Highly Accelerated Phase Contrast Imaging using Compressed Sensing and Iterative Reconstruction for High Resolution Short Breathhold Flow Acquisitions

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Introduction Phase-contrast flow imaging is widely available for clinical exams and has the potential of providing significant benefits over echo as it can overcome user-dependency and limited accessibility. However, due to the limitations of ECG-triggered cine imaging and additional aspects specific to flow (longer echo spacing, repeated acquisitions for multiple flow encodings), only highly segmented acquisitions with compromises in spatial and temporal resolution and rather long breath holding times or even longer free breathing scans with compromised image quality are achievable. Therefore a significant acceleration of MR flow imaging is desirable, enabling high resolution flow imaging in short breath holdings. Phase contrast flow imaging seems most suitable for acceleration due to its multi-dimensionality and data redundancy. Methods have been proposed to accelerate flow imaging [1,2]. We demonstrate the feasibility of using L1 regularized wavelet based compressed sensing [3,4] for Cartesian MR flow imaging (CS Flow) with inline reconstruction and compare it to a standard breathhold flow protocol. Parameters for temporal resolution and regularization are varied and effects on flow results are analyzed.

Methods CS Flow quantification was implemented by combining compressed sensing and iterative reconstruction methods with flow imaging. Pseudo-random sampling was implemented for a spoiled gradient echo 2D k-t-sparse cine phase contrast acquisition. High resolution single slice datasets with through-plane flow encoding were acquired in volunteers (n=12) in the aorta at pulmonary level (TE/TR 2.5/3.8 ms, 240x196 matrix, in-plane res. 1.4x1.7 mm, slice thickness 6 mm, R_{eff}=7.5). Nominal temporal resolution (TR) was varied between 9 and 36 ms, resulting in acquisition durations between 6 and 24 heartbeats. For example, the protocol with TR 18 ms required 12 heartbeats. For comparison, an equivalent conventional flow protocol (Ref) with longer scan time (GRAPPA R=2, 19 heartbeats, TR 38 ms) was acquired. Volunteer measurements were repeated 5 times for reproducibility for a selected CS Flow protocol and Ref. To investigate the influence of the regularization parameter on the quantitative flow results, it was varied starting from a value optimized for cine imaging. Analysis was performed using commercial flow analysis software (ARGUS Flow, Siemens AG Healthcare Sector, Erlangen, Germany). Forward flow and peak velocity were calculated. As a measure for temporal fidelity, the peak acceleration was determined.

Results CS Flow iterative data reconstruction could be performed in-line at 1 s/frame. Forward volume (FV) and peak velocity (PV) results correlated well with the reference (r^2>0.9 for CS vs. Ref, highest correlation r^2=0.97 for TR 18 ms) but were higher compared to Ref (rel. difference FV TR 9 ms: 5.62%, 18ms: +4.83%; 27ms: +5.67%, 36ms : +5.27%; PV TR 9 ms: 8.71%, 18ms: +7.84%; 27ms: +10.15%, 36ms: +14,41%) but did not show any significant dependency on the regularization parameter (fig. 3). Temporal fidelity was improved in the CS Flow protocols with shorter TR and was preserved in accelerated protocols with comparable temporal resolution (9 ms: 15.3 m/s^2; 18ms: 13.2 m/s^2; 27ms: 12.0 m/s^2; 36ms: 9.9 m/s^2; reference: 9.2 m/s^2). Reproducibility of the CS Flow protocol was slightly lower than of the reference (stdev. CS Flow 18ms: FV/PV 4.99%/4.33%; reference: 4.52%/2.85%). Figure 1 shows the flow results for FV and PV of a volunteer measurement using the accelerated CS Flow protocols and the standard sequence. In figure 2 some examples of systolic and diastolic magnitude and phase images for TR 18 ms with different regularization parameters and reference from the same volunteer and the corresponding flow curves are shown. Higher regularization resulted in improved signal-to-noise ratio. Analysis of the background signal showed an increased signal in CS Flow data vs. reference (fig. 3).

Discussion and Conclusions CS Flow opens up the possibility of phase contrast flow acquisitions with short breathhold times or with higher temporal and spatial resolution. This extends the applicability of flow measurements to patients with low breath holding capabilities and arrhythmia. The temporal fidelity in the aortic flow data was improved for CS Flow protocols with higher temporal resolution. In the initial implementation CS Flow showed an increased background signal compared to the reference, as a consequence of the irregular sampling and regularization [5]. This implies the need for further adaptation of the method to the specific application as well as a wider clinical evaluation to identify the best compromise between acceleration and required data quality for diagnosis. However, shorter breath holdings and higher resolution may also result in a gain in quality on top of the actual speed-up. Due to the high level of integration CS Flow can easily replace the current standard.

References
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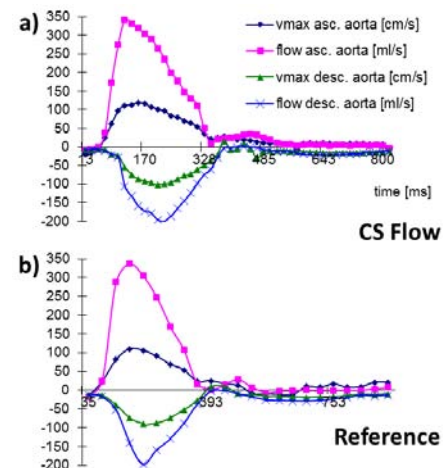
Fig.1: Flow and peak velocity curves for a): CS Flow and b) reference for ascending and desc. aorta.
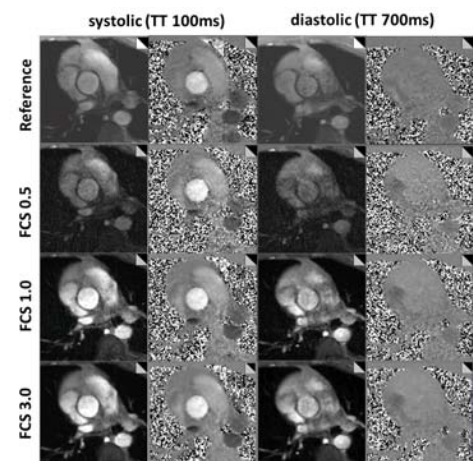

Fig.2: Magnitude and phase contrast images of reference protocol vs. accelerated CS Flow protocol (FCS) for different levels of regularization in systole (left) and diastole (right).
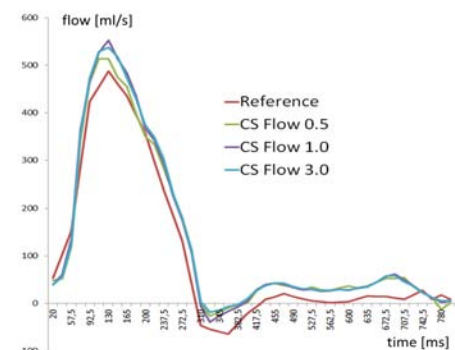

Fig.3: Flow curves for CS Flow with TR 18 ms with various regularization values compared to ref. with TR 38 ms.