Comparison of ASL inversion efficiency and CBF quantification for 3 perfusion techniques at 3 magnetic fields

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TARGET AUDIENCE: MRI Methodologists.

PURPOSE:

The purpose of this study is to quantify cerebral blood flow (CBF) using three arterial spin labeling (ASL) methods: pulsed ASL (PASL), Continuous ASL (CASL), and pseudo-continuous ASL (pCASL), and three magnetic fields (4,7T, 7T, and 11,7T)in the context of preclinical imaging.

METHODS:

Subjects: Male Wistar rats (n=43, ~ 300 g), isofluorane anesthesia (2%).

MRI: MRI was performed at 4.7 T (n=16 rats), 7T (n=16 rats) (Avance III; Bruker) with a volume transmit/surface receive coil configuration and a gradient coil capable of generating 660mT/m with a 114µs rise time; and at 11.7T (n=11 rats) (Avance III; Bruker) with a volume transmit/surface (phased array) receive coil configuration and a gradient coil capable of generating 550mT/m with a 156µs rise time. A global first order shim was performed.

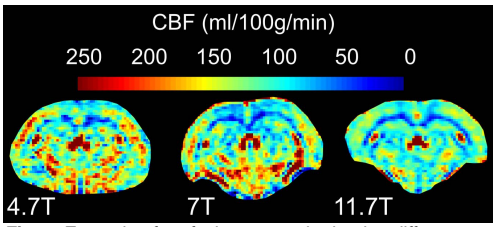

Fig. 1: *Example of perfusion maps obtained at different magnetic fields with the pCASL sequence.*

Inversion Efficiency (IE). For PASL, a gradient echo sequence was used to acquire selective and global inversion profiles (hyperbolic secant inversion shape: duration/bandwidth = 15ms/5190Hz). For CASL and pCASL, a Gradient Echo Flow Compensated (GEFC) sequence (TR/TE=225ms/5ms, matrix=256x256, FOV=30x30mm) with a labeling module (CASL: labeling duration=200ms, postlabeling delay<1ms; pCASL: pulse duration=400µs, interpulse delay=800µs, labeling duration=200ms, postlabeling delay<1ms) was used to measure blood magnetization in label and in control conditions. Due to hardware constraints, the average amplitude of radiofrequency field B_1^{rms} was: 5/4/3µT at 4/7/11.7T for pCASL and 5/5/3µT at 4/7/11.7T for CASL . Prior to the pCASL sequence, a pre-scan was performed to determine the interpulse phase increment that maximizes the perfusion signal.

Perfusion acquisitions: For perfusion acquisition, the aforementioned CASL and pCASL modules were combined with an EPI readout module (TR/TE=3500/21.7 ms, number of repetitions=30, matrix: 128 × 128, resolution: 250 × 250 µm × 1 mm, Tacq = 3 min30 s). The labeling parameters were those described above except the labeling duration which was set to 3s and the postlabeling delay, set to 200ms. For PASL, a FAIR scheme was used with the following parameters: TE=21.5 ms, recovery time=10 000 ms, sech80 adiabatic inversion pulse of 15 ms, 18 inversion times (TI) between 30 and 10 000 ms, number of averages=1, Tacq = 4 min and same lecture as previous.

IE processing: The IE was computed using Eq. 1[2], where M_a^0 is the equilibrium magnetization of arterial blood (or of tissue for PASL) and M_a is the magnetization of arterial blood after inversion. For CASL and pCASL, the arterial magnetization was measured in two ROIs on the carotid arteries and for PASL, it was extracted from the global inversion profile.

CBF processing: For PASL, we used the Bruker tool for CBF quantification and Eq. 2 introduced by Belle et al.[3] where T_1^b is the longitudinal relaxation time of blood, λ is the blood/tissue water partition coefficient, T_1^{glo} (resp. T_1^{sel}) is the T_1 of tissue after a global (resp. selective) inversion. For CASL and pCASL, we used the standard kinetic model developed by Buxton et al.[4] with Eq. 3, where ΔM is the signal difference between control and label acquisitions, ω is the post-labeling delay, τ is the labeling duration, α is the inversion efficiency, M_0^t is M0 map derived from the non-selective FAIR sequence, T_1^t is the apparent T_1 of tissue and is approximated by the T_1 derived from the non-selective FAIR sequence.

Statistical analysis: An unpaired Wilcoxon test was used to compare data between magnetic fields.

$$IE = \frac{M_a^0 - M_a}{2M_a^0}$$

Eq. 1: IE for ASL sequence.

$$CBF = \frac{\lambda}{T_1^b} \times \left(\frac{T_1^{glo}}{T_1^{sel}} - 1 \right)$$

Eq. 2: CBF quantification of PASL acquisitions.

$$CBF = \frac{\lambda \Delta M \times \exp(\omega / T_1^b)}{2\alpha M_0^t T_1^t \times (1 - \exp(-\tau / T_1^t))}$$

Eq. 3: CBF quantification of CASL and pCASL acquisitions.

