k-t Accelerated 4D Flow MRI in the Aorta: Effect on Scan Time, Flow Quantification and Analysis of Wall Shear Stress

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Target audience: Researchers working in the field of flow-sensitive or parallel MRI.

Purpose: Flow-sensitive MRI is a powerful tool to non-invasively assess the cardiovascular hemodynamics in-vivo. However, total imaging time is still a limiting factor of this method and one of the reasons why it is often difficult to add 4D flow MRI as a standard method in clinical routine. Advanced imaging acceleration methods such as k-t SENSE or k-t GRAPPA have high potential to substantially accelerate 4D flow MRI [1]. However, it is known that k-t acceleration can induce temporal and spatial blurring and thus may impact 3D flow visualization and quantitative accuracy of the velocity data or derived parameters such as wall shear stress (WSS). The purpose of this study was to evaluate the utility of k-t parallel imaging for the acceleration of aortic 4D flow MRI by systematically investigating the impact of different acceleration factors and number of coil elements on image quality and quantification of hemodynamics parameters such as blood flow and WSS.

Methods: measurements were performed in ten healthy volunteers (28.4 years +/- 2.4) on a 3T system (Trio, Siemens Medical Solutions) using a time-resolved prospectively ECG-gated 3D phase contrast gradient echo sequence with three-directional velocity encoding (*venc* = 150 cm/s) [2]. 4D flow data were acquired using respiratory navigator gating in a sagittal oblique 3D volume covering the entire thoracic aorta with TE/TR = 2.6/5.0 ms, flip angle = 7°, temporal resolution = 40.0 ms, spatial resolution = 2.1 × 2.5 × 2.5 mm, bandwidth = 450 Hz/pixel.

For each volunteer, five 4D flow MR scans were acquired during the same session: (i) standard GRAPPA with R=2 (12-channel coil); k-t-GRAPPA with (ii) R=3 and (iii) R=5 (both 12-channel coil); k-t-GRAPPA with (iv) R=5 and (v) R=8 (both 32-channel coil). The k-t-GRAPPA accelerated scans (i.e. undersampling along ky, kz and t dimensions) were performed as described previously [1]. The number of autocalibration (ACS) lines and the resulting nominal acceleration R_{net} for the different acceleration factors R are summarized in Table 1. The k-t algorithm was integrated into the scanner's data reconstruction workflow and all undersampled data were acquired and reconstructed directly on the MR system.

Data preprocessing included a correction for aliasing, eddy currents and background noise and the calculation of a 3D phase contrast MR angiogram. Data analysis consisted of a time-resolved pathlines 3D visualization (ENSIGHT 9.2, CEI, USA) of aortic blood flow and the positioning of four 2D planes along the aorta (aortic root, mid-ascending aorta, mid arch, and descending aorta, see Fig. X) for quantification of blood flow and WSS. For each plane, the aortic lumen boundaries were manually segmented for each time frame using a home-built Matlab tool. Flow quantification included the extraction of flow-time curves and the calculation of peak systolic velocity and net flow over the cardiac cycle. For each plane mean absolute WSS (averaged over the cardiac cycle) as well as peak systolic WSS were calculated as described previously [3]. The differences between means of all parameters were statistically compared to the standard method GRAPPA R=2 using paired t-test.

Results: A representative example of 3D blood flow visualization for all five scans is shown for one volunteer in Fig. 1. The net flow values showed no significant difference (Fig.2B). For the peak velocity a significant difference between the means could be detected between 12-channel GRAPPA R=2 and 32-channel k-t Grappa R=8 for the root plane, mid-arch and descending aorta (Fig.2A). A direct comparison of absolute WSS over the cardiac cycle R = 2, 3 and 5 using the 12-channel coil showed similar mean WSS with similar variability between subjects as indicated by the standard deviation. However, k-t GRAPPA with R=5 had a significant different mean WSS and peak WSS at the aortic root and the mid-ascending aorta (Fig.2C,D).

Discussion: The results revealed overall good image appearance and thus demonstrate the feasibility to accelerate 4D flow measurements in the aorta of using k-t-GRAPPA. All acceleration factors and coil configuration used in this study allowed a robust pathlines visualization as well as a reliable determination of flow rates. However, when looking at quantitative measures such as WSS in analysis planes prone to movement such as in the aortic root and ascending aorta, the use of higher acceleration factors can yield to low-pass filter effects and therefore to somewhat reduced peak WSS values. The results suggest the use of acceleration factors of up to R=5 for visualization of hemodynamics and quantification of flow rates and R=3 for quantification of WSS. The performance may vary in other applications, i.e. other vascular territories, due to different volume locations in different coil configurations.

