Parallel MRI Acceleration of Dynamic and High Resolution Hyperpolarized ^{13}C MRI

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Introduction: Imaging with hyperpolarized agents like ^{13}C-enriched pyruvate requires extremely fast imaging techniques as the hyperpolarized state only lasts for a few seconds to perhaps as much as a minute. Unfortunately, the method MRI traditionally uses for encoding spatial information into images - the switching of magnetic field gradients - is very slow, making it difficult to fully exploit the biochemical information available in the hyperpolarized MRI signal in the short imaging window for hyperpolarized ^{13}C. Parallel MRI (PMRI) can alleviate this image encoding bottleneck, allowing hyperpolarized images to be acquired faster, or with higher spatial resolution than would otherwise be possible. Using parallel MRI for imaging hyperpolarized nuclei has the added advantage that the image acquisition can be accelerated with little to no loss in SNR [1]. This contrasts with parallel MRI of thermally polarized nuclei where SNR falls at least as the square root of the acceleration factor. The use of parallel imaging with hyperpolarized nuclei effectively boosts the SNR that can be achieved in a fixed amount of imaging time by a factor equal to the square of the acceleration factor. Given the imperative to acquire images of hyperpolarized images rapidly within the short window of high polarization, the use of parallel MRI techniques will be critical to achieving high spatial and temporal resolution imaging.

In this work, PMRI is used to accelerate dynamic and high resolution imaging of rats after bolus injection of hyperpolarized ^{13}C enriched pyruvate. Our data demonstrate the feasibility and advantages of PMRI accelerated imaging at high spatial and temporal resolutions.

Methods: Approval for MRI experiments with normal male Sprague-Dawley rats was obtained from the institutional Animal Use Subcommittee. Fully gradient-encoded datasets were collected from a rat following bolus injection of pre-polarized [1-^{13}C] pyruvate in solution (CIL, Cambridge MA) with a nominal concentration of 80mM, and pH ~7.4 into the tail vein. A Hypersense DNP polarizer (Oxford Instruments, Abingdon UK) was used for sample polarization. The injection volume was 2.5 ml and the injection tool place over a 12s period. Images were collected with a 2D fast gradient recalled echo (FGRE) sequence (TR = 10.7 ms, TE = 4.8 ms, flip angle = 5°, bandwidth ± 4 kHz, FOV=180x180 mm, 200 mm slice, 64x 64 matrix, acquisition time 0.58 s/image) using a custom 8 coil array designed for ^{13}C imaging at 3.0T (MR750, GE Healthcare, Waukesha, WI). Ten images were collected at 2 s intervals starting 8 s after the start of the pyruvic acid injection. The datasets were sub-sampled to simulate outer reduction factors (ORF) of 2, 3 and 4. Twelve lines were fully sampled at the centre of each k-space and coil sensitivities determined from those fully sampled lines were used to reconstruct the images with a generalized encoding matrix (GEM) reconstruction [2]. Net reduction factors were R=1.7, 2.2 and 2.6 for ORF=2, 3, 4 respectively.

A second set of higher resolution images was collected in the same animal at 8 and 15 s after a second pyruvic acid injection with the 2D FGRE sequence (TR = 11.2 ms, TE = 5.0 ms, flip angle = 10°, bandwidth ± 8 kHz, FOV=180x72 mm, 200 mm slice, 128x 52 matrix, acquisition time = 0.58 s/image). The datasets were sub-sampled to simulate ORF of 2, 3 and 4. Sixteen lines were fully sampled at the centre of k-space and coil sensitivities determined from those fully sampled lines were used to reconstruct the images with a self calibrated GEM reconstruction [2]. Net reduction factors were R=1.5, 1.9 and 2.1 for ORF=2, 3, 4 respectively.

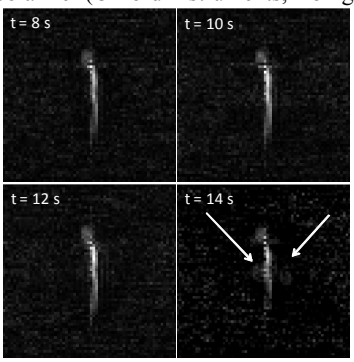

Figure 1: Series of PMRI accelerated (R=1.7) projection images acquired starting 8s following injection of 0.8 mM ^{13}C enriched pyruvic acid. In-plane resolution is 2.8 mm for all images. Effective acquisition time was 0.41 ms and images were acquired every 2.0 s. Flow of pyruvic acid into the kidneys is apparent at 14 s post injection (arrow).

Results: Figure 1 shows a set of dynamically acquired low resolution images acquired following pyruvic acid injection after decimation to simulate a reduction factor of R=1.7. These images clearly show the flow of the hyperpolarized contrast agent into the heart, abdominal vasculature and kidneys.

Figure 2 compares reconstructions of one of the higher resolution images at accelerations from R=1 (no acceleration) to R=2.1 (ORF=4). Mean g-factors for these images were 1.0, 1.5, 1.9 and 2.5 for R=1-4 respectively. Image quality is largely preserved up to R=1.9 but is significantly degraded at R=2.1 due to SNR reduction from the large g-factor at that acceleration.

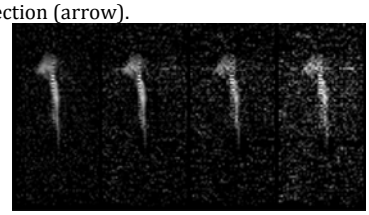

Figure 2: Series of PMRI accelerated projection images acquired 8s following injection of 0.8 mM ^{13}C enriched pyruvate. The k-space data were decimated to have net reduction factors of R=1 (no acceleration), 1.5, 1.9 and 2.1 (left to right) and then reconstructed with a self calibrated GEM reconstruction. In-plane resolution is 1.4 mm for all images. Effective acquisition times were 0.58 ms, 0.39 ms , 0.31 ms and 0.28 ms.

Discussion: We have demonstrated the successful use of self-calibrated PMRI to accelerate the acquisition of both dynamic images and high spatial resolution images of a rat following injection of hyperpolarized pyruvate. The eight-element coil array used here allowed self-calibrated imaging at one-dimensional reduction factors up to 2 before excessive SNR was lost due to increasing g-factor.

It is important to note that the SNR losses seen in these artificially decimated data sets significantly overestimate the SNR loss that would be seen in a truly accelerated image. In truly accelerated images, k-space would have been generated from fewer phase encodes (and therefore fewer RF pulses), which would allow the use of larger flip angles to generate the image that would compensate for the SNR loss from acquiring fewer phase encode lines. We also expect that the use of variable flip angle schemes, instead of the constant flip angle used in these experiments, would significantly increase the SNR of these images [3]. We hope to extend this work to 3D acquisitions with 2D self-calibrated parallel imaging.

Conclusion: These results represent the first hyperpolarized ^{13}C parallel imaging experiments conducted with a receive array with more than four coils. This work demonstrates the feasibility of using self-calibrated parallel MRI for dynamic and high resolution imaging of small animals injected with hyperpolarized ^{13}C enriched contrast agents like pyruvate.

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References: 1. Lee, et al., Magnetic Resonance in Medicine, 2006 **55**:1132-1141. 2. Sodickson and McKenzie, Med Phys, 2001 **28**:1629-43. 3. Santyr, G.E., W.W. Lam, and A. Ouriadov, Magn Reson Med, 2008 **59**:1304-10.