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Authors

Lyu, Jinhao
Ma, Ning
Liebeskind, David S
et al.

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Arterial Spin Labeling Magnetic Resonance Imaging Estimation of Antegrade and Collateral Flow in Unilateral Middle Cerebral Artery Stenosis

Jinhao Lyu, BS*; Ning Ma, MD*; David S. Liebeskind, MD; Danny J.J. Wang, PhD; Lin Ma, MD, PhD; Yang Xu, BS; Ting Wang, BS; Zhongrong Miao, MD; Xin Lou, MD, PhD

Background and Purpose—Three-dimensional pseudocontinuous arterial spin labeling with multiple postlabeling delays has been used to assess cerebral blood flow (CBF). We used this modality to estimate antegrade and collateral flow in patients with unilateral middle cerebral artery stenosis.

Methods—Consecutive patients with unilateral middle cerebral artery 50% to 99% stenosis at 2 centers underwent pseudocontinuous arterial spin labeling with a postlabeling delays of 1.5 and 2.5 s. Mean CBF of bilateral middle cerebral artery territory at the postlabeling delays 1.5 and 2.5 s was measured. Early-arriving flow proportion was defined as (CBF 1.5 s at lesion side/CBF 2.5 s at normal side)×100%. Late-arriving retrograde flow proportion was defined as ([CBF 2.5 s−CBF 1.5 s] at lesion side−[CBF 2.5 s−CBF 1.5 s] at normal side)/CBF 2.5 s at normal side×100%. Antegrade and collateral scales were evaluated in patients with conventional angiography. Spearman correlation coefficients were calculated between early-arriving flow and late-arriving retrograde flow proportions on arterial spin labeling and antegrade and collateral scales on conventional angiography, respectively.

Results—Forty-one patients (46.0±12.0 years) were enrolled. The mean early-arriving flow proportion was 78.3±14.9%. The mean late-arriving retrograde flow proportion was 16.1±10.2%. In 21 patients with conventional angiography, Spearman correlation coefficient was 0.53 (95% confidence interval, 0.11–0.79) between antegrade grade and early-arriving flow proportion (P=0.01) and 0.81 (95% confidence interval, 0.56–0.92) between collateral grade and late-arriving retrograde flow proportion (P<0.0001).

Conclusions—Three-dimensional pseudocontinuous arterial spin labeling with 2 postlabeling delays may provide an empirical approach for estimating antegrade and collateral flow in patients with unilateral middle cerebral artery stenosis.

Clinical Trial Registration—URL: http://www.clinicaltrials.gov. Unique identifier: NCT02479243.

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Key Words: atherosclerosis ■ collateral circulation ■ magnetic resonance imaging ■ middle cerebral artery ■ stroke

In patients with hemodynamic impairment caused by middle cerebral artery (MCA) atherosclerotic stenosis, the blood perfusion distal to the lesion site incorporates antegrade flow through the stenotic MCA and the retrograde flow through pial arteries form anterior cerebral artery or posterior cerebral artery.[1,2] Antegrade and collateral perfusion combined account for target downstream territory perfusion in ischemic stroke and have a strong correlation with clinical outcome.[3–7] Past studies have attempted to estimate or quantify collateral blood flow using computed tomographic angiography or conventional angiography with graded scales.[8,9] It remains difficult to quantify the proportion of cerebral blood flow (CBF) via antegrade flow through the stenotic vessel versus retrograde flow via collateral vessels with current imaging modalities.[10]

Arterial spin labeling (ASL) perfusion is a novel method to evaluate cerebral hemodynamic impairment. It is sensitive to both temporal (arterial bolus arrival) and perfusion information with varying postlabeling delays (PLDs), a technique

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From the Department of Radiology, Chinese PLA General Hospital, Beijing, China (J.L., L.M., Y.X., T.W., X.L.); Department of Interventional Neuroradiology, Beijing Tiantan Hospital, Capital Medical University, China National Clinical Research Center for Neurological Diseases, Center of Stroke, Beijing Institute for Brain Disorders, Beijing, China (N.M., Z.M.); and Department of Neurology, UCLA Stroke Center, Los Angeles (D.S.L., D.J.J.W.).

*J. Lyu and Dr N. Ma contributed equally.

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Correspondence to Xin Lou, MD, PhD, Department of Radiology, PLA (People's Liberation Army) General Hospital, 28 Fuxing Rd, Beijing 100853, China, E-mail louxin301@gmail.com or Zhongrong Miao, MD, Department of Interventional Neuroradiology, Beijing Tiantan Hospital, Capital Medical University, 6 Tiantan Xili, Beijing 100050, China, E-mail zhongrongm@163.com

termed dynamic perfusion imaging.[11] Three-dimensional pseudocontinuous ASL (3D pCASL) is an improved ASL technology with high signal:noise ratio and spatial resolution for quantitative CBF measurement.[12–14]

To the target downstream territory supplied by the stenotic vessel, antegrade flow traverses a relatively short vessel segment, whereas collateral flow passes through relatively longer pathways.[1] This difference in flow pathways may cause a critical distinction in that collateral perfusion is delivered with a substantially delayed transit time when compared with that of antegrade flow.[15,16] ASL is generally applied to measure CBF at a single PLD. Because of its sensitivity to arterial transit time, delayed arterial transit artifact has been used to identify and grade collateral flow in Moyamoya disease.[17] In the present study, we presented an empirical approach to estimate antegrade and collateral flow using a 2-PLD 3D pCASL protocol in a cohort of patients with unilateral MCA atherosclerotic stenosis.

Methods

Patients

The study was approved by the institutional ethnic committees of 2 centers. Written informed consent was obtained from all enrolled patients or his or her legally authorized representative.

