Accelerated In Vivo 3D Pseudo-Continuous ASL with Balanced Steady State Free Precession using k-t FOCUSS

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Introduction

Pseudo-continuous arterial spin labeling (pCASL) is a recent ASL technique that consists of multiple short RF pulses to achieve labeling of the arterial blood water [1,2]. Because pCASL techniques require a relatively long labeling time of arterial blood water, echo planar imaging (EPI) is commonly used due to its high imaging speed. However, EPI is known to suffer from signal drop-out and magnetic susceptibility effects. Recently, pCASL with balanced steady state free precession (bSSFP) has been developed and proposed to overcome these limitations while maintaining a relatively high temporal resolution and SNR per unit time [3]. Although the temporal resolution of bSSFP is much higher than that of conventional gradient echo imaging sequences, it is lower than EPI which may lead to limited spatial coverage. One potential approach to improve the spatial coverage of pCASL-bSSFP is to use compressed sensing (CS). In this study, we performed the first accelerated in vivo imaging of 3D pCASL-bSSFP with k-t FOCUSS [4] at 3T for human brain. Experimental results show that CS acceleration by a factor of 4 works well for pCASL-bSSFP, which confirms that combination of CS and pCASL-bSSFP may be a good solution for blood perfusion imaging.

Material and Methods

Fully sampled 2D pCASL-bSSFP images were acquired to perform a simulation study to test the feasibility of CS using retrospective down-sampling. Afterwards, down-sampled 3D in-vivo pCASL-bSSFP data were acquired with actual implementation of down-sampling scheme in the scanner. Another set of 3D pCASL-bSSFP images were acquired using parallel imaging (PI) with the same down-sampling factor for comparison.

All experiments were performed on a 3 T whole body scanner (Siemens Medical Solutions, Erlangen, Germany) with a circularly polarized 12-element head coil. The study protocol was approved by the local ethics committee. The pCASL parameters were: RF pulse shape = Hanning window, RF duration = 0.5ms, flip angle = 25°, and spacing between two RF pulses = 0.92ms, slice-selective gradient = 6 mT/m , tagging duration = 1500 ms, post-labeling delay = 1000 ms, distance between the labeling plane and the center of the imaging group = 8 cm, and balanced tagging scheme [3]. The bSSFP experiments were conducted with a phase cycling angle of 180° and dummy phase-encoding (PE) lines of 10. The 2D bSSFP parameters were: TR / TE = 3.76 / 1.62 ms, flip angle of 40°, bandwidth = 592 Hz/pixel, matrix size = 128×128, FOV = 240×240 mm^2, number of slice = 1, and slice thickness = 5 mm. The 3D bSSFP parameters were: TR / TE = 4.02 / 1.77 ms, flip angle of 30°, bandwidth = 592 Hz/pixel, matrix size = $128 \times 32 \times 8$, FOV = $240 \times 240 \times 40$ mm^2, with slice oversampling = 25%. For 3D bSSFP parallel imaging with GRAPPA, acceleration factor of 4 was used with reference PE line numbers of 24. All experiments were repeated 60 times for averaging.

For CS application, a temporally varying down-sampling scheme with a fixed down-sampling factor of 4 was generated using a combination of uniform random and Gaussian probability distribution with full sampling of k-space center 6 line (Fig.1f) along the first PE (PE1) direction. To verify the need of CS for pCASL-bSSFP, the temporal average of the down-sampled k-space data was generated for comparison. For the generation of the temporally averaged k-space data, each corresponding PE1 lines were averaged independently by the number repeated across time.

CS reconstruction was performed using k-t FOCUSS algorithm [4]. The following k-t FOCUSS parameters were used for reconstruction: weighting matrix power factor (p) of 0.5, FOCUSS iteration number of 6, Conjugate Gradient (CG) iteration number of 100, regularization factor (λ) of 0, and no prediction.

