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Monitoring Cerebral Perfusion Changes Using Arterial Spin-Labeling Perfusion MRI after Indirect Revascularization in Children with Moyamoya Disease

Seul Bi Lee[1], Seunghyun Lee[1, 2], Yeon Jin Cho[1, 2], Young Hun Choi[1, 2], Jung-Eun Cheon[1, 2, 3], Woo Sun Kim[1, 2, 3]

[1]Department of Radiology, Seoul National University Hospital, Seoul, Korea; [2]Department of Radiology, Seoul National University College of Medicine, Seoul, Korea; [3]Institute of Radiation Medicine, Seoul National University Medical Research Center, Seoul, Korea

Objective: To assess the role of arterial spin-labeling (ASL) perfusion MRI in identifying cerebral perfusion changes after indirect revascularization in children with moyamoya disease.

Materials and Methods: We included pre- and postoperative perfusion MRI data of 30 children with moyamoya disease (13 boys and 17 girls; mean age ± standard deviation, 6.3 ± 3.0 years) who underwent indirect revascularization between June 2016 and August 2017. Relative cerebral blood flow (rCBF) and qualitative perfusion scores for arterial transit time (ATT) effects were evaluated in the middle cerebral artery (MCA) territory on ASL perfusion MRI. The rCBF and relative time-to-peak (rTTP) values were also measured using dynamic susceptibility contrast (DSC) perfusion MRI. Each perfusion change on ASL and DSC perfusion MRI was analyzed using the paired *t* test. We analyzed the correlation between perfusion changes on ASL and DSC images using Spearman's correlation coefficient.

Results: The ASL rCBF values improved at both the ganglionic and supraganglionic levels of the MCA territory after surgery ($p = 0.040$ and $p = 0.003$, respectively). The ATT perfusion scores also improved at both levels ($p < 0.001$ and $p < 0.001$, respectively). The rCBF and rTTP values on DSC MRI showed significant improvement at both levels of the MCA territory of the operated side (all $p < 0.05$). There was no significant correlation between the improvements in rCBF values on the two perfusion images ($r = 0.195$, $p = 0.303$); however, there was a correlation between the change in perfusion scores on ASL and rTTP on DSC MRI ($r = 0.701$, $p < 0.001$).

Conclusion: Recognizing the effects of ATT on ASL perfusion MRI may help monitor cerebral perfusion changes and complement quantitative rCBF assessment using ASL perfusion MRI in patients with moyamoya disease after indirect revascularization.

Keywords: *Children; Arterial spin-labeling; Moyamoya disease; Magnetic resonance imaging*

INTRODUCTION

Moyamoya disease (MMD) is a cerebrovascular disease characterized by steno-occlusive changes in the distal portion of the internal carotid arteries [1]. Progressive characteristics can lead to brain injuries due to multiple stroke events, resulting in significant brain disability and worse prognosis when present at younger ages [1]. Therefore, revascularization surgery should be considered for restoring cerebral perfusion and preventing neurocognitive decline [2].

Arterial spin-labeling (ASL) perfusion magnetic resonance imaging (MRI) is magnetically labeled by the radiofrequency (RF) pulse protons of arterial blood flowing into the brain as an endogenous tracer [3]. Labeled arterial blood water acts as a diffusible tracer for quantitatively estimating cerebral

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Corresponding author: Seunghyun Lee, MD, Department of Radiology, Seoul National University College of Medicine, Seoul National University Hospital, 101 Daehak-ro, Jongno-gu, Seoul 03080, Korea.
• E-mail: seunghyun.lee.22@gmail.com

blood flow (CBF) in brain tissues without using gadolinium-based contrast agents [4]. ASL perfusion images can be generated by subtracting an image that labels arterial spin from one without such spin-labeling to suppress the signal from the static tissue [3-5]. The ASL technique has three main categories: continuous ASL (cASL), pulsed ASL (pASL), and pseudo-continuous ASL [5,6]. The cASL has a higher signal-to-noise ratio (SNR) than the pASL, but it cannot be used in clinical MRI scanners because it requires long and continuous RF transmission. In contrast with cASL, pASL has a labeling efficiency, as a short RF pulse with a thick slab is used to label arterial blood, but it allows a lower SNR than cASL. Pseudo-continuous ASL is a widely used ASL technique, and it divides the long continuous RF pulse into multiple short pulses, resulting in a high labeling efficiency in the clinical MRI scanner while maintaining a better SNR [5,6]. This pseudo-continuous ASL perfusion MRI can help predict clinical outcomes and evaluate surgical success in patients with MMD [4,7-10]. However, the arterial transit time (ATT) effect, which is the hyperintense focus of intravascular signals on ASL perfusion MRI, confounds CBF measurement and introduces an error into the estimate [11,12]. However, the ATT effect has essential information on delayed-arriving arterial flow via collateral vessels and may complement perfusion MRI even though it complicates quantitative CBF value calculation [13].

This study aimed to assess whether 1) ASL perfusion MRI can identify quantitative changes in CBF despite the presence of ATT effects, and 2) perfusion scores with ATT effects can help detect perfusion changes after indirect revascularization, compared with dynamic susceptibility contrast (DSC) perfusion MRI. Therefore, this study sought to assess the role of ASL perfusion MRI in identifying cerebral perfusion changes after indirect revascularization in children with MMD.

