REAL-TIME NON-GATED CARDIAC MRI USING *PARADISE*: DOUBLY ADAPTIVE ACCELERATED IMAGING

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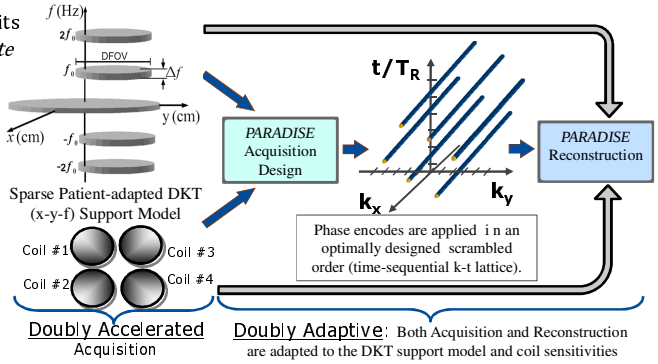
INTRODUCTION In conventional cardiac MR with no synchronization or ECG gating, the MR data is progressively acquired in the k-t space (k=spatial frequency, t=time) and images are reconstructed frame by frame using a sliding window (or view-sharing) along the temporal dimension. However, in order to satisfy the Nyquist sampling criterion for the dynamic imaging problem, the required sampling rate becomes infeasible for diagnostically useful resolutions even for the fastest pulse sequences implemented on modern scanners. Patient-Adaptive Reconstruction and Acquisition Dynamic Imaging with Sensitivity Encoding (PARADISE) [3-5], optimally adapts data acquisition and image reconstruction to both the object model and receiver coil sensitivities, thus enabling artifact-free imaging while providing performance guarantees on achievable SNR and spatial and temporal resolutions. The degrees of freedom in designing the k-t acquisition scheme are: (1) Repetition time (TR) (2) PE step size (3) Phase-encode (PE) ordering (possibly scrambled but restricted to a k-t lattice [2]). In addition to using parallel imaging, PARADISE gains acceleration from a sparse spectral support model (in the x-y-f space) that is adapted to the imaged subject; hence it is *doubly accelerated*. It uses the support information and coil sensitivities to adapt both the acquisition and reconstruction, hence the *doubly adaptive* feature. This paper presents the first state-of-the-art implementation of PARADISE for cardiac MR with comparisons to non-gated TSENSE [6].

THEORY ***Dual k-t (DKT) Support Model*** [1,2], characterizes the imaged slice by its support in the x-y-f space as shown in the adjoining figure. It captures the *approximate* periodicity (harmonics) of cardiac motion and the localized dynamic FOV. Model parameters differ among the subjects depending on average heart-rate (f_0 in the adjoining Fig), heart-rate variability (Δf) and heart position (DFOV). These three scalar parameters fully describe the support model and can be robustly estimated.



Acquisition: Given the desired resolution, the PARADISE acquisition-design algorithm adapts the sample locations in k-t space based on the object model (DKT support) while concurrently satisfying the scanner hardware and physiological constraints (TR limits, SAR, etc.). A key feature is that the k-t sampling schedule is adapted so that it guarantees reconstructibility while maximizing the expected reconstruction SNR (spatio-temporal g-factor) [4]. The algorithm solves a geometric optimization problem [4] and is based on time-sequential sampling theory [2].

Reconstruction: The data acquisition (sampling in k-t space) leads to aliasing in the DKT space; note though that the aliasing pattern is controlled through the acquisition design. Aliasing within the object's DKT support, which occurs in both y and f dimensions, is dealt with using an unfolding scheme similar to the SENSE method [4] using a optimal solution for all (y, f) pixels within the DKT support. Finally, a DFT along f gives the reconstructed image sequence.

