Multi-Phase Pseudo-Continuous Arterial Spin Labeling (MP PCASL): Robust PCASL method for CBF quantification

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INTRODUCTION

The pseudo-continuous arterial spin labeling (PCASL) method [1] for CBF quantification offers higher SNR and therefore the potential for improved quantification compared to pulsed ASL (PASL). In addition, it can be implemented without the need for a special RF system, which is often required for continuous ASL (CASL). However, because the tagging mechanism is highly sensitive to the accurate specification of phase between successive RF pulses [2], the tagging efficiency of PCASL can be significantly modulated by both gradient imperfections and the presence of off-resonance fields at the tagged vessels. Here we propose a novel PCASL method with multiple phase offsets which is less sensitive to these factors. We show that the proposed method provides more robust CBF values than the conventional PCASL method and higher SNR than FAIR ASL [3], a commonly used pulsed ASL method.

THEORY

Conventional ASL has two phases in its acquisition (tag and control). For PCASL the tag and control phases are defined by the phase increment between two successive RF pulses. The overall phase increment between two successive RF pulses can be expressed by an equation: $\Delta\theta_n = \gamma Gtd + 2\pi n/N$, where γ is the gyromagnetic ratio, G is the average gradient strength, t is the interval between RF pulses, d is the distance from the gradient center to tagging location, n denotes the nth phase, and N is the number of phases. Here γGtd is the phase tracking term and $2\pi n/N$ is the phase offset which generates different amounts of inversion. Fig. 1 shows the inversion response as a function of the phase offset. Conventional PCASL method uses two phase offsets: 0° for tag and 180° for control. When the predefined tracking phase has errors due to off-resonance and gradient imperfections, the desired tagging efficiency may not be achieved. For example, if there is a 90° phase offset, the tagging efficiency becomes zero. Acquiring multiple phases with evenly distributed phase offset (□ for 4 phases and × for 8 phases in Fig. 1) reduces sensitivity to the phase errors because it allows the acquired data to be fit to a predefined inversion response function. This enables the estimation of the perfusion signal on a per-voxel basis. From the fitting algorithm the phase tracking errors can also be estimated.

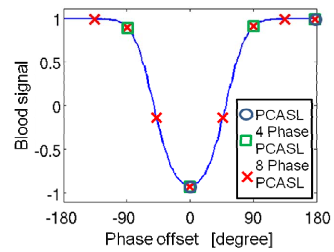

FIG.1. Simulated inversion response to the phase offset. The acquired offset points for each method are indicated

METHOD

We performed Monte-Carlo simulation to estimate the ASL signal and examine the SNR efficiency (SNR in unit of scan time normalized to that of pulsed ASL) as a function of phase offset (Fig. 2). In the simulation the multi-phase PCASL method provides consistent estimation of the ideal ASL signal and no significant loss of SNR. (SNR loss of 22.4%). We compared the CBF values from 4 different ASL methods over 5 subjects (3 men and 2 women): FAIR ASL, PCASL with high order shimming, and 4 and 8 phase PCASL. The experiment was executed on a 3T Signa HDx scanner with an 8-channel head coil (GE Healthcare, Waukesha, WI). The FAIR ASL scan was performed with QUIPSS II post-inversion saturation pulses [4] and scan parameters were TI1/TI2 = 600ms/1600ms, 10cm tag width, 3cm tag-slice gap TR 2.6 sec, 112 reps. PCASL scan parameters were 1600 msec tag duration, 1000ms post labeling delay, TR 3.6 sec, 80 reps. All methods have 240mm FOV, 20 slices (5 mm thick, skip 1mm), single-shot spiral acquisition (TE = 3ms), and 5 min. scan time. A mean gray matter CBF values were obtained from the gray matter mask which was defined with a high resolution anatomical scan.

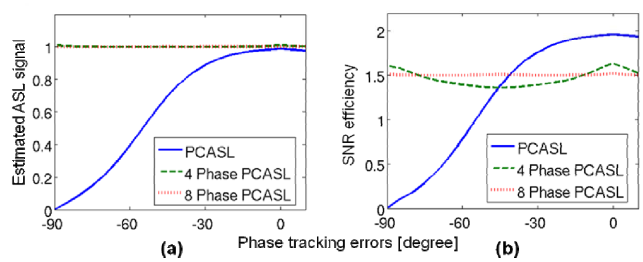

FIG. 2. Monte-Carlo simulation result of estimated ASL signal (a) and SNR efficiency (b) corresponding to phase tracking error which are normalized to unity and that from pulsed ASL, respectively.

RESULTS AND CONCLUSION

As shown in Fig 3(a,b), the CBF maps acquired with the proposed multi-phase PCASL (MP PCASL) method provides higher CBF estimates than conventional PCASL when the tagging efficiency of the latter is reduced by phase errors. In addition to the ASL signal, the fitting algorithm provides estimates of the phase tracking errors on a per-voxel basis. These errors should be uniform across each vascular territory, providing additional opportunities for robust estimation (Fig. 3c). Fig. 4 shows the mean gray matter CBF values and SNR efficiency (SNR per unit of scan time) normalized to those from FAIR ASL images. The CBF measures obtained with the MP PCASL method were more consistent with the reference CBF values obtained with FAIR ASL as compared to those from conventional PCASL (see paired t-test p values in Fig.4). In addition, the smaller error bars in the normalized MP-CASL values indicates that the method is more robust than convention PCASL. There was not a significant difference between the mean gray matter CBF values acquired with the 4-phase and 8-phase PCASL methods (paired t-test p-value of 0.83). Both conventional PCASL and MP PCASL provide higher SNR than FAIR ASL method (blue bars in Fig. 4).

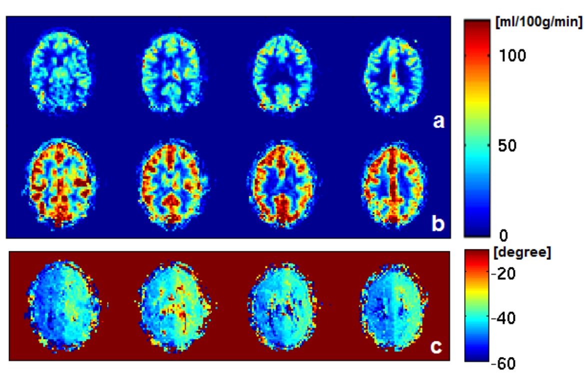

FIG. 3. CBF maps from (a) PCASL and(b) 4-phase PCASL shows overall increase in CBF estimates with 4-phase PCASL. Phase tracking error map (c) show asymmetry of the errors induced at tagging locations.

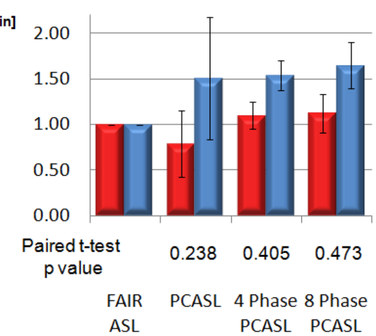

FIG. 4. Comparisons of gray matter CBF (red bar) and SNR efficiency (blue bar) normalized to the values from FAIR ASL. The error bars show the standard deviations.

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