Single-Breathhold Three-Dimensional Cardiac Cine MRI with Retrospective Cardiac Gating using High Acceleration kat ARC (k- & adaptive t- Autocalibrating Reconstruction for Cartesian Sampling)

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Introduction:
Cardiac cine MRI is routinely used to evaluate cardiac function. For quantitative assessment, high-resolution depiction of the motion of the whole heart for a complete cardiac cycle is needed, requiring volumetric cine imaging and retrospective cardiac gating. However, obtainable slice coverage has been largely limited by patients' breathhold capability and alternative approaches based on multiple breathholds suffer from slice misregistration. Recent work has demonstrated the potential of kt techniques for highly-accelerated cardiac MRI by exploiting spatiotemporal correlation [1,2,3]. However, very limited work has been done to address retrospective cardiac gating, especially with 3D cine imaging. This study develops an ultra-fast imaging approach based on kat ARC [3] (**k**- & **a**daptive-**t** **A**utocalibrating **R**econstruction for **C**artesian sampling) that is capable of single breathheld 3D cardiac cine MRI and compatible with retrospective-cardiac gating.

Methods & Materials:
kat ARC was originally demonstrated for 2D cine MRI with prospective cardiac gating. The original method was extended with the following two modifications for the purpose of this study:

1. Accelerating autocalibration signal (ACS) acquisition: kt methods require a certain number of fully sampled center k-space lines for calibration, which is an increasing large scan time overhead as the outer k-space acceleration increases, thus limiting overall acceleration. To address this issue, we implemented a tGRAPPA-like method [4] to accelerate ACS acquisition. The ACS lines were undersampled with low acceleration in a time-interleaved fashion. In reconstruction, a fully sampled calibration dataset was obtained by averaging the acquired ACS data along time and used to synthesize missing ACS lines at all time points using autocalibrating parallel imaging (ARC [5]).

2. kat ARC with retrospective cardiac gating: Unlike conventional parallel imaging, time-interleaved k-space sampling needed for exploiting spatiotemporal correlations is used by kat ARC, generating large temporal distances (acceleration factor × temporal resolution) between two temporal neighbors with the same phase-encoding. Therefore, linear temporal interpolation (LTI) conventionally used for retrospective gating itself would cause significant temporal blurring. Thus, nearest-neighbor temporal interpolation (NTI) is used to resort outer k-space acquired with kt sampling, while LTI is used for retrospective gating for ACS data that are fully recovered after the previous tGRAPPA processing.

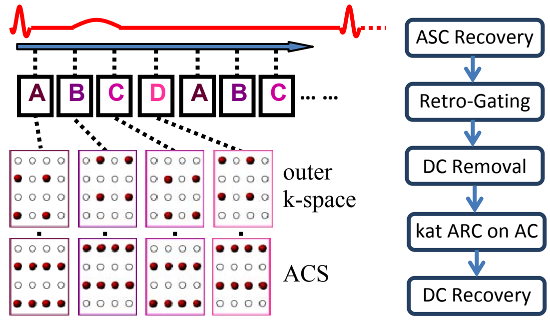

Fig.1 left: time-interleaved sampling for 4× kat ARC with 2× ACS acquisition; right: reconstruction flow chart

Fig.1 demonstrates the acquisition scheme and reconstruction flowchart of the proposed method. Both outer k-space and ACS data are undersampled using a time-interleaved scheme, with high and low acceleration, respectively. For image reconstruction, first the entire ACS k-space region was completed using tGRAPPA and then retrospective cardiac gating was performed to synchronize outer k-space and center ACS lines with cardiac motion separately based on simultaneously recorded peripheral gating signals. Next, a DC signal mask was estimated by averaging the time-series data along cardiac phases and subtracted from the k-space to reduce reconstruction error caused by static tissues (e.g. chest wall) [2]. kat ARC was then performed to recover the entire outer k-space. Similar to [3], a cardiac phase-specific temporal window was determined for each individual cardiac phase based on local motion estimated from ACS lines, selecting the most consistent temporal neighbors for data synthesis. Missing k-space data at a cardiac phase were synthesized using acquired ky-kz neighbors at the same time point and temporal neighbors within the temporal window. Finally, DC signals were added back to the recovered dynamic signals as the final reconstruction.

