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5D Flow – A quantitative in vivo comparison between Self-Gating and Pilot Tone Gating

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Synopsis

Conventional 4D flow MRI techniques often have prolonged and unpredictable scan times, due to the use of respiratory navigation. To address this, a fully self-gated cardiac and respiratory motion-resolved whole-heart 5D flow protocol with a fixed scan time was recently developed using a free-running framework. This protocol extracts cardiac and respiratory signals from periodic readouts (self-gating). In this study, we explore the use of Pilot Tone signals as an alternative method for cardiac and respiratory signal extraction to reconstruct 5D flow data and compare reconstructions to those using the previously established self-gating method and the conventional 4D flow sequence.

Introduction

Conventional 4D flow MRI techniques often have prolonged and unpredictable scan times, due to the use of respiratory navigation. As a result, acquiring whole-heart 4D flow images in a clinically acceptable scan time (<10min) is challenging. To address this, a fully self-gated cardiac and respiratory motion-resolved whole-heart 5D flow protocol with a fixed scan time was recently developed using a free-running framework[1,2,3]. This method employs a continuous, non-ECG triggered 3D radial acquisition with phyllotaxis sampling[4] and periodic readouts for cardiac and respiratory self-gating (SG)[2]. Pilot Tone signals (PT), acquired in parallel to the MR acquisition, have also been recently proposed for cardiac and respiratory gating[5,6]. The PT Navigation system consists of a transmitter that generates an alternating magnetic field with a frequency outside the band occupied by the MR signal. The field received by the local MR coils is modulated by motion[5,6]. Both SG and PT potentially replace the ECG signal and navigator scans in 4D/5D flow imaging. In this study, we explore the use of PT signals to reconstruct 5D flow data and compare reconstructions to those using the previously reported SG method[3] as well as a reference standard 4D flow sequence.

Methods

One navigator gated 4D flow sequence[7] covering the aorta and one prototype free-running radial whole-heart 5D flow sequence[3] were used for imaging in 11 healthy adult volunteers (age: 27.9±3.6 years) who provided written informed consent on a 1.5T MAGNETOM Sola (Siemens Healthcare, Erlangen, Germany), using a 12-channel body coil with an integrated PT transmitter. Scan parameters were: field of view (4D: (200-292.8 mm) x (360-366 mm) x (75-137.4 mm), 5D: (220mm)^3-(260mm)^3); spatial resolution (4D: 2.4x2.4x2.5 mm^3, 5D: (2.3mm)^3); temporal resolution (4D: 38.6-57.9ms, 5D: 50ms); velocity encoding (4D/5D: 150cm/s). Both 4D flow and 5D flow were performed during free-breathing and the ECG signal was measured during 5D flow scans for subsequent comparison. The acquisition time of each sequence was also recorded. For 5D flow, cardiac and respiratory signals were retrospectively extracted from SG and PT signals using the post-processing steps outlined in **Figure 1**. For both SG and PT, the cardiac gating error was quantified as the standard deviation of the difference between SG or PT triggers and the recorded ECG, normalized by the mean ECG RR-Interval[2]. After signal extraction, the SG and PT 5D flow datasets were binned into 4 respiratory and 17-23 cardiac frames, depending on the subject's heart rate, and reconstructed using XD-GRASP[8]. For the 4D flow datasets and the two 5D flow datasets (with SG and PT), flow curves were calculated in two segments of the ascending aorta (AAo1, AAo2), one segment of the descending aorta (Dao), and one segment of the aortic arch (Arch) using *Siemens 4D Flow v2.4*. Additionally, the net flow volume and peak flow were computed and compared using the Wilcoxon signed rank test.

Results

The acquisition time of the 5D flow sequence (7min 57s±15s) was shorter (p=0.08) and less variant than that of the 4D flow protocol (10min 16s±3min 55s) across all subjects (**Figure 2**). The mean and standard deviation of the cardiac gating error across volunteers were 2.9±1.3% for SG and 3.3±1.4% for PT (**Figure 2**, p=0.08). **Figure 3** shows flow curves for the four aortic segments in four subjects, as well as flow streamlines immediately after peak systole for 4D flow and 5D flow reconstructed with self-gated and Pilot Tone gated signals. A flow animation for a full cardiac cycle using the three reconstructions is depicted in **Figure 4**. The 3D hemodynamics of the flow streamlines across the same subject were consistent, although some reduced flow values were observed on both 5D flow reconstructions. Regarding the net flow volume (**Figure 5**), there were no significant differences between 4D flow and either SG or PT 5D flow. Nevertheless, compared to the 4D flow measurements, the peak flow was significantly decreased for both SG and PT 5D flow for the lower segment of the ascending aorta, the descending aorta and the aortic arch (p<0.05).

Discussion

5D flow scans provided whole-heart coverage in a predictable and shorter scan time, whereas 4D flow suffered from variable efficiency due to heart rate and variable navigator efficiency secondary to variability in breathing patterns. The cardiac gating error was consistent between SG and PT and within the range of previously reported values for SG[2], demonstrating the feasibility of PT as an alternative method for cardiac and respiratory gating in 5D flow imaging. While underestimation of the peak flow has been reported before[3] and may be caused by temporal undersampling and regularization, further investigation is required. Still, the temporal evolution of the flow curves and agreement in net flow volumes suggests 5D flow using SG or PT is a promising alternative to 4D flow, providing whole-heart coverage with matching temporal and spatial resolution predictably in less than 10min.

