Highly Accelerated 4D Flow Imaging using Compressed Sensing – a Comparison with Conventional 4D Flow in Healthy Volunteers and Patients with Aortic Diseases

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Introduction

3D cine phase-contrast (PC) imaging with three-dimensional velocity encoding (4D Flow) is an emerging imaging tool in cardiovascular diseases. 4D Flow allows the visualization of flow in all directions and spatial regions within the volume imaged and can be used to analyze complex hemodynamic properties without the need for invasive procedures and ionizing radiation. Compared with conventional 2D PC imaging, 4D Flow enables investigation of the internal data consistency (i.e. Qp/Qs measurement within the same dataset) and provides the flexibility to retrospectively place the analysis plane at any location within the imaging volume [1]. Furthermore, novel imaging biomarkers, such as wall shear stress (WSS) or loss of kinetic energy, can be estimated from 4D Flow datasets.

Nevertheless, clinical applications with 4D Flow are limited by their long acquisition time and the need for offline reconstruction, which takes several hours. Recently, a highly accelerated 4D Flow sequence[1] has been developed using Compressed Sensing (CS) acceleration with image reconstruction implemented on the scanner, which allows 4D Flow imaging of the aorta in less than two minutes, whole heart and the aorta in under seven minutes, and online image reconstruction under five minutes. This article describes our initial experience of CS 4D Flow[1] sequences in healthy volunteers and aortic diseased patients.

[1]*WIP, the product is currently under development and is not for sale in the U.S. and in other countries. Its future availability cannot be ensured.*

Table 1: Average volunteer stroke volume and peak velocity.

	Ascending Aorta	Aortic Arch	Descending Aorta	Mean
4D net flow (ml/cycle)	85.25	59.87	67.43	70.85
Δ% net flow	-5.34	-7.33	-11.55	-8.07
4D mean peak velocity (cm/s)	61.10	46.97	58.06	55.38
Δ% mean peak velocity	-6.09	-7.51	-6.20	-6.60

Δ%: Mean difference in percent between conventional and CS accelerated 4D Flow acquisition. Negative values in Δ% net flow show underestimation by CS 4D Flow.

Technical background

4D Flow MRI sequence was implemented using retrospective ECG gating and symmetric 4-point velocity encoding. Images were acquired during free-breathing with navigator gating and Respiratory Controlled Adaptive *k*-space Reordering (ReCAR) to acquire central *k*-space during end expiration and peripheral *k*-space during inspiration to reduce motion artifacts [2]. CS acceleration was achieved using a variable-density phyllotaxis pattern for subsampling with sampling patterns rotated between successive cardiac time frames to form a fully sampled center for coil sensitivity estimation and spatial-temporal L1 regularization for image reconstruction (Fig. 1).