MATERIALS AND METHODS

The Institutional Review Board approved this study. The requirement for obtaining informed consent was waived because of its retrospective nature (IRB No. 2007-033-1139).

Patient Selection

We retrospectively reviewed 34 patients with MMD who underwent indirect revascularization surgery using encephaloduroarteriosynangiosis (EDAS) at our institution between June 2016 and August 2017. The inclusion criteria were as follows: 1) perfusion MRI with ASL and DSC technique at baseline and postoperative follow-up, 2) age of < 18 years at the time of diagnosis, and 3) no history of revascularization surgery. Four patients were excluded because of inadequate image quality of ASL and DSC perfusion (two labeling errors and two severe motions). Thirty patients were included in the study. Six patients in this study also participated in the previous report by Ha et al. [9]; however, the quantitative data for DSC perfusion MRI and the qualitative change in the ATT effect for ASL perfusion MRI were not analyzed in the previous study. The patient characteristics are summarized in Table 1. Age, sex, family history, and clinical symptoms of transient ischemic attacks, headache, and others were collected. Clinical status, including bilateral involvement of MMD and the presence of an old infarction, was also collected. The preoperative angiographic severity was assessed using the Suzuki staging system [14].

Image Acquisition

The standard imaging protocol for MMD patients at our institution was defined as follows: 1) baseline ASL and DSC perfusion imaging within 1 month before the first surgery for MMD diagnosis and 2) postoperative ASL and DSC perfusion imaging within 1 month before the second surgery on the opposite side. If there was no contralateral involvement of MMD, only perfusion imaging was performed after 6 months. Patients under seven years of age underwent MRI scans

Table 1. Patient Characteristics

Characteristics	Value
Age, year, mean ± SD	6.3 ± 3.0 (range, 2–13)
Sex, boys	13 (43.3)
Family history, present	3 (10.0)
Clinical symptoms	
Transient ischemic attack	19 (63.3)
Headache	4 (13.3)
Others	7 (23.3)
Bilateral involvements	30 (100.0)
Presence of old infarction	5 (16.7)
Preoperative Suzuki staging	
1	1 (3.3)
2	11 (36.7)
3	10 (33.3)
4	3 (10.0)
5	5 (16.7)

Data are number of patients with the percentage in parentheses unless specified otherwise. SD = standard deviation under mild to moderate sedation using sedative drugs.

ASL perfusion MRI was performed using 1.5T MR scanners (Avanto, Siemens Healthineers) with a 12-channel head coil. Raw data acquisition of ASL perfusion MRI was performed before subtraction using the following parameters: repetition time/echo time (TR/TE), 4290.0/22.0 ms; section thickness, 10 mm; a generalized autocalibrating partially parallel acquisition acceleration factor, 2; number of sections, 30; readout, eight arms x 512 samples; field of view, 25 x 25 cm; matrix, 96 x 96. Pseudo-continuous spin-labeling with two-dimensional single-shot-gradient-echo echo-planar imaging readout was performed for 1.8 seconds before a post-spin-labeling delay of 1.5 seconds. The total scan duration for ASL perfusion MRI was 4.5 minutes.

DSC perfusion MRI was performed using a single-shot gradient-echo echo-planar imaging sequence during intravenous injection of the gadolinium-based contrast agent with the following parameters: TR/TE, 1500/30 ms; flip angle, 60°; field of view, 24 x 24 cm; 17 sections; matrix, 128 x 128; thickness, 5 mm; intersection gap, 1.5 mm. For each section, 50 images were obtained at intervals equal to the TR. Gadobutrol at a dose of 0.1 mmoL/kg and rate of 2 mL/s was injected with an MR-compatible power injector (Spectris, Medrad) four or five times. The total scan duration for DSC perfusion MRI was 2 minutes.

ASL Perfusion Image Analysis

On a picture archiving and communication system workstation (Infinitt; Infinitt Healthcare), regions of interest (ROIs) were drawn manually, covering the middle cerebral artery (MCA) territories of the operative side by a pediatric radiologist according to previous studies [4,15,16]. ROIs were drawn at the six locations for the Alberta Stroke Program Early CT score (ASPECTS), and a segmental assessment of the MCA vascular territory over the standard ganglionic and supraganglionic levels was performed (Fig. 1). CBF calculations for ASL images have been described previously [9]. All CBF map values were measured in absolute units (mL/100 g/min). The average CBF values at each level were derived based on the CBF values at the ganglionic and supraganglionic levels. To adjust for interindividual variation, additional ROIs were drawn within the cerebellum for CBF normalization. Subsequently, relative CBF (rCBF) values were calculated using the following equation: rCBF on ganglionic level = $CBF_{ganglionic}/CBF_{cerebellum}$; rCBF on supraganglionic level = $CBF_{supraganglionic}/CBF_{cerebellum}$.