This retrospective study enrolled consecutive patients from August 2013 to November 2014 who underwent magnetic resonance imaging by the inclusion criteria as follows: (1) symptomatic unilateral moderate to severe MCA stenosis (50%–99%) as confirmed by magnetic resonance angiography or conventional angiography with ischemic stroke or transit ischemic attack within 90 days; (2) age of patients >18 years old; (3) patient presenting ≥2 atherosclerotic risk factors including hypertension, hyperlipidemia, diabetes mellitus, obesity, and cigarette smoking[18]; and (4) patients who did not receive endovascular therapy. Patients with multiple moderate to severe stenoses (>50%) in intracranial arteries and extracranial arteries or those with <2 atherosclerotic risk factors were excluded. Extracranial arterial stenosis was evaluated by routine carotid ultrasound. Other clinically and radiologically suspected vascular diseases such as vasculitis or dissection were excluded. Patients having stroke with a large infarction area (greater than one third area of MCA territory) were excluded.

Image Acquisition

All magnetic resonance imaging studies were performed at 3.0T (DISCOVERY MR 750; GE Healthcare). Three-dimensional magnetic resonance angiography, 3D inversion recovery–prepared fast spoiled gradient recalled echo, and 3D pCASL were acquired for each patient.

Magnetic resonance angiography was performed using the following parameters: repetition time=34 ms, echo time=3.1 ms; field of view=24 cm, matrix=512×128, slice thickness=1 mm, and overlap=0.5 mm. High-resolution volumetric fast spoiled gradient recalled echo was acquired with whole brain coverage and the following parameters: field of view=24 cm, slice thickness=1 mm, number of slices=156, repetition time=8.2 ms, echo time=3.2 ms, bandwidth=31.2 kHz, inversion time=450 ms, matrix=256×256, and number of excitations=1.

Three-dimensional pCASL was acquired using 3D spiral fast spin echo with the following parameters: repetition time=4590 ms (PLD=1.5 s), 5285 ms (PLD=2.5 s), labeling duration=1500 ms, echo time=10.5 ms, field of view=24 cm, 512 sampling points on 8 spirals, spatial resolution=3.64 mm, slice thickness=4.0 mm, number of slices=36, number of excitations=2, background suppressed. Three-dimensional pCASL was acquired twice with the PLD of 1.5 and 2.5 s. Total acquisition time was 20 minutes. Conventional angiography was acquired from arterial phase through late venous phase.

Image Postprocessing and CBF Estimation

The CBF map of 3D pCASL was postprocessed and generated by Function Tool (AW 4.5 Workstation; GE Healthcare). Fast spoiled gradient recalled echo was normalized to Montreal Neurological Institute template space using SPM8 (Statistical Parametric Mapping, University College of London, available at www.fil.ion.ucl.ac.uk/spm/software/Spm8) on the Matlab platform (R2013b; MathWorks, Natick, MA). CBF map was coregistered to the normalized T1-weighted fast spoiled gradient recalled echo and spatially smoothed. A volumetric MCA territory based on gray matter mask according to previous work was extracted from the automated anatomic labeling template.[19–21] Volume of interest covered all the MCA territory including leptomeningeal and insular area but not basal ganglion (Figure I in the online-only Data Supplement). Mean CBF value of each side was obtained by applying the volume of interest to normalized CBF map.

On the lesion side, perfusion on the CBF map of PLD 1.5 s was assumed as early-arriving flow, and perfusion on the CBF map of PLD 2.5 s was assumed as combination of early-arriving flow, late-arriving antegrade flow, and late-arriving retrograde flow (Figure 1). Early-arriving flow was defined as the mean CBF of PLD 1.5 s on the lesion side. Late-arriving retrograde flow was defined as ([CBF 2.5 s−CBF 1.5 s] on the lesion side minus [CBF 2.5 s−CBF 1.5 s] on the normal side). Early-arriving flow proportion was calculated as (CBF 1.5 s on the lesion side/CBF 2.5 s on the contralateral side)×100%, late-arriving retrograde flow proportion was calculated as (the late-arriving retrograde flow/CBF 2.5 s on the normal side)×100%.

Conventional Angiography Antegrade Scale and Collateral Grade Assessment

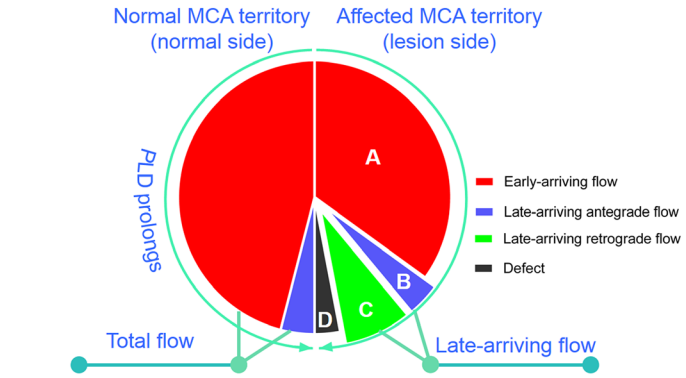
Two experienced interventional neuroradiologists (N.M. and J.L.) who were blinded to clinical findings assessed the status of antegrade and collateral flow in patients with available conventional angiography using the modified Thrombolysis in Cerebral Infarction (mTICI) scale,[22] and the American Society of Interventional and Therapeutic Neuroradiology (ASITN/SIR) collateral grading system based on consensus.[9]

Statistical Analysis

Categorical variables were expressed as n (%), and continuous variables were expressed as mean±SD. Comparisons of mean CBF at the PLD 1.5 s and 2.5 s between bilateral MCA territories were analyzed using 1-way ANOVA. Spearman correlation coefficient was used to assess the correlation of perfusion proportion with angiographic grading scales in cases with available conventional angiography. A $P<0.05$ (2 sided) was considered to indicate statistically significant difference. All statistical analyses were performed using SPSS 17.0.

