Continuous adaptive sampling of k-space from real-time physiologic feedback in MRI

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Target Audience: Clinicians and scientists interested in the improved k-space sampling of objects with aperiodic motion.

Background: Clinical cardiac CINE MRI takes advantage of the periodic nature of heart motion to combine data from multiple heartbeats to improve image quality [1]. However, the method is very sensitive to aperiodicity. Figure 1 illustrates the complications associated with retrospective CINE MRI in the setting of an arrhythmia. Inconsistent RR-intervals result in substantial rejection and reacquisition of data which prolongs the scan duration and leads to motion artifacts as well as contrast variation due to inconsistent data between heartbeats [2-3]. To overcome this hurdle, we propose a method, Adaptive Real-time K-space Sampling (ARKS), for continuously adapting the MRI acquisition in response to a real-time physiologic feedback signal. The algorithm allows for real-time display, improves the signal-to-noise and artifacts relative to traditional real-time acquisitions, and mitigates the motion artifacts encountered via multi-shot techniques.

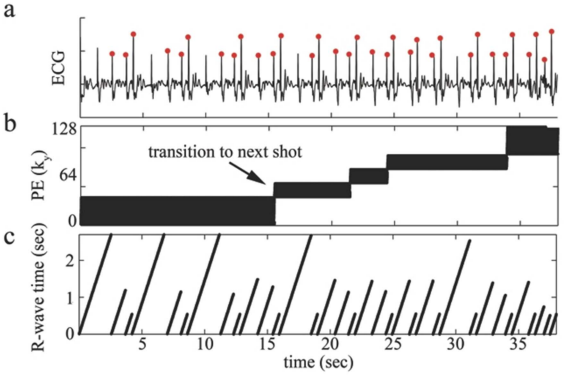

Figure 1: Acquisition of retrospective cine MRI k-space data during a severe arrhythmia and using arrhythmia rejection. **a**, ECG data is continuously acquired and R-waves (red) are detected. **b**, After each detected R-wave, $\mathbf{N}k_y$ segments of k-space are collected until, after a number of periods, all 128 $\mathbf{k}_y$ phase encodes (PE) are collected. For a normal subject in sinus rhythm, the transition from one $\mathbf{N}k_y$ to the next occurs after each R-wave is detected. For this patient with a severe arrhythmia, the inconsistent RR-interval causes these $\mathbf{N}k_y$ data to be rejected and reacquired during the subsequent, detected RR interval. This causes motion artifacts since the beat-to-beat data is inconsistent. **c**, a plot of the time from the last detected R-wave to the next clearly shows that the acquisition time is not consistent.

Methods: In ARKS, a physiologic signal, such as the ECG waveform, is measured, and the most recent signal S_s is continuously compared to the signal history S_L to determine the occurrence of similar periods in the past. The k-space location of data obtained from previous periods is used to determine how subsequent data is acquired. We hypothesized that this approach could be used to obtain near-uniform radial sampling for all time periods and would adapt well in response to arrhythmias. 3-lead chest ECG data was collected from 10 normal subjects to investigate the k-space locations chosen by the algorithm. The uniformity of radial sampling was evaluated by the comparison of angular differences obtained via ARKS, random angle, and golden angle sampling. Simulation at ARKS-based radial k-space locations was performed by encoding images obtained using golden angle radial MR data with synchronous ECG logging on a 1.5T Siemens Avanto scanner in one normal human subject and two patients with arrhythmias.

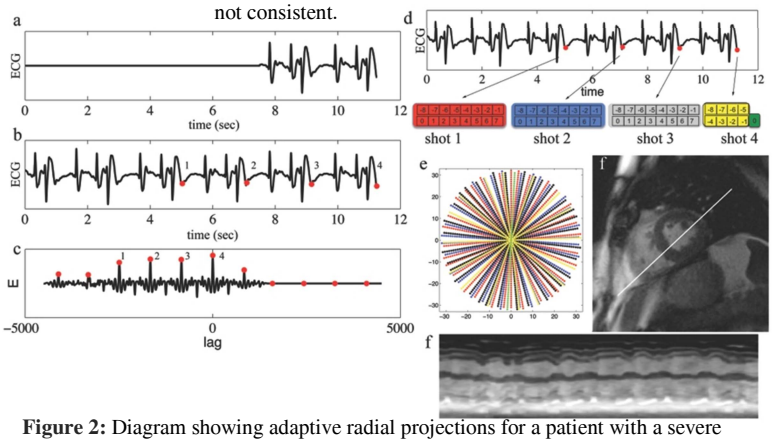

Figure 2: Diagram showing adaptive radial projections for a patient with a severe arrhythmia using a 4-16-57 sampling scheme (shots-segments-projections). **a**, Signal buffer Ss with the most recent physiologic data (1-2 heart beats). **b**, Large buffer S_L storing a previous history of the physiologic signal. 4 similar periods of the cardiac cycle are labeled (red). **c**, cross-correlation between buffers Ss and S_L. Local maxima of signal overlap are labeled (red). The negative lags for the first 4 local maxima are used to label the ECG in b. **d**, For the first 3 shots, 16 radial projections (segments) are acquired and labeled -8 to 7, with the 0 projection corresponding to the lag index in **c**. 8 projections are acquired in the last shot and together these 56 projections are used to determine the angle of the 57th projection. **e**, 57 k-space radial projections. The color of each projection corresponds to the shot index in d. **f**, simulated image from the radial projections acquired in e. **g**, time-varying ventricular volume is shown from the intersection (white line) in f.

Results: Figure 2 shows the ARKS method during a regular arrhythmia. The number of radial projections is controlled via the number of shots (number of previous periods) and segments (radial projections per period). In the example, 4 previous periods of similar ECG waveform were found and accurately labeled (red dots) despite the aperiodicity associated with the arrhythmia. Across several combinations of shots and segments, ARKS resulted in higher sampling uniformity than random sampling or golden angle sampling [4]. In this subject, the rhythm featured a normal beat, a second beat interrupted by a pre-ventricular contraction, followed by a third long beat with a longer RR-interval. Each of the three beats were correctly differentiated and segmented for ARKS, despite distortion of the ECG by the MRI scanner. Simulated ARKS images correctly depicted the tri-beat arrhythmia morphology in real-time (Fig. 2G) [5-6].

Conclusion: Adaptive real-time k-space sampling shares the benefits of real-time display, improves the signal-to-noise and artifact levels of a multi-shot radial k-space trajectory and, by adapting to a physiologic signal, mitigates deleterious motion artifacts. We anticipate that this approach will improve clinical examinations of the heart and aid in interventional studies.

References: [1] Glover et al. *Magn Reson Annu*. 1988;:299–333. [2] Klem et al. *J Am Coll Cardiol*. 2006;47:1630–1638. [3] Witschey et al. *Ann Thorac Surg*. 2014;97:1597–603. [4] Winkelmann et al. IEEE 2007 [5] Pruessmann et al. *Magn Reson Med*. 2001;46:638–51. [6] Hansen et al. *Magn Reson Med*. 2013;69:1768–76.