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Original Article

Arterial spin-labeling perfusion imaging of children with subdural hemorrhage: Perfusion abnormalities in abusive head trauma

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ABSTRACT

Background and purpose. – Perfusion abnormalities have not been well described in children with subdural hemorrhage (SDH). We investigated whether patients with abusive head trauma (AHT+) had more perfusion abnormalities than those without (AHT−).
Materials and methods. – We reviewed the perfusion MR studies of 12 infants with SDH and 21 controls. The perfusion images were obtained using a pseudo-continuous arterial spin-labeling sequence with volumetric fast spin-echo readout. An MR perfusion scoring system (0–6 points) was devised to facilitate appraisal of the extent of abnormalities. An asymmetry index (AI) was calculated for each region of perfusion abnormality. Comparison of perfusion scores across the AHT+, AHT−, and control groups was performed. The AIs of the hypoperfused lesions and hyperperfused lesions in patients were separately compared with those of the controls. The neurological outcomes of the patients were associated with imaging abnormalities.
Results. – Perfusion abnormalities were found in five (83%) of six AHT+ patients and in one (17%) of six AHT− patients. The AHT+ group recorded a significantly higher perfusion score than did both the AHT− group and the controls. Four patients with hypoperfused lesions exhibited significantly lower AI ($P = .002$) than did the controls, and three patients with hyperperfused lesions had significantly higher AI ($P = .006$) than did the controls. Of the four patients with hypoperfused lesions, two expired and one experienced hemiparesis.
Conclusions. – Patients with AHT have higher perfusion abnormality scores than patients with other causes of SDH and controls. Moreover, hypoperfusion may suggest a poor clinical outcome.

Introduction

Subdural hemorrhages (SDH) in infants and young children are most commonly caused by abusive head trauma (AHT) [1–4]. Other causes of SDH include accidents, birth trauma, meningitis, coagulopathy, vascular malformations, and metabolic diseases. The clinical outcomes in infants with AHT are worse than those in patients with other conditions [3,4].

SDH-related brain parenchymal injury, rather than the SDH itself, are more closely associated with the outcome of the patients [2]. Brain parenchymal injuries may cause secondary hypoxic-ischemic injury and brain edema, resulting in decreased perfusion of the brain. Decreased cerebral perfusion pressure has been reported to be associated with poor clinical outcomes in children with traumatic brain injury [5]. Conventional neuroimaging studies such as computed tomography or magnetic resonance imaging (MRI) examinations cannot reveal the hemodynamic changes in the traumatic brain.

Arterial spin labeling (ASL) perfusion imaging is a non-invasive, advanced MRI method that directly measures the cerebral blood flow (CBF) and uses arterial water as an endogenous tracer, thus requiring no injection of contrast agents. A recently developed ASL sequence, incorporating pseudo-continuous labeling with a

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volumetric fast-spin-echo (FSE) readout (3D-PCASL) yielded results comparable to those obtained using dynamic susceptibility contrast MRI [6–8]. ASL perfusion imaging may reveal hemodynamic changes in the brain otherwise not identified using conventional neuroimaging techniques. The purpose of this study was to determine the perfusion abnormalities in children with SDH, and particularly, investigate whether children with AHT had more perfusion abnormalities than did children without AHT.

Materials and methods

Patients

Perfusion MR studies of 12 infants [gestational age (GA) at birth: 30–42 weeks, and postmenstrual age (PMA) at the time of scan: 32–78 weeks] with MR imaging finding of SDH evaluated between 2012 and 2015, were retrospectively reviewed. Subjects younger than two years old having a MR finding of subdural hemorrhage, who were admitted to our pediatric ward or pediatric intensive care unit, were included in this study. Subjects with encephalopathy secondary to infections, neoplasms, toxic or metabolic diseases, or vascular diseases were excluded. Subjects eligible for this study were categorized as those having AHT (AHT+ group) and those without AHT (AHT− group). AHT was diagnosed on the basis of the presence of SDH in conjunction with parenchymal hemorrhages of different stages, multiloculated SDH or SDH showing a fluid-fluid layer, retinal hemorrhages, and traumatic lesions not compatible with the reported history of injury [9,10]. The patients with AHT were evaluated by a multi-disciplinary team composed of pediatricians, radiologists, ophthalmologists, surgeons, nurses, and social workers. In the AHT− group, clinical indications for MR examination included respiratory distress, hypotonia, seizure, and post-resuscitation evaluation. We also selected 21 controls (GA at birth (GA: 30–42 weeks, and PMA at the time of scan: 32–78 weeks) with a normal conventional MR study acquired during 2012–2015. All controls had unremarkable structural MRI findings and no developmental abnormality, pre-existing neuro-psychiatric disorders, nor motor deficits. The controls were enrolled according to their admission sequence. The clinical indications for MRI in the control group included scalp hematomas, hypotonia, cyanosis, fever, nystamus, hypermelanosis, prematurity, suspected pituitary gland dysfunction, suspected intracranial vascular lesions, or suspected seizure. Institutional review board approval was obtained for this retrospective study.

