCA bypass and requires perfusion imaging to aid in patient selection.

Although not a truly quantitative study, computed tomography perfusion (CTP) with acetazolamide (Diamox) challenge is a convenient and widely available perfusion modality.⁹ Data from CTP include baseline parameters, these parameters after Diamox administration, and these parameters relative to the contralateral asymptomatic hemisphere. Of the mass of data obtained from CTP, analysis of which parameters improve after STA-MCA bypass and to what degree they improve would contribute to our understanding of cerebral steno-occlusive diseases and the therapeutic effect of STA-MCA bypass. Further, the effects of patient demographics, timing of perfusion imaging, location of steno-occlusive lesions, and other variables on changes in cerebral perfusion would offer more insight into this disease process.

We have used CTP as an adjunct to select patients for STA-MCA bypass since 2004. We report a retrospective review of 29 surgeries on 23 patients who had both pre- and postoperative CTP to determine the change of CTP parameters after STA-MCA bypass. Additionally, other clinical and radiographic variables that may predict changes in CTP parameters after STA-MCA bypass are evaluated.

Methods

Patient Selection

We reviewed the surgical series by the senior cerebrovascular surgeon (M.Z.) at a single academic institution from 1997 to 2013. In this time period, 188 cerebral bypasses were performed on 164 patients. Patients with vascular occlusion of any etiology (most commonly Moyamoya arteriopathy or athero-occlusive disease) and stroke or transient ischemic attack (TIA) refractory to medical management including antiplatelet therapy were considered for surgery. Given that guidelines for patient selection with CTP do not currently exist, no rigid CTP criteria were applied to patient selection. At the discretion of the senior cerebrovascular surgeon (M.Z.), patients with asymmetric CBF, cerebrovascular reserve < 10%, or mean transit times > 5 seconds were deemed favorable surgical candidates. From 2006 to 2012, there were 29 cerebral hemispheres bypassed on 23 patients that

had both preoperative and postoperative CTP studies with Diamox challenge. Data from these studies were analyzed further. The study was approved by the University of Cincinnati institutional review board.

Surgical Procedure

All patients were given aspirin preoperatively and intraoperatively. Mean arterial pressure goals of 70 mm Hg were used. Surgeries were performed with neuro-monitoring of electroencephalography and somatosensory evoked potentials. The procedure consisted of anastomosis of the frontal, parietal, or both branches of the superficial temporal artery to an M4 segment of the middle cerebral artery. Anastomoses were done with 10-0 Prolene suture and confirmed patent intraoperatively with a combination of indocyanine green angiography and Doppler ultrasound.

Follow-up

Patients were evaluated at an outpatient clinical follow-up at 10 to 14 days postoperatively. History and neurologic examination at this visit were used to determine the incidence of perioperative stroke. Assessment of long-term follow-up was done by review of office visits of the surgeon and hospital records. Long-term follow-up was defined as at least 6 months from surgery.

CT Perfusion Technique

CTP was performed with dynamic axial imaging during bolus administration of 40 mL of contrast at an injection rate of 6 mL/second followed by 40 mL of saline at 6 mL/second. Two slices, each of 14.4 mm slice thickness, were performed at the level of the basal ganglia and the adjacent supraganglionic level (centrum semiovale) with a total anatomical coverage of 28.8 mm. Then 1,000 mg Diamox was administered intravenously and a repeat CTP was performed after a delay of 15 minutes to assess vasodilatory capacity.

The CTA study was done after an additional delay of 15 to 20 minutes after completion of the CTP. Vitrea 2, v.4.0 CT perfusion software (Vital images, Inc.), was used for perfusion data analysis. The input artery and the vein was selected using a semiautomated process, which allows the operator to select an appropriate artery and vein for the arterial input function and the venous function curves. Importantly, the same input artery and vein was selected for pre and post-Diamox perfusion studies. A computer-automated vascular pixel elimination method was used to minimize the conspicuity of vascular structures. Using an automatic template, regions of interest (ROIs) were placed over the cortex and large vessels were excluded from the ROIs. The ROIs were placed in six cortical arterial territories in each hemisphere (ACA, ACA-MCA, anterior MCA, posterior MCA, MCA-posterior cerebral artery watershed [MCA-PCA], and PCA distributions). Quantitative evaluation of the pre- and post-Diamox images was performed using cerebral blood volume (CBV), cerebral blood flow (CBF), mean transit time (MTT), and time to peak (TTP). The absolute changes in these parameters with Diamox defined the "Diamox reserve" for each parameter.