Results

Forty-one patients (mean age, 46.0±12.0 years; 29 men) were included in our study. Thirty-nine stenosis lesions were located in the M1 segment of MCA, and 2 lesions were located in the M2 segment. The demographic and clinical information at baseline of all patients are listed in the Table (Table I in the online-only Data Supplement). The mean CBF values of the lesion side at the PLD of 1.5 and 2.5 s were 38.8±9.5 and 50.7±8.5 mL/100 g per minute, and those of the normal side were 45.3±8.2 and 49.3±6.2 mL/100 g per minute, respectively. The ANOVA revealed significant differences between mean CBF of normal and lesion side at the PLD of 1.5 s ($P<0.05$) but not for the PLD of 2.5 s ($P=0.46$). The ANOVA also revealed significant difference between mean CBF of the same side at the 2 PLDs ($P<0.05$). Figure 2 shows that the mean CBF increases from 1.5 s PLD to 2.5 s PLD in bilateral



$A = CBF_{1.5s}$ on the lesion side

$B \leq CBF_{2.5s} - CBF_{1.5s}$ on the normal side

$C \approx [\ CBF_{2.5s} - CBF_{1.5s}$ on the lesion side $] - [\ CBF_{2.5s} - CBF_{1.5s}$ on the normal side $]$

Early-arriving flow proportion = $A / CBF_{2.5s}$ on the normal side X 100%

Late-arriving retrograde flow proportion = $C / CBF_{2.5s}$ on the normal side X 100%

Figure 1. Diagram and formulas of blood flow in middle cerebral artery (MCA) territory with postlabeling delay (PLD) increasing at normal and lesion side of patients with unilateral MCA atherosclerotic stenosis. CBF indicates cerebral blood flow.

MCA territory with different trends. The mean early-arriving flow proportion was 78.3±14.9%. The mean late-arriving retrograde flow was 7.9±5.3 mL/100 g per minute. The mean late-arriving retrograde flow proportion was 16.1±10.2% (Table II in the online-only Data Supplement).

Modified TICI Scale and Early-Arriving Flow Proportion

Twenty-two patients (mean age, 47.2±9.6 years; 17 men) underwent conventional angiography. One patient was excluded because of the lack of late venous phase for assessment. Modified TICI scale and ASITN/SIR collateral grade of 21 patients (mean age, 47.7±9.5 years; 17 men) were assessed.

Modified TICI scale was assessed as 0 patient for mTICI 0, 1 patient for mTICI 1, 10 patients for mTICI 2a, 8 patients for mTICI 2b, and 2 patients for mTICI 3. The relationship of early-arriving perfusion proportions and mTICI scales in the 21 patients is shown in Figure 3A. Spearman correlation coefficient was 0.53 (95% confidence interval, 0.11–0.79) between antegrade mTICI scale 1 to 3 and early-arriving flow proportion (P=0.01). Early-arriving flow proportion was moderately correlated with mTICI scale 1 to 3.

Collateral Circulation Grade and Late-Arriving Retrograde Flow Perfusion Proportion

Collateral ASITN/SIR grades were assessed as 3 patients for grade 0, 4 patients for grade 1, 8 patients for grade 2, 6 patients for grade 3, and 0 patients for grade 4. The relationship of late-arriving retrograde flow proportions and collateral grades in the 21 patients is shown in Figure 3B. Spearman correlation coefficient was 0.81 (95% confidence interval, 0.56–0.92) between collateral ASITN/SIR grade 0 to 3 and late-arriving retrograde flow proportion (P<0.0001). Late-arriving retrograde flow proportion was strongly correlated with ASITN/SIR collateral grade 0 to 3. Figure 4 illustrates a representative patient with conventional angiographic antegrade and collateral scales, as well as the CBF maps at 2 PLDs (one more example is available in Figure II in the online-only Data Supplement).

Discussion

There remain no existing imaging modalities to quantify antegrade flow through a stenotic vessel versus the retrograde flow via potential collateral blood vessels in patients with intracranial atherosclerotic stenosis.[23] Our study showed significant correlations between early-arriving flow and late-arriving flow on 2-PLD pCASL with conventional angiographic antegrade and collateral scales, suggesting that the early-arriving flow and late-arriving retrograde flow to the territory supplied by the stenotic MCA may primarily represent antegrade and collateral flow, respectively.

Antegrade flow assessment is important in predicting the clinical outcome of patients with intracranial arterial stenosis. In studies focusing on acute ischemic stroke, patients with better antegrade mTICI scale typically have an improved 90-day outcome.[5,6] However, this scale is categorical, and there are only a handful studies on using it to predict clinical outcome in patients with chronic intracranial arterial stenosis.[24] Our

Table. Demographics of Patients

	Patients (n=41)
Age, y, mean (SD)	46.0 (12.0)
Women, n (%)	12 (29)
Hypertension, n (%)	27 (66)
Diabetes mellitus, n (%)	9 (22)
Coronary artery disease, n (%)	2 (5)
Smoking history, n (%)	16 (39)
Lipid disorder, n (%)	36 (88)
Obesity, n (%)	0 (0)
Stenosis of middle cerebral artery, n (%)	
Moderate stenosis (50%–70%)	4 (10)
Severe stenosis (70%–99%)	37 (90)
Stroke as a qualifying event, n (%)	21 (51)
Time from qualifying event to MRI scan, d, mean (SD)	34.1 (21.3)
NIHSS score at admission, median (IQR)	0 (0–2.5)

IQR indicates interquartile range; MRI, magnetic resonance imaging; and NIHSS, National Institutes of Health Stroke Scale.

