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Superselective pseudo-continuous arterial spin labeling angiography

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ABSTRACT

Purpose: To evaluate the utility of a novel non-contrast enhanced, vessel-selective magnetic resonance angiography (MRA) approach based on superselective pseudo-continuous arterial spin labeling (ASL) for the morphologic assessment of intracranial arteries when compared to a clinically used time-of-flight (TOF) MRA.

Materials and methods: Three sets of selective ASL angiographies (right and left internal carotid artery, basilar artery) as well as one TOF data set were obtained from each of the five volunteers included in this study on a clinical 1.5T system. The depiction of arterial segments as well as their delineation was evaluated and independently analyzed by two radiologists. Additionally, the ASL angiography approach was performed in two patients suffering from arterio-venous malformations (AVM) in order to illustrate potential applications in a clinical setting.

Results: In both angiography techniques, intracranial arteries and their segments (distal branches up to A5 segments of the anterior cerebral arteries, M8 segments of the middle cerebral arteries, and P5 segments of the posterior cerebral arteries) were continuously depicted with excellent inter-reader agreement ($\kappa > 0.81$). In AVM patients, reconstructed images of the TOF angiography presented similar information about the size and shape of the AVM as did superselective ASL angiography. In addition, the acquired ASL angiograms of selected vessels allowed assessing the blood supply of individually labeled arteries to the AVM which could also be confirmed by digital subtraction angiography.

Conclusion: Superselective ASL angiography makes it possible to visualize arterial trees of selected vessels, thereby, providing information about the macrovascular blood supply and flow territories of intracranial arteries. Similar image quality is achieved when compared to clinically used TOF angiography with respect to the identification and delineation of arterial segments. Initial application of superselective ASL angiography in two patients with AVM's demonstrates the ability to gather additional important information about feeding vessels and blood supply.

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1. Introduction

A detailed visualization of the arterial vasculature of the brain is important in the diagnosis and treatment planning of many cerebrovascular diseases like aneurysms, arterio-venous malformations (AVM), and steno-occlusive diseases. Arterial digital subtraction angiography (DSA) is considered the gold standard for imaging of cerebral arteries with respect to vessel selectivity, spatial and temporal resolution. The procedure, however, is invasive and it bears the risk of severe complications, such as vessel dissection, intracranial bleeding or ischemic stroke [1]. Moreover, DSA requires the administration of exogenous contrast agents and the use of ionizing radiation. As a projective angiography method, standard DSA usually does not allow for retrospective review of the radiographed vessel morphology along arbitrary views [2]. However, nowadays 3D rotational DSA can also be performed with small amounts of contrast agent and low-dose radiation protocols which allows for arbitrary image reconstructions [3]. Magnetic resonance imaging (MRI) may overcome some of the limitations and offers a variety of angiography techniques for the assessment of the cerebral vasculature. These can be divided into contrast enhanced (CE) and non-contrast enhanced (NCE) MR angiography (MRA) methods

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[4,5]. CE MRA can be used to generate high-resolution static images, but also to acquire dynamic angiograms for the evaluation of cerebrovascular hemodynamics [6]. Imaging is usually performed during the first passage of the bolus to follow its course through the vasculature which requires precise timing between contrast agent administration and start of measurement. Varying degrees of temporal resolution can be achieved which is limited by the width of the injected bolus of contrast agent and by the acquisition time of the images [7]. However, repeated contrast agent injections are usually avoided especially due to recent associations between gadolinium based contrast agents and nephrogenic systemic fibrosis [8]. Hence, alternative MRA approaches are required, preferably without the need for exogenous contrast agent materials. These include three-dimensional (3D) time-of-flight (TOF) sequences and phase-contrast angiography techniques [9,10]. Such methods are commonly used in clinical MRI protocols for the assessment of the cerebrovascular morphology and hemodynamics [11].

However, the above mentioned MRA approaches are lacking the ability to acquire selective angiograms of individual vessels, hence, making it difficult or impossible to identify collateral circulation and evaluate altered blood supply.

Arterial spin labeling (ASL) techniques have the potential to be used for the imaging of vascular architectures in different organs in a complete non-invasive way [5,12]. In ASL, the blood itself is utilized as an endogenous contrast agent. Water spins of arterial blood are magnetically labeled before flowing into the imaging region [13]. Compared to other imaging methods, ASL has the advantage that some of the labeling approaches can be modified in order to selectively label the blood of an individual artery, thereby, making it possible to visualize the branches of only a single arterial tree [14]. It has already been shown that ASL based methods may be used for assessing and monitoring the cerebral vasculature in a non-invasive way while providing similar information as conventional MRI sequences or even DSA [15–17].