Conclusions

Pilot Tone signals provide a valuable alternative to self-gating for ECG- and navigator-free cardiac and respiratory motion-resolved 5D flow, while being completely independent of the acquisition. As a result, the feasibility of using Pilot Tone for signal extraction may open new opportunities for improving flow acquisitions, including reduced scan times, and improved k-space sampling.

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Figures

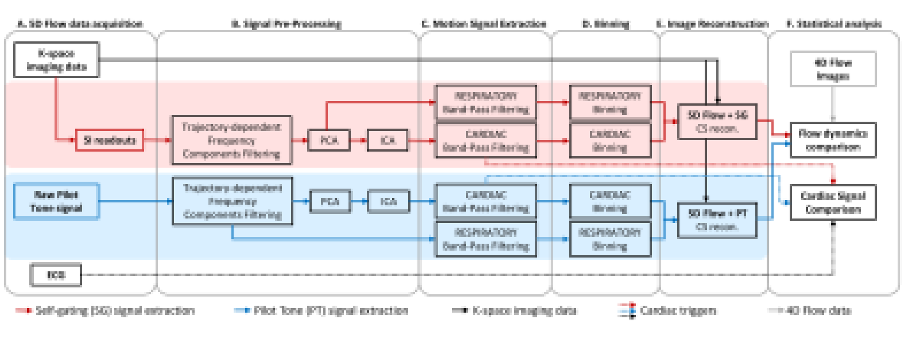

Figure 1. Study Pipeline. **A.** Free-running 5D flow data were acquired and the ECG signal was recorded for subsequent comparisons (**F**). **A-C.** Cardiac and respiratory signals were extracted from either periodically acquired SI readouts or Pilot Tone signals. **D-E.** Finally, k-space data were binned and reconstructed with XD-GRASP [8].**F.** The end-expiratory datasets were used for flow calculations and comparison with 4D flow values.

	A. Acquisition Time (min:sec)		B. Trigger Precision Cardiac Gating Error (%)	
Volunteer	**4D Flow**	**5D Flow**	**ECG vs SG**	**ECG vs PT**
1	13:43	7:53	3.1	3.3
2	14:33	7:53	4.4	5.6
3	16:35	7:53	1.8	2.0
4	7:11	7:53	1.6	2.9
5	5:20	7:53	2.6	1.7
6	10:33	8:43	5.7	5.7
7	6:00	7:50	2.8	3.4
8	5:57	7:50	2.1	2.4
9	12:8	7:52	1.4	2.4
10	8:21	7:50	3.9	4.7
11	12:34	7:50	2.6	2.2
Mean ± SD	10:16 ± *3:55*	7:57 ± *0:15*	2.9 ± 1.3	3.3 ± 1.4
T-Test	0.08		0.08	

Figure 2. **A.** Acquisition time of the 4D flow and 5D flow sequences for all subjects. Variation in 5D flow acquisitions times are due to field-of-view size. 4D flow times varied due to navigator efficiency and heart rate. **B.** Cardiac gating error given as the standard deviation of the difference between SG or PT triggers and the recorded R-wave of the ECG, normalized by the mean ECG RR-Interval.