Statistical Analysis

The CBV, CBF, MTT, and TTP of the four ROIs in the MCA territory were averaged for a cumulative MCA distribution value. The baseline CTP parameters (CBV, CBF, MTT, and TTP), post-Diamox CTP parameters (CBV^{Diamox} , CBF^{Diamox} , MTT^{Diamox} , TTP^{Diamox}), as well as the change in baseline CTP parameters with Diamox ("Diamox reserve") (ΔCBV^{Diamox} , ΔCBF^{Diamox} , ΔMTT^{Diamox} , ΔTTP^{Diamox}) were compared from before and after STA-MCA bypass surgery. In addition, ratios of the baseline parameters (CBV, CBF, MTT, and TTP) and post-Diamox parameters (CBV^{Diamox} , CBF^{Diamox} , MTT^{Diamox} , TTP^{Diamox}) of bypassed hemispheres to the contralateral non-bypassed hemispheres (serving as internal controls) were calculated for patients who had only one bypass. Patients who had bilateral bypasses were not included in this secondary analysis because the internal control (i.e., contralateral hemisphere) was modified. Comparisons were made with a one-sample *t* test with statistical significance defined as $p < 0.0025$ after Bonferroni correction for multiple comparisons.

The effect of gender, age, time until postoperative CTP, occlusion location, presence of Moyamoya arteriopathy, and double-vessel versus single-vessel bypass on changes after STA-MCA bypass in the previously described 20 CTP variables were evaluated. Moyamoya arteriopathy was defined as meeting all the following criteria: (1) vascular steno-occlusive disease involving the carotid terminus, proximal ACA, or proximal MCA, (2) presence of abnormal vascular networks in the vicinity of steno-occlusive disease, and (3) bilaterality.¹⁰ CT angiography (CTA) patency was scored by a neuro-radiologist (A.V.) in a qualitative 4-grade scale: grade 0, no extracranial graft visualized; grade 1, small extracranial graft visualized (< 1.5 mm) but no anastomotic connection visualized; grade 2, large extracranial graft (> 1.5 mm) but no anastomotic connection visualized; and grade 3, graft and anastomotic connections visualized. Patency was defined as grade 1 to 3. The steno-occlusive lesions were divided into three locations: (1) Internal carotid artery (ICA) proximal to the terminus, (2) ICA terminus, or (3) M1 segment of the MCA. Gender and the presence of Moyamoya arteriopathy were assessed with two-sample *t* tests. Age at surgery and months from surgery until CTP study were assessed with linear regression models. Occlusion location classification was assessed with analysis of variance (ANOVA) models. All statistical analysis was done using SAS software (SAS, Cary, North Carolina, United States).

Results

Patient Characteristics

There were 17 patients who underwent unilateral STA-MCA bypass and 6 patients who had bilateral STA-MCA bypass totaling 29 bypasses in 23 patients (►Table 1). Females accounted for 13 of 23 patients (56.5%) and 17 of 29 bypasses (58.6%). The average age of all patients was 47.7 years. Moyamoya arteriopathy was diagnosed in 15 patients (65.2%), athero-occlusive disease in 6 patients (26.1%), dissection in 1 patient (4.3%), and radiation-induced vasculop-

athy in 1 patient (4.3%). The location of vascular occlusion was the carotid terminus in 13 bypasses (44.8%), ICA proximal to the terminus in 12 bypasses (41.3%), and MCA in 4 bypasses (13.8%). Bypasses were patent in 28 of 29 cases (96.6%) and consisted of one STA branch in 26 cases (89.7%) and two STA branches in 3 cases (10.3%). None of the 29 bypasses in 23 patients had a perioperative stroke. Long-term follow-up was available in 23 bypasses (79.3%) in 18 patients (78.3%). The average long-term follow-up was 18.2 months (median: 10 months). Twenty-two of 23 bypasses (95.7%) had no postoperative TIA or stroke. One patient had recurrent TIAs that resolved after additional indirect bypass with placement of multiple burr holes.