Two pediatric radiologists reviewed the ASL images for ATT at the ganglionic and supraganglionic levels of the MCA territory, which were the same levels used in the quantitative analysis. Qualitative perfusion scoring on ASL utilizes a 4-point scale: 0, complete absence of parenchymal perfusion; 1, incomplete parenchymal perfusion (i.e., partially absent or conspicuously decreased perfusion with ATT effect); 2, delayed-but-complete parenchymal perfusion (i.e., ASL demonstrates complete parenchymal perfusion, but shows an ATT effect); 3, complete/normal perfusion (i.e., ASL shows approximately homogeneous parenchymal perfusion, without obvious ATT effect) [11,13,17,18]. These perfusion scores were recorded at six ASPECTS areas at the same location where the ROI was drawn for quantitative analysis. The average perfusion scores for the ganglionic and supraganglionic levels were used as the ASL perfusion scores.

DSC Perfusion Image Analysis

DSC perfusion images with CBF and time-to-peak (TTP) maps were generated using a commercially available

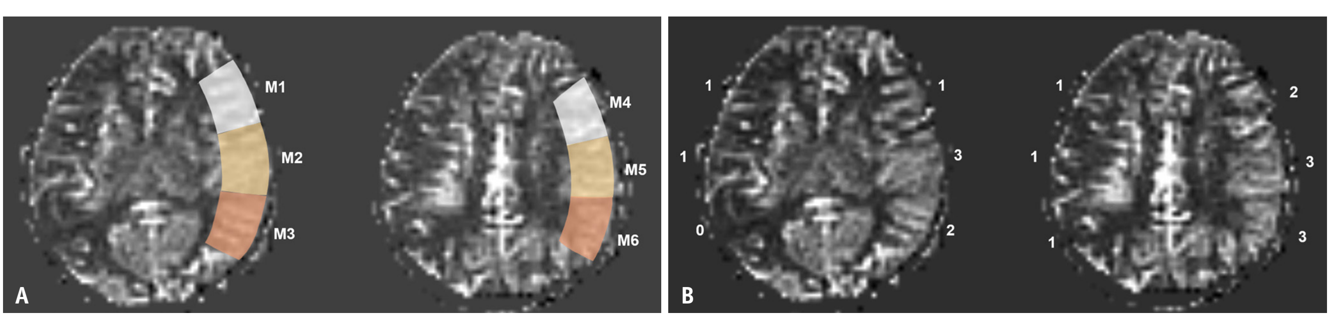

Fig. 1. Example of region of interest placement for ASL imaging assessment.
A. The region of interest manually drawn to cover the cortex of the operated side of the middle cerebral artery territories for each of the ganglionic and supraganglionic levels on ASL perfusion MRI and dynamic susceptibility contrast perfusion MRI. **B.** The qualitative perfusion scoring for ASL utilizes a 4-point scale: 0, complete absence of parenchymal perfusion; 1, incomplete parenchymal perfusion (i.e., partially absent or conspicuously decreased perfusion with ATT effect); 2, delayed-but-complete parenchymal perfusion (i.e., ASL demonstrates complete parenchymal perfusion, but shows ATT effect); 3, complete/normal perfusion (i.e., ASL shows approximately homogeneous parenchymal perfusion, without obvious ATT effect). ASL = arterial spin-labeling, ATT = arterial transit time

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software package (Olea Sphere, Olea Medical) [19,20]. All CBF and TTP values were measured on each DSC perfusion map for the ganglionic and supraganglionic levels of the MCA territory and cerebellum using the same method utilized for the ASL CBF measurement by a pediatric radiologist. The rCBF values for the DSC images were calculated using the same CBF normalization method used for the ASL image. The relative TTP (rTTP) value was calculated using the following equation according to a previously reported method: rTTP = $TTP_{measured\ level}$ - $TTP_{cerebellum}$ [21].

Statistical Analysis

Clinical characteristics and preoperative radiologic status were analyzed using descriptive statistics. The quantitative and qualitative perfusion changes on ASL perfusion MRI for the operated side were pre- and postoperatively assessed using a paired *t* test. Quantitative changes in DSC perfusion parameters were pre- and postoperatively assessed using a paired *t* test.

The changes in rCBF and rTTP values on DSC perfusion MRI were used as reference standards for postoperative perfusion changes after indirect revascularization [21,22]. We analyzed the correlation between the rCBF changes on the ASL and DSC images and the correlation between the ATT effect changes on ASL images and the rTTP changes on DSC images using Spearman's correlation test.

Interobserver agreement of the reviewers was expressed as the κ value for qualitative perfusion scoring on ASL perfusion MRI. The κ value was interpreted as follows: < 0, negative agreement; 0–0.20, positive but poor agreement; 0.21–0.40, fair agreement; 0.41–0.60, moderate agreement; 0.61–0.80, good agreement; > 0.81, excellent agreement.

All statistical analyses were performed using MedCalc software (version 12.1.0; MedCalc Software). Statistical significance was considered when the *p* value was < 0.05.