Methods

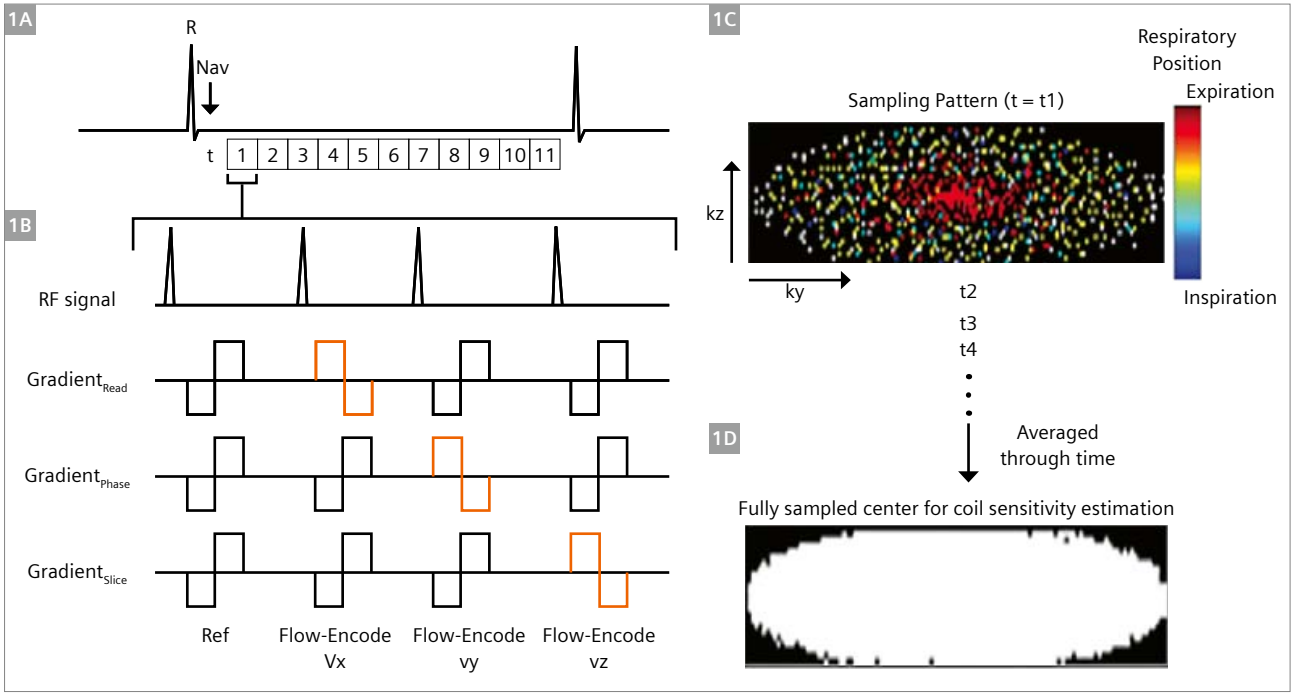
4D Flow imaging was performed on a MAGNETOM Prisma 3 Tesla MRI scanner (Siemens Healthcare, Erlangen, Germany). The study population was recruited from two prospective cohort studies at the University Medical Center Mainz, Germany.

All 4D Flow acquisitions were performed in sagittal orientation to cover the whole heart and the thoracic aorta during free-breathing with navigator gating. CS 4D Flow was acquired with an acceleration rate of 7.7, and the conventional 4D Flow was acquired with a GRAPPA acceleration rate of 3. Imaging protocols include the following parameters: TE/TR for conventional and CS 4D Flow: 38.64 / 2.28 ms and 40.48 / 2.36 ms; FOV: 380 and 360 mm, Matrix: 160 x 80 and 160 x 102, FA: 8° and 7°. All image processing was performed using the cvi[42] 4D Flow plugin (Circle Cardiovascular Imaging, Calgary, Canada).

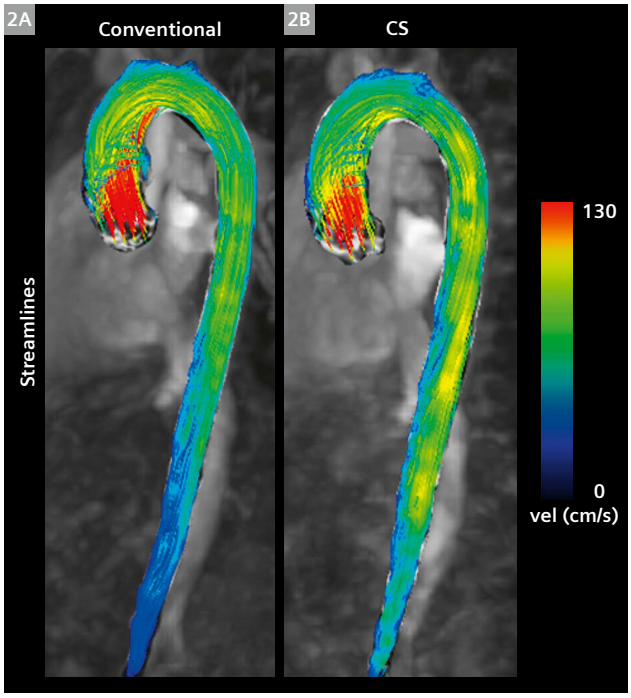
Clinical applications

We want to demonstrate the clinical applications of this prototype in three case-based steps:

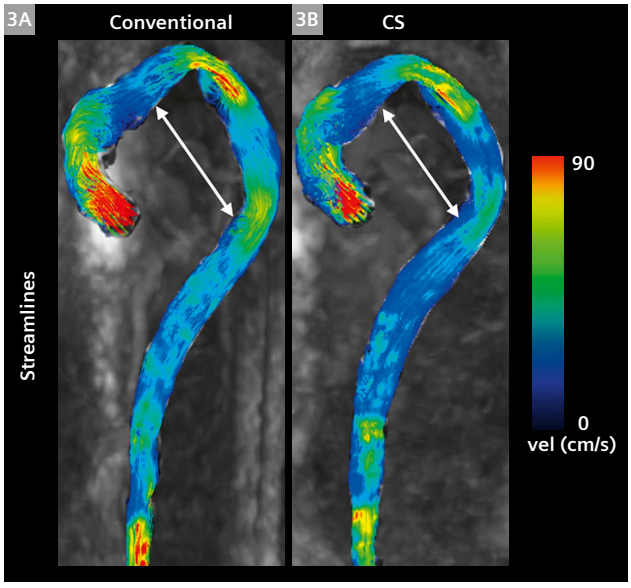
1. Validation in healthy volunteers
For validation, CS and the conventional 4D Flow were acquired on 20 volunteers from the Mainz Cohort MR (MaiCo-MR) study before contrast injection. Both 4D Flow datasets were successfully acquired in all subjects.



1 CS acquisition and reconstruction. **(1A, 1B)** Retrospectively-gated flow acquisition using symmetric 4-point encoding gated to the cardiac cycle. Only bipolar flow gradients are depicted. Imaging gradients are not included for simplicity. Navigator echoes (Nav) were played out after R-wave detection in the ECG tracing. Numbers (1–11) represent succesive cardiac time frames t_n, n = 1, 2 ... 11). In each cardiac phase a segment of *k*-space (views per segment = 2) is acquired. **(1C)** ReCAR with combined with spiral phyllotaxis subsampling pattern in the kz/ky dimensions of a single time frame that is subsequently rotated for each frame (t_n). Central *k*-space is acquired during expiration (red) and outer *k*-space is acquired during inspiration (blue) to mitigate respiratory motion artifacts. When all cardiac time frames are combined they form a fully sampled center of *k*-space, **(1D)**, for coil sensitivity estimation.
Adapted with permission from [2].



2 Peak systolic 3D streamlines of the thoracic aorta reconstructed from **(2A)** conventional 4D Flow (GRAPPA R3) and **(2B)** CS 4D Flow (R7.7) acquisitions.



3 Peak systolic 3D streamline visualization of the aortic arch with "frozen elephant trunk", reconstructed from conventional 4D Flow (**3A** left) and CS 4D Flow images (**3B** right). The arrows show the beginning and the end of the stent-graft.

Compared with conventional 4D Flow, CS 4D Flow significantly reduced scan time, whilst image quality was subjectively equal for both techniques (Fig. 2). The mean total acquisition time was 6:51 min for CS 4D Flow as opposed to 10:56 min for the conventional 4D Flow, which equates to a 37% reduction in time. Flow quantification was performed at three locations along the aorta: ascending aorta, the aortic arch and the descending aorta.

A mild underestimation of stroke and velocity was found in the comparison of CS-based measurements compared with conventional acquisitions (mean underestimation net flow: -8.07%, mean underestimation total volume: -7.38%, mean underestimation peak velocity: -6.60%) (Table 1).