Change in CTP Parameters after STA-MCA Bypass

The preoperative CTP was obtained at an average of 0.9 months (range: 0–4.7 months) before surgery and the postoperative CTP at an average of 11.0 months (range: 1.8–34.1 months) after surgery. Of the 20 CTP parameters evaluated, 8 changed significantly after STA-MCA bypass (►Table 2). Four of the baseline parameters improved after STA-MCA bypass (MTT , MTT^{Diamox} , TTP , and TTP^{Diamox}). The Diamox reserve of any parameter did not change significantly after STA-MCA bypass. Four of the ratios (bypassed hemisphere parameter-to-non-bypassed hemisphere parameter) improved after STA-MCA bypass (CBF , MTT , TTP , and TTP^{Diamox}).

CTP Baseline Parameters Before and After Diamox

The most statistically significant changes due to STA-MCA bypass were seen in the pre- and post-Diamox MTT and TTP parameters (►Fig. 1). MTT , MTT^{Diamox} , TTP , and TTP^{Diamox} improved by 19.0, 23.7, 11.8, and 12.9%, respectively. Although CBV , CBV^{Diamox} , CBF , and CBF^{Diamox} improved after STA-MCA bypass, this was not statistically significant.

Diamox Reserve of CTP Parameters

The Diamox reserve of any parameter did not change significantly after surgery (►Fig. 2). The Diamox reserve of MTT (ΔMTT^{Diamox}) decreased by 154% after STA-MCA bypass, but this was not statistically significant after Bonferroni correction ($p = 0.01$). The Diamox reserve of CBF (ΔCBF^{Diamox}) increased 117% after STA-MCA bypass, but this was also not statistically significant ($p = 0.063$). Of note, ΔCBF^{Diamox} represents the absolute change in CBF , whereas cerebrovascular reserve is the relative change in CBF . Cerebrovascular reserve similarly improved from 10% to 18% after STA-MCA bypass, but this was not statistically significant ($p = 0.08$).

Changes in Ratios of CTP Parameters to Contralateral Hemisphere after ECIC Bypass

All patients who had unilateral surgery had the ratios of the CTP parameters in the bypassed hemisphere to the CTP parameters in the contralateral non-bypassed hemisphere evaluated. This analysis included the ratio of the baseline parameters (CBV , CBF , MTT , TTP) and these parameters after Diamox administration (CBV^{Diamox} , CBF^{Diamox} , MTT^{Diamox} , TTP^{Diamox}). The ratios of CBF , MTT , TTP , as well as TTP^{Diamox}

Table 1 Clinical data and outcomes from patient cohort

Patient	Age at surgery, y	Pathology	Hemisphere	Occlusion location	Bypass type	Patency	Surgery to CTA, mo	Postoperative clinical	Follow-up, mo
1	24.0	Moyamoya	Right	ICA	Double	Patent	18.1	Stable/Improved	48
1	24.4	Moyamoya	Left	ICA	Single	Patent	12.6	Stable/Improved	42
2	29.2	Moyamoya	Right	M1	Single	Patent	8.9	Stable/Improved	9
3	54.8	Moyamoya	Right	M1	Single	Patent	34.1	Stable/Improved	10
3	55.0	Moyamoya	Left	M1	Single	Patent	31.0	Stable/Improved	2
4	57.9	Atherostenotic	Left	M1	Single	Patent	16.6	Stable/Improved	18
5	41.2	Moyamoya	Left	M1	Single	Patent	10.3	Stable/Improved	12
5	41.6	Moyamoya	Right	ICA	Single	Patent	5.7	Stable/Improved	2
6	40.4	Moyamoya	Left	Terminus	Single	Patent	1.8	Unknown	12
7	70.6	Radiation vasculopathy	Left	ICA	Single	Patent	15.1	Stable/Improved	3
8	67.5	Atherostenotic	Left	ICA	Single	Patent	3.1	Stable/Improved	10
9	31.3	Moyamoya	Left	Terminus	Single	Patent	7.7	Stable/Improved	6
10	47.6	Moyamoya	Right	Terminus	Single	Patent	7.2	Stable/Improved	7
11	53.3	Moyamoya	Left	Terminus	Single	Patent	4.4	Stable/Improved	36
12	61.0	Atherostenotic	Left	ICA	Single	Patent	6.8	Stable/Improved	42
13	71.9	Moyamoya	Left	Terminus	Double	Patent	6.6	Stable/Improved	9
14	36.6	Moyamoya	Right	Terminus	Single	Occluded	9.8	Stable/Improved	8
14	36.8	Moyamoya	Left	Terminus	Single	Patent	8.2	Stable/Improved	72
15	78.5	Atherostenotic	Left	ICA	Single	Patent	20.8	Stable/Improved	3
16	58.5	Dissection	Left	ICA	Double	Patent	7.3	Stable/Improved	18
17	78.0	Atherostenotic	Right	ICA	Single	Patent	8.4	Stable/Improved	48
18 ^a	20.1	Moyamoya	Right	Terminus	Single	Patent	15.3	Progressive TIA/Stroke	36
18	20.3	Moyamoya	Left	Terminus	Single	Patent	13.4	Stable/Improved	8
19	47.5	Atherostenotic	Left	ICA	Single	Patent	5.4	Stable/Improved	4
20	57.0	Dissection	Left	ICA	Single	Patent	16.4	Stable/Improved	18
21	43.0	Moyamoya	Left	M1	Single	Patent	3.1	Stable/Improved	3
21	43.3	Moyamoya	Right	ICA	Single	Patent	6.7	Stable/Improved	1
22	41.3	Moyamoya	Right	Terminus	Single	Patent	6.7	Stable/Improved	36
23	51.8	Moyamoya	Right	Terminus	Single	Patent	6.3	Stable/Improved	6

