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Original contributions

Perfusion imaging of cerebral arteriovenous malformations: a study comparing quantitative continuous arterial spin labeling and dynamic contrast-enhanced magnetic resonance imaging at 3 T

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Abstract

Assessment of hemodynamics in arteriovenous malformations (AVMs) is important for estimating the risk of bleeding as well as planning and monitoring therapy. In tissues with perfusion values significantly higher than cerebral cortex, continuous arterial spin labeling (CASL) permits both adequate representation and quantification of perfusion. Thirteen patients who had cerebral AVMs were examined with two magnetic resonance imaging (MRI) techniques: perfusion imaging using a CASL technique with two delay times, 800 and 1200 ms, and T_2-weighted dynamic contrast-enhanced MRI (T_2-DCE-MRI). The signal-to-noise ratio obtained in our study with the CASL technique at 3 T was sufficient to estimate perfusion in gray matter. Both nidal and venous perfusion turned out larger by factors of 1.71±2.01 and 2.48±1.51 in comparison to T_2-DCE-MRI when using CASL at delay times of 800 and 1200 ms, respectively. Moreover, the venous and nidal perfusion values of the AVMs measured at T_2-DCE-MRI did not correlate with those observed at CASL. Evaluation of average perfusion values yielded significantly different results when using a shorter versus a longer delay time. Average gray matter perfusion was 15.8% larger when measured at delay times of w=800 ms versus w=1200 ms, while nidal perfusion was 15.7% larger and venous perfusion was 34.6% larger, respectively.

In conclusion, the extremely high perfusion within an AVM could be successfully quantified using CASL. A shorter postlabeling delay time of w=800 ms seems to be more appropriate than a longer time of w=1200 ms because of possible inflow of unlabeled spins at the latter.

Keywords: Arteriovenous malformations; AVM; ASL; CASL; Continuous arterial spin labeling; DCE-MRI; Dynamic contrast-enhanced MRI

1. Introduction

Arteriovenous malformations (AVMs) of the brain are localized arteriovenous shunts consisting of a tangle of vascular channels [1]. Usually, they are composed of one or more feeding arteries, a nidus and draining veins lacking a capillary bed. Low resistance in these shunts causes very high blood flow compared to the surrounding vascular compartments, eventually leading to intracerebral hemorrhage. High flow in the nidus is also considered to cause arterial hypotension in adjacent brain tissue, known as "steal phenomenon," and may be associated with neurologic deficits. It is now a generally accepted therapeutic approach to attempt full occlusion of an AVM with catheter-based techniques in multiple steps, each requiring close monitoring of outcome [2]. In general, the anatomy and vascular supply of an AVM can be assessed using conventional digital subtraction angiography. Magnetic resonance (MR) perfusion imaging might contribute additional information on functional features of the AVM itself, thereby overcoming pertinent shortcomings of anatomic angiography. Hemodynamic information is considered to be important for estimating the risk of bleeding from an AVM as well as planning treatment and monitoring outcome [3].

Several methods have been described to measure regional blood flow in an AVM [4,5]. Positron emission tomography

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(PET) studies have been shown to be useful for assessing therapeutic efficacy by quantification of cerebral blood flow (CBF) in AVMs. The PET studies have demonstrated reduced CBF in surrounding brain tissue [2] and also changes in perfusion during therapy [2].

T_2^*-based dynamic susceptibility contrast-enhanced magnetic resonance imaging (DSC-MRI) typically provides representative images of perfusion distribution in the brain, but perfusion quantification remains challenging [6,7], and the method fails to adequately represent perfusion in the large vessels of an AVM [8] with perfusion significantly above that of the cerebral cortex. Nevertheless, DSC-MRI studies in patients with AVMs demonstrated transnidal flow higher than that of cerebral cortex and perinidal hemodynamic disturbances [9]. Contrast-enhanced dynamic imaging techniques are based on a large amount of contrast medium (CM) injected as a short bolus. A large amount of paramagnetic CM is flowing through the tissue during bolus passage. The high concentration of paramagnetic CM leads to inhomogeneities of the magnetic field, distorting the images acquired. Such distortions become more apparent as either the vessels become larger or the number of vessels increases, e.g., in AVMs (see video). Since the CM concentration in the tissue changes dynamically during bolus passage, the image distortions change as well. Especially echo-planar imaging (EPI) sequences based on free induction decay, as used for DSC-MRI, are strongly sensitive to these distortion phenomena. Therefore, DSC-MRI does not allow unequivocal calculation of perfusion maps from within the AVM. T_2-based dynamic MRI is less sensitive to susceptibility artifacts, and image distortions during bolus passage are less severe.

