# Highly Accelerated 4D Flow using Spiral Sampling and Dynamic Compressed Sensing for Flow Quantification in Abdominal Vessels

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Target audience: Physicists and radiologists interested in technical development and applications of 4D flow phase contrast.

Purpose: Circulation can be comprehensively and noninvasively assessed in vivo with phase contrast MRI, using a cardiac triggered volume acquisition of the velocity vector field (4D flow). However, common 4D flow techniques need a long acquisition time[1]. The purpose of this study is to develop a highly accelerated 4D flow technique based on efficient spiral sampling[2] combined with dynamic compressed sensing reconstruction[3] of subsampled k-space data in abdominal vessels, and validate the novel sequence against a Cartesian 4D flow acquisition and a standard 2D phase contrast acquisition.

Methods: Experiments were performed at 1.5T (Magnetom Aera, Siemens). A novel 4D flow sequence prototype (labeled SPIR4D) was developed, featuring stack-of-spiral acquisition, designed as follows: center-out variable density sampling (linear decrease to 1/5 of Nyquist limit), 160 acquisition matrix, 6 interleaves, 2 acquired shots (R=3), 7.43ms per readout. Spirals were randomly rotated for each cardiac frame and velocity encoding, thereby generating pseudorandom noise in the dynamic dimension. SPIR4D was reconstructed using dynamic compressed sensing (**Fig. 1**) using temporal principal component analysis applied in the cardiac phase dimension as a regularization term[3]. SPIR4D was compared to a GRAPPA-accelerated Cartesian sequence prototype with matched spatiotemporal resolution (R=2, labeled CART4D) validated previously[1]. Other sequence parameters were FOV 370 mm, 60 mm coronal oblique slab, 12 slices, cardiac triggering, Venc 60 cm/s, TE/TR/time resolution 3.3/5.7/68.4ms and 3.8/16.5/66.2ms for CART4D and SPIR4D respectively. In addition to 4D flow, 2D cine phase contrast (PC, GRAPPA 2) was acquired in the portal vein and used as a reference technique. 5 subjects (one healthy, 4 with liver disease) were enrolled prospectively with written informed consent. All subjects were asked to fast for 6 hours. Flow acquisition was performed before contrast injection. Acquisition time was 1 breath-hold (<25 s) for SPIR4D and average of 11:14 min for CART4D (with respiratory tracking). Blood flow was visualized and measured using 4D Flow V2.4 prototype software (Siemens) in abdominal vessels (aorta, IVC, celiac artery, hepatic/splenic/superior mesenteric/renal arteries and veins). Time-averaged net flow was compared between sequences using Bland Altman 95% limits of agreement (BALA), Pearson correlation and paired T test.
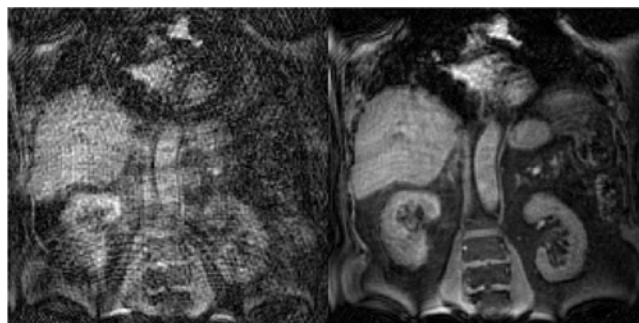
Fig. 1 Left: zero-filled reconstruction of variable density subsampled spiral 4D flow. Right: final image with compressed sensing reconstruction.

	4D Cartesian vs. 2D cine*	4D Spiral vs. 2D cine*	4D Cartesian vs. 4D Spiral**
Pearson r	0.59	0.69	0.96
Pearson p	0.165	0.084	<0.001
p	0.900	0.957	0.021
LA low	-18.9	-9.9	-24.3
LA high	19.8	9.7	18.1

Table 1 Comparison between Cartesian and spiral 4D flow in abdominal vessels (**) and between both 4D flow acquisitions and 2D cine phase contrast in portal vein (*) in 5 subjects. Pearson correlation, T test and Bland Altman limits of agreement (LA) are given (in mL/s)

Results: A high correlation (r 0.96, p<0.001, computed using all vessels) was observed between SPIR4D and CART4D (**Table 1**), although flow was significantly lower for SPIR4D (p=0.021). When compared with 2D cine PC acquisition in the portal vein, better concordance was observed for SPIR4D, together with higher correlation (without reaching significance). In all 5 subjects, no significant difference in portal venous flow was observed between spiral 4D flow (18.0 ±5.2 mL/s) and 2D cine PC (18.4 ±4.8 mL/s), or between Cartesian 4D flow (19.8 ±12.5 mL/s) and 2D cine PC. An example of flow visualization is shown in **Fig. 2**.

Discussion: Lower flow observed with SPIR4D could be due to reduced motion blurring, leading to better vessel definition. Further work will involve validating this novel technique against 2D cine PC and Doppler ultrasound in a larger population of patients with portal hypertension.

Conclusion: Using a highly accelerated spiral readout with compressed sensing reconstruction, 4D flow may be performed in the abdomen in significantly reduced acquisition time, down to a breath-hold. Our technique shows high potential, as evidenced by strong correlation with a validated Cartesian 4D flow (with acquisition time of order 10 min), and good agreement with 2D phase contrast acquisition.
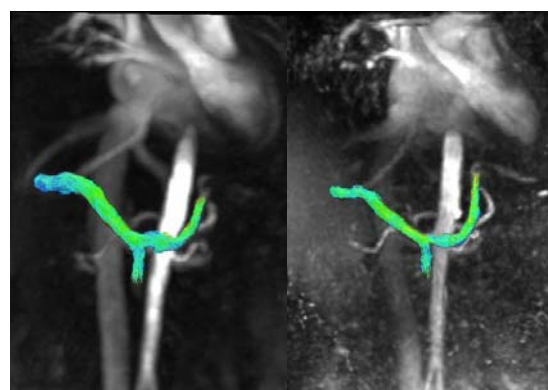
Fig.2 Phase contrast angiograms computed from the Cartesian (left) and spiral (right) 4D flow acquisitions. Colors represent flow in the portal, splenic and superior mesenteric veins.

References:
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3. D. Kim et al. MRM 67: 1054-1064 (2012)
This work was supported by NIH grant #1R01DK087877