In this study, an alternative approach is demonstrated based on superselective pseudo-continuous ASL (pCASL) for the morphologic assessment of selected intracranial arteries [18]. ASL datasets acquired in healthy volunteers are quantitatively analysed and compared to the current clinical standard TOF MRA. Furthermore, the proposed superselective ASL angiography technique is utilized in two AVM patients in order to demonstrate potential clinical applications.

2. Materials and methods

The data for this study were acquired under a general protocol for MRI pulse-sequence development as approved by the local ethical committee. All volunteers and patients gave written informed consent before they underwent MR imaging. The study population included five healthy volunteers who had no contraindications to MRI and no recent health problems or surgery (2 men, 3 women; mean age: 25.2 years; range 22–31 years) and also two AVM patients (1 man, 20 years, and 1 woman, 65 years).

2.1. MR image acquisition

MR measurements were performed on a clinical Philips Achieva 1.5T system (Philips Healthcare, Best, The Netherlands) using the body coil for RF transmission and an 8-element phased-array receive coil for signal reception.

The scan protocol for each subject included a conventional MR localizer and a sensitivity encoding (SENSE) reference acquisition. In order to visualize the cerebrovascular architecture, a clinically used TOF MRA was performed with the following scan parameters: field-of-view (FOV) $220 \times 220 \times 90\,mm^3$, voxel size $0.45 \times 0.45 \times 0.5\,mm^3$, 3D fast-field echo acquisition, flip angle 20°, and repetition time (TR)/echo time (TE) was 20/3.5 ms, resulting in a total acquisition time of 5:50 min. The acquired TOF images were used to plan the labeling plane of the superselective pCASL sequence. In each subject, both internal carotid arteries (ICA) as well as the basilar artery (BA) were selectively labeled. Preferably, the labeling spot was positioned onto a straight part of the selected vessel proximal to the entrance of the cranium in order to minimize effects on the labeling efficiency (Fig. 1). In addition, patients with AVM's underwent selective labeling of potential feeding vessels distal to the Circle of Willis (Fig. 1). Scan parameter were as follows: FOV $220 \times 220 \times 90\,mm^3$, $0.5 \times 0.5 \times 1.5\,mm^3$, segmented 3D balanced Turbo Field Echo (b-TFE) acquisition, TFE factor 70, flip angle 90°, and TR/TE 4.8/2.4 ms, resulting in a total measurement time of 4:30 per artery. The labeling duration was set to 1000 ms in order to ensure sufficient filling of intracranial vessels after spin tagging according to arterial transit times measured in [19,20]. Image acquisition started immediately after tagging with no effective post-labeling delay.

2.2. Image post processing

ASL angiography images were obtained by subtraction of label and control acquisitions. Maximum intensity projections were generated in transversal, coronal and sagittal orientation using Matlab R2010a (The Mathworks, Natick, MA). The resulting images were combined into a color-encoded frame in order to visualize the course of the individually labeled vessels. Joined blood flow between selectively labeled arteries will therefore result in the mixing of two or more colors.

2.3. Image analysis

Three sets of ASL angiography images (right and left ICA, BA) as well as one TOF data set were obtained from each volunteer and compared in a quantitative way. The depiction of arterial segments as well as their delineation were evaluated on native ASL angiography and native TOF images and independently analyzed by two radiologists. The arterial segments of the carotid artery were selected and numbered according to the literature [21]. For the purpose of this paper, the segments of the middle, anterior, and posterior cerebral artery (MCA, ACA, PCA) were numbered beginning with the proximal trunk (M1, A1, P1) and in ascending order at every junction. The ophthalmic artery (OA) branches from the carotid artery in the C2 segment [22]. The superior cerebellar arteries (SUCA) branch from the superior BA. Anterior and posterior communicating arteries (Acom, Pcom) branch from the C1 and A1 segments. The ratings were arrived at by consensus using the following 4-point score as proposed in [23]:

- 0: not identified
- 1: identified, but not continuously
- 2: identified continuously, but with an inhomogeneous signal
- 3: identified continuously, and with homogeneous signal.

Cohen's Kappa was calculated to evaluate the inter-reader agreement between both raters in the identification of vessels (a value of 0.21–0.40, fair agreement; 0.41–0.60, moderate agreement; 0.61–0.80, substantial agreement; 0.81–1.00, excellent agreement).

The differences in the outcome of the consensus decisions between ASL angiography and TOF angiography ratings were averaged across all subjects and analyzed with Student-*T*-tests considering $P < 0.1$ as statistically significant.

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