High-Acquisition-Efficiency Cardiac 4D Flow MRI for High-SNR Motion-Robust Imaging with Contrast Agent During Delayed Enhancement Wait Time

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TARGET AUDIENCE: Researchers and clinicians interested in 4D flow or fast dynamic MRI

PURPOSE: Time-resolved volumetric phase-contrast MRI (4D Flow) has demonstrated potential for quantitative measurement of blood flow in the entire chest and thus enables comprehensive assessment of hemodynamics-related pathologies [1-3]. However, the needs of 4D flow for high spatial and temporal resolution, whole-chest coverage and respiratory motion compensation [4] contribute to a very long scan time, typically >20min with conventional parallel imaging and respiratory gating. Such a long scan time could significantly impact not only workflow but also the quality of 4D flow. Performing cardiac 4D flow without a contrast agent gives low blood SNR for flow measurement and increases the prominence of motion artifacts from chest wall. Though contrast agent is administered on a large percentage of cardiac patients for late Gd enhancement (LGE) imaging acquired 8-10 min post-injection, 4D flow with a long scan time can only be performed after LGE, which is not SNR optimal due to contrast washout and also prolongs the total exam time substantially. In this work, we aimed to develop an efficient cardiac 4D flow approach with sub-7min scan time and preliminarily evaluated its performance in comparison with conventional methods and its potential for contrast-enhanced imaging within 8 min.

METHODS: The following methods were used for improving the acquisition efficiency of cardiac 4D flow.

1. **k-t Acceleration**: kat ARC [5], a spatiotemporal-correlation-based autocalibrating parallel imaging method with cardiac motion adaptive temporal window selection, was used for fast imaging. The acquisition and reconstruction were optimized for high acceleration. As shown in Figure 1, data was collected with a variable density random (VDR) k-t sampling scheme [6], with denser center k-space sampling to improve overall reconstruction accuracy and randomization along k_y, k_z and time to reduce coherent residual artifacts. In reconstruction, a static tissue removal scheme [7], previously demonstrated for 3D CINE MRI, was adapted for 4D flow to reduce residual aliasing artifacts. Specifically, static tissues (e.g. chest wall, spine, etc) with no flow or motion were identified from initial view-sharing reconstruction based on voxel-wise analysis of signal variations along time. Next, signals from the static voxels were removed from the original data to sparsify the image and thus reduce the signal aliasing in the undersampled data. After kat ARC reconstruction of the dynamic tissue signals, the static tissue signals were added back to generate the final image.

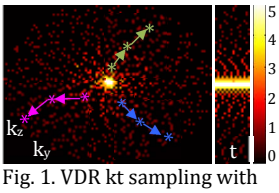

Fig. 1. VDR kt sampling with golden angle vieworder & CNEX in [k_y, k_z, t]. 3 near-radial lines indicate 3 consecutive trajectories. Different colors indicate NEX factors of k-space samples.

2. **Variable density signal averaging**: Respiratory gating is a commonly used strategy for free-breathing MRI, but it requires multiple-fold increase in scan time. Instead, this work used a scan-efficient variable density signal averaging scheme based on k-space location-dependent number of excitations (NEX). As shown in Fig. 1, the NEX factor is the highest at center k-space (=5) and decreases linearly toward outer k-space for an optimal compromise between motion compensation and scan time. Such NEX scheme at near-center k-space is termed CNEX below. Furthermore, a radial golden angle vieworder was used to minimize the adverse effects of residual motion artifacts [8,9]. At each cardiac phase, k-space sampling transits from center to outer k-space in a near radial trajectory and increments by 111.25° from one segmented acquisition to the next. With this vieworder, repeated acquisitions of the same k-space line occur at different respiratory phases such that signal averaging can effectively reduce motion artifacts. Also, respiratory motion is modulated in k-space in a pseudo-random fashion such that residual motion manifests as noise-like artifacts. In addition, fat saturation was applied before each acquisition of 4 flow-encoding echoes to further suppress chest wall fat signal and the resulting motion artifacts.

To evaluate the proposed method, 3 healthy adult volunteers were scanned on GE 3T (MR750) using 32-channel cardiac coil without contrast agent. Three 4D flow images were obtained from each volunteer using 1. the proposed method, 2. katARC without CNEX and 3. conventional ARC with the same CNEX factor. Typical imaging parameters were: 380×260 mm^2 FOV, 2.2×2.2mm^2 resolution, 76 slices with 2.4mm thickness, VPS of 1-3 (corresponding to 22, 43 or 65ms temporal resolution) depending on heart rate, 8× acceleration for katARC and 4× acceleration for ARC, CNEX on 20% central k-space data producing ~20% increase in scan time. Also, 3 pediatric patients were scanned during free breathing on MR750 using the proposed 4D flow method after injection of 0.1 mL/kg of ferumoxytol.

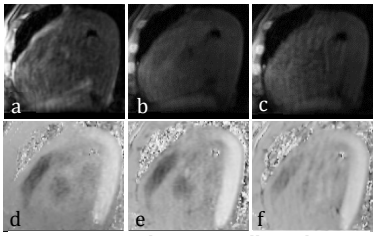

Fig. 2. Magnitude image collected using katARC without CNEX (a) & with CNEX (b) and ARC with CNEX (c) and the corresponding SI flow images in (d-f).

RESULTS: Fig.2 shows a representative comparison of different acquisitions. The proposed acquisition scheme (b & e) effectively reduces respiratory motion artifacts that are apparent in acquisition without CNEX (a & d), and produces less visible aliasing artifacts compared to ARC 4× (c & f). On all subjects, we were able to obtain 4D flow images with only minor motion artifacts and perform offline visualization and measurement of blood flow in the entire chest volume. The average scan time was 5.5 to 6.5min and 12 to 14min for the proposed method with kat ARC and 4× with ARC, respectively. The anticipated scan time for conventional 4D flow with 4× parallel imaging and respiratory gating would be ≥ 25min. Fig. 3 shows a representative contrast-enhanced case from a 5 yr old patient. Post-contrast 4D flow provides much brighter blood signal with less apparent motion artifacts than non-contrast images, which improves the confidence of flow measurements and provides better anatomic delineation. The proposed reconstruction was performed on the scanner and completed within 15min using single-thread computation.

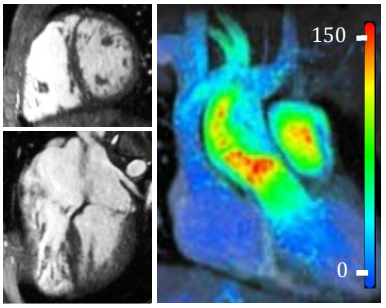

Fig. 3. Contrast enhanced 4D flow. Left: reformatted anatomy. Right: aortic root flow (cm/s) in a coronal slice.

CONCLUSION: This work developed and evaluated a new free-breathing cardiac 4D flow MRI approach with high scan efficiency that can effectively suppress respiratory motion artifacts and provide much higher acceleration than conventional parallel imaging. The proposed method enables whole-chest blood flow measurement under 7min, which can potentially be integrated easily into routine cardiac exam workflow to take advantage of the high signal pre-LGE wait time for high quality 4D flow without impacting overall cardiac exam time.

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