Abbreviations: CTA, computed tomography angiography; ICA, internal carotid artery proximal to terminus; M1, M1 segment of middle cerebral artery; terminus, internal carotid artery terminus.

^aSymptoms resolved with placement of multiple burr holes.

changed significantly after STA-MCA bypass (→Fig. 3). The ratio of CBF, MTT, TTP, and TTP^{Diamox} improved by 29.2, 25.5, 7.5, and 9.4%, respectively. Of note, CBF only changed significantly when evaluated as a ratio. However, MTT, TTP, and TTP^{Diamox} changed significantly when interpreted both as absolute values and as ratios to the contralateral hemisphere.

Effect of Other Clinical and Radiographic Variables on CTP Parameters after STA-MCA Bypass

Age, gender, time until postoperative CTP, and double-versus single-vessel bypass had no effect on changes in any of the 20

CTP parameters after STA-MCA bypass. However, patients with Moyamoya arteriopathy had a reduction in the Diamox reserve of TTP (Δ TTP^{Diamox}), whereas patients without moyamoya arteriopathy had an increase in the Δ TTP^{Diamox} (− 0.92 versus 1.80 seconds, respectively; $p = 0.002$). This was the only instance in this study where a parameter obtained with Diamox administration changed when baseline parameters did not change. Lastly, the TTP ratio improved most with more distal occlusion locations. The TTP ratio improved most with an M1 steno-occlusive lesion, followed by patients with an ICA terminus lesion, followed by patients with a proximal ICA steno-occlusive lesion ($p = 0.002$).

Table 2 Computed tomography perfusion parameters change after superficial temporal artery-middle cerebral artery bypass

Parameter	Mean preoperative value	Mean postoperative value	Mean differences (%)	p value
CBV	4.11	3.60	− 0.51 (− 12.4)	0.03
CBV ^{Diamox}	4.60	4.25	− 0.35 (− 7.7)	0.21
CBF	50.54	53.60	3.06 (6.0)	0.44
CBF ^{Diamox}	54.95	63.19	8.25 (15)	0.07
MTT	5.55	4.49	− 1.06 (− 19.0)	< 0.0001 ^a
MTT ^{Diamox}	5.75	4.38	− 1.36 (− 23.7)	< 0.0001 ^a
TTP	21.11	18.63	− 2.48 (− 11.8)	0.0002 ^a
TTP ^{Diamox}	20.53	17.89	− 2.65 (− 12.9)	< 0.0001 ^a
ΔCBV ^{Diamox}	0.49	0.65	0.16 (32.6)	0.51
ΔCBF ^{Diamox}	4.40	9.59	5.19 (117)	0.063
ΔMTT ^{Diamox}	0.20	− 0.11	− 0.31 (− 154)	0.01
ΔTTP ^{Diamox}	− 0.57	− 0.74	− 0.17 (− 29.7)	0.68
Ratio CBV	1.10	1.07	− 0.03 (− 2.9)	0.35
Ratio CBV ^{Diamox}	1.18	1.01	− 0.17 (− 17)	0.003
Ratio CBF	0.78	1.01	0.23 (29.2)	0.001 ^a
Ratio CBF ^{Diamox}	0.72	0.95	0.23 (31.3)	0.003
Ratio MTT	1.50	1.11	− 0.38 (− 25.5)	0.001 ^a
Ratio MTT ^{Diamox}	1.98	1.20	− 0.79 (− 39.6)	0.003
Ratio TTP	1.09	1.01	− 0.08 (− 7.5)	0.001 ^a
Ratio TTP ^{Diamox}	1.12	1.02	− 0.10 (− 9.4)	0.001 ^a