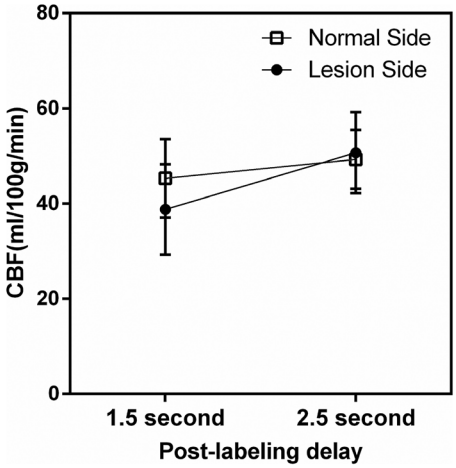


Figure 2. Mean cerebral blood flow (CBF) of bilateral middle cerebral artery territory increases from postlabeling delay (PLD) 1.5 s to PLD 2.5 s.

study reveals that antegrade flow may be quantified using 2-PLD ASL, and that it accounts for a larger proportion of perfusion than collateral flow in patients with unilateral MCA stenosis. This indicates that antegrade flow plays an important role in maintaining perfusion of the target downstream territory in this population. The proposed approach may help establish or define a critical threshold of antegrade perfusion to predict a good clinical outcome in future studies.

Quantification of collateral perfusion is likely as important as antegrade flow. Patients with the same amount of antegrade flow exhibited a varied degree of clinical outcomes, which is likely because of the variation of collateral compensation. Previous studies indicated that ASITN/SIR collateral grade is an independent prognostic factor for patients with intracranial arteries stenosis.[7,24] Because conventional angiography is invasive, alternative approaches and imaging modalities have been applied but rarely used in a routine clinical setting. Quantification of collateral perfusion may help to evaluate the capacity of collateral vessels and to stratify patients at high risk of recurrent ischemic events and patients with high risk of hemorrhage caused by hyperperfusion after recanalization. Our study showed that the mean fraction of collateral perfusion was 16.1±10.2% of total cerebral perfusion in patients with unilateral MCA stenosis using 3D pCASL, which may reflect the extent of CBF contributed by collateral vessels.

Multi-PLD ASL has been investigated by many studies in both health volunteers and patients with stroke.[25–28] It often refers to ASL using >5 PLDs to quantitatively estimate arterial transit time and CBF. Arterial transit time maps generated using multi-PLD ASL may offer a method to define the optimal PLDs of specific vascular territories. The early-arriving flow and late-arriving retrograde flow proportions acquired from optimal PLDs according to arterial transit time map from multi-PLD ASL may be more accurate than that from 2 empirical PLDs in present study.

Limitations of our study include a relatively small sample size. Second, because of the complexity of cerebral hemodynamics in patients with artery stenosis, antegrade flow may be slower than normal flow in contralateral side and the transit time of collateral flow may be longer than 2.5 s. The ASL signal acquired at the PLD of 1.5 s may also contain a small portion from collateral supply. Therefore, it is challenging to absolutely quantify antegrade flow and separate slow antegrade flow from late-arriving flow completely. Such differentiation may have to use vessel-selective ASL. However, considering the moderate to high correlations between the proposed ASL quantification at the 2 PLDs and DSA mTICI and ASITN/SIR scores in our patient cohort, the formulas proposed in our study may provide an empirical estimation of antegrade and retrograde flows. Third, the temporal parameters including PLD and delayed filling time through the stenotic lesion were based on an empirical definition, as no standards exist. To estimate antegrade perfusion and collateral perfusion in a given individual, time to reach the peak flow of the affected hemisphere and contralateral normal side is essential. Our analyses demonstrated that the PLDs of 1.5 and 2.5 s may be rational, considering that it may not be feasible to obtain a reliable CBF map if PLD is longer than 3 s with current technology.[25] Furthermore, arterial transit artifacts caused by slow blood flow within the vessels may also influence the measurement. Fourth,

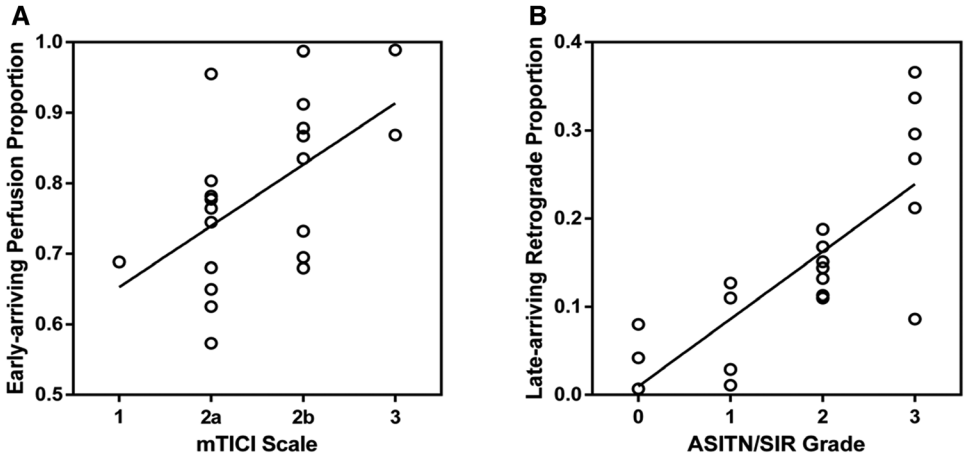


Figure 3. Scattered plots shows the relationship of early-arriving flow perfusion proportion and modified Thrombolysis in Cerebral Infarction (mTICI) scale (**A**), late-arriving retrograde flow perfusion proportion and American Society of Interventional and Therapeutic Neuroradiology (ASITN/SIR) collateral grade (**B**) in patients with an available conventional angiography. The line represents linear regression.

