Adaptive Dynamic Imaging in Cardiac MR Fluoroscopy: First in-Vivo Results

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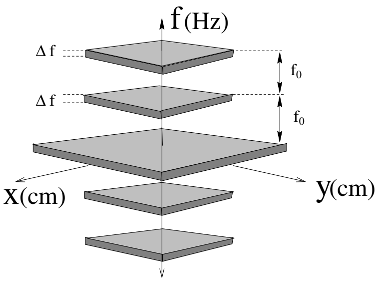
Introduction

The goal in real-time cardiac MR imaging is to reconstruct a cardiac cine from MR data acquired without ECG gating. Since MR data acquisition speed is limited, it is usually not feasible to sample each point in k-space at the required Nyquist rate. Adaptive Dynamic Imaging (ADI), proposed in [1], is an approach that enables reconstruction of a high-spatial and temporal resolution movie of the object from data acquired at a sub-Nyquist rate, by adapting the MR data acquisition and the reconstruction to the spatial and temporal characteristics of the object being imaged. This paper presents the first in vivo experimental results with human subjects that demonstrate the effectiveness and advantage of the adaptive scheme.

Theory



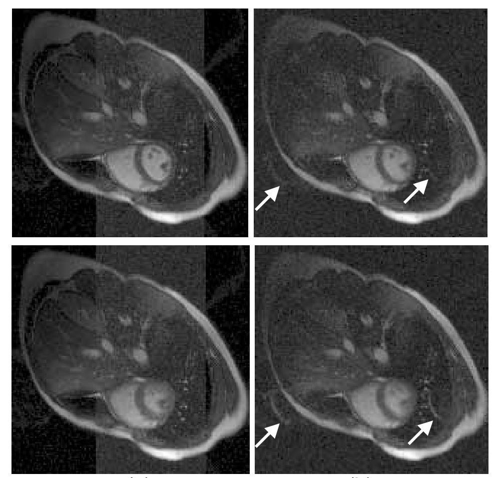
Banded Spectral Model: The banded spectral model, characterizes the cardiac TVI by its spatio-temporal-spectral (STS) support as shown in the adjoining figure. This model captures the approximate periodicity of cardiac motion and also the fact that the highly dynamic portion of the FOV (DFOV) is localized 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 can be estimated using a calibration MR scan as described in [2].
Adaptive Acquisition: Based on the banded spectral model, we seek to determine when and where to sample in k-space so that the underlying TVI can be reconstructed from the acquired data with the desired temporal and spatial resolution and SNR. Concurrently the scanner hardware and physiological constraints also have to be met. This problem was discussed in [2], and leads to an ADI scheme that prescribes the order in which the phase-encoding need to be applied and the repetition time T_R

Reconstruction: The TVI can be efficiently reconstructed from the ADI data by filtering the data with a multidimensional (spatial and temporal) linear shift-invariant filter that has unit magnitude response over the STS support of the object.

Method

The ADI method was implemented on a 1.5T GE EXCITE scanner by modifying the GE FIESTA (SSFP) pulse sequence to acquire data with operator-defined T_R and ordering of phase encodes. The method was used to image a healthy volunteer during a single breathold without cardiac gating. A pilot scan acquisition was used to determine the banded-spectral-model parameters for the subject (DFOV: 40% of the FOV; HR: 55-65 bpm). The harmonic bands were modeled to have a width of 0.2Hz to account for the subject's heart-rate-variability. The goal was to reconstruct a cardiac cine with 192×192 image frame size that captured energy in the first 5 harmonic bands. The acquisition scheme was adapted to the subject in real time, and the optimal T_R (=3.7ms), and ordering of phase-encodes were computed and used in the acquisition with the ADI method. 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 about 0.5ms i.e. 7 times smaller and un-achievable on present day scanners. Instead, the progressive acquisition used the same T_R =3.7ms as the ADI scheme.

The adjoining figure shows two frames from the 270 frames/s cines reconstructed using (a) the ADI approach and (b) the progressive sampling scheme. The frames display the cardiac MR during the systolic and diastolic phase of the heart cycle.



(a) (b)

Results and Discussion:

The two reconstructions have comparable contrast and similar SNR in the dynamic-FOV (27dB), but the ADI method uses the object model to filter out high (temporal) frequency noise in the static regions of the image, significantly improving the SNR in those regions (40dB). The adaptive scheme produces virtually artifact-free reconstructions, while the reconstructions from the progressive scheme show image blurring and ghosting artifacts (indicated by arrows). This is expected since the progressive scheme implicitly assumes that the heart is effectively stationary for a period of N_yT_R (=700ms in our case); an assumption that is clearly inaccurate. In practice, if the heart is approximately static during the acquisition of central k-space lines, the ghosting artifacts may not be apparent; however since the outer k-space data is still acquired at different phases of the heart cycle, it is inconsistent and the image is spatially blurred. Furthermore the temporal resolution of the cine is determined by the time interval between acquisitions of the central k-space data*, i.e.* by N_yT_R for progressive sampling. This resolution is insufficient to capture the true dynamics of the heart [3]. This is apparent from the progressive reconstruction during systole, in which the rapid thickening of the heart wall is not accurately captured. Segmented k-space methods can increase the cine's temporal resolution by acquiring central k-pace data more often; but only at the cost of increased spatial blurring due to the reduced rate of acquisition of outer k-space data.
The ADI method on the other hand does not assume that the object is static over a period of multiple T_R. The method is designed to account not only for the constant temporal variation of the heart, but also its aperiodicity. By adapting both the MR acquisition and the reconstruction to the imaged subject, it enables high-spatial and temporal resolution cardiac imaging. ADI also admits additional acceleration by using a receiver coil array for spatial encoding [4], thus preserving its advantages over similarly accelerated progressive or other known acquisition schemes.

References:

[1] Zhao, Q, ISMRM, pp 1776, 2001
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[4] Sharif, B, and Bresler, Y, ISBI, 2006

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