Application of Fast Imaging Techniques: Real Time

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Introduction

Real-time MRI [1-3] refers to the rapid acquisition and reconstruction of magnetic resonance images without significant delay. To be able to image dynamical processes in real-time, the acquisition time of a single frame must be small enough to "freeze" the dynamics of the observed process. Especially for cardiovascular MRI, this requires the use of fast imaging sequences and advanced reconstruction algorithms that achieve high acceleration beyond the Nyquist limit. Recent methods for real-time MRI combine fast imaging sequences, parallel imaging, non-Cartesian encoding, with new reconstruction algorithms. They enable imaging of the human heart with reasonable image quality and high spatiotemporal resolution during free breathing and without synchronization to an electrocardiogram. This lecture will explain fundamental concepts and discuss recent technical advances.

Real-time acquisition

Most approaches to real-time MRI rely on fast steady-state imaging sequences such as FLASH or balanced SSFP for continuous data acquisition [2-4] and non-Cartesian sampling schemes such as variable-density radial or multi-shot spiral trajectories [5-9]. While technically more demanding, non-Cartesian acquisition schemes are more robust to motion than Cartesian sampling and exhibit more benign undersampling artifacts at higher acceleration. Due to their inherent symmetry, images can be continuously updated as data is acquired. Interleaved acquisition schemes offer a flexible trade-off between spatial and temporal resolution, which can be exploited with sliding window schemes or with more advanced reconstruction methods. Interactive control of the MRI sequence allows changes of the scan plane and other scan parameters, *e.g.* to obtain different image constrast [10,11]. Real-time imaging can also be combined with phase-contrast MRI for imaging of cardiovascular flow [12-14].

Parallel Imaging

Parallel imaging exploits the information from multiple receive channels to accelerate the scan. Starting with the application of SENSE to real-time MRI [15], parallel imaging became an important tool in the development of new reconstruction for fast dynamic imaging. Parallel imaging relies on calibration information about the spatial sensitivity profiles of the receive coils, which poses additional challenges for real-time MRI: Movement, breathing, or changes in scan plane require (continuous) updating of this calibration information for optimal results. To some degree this can be achieved by using a sliding-window technique to obtain a fully-sampled low-resolution k-space with lower temporal resolution and the use of auto-calibration methods [16,17]. Recently, regularized non-linear inversion has been applied to real-time MRI [18,19]. In this method, image and coil sensitivities are jointly estimated for each frame, which avoids artifacts caused by inconsistencies in the calibration of the coil sensitivities. For non-Cartesian MRI, higher acceleration can be achieved with parallel imaging by using undersampling in all spatial dimensions.

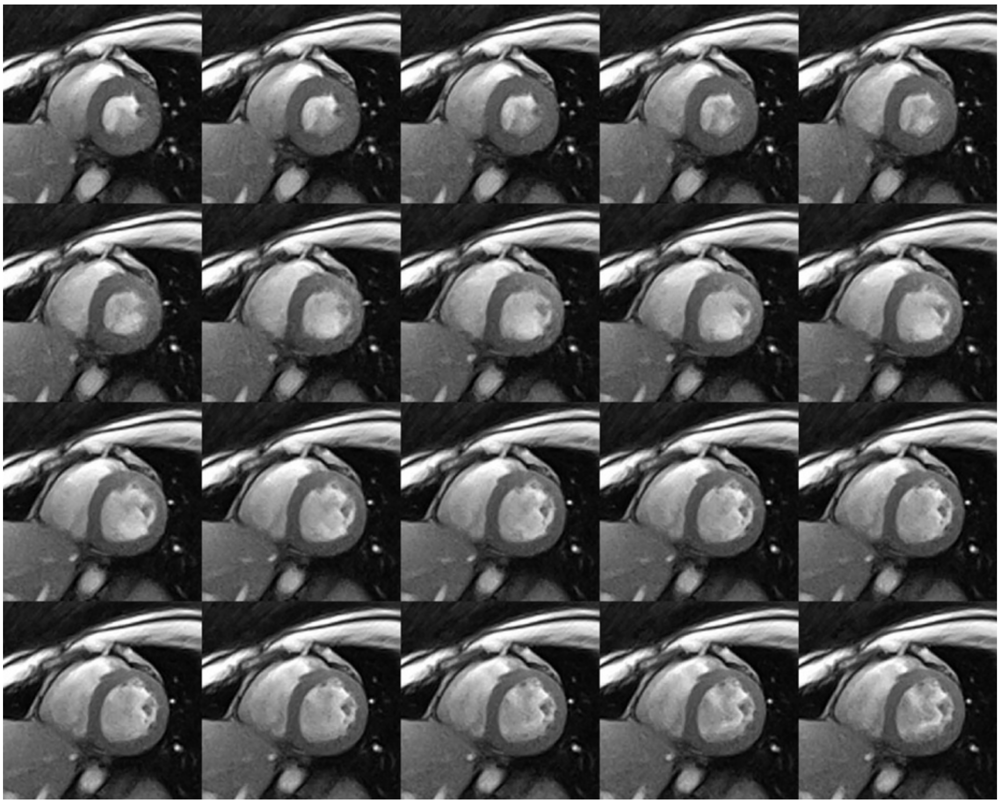

Figure 1: Real-time MRI with radial FLASH and non-linear inverse reconstruction (Zhang et al. [20]), TR/TE = 2.2/1.4 ms, FA 8°, 15 spokes, 1.5 mm resolution, 8 mm slice thickness, 33 ms acquisition time

Advanced Reconstruction with Temporal Constraints

Reconstruction methods can further enhance the temporal fidelity and quality of the reconstructions by exploiting the temporal redundancy in a time series of images. Related algorithms which have been applied to real-time MRI include UNFOLD [21] and TSENSE [22] which use linear temporal filtering, k-t BLAST and k-t SENSE using a linear reconstruction adapted to the signal distribution in k-t space [23,24], NLINV with temporal regularization and (optional) non-linear temporal filtering [25,26], and through-time GRAPPA [27]. Another promising area of research are methods based on compressed sensing using spatiotemporal sparsity [28,29] or partial separability [30]. Many new reconstruction methods for MRI combine parallel imaging with compressed sensing [31-36].

Not all methods which can be used to reconstruct data acquired in real-time can also be used for real-time image reconstruction: Algorithms using temporal constraints which integrate information from all time points (e.g. Fourier transform, temporal total-variation, or low-rankness) can only be applied to a complete data set after the acquisition is finished. In contrast, reconstruction methods designed for real-time reconstruction must be causal: To reconstruct a frame corresponding to a specific time only information from earlier times is used. In addition to using a causal algorithm, real-time image reconstruction also needs to be fast enough to keep up with the acquisition. Iterative methods have a very high computational demand and require the use of parallel processing on Graphical processing units (GPUs) for fast reconstruction [37-39,19].

Conclusion

Recent progress in real-time MRI is based on the development of advanced reconstruction algorithms. Real-time MRI opens new opportunities for basic and clinical research and promises more robust cardiovascular imaging for uncooperative patients, patients with arrhythmia, and patients who have difficulty holding their breath.

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