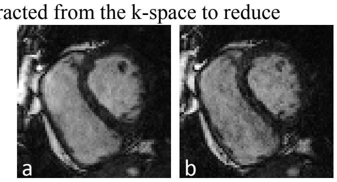

Fig.2 a) full & b) 2× ACS acquisition

To evaluate the proposed method, cardiac cine exams were conducted on 4 healthy volunteers with acceleration of 8× (4×2 in ky-kz) in outer k-space & 2× along ky for ACS (15×9 center ky-kz lines). For the purpose of this feasibility study, images with low acceleration of 4× (2×2) & 6× (3×2) were also acquired from subjects with long breathhold capability as a reference to evaluate the true single-breathhold scan with 8×. The average breathhold time was ~40sec, 30sec and 20sec for 4×, 6× 8×, respectively. All images were acquired on a GE 1.5T MR system with an 8-channel cardiac coil. Typical imaging parameters included: 320×230 mm^2 FOV, 1.7×1.7 mm^2 in plane spatial resolution, 52 ms temporal resolution, short-axis slab covering the entire ventricle, 36 slices with slicethickness of 2.5 mm (interpolated from 18 slices in acquisition). Images acquired with different acceleration factors were compared based on overall image quality and cardiac motion depiction.

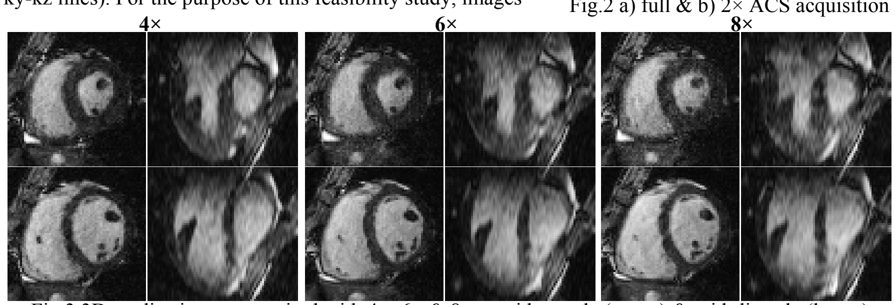

Fig.3 3D cardiac images acquired with 4×, 6× & 8× at mid-systole (upper) & mid-diastole (lower)

Results:
On all subjects, kat ARC provided good-quality 3D cine images without significant noise and artifacts. Fig.2 shows kat ARC images acquired with 2x ACS acceleration from a 20 second scan are similar to those from a 25 second scan without ACS acceleration. Fig.3 compares cardiac images (left: original, right: reformatted) collected from the same volunteer with different acceleration factors. (Note: slice is slightly shifted in different acquisitions from different breathholds.) All reconstructions provide good image quality depicting cardiac motion of the entire ventricle. The 8× image is similar to 4× and 6× at both mid-systole and diastole, except slightly increased noise and artifact level. Fig.4 compares temporal profiles obtained from the same dataset reconstructed using prospective- (a) and retrospective- (b) gating. Clearly, early-systolic phases (indicated by arrows in b) are missing in reconstruction with prospective gating; retrospective gating captures cardiac motion in the entire cardiac cycle without visible temporal blurring.

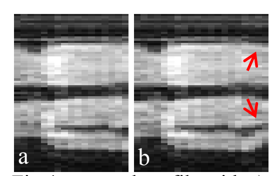

Fig.4 temporal profile with a) pro- & b) retro- gating. x axis in a & b is time direction.

Discussion:
This work developed a fast imaging technique based on kat ARC for 3D dynamic imaging and investigated its feasibility for 3D cardiac cine MRI with retrospective gating. Based on our *in vivo* results, kat ARC enables high acceleration needed for breathheld volumetric cine imaging of the entire ventricle. Also, kat ARC based on direct data synthesis in k-t space provides a flexible reconstruction scheme that addresses retrospective cardiac gating without requiring iterative reconstruction like kt SENSE [6]. Current results are mainly limited by the 8-channel coil used in this study, especially in terms of slice resolution and coverage. Using state-of-art cardiac coils with higher channel numbers should further improve image quality and achievable acceleration for both outer k-space and ACS data and can potentially provide near-isotropic volumetric motion depiction for the entire heart.

References: [1] Tsao J, MRM 2003, 50:1031; [2] Huang F, MRM 2005, 54:1172; [3] Lai P, ISMRM 2009:766; [4] Breuer FA, MRM 2005, 53:981; [5] Beatty P, ISMRM 2007:1749; [6] Hansen MS, MRM 2006, 55:85