RESULTS

Patient Characteristics

This study enrolled 13 boys and 17 girls (mean age, 6.3 years [range, 2–13 years]). All patients underwent unilateral EDAS, and only one patient underwent a combination of EDAS and bifrontal encephalogaleoperiosteal synangiosis. Baseline and postoperative perfusion MRI were performed 3.5 ± 3.6 (mean ± standard deviation [SD]) days before surgery and 73.8 ± 56.7 days after surgery.

All patients had bilateral MMD, three (10%) had a family history of MMD, and none of the patients had moyamoya syndrome with associated diseases. Transient ischemic attack was the most common initial clinical symptom (63.3%), followed by a headache. Four children had an old infarction injury at the watershed zone, and one patient had a territorial cortical infarction on MRI preoperatively. None of the patients had a newly noted postoperative infarction. Preoperative angiographic findings with two or three grades of the Suzuki stage were common findings in our patients.

Perfusion Changes on ASL Perfusion MRI

The results of the quantitative and qualitative analyses of ASL perfusion MRI are summarized in Table 2. Postoperatively, the rCBF values improved at both the ganglionic and supraganglionic levels of the MCA territory on the operated side (mean ± SD of 1.04 ± 0.28 vs. 1.19 ± 0.44 and 0.92 ± 0.35 vs. 1.23 ± 0.51; *p* = 0.040 and *p* = 0.003). The qualitative perfusion scores for parenchymal perfusion and ATT also improved at both the ganglionic and supraganglionic levels (mean ± SD of 1.74 ± 0.74 vs. 2.54 ± 0.39 and 1.33 ± 0.63 vs. 2.12 ± 0.53; *p* < 0.001 and *p* < 0.001). The interobserver agreement for qualitative perfusion scoring for the two reviewers showed good agreement (κ = 0.797).

Perfusion Changes on DSC Perfusion MRI

The results of the quantitative analysis of the perfusion values on DSC perfusion MRI are summarized in Table 3.

Table 2. Perfusion Changes on ASL Perfusion MRI after Indirect Revascularization

Parameter	Preoperative	Postoperative	P
Relative CBF*			
Ganglionic level	1.04 ± 0.28	1.19 ± 0.44	0.040
Supraganglionic level	0.92 ± 0.35	1.23 ± 0.51	0.003
ASL perfusion scoring†			
Ganglionic level	1.74 ± 0.74	2.54 ± 0.39	< 0.001
Supraganglionic level	1.33 ± 0.63	2.12 ± 0.53	< 0.001

Values are presented as mean ± standard deviation. *Relative CBF values were calculated as follows: $CBF_{measured\ level}/CBF_{cerebellum}$, †The scoring of ASL perfusion was defined as follows: 0, complete absence of parenchymal perfusion; 1, incomplete parenchymal perfusion (i.e., partially absent or conspicuously decreased perfusion with ATT effect); 2, delayed-but-complete parenchymal perfusion (i.e., ASL demonstrates complete parenchymal perfusion, but shows ATT effect); and 3, complete/normal perfusion (i.e., ASL shows approximately homogeneous parenchymal perfusion, without obvious ATT effect). ASL = arterial spin-labeling, ATT = arterial transit time, CBF = cerebral blood flow

DSC perfusion MRI showed a significant increase in rCBF values (ganglionic; mean ± SD of 1.04 ± 0.20 vs. 1.18 ± 0.26, supraganglionic; mean ± SD of 0.95 ± 0.20 vs. 1.07 ± 0.22; both p = 0.001). The rTTP values showed a significant decrease at the ganglionic and supraganglionic levels of the MCA territory on the operated side (mean ± SD of 2.48 ± 1.52 vs. 1.54 ± 0.86 and 3.00 ± 1.82 vs. 1.73 ± 1.09; p < 0.001 and p < 0.001).

Correlation between the Change Degrees in ASL and DSC Perfusion Parameters

When evaluating the correlation between the degrees of improvement in ASL and DSC parameters, no significant correlation between the changes in rCBF values for ASL and DSC perfusion MRI was found (r = 0.195, p = 0.303). However, there was a significant correlation between the changes in perfusion scores for ASL and rTTP on DSC perfusion MRI (r = 0.701, p < 0.001). The correlation plots are shown in Figure 2. Representative good and poor postoperative cases are presented in Figures 3 and 4, respectively.

Table 3. Perfusion Changes on Dynamic Susceptibility Contrast Perfusion MRI after Indirect Revascularization

Parameters	Preoperative	Postoperative	P
Relative CBF*			
Ganglionic level	1.04 ± 0.20	1.18 ± 0.26	0.001
Supraganglionic level	0.95 ± 0.20	1.07 ± 0.22	0.001
Relative TTP†			
Ganglionic level	2.48 ± 1.52	1.54 ± 0.86	< 0.001
Supraganglionic level	3.00 ± 1.82	1.73 ± 1.09	< 0.001

Values are presented as mean ± standard deviation. *Relative CBF values were calculated as follows: $CBF_{measured\ level}/CBF_{cerebellum}$, †Relative TTP value was calculated as follows: $TTP_{measured\ level} - TTP_{cerebellum}$. CBF = cerebral blood flow, TTP = time-to-peak

DISCUSSION

Our study assessed whether ASL perfusion MRI can be used to monitor perfusion after indirect revascularization surgery in pediatric patients with MMD. ASL perfusion MRI showed an increase in quantitative rCBF values and improved qualitative perfusion scores for the MCA territory on the operated side after indirect revascularization. Compared with the DSC perfusion parameters, there was a significant correlation between the degree of change in the qualitative perfusion scores using the ATT effect and the rTTP improvement on DSC perfusion MRI.