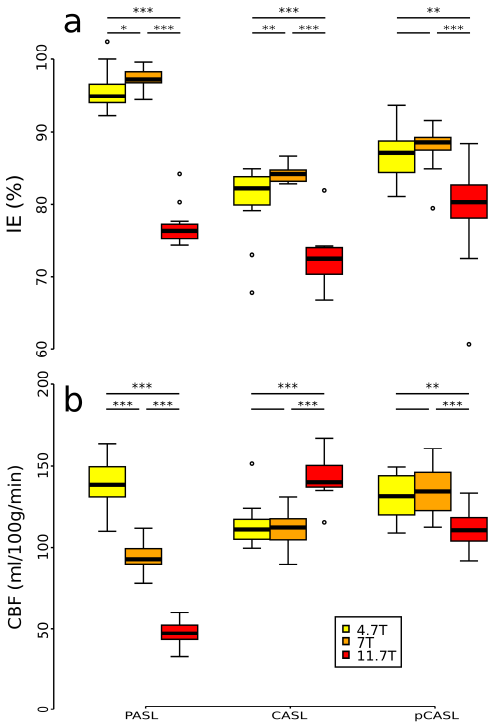

Fig. 2: *Value of IE for the three ASL methods studied, at 4.7, 7 and 11.7T. The error bars correspond to the standard deviation. Asterisks indicate the results of Wilcoxon test . *: p<0.05, **: p<0.01, ***: p<0.001. Circles correspond to outliers.*

RESULTS and DISCUSSION:

Fig. 1 shows an example of perfusion maps obtained at each magnetic field with the pCASL method. We can observed a SNR increase with the magnetic field as shown hereafter: 26/50/70 at 4.7/7T/11.7T for pCASL sequences in cortex. Fig. 2 shows the IE and the CBF for each method and each magnetic field. As expected, the IEs of PASL, which uses an adiabatic inversion pulse, are greater than 90% at 4.7T and 7T, but at 11.7T, IE drops to 77%. This could be due to a reduced blood T_2 and/or larger field inhomogeneities. The IE for CASL are 81±4% at 4.7T, 84±1 % at 7T and 72±4 % at 11.7T. These values are lower than that of PASL, in agreement with literature. For pCASL, the IE is: 88±4 % at 4.7T, 88±2 % at 7T and 78±7 % at 11.7T, the IE of pCASL is comparable to that of CASL, as reported in human literature. IE was comparable between 4.7T and 7T for all methods, but decreased between 7T and 11.7T (by14% for CASL, 11% for pCASL and 21% for PASL). This reduction might be explained by the decrease in B_1 (cf. methods) and by the sensitivity of pCASL to B_0 homogeneity in the labeling area[5]. Fig. 2.b. presents CBF values for the three magnetic fields and for the PASL, CASL and pCASL sequences. CBF values obtained with the PASL sequence decreased as the static magnetic field increased. This may be ascribed to non optimized acquisitions and to the loss of signal due to the above mentioned T_2 decrease. Conversely, CBF values remained constant for the CASL and the pCASL sequences, except at 11.7T where CBF values were over estimated by the CASL sequence due to the residual magnetization transfer (MT) effects (data not shown), and faintly reduced with the pCASL sequence, probably due a lower hear rate of rat at 11.7T (455±20 beat per min at 4,7T, 462±21 bpm at 7T, and 292±38 bpm à 11,7T)[6].

CONCLUSION:

The IE of all ASL methods decreases as B_0 increases from 7T to 11.7T. The IE of pCASL appears more sensitive to the magnetic field than that of CASL, if the interpulse phase is not optimized. With this phase optimization, the IE of pCASL reaches that of CASL. In our experimental conditions, the use of second order shim had a strong negative impact on the IE of pCASL (data not shown).The good IE obtained at 7T is promising for human studies with ASL at high magnetic fields, for all methods. The residual MT effects bias the CBF quantification obtained with the CASL sequence. This could be overcome by optimizing the control frequency. Overall, our result advocate for the use of pCASL at high magnetic fields.

1. Alsop et al., *J. Cereb. Blood Flow Metab.* 1996, 2. Zhang et al., *Magn. Reson. Med.* 1993, 3. Belle at al., *J. Magn. Reson. Imaging* 1998, 4. Buxton et al., *Magn. Reson. Med.* 1998, 5. Jahanian et al., *Nmr Biomed.* 2011, 6. Kreis et al., *Neurol. Res.*, 2011.