Externally Calibrated ARC Parallel Imaging Reconstruction for DENSE Imaging: Initial Experience

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Introduction:

Displacement encoding with stimulated echoes (DENSE) is a method that provides high spatial density displacement measurements in the myocardium, by encoding displacement onto the phase of a spin during the mixing time of a STEAM experiment, which are processed to reveal myocardial shortening and thickening [1]. Phase-cycled complex meta-DENSE acquisition has been shown to improve cardiac strain imaging quality [2,3], but this requires doubling or tripling the scan time.

Reduction of DENSE scan time using SENSE and an acceleration factor of R=2 has been previously described [4]. However, DENSE cardiac strain imaging may benefit from the availability of non-integer acceleration factors, as this enables tailoring of acquisition times to each patient's individual heart rates and breath holding capability. This would, in turn, facilitate further optimization of resolution, realizing the SNR penalty incurred with parallel imaging. In addition, k-space based (GRAPPA) or hybrid (x,k_y)-space based (ARC) [5] parallel reconstruction techniques, have been shown to have a more uniform spatial noise distribution, as compared with image-domain unfolding algorithms (SENSE) [6], and may provide good-quality image reconstructions even when accurate coil sensitivity maps are difficult to obtain [7].

We developed and evaluated a DENSE acquisition that was modified to enable integer and non-integer accelerations, with or without utilizing a variable sampling density. Low-resolution full field-of-view data was acquired in the same breath hold as the DENSE acquisition and used to externally calibrate the ARC parallel imaging reconstruction.

Methods:

9 healthy subjects (3M/6F; ages 54±11 years; weight 160±38lbs; heart rate 65±8bpm) were scanned on a 1.5T MRI (GE Healthcare, Waukesha WI) using an 8-channel cardiac coil, under an IRB-approved protocol. A mid-ventricular slice was acquired with systolic-phase ECG-gated DENSE with parameters: FSE readout, ETL: 24-32, TE: 4.4ms/TR: 1-2RR. 128x128, 36x27cm FOV, 8mm slice thickness, 6 mm/π encoding strength, 210-350ms encoding interval (TM). Discarded acquisitions (dda) were used to establish steady state: 2 dda for non-accelerated scans; 1 dda followed by the B1map (a 1 ETL full FOV FSE image) for accelerated scans. The following protocols, ordered by scan time, were compared: (1) 14 cardiac cycles (32 ETL and 1RR imaging, 1.5x acceleration); (2) 20 cardiac cycles (24 ETL, 1RR imaging, 1.3x acceleration); (3) 26 cardiac cycles (24 ETL, 1RR imaging, no acceleration); (4) 29 cardiac cycles (24 ETL, 2RR imaging, 2.0x acceleration).

Data was processed offline using IDL-based (ITTVIS) custom software (Denseviewer, GE Healthcare). In all subjects, the left-ventricular epicardial and endocardial contours were manually traced, and blood pool and lung pixels automatically removed. The myocardium was then automatically divided into 6 circumferential sectors, and strain map processing was performed. Averages and standard deviations for each subject, for each protocol, for each of the 6 sectors were recorded for circumferential shortening (CS) and radial thickening (RT), and compared with paired t-tests.

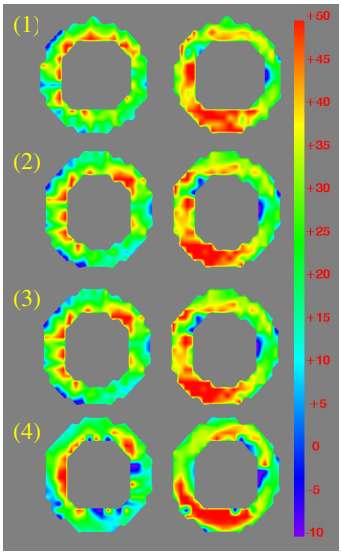

Figure 1: DENSE strain (protocols 1-4) in one subject. CS (left); RT (middle) (-10-50%); magnitude image (right). Note that major features are preserved at all accelerations.

Results: There was no statistically significant difference in average CS or RT strain between any of the protocols. There was also no difference in mean intra-sector variability (V1, standard deviation of strain within sectors) between protocols 1 and 2, or between protocols 3 and 4, for CS or RT. V1 decreased with increasing scan time from protocol 2 (1.3x acceleration) to protocol 3 (no acceleration) for both CS and RT ($p<0.01$).

Average CS strain (25.9%) and RT strain (28.6%) were comparable to previously published values [1-4], with V1 of 14.5% (CS) and 12.7% (RT), across all myocardial sectors, all subjects and acceleration factors. Inter-sector CS and RT variability (V2, standard deviation of mean strain across subjects) ranged from 5.3% to 6.2% and was also consistent across protocols. CS and RT strain results are summarized in Table 1, for each protocol. Figure 1 also shows the consistency of CS and RT maps for one subject, over all protocols.

The noise floor in strain measurements was established by repeating the same gradient waveforms three times in the same direction. In a stationary phantom without acceleration, the noise floor was 0.0±1.4% (CS and RT). This represents the minimum noise expected without effects such as motion, body size, and coil loading. In-vivo noise is summarized in Table 2. CS noise standard deviation decreased as scan time increased from protocol 1 to protocol 2 to protocol 3 ($p<0.01$), while no significant difference is observed between protocols 3 and 4; RT noise didn't significantly change between protocols 1 and 2, or between protocols 3 and 4, but decreased from protocols 1 and 2 to protocols 3 and 4 ($p<0.05$).

Protocol	CS %	CS V1	CS V2	RT %	RT V1	RT V2
(1) 1.5x 1RR	27.4	15.4	5.5	29.9	13.5	6.2
(2) 1.3x 1RR	24.7	15.6	5.8	28.2	13.4	5.3
(3) 1.0x 1RR	26.1	13.6	5.5	28.5	12.0	5.4
(4) 2.0x 2RR	25.4	13.4	5.8	27.8	12.0	5.3

Table 1: CS and RT averages, intra-sector (V1) and inter-sector (V2) variability.

Protocol	CS %	RT %
(1) 1.5x 1RR	-0.3 ± 10.7	0.1 ± 9.1
(2) 1.3x 1RR	-0.3 ± 9.0	0.2 ± 9.0
(3) 1.0x 1RR	-0.1 ± 7.4	0.5 ± 6.9
(4) 2.0x 2RR	-0.3 ± 8.3	-0.5 ± 7.8

Table 2: In vivo noise floor (mean strain ± standard deviation).

Conclusion: We have shown that the acceleration of DENSE with externally calibrated ARC, using both integer and non-integer acceleration factors, can provide consistent CS and RT strain results. Flexible use of intermediate acceleration factors can optimize imaging for individual patient breath hold capacity and heart rate while maximizing SNR, since the acceleration can be customized to each subject. The promise of performing DENSE scans consistently in a wide variety of patients may now be realized.

References:

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