Isotropic 3-D CINE Imaging with Sub-2mm Resolution in a Single Breath-Hold

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INTRODUCTION – MR CINE acquisitions represent the gold standard for the assessment of left ventricular function. For this purpose, a stack of 2-D CINE acquisitions is typically acquired in multiple breath-holds to cover the left ventricle and to quantitatively assess cardiac function. Recently, single breath-hold acquisitions have been proposed utilizing real-time 2-D CINE[1] and 3-D CINE[2,3] acquisitions. Although these methods feature a high in-plane resolution, small details could be missed by the low spatial resolution in slice direction. To address this limitation, a single breath-hold 3-D CINE acquisition is proposed in this work featuring an isotropic resolution below 2 mm. In-vivo experiments were performed on 5 healthy volunteers and cardiac function was compared to gold standard 2-D CINE.

MATERIALS and METHODS – The single breath-hold scan was achieved by highly accelerated data acquisition using an incoherent sub-sampling of the Cartesian phase-encoding (PE) plane with the spiral phyllotaxis pattern[4]. The prototype sequence was prospectively ECG triggered and the pattern was rotated for each cardiac phase. For the SENSE-type image reconstruction, the coil sensitivity maps (CSM) were calculated from the largest fully sampled rectangle around k-space center after data from all cardiac phases was combined. Sample locations were modified to enlarge this area, as exemplarily illustrated for 3 cardiac phases in Fig. 1.

Image reconstruction was performed using the mFISTA[5] algorithm with spatiotemporal wavelet regularization as $\boldsymbol{x} = \text{argmin}_{\hat{\boldsymbol{x}}} \sum_c \|\boldsymbol{AFS}_c\hat{\boldsymbol{x}} - \boldsymbol{y}_c\|_2^2 + \lambda\|\boldsymbol{W}\hat{\boldsymbol{x}}\|_1$, where $\boldsymbol{A}$ is the sampling pattern, $\boldsymbol{F}$ is the Fourier transform, $\boldsymbol{S}_c$ is a matrix containing the CSM of coil c, $\boldsymbol{y}_c$ is the measured data of coil c, $\boldsymbol{W}$ is a wavelet transform and λ is the regularization parameter. Image reconstruction is fully integrated into the scanner software, utilizing its graphics processing unit (GPU). The optimization was run for 50 iterations with $\lambda = 10^{-3}$ of the max. intensity.

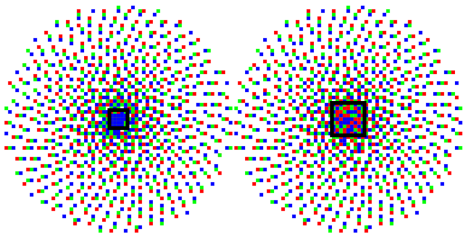

Fig. 1. Rotated phyllotaxis (left) and modified pattern (right) for 3 cardiac phases (red, green, blue). The fully sampled area is outlined in black.

3-D CINE imaging in short-axis (SA) orientation was performed in 5 healthy volunteers (male, age 30±8) on a 1.5 T clinical MR scanner (MAGNETOM Aera, Siemens AG, Healthcare, Erlangen, Germany). 3-D volume-selective, ECG-gated, balanced-SSFP images were acquired with the following parameters: TR = 3 ms, TE = 1 ms, α = 31°, FOV = 400×335±32×123 mm^3, voxel size (1.9 mm)^3 and a receiver bandwidth of 1045 Hz/Px. Slice resolution was 75 %, slice oversampling was 25 %, temporal resolution was 46 ms and the acceleration factor was 21.7. Signal reception was performed with the body and spine matrix coils. For reference, a multi-slice SA 2-D bSSFP CINE acquisition with retrospective gating using 2× accelerated GRAPPA in multiple breath-holds was performed to cover the same volume with similar temporal, identical in-plane resolution and a slice thickness of 8 mm. For evaluation, we compared the acquisition time, contrast-to-noise ratio (CNR) as well as the root-mean-square error (RMSE) of ventricular function (VF) parameters computed from the images of the gold standard 2-D CINE and our proposed 3-D CINE in corresponding slices of both data sets. The reconstruction time for 3-D CINE using the GPU was compared to an equivalent CPU implementation.

