Highly-Accelerated Real-Time Cine MRI Using Compressed Sensing and Parallel Imaging

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Introduction: Breath-hold cine MRI with balanced steady-steady free precession (b-SSFP or TrueFisp) readouts [1] provides exquisite image quality and is now considered the gold standard for imaging myocardial function. However, in patients with impaired breath-hold capacity and/or arrhythmias, breath-hold cine MRI may yield non diagnostic image quality. In such patients, it may be necessary to perform real-time cine MRI. Currently, dynamic parallel imaging methods, such as TSENSE [2] and TGRAPPA [3], can be used to achieve an acceleration rate (R) of 2 using a standard coil array and R of 3 or 4 with a 32-element cardiac coil array. The feasible R using dynamic parallel imaging alone typically limits achievable spatial resolution and temporal resolution in real-time cine MRI. We propose to employ a recently developed joint acceleration technique that combines compressed sensing (CS) [4] and parallel imaging (PI) to exploit the joint sparsity of randomly undersampled multi-coil data [5], in order to perform real-time cine MRI with relatively high spatial and temporal resolution and clinically acceptable image quality. The purposes of this study were to highly accelerate real-time cine MRI using the joint CS-PI technology and evaluate the resulting the image quality in vivo.

Methods: Real-time cine MRI pulse sequences with b-SSFP readouts and TGRAPPA and CS-PI accelerations were implemented on 3T whole-body MRI scanners (Siemens; Tim Trio; Verio) equipped with a 32-element cardiac coil array (Invivo). The relevant imaging parameters include: FOV=300 mm x 300 mm, acquisition matrix size=128 x 128, (zero filled to 256x256 for image reconstruction), TE/TR=1.37/2.7ms, receiver bandwidth = 1184 Hz/pixel, and flip angle =40^{o}. The temporal resolutions were 86.4, 57.6, and 43.2 ms for R =4, 6, and 8, respectively. Seven adult volunteers (5 males and 2 females; mean age = 32.3 ± 14.0 years) were imaged in a mid-ventricular short-axis plane, under free breathing with electrocardiogram gating. The total scan time was 2s per slice, 1s for dummy pulses to achieve steady state magnetization, and another 1s to acquire the real-time cine data. Figure 1 shows an example of ky-t sampling pattern used for 8-fold accelerated real-time cine MRI pulse sequence, where a different random pattern along ky (phase-encoding) is used for each t in order to produce the required incoherence in the sparse y-f space [5]. TGRAPPA image reconstruction was performed on-line using a commercially available reconstruction algorithm. CS-PI image reconstruction was performed off-line using customized software developed in Matlab (MathWorks, MA). For more details on the joint CS-PI reconstruction, please see reference 5. The cine data sets were randomized and blinded for qualitative evaluation. Specifically, a cardiologist and a radiologist independently scored the image quality (1-5; highest-lowest), artifact level (1-5; highest-lowest), and noise (1-5; highest-lowest) for each cine MRI set. The reported scores represent mean ± standard deviation (SD). A single-factor analysis of variance (ANOVA) was used to compare the mean scores between the six groups ($p < 0.05$ was considered significant), and the Tukey's multiple comparison test was used to compare the mean scores between each pair of two groups ($p < 0.05$ was considered significant).

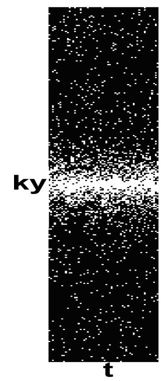

Fig. 1. ky-t sampling pattern for R =8.

Results: Figure 2 shows representative sets of end-systolic frames in a mid-ventricular short-axis plane. At R=4 and 6, TGRAPPA produced better image quality, lower artifact, and more noise than CS-PI. At R=8, CS-PI produced better image quality, lower artifact, and less noise than TGRAPPA (see Table 1 for details). According to ANOVA, the six groups were different ($p < 0.001$). All pairs were not different, except for the following pairs ($p < 0.05$): CS-PI R=4 vs. TGRAPPA R=8, CS-PI R=6 vs. TGRAPPA R=8, CS-PI R=8 vs. TGRAPPA R=4, TGRAPPA R=4 vs. TGRAPPA R=6, and TGRAPPA R=6 vs. TGRAPPA R=8. These preliminary results suggest that TGRAPPA can yield robust results at R =4 with a 32-element coil array, whereas CS-PI can yield robust results up to R=8 with 32-element coil array.

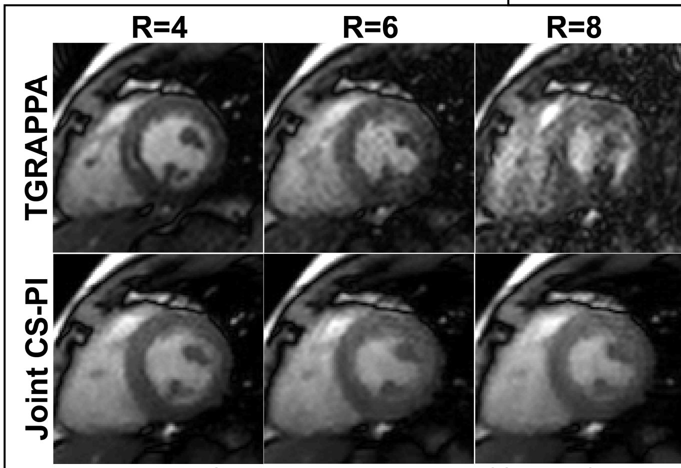

Fig. 2: (Top row) TGRAPPA; (bottom row) joint CS-PI. (Left column) R=4, (middle column) R=6 and (right column) R=8.

Discussion: This study demonstrates the feasibility of performing highly-accelerated real-time cine MRI using a joint CS-PI technique. An 8-fold accelerated real-time cine MRI protocol can achieve spatial resolution of 2.3 mm x 2.3 mm and temporal resolution of 43.2 ms, with adequate image quality (Table 1). We hypothesize that this real-time cine MRI protocol may be useful for imaging valve motion, where BH cine MRI may suffer from inconsistent valve motion over multiple heart beats. This accelerated protocol may be useful for patients with reduced breath-hold capacity and/or arrhythmias for rapid left ventricular functional evaluation. Future work includes imaging patients with various types of heart disease, performing comprehensive statistical analysis on the image quality, artifact, and noise scores, and evaluating the accuracy of quantitative volume and ejection fraction calculations using the accelerated real-time cine MRI protocol.

References: [1]. Carr, JC, et al. Radiology 2001; 219:828-34. [2]. Kellman, P, et al. MRM 2001; 45:846-52. [3]. Breuer, FA, et al. MRM 2005; 53:981-85. [4]. Lustig M, et al. MRM 2007;58:1182-1195. [5]. Otazo R et al. ISMRM 2009; 378.

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Table 1: Image quality, artifact, and noise scores (n =7). Scores represent mean ± SD.

	Image Quality (1-5; highest-lowest)			Artifact (1-5; highest-lowest)			Noise (1-5; highest-lowest)		
Technique	R=4	R=6	R=8	R=4	R=6	R=8	R=4	R=6	R=8
TGRAPPA	3.86±0.66	3.25±0.87	1.93±0.83	1.36±0.50	2.75±0.62	4.07±0.92	1.64±0.63	2.83±0.94	4.14±0.86
CS-PI	3.07±0.62	3.00±0.74	2.79±0.58	2.43±0.76	2.92±0.67	3.07±0.83	1.57±0.51	1.33±0.49	1.43±0.65