References: [1] Jung B et al. *Magn Reson Med* 2011;66:966-975. [2] Markl M et al. *J Magn Reson Imaging* 2007;25:824-831. [3] Stalder AF et al. *Magn Reson Med* 2008; 60:1218-1231.

Table 1	**GRAPPA**	**k-t-GRAPPA**			
Coil	12-channel	12-channel		32-channel	
R	2	3	5	5	8
ACS lines (ky × kz)	24 × Nz	18 × 6	20 × 7	20 × 7	16 × 7
R_{net}	1.6	2.8	4.2	4.2	6.3
Scan time	25:36	14:34	9:30	9:30	6:06

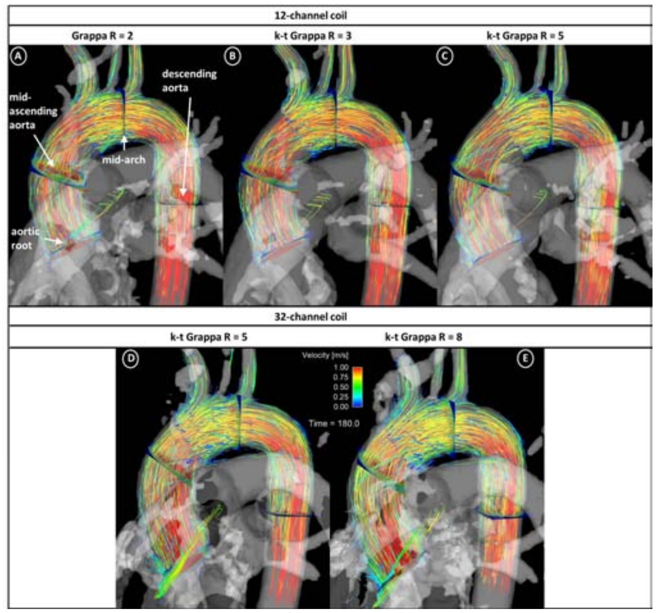

Fig. 1: Representative example of systolic 3D blood flow visualization using 3D pathlines for all five scans in one volunteer.

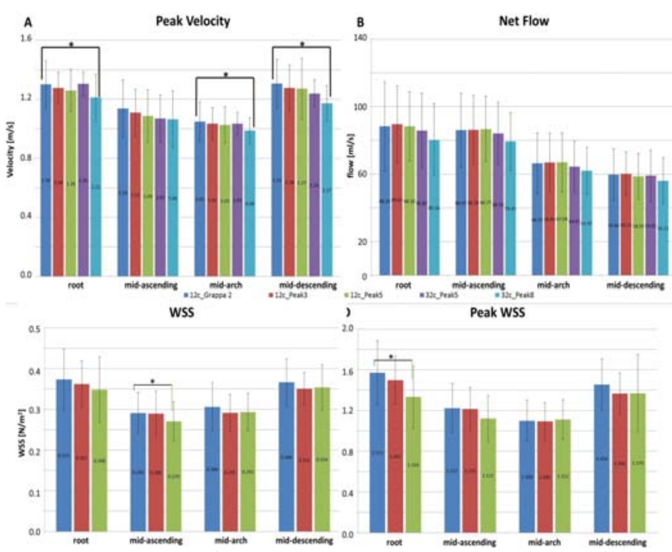

Fig. 2: Comparison of mean peak velocity (A) and mean net flow (B) averaged over all volunteers for the five different parallel imaging methods and the two different coils, and mean WSS (C) and peak WSS (D) averaged over all volunteers in comparison with the three parallel imaging methods used with the 12-channel coil. Blue: GRAPPA R=2, red: k-t-GRAPPA R=3, green: k-t-GRAPPA R=5, purple: k-t-GRAPPA R=5, turquoise: k-t-GRAPPA R=8. The WSS analysis has not been performed for the 32-channel coil yet. However, the differences of the 12- and 32-channel data are expected to be similar WSS as observed for peak velocities and net flow.