MMD is a progressive steno-occlusive change in the intracranial vessels, and bypass surgery is currently

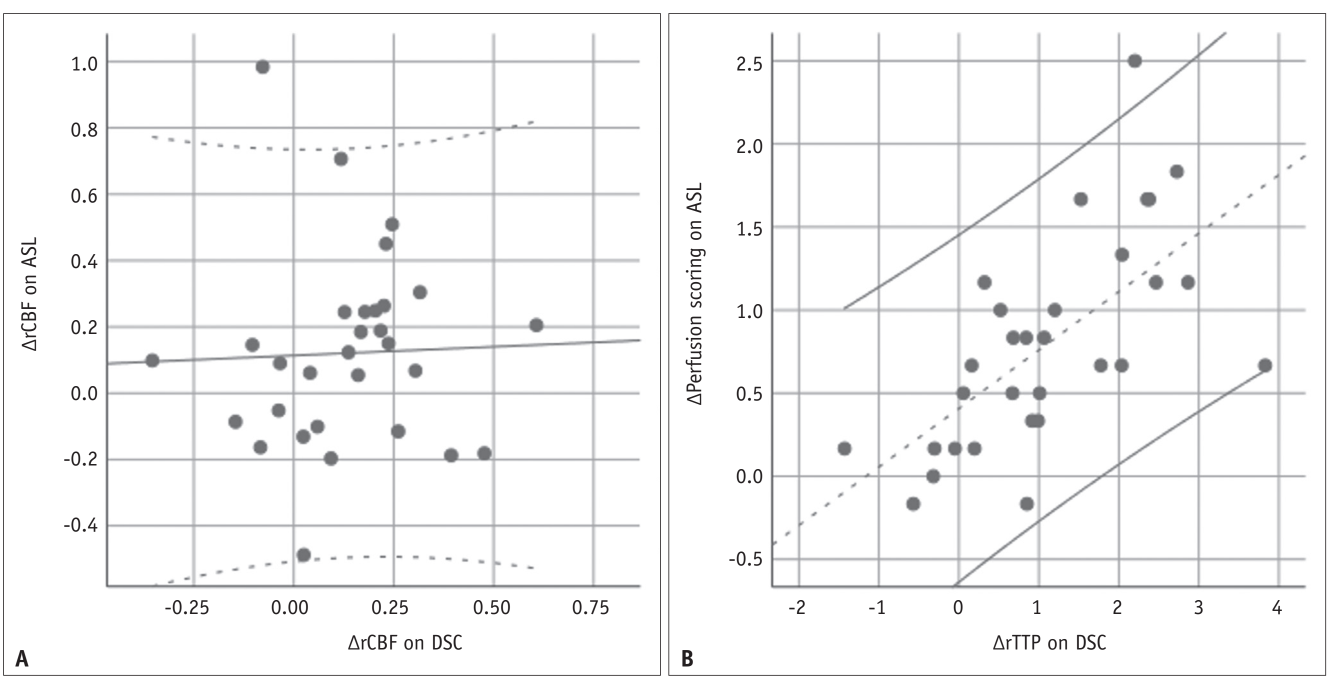

Fig. 2. Correlation plots for the change degrees after surgery for the ASL and DSC perfusion parameters.
A. There was no significant correlation between the mean improvement in rCBF assessed with DSC MRI and the mean improvement in rCBF assessed by ASL MRI (r = 0.195, p = 0.303). **B.** There was a significant correlation between the mean improvement in rTTP values on DSC MRI and the mean improvement in the arterial transit time perfusion score on ASL perfusion MRI (r = 0.701, p < 0.001). ASL = arterial spin-labeling, DSC = dynamic susceptibility contrast, rCBF = relative cerebral blood flow, rTTP = relative time-to-peak

