Accelerated 4D Flow Imaging using Randomly Undersampled Echo Planer Imaging with Compressed-Sensing Reconstruction

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Target Audience

Scientists and clinicians who are interested in flow imaging and accelerated imaging techniques.

Introduction

2D phase contrast (PC) CMR is currently the standard clinical imaging sequence for evaluation of blood flow [1]. Recently, 3D time-resolved PC CMR (4D-PC) has been used for quantification and visualization of blood flow in all three directions of a volume [2]. However, such acquisitions require long scan times (often 10-20 minutes), which reduces its clinical feasibility and leads to motion artifacts. In this study, we sought to investigate an accelerate 4D-PC that combines an efficient data sampling strategy using echo planar imaging (EPI) with a randomly undersampled 3D k-space sampling pattern. The randomly undersampled k-space data are then reconstructed using compressed sensing (CS).

Methods

Acquisition Strategy: Figure 1 shows the k-space acquisition strategy for the proposed 3D-EPI-CS sequence. Similar to a conventional EPI acquisition, the k-space data are divided into multiple segments. For each segment, the profiles are undersampled with a CS rate such that all EPI segments have the same undersampling pattern.

Experimental Evaluation: Eleven healthy adult subjects (29±12 years; 5 males) underwent 4D-PC flow CMR on a 1.5T Philips Achieva CMR system. Images were acquired axially using a GRE sequence (FOV=340×280×60mm^3, resolution=2×2×3mm^3, EPI factor=3, Turbo Factor=2, CS rate=3, TR/TE/α=7.4/3.8ms/20°) in a volume covering the ascending and descending aorta at the level of the pulmonary artery bifurcation. Only foot-head flow encoding was used to provide an adequate temporal resolution of 30ms for the measurements. The nominal scan time for this scan was 3:30 minutes at 70 bpm. A single beam navigator placed on the right hemi-diaphragm was used to gate the acquisition with the respiratory cycle. For each subject, the 4D-PC scan was followed by a standard breath-hold 2D-PC scan with the same flow encoding direction (FOV=340×280mm^2, resolution=2×2mm^2, slice thickness=5mm^3). The 2D slice is selected from the previously obtained 4D scan and approximately at the pulmonary artery bifurcation. Flow measurements were performed both on the ascending and the descending aorta for all acquisitions. Bland-Altman analyses were performed to compare the peak values of the mean velocity measurements between the 2D scans and the corresponding slices in the 3D-EPI-CS scans.

Results

The scan time for the proposed sequence was 3:30min relative to 8:40min for a conventional parallel imaging acceleration (with a SENSE rate of 2 in Ky and 2 in Kz). Figure 2 shows flow results from one subject. Figure 2a,b shows the phase image from both the 2D and the 3D-EPI-CS scans while Figure 2c shows the mean velocity curve in the ascending aorta from the two scans. Figure 3a shows the correlation between the mean velocity measurements from the 2D and the 3D-EPI-CS scans (R^2 = 0.93), and Figure 3b shows the Bland-Altman plot for the peak values of the flow curves calculated using from both scans.

Conclusions

We propose and demonstrate a combination of EPI 4D-PC sequence with randomly underampling k-space to reduce scan time. Our initial results show no systematic difference in flow measurements between standard 2D PC and our proposed 4D-PC-CS sequences.

Acknowledgements

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References [1] Szolar, JCMR, 1996. [2] Markl, JMRI, 2003.

