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Radial simultaneous multi-slice CAIPI for ungated myocardial perfusion

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ABSTRACT

Objective: Simultaneous multi-slice (SMS) imaging is a slice acceleration technique that acquires multiple slices in the same time as a single slice. Radial controlled aliasing in parallel imaging results in higher acceleration (radial CAIPIRINHA or CAIPI) is a promising SMS method with less severe slice aliasing artifacts as compared to its Cartesian counterpart. Here we use radial CAIPI with data undersampling and constrained reconstruction to improve the utility of ungated cardiac perfusion acquisitions. We test the proposed framework with a traditional saturation recovery fast low-angle shot (turboFLASH) sequence and also without saturation recovery as a steady-state spoiled gradient echo (SPGR) sequence on animal and human studies.
Methods: Simulations and phantom studies were performed for both the turboFLASH and the SPGR radial CAIPI methods. Ungated undersampled golden ratio radial CAIPI data with saturation recovery were acquired in 8 dogs and 2 human subjects. The CAIPI data without saturation pulses were acquired in 4 human subjects. For both methods, slice acceleration factors of two and three were used. A new spatio-temporal reconstruction using total variation and patch-based low rank constraints was used to jointly reconstruct the multi-slice multi-coil images.
Results: Phantom scans and computer simulations showed that ungated SPGR generally provides better contrast to noise ratio (CNR) than the saturation recovery sequence if the saturation recovery time is less than 100 ms. Both of the ungated radial CAIPI methods demonstrated promising image quality in terms of preserving dynamics of the contrast agent and maintaining anatomical structures, even with three slices acquired simultaneously.
Conclusion: Ungated simultaneous multi-slice acquisitions with either a saturation recovery turboFLASH sequence or a steady-state gradient echo SPGR sequence are feasible and provide increased slice coverage without loss of temporal resolution. Compared with a sensitivity encoding (SENSE) SMS reconstruction, the constrained reconstruction method provides better image quality for undersampled radial CAIPI data.

1. Introduction

First-pass myocardial perfusion magnetic resonance imaging (MRI) is a valuable method for characterizing blood flow in myocardial tissue and is a powerful tool for assessment of coronary artery disease [1–5]. Despite numerous advances, clinical application of first-pass myocardial perfusion MRI is still hampered by several factors, including the limited slice coverage achieved by current methods, and by electrocardiogram (ECG)-gating issues [6].

Obtaining high spatial and temporal resolution often limits the number of slices to three per heartbeat at high heartrates. Greater or complete heart coverage without losing spatial and temporal resolution is desired as this may allow better and more confident detection of disease due to visualizing more of the myocardium. This can also enable more accurate identification and sizing of ischemic zones.

To address this problem of limited coverage, undersampled acquisitions combined with advanced reconstruction methods like compressed sensing have been proposed [7,8]. Non-Cartesian k-space acquisition trajectories like radial and spiral have also been used to achieve increased slice coverage without sacrificing spatial and temporal resolutions [9–14]. 3D acquisitions offer more coverage but thus far are slow (~200 ms readout) and have relatively

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poor spatial resolution [15]. Alternatively, parallel imaging can be performed not only in-plane but also in the slice direction with 2D acquisitions to obtain multiple slices at the same time. This method is termed SMS imaging or, when the phase of each slice is adjusted separately to improve the separability of the slices, "controlled aliasing in parallel imaging results in higher acceleration" (CAIPIRINHA or CAIPI). Cartesian CAIPI achieves increased imaging coverage without losing temporal resolution and image quality [16–18]. The CAIPI method uses alternating multi-band RF pulses to excite multiple slices simultaneously. The phase modulation of the individual slices, along with reconstructions that exploit coil sensitivity, provides good image quality. Benefits from applying CAIPI to Cartesian myocardial perfusion imaging have been shown [18]. Radial CAIPI phase modulates sequential rays instead of sequential phase encodes [19], and may offer advantages compared to Cartesian CAIPI. Instead of shifting the FOV in the modulated slices as in Cartesian CAIPI, the adjacent rays in the modulated slices of radial CAIPI cancel to an extent so only a residual of each slice interferes with the non-modulated slice.

Standard perfusion imaging requires ECG gating to minimize cardiac motion effects. Gating depends on a reliable electrocardiographic (ECG) signal to image a given slice at the same phase of the cardiac cycle over multiple heartbeats [20,21]. In many patients a regular ECG signal cannot be obtained, particularly when the patient has a cardiovascular disorder like arrhythmias. Low amplitude ECG signals or the varied R-R interval width of the ECG can make accurate gating challenging. The amount of information obtained from the scans can be significantly affected if the ECG signal is poor and misses beats, or if the heart rate increases such that an acquisition is only acquired every other beat. Eliminating the need for the ECG signal also makes the protocol simpler to prepare, since the number of slices acquired is not dependent on the heart rate.