RESULTS and DISCUSSION – The 3-D CINE acquisitions were successfully performed in all volunteers. Fig. 2 demonstrates its isotropic resolution that allows for arbitrary retrospective reformatting. The mean breath-hold duration was 24±5 s, dependent on the subject's heart rate and the FOV. In comparison, 2-D CINE acquisitions took 176±6 s, including 10 s recovery time inbetween the 6 breath-holds. The CNR between blood pool and myocardial tissue was 15.5±3.2 for 3-D CINE and 20.8±5.3 for 2-D CINE. The RMSE of VF parameters of corresponding 2-D and 3-D CINE data sets was 12.2 ml for the end-diastolic volume (EDV), 2.1 ml for the end-systolic volume (ESV), 12.4 ml for the stroke volume (SV) and 3.2 % for the ejection fraction (EF) was determined. The EDV of the 3-D CINE was consistently lower by 7±3 %. The reconstruction time using a Tesla K10 GPU was 9.2±2.4 min, 7 times faster than a similar CPU implementation.

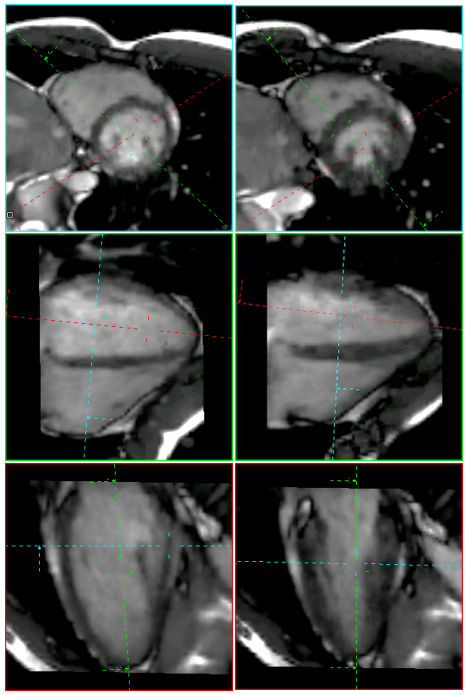

Fig. 2. Reformatted views in end-diastole (left) and end-systole (right), in short-axis orientation (top), 4-chamber view (middle) and 2-chamber view (bottom). The atria were not part of the FOV.

The acquisition time for 3-D CINE was reduced by 85 % compared to the 2-D reference, due to the high sub-sampling of k-space and lack of recovery time. The lower CNR for 3-D CINE imaging is in part due to the smaller flip angle, which had to be used to comply with specific absorption rate (SAR) limitations. However, the inherent signal-to-noise ratio benefit of volume-selective 3-D imaging allows a higher degree of sub-sampling compared to 2-D imaging. The ESV error is most probably due to segmentation variability and is not systematic. The underestimation of the EDV is largely caused by different acquisition protocols, retrospective ECG gating for 2-D vs. prospective ECG triggering for 3-D CINE, and is in accordance with previously published results[1]. Naturally, this also impacts the SV and EF errors.

CONCLUSIONS – The highly accelerated data acquisition of the presented method enables single breath-hold 3-D CINE imaging with high isotropic resolution. Promising results were achieved in the volunteer experiment, and the ventricular function parameters match the values of the gold standard. In future work, the method could be easily combined with motion compensation, allowing a free-breathing acquisition and rendering it easier to use in a clinical setting. While our experiments exemplarily focused on the ventricles, whole-heart coverage would also be beneficial for a full analysis of cardiac function. Finally, the reconstruction time has the potential to be halved by full usage of the available GPU in an optimized implementation.

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ACKNOWLEDGEMENTS – The authors gratefully acknowledge funding of the Erlangen Graduate School in Advanced Optical Technologies (SAOT) by the German Research Foundation (DFG) in the framework of the German excellence initiative.