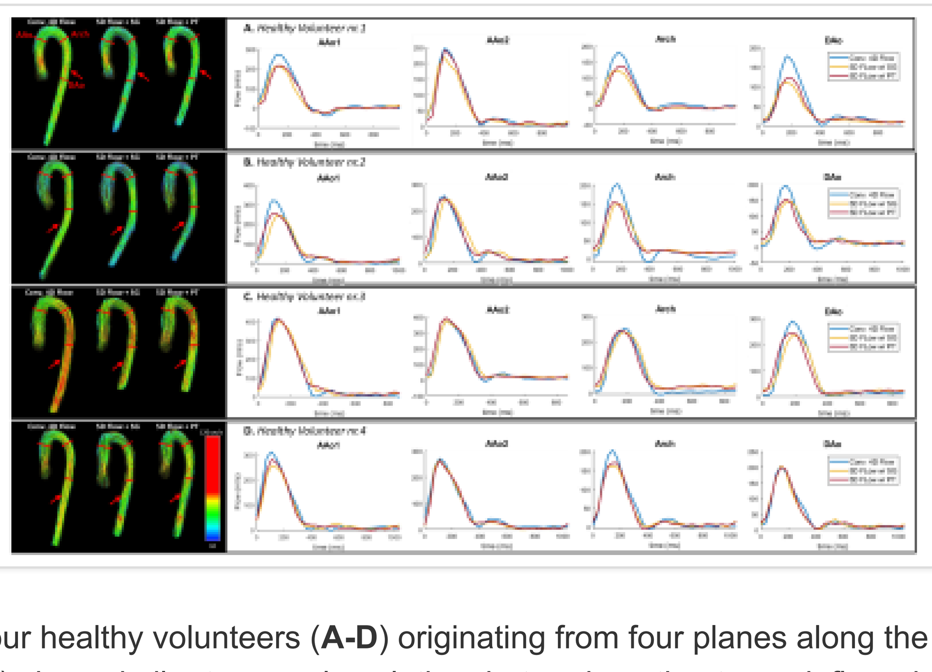

Figure 3. Comparison of flow curves from four healthy volunteers (**A-D**) originating from four planes along the aorta. The flow curves from the two 5D flow reconstructions (SG and PT signal extraction) show similar temporal evolution, but underestimate peak flows in comparison to 4D flow (see arrows). **AAo1:** lower segment of the ascending aorta, **AAo2:** upper segment of the ascending aorta, **DAo:** descending aorta, **Arch:** aortic arch.

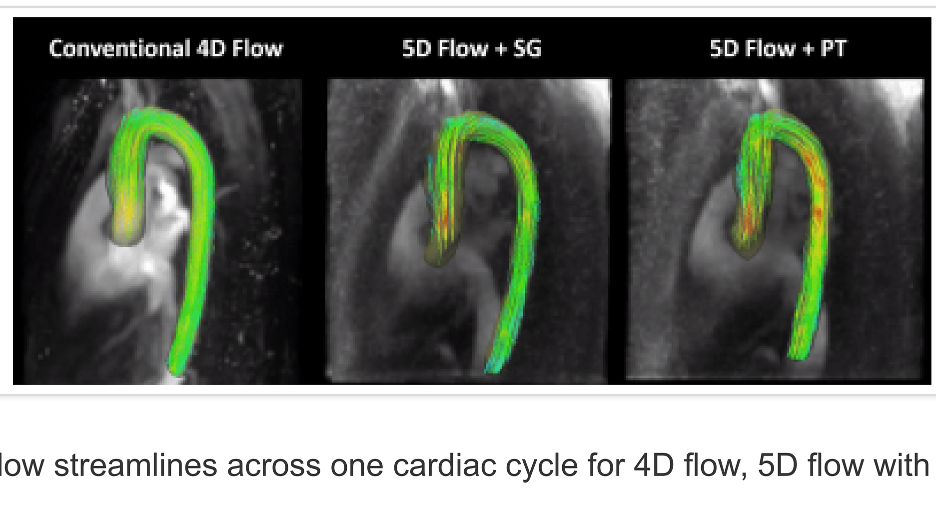

Figure 4. **Movie:** Flow streamlines across one cardiac cycle for 4D flow, 5D flow with SG and 5D flow PT.

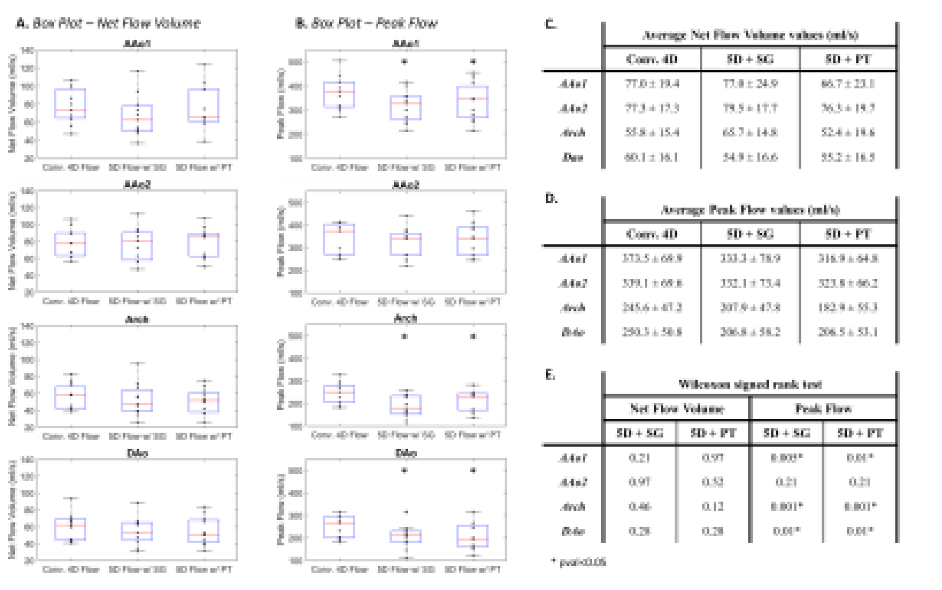

Figure 5. Net flow volume (**A**) and peak flow (**B**) population distributions for 4D flow, SG and PT 5D flow reconstructions. The interquartile range is shown by the blue boxes. Mean and Standard Deviation values are shown in **C.** and **D.**, respectively. **E.** The Wilcoxon signed-rank test shows that both SG and PT 5D flow underestimated peak flow values in comparison to 4D flow, with the exception of the AAo2. **AAo1:** lower segment of the ascending aorta, **AAo2:** upper segment of the ascending aorta, **Dao:** descending aorta, **Arch:** aortic arch.