Robust Inter-Pulse Phase Correction for Brain Perfusion Imaging at Very High Field using Pseudo-Continuous Arterial Spin Labeling (pCASL)

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Target Audience: Researchers in the field of perfusion MRI through arterial spin labeling (ASL) at very high magnetic field.

Purpose: To overcome limitations such as high SAR encountered in continuous arterial spin labeling (CASL), a pseudo-continuous approach (pCASL) has been introduced. This labeling technique imitates the continuous one by applying a series of short RF pulses in rapid succession. To match the phase evolution of the flowing spins during labeling, an inter-pulse phase increment is applied[1]. However, at very high field, B_0 inhomogeneities in the labeling plane, away from the isocenter, strongly affect the spins' phase. This results in reduced inversion efficiency (IE) and therefore lower relative ASL signal. Previous reports[2] at very high magnetic field placed the labeling plane at the isocenter, thus favoring IE at the cost of image quality. Other studies demonstrated, for the balanced pCASL[3] (bpCASL), that performing a phase sweep during a pre-scan to measure the optimal phase increment improved the overall perfusion signal. The aim of this study is to show that for unbalanced pCASL at very high field a phase optimization for labeling followed by a phase optimization of the control experiment considerably improves the perfusion signal and reduces asymmetry between brain hemispheres.

Methods:

Animals: 8 healthy rats (Sprague Dawley male rats) were anaesthetized with 1-2% isoflurane. Their respiration rate was maintained at 40-60 bpm.

MR experiments: Experiments were performed on a 9.4T horizontal scanner (Bruker Biospec, AVIII HD) with a volume transmit/surface (phased-array) receive coil configuration. Unbalanced labeling pCASL pulses were applied in the rat's neck (at -2 cm from the isocenter) during 3s followed by a 300ms post-labeling delay. The labeling pulse train consisted of Hanning window shaped RF pulses with an average amplitude of 5µT, duration of 400µs, repeated every 800µs. Gmax/Gave was set to 45/5 mT/m. Image acquisition was performed through single-shot EPI: FOV=3x3cm², slice thickness=1mm, matrix=128x128, TE=22ms, TR=4000ms, 30 repetitions. Both label and control phase optimization pre-scans were performed with the same parameters as for the pCASL-EPI, except that the labeling duration was reduced to 1.5s, the slice thickness was set to 4mm, and only one repetition per phase step was performed. The optimal labeling phase was used in the control phase optimization. Three pCASL-EPI experiments were then performed: one without phase optimization, one with an optimal label phase increment and one with both optimal label and control phase increments. MT corrected CASL-EPI[4] were acquired (same parameters as pCASL-EPI, n=5) to compare with the pCASL experiments. To quantify CBF, T_1 maps were acquired (inversion recovery sequence) and inversion efficiencies were measured 5mm upstream the labeling plane with a TOF angiography (FOV= 3x3cm², 1mm slice thickness, matrix=256x256, NA=2).

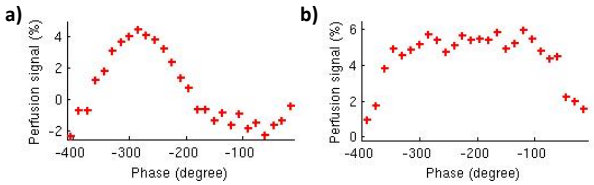

Fig.1: Example of (a) labeling phase sweep (b) control phase sweep

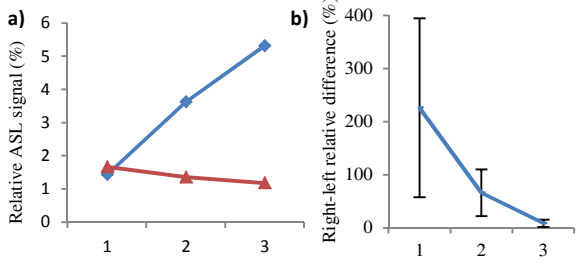

Fig. 2: (a) Relative ASL signal (blue); SD across rats (red); (b) Asymmetry between hemispheres (mean+/-SD); **1:** No correction; **2:** Label phase correction only; **3:** Label + control phase correction.

Data Processing: The relative perfusion signal was calculated with: $\frac{MControl-Mlabel}{MControl} * 100$, where $M_{control}$ and M_{label} are respectively the magnetizations from the control and from the label experiments. The relative difference between hemispheres was computed to evaluate perfusion asymmetry. To calculate quantitative CBF maps, the formula given in the recommended implementation of ASL MRI[5] was applied.

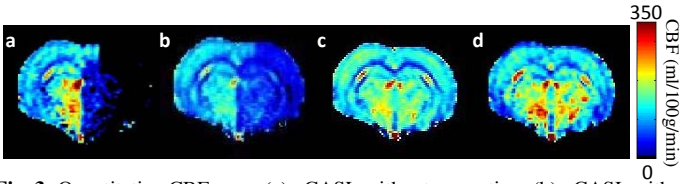

Fig. 3: Quantitative CBF maps (a) pCASL without correction; (b) pCASL with label phase correction only; (c) Label and control phase correction; (d) CASL

Results and discussion:

Fig.1 shows the relative perfusion signal as a function of the inter-pulse phase increment correction for labeling and control experiments. For this rat, the inter-pulse phase needed a correction of -285° for labeling and of -120° for control. These corrections differ from one rat to another (mean label correction= -283±23°, mean control correction= -223±63°), therefore the optimal phases were measured for each animal. Fig.2a presents the improvement of the relative perfusion signal when performing corrections (blue diamonds): the labeling correction increases the perfusion signal by more than a factor 2. When adding a control phase correction, another 50% increase is gained. The red triangles indicate the standard deviation (SD) across rats for each experiment. Without correction, the mean relative CBF is lower than the SD across rats, meaning that the perfusion measurement is very unstable. These inter-subject variations are corrected with labeling and control phase optimization. Fig. 2b shows the asymmetry between brain hemispheres in each condition. The error bars indicate the SD of the relative difference across rats. If no correction or only the labeling phase correction is performed, results are significantly different between hemispheres, as determined by a paired t-test ($p_{no\ correction} = 0.004$, $p_{label\ correction} = 0.005<0.01$). Asymmetry disappears when both label and control corrections are performed (paired t-test: p=0.12). Fig.3 presents typical quantitative CBF maps for each experiment (a, b, c). They can be compared to a CASL acquisition performed on the same healthy rat (d). If only one or no labeling phase correction is performed, CBF maps are unusable due to huge asymmetry (paired t-test pCASL-CASL: $p_{no\ correction} =0.001$, $p_{label\ correction}=0.006 < 0.01$). Label and control phase corrected pCASL (c) yield CBF maps comparable to those from CASL (paired t-test: p=0.21). Differences between them may be ascribed to physiological perfusion fluctuations. The average brain CBF (label+control corrections) found was 153±25mL/100g/min, which is comparable to values from literature. In conclusion, this study shows that performing both label and control phase correction improves relative perfusion signal, corrects asymmetry arising when labeling far from isocenter at high field and preserves high image quality at the same time. This approach could benefit human studies performed at high magnetic field.

References:

1. Dai et al., MRM (2008); 2. Duhamel et al.,MRM (2011); 3. Luh et al., MRM (2013) ; 4. Barbier et al., MRM (1999) ; 5. Alsop et al., MRM (2014)