Improved Pseudo-Continuous Arterial Spin Labeling (ASL) For Cerebral Blood Flow Mapping

M. Nezamzadeh[1,2], G. B. Matson[2,3], K. Young[1,2], M. W. Weiner[1,2], and N. Schuff[1,2]

[1]Radiology, University of California San Francisco, San Francisco, CA, United States, [2]Center for Imaging of Neurodegenerative Diseases, CIND, VA medical center, San Francisco, san francisco, CA, United States, [3]Pharmaceutical Chemistry, University of California San Francisco

Introduction

Previously, pseudo-continuous arterial spin labeling (pCASL) was introduced [1] to overcome limitations inherent with conventional continuous arterial spin labeling (CASL). However, simulations showed that the control scan (null pulse) in pCASL can be degraded by flow, diminishing the ASL signal [2]. Here, we report a modified version of pCASL, termed mpCASL, in which the immunity of the null pulse to flow is improved. This is demonstrated by simulations and by comparison of in-vivo brain perfusion experiments using either mpCASL, pCASL or CASL.

Methods

The new mpCASL was developed and implemented on a 4T MR scanner (Bruker, Siemens). Similar to pCASL, spin labeling (inversion) is achieved in mpCASL by applying shallow flip angle radiofrequency (RF) pulses in presence of alternating, bipolar slice-selective gradients. Furthermore, the control scan (null pulse) is achieved by repeating the RF and gradient pulse trains but with an alternating zero and pi phase of the RF pulses in an attempt to keep spin magnetization close to equilibrium. In contrast to pCASL, however, the repeated RF pulses are shifted off resonance to randomize the phase errors that can accumulate in presence of flow. The RF pulse parameters for pCASL and mpCASL were 600 μs duration and B_1= 5μT strength and the strength of the bipolar gradients was G=6 mT/m. For the control scan, the RF pulses in mpCASL had an offset frequency of 200 Hz, whereas the RF pulses in pCASL were always on resonance. Acquisitions using either CASL, pCASL or mpCASL, were conducted using a transmit/receive (Tx/Rx) 8-channel head coil. Five healthy human subjects were imaged back to back with each ASL version while keeping the parameters for mapping constant (spatial resolution=3.8x3.8 mm^2, 6/8 partial Fourier encoding TR/TE=5200 ms /9 ms, 80 averages to boost SNR). Sixteen slices, each 5 mm thick were acquired to cover the brain with 80 mm offset for the labeling band using 1.2 s labeling duration and 1.0 s post labeling delays. The perfusion images were processed offline for the subtraction of the averaged control from the averaged labeled signals.

For simulations we used relaxation times T_1=1500 ms and T_2=150 ms (to approximate human blood at 4.0 T) and an appropriate range of blood flow for the numerical solution of the Bloch equations in Matlab 7.0.4 (see Ref.[3]). The magnetization profiles through the imaging slices were generated by applying RF pulses corresponding to CASL, pCASL and the new mpCASL sequences to compare the perfusion signals (produced by subtracting the magnetization provided by the labeling and null pulses) and the perfusion signal sensitivity to the flow velocity.

Results

Simulations of the spin magnetization profiles for labeling (inversion) and control (null) pulses in the presence of blood flow of 200mm/s are shown in figure 1 separately for pCASL and mpCASL. While both methods achieve a similar spin inversion (blue), the null pulse of pCASL reduces the magnetization by 30% (pink) in contrast to mpCASL which almost completely preserves the magnetization (orange). The perfusion signals in CASL, pCASL, and mpCASL as a function of blood velocity are depicted in Figure 2. This shows that mpCASL consistently achieves a greater yield of the perfusion signal than CASL and pCASL for higher blood velocities. Representative perfusion images from two volunteers using (a) CASL, (b) pCASL, and (c) mpCASL are displayed in Figure 3. In general, perfusion images using mpCASL had higher contrast and those using CASL or pCASL and less blurring than those using CASL. Initial estimations of short- and long- term reproducibility of perfusion measurements also showed less variability within the subjects for mpCASL than for either CASL and pCASL (see figure 4). The standard deviation corresponds to the variation between the subjects.

Conclusion

The improved immunity to blood velocity suggests that perfusion measurements based on mpCASL are less confounded by the cystolic/diastolic cardiac cycle than CASL and pCASL. Furthermore, the experimental findings that perfusion maps using mpCASL show generally better contrast and less spatial blurring than those using CASL or pCASL is consistent with the hypothesis that mpCASL achieves more effective and consistent labeling in presence of variable blood velocity. In conclusion, mpCASL offers improved perfusion maps and thus has advantages for quantitative perfusion measurements.

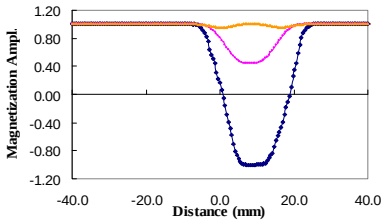

Figure 1. Simulated excitation slice profile from labeling pulses (blue) and null pulses for pCASL (pink) and the mpCASL (orange) for v=200 mm/s without relaxation effects.

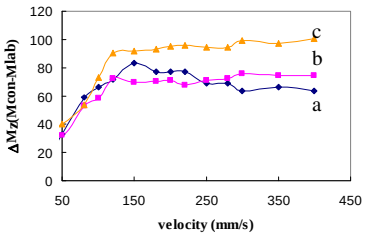

Figure 2. A comparison of perfusion signal over an extended range of the flow velocity between a. CASL, b. pCASL and c. mpCASL by simulations with T_1=1500 ms and T_2=150 ms.

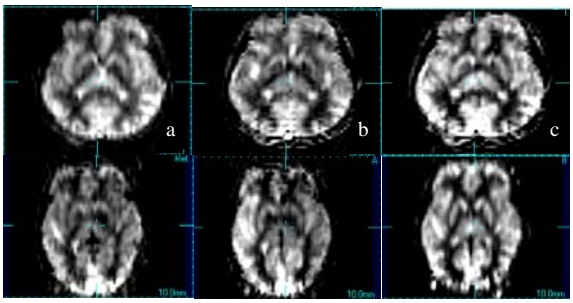

Figure 3. Representative raw perfusion images using either (a) CASL, (b) pCASL or (c) mpCASL from two subjects.

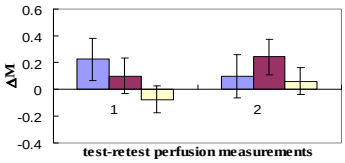

Figure 4. Variability of the mean perfusion signal (ΔM) between test-retest measurements with (1) short gap and (2) long gap using either CASL (blue), pCASL (red) or mpCASL (yellow) experiments over the multiple subjects.

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