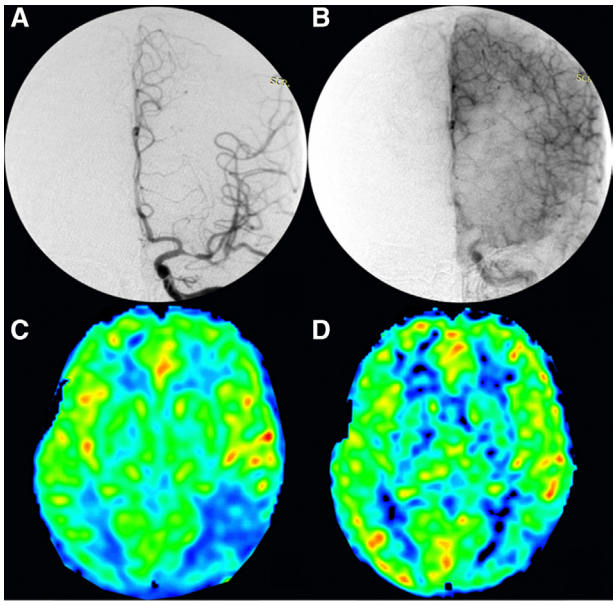


Figure 4. A 52-year-old male patient with severe left M1 segment stenosis is scored modified Thrombolysis in Cerebral Infarction 2b and American Society of Interventional and Therapeutic Neuroradiology (ASITN/SIR) grade 2 (**A** and **B**). Early-arriving flow perfusion proportion is measured as 87.8%, and late-arriving retrograde flow perfusion proportion is 13.2%. **C** and **D**, The cerebral blood flow maps of postlabeling delay 1.5 s and 2.5 s.

this quantification method could not provide information about the sources of collateral perfusion. Vessel-selective or vessel-encoded ASL may be used to quantify collateral perfusion in those patients with intracranial stenosis and depict the sources of collateral vessels in future studies.[29,30] Finally, we hypothesized that the ideal perfusion of affected territory would equal to that of the contralateral normal MCA territory. The hemodynamic status of the normal side may also influence the results, as well (Figure III in the online-only Data Supplement).

Conclusions

Three-dimensional pCASL with 2 PLDs may provide a useful tool to quantify early-arriving and late-arriving flows in patients with unilateral MCA stenosis and may provide an empirical index of antegrade and collateral flow. The clinical use of the proposed approach for identifying patients with high risk of recurrent stroke requires evaluation in further studies.

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Disclosures

None.

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SUPPLEMENTAL MATERIAL

Arterial Spin Labeling MRI Estimation of Antegrade and Collateral Flow in Unilateral Middle Cerebral Artery Stenosis

Supplemental Figure I

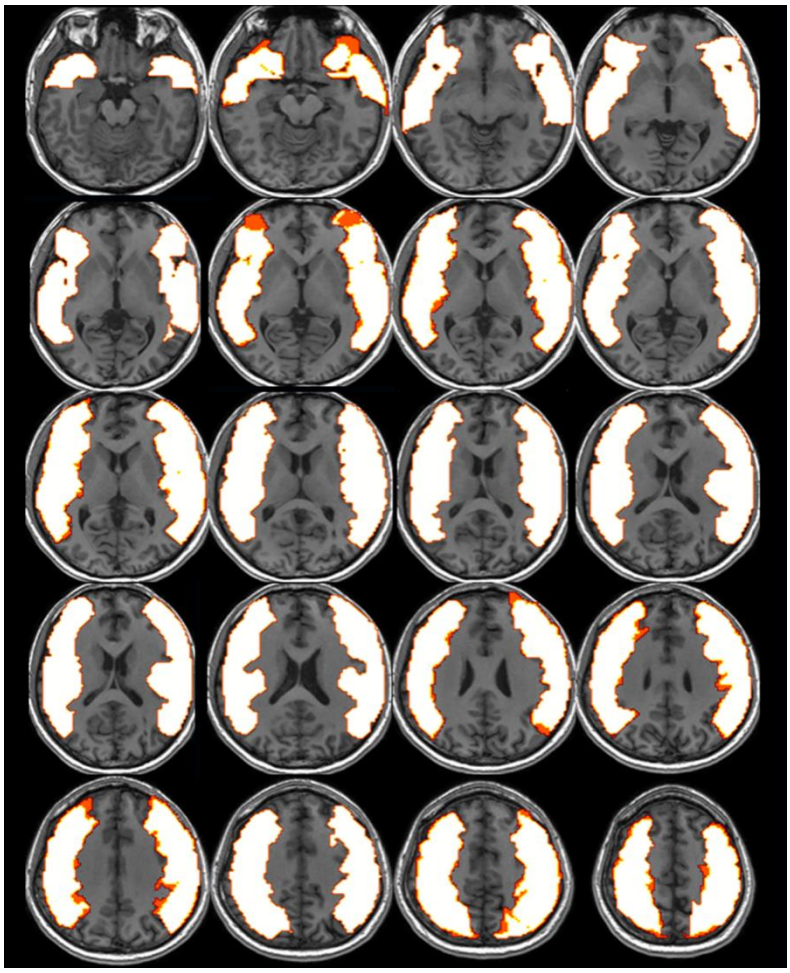

Figure I Volume of interest (VOI) covering all the MCA territory including leptomeningeal and insular area but not basal ganglion. Mean CBF value of each side was obtained by applying the VOI to normalized CBF map. MCA, middle cerebral artery; CBF, cerebral blood flow.