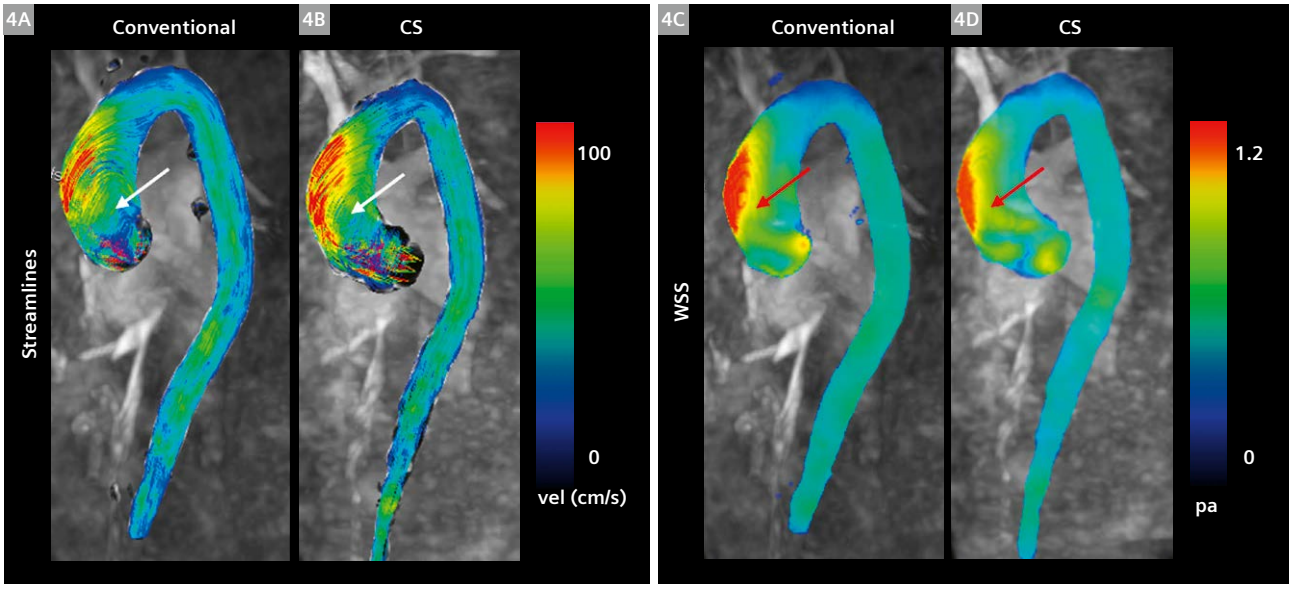
2. Application in aortic diseased patients to visualize and quantify pathologic flow patterns

CS and the conventional 4D Flow acquisitions were performed in 15 participants of the prospective "4D Flow in Aortic Disease (AD4D)" study. All participants had undergone aortic surgery for treatment of aortic dissection with supracoronary aortic replacement and "frozen elephant trunk" antegrade stent-graft implantation. 4D Flow imaging was performed within seven days of surgery. The mean total imaging time for CS and conventional acquisitions was 7:12 and 11:02 minutes respectively.

Overall, there are no statistically significant differences between conventional and CS measurements regarding total volume, mean pressure gradient, maximum mean velocity, and peak flow (e.g., Wilcoxon rank test for paired samples for conventional and CS 4D Flow total volume, $p = 0.715$; mean pressure gradient: $p = 0.255$; maximum mean velocity: $p = 0.255$; maximum flow: $p = 0.265$). Compared with conventional 4D Flow, CS 4D Flow tends to slightly underestimate maximum flow (-4.4%) and peak velocity (-5.9%). Peak systolic streamline visualization shows good agreement between conventional (Fig. 3A) and CS 4D Flow (Fig. 3B) acquisitions. The complicated flow pattern could be visualized by both techniques.

3. Application for novel imaging parameters, e.g., WSS analysis

Finally, we want to demonstrate that not only basic flow information but also novel imaging biomarkers such as WSS or vortex analysis can be derived in a comparable way from highly accelerated CS 4D Flow imaging. Figure 4 presents the case of a 54-year-old patient with bicuspid aortic valve and aneurysm in the ascending aorta. Systolic streamlines depict a complex helical flow pattern in the ascending aorta in both conventional and CS 4D Flow (Fig. 4A, B white arrows). CS 4D Flow is able to visualize areas of increased WSS in the same area as in the conventional 4D Flow (Fig. 4C, D red arrows).



4 Peak systolic 3D streamlines and WSS from the conventional and CS 4D Flow in a 54-year-old patient with bicuspid aortic valve and aneurysm in the ascending aorta. Systolic streamlines depict complex helical flow pattern in the ascending aorta (**4A, B**, white arrows). Both techniques depict increased WSS in the same region (**4C, D**, red arrows).

Further studies are needed to quantitatively compare changes in advanced flow parameters from highly accelerated CS 4D Flow imaging to the conventional 4D Flow sequences.

Conclusion and outlook

In conclusion, CS and conventional 4D Flow acquisitions demonstrate the feasibility of visualizing blood flow pattern in healthy volunteers and patients with aortic diseases. Compared with conventional 4D Flow, CS 4D Flow significantly reduces the total acquisition time, making its integration into daily clinical routine feasible. However, highly accelerated CS 4D Flow acquisitions tend to slightly underestimate flow measurements. Future investigations will study CS 4D Flow in larger patient cohorts and validate classic and novel flow parameters against gold-standard measurements as well as determine prognostic implications of this method.

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