4D Flow Imaging in the Aorta at 7T: Impact of Dynamic RF Shimming and kt-Acceleration

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AUDIENCE: MR physicists, Cardiologists, Radiologists, RF Coil Engineers, Sequence developers

INTRODUCTION. There is a rapidly growing interest in using time-resolved 3D phase-contrast MRI with three-directional velocity encoding (4D flow MRI), for the assessment of aortic hemodynamics in clinical settings[1]. Previous studies investigating intracranial 3D blood flow [2] have shown that 4D flow MRI directly benefits from ultra-high fields (i.e.≥7T), which provide gains in SNR and parallel imaging performances[3]. However, at 7T short RF wavelength can result in areas void of transmit B1 (B_1^+), especially in the torso[4], requiring multi-channel B_1^+ methods[5]. In this study, we demonstrate successful 4D flow imaging in the entire thoracic aorta at 7T. Two critical methodological components are investigated: 1) dynamically applied multiple B_1^+ shim settings through the acquisition, 2) kt-Grappa acceleration.

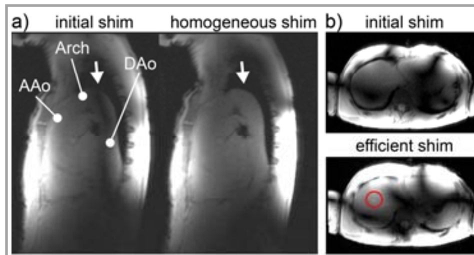

***Fig.1:** a) localizer in sagittal-oblique view covering AAo, Arch and DAo before/after homogeneous shim. b) transverse localizer of the diaphragm before/after efficient B_1^+ shim*

METHODS. 3 healthy volunteers were imaged, after informed consent, at 7T (Siemens, Germany) using a 16-ch B1 shimming unit (CPC, USA) (16 x 1kW Amps) and a 16-ch transceiver body array[6]. B_1^+ sensitivity maps for each channel were obtained in a single breath-hold using a cardiac gated single-slice gradient echo (GRE) sequence based on a small flip angle estimation[7]. B_1^+ maps were calibrated sequentially in two orientations: i) sagittal-oblique (Fig1a), covering ascending aorta (AAo), Arch and descending aorta (DAo), ii) transverse (Fig 1b), covering the diaphragm dome. Two B1 phase shimming algorithms were used: with 'B1Hom', B_1^+ *homogeneity* is increased by minimizing the coefficient of variation (CV=std/mean) of $|B_1^+|$, with 'B1Eff' the transmit *efficiency* is maximized (i.e. the constructive