METHODS MR imaging was performed using a 1.5T Siemens Avanto scanner (Siemens Medical Solutions) with a 32-element cardiac-torso receiver array. Imaging with informed consent was performed under the NHLBI IRB. MR data was collected for volunteers (N=4) during a single breathhold. Initially, a retrospectively-gated segmented SSFP cine was acquired (256x224 matrix, 30 phases, temporal resolution=28.3ms, TR=3.54ms, Rate 4 GRAPPA, 32 reference lines, FOV=420x420mm, acquisition time=19s). The rest of the experiment was performed without ECG gating (the same FOV was retained). The DKT support model parameters were computed as follows: (1) Subject's average heart-rate (HR) during the gated scan was noted and used as an estimate for f_0 (=1.07Hz) (2) Heart position was estimated from localizer scans (|DFOV|=35%*|FOV|) (3) Harmonic bands were modeled to have a width of $\Delta f = 33\% * f_0$ to account for HR variability during the scan (actual scan HR: 62-66bpm). The design goal was to reconstruct a 256x220 image matrix size (1.6x1.9mm in-plane resolution) that captures energy in the harmonic bands at frequencies nf_0, $-5 \le n \le 5$. Having the adapted model, the PARADISE design algorithm was run (30s computation time) to achieve the optimal k-t sampling schedule (best ordering of PEs and optimal TR=3.09ms). The result was augmented with 2.4s of coil-calibration (conventional sampling with 128 PEs acquired 6 times sequentially) to make the scan self-calibrating. The final sampling schedule was fed to a customized SSFP pulse sequence (total acquisition=14.8s which is 22% shorter than 19s for cine). Next, two TSENSE acquisitions [6] with accelerations of rate R=2 (192x192 matrix, TR=2.89ms) and rate R=5 (256x223 matrix, TR=3.09ms) were performed. Figs. 1-2 show reconstructed frames and temporal changes of a 1-D cut (dashed line in Fig 1A) over 2 heartbeats.

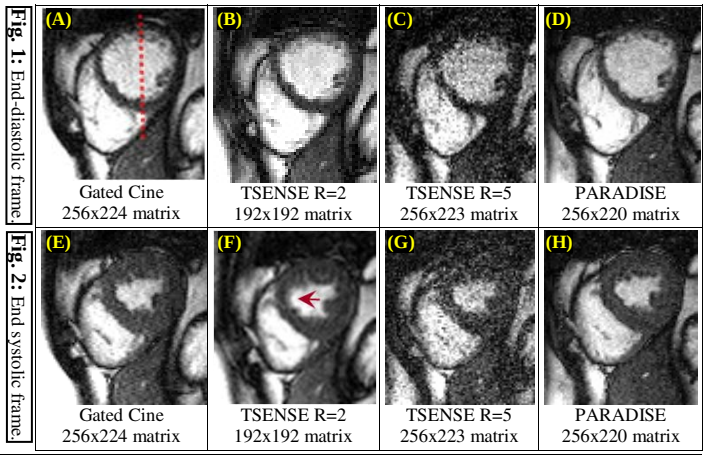


Fig. 1: End-diastolic frame.

Fig. 2: End systolic frame.

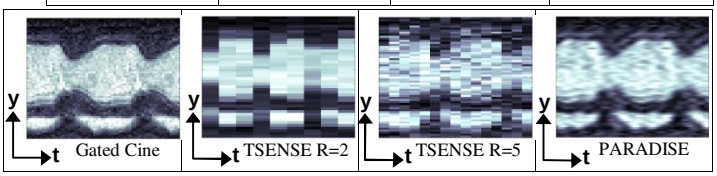


Fig. 3: y-t plots.

DISCUSSION Using gated cine results (Fig 1A,E) as a reference for real-time scans, PARADISE images are visually artifact-free (Fig 1D,H). However, rate 2 TSENSE results (Fig 1B,F) show motion artifacts (see arrow in Fig 1F) and the rate 5 TSENSE images are very noisy (Fig 1C,G). Furthermore, the temporal resolution of TSENSE is insufficient to capture the true heart dynamics as is seen clearly by comparing the plots in Fig 3. It is seen that among the non-gated results only the PARADISE result has a physiologically sound wall motion. For TSENSE, the rapid end-systolic wall thickening is not accurately captured (although R=5 is better than R=2). This is expected since TSENSE essentially assumes that the heart is static during the acquisition time of a single frame (for R=2 temporal resolution is 280ms; for R=5 is 138ms). PARADISE acceleration (sparse modeling multiplied by parallel imaging) relative to Nyquist is 7.5. This acceleration allows for matching or outperforming the gated cine's high spatial /temporal resolution (Figs 1-3) with a 22% reduction in scan time.

REFERENCES [1] Zhao Q. *et al*, ISMRM 2001, p. 1776 [2] Aggarwal N, Bresler Y, Inverse Problems v. 24, pp. 045015, 2008 [3] Sharif B, Bresler Y, IEEE ISBI 2006, pp. 45-48 [4] Sharif B, Bresler Y, IEEE ISBI 2007, pp. 1020-23 [5] Sharif B. *et al*, ISMRM 2007 (15), p. 151 [6] Kellman P. *et al*, MRM 45(5):846–52, 2001.

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