MR image acquisition

All patients were scanned using an eight-channel brain array coil on a clinical 3-T MRI scanner (Discovery MR750, GE Healthcare, Milwaukee, WI, USA). Conventional MR pulse sequences included axial T1WI, axial and coronal FLAIR imaging, sagittal T2WI, axial DWI with ADC map, and axial and coronal postcontrast T1WI. The PCASL perfusion imaging was performed using a 3D background-suppressed FSE stack-of-spiral readout module with eight in-plane spiral interleaves (TR/TE = 4463 ms/10.2 ms; labeling duration, 1500 ms; post-labeling delay, 1525 ms; no flow-crushing gradients; in-plane matrix, 128 × 128; number of averages = 3; field of view, 240 mm × 240 mm; slice thickness, 5 mm) and an echo train length of 23 to obtain 23 consecutive axial slices [6]. The labeling plane, placed 20 mm inferior to the lower edge of the cerebellum, was 10 mm thick. The PCASL scan also included the acquisition of a reference image after saturation recovery with a saturation time of 2 s. The total scan time was 259 s.

Data analysis

The ASL perfusion data were analyzed on the Advantage Windows workstation using Functool software (Version 9.4, GE Medical Systems, Milwaukee, WI, USA). The blood flow per volume, F_ρ (mL/100 mL/min), was calculated using the following equation:

$$\mathrm{CBF} = 6000 \cdot \lambda \frac{(1 - e^{\mathrm{ST}/T_{1t}})e^{\mathrm{PLD}/T_{1b}}}{2\varepsilon T_{1b}(1 - e^{-(\mathrm{LT}/T_{1b})})} \left(\frac{\mathrm{PW}}{\mathrm{SF_{PW}PD}}\right)$$

where PW is the perfusion-weighted or raw difference image and PD is the partial saturation of the reference image. Other parameters, which included T_1 of blood (T_{1b}) = 1.6 s, T_1 of tissue (T_{1t}) = 1.2 s, partition coefficient (λ) = 0.9 and the labeling efficiency (ε) = 0.6, were assumed to be constant. The F_p map was then calculated by assuming hematocrit = 0.45.

Two neuroradiologists, both having over 10 years of experience in practicing neuroradiology which included interpretation of MRI of the brain, independently reviewed all MR images. One of them is a pediatric neuroradiologist with more than 10 years of experience in practicing pediatric neuroradiology. Different interpretations were solved by consensus.

ASL perfusion images were visualized and analyzed by the pediatric neuroradiologist by using Mango software (Research Imaging Institute, University of Texas Health Science Center, San Antonio, TX, USA). The perfusion images were interpreted for abnormalities which consisted of deviation from a normal brain perfusion pattern or perfusion asymmetry. A normal brain perfusion pattern in an infant includes a descending order of perfusion from the basal ganglia and thalamus, to the cerebral cortex, and the white matter [11,12] (Fig. 1). Also, higher perfusion was observed around the central sulcus (Fig. 1a) than in other parts of the cerebral cortex. For detecting perfusion asymmetry, color-coded perfusion images were examined for a mismatch in color between both sides of the brain. When a color mismatch was observed, the region with color different from that of most of the remainder of the brain was regarded as the ipsilateral abnormal side, and the corresponding region on the other side with color similar to that of most of the remainder of the brain was regarded as the contralateral normal side. Because hyperperfusion was occasionally found in the occipital lobe of a normal child, possibly attributed to physiologic visual stimulation [13], the occipital regions were not analyzed.

An MR perfusion scoring system was devised to facilitate appraisal of the imaging abnormalities according to a point system (0–6 points) based on the extent of imaging abnormality (either hypoperfusion or hyperperfusion). The scoring system was defined as follows: perfusion abnormality in one of the frontal, temporal, or parietal lobe on one side = 1 point; in two lobes = 2 points; and in three lobes = 3 points. The final score was the summation of scores of bilateral sides.

A perfusion asymmetry index (AI) was calculated from the mean CBF value obtained from a region-of-interest (ROI) placement within the most prominent perfusion abnormality, using the following formula: AI (%) = 100 × (ipsilateral − contralateral)/[(ipsilateral + contralateral)/2] [14,15]. The size of ROI was at least 20 × 30 mm^2. A negative AI implies relative hypoperfusion in the lesion. For the controls, AI was calculated according to the left-right asymmetry with ROIs placed in the fronto-parietal cortical regions at the level of the corpus callosum: AI (%) = 100 × (left − right)/[(left + right)/2].

Statistical analysis

Kruskal–Wallis test was used to assess the differences in perfusion score in the three groups. Mann–Whitney *U* test was used for intergroup comparison of the perfusion scores between the control