Supplemental Figure II

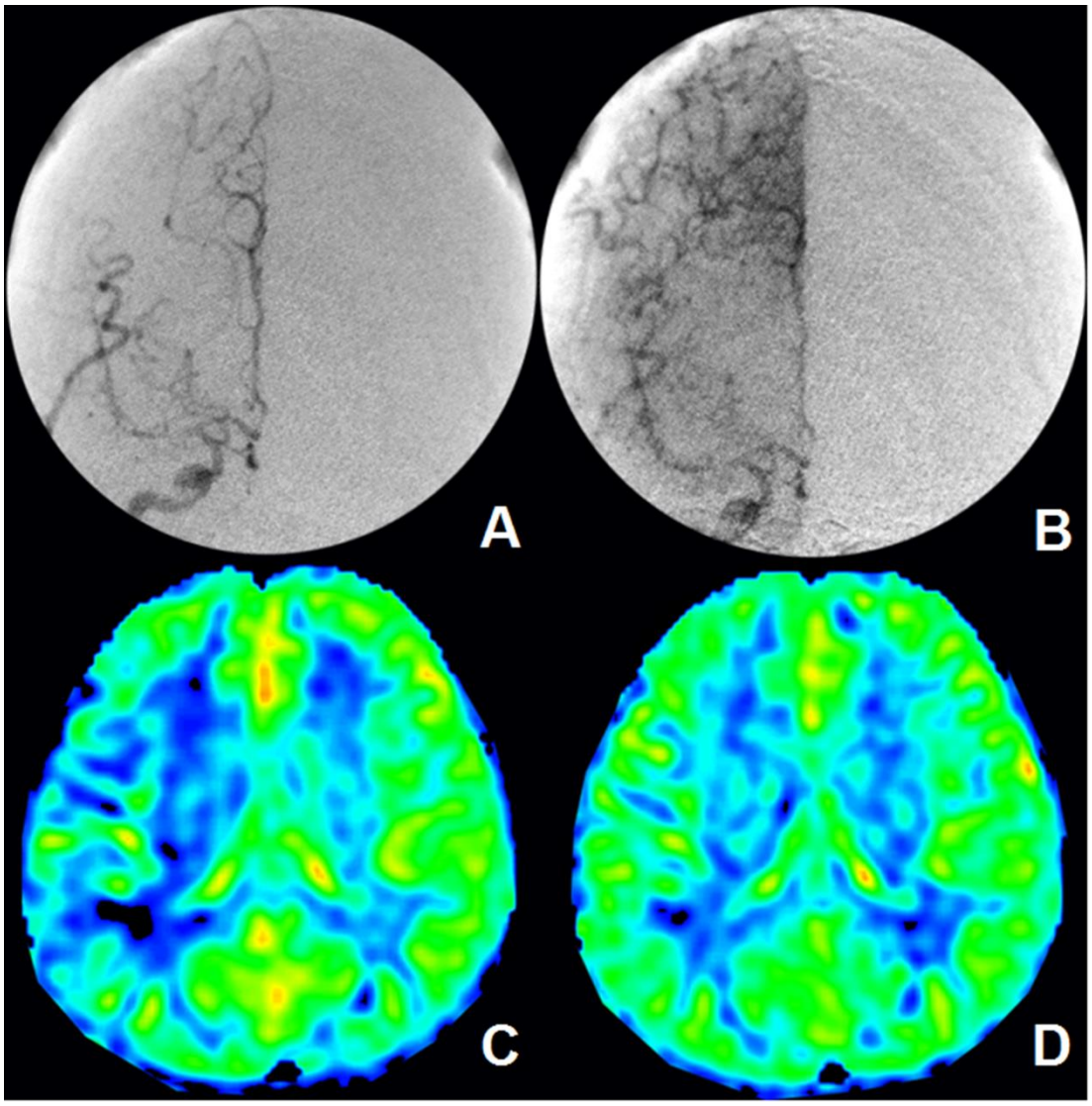

Figure II A 40-year-old male patient with right M1 segment severe stenosis is scored mTICI 1 and ASITN/SIR grade 2(A and B). Early-arriving flow perfusion proportion is measured as 68.8% and late-arriving retrograde flow perfusion proportion is 18.8%. C and D shows the ASL CBF maps of 1.5s and 2.5s PLD. mTICI, modified Thrombolysis in Cerebral Infarction; ASITN/SIR, American Society of Interventional and Therapeutic Neuroradiology / Society of Interventional Radiology; ASL, arterial spin labeling; CBF, cerebral blood flow; PLD, post-labeling delay.