To address the limitations of the ECG problem, ungated (non-ECG-gated) perfusion acquisitions have been proposed [22–27]. These methods typically shorten the acquisition time of each time frame to obtain sufficient temporal frames of each slice to self-gate the images retrospectively. The ungated methods have been employed with saturation recovery turboFLASH sequences, and with steady state spoiled gradient echo (SPGR) sequences to acquire first pass cardiac perfusion imaging.

An ungated saturation recovery turboFLASH method was implemented on three to five slices in [22,24], and SPGR sequences were performed in 3D, 2D single slice and 2D with three slices interleaved in Refs. [23,25–27]. Although the ungated approach provides a new method for cardiac perfusion studies, the acquisition is still restricted by the limited spatial coverage due to the requirement of high temporal resolution. In this study we propose a multi-slice acquisition pattern that combines the simultaneous multi-slice excitation imaging technique and the ungated acquisition method. Both the saturation recovery turboFLASH sequence and the steady-state-based SPGR sequences are demonstrated using CAIPI for the application of myocardial perfusion imaging.

2. Materials and methods

Two different ungated acquisition methods with radial CAIPI were implemented in this study: a 2D saturation recovery turboFLASH sequence [28,29], and a steady-state SPGR sequence without saturation pulses [30]. Both the ungated saturation recovery turboFLASH and steady-state SPGR sequences employed a golden ratio radial k-space trajectory with 2, 3, or 5 simultaneous multiple slices acquired. The acquisition scheme is demonstrated in Fig. 1. A more conventional single slice sequence with golden ratio radial trajectory for both types of acquisitions was also performed for comparison. The term "multi-band factor" or MB indicates the number of slices that were acquired simultaneously.

2.1. Simulation

Simulation and phantom studies were performed initially to help better understand the image differences with and without saturation preparation at multi-band factor = 2.

For the simulations, we assumed that the multi-band radiofrequency (RF) pulse was perfectly formed by the summation of single-band RF pulses. Single-band RF profiles used in the simulation were exported from the pulse sequence in order to have realistic slice profiles. The simulation split the RF pulse into 300 subsections. The signal level of each subsection was evaluated based on the effective flip angle at the position of the subsection. The summation of all subsections was taken to determine the signal level of the slice. For the saturation recovery sequence, we performed 24 selective excitations to simulate acquiring 24 rays, and then averaged the signal level from each excitation to calculate the final signal level. For the SPGR sequence, 1500 excitations were used. The signal

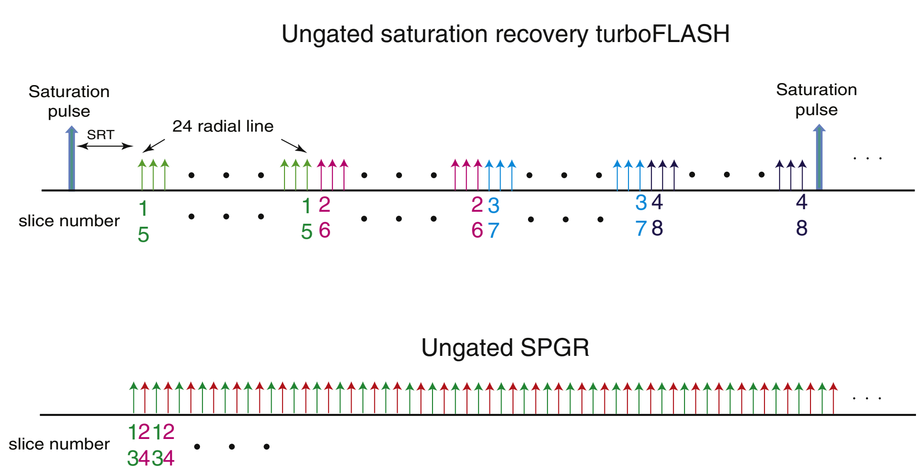

Fig. 1. Illustration of the acquisition scheme for the ungated saturation recovery sequence and ungated SPGR sequence. A multi-band factor of 2 is shown here for brevity. For each excitation, two slices were excited simultaneously as a pair. In the saturation recovery sequence, the phase was alternated between (0, 0) and (0, pi) for subsequent RF pulses. In the ungated SPGR sequence, interleaving makes the phase ordering (0, 0), (0, 0) and (0, π), (0, π). A multi-band factor of 3 will have three slices excited simultaneously, and the phase will follow (0, 0, 0) and (0, $2\pi/3$, $4\pi/3$).