Highly-Accelerated Real-Time Cine MRI using Compressed Sensing and Parallel Imaging with Cardiac Motion Constrained Reconstruction

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Introduction: Real-time cardiac cine MRI is a valuable technique for imaging myocardial function in patients with impaired breath-hold capacity and/or arrhythmias. Currently, dynamic parallel imaging methods, such as TSENSE [1] and TGRAPPA [2] can be used to achieve moderate acceleration rates (R) of 2-3 using coil arrays but the achievable spatio-temporal resolution within one heart beat for real-time imaging is still limited. Compressed sensing (CS)[3] is an alternative method to accelerate image acquisition. Recently, highly-accelerated real-time cine MRI using a combination of CS and parallel imaging (CS-PI) [4], which jointly exploits image sparsity in dynamic data and coil sensitivity encoding was proposed to achieve R = 8 [5]. However, use of the temporal FFT as sparsifying transform yielded temporal blurring in regions with large signal variation due to cardiac motion (e.g., pixels that occupied both the myocardium and blood over time). In this work, we propose cardiac motion constrained CS-PI (MC CS-PI) reconstruction method to minimize the aforementioned artifact, by generating multiple CS-PI reconstructions with a different number of cardiac frames and combining the results in a way that minimizes temporal blurring based on a prior knowledge of cardiac motion through a cardiac cycle.

Methods: The specific image reconstruction artifact appears as temporal blurring in cine display. As shown in Fig. 1, over the course of one cardiac cycle, myocardial wall contraction and relaxation produces signal variation over time for pixels that occupy both the myocardium and blood (see green line curve in Fig. 1b,c). We simulated an 8-fold CS-PI reconstruction from a fully sampled cine data set (Fig 1a). The CS-PI reconstruction (Fig. 1e) yields good results for regions that have minimal signal variation (e.g., myocardium and blood signal curves in Fig. 1c), whereas it yields temporal blurring in regions that occupy both the myocardium and blood over time, because signal variation causes increased temporal frequency components and, consequently, reduces sparsity in temporal frequency domain (note that the green line curve in Fig. 1d is broader than black, red, and pink curves). Based on this observation, as well as on prior knowledge of cardiac motion through a cardiac cycle (periodic contraction and relaxation), we propose to perform multiple CS-PI reconstructions with user defined number of cardiac frames such that the reconstruction results are constrained to minimize temporal blurring (see Fig. 1 f,g).

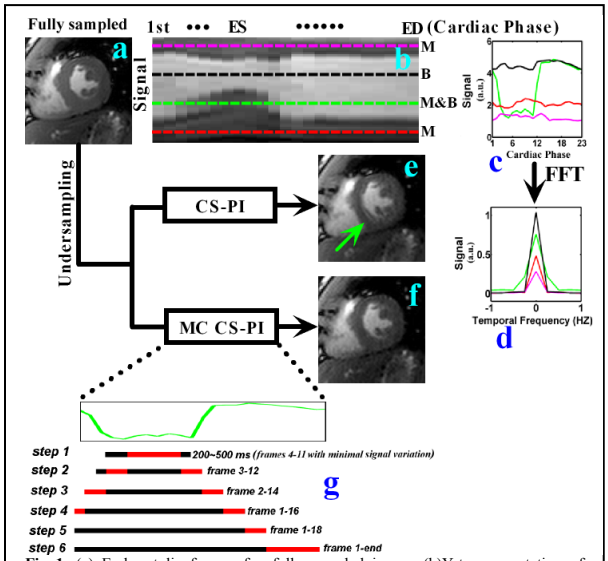

Fig 1. (a) End-systolic frame of a fully sampled image. (b)Y-t representation of intensity profile through the myocardium-blood-myocardium transitions from (a). (c) Signal intensity profiles of four pixels as a function of time (M: myocardium; B: blood; M&B: myocardium and blood) and (d) their frequency response. Simulated (e) CS-PI and (f) MC CS-PI reconstruction results. (g) Schematic of MC CS-PI reconstruction. For each step, red lines indicate frames that are reserved for the final composite combination.

