Multi-echo 3D Hybrid Radial SSFP Cardiac CINE Imaging for Whole Heart Coverage in a Single Breathhold

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INTRODUCTION

Recent advances in accelerated acquisition strategies allow single breath-hold, whole heart cardiac exams in research sequences [1][2]. Conventional cardiac functional measurements are made with a standard 2D Cartesian SSFP sequence which images one slice per breath-hold, a cumbersome procedure sensitive to misregistration errors. Multi-echo 3D hybrid radial SSFP acquisitions have improved both temporal and spatial information in co-axial thoracic studies [3]. However, cardiac imaging, with its need for oblique, off-axis imaging, requires additional gradient and system calibration for robust multi-echo non-Cartesian imaging. We present additional methods to achieve whole heart short axis views within a single breath-hold of less than 20 s, with in-plane spatial resolution 1.0×1.0 mm and temporal resolution of 40-50 ms. The method is validated by measuring the left ventricle volume as a function of cardiac phase against the standard 2D multi-slice method.

MATERIALS AND METHODS

The 3D SSFP hybrid cine acquisition uses radial encoding in-plane, where four radial lines forming a bow-tie like trajectory are acquired over a 4.3 ms TR. A k-space blade is acquired by sequentially varying the Fourier-encoding in the slice dimension before changing the in-plane angle for the next cardiac phase, as shown in Fig. 1. Combining multiple echoes with off-axis, oblique, non-Cartesian imaging robustly requires additional care. We remove demodulation phase errors by measuring hardware receiver delays [4]. K-space deviations due to eddy currents and anisotropic gradient delays are also measured to further remove demodulation phase errors and properly regrid k-space data [4][5].

Radial trajectories can provide the beneficial features of retrospectively determining the temporal resolution and breath-hold duration if the ordering of projections is chosen wisely across cardiac phases (N_{phases}) and across multiple heartbeats ($N_{heartbeats}$). To interleave unique projection angles uniformly, we introduce an algorithm where the two numbers $N_{heartbeats}$ and N_{phases} are chosen to be co-prime (contain no common factors other than 1). The projection angle at i^{th} heartbeat and j^{th} cardiac phase is calculated as: $\theta_{i,j} = [(i \cdot N_{phases} + j \cdot N_{heartbeats}) \cdot \pi / (N_{phases} \cdot N_{heartbeats})] \bmod \pi$. With this strategy, SNR and temporal resolution can be traded off by combining cardiac phases, as illustrated by columns in Fig. 1. The last row shows how a running summation of cardiac phases continues to create a relatively even density sampling pattern with higher SNR if temporal resolution is sacrificed.

This angle ordering strategy can be exploited to improve SNR and CNR and decrease breath-hold duration by sharing undersampled higher spatial frequencies data from adjacent phases. We designed a temporal filter whose aperture varies at each spatial frequency using an iterative density compensation method [6] to create a minimal loss in temporal resolution.

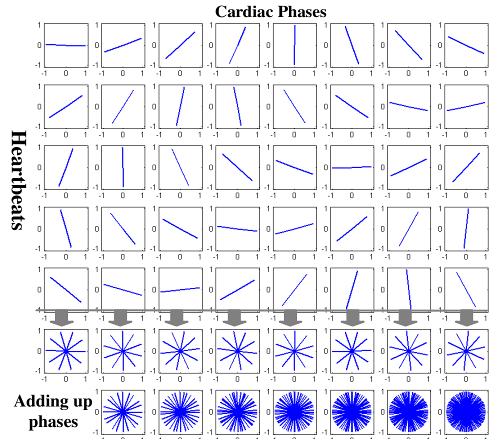

Fig. 1 Flexible reconstruction is allowed by projection distribution in k_x-k_y plane using a co-prime scheme, demonstrated with 8 phases and 5 heartbeats.

RESULTS AND DISCUSSION

The sequence was implemented on a GE 1.5T TwinSpeed scanner (GE Healthcare, Waukesha, WI) using an eight-channel cardiac coil. A slab in the short axis plane consisting of 10~12 slices of 8 mm thickness was excited and imaged with 256 resolution over a 26 cm FOV with a 30° flip angle. A longer RF pulse with an improved slab profile than our earlier work was used to cover the entire left ventricle. The breath-hold requirement was reduced to 17 s from our earlier work at 30 s [3]. These performance criteria compare favorably with currently published methods using parallel imaging [1].

Short axis images acquired with a healthy volunteer are shown in Fig. 2 for three representative slices across the R-R interval.

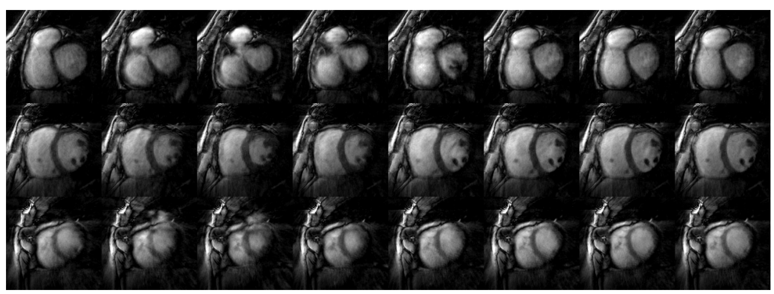

Fig. 2 High performance is demonstrated in 3 of 10 slices shown at every fourth cardiac phase out of 22 total phases. Scan parameters: 43 ms temporal resolution, 8 mm slices, 26 cm FOV, 1.0×1.0 mm in-plane resolution in 17 heartbeats (17 s).

With the standard 2D Cartesian scan, a single breath-hold of 30 s only acquires 3 slices. Fig. 3 plots the volume measurements of the left ventricle (three central slices) for both the 2D and proposed method on the same volunteer. Good agreement is demonstrated, except the proposed method slightly deviates at the end of systole (black arrow in Fig. 3). Further investigation is needed to determine the source of the disagreement.

Temporal resolution is the product of the TR and the number of slices, while a method that decreases the frame-rate during diastole may be desirable. The 2D co-prime scheme may be extended to 3D with the number of slices, cardiac phases and heartbeats co-prime to each other. Reduction in undersampling artifacts can be achieved by adding parallel imaging, using larger coil arrays, synthesizing unacquired in-plane data.

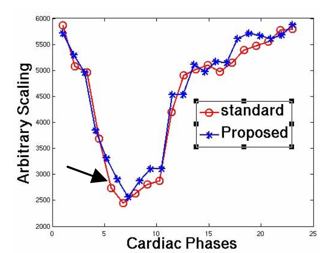

Fig. 3 Volume of left ventricle using standard single slice Cartesian method agrees well with proposed whole heart method.

CONCLUSIONS

Cardiac function evaluated through the entire heart has been achieved in a reasonable 17 s breath-hold at 1.5T with 1 mm in-plane resolution. 3D hybrid acquisitions provide several advantages for flexible breath-holds, and spatial and temporal resolutions.

ACKNOWLEDGEMENTS

We gratefully acknowledge the funding support NIH NCI 1R01CA116380 and the assistance of GE Healthcare.

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