In principle, each contrast-agent-based dynamic MRI technique as well as T_2^*-, T_2- or T_1-weighted sequences will allow perfusion quantification directly or by using a reference tissue. However, they will also fail to provide adequate perfusion estimates for the large vessels of an AVM with perfusion significantly higher than in the cerebral cortex. The intrinsic problem of intravascular tracer-based methods is that they depend on dispersion of the tracer bolus. Bolus dispersion decreases as perfusion becomes larger, i.e., the change in bolus width becomes very small in tissues with much higher perfusion than the cerebral cortex. Since CM is injected intravenously, it circulates through the vascular system and passes the right cardiac ventricle, the lungs and the left ventricle. Therefore, it is impossible to reduce tracer bolus width below a certain level, approximately six to seven times the full width half maximum. In such highly perfused tissues, the change in bolus width becomes very small (<1s) and, therefore, difficult to measure.

An alternative MRI technique is arterial spin labeling (ASL), which has been demonstrated to be capable of assessing both hypoperfusion and hyperperfusion on a global or localized scale for a wide range of diseases [10–12]. Arterial spin labeling has already been shown to provide additional clinically relevant information on AVMs [11–13]. In contrast to CM-based methods, the signal-to-noise ratio (SNR) of ASL increases with perfusion. In tissues with higher perfusion compared to brain cortex, ASL permits both adequate representation of blood flow through the AVM and local perfusion quantification [14]. Moreover, repeated investigations without the need for CM administration become possible. The aim of the present study was to examine continuous arterial spin labeling (CASL) at 3 T for its capability of quantifying regional perfusion in AVM.

Generally, quantification of perfusion using ASL requires determination of the local relaxation rate and the extent of spin exchange with tissue water [15]. In an AVM, both parameters are often difficult to estimate. Therefore, we use two different inversion times to quantify AVM perfusion and to estimate the accuracy in perfusion quantification using CASL. The CASL results are compared with T_2-weighted spin-echo dynamic contrast-enhanced MRI (T_2-DCE-MRI).

2. Material and methods

2.1. Imaging

Thirteen patients (10 male and 3 female; mean age 31 years, range 20–40 years) who had an AVM were investigated with MRI perfusion imaging on a 3-T whole-body scanner (Signa, GE Healthcare, Milwaukee, WI, USA) equipped with the manufacturer's standard S/R quadrature head coil. The total patient scan time was approximately 40 min. The investigations were approved by the local ethics committee, and all patients gave their written informed consent prior to the examinations.

The MRI protocol included a three-plane localizer, axial T_1-weighted inversion recovery fast spin-echo [repetition time (TR)=2358 ms; inversion time (TI)=860 ms; echo time (TE)=10.6 ms; two acquisitions; echo train length (ETL)=6] and axial T_2-weighted fast spin-echo (FSE; TR=3500 ms; TE=105 ms; two acquisitions; ETL= 16), CASL MRI and DCE-MRI.

Continuous arterial spin labeling was based on gradient-echo EPI readout [TR=4000 ms; TE=20 ms; field of view (FOV)=22 cm; matrix=128×128; slice thickness=7 mm; seven slices; number of pairs=32; labeling duration=2.5 s]. Image acquisition was repeated twice with delay times of 800 and 1200 ms and a labeling distance of 50 mm from the bottom image. The total CASL scan time was 256 s.

For comparison with CASL perfusion imaging, a T_2-weighted spin-echo DCE-MRI (TR/TE=1000 ms/60 ms; FOV=22 cm; matrix=128×128; slice thickness=7 mm; seven slices) acquisition was performed with a bolus of 0.2 ml/kg body weight of gadopentetate dimeglumine (Magnevist, Bayer Healthcare, Leverkusen, Germany) as paramagnetic contrast agent, administered via the antecubital vein at a flow rate of 5 ml/s. The total DCE-MRI scan time was 60 s.