Supplemental Figure III

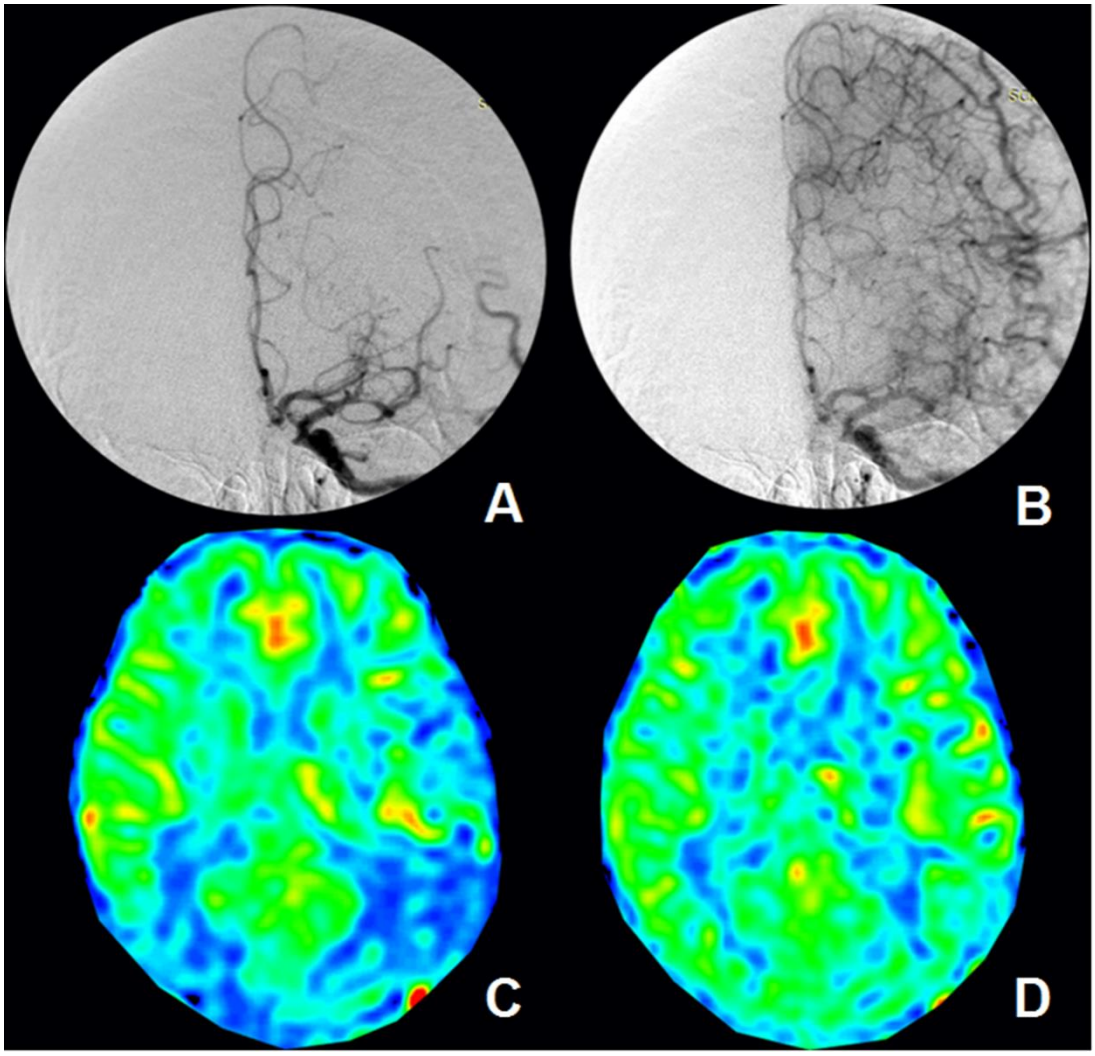

Figure III A 51-year-old male patient with left M1 segment severe stenosis is scored mTICI 2a and ASITN/SIR grade 3 (A and B). Early-arriving flow perfusion proportion is measured as 74.5% and late-arriving retrograde flow perfusion proportion is 8.6% merely. Error may be induced by the contralateral relative slow flow and collateral flow not completing in 2.5 second delay. C and D shows the ASL CBF maps of 1.5 and 2.5 second PLD. mTICI, modified Thrombolysis in Cerebral Infarction; ASITN/SIR, American Society of Interventional and Therapeutic Neuroradiology / Society of Interventional Radiology; ASL, arterial spin labeling; CBF, cerebral blood flow; PLD, post-labeling delay.

Supplemental Table I. Patients' Characteristics

Number	Gender	Age	Lesion	Diabetes	Hypertension	Lipid disorder	Coronary artery disease	Smoking history	Obesity	Qualifying event	Stenosis(n%),MRA	Time from qualifying event to MRI scan (d)	NIHSS
1	F	25	LMCA	0	1	1*	0	0	0	STROKE	90	7	3
2	M	42	RMCA	0	1	0	1	0	0	TIA	85	30	0
3	F	52	RMCA	0	1	1	0	0	0	TIA	95	18	0
4	F	51	LMCA	1	1	1	0	0	0	TIA	90	20	0
5	M	38	LMCA	0	1	1	0	1	0	STROKE	95	7	2
6	F	42	RMCA	0	1	1*	0	0	0	TIA	92	50	0
7	M	67	LMCA	0	1	1	0	0	0	STROKE	90	6	3
8	F	50	LMCA	1	1	0	0	0	0	STROKE	88	4	8
9	M	34	LMCA	0	0	1	0	1	0	STROKE	60	13	0
10	M	50	LMCA	1	0	0	0	1	0	TIA	65	6	0
11	M	43	RMCA	0	0	1*	0	1	0	STROKE	75	47	0
12	M	31	LMCA	0	1*	1	0	0	0	TIA	75	60	0
13	M	48	LMCA	0	1*	1	0	0	0	TIA	75	85	0
14	M	51	LMCA	0	0	1*	0	1	0	TIA	86	25	0
15	M	48	RMCA	1	0	1	0	1	0	STROKE	90	21	4
16	M	52	LMCA	0	1*	1	0	0	0	STROKE	78	31	2
17	M	50	RMCA	0	0	1	0	1	0	TIA	75	40	0
18	M	40	RMCA	0	0	1	0	1	0	STROKE	95	22	4
19	M	62	LMCA	0	1	1*	0	0	0	STROKE	80	40	2
20	M	40	RMCA	1	0	1	0	0	0	STROKE	85	45	2
21	F	47	LMCA	0	1*	1*	0	0	0	TIA	85	41	0
22	M	65	LMCA	1	1	1	0	1	0	STROKE	85	35	5
23	M	31	RMCA	0	1	1	0	0	0	TIA	95	13	0
24	F	53	LMCA	0	1	1	0	0	0	TIA	90	20	0
25	F	45	LMCA	0	1*	1	0	0	0	TIA	95	30	0
26	F	59	LMCA	0	1	1	0	0	0	TIA	95	80	0
27	M	60	LMCA	0	1	1	0	0	0	TIA	95	71	0
28	M	53	RMCA	1	1	0	0	0	0	STROKE	90	42	5
29	M	53	RMCA	1	0	1	0	0	0	STROKE	85	40	3
30	M	41	RMCA	1	0	1	0	1	0	TIA	85	82	0
31	F	68	LMCA	0	1	0	1	0	0	STROKE	90	20	0
32	M	46	LMCA	0	1*	1*	0	0	0	TIA	80	49	1
33	M	29	LMCA	0	1*	1	0	0	0	TIA	55	30	0
34	F	47	RMCA	0	0	1*	0	1	0	STROKE	90	25	0

(Continued)

Supplemental Table I. Continued

Number	Gender	Age	Lesion	Diabetes	Hypertension	Lipid disorder	Coronary artery disease	Smoking history	Obesity	Qualifying event	Stenosis(n%),MRA	Time from qualifying event to MRI scan (d)	NIHSS
35	M	20	LMCA	0	1	1	0	1	0	TIA	85	20	0
36	M	32	RMCA	0	1	1	0	1	0	STROKE	90	48	5
37	M	69	LMCA	0	0	1	0	1	0	STROKE	90	21	2
38	M	43	RMCA	0	0	1	0	1	0	STROKE	90	32	4
39	M	30	LMCA	0	1*	1*	0	0	0	TIA	65	60	0
40	F	28	RMCA	0	1*	1	0	0	0	STROKE	80	49	0
41	M	52	LMCA	0	0	1	0	1	0	STROKE	90	13	1

* denotes having a hostory of use of antihypertensive drug or statin for controlling blood pressure or cholesterol level; NIHSS indicates National Institutes of Health Stroke Scale; MCA, middle cerebral artery.

