Accelerated 4D Flow CMR Imaging with Variable-Density Random Undersampling and Parallel Imaging

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INTRODUCTION

4D flow cardiovascular MR is hampered by long scan times. In this study, we investigated an effective undersampling scheme and an efficient parallel image reconstruction method to achieve highly accelerated 4D flow CMR with high reconstruction accuracy.

MATERIALS AND METHODS

Variable-density Poisson Disk sampling (vPDS) has been shown to be efficient for accelerating MR scans [1]. In this study, vPDS was applied to 4D flow imaging. By applying vPDS independently at each time frame (Fig.1a), we achieved random undersampling in both the k_y-k_z plane and temporal domains. We propose Sample-selective sliding window reconstruction for this TIme-Resolved Random UndersamPling (STIRRUP) to reduce undersampling by sharing data from other frames based on the temporal distance to the time frame of interest (Fig.1b). k-space was filled to the extent possible from selected adjacent time frames to form composite data sets (Fig.1c). The images reconstructed from the composite data through time (Fig1c), denoted as STIRRUP results, were also used to improve the initial solution for parallel imaging method SPIRIT [2], which iteratively achieves the final solution subjecting to data fidelity and usually uses a zero-filled initial solution (zfSPIRIT). This improved initial solution SPIRIT (iiSPIRIT) achieved improved reconstruction accuracy and robustness.

In this study, we evaluated the accelerated 4D flow CMR results with this time-resolved variable-density random sampling scheme and different reconstruction methods including STIRRUP, zfSPIRIT and iiSPIRIT. For comparison we also evaluated the results of low resolution imaging which only contains the low frequency data with the same acceleration factor as vPDS. Undersampling and reconstruction schemes were applied on fully sampled 4D flow CMR data acquired on a 1.5T Siemens Avanto scanner with a 5-ch coil in 3 volunteers. Scan settings were venc=200cm/s, FOV=320x240x55mm^3, matrix=128x96x22, ~18 time frames of 35ms temporal resolution, ~25mins scan time. vPDS (center 12x12 fully sampled; R=6) and low-resolution sampling (center 36x10 sampled; R=6) were retrospectively applied to the full data at each time frame. Flow-waveforms in the ascending (AA) and descending aorta (DA) were measured in 5 locations in each subject. Relative error was calculated with the fully sampled data as reference.

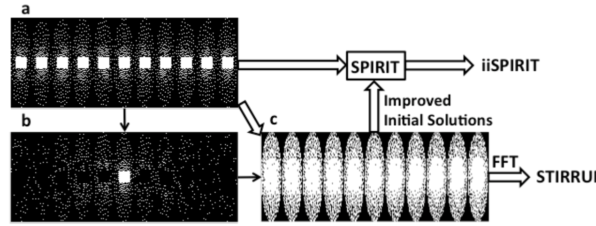

Fig.1 a) Variable-density Poisson-Disk sampling on k_y-k_z plane through time (each block is for one time frame; k-space center is fully sampled), b) the samples at each time frame selected with STIRRUP for generating a composite data at the time frame of interest, c) composite sampling patterns through time. The composited data sets are reconstructed as STIRRUP results, which are also used for improving initial solution for SPIRIT (iiSPIRIT).

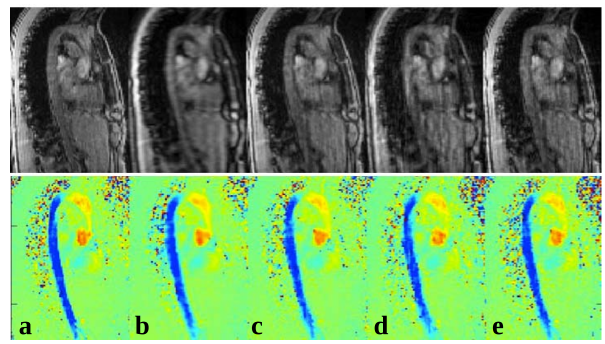

Fig.2 Magnitude (top row) and flow (bottom row) images obtained with a) full, b) low resolution (R=6), vPDS (R=6) with c) STIRRUP, d) zfSPIRIT and e) iiSPIRIT.

RESULTS AND DISCUSSION

Image reconstruction and evaluation have been successfully applied to all subjects. Fig.2 shows representative magnitude and flow images with different reconstruction methods. Although the accelerated magnitude images may degrade from the original image with variable degrees, flow images appeared to compare favorably to the fully sampled flow image (Fig.2). Representative flow-waveforms of AA and DA with different acceleration methods are shown in Fig.3a. The normalized root-mean-square errors in flow measurement of AA and DA of 3 subjects were 0.04±0.02 (low res), 0.07±0.04 (STIRRUP), 0.16±0.12 (zfSPIRIT), and 0.06±0.02 (iiSPIRIT). In Fig.3b a line of points along y direction (left-right direction of Fig.2, crossing both AA and DA) were plotted through time. It demonstrated that low-resolution results contained inaccurate contour information, STIRRUP results had a slight temporal compromise, zfSPIRIT suffered from artifacts, and iiSPIRIT achieved outstanding performance with 6-fold acceleration. Our future work includes implementation of prospective undersampling, application with a larger number of coils, evaluation of flow images with streamline visualization, and combination of compressed sensing with SPIRIT.

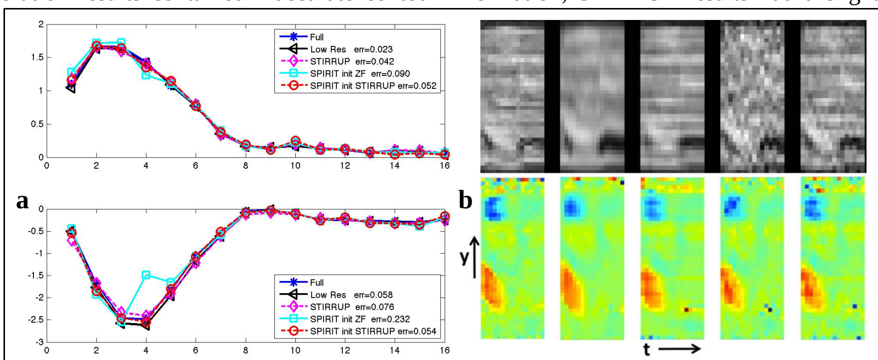

Fig.3 Left block shows representative flow-waveforms of AA and DA with full data and accelerated (R=6) methods; Right block (top magnitude images; bottom flow images) shows the profiles crossing AA and DA changing through time with different reconstruction methods (Fig2).

CONCLUSIONS

We employed undersampling patterns based on vPDS, a temporal sharing scheme STIRRUP, and parallel imaging SPIRIT to achieve 6-fold accelerated 4D flow CMR with a small number of coils. Our preliminary results with qualitative and quantitative evaluations demonstrated that the time-resolved variable-density random sampling vPDS was efficient for highly accelerating 4D flow imaging with either STIRRUP which was easy to apply but may have a slight temporal compromise, or iiSPIRIT which needed higher computation cost but maintained high image reconstruction accuracy.

REFERENCES

1. Vasanawal SS, et al, IEEE BMI 2011; p1039. **2**. Lustig, M, et al. MRM 2010;64:457-71.