PARADISE: PATIENT-ADAPTIVE RECONSTRUCTION AND ACQUISITION IN DYNAMIC IMAGING WITH SENSITIVITY ENCODING

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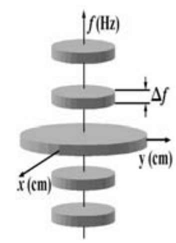
INTRODUCTION The goal of un-gated real-time cardiac MRI is to reconstruct a cardiac cine from MR data acquired without ECG triggering. Even with the fastest pulse sequences, it is infeasible to sample the entire k-space at the required Nyquist rate. The PARADIGM scheme [1-3], which was validated in-vivo [4], overcomes this limitation by adapting the MR data acquisition and the reconstruction to the spatial and temporal characteristics of the imaged object, but does not take advantage of parallel imaging hardware. Patient-Adaptive Reconstruction and Acquisition Dynamic Imaging with Sensitivity Encoding (PARADISE) [5] is a recent extension of PARADIGM that optimally adapts data acquisition and cine 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 proposed real-time method accommodates beat-to-beat variations in both heart rate and cardiac motion. This paper presents the first experimental PARADISE results with human subjects, demonstrating the effectiveness and some of the advantages of the scheme.

THEORY ***The Banded Spectral Model*** [1, 2], characterizes the cardiac object by its support in the dual k-t (DKT) space, i.e., the x-y-f space as shown in adjoining Figure. It captures the approximate periodicity of cardiac motion and the fact that the highly dynamic portion of the FOV is localized in the central heart region. The specific parameters for the model differ among subjects depending on their heart rate, heart-rate variability and heart position, and is robustly estimated using a pilot MR scan [2].



PARADISE Acquisition adapts the sample locations in k-t space based on the object model, coil-sensitivity profiles and the desired spatial and temporal resolutions. Concurrently, the scanner hardware and physiological constraints (SAR, gradient slew-rate, T_R limits) are met and the expected reconstruction SNR maximized. The solution to this optimization problem [5] is based on time-sequential sampling theory and explicitly accounts for the intrinsic constraint on the amount of data that can be acquired in a single readout.

PARADISE Reconstruction: The data acquisition (sampling in k-t space) leads to aliasing in the DKT space; note though that the aliasing pattern is controlled during the acquisition design. The aliases outside the object's DKT support are eliminated using a filter with unit magnitude response over the support. The remaining aliasing within the object's DKT support, which occurs in both spatial and temporal-frequency dimensions, is dealt with using an unfolding scheme similar to the SENSE method [5]. This is achieved using a regularized minimum-error solution for all pixels within the object's DKT support. Finally, a DFT along temporal frequency gives the reconstructed cine.

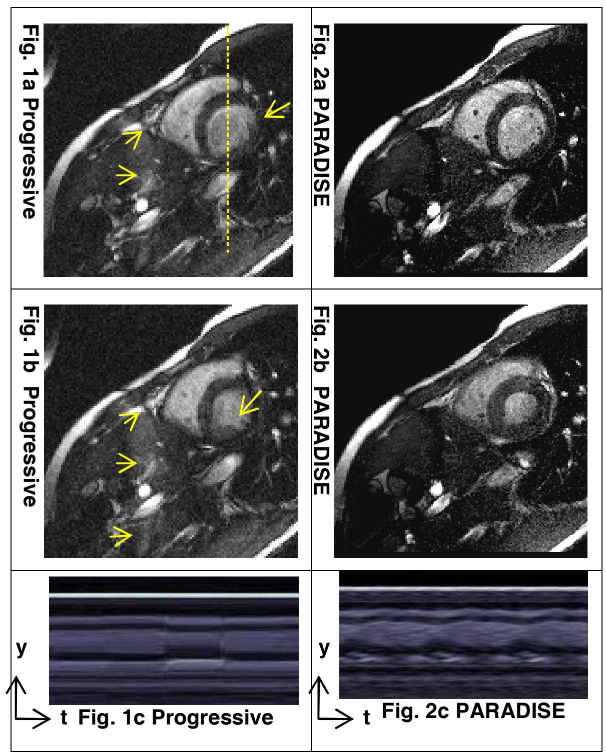


Fig. 1a Progressive; Fig. 2a PARADISE; Fig. 1b Progressive; Fig. 2b PARADISE; Fig. 1c Progressive; Fig. 2c PARADISE

METHODS The PARADISE method was tested on a 1.5T GE EXCITE scanner with a 4-element torso receiver array, using a GE FIESTA (SSFP) pulse sequence modified to allow operator-defined repetition time T_R and ordering of phase encodes. The method was used to image a healthy volunteer during a single 31s breathhold without cardiac-gating. A pilot scan was used to determine the banded-spectral-model parameters for the subject (dynamic FOV: 40% of FOV; HR: 56-64bpm). The harmonic bands were modeled to have a width Δf=0.2Hz to account for the subject's heart-rate variability. The goal was to reconstruct a cardiac cine with 256x256 image matrix size (1.56mm isotropic in-plane resolution) that captured energy in the first 5 temporal harmonic bands. The PARADISE acquisition scheme was adapted to the subject and hardware in real-time, and the best ordering of phase-encodes and optimal T_R (4.9ms) were computed. The acquisition was optimized for best SNR performance and an average g-factor (in DKT space) of 1.15 (range: 1-3.5) was achieved. For comparison, we used a non-adaptive progressive acquisition scheme that sequentially acquires adjacent k-space lines, repeating the acquisition in a loop, and uses the sliding window method for reconstruction. The T_R required by this method to meet the resolution goals is 0.4ms which is 12 times smaller (i.e., acceleration R=12) and unachievable on modern scanners. Instead, the progressive acquisition used the scanner's minimum available T_R of 3.6ms and the target image resolution was reduced to 192x192 so that a reasonable temporal resolution could be obtained. The adjoining figures shows two reconstructed frames from the 200 frames/s cines and the temporal changes of a long-axis cut through the heart (marked by a dashed line in Fig. 1a), using (1) progressive acquisition and (2) PARADISE.

DISCUSSION AND CONCLUSIONS The two schemes have comparable contrast and SNR. However while the PARADISE reconstructions are visually artifact-free (Fig. 2), the non-adaptive scheme reconstructions (Fig. 1) show blurring and ghosting artifacts (marked by arrows). More importantly, the temporal resolution of the progressive scheme is insufficient to capture the true dynamics of the heart [3,4] as is seen most clearly by comparing Figs. 1c and 2c, which show that only the PARADISE reconstructions of the myocardium has a physiologically sound motion. This is also apparent from Fig. 1b in which the rapid end-systolic wall thickening is not accurately captured by the non-adaptive scheme. This is expected since the progressive scheme essentially (and falsely) assumes that the heart is static over a period of N_yT_R (= 0.7s) while the PARADISE scheme is designed to account not only for the periodic motion of the heart, but also its beat-to-beat variation.

PARADISE also permits acceleration relative to the single-channel PARADIGM method (R=1.5 for our experiment) by taking advantage of the parallel hardware. One cannot achieve this relative performance gain by simply skipping k-space sample locations from the k-t space sampling sequence prescribed by PARADIGM, since that does not yield the optimal SNR performance, and can even violate the reconstructability condition in general. Thus the coil-sensitivity profiles are considered both at the acquisition design and at the reconstruction stages. In conclusion, the results indicate that the PARADISE technique acquires and reconstructs a full cine with high spatial and temporal resolutions by effectively combining accelerations gained by (i) patient-adaptive imaging and, (ii) parallel imaging, hence achieving accelerations higher than either of (i) or (ii) individually.

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