To minimize temporal blurring, we developed the MC CS-PI reconstruction method (Fig. 1g) as follows. For pixels which undergo signal variation over time (e.g., green line curve in Fig. 1g), there is a period in which signal variation is minimal (i.e., flat trough of the green line curve in Fig. 1c). The center of this period approximately coincides with end systole (~300-340ms), which we can identify based on the temporal resolution of our pulse sequence. We then restrict the reconstruction to include frames (4-11) that capture this period with minimal signal variation (step 1), as well as few additional frames at the edges of this segment to increase image sparsity and incoherence. Only frames corresponding to this period with minimal signal variation are kept (red line in the 1st step in Fig 1e), whereas additional edge frames (shown as black lines in the 1st step of Fig. 1e) are discarded to ensure smooth myocardial motion when combined with subsequent results for composite reconstruction. In step 2, additional frames are added on both sides to form a longer segment (frames 3-12), and CS-PI reconstruction is used to reconstruct frames 3-12 but only the frames of interest (shown as red lines, which coincides with periods where the signal variation is minimal) are kept. In subsequent steps, the process continues until all other edge frames (with respect to the end systolic frame) are reconstructed as shown in Fig. 1g. The number of steps (typically 6) in the composite reconstruction is determined by heart rate. A final composite result is then generated by combining relevant frames (red lines) from all steps. Imaging was performed using a 3T whole-body MRI scanner (Siemens; Tim Trio) equipped with a 12-element body matrix coil array. Real-time cine MRI pulse sequences with TGRAPPA and CS-PI accelerations (R=8) were implemented on the same scanner. The relevant imaging parameters include: FOV=320mm x 320mm, acquisition matrix size=128 x 128, TE/TR=1.37/2.7ms, receiver bandwidth=1184 Hz/pixel, flip angle=40^0 and temporal resolution=43.2 ms. 14 subjects (5 volunteers and 9 patients; mean age=33±14.7 years) were imaged in a mid-ventricular short-axis plane under free breathing with electrocardiographic triggering. Image reconstruction of accelerated data was performed off-line using customized software developed in Matlab (MathWorks, MA). TGRAPPA image reconstruction was performed on-line using commercially available reconstruction software. All in vivo cine data sets (n=42 including TGRAPPA, CS-PI and MC CS-PI) were randomized and blinded for qualitative evaluation. A cardiologist and a radiologist independently scored the image quality (IQ), artifact level, noise for each cine MRI set. Myocardial wall motion quality was also evaluated MC CS-PI and CS-PI results (see table for detail). The reported scores represent mean ± standard deviation (SD). The Kruskal-Wallis test was used to compare the mean scores between three groups, and the Bonferroni test was used to compare the mean scores between each pair of two groups. Additionally, the Wilcoxon signed-rank sum test was used to compare myocardial wall temporal blurring between MC CS-PI and CS-PI. For all statistical tests, $p < 0.05$ was considered to be significant.

Results: Fig. 2 shows representative 8-fold accelerated end-systolic frames acquired in a volunteer (top) and a patient (bottom). Both CS-PI and MC CS-PI produced better IQ, lower artifact, and less noise than TGRAPPA (Table 1). CS-PI often produced artifacts in the mid wall due to temporal blurring (green arrows), whereas the MC CS-PI did not. These preliminary results suggest that MC CS-PI reconstruction can minimize temporal blurring in regions that occupy both the myocardium and blood over time, whereas the previously proposed CS-PI reconstruction is sensitive to myocardial wall motion [5]. The 3 groups were significantly different for IQ, artifacts and noise scores ($p<0.05$). All pairs were significantly different, except for CS-PI vs MC CS-PI in IQ, artifact and noise ($p>0.05$). CS-PI and MC CS-PI only differed in temporal blurring scores ($p<0.01$).

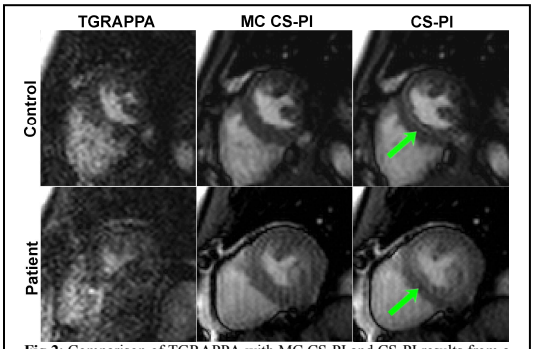

Fig 2: Comparison of TGRAPPA with MC CS-PI and CS-PI results from a volunteer (top) and patient (bottom) (R=8). Green arrow shows the temporal blurring in the mid wall, which corresponds to pixels that occupy both the myocardium and blood over time.

Conclusion: This study describes a method to perform cardiac motion constrained CS-PI reconstruction to minimize temporal blurring of pixels that occupy both the myocardium and blood over time. Future work includes the development of a more robust temporal sparsifying transform, which may be needed to compensate for loss of incoherence through use of fewer frames to generate data sets.

Reference: [1]. Kellman, P, et al. MRM 2001; 45:846-52. [2]. Breuer, FA, et al. MRM 2005; 53:981-85. [3]. Lustig M, et al. MRM 2007; 58:1182-1195. [4]. Otazo R et al. MRM 2010; 64:767-776. [5]. Feng L et al. ISMRM 2010; 4044.

Table 1: Image quality, artifact, and noise scores (n =14). Scores represent mean ± SD.

	Image Quality (5-1: highest-lowest)	Artifact (5-1: highest-lowest)	Noise (5-1: highest-lowest)	Temporal blurring (5-1: highest-lowest)
TGRAPPA	1.71±0.54	4.29±0.58	3.96±0.54	NA
CS-PI	3.64±0.41	1.86±0.36	2.00±0.34	3.32±0.82
MC CS-PI	3.71±0.64	1.93±0.58	1.89±0.53	2.46±0.69

Grant Sponsor: AHA 0730143N, AHA 0630041N, NIH R01-HL083309, NIH R01-EB000447