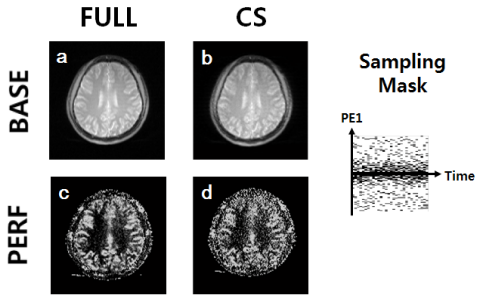

FIG.1. 2D pCASL-bSSFP images of baseline (a,b) and perfusion maps (c,d) from full-sampling (a,c) and CS reconstruction after retrospective down-sampling (b,d). The sampling geometry for retrospective down-sampling is shown on the right.

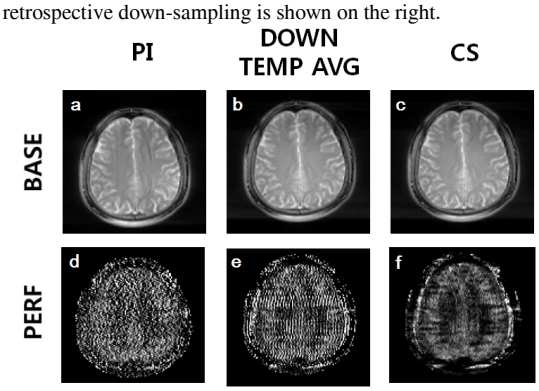

FIG.2. 3D pCASL-bSSFP images of baseline (a,b,c) and perfusion maps (d,e,f) reconstructed using PI (a,d), temporal average of the CS down-sampled k-space data (b,e), and CS (c,f) of the 3rd slice.

Results and Discussion

The 2D simulation results using the proposed sampling scheme showed overall good reconstruction of the baseline images and perfusion maps using CS on 2D pCASL-bSSFP (Fig.1). Hence, the same sampling patterns were used for 3D in vivo acquisition. As for 3D pCASL-bSSFP, baseline images are reconstructed well using PI, CS and temporally averaged k-space data, while the perfusion maps were not reconstructed well using PI and simple temporal averaging of the k-space lines (Fig.2d,f). Although perfusion maps reconstructed using CS showed minor presence of artifacts, the reconstruction quality of perfusion was much better than PI and temporal averages: overall, the structural details were reconstructed significantly better across all slices using CS (Fig.2 and Fig.3). Further studies are required for reducing artifacts by understanding the sources perfusion signal improvements, and the optimization of CS algorithm.

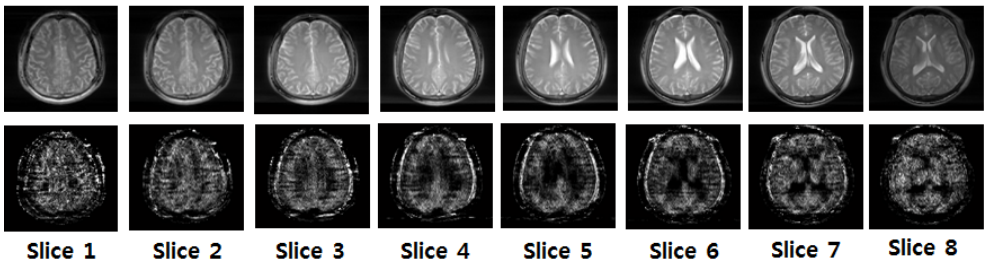

FIG.3. Baseline and perfusion maps of each slice reconstructed from down-sampled 3D pCASL-bSSFP using CS.

Conclusion

In conclusion, we found that the k-t FOCUSS algorithm with reduction by a factor of 4 may work for pCASL-bSSFP, demonstrated using 3-D in vivo data with actually accelerated imaging in the MRI scanner. The combination with CS may be a good solution to increase spatial coverage of pCASL-bSSFP.

References: 1. Wu et al, Magn Reson Med 58:1020-7 (2007) 2. Dai et al. Magn Reson Med 60(6):1499-1497 (2008). 3. Park et al, Magn Reson Imag 31:1044-50 (2013). 4. Jung et al, Ma gn Reson Med 61:103-11 6 (2009).