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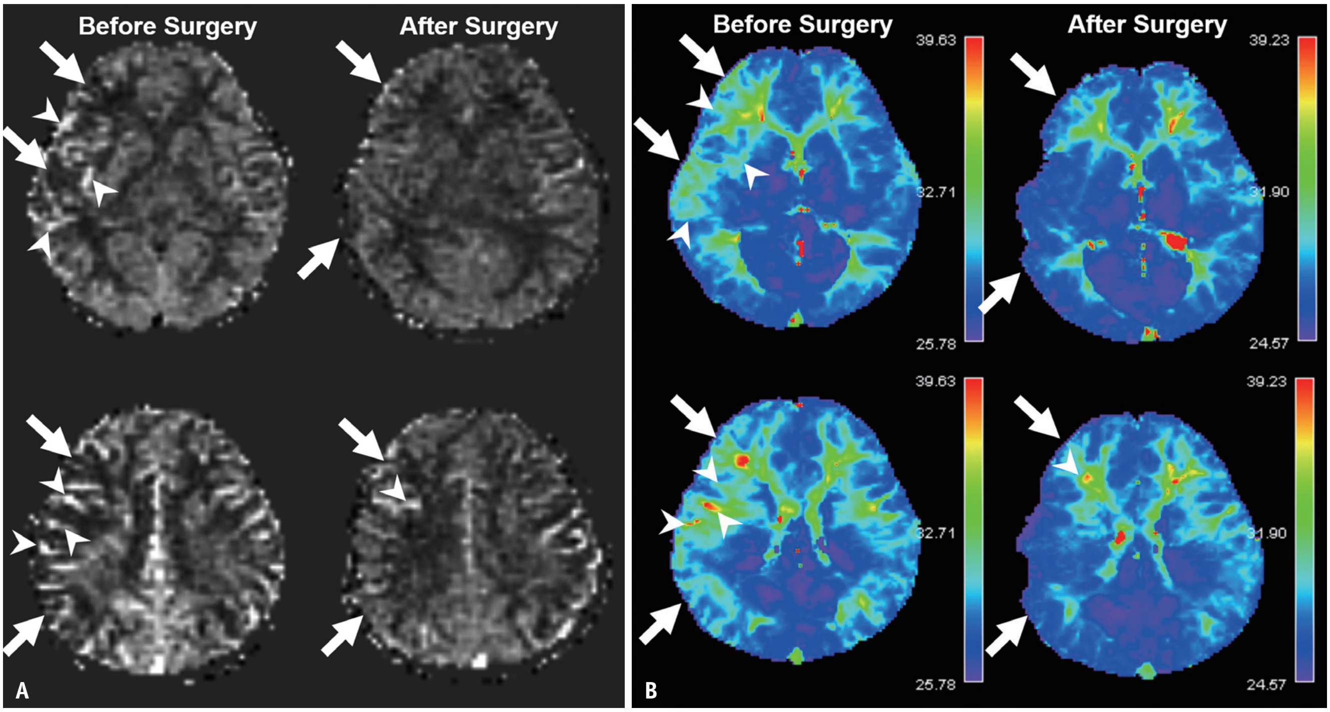

Fig. 3. Good postoperative case. A 6-year-old girl underwent right encephaloduroarteriosynangiosis with good postoperative outcomes. **A.** Preoperative ASL perfusion image showing ATT effects (arrowheads) and no parenchymal signal areas (arrows) at the ganglionic and supraganglionic levels of the right MCA territory. Postoperative ASL images show decreased ATT effects (arrowhead) and improved parenchymal signal intensity (arrows) at the same level in the right MCA territory. **B.** Preoperative TTP maps of dynamic susceptibility contrast perfusion MRI showing a delayed TTP area in the right MCA territory (arrows) with several foci having delayed transit times (arrowheads) corresponding to the ATT areas on ASL images. Postoperative TTP maps show an improved TTP area in the operative MCA territory. Only a subtle delayed TTP area remained at the supraganglionic level with a delayed transit time (arrowheads) corresponding to the ATT area on the ASL image. ASL = arterial spin-labeling, ATT = arterial transit time, MCA = middle cerebral artery, TTP = time-to-peak

regarded as its effective treatment [23]. EDAS is an indirect revascularization method in which the parietal branch of the superficial temporal artery, together with the surrounding connective tissue, is separated and sutured into the MCA territory [1]. Therefore, indirect revascularization involves grafted cortical blood vessel growth in ischemic vulnerable brain tissue from the cortical brain surface [1,23]. The effect of indirect revascularization is based on the extent of postsurgical neo-angiogenesis; thus, overall hemodynamic change monitoring is important [24].

For assessing cerebral hemodynamic changes, positron emission tomography (PET) and single-photon emission computed tomography (SPECT) have been useful for quantifying CBF and cerebrovascular reserve alterations. However, there are intrinsic disadvantages of serial examinations, radiation concerns, and poor spatial resolution [25,26]. For the MRI techniques, postoperative hemodynamic changes on DSC perfusion MRI may be well-correlated with clinical outcomes after revascularization surgery in children with MMD [12,21,22]. Yun et al. [21] reported that the rTTP value of DSC perfusion parameters is a useful marker for postoperative hemodynamic monitoring and clinical outcomes in pediatric patients with MMD. Lee et al. [22] also showed that the TTP perfusion map reflects the ischemic status of patients with MMD and the degree of ischemia reduction after revascularization surgery. As reported in previous studies, our study also showed that rCBF and rTTP values on DSC perfusion MRI improved after indirect revascularization surgery.