Supplemental Table II. Angiographic Grading Scales and Arterial Spin Labeling Measurements of Blood Flow

Number	ASITN/SIR Grade	mTICI	1.5s PLD CBF of Lesion Side (ml/100g/min)	2.5s PLD CBF of Lesion side (ml/100g/min)	1.5s PLD CBF of Normal Side (ml/100g/min)	2.5s PLD CBF of Normal side (ml/100g/min)	CBF 2.5s minus CBF 1.5s at normal side	CBF 2.5s minus CBF 1.5s at lesion side	Late-arriving retrograde perfusion (ml/100g/min)	Early-arriving perfusion proportion (%)	Late-arriving retrograde perfusion proportion (%)
1			53	59.3	49.7	47.1	-2.6	6.3	8.9	1.125	0.189
2			36.7	50	43.3	47.3	4	13.3	9.3	0.776	0.197
3			45.1	58	54.7	53	-1.7	12.9	14.6	0.851	0.275
4			33.2	47.3	47	45	-2	14.1	16.1	0.738	0.358
5			33.7	46.7	44.7	42.1	-2.6	13	15.6	0.800	0.371
6	1	2b	43.1	47.9	51.2	49.7	-1.5	4.8	6.3	0.867	0.127
7			26.3	38.6	39.9	47.2	7.3	12.3	5	0.557	0.106
8			18.2	37.5	26	38.8	12.8	19.3	6.5	0.469	0.168
9	1	3	46.9	54.6	45.7	54	8.3	7.7	-0.6	0.869	0.000
10	0	2b	32.1	49.8	32.2	46.2	14	17.7	3.7	0.695	0.080
11	2	2b	25.7	34.8	34.4	37.8	3.4	9.1	5.7	0.680	0.151
12			33.3	42.4	33.1	40	6.9	9.1	2.2	0.833	0.055
13	2	2a	36.2	43.7	46.6	46.3	-0.3	7.5	7.8	0.782	0.168
14	3	2a	33	43	38.1	44.3	6.2	10	3.8	0.745	0.086
15	3	2a	38.1	54	49.6	49	-0.6	15.9	16.5	0.778	0.337
16	2	2b	41.8	50.1	45.6	47.6	2	8.3	6.3	0.878	0.132
17	2	2b	49.9	57.4	53.4	54.7	1.3	7.5	6.2	0.912	0.113
18	2	1	34.7	46	48.6	50.4	1.8	11.3	9.5	0.688	0.188
19			40	52.8	42	42.9	0.9	12.8	11.9	0.932	0.277
20			57.3	65	64.4	61.2	-3.2	7.7	10.9	0.936	0.178
21	3	2a	43.8	64.1	58	57.3	-0.7	20.3	21	0.764	0.366
22			45.6	51.5	41.5	45.1	3.6	5.9	2.3	1.011	0.051
23			38.8	50.3	49.6	48	-1.6	11.5	13.1	0.808	0.273
24	1	2a	30.1	49.3	39.1	52.5	13.4	19.2	5.8	0.573	0.110
25	3	2a	48.9	63.2	50.6	51.2	0.6	14.3	13.7	0.955	0.268
26	3	2b	33.9	43.5	39.6	40.6	1	9.6	8.6	0.835	0.212
27	2	2a	46.6	63.4	48.8	58	9.2	16.8	7.6	0.803	0.131
28			27.4	42.4	45	57.2	12.2	15	2.8	0.479	0.049

(Continued)

Supplemental Table II. Continued

Number	ASITN/SIR Grade	mTICI	1.5s PLD CBF of Lesion Side (ml/100g/min)	2.5s PLD CBF of Lesion side (ml/100g/min)	1.5s PLD CBF of Normal Side (ml/100g/min)	2.5s PLD CBF of Normal side (ml/100g/min)	CBF 2.5s minus CBF 1.5s at normal side	CBF 2.5s minus CBF 1.5s at lesion side	Late-arriving retrograde perfusion (ml/100g/min)	Early-arriving perfusion proportion (%)	Late-arriving retrograde perfusion proportion (%)
29	2	2b	40.2	55.9	47.1	54.9	7.8	15.7	7.9	0.732	0.144
30			40.8	51.4	47.6	46.8	-0.8	10.6	11.4	0.872	0.244
31			33.9	49.3	48.2	52.8	4.6	15.4	10.8	0.642	0.205
32	3	2a	35.9	57.9	52.4	57.4	5	22	17	0.625	0.296
33	0	3	54.3	59	49.8	54.9	5.1	4.7	-0.4	0.989	0.000
34			44.5	54.5	46.3	54.6	8.3	10	1.7	0.815	0.031
35			41.2	51.6	45.9	49.5	3.6	10.4	6.8	0.832	0.137
36			28.5	39.9	36.9	43.6	6.7	11.4	4.7	0.654	0.108
37	2	2a	31.9	47.6	38.8	49.1	10.3	15.7	5.4	0.650	0.110
38			27.8	39.8	39.7	50.6	10.9	12	1.1	0.549	0.022
39	0	2b	47.5	53	44.6	48.1	3.5	5.5	2	0.988	0.042
40			63	73.4	66.7	65	-1.7	10.4	12.1	0.969	0.186
41	1	2a	28.1	38.5	32.1	41.3	9.2	10.4	1.2	0.680	0.029

ASITN/SIR, American Society of Interventional and Therapeutic Neuroradiology / Society of Interventional Radiology; mTICI, modified Thrombolysis in Cerebral Infarction; CBF, cerebral blood flow; PLD, post-labeling delay.

Arterial Spin Labeling Magnetic Resonance Imaging Estimation of Antegrade and Collateral Flow in Unilateral Middle Cerebral Artery Stenosis

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