Real-Time Interactive Radial Multi-Echo Steady State Free Precessing (SSFP) Imaging

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Abstract
A radial multi-echo steady state free precessing (SSFP) sequence is presented that provides a high contrast, high signal-to-noise and a good temporal resolution for cardiac function studies. A dedicated profile order allows for the inherent correction of eddy currents and B0-inhomogeneity effects during real-time scanning without any additional measurements. The cardiac function of healthy volunteers was studied during real-time interactive scanning. The effect of angular undersampling on the temporal resolution and image quality was investigated.

Introduction
Recently, steady state free precessing (SSFP) imaging, also named balanced or true FISP [1], has been successfully used in heart function studies [2]. SSFP imaging results in a high signal-to-noise ratio and in a high contrast between myocardium and blood. It has been shown that a radial SSFP acquisition has advantages in comparison with a Cartesian acquisition [3]. However, the time resolution of a single echo acquisition is still a limitation for quantitative cardiac function studies. In this work, a multi-echo version of the radial SSFP acquisition is presented using a dedicated profile order for inherent correction of eddy currents and B0-effects. The sequence was used in combination with real-time reconstruction and interactive scan capabilities.

Methods
In multi-echo acquisitions, two main phase effects have to be considered. Firstly, the difference in the eddy currents between positive and negative readouts, and secondly, the influence of B0-inhomogeneities along the echo train. To compensate for the first effect, in Cartesian acquisitions two echo trains are obtained with opposite readout directions usually in a prescan, which has to be repeated, when the orientation is changed. In radial multi-echo imaging, this calibration scan can be avoided, if a dedicated profile order is used (Fig.1). The complete acquisition is divided into two sweeps. In the first sweep, positive multi-echo trains (1,2,3,4) are obtained, i.e. each echo train starts with a positive readout. In the second sweep, the readout direction alters (trains 5,6,7,8), and echoes with opposite readouts are obtained. Assuming that the angle, under which positive and negative trains are measured, is nearly the same the phase effects due to eddy currents can be estimated for each echo separately, e.g. the phase difference can be estimated for corresponding echoes from train 1 and 6. In the real-time implementation, zero and first order phase effects are determined and corrected.

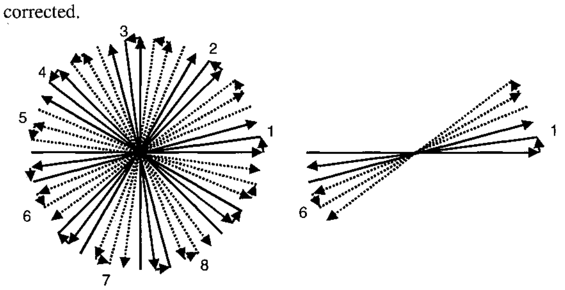

Fig. 1: Profile order used in multi-echo radial imaging. Phase correction profiles are determined from opposite trains (e.g. train 1 and 6).

B0-inhomgeneties result in azimuthal modulation of the k-space (phase and amplitude), because the projections are acquired at different echo times in each echo train. A zero-order phase correction is applied to each projection to reduce this phase-effect. The sequence has been implemented in the interactive scan mode of our scanner [4] that allows to control several MR parameters such as slice position and angulations, in-plane off-centers, excitation flip-angle, etc. during continuous scanning.

The real-time system is based on a conventional 1.5 T MR scanner (Gyroscan, ACS-NT15, Philips Medical Systems, gradients 23 mT/m in 0.2 ms) equipped with a general-purpose real-time reconstruction hardware for reconstruction of data sampled along arbitrary k-space trajectories [5]. Parallel acquisition and reconstruction of data from six phased-array coils are supported in real-time. Continuous real-time sliding window [6] image reconstruction is performed, with a frame rate of 20 images per second. The images of the individual coils are combined using the sum of squares approach. For cardiac real-time imaging, a five-element synergy coil was used. The FOV was set to 300mm, and images with a numerical resolution of 128^2 were obtained resulting in an in-plane resolution of 2.3 mm. In all experiments three echoes were obtained using a repetition time of TR=5.3 ms. Different numbers of projections (126, 96, 66) were obtained to evaluate the effect of angular undersampling on temporal resolution and image quality.

Results
In-vivo experiments to study the performance of this approach were performed on healthy volunteers. The short latency and the high update rate of 20 frames per second of the reconstructed images allow the monitoring of the cardiac motion with good temporal resolution. With the additional tool of the interactive scanning mode, scouting and/or positioning procedures are supported.

Figure 2 shows two frames (diastole and systole) of short axis view movies obtained with a radial multi-echo SSFP acquisition using two percentages of angular undersampling (0%, 50%). The angular undersampling results in a reduction of the acquisition time (220ms, 115ms), which results in a better discrimination of the myocardium (Fig. 2 b, e). However, angular undersampling results also in slightly higher undersampling artifacts (streaking) in the spatial domain.

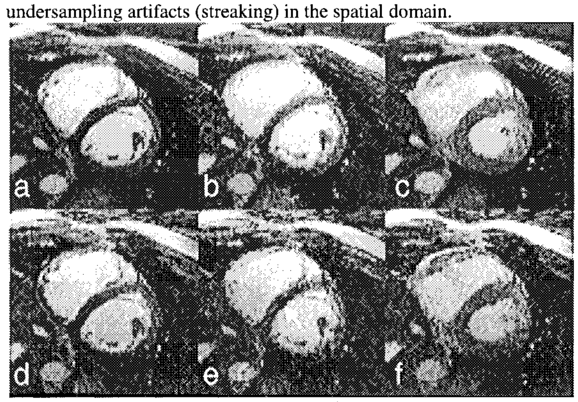

Fig. 2: Short axis view obtained with a radial multi-echo SSFP acquisition (from left to right: diastolic intermediate and systolic phase). Effect of angular undersampling in radial balanced FFE obtaining 126 (a, b ,c), 66 (d, e, f) projections. The higher time resolution allows for better discrimination of the myocardium (see arrows).

Discussion:
Radial multi-echo SSFP acquisition results in high image contrast and signal-to-noise. In comparison with a single echo acquisition, the multi-echo acquisition reduces the scan time by a factor of two. Angular undersampling can be used to reduce the scan time further. However, in case of strong angular undersampling (<50%), errors in the eddy-current correction occur due to large angular spacing of opposite echo trains. For strong angular undersampling this effect can be reduced, if the sweeps are interleaved, so that opposite trains are measured under a smaller angle.

We demonstrated that radial multi-echo SSFP imaging is a valuable tool to study cardiac function. The multi-echo acquisition significantly improves the acquisition speed in comparison with a single echo acquisition. In addition, moderate angular undersampling can be applied to increase the temporal resolution further.

References
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