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Original Article

Clinical assessment of cerebral hemodynamics in Moyamoya disease via multiple inversion time arterial spin labeling and dynamic susceptibility contrast-magnetic resonance imaging: A comparative study

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Background and purpose. – For Moyamoya disease (MMD) patients, accurate hemodynamic assessment is critical for treatment selection and efficacy assessment. This study aims to investigate the clinical value of mTI-ASL in assessing the cerebral hemodynamics of MMD patients before and after revascularization, relative to DSC-MRI.

Materials and methods. – Forty-one MMD patients underwent mTI-ASL and DSC-MRI during blood perfusion. Quantitative parameters for the bilateral supply vessels of middle and anterior cerebral arteries, including DSC-TTP, DSC-CBF, ASL-BAT, and ASL-CBF were measured. The correlations between DSC-ΔTTP ($TTP_{hemisphere} - TTP_{brainstem}$) and ASL-ΔBAT ($BAT_{hemisphere} - BAT_{brainstem}$) and between DSC-CBF and ASL-CBF were determined. The consistency between the two techniques in assessing the cerebral ischemic state before and after revascularization was analyzed.

Results. – DSC-ΔTTP and ASL-ΔBAT ($r = 0.36$, $P < 0.001$) and DSC-CBF and ASL-CBF ($r = 0.32$, $P < 0.001$) exhibited significant correlation on 824 regions of interest (ROIs) and similar numbers of ischemic areas on 902 ROIs ($\kappa = 0.82$, $P < 0.001$). The ischemic scores were 3.17 ± 3.02 and 2.98 ± 2.81 by DSC-MRI and ASL-MRI, respectively (ICC = 0.92). For 15 surgically treated patients, the scores for blood perfusion improvement on the operated side were 3.13 ± 1.68 and 3.27 ± 1.33 with DSC-TTP and ASL-BAT, respectively (ICC = 0.94).

Conclusion. – Compared to DSC-MRI, mTI-ASL can assess the cerebral hemodynamics in MMD and evaluate ischemic state before revascularization and ischemia reduction after revascularization effectively. And mTI-ASL is more advantageous because it does not require contrast agents.

Abbreviations: ASL, arterial spin labeling; mTI-ASL, multiple inversion time-pulsed ASL; MMD, Moyamoya disease; DSC-MRI, dynamic susceptibility contrast-magnetic resonance imaging; TTP, time to peak; CBF, cerebral blood flow; BAT, bolus arrival time; ICC, intraclass correlation coefficient; ICA, internal carotid artery; MCA, middle cerebral artery; ACA, anterior cerebral artery; PET, positron-emission tomography; SPECT, single-photon emission computed tomography; CTP, computed-tomography perfusion; sTI-ASL, single inversion time ASL; ATT, arterial transit time; PLD, post-labeling delay; RCCs, response characteristic curves; DSA, digital subtraction angiography; EDAS, encephaloduroarteriosynangiosis; AIF, arterial input function; T1WI, T1-weighted image; T2WI, T2-weighted image; FLAIR, fluid attenuation inversion recovery; 3D-TOF MRA, 3D-time of flight MR angiography; ROI, region of interest; ASPECTS, Alberta Stroke Programme Early CT Score.

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Introduction

Moyamoya disease (MMD) is a chronic cerebrovascular disease and is characterized by gradual intimal thickening and progressive luminal narrowing (or occlusion) at the junction of bilateral ICA and the common origin of MCA and ACA. It is associated with a compensatory expansion and stenosis of perforating arteries in the Circle of Willis [1]. The cerebral hemodynamics in MMD patients is complex and dynamic because of the combined effects of two phenomena:

- decrease in CBF caused by intimal thickening and luminal narrowing of intracranial arteries;
- increase in CBF velocity because of compensatory collateral circulation [2].

Thus, accurate hemodynamic assessment is critical for treatment selection and efficacy assessment in MMD [2].

Clinical assessment of cerebral hemodynamic state is primarily performed using two diagnostic tools, namely, nuclear medicine imaging, which includes PET and SPECT, and first-pass contrast-enhanced imaging, which includes CTP and perfusion-weighted MRI. Of these techniques, PET is considered the most suitable for monitoring cerebral hemodynamic changes. However, its high costs limit the frequent use of PET for routine examination. Alternatively, CTP enables the quantitative assessment of multiple parameters associated with cerebral hemodynamic changes. However, CTP is also unsuitable for frequent clinical use because it requires administration of large doses of radiation and the injection of a contrast agent, which may cause allergic reactions or renal impairment. DSC-MRI is an MRI technique that can assess multiple hemodynamic parameters. Because it involves the use of non-ionizing radiation, DSC-MRI is most commonly used to assess cerebral perfusion. The main disadvantages of DSC-MRI are non-quantity and requirement of a contrast agent.