However, DSC perfusion MRI is technically more challenging in children because it requires a gadolinium contrast agent with high-flow bolus injection, despite the advantage of providing several quantified perfusion parameters [27]. Another critical limitation of DSC perfusion MRI is that confounding due to the presence of collateral vessels with the effects of arterial arrival delay may lead to rCBF underestimation and rTTP overestimation [4,28]. This drawback caused by delayed-arriving collateral flow can also occur during ASL perfusion MRI. However, ASL perfusion MRI may leverage this disadvantage to facilitate interpretations for collateral vessels; it also does not require the use of a gadolinium-based contrast agent, which is an

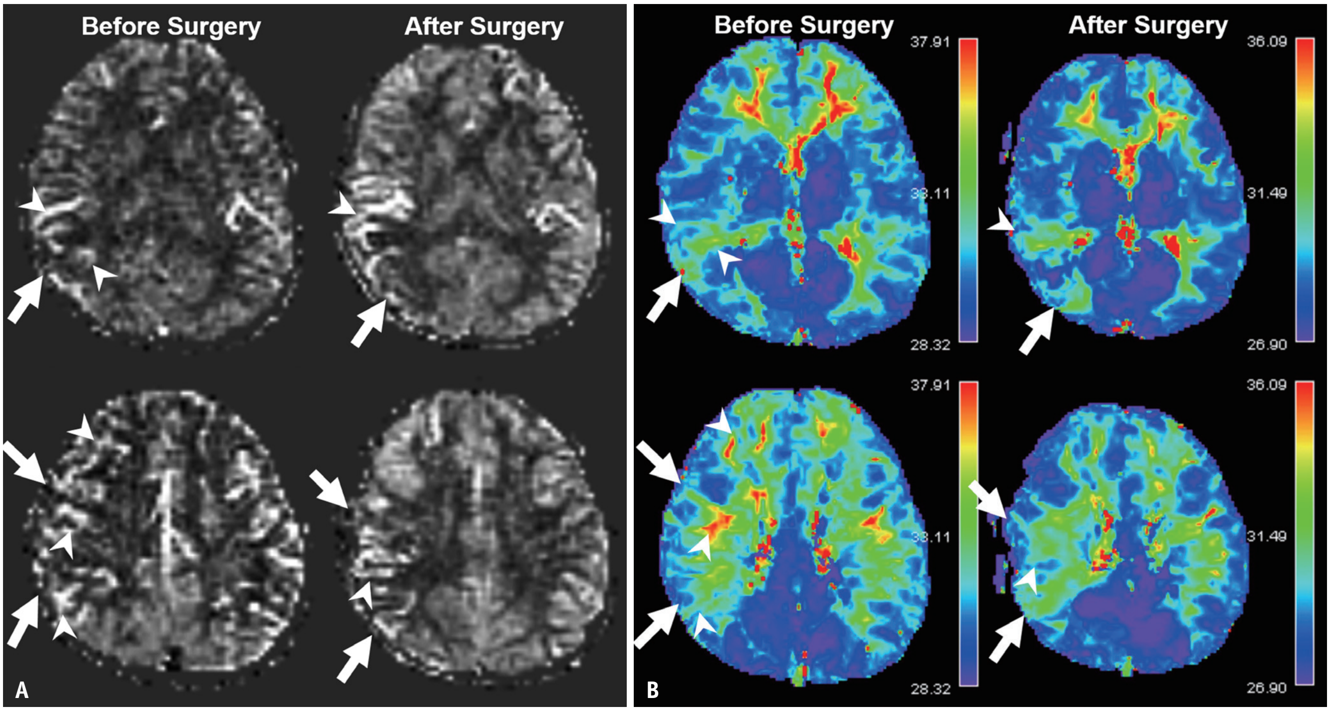

Fig. 4. Poor postoperative case. A 7-year-old boy underwent right encephaloduroarteriosynangiosis with poor postoperative outcomes. **A.** Preoperative ASL perfusion image showing ATT effects (arrowheads) and no parenchymal signal areas (arrows) at the ganglionic and supraganglionic levels of the right MCA territory. Postoperative ASL images show impaired perfusion (arrows) and ATT effects (arrowheads) in the right MCA territory, indicating flow stagnation in the cephaloduroarteriosynangiosis area. **B.** Preoperative TTP maps of dynamic susceptibility contrast perfusion MRI showing delayed TTP area in the right MCA territory (arrows) with profound delayed transit time (arrowheads) corresponding to those of the ATT areas on ASL images. Postoperative TTP maps show delayed TTP areas (arrows) in the operative MCA territory. Multiple delayed TTP areas (arrows) remained at the supraganglionic level with a delayed transit time (arrowheads) corresponding to the ATT area on the ASL image. ASL = arterial spin-labeling, ATT = arterial transit time, MCA = middle cerebral artery, TTP = time-to-peak

advantage [4,8,13]. ASL perfusion MRI has a characteristic feature: the ATT effect refers to labeled blood, which fails to reach the capillary bed and remains inside the artery, appearing as a strong bright signal intensity, which indicates collateral vascular flow [13]. Therefore, careful use of ASL images facilitates the assessment of postoperative hemodynamic status, in which collateral vessels possibly exist and are reduced in patients with MMD [4,29].

The ATT effect has two conflicting characteristics regarding CBF estimation: derived CBF may be underestimated due to a very long ATT when no labeled blood has reached the imaging volume or overestimated because the bright intravascular signal blood has slowly come to the precapillary arterioles [11,12,30]. However, Fahlström et al. reported that the ATT effects used for CBF calculations may have negligible overestimated effects when assessed using a vascular region-based CBF on a single delayed pseudo-continuous ASL perfusion MRI [11]. Our study showed that rCBF on ASL slightly improved after indirect revascularization surgery, but the difference in rCBF between the pre- and postoperative stages was low, and the standard variation was higher postoperatively. This phenomenon should be considered as the combined effect of high (due to the ATT effect) and low (due to the apparent perfusion deficit) CBF voxels [17].