CBF, cerebral blood flow; CBV, cerebral blood volume; MTT, mean transit time; TTP, time to peak.

^ap < 0.0025; Bonferroni correction.

Discussion

Our study showed which CTP perfusion parameters change after STA-MCA bypass surgery. Specifically, it showed the

baseline and post-Diamox values of MTT and TTP improve and the ratios of CBF, MTT, TTP, and TTP^{Diamox} improve. As pertinent negative findings, age, gender, time until obtaining a postoperative CTP, and double- versus single-vessel bypass do

Change in CTP Baseline and Post-Diamox Parameters after STA-MCA bypass

Fig. 1 This graph represents the percentage change after superficial temporal artery-middle cerebral artery (STA-MCA) bypass of all baseline computed tomography perfusion (CTP) parameters (cerebral blood flow [CBF]; cerebral blood volume [CBV]; mean transit time [MTT]; time to peak [TTP]) and parameters after Diamox administration (CBV^{Diamox}, CBF^{Diamox}, MTT^{Diamox}, TTP^{Diamox}). Asterisks represent p < 0.0025 for Bonferroni correction. CI, confidence interval.

Change in "Diamox Reserve" of CTP Parameters after STA-MCA bypass

Fig. 2 This graph represents the percentage change after superficial temporal artery-middle cerebral artery (STA-MCA) bypass of the "Diamox reserve" of the computed tomography perfusion (CTP) parameters (ΔCBV^{Diamox}, ΔCBF^{Diamox}, ΔMTT^{Diamox}, ΔTTP^{Diamox}). Asterisks represent p < 0.0025 for Bonferroni correction. CBF, cerebral blood flow; CBV, cerebral blood volume; MTT, mean transit time; TTP, time to peak.

Fig. 3 This graph represents the percentage change after superficial temporal artery-middle cerebral artery (STA-MCA) bypass of the ratios of all baseline computed tomography perfusion (CTP) parameters (cerebral blood flow [CBF]; cerebral blood volume [CBV]; mean transit time [MTT]; time to peak [TTP]) and parameters after Diamox administration (CBV^{Diamox} , CBF^{Diamox} , MTT^{Diamox} , TTP^{Diamox}). Asterisks represent $p < 0.0025$ for Bonferroni correction.

not significantly affect changes in CTP parameters after STA-MCA bypass. Also, in nearly all instances, the parameters acquired after Diamox administration do not change if the baseline parameter does not change.

We chose to evaluate the change of CTP parameters relative to the contralateral unoperated hemisphere as done by other investigators.^{11–13} This method has flaws, the largest being that the CTP parameters of the unoperated hemisphere also change after bypass due to reduced shunting. Additionally, the contralateral hemisphere is rarely without disease as seen in Moyamoya disease or in patients with diffuse atherosclerosis. With these limitations in mind, our finding that the ratio of MTT to the contralateral hemisphere changes significantly after STA-MCA bypass parallels the findings of Gu et al. These authors, also using CTP, report the MTT was prolonged compared with the contralateral hemisphere by 23.8% preoperatively and improved to 11.99% postoperatively.¹³ Similarly our preoperative MTT was prolonged 50% compared with the contralateral hemisphere and improved to 11% postoperatively.