ASL is an emerging technology that does not require the use of a contrast agent to determine the changes in hemodynamic parameters, such as CBF. Several studies have employed ASL to assess CBF changes in MMD patients [3]. However, most of these studies adopted sTI-ASL, which has the disadvantage of measuring only one parameter in ischemia studies. Specifically, only one semi-quantitative parameter (i.e., CBF), other than time-dependent hemodynamic parameters, can be acquired by sTI-ASL. Moreover, CBF changes are often underestimated because of the delay in blood flow during ischemia [4]. mTI-ASL is an advanced ASL technique that can simultaneously measure multiple parameters, such as CBF and time-dependent parameters, namely, BAT or ATT. Wang et al. adopted a 4 PLD ASL protocol that could simultaneously measure CBF and ATT in MMD patients and show good agreement with CTP [5]. However, 4–6 PLDs are insufficient to reflect complex hemodynamic changes associated with MMD. In the present study, we employed mTI-ASL in the parallel acquisition mode [6] to reduce the acquisition time of single TI and allowing ASL data acquisition at 16 different TIs within 5 min. Thereafter, we obtained accurate BAT and CBF values by fitting the RCCs for hemodynamic changes in each patient. The results of mTI-ASL were compared with DSC-MRI data before and after revascularization in order to assess the clinical value of mTI-ASL in MMD.

Materials and methods

Patients

Forty-one patients (24 men and 17 women) diagnosed with MMD via DSA from May 2014 to December 2015 were recruited in the study. The mean age of patients was 35.7 years (range: 7–59 years). Vascular involvement was unilateral in eight patients and bilateral in 33 patients. All patients underwent MRI examination before operation. Fifteen patients of them underwent EDAS on one side and followed by MRI examination 3–4 months after revascularization. All patients or their guardians provided written informed consent before the MRI examination. The ethics committee of Affiliated Hospital of Academy of Military Medical Sciences approved the study.

MRI examination

The MRI examination was performed using a MAGNETOM Skyra 3T MRI scanner (Siemens, Germany) with a 20-channel head coil. The scanning sequences included DSC-MRI, ASL-MRI, and other conventional MRI sequences.

DSC-MRI

Axial brain images were acquired with an echo-planar imaging sequence using the following specifications: TR: 1870 ms; TE: 30 ms; FOV: 220 mm; matrix: 128×128; slice thickness: 4 mm; interslice spacing: 1.2 mm; number of slices: 24; and number of acquisitions: 60. A gadolinium contrast agent (Magnevist, Bayer HealthCare Pharmaceuticals Inc., Wayne, NJ, USA) was intravenously administered using a high-pressure syringe at the sixth acquisition (0.2 mL/kg, 4∼5 mL/s).

The DSC-MRI images acquired were processed into the post-processing workstation (Syngo Via 20, Simens) and analyzed using the MR Neuro-Perfusion software. Maps for various hemodynamic parameters, namely, relative CBV, relative CBF, relative MTT, and TTP, were generated using the local AIF model.

ASL-MRI

The mTI-ASL images were acquired with a prototype sequence using the following specifications: 3D GRASE imaging with FAIR Q2TIPS labeling; TR: 4600 ms; TE: 22 ms; number of slices: 20; slice thickness: 4 mm; GRAPPA: 2; FOV: 192 mm; matrix: 64; bolus duration: 700 ms; 16 TIs range: 480–4080 ms, 1 average per TI; and total acquisition time: 5 min including the time required for an M0 scan (Fig. 1). The Buxton model with a non-linear fit for CBF and BAT was used for quantification based on the 16 perfusion-weighted images (Label-Control of each TI) of each voxel.

Other sequences

T1WI, T2WI, FLAIR, and 3D-TOF MRA sequences.

Image analysis

Measurement of quantitative parameters

Quantitative parameters of DSC and ASL for the supply territories of MCA and ACA were measured in both the bilateral cerebral hemispheres of all 41 patients. The ROIs were determined as shown in Fig. 2, the total ROIs were 902. TTP and rCBF were measured in the ROIs of DSC parameter maps, whereas BAT and CBF were measured in the ROIs of ASL parameter maps. DSC-TTP and ASL-BAT were simultaneously measured in the brainstem region of each patient. The areas of signal loss due to delay in blood flow were excluded from the ROIs of ASL images. The differences in DSC-TTP and ASL-BAT for each ROI and brainstem region were calculated as follows: $\Delta TTP = (TTP_{hemisphere} - TTP_{brainstem})$ and $\Delta BAT = BAT_{hemisphere} - BAT_{brainstem}$. Thereafter, the correlations between DSC-TTP and ASL-BAT and between DSC-CBF and ASL-CBF were analyzed.

Monitoring of areas of signal loss

The areas of signal loss on ASL parameter maps were observed, and the DSC-ΔTTPs in the corresponding areas were recorded. The