In our study, there was no significant correlation between rCBF on ASL and the degree of improvement of rCBF on DSC perfusion MRI, although the rCBF values on ASL significantly increased in the MCA territory after revascularization surgery. The lack of correlation with DSC perfusion parameters may be related to CBF measurements based on ASL perfusion MRI and the ATT effects of the single-delay pseudo-continuous technique. However, regarding qualitative perfusion changes, we hypothesized that there was a decrease in collateral vessels at the operated side of the MCA territory after revascularization surgery, which may have improved the perfusion scores with ATT decrease. Recently, Ukai et al. [18] reported that severe ATT effects on ASL perfusion MRI may suggest a decrease in cerebrovascular reserve and a severe MMD stage. Our study showed an ATT effect reduction on ASL due to improved MCA territory perfusion through the newly grafted

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EDAS flow and decreased delayed-arriving flow through the collateral vessels.

The qualitative ASL perfusion score was correlated with an improvement in rTTP on DSC perfusion MRI. Lee et al. reported the excellent diagnostic performance of the ATT effect in adult patients with MMD in evaluating collateral grading and anastomosis patency after direct revascularization [8]. However, there are few studies on the changes in ATT effects related to the DSC perfusion parameters before and after surgery in pediatric patients with MMD. Therefore, this study suggests the potential application of single-delay pseudo-continuous ASL perfusion MRI to postoperative perfusion status monitoring in pediatric patients with MMD. Additionally, single-delay pseudo-continuous ASL perfusion MRI is more advantageous than the multi-delay ASL technique in terms of SNR and scan time [31].

This study has some limitations. First, we only evaluated the perfusion status for the ganglionic and supraganglionic levels of the MCA territory. Perfusion changes in the basal collateral vessels in the basal ganglia region should also be evaluated in patients with MMD. However, we emphasized perfusion changes before and after the EDAS area using perfusion MRI data, even though the EDAS area did not exactly match these MCA territories. Potential bias may have been introduced in the ROIs by only including the ganglionic and supraganglionic levels of the MCA territories. Second, only a few patients with MMD were studied. However, our study included only a homogenous population of pediatric patients undergoing indirect revascularization, mostly EDAS, showing changes in perfusion between the pre- and postoperative stages. Third, we could not compare the data of ASL perfusion MRI and standard methods, including PET, SPECT, or perfusion CT, to validate the quantitative CBF results, because these examinations were not performed in our hospital. Since SPECT or PET was not used as a reference standard in this study, the interpretation of these quantitative results may have some limitations for both ASL and DSC perfusion MRI. However, rTTP on DSC has been used as a reference standard for postoperative perfusion improvement in previous studies [4,21,22]. Therefore, we compared the perfusion changes on ASL images with the rTTP value for DSC perfusion MRI after indirect revascularization. Finally, our study was conducted using an MR imager with a magnetic field strength of 1.5. Theoretically, 3T can offer an advantage over 1.5T related to the SNR. However, 1.5T is preferred over 3T for postoperative follow-up studies, and it has fewer susceptible artifacts. In previous studies, there was a slight difference between the normalized CBF measurements coordinated in the cerebellum between the 1.5T and 3T imagers [8].

In conclusion, recognizing the effects of ATT on ASL perfusion MRI may help monitor cerebral perfusion changes and complement quantitative CBF assessment in MMD patients after indirect revascularization.

Conflicts of Interest

The authors have no potential conflicts of interest to disclose.

Acknowledgments

Six patients in this study overlapped with a previous report (Ha JY et al. Korean J Radiol 2019;20:985-996) [9].

Author Contributions

Conceptualization: Seul Bi Lee, Seunghyun Lee. Data curation: Seul Bi Lee, Seunghyun Lee, Yeon Jin Cho, Young Hun Choi. Formal analysis: Seul Bi Lee, Seunghyun Lee. Funding acquisition: Seunghyun Lee. Investigation: Seul Bi Lee, Seunghyun Lee, Yeon Jin Cho, Young Hun Choi. Methodology: all authors. Project administration: Seunghyun Lee. Resources: all authors. Software: Seul Bi Lee, Seunghyun Lee. Supervision: Seunghyun Lee. Validation: all authors. Visualization: Seul Bi Lee, Seunghyun Lee. Writing—original draft: all authors. Writing—review & editing: all authors.

ORCID iDs

Seul Bi Lee
https://orcid.org/0000-0002-5163-3911
Seunghyun Lee
https://orcid.org/0000-0003-1858-0640
Yeon Jin Cho
https://orcid.org/0000-0001-9820-3030
Young Hun Choi
https://orcid.org/0000-0002-1842-9062
Jung-Eun Cheon
https://orcid.org/0000-0003-1479-2064
Woo Sun Kim
https://orcid.org/0000-0003-2184-1311

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