Many values derived from TTP in our study changed significantly after STA-MCA bypass including the baseline TTP, TTP^{Diamox} , and the ratio of both of these values to the contralateral hemisphere. Also, patients with more distal vascular steno-occlusive lesions had more improvement in TTP ratio compared with more proximal steno-occlusive lesions. Fujimura et al, using MR perfusion-weighted imaging, found TTP to be decreased after STA-MCA bypass that correlated with increased CBF by single-photon emission CT.¹⁴ In evaluating 26 bypasses with whole-brain CTP, Tian et al found TTP and delay time to be the only two variables improved acutely after surgery with all variables improving after 3 months.¹⁵ In a smaller series of 10 patients, Langner et al similarly found that TTP improved after STA-MCA bypass but CBF did not. However, these authors found a statistically significant normalization of CBV, which was not statistically significant in our series.¹⁶ TTP parameters

may be the most reliable values to change after STA-MCA bypass.

Diamox is commonly administered during CTP for calculation of cerebrovascular reserve. We not only looked at the change of CBF with Diamox, but also the change in CBV, MTT, and TTP with Diamox. In our series, there was only one instance where data obtained from Diamox administration changed after surgery when the baseline parameter was unchanged. This single parameter was the Diamox reserve of TTP (ΔTTP^{Diamox}), which decreased in Moyamoya patients and increased in non-Moyamoya patients. The relevance of this finding in the absence of significance in numerous other variables evaluated is not clear. Although Diamox itself poses little risk to patients, it does double the radiation exposure because it requires a second acquisition of perfusion data. Consideration may be given toward not using Diamox for postoperative evaluation of perfusion with CTP.

However, it is hard to argue not to use Diamox for patient selection based on findings from other investigators.¹⁷ First, the Japanese Extracranial Intracranial Bypass (JET) study is the only randomized controlled trial to show better outcomes with cerebral bypass versus medical management.⁴ This study used cerebrovascular reserve by CTP as selection criteria. Another investigator was able to predict stroke risk in Moyamoya patients using Xenon-CT with Diamox. These investigators found that patients with both an abnormal CBF (< 37.1 mL/100 g/min) and abnormal cerebrovascular reserve ($< 9.7\%$ increase of CBF after Diamox challenge) had a drastically elevated stroke risk without cerebral bypass. And more importantly, these patients had normalization of the CBF and cerebrovascular reserve after surgery and had no postoperative strokes.^{18,19}

In our series, we found improvement in variables of MTT and TTP, marginal improvement in CBF, and no statistically significant improvement in CBV or cerebrovascular reserve. An explanation for these findings could be that the direct collateral flow provided by an STA-MCA bypass reduces MTT, TTP, and increases CBF. However, with chronic cerebral vasodilation, the mechanism for autoregulation may be irreversibly lost due to smooth muscle atrophy. Cerebral arterioles no longer vasoconstrict adequately and remain vasodilated resulting in persistently elevated CBV and minimal change in perfusion parameters with Diamox. Another explanation may be that CTP, as a nonquantitative study, does not assess cerebrovascular reserve well.

There were two pertinent negative findings in our study. First, obtaining a more delayed CTP, which should allow maturation of the bypass graft with subsequent improvement in CTP parameters, did not affect CTP parameters. Second, double-vessel bypass patients did not have statistically improved CTP parameters compared with single-vessel bypasses. However, double-vessel bypasses represented only 10.3% of our series and may not have been powered well enough to show statistical significance.

One of the major limitations of this study is that it was a retrospective review of a nonconsecutive group of patients that included only 15.4% of all bypasses over the reviewed period. Selection bias likely occurred in which patients

received or did not receive a postoperative CTA/CTP. The clinical course of the patients was not documented in a standardized fashion. The assessment of perfusion with CT allows limited brain coverage versus other modalities. And lastly, all patients in this series had a STA-MCA bypass without a control arm. This makes determination of the strength of benefit of the operation difficult. Future studies with control arms, serial examination of cerebral perfusion with CTP, and long-term longitudinal assessments of stroke risk will offer more direction on which CTP parameters should be used for patient selection for STA-MCA bypass.

Conclusions

With much controversy over the use of cerebral bypass and as much controversy over choice of perfusion imaging, we present an exploratory analysis of how CTP parameters change after STA-MCA bypass. Blood flow augmentation after STA-MCA bypass may best be assessed by CTP using changes in baseline MTT or TTP and changes in the ratio of MTT, TTP, or CBF to the contralateral hemisphere. The change in parameters due to Diamox challenge is not statistically significant after STA-MCA bypass and may indicate irreversible loss of cerebral autoregulation versus the inability of CTP to detect improvements in cerebrovascular reserve.

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