Application of Highly Accelerated Cartesian Phase Contrast Imaging Using Compressed Sensing and Iterative Reconstruction to Real-Time and Vector Encoded Flow Imaging

Andreas Greiser1, Michael Zenge1, Michaela Schmidt1, Mehmet Akif Gulsun2, and Aurelien F. Stalder1
1Siemens AG Healthcare Sector, Erlangen, Bavaria, Germany, 2Imaging and Computer Vision, Siemens Corporation, Corporate Technology, Princeton, NJ, United States

Introduction
MR phase contrast flow imaging is often used in routine clinical exams and has the potential of providing benefits over ultrasound doppler imaging in terms of applicability and spatial coverage. However, due to the limitations of segmented CINE imaging and aspects specific to flow encoding (longer echo spacing, repeated acquisitions for multiple flow encodings), so far only highly segmented acquisitions with unidirectional velocity encoding were achievable even in a breathhold. Recently, fast MR flow acquisition methods have been presented [1,2], but they either suffer from artifacts of non-Cartesian imaging or present other unwanted properties like long echo times. We demonstrate the feasibility of using L1-regularized wavelet based compressed sensing [3,4] for Cartesian MR flow imaging (CS Flow) with inline reconstruction to enable real-time and high-resolution 3-directional flow imaging in short breathhold times.

Methods
Compressed sensing flow quantification was implemented in a prototype sequence by combining compressed flow sampling and iterative reconstruction methods with phase contrast flow imaging. Iterative reconstruction was individually applied to the velocity images and subsequently passed to the flow-specific phase difference reconstruction. Pseudo-random sampling was implemented for spoiled gradient echo 2D k-t-sparse cine phase contrast acquisitions. Single-slice phase contrast datasets were acquired on a clinical 3T scanner (MAGNETOM Skyra, Siemens AG Healthcare Sector, Erlangen, Germany) in healthy volunteers (n=7) using a real-time protocol with unidirectional velocity encoding (TE/TR 2.0 ms/3.5 ms, BW 1200 Hz/px, temp. res. 55 ms, 144x128 matrix, 10 mm slice thickness, FoV 380x230 mm2, PF 66%, RTR = 11.2, 8 lines per phase, T=6s) and a segmented flow protocol with 3-directional flow encoding (TE/TR 2.5 ms/4.5 ms, BW 500 Hz/px, temp. res. 36 ms, 240x144 matrix, 6 mm slice thickness, FoV 340x255 mm2, RTR = 7.7, 2 lines per phase, TR=12 heartbeats). For comparison of quantitative flow results, an equivalent standard flow protocol was acquired (temp. res. 38 ms, 240x144 matrix, 6 mm slice thickness, FoV 340x255 mm2, GRAPPA R=2, TR=19 heartbeats). Data were analyzed using a commercial Flow analysis software (ARGUS Flow Quantification, Siemens, Erlangen, Germany). For visualization of the vector flow data, a prototype software (Siemens 4D Flow V2.4) was used.

Results
In all real-time measurements, the aortic flow parameters could be quantified. Figure 1 shows the image results of a volunteer measurement using the accelerated real-time CS Flow and the corresponding segmented standard measurement. There was a correlation between CS RT and segmented reference acquisition for peak velocity (r=0.70) and forward flow (r=0.66). The peak velocity and forward flow results from the CS Flow were validated real-time protocol were higher than from the reference protocol (PV: +6.54%, FV: +37.5%), shown in fig. 2. Vector flow data could be acquired and visualized in various slice orientations and for all temporal phases. Figure 2 shows the vector flow and velocity magnitude display in LVOT and coronal slice orientation.

Discussion and Conclusions
The use of compressed sensing in phase contrast imaging and the resulting acceleration opens up a variety of different new directions for flow measurements. Besides a higher resolution within breathhold capable scans, real-time performance and the simultaneous acquisition of multiple velocity encodings becomes available. The achieved temporal resolution acquiring as little as 8 k-space lines per phase of 56 ms needs further improvement which seems achievable by using velocity sharing [6] or even more elaborate subsampling in the velocity dimension [7]. Effects like increased background noise due to regularization [8] and increased eddy currents due to irregular step sizes in k-space require further investigation [8]. Nevertheless, accelerated protocols may improve image quality in in-cooperative and arrhythmic patients due to rapid acquisition. Enabling high-resolution vector-encoded flow imaging in a single short breathhold may improve reliable peak velocity and vortex quantification [9] in clinically feasible scan times and analysis of derived flow field properties like e.g. vorticity for pressure gradient estimate in pulmonary hypertension [10].

References