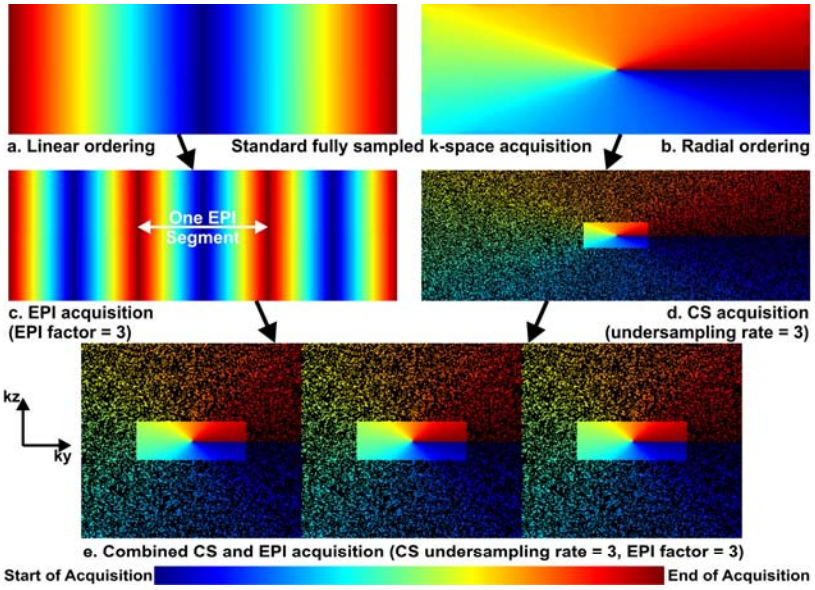

Figure 1. K-space acquisition strategy: With conventional 3D imaging, the profiles are spanned/acquired in either a linear (a) or radial ordering (b) fashion in the ky-kz plane. Based on the linear ordering strategy, EPI acceleration (c) divides the k-space into multiple segments, where one line from each segment is acquired within the same EPI shot. In contrast, CS acceleration (d) is primarily based on radial ordering, where the k-space profiles are randomly undersampled and acquired in a radial fashion while keeping the center area of the k-space fully sampled. Both EPI and CS can be combined into one acquisition with a higher acceleration rate as shown in (e). While the k-space is divided into multiple segments, each segment is randomly undersampled with the same pattern and then acquired in a radial fashion. The major advantage is the high overall acceleration rate (9 in this example) for the whole 3D acquisition, while one drawback is the necessity to fully sample parts of the k-space even if it is not at the center of the k-space.

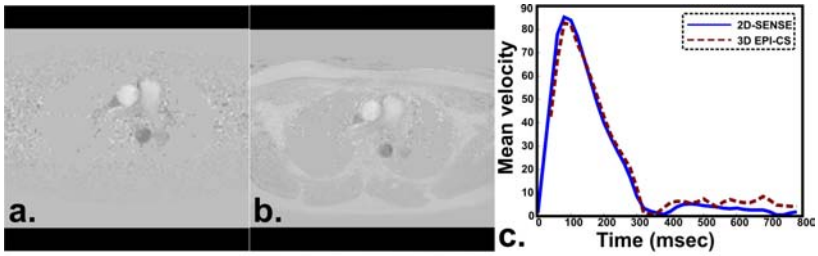

Figure 2. Representative data from one subject: (a) standard 2D flow, (b) corresponding accelerated 4D-PC-CS flow, (c) Mean ascending aorta velocity from both acquisitions.

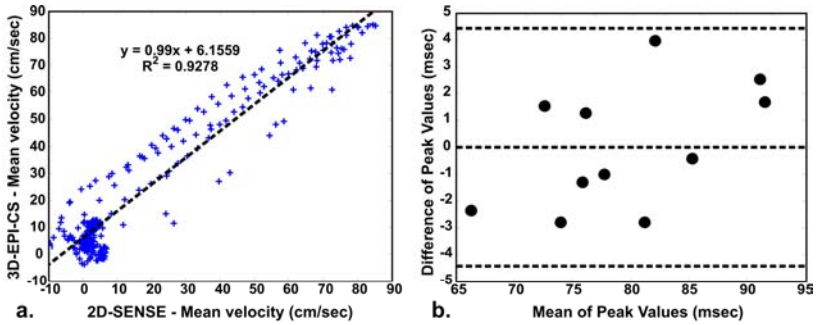

Figure 3. (a) Correlation between the mean velocity values in ascending aorta in all subjects using standard 2D-PC and the proposed 4D-PC-CS sequence; (b) Bland-Altman plot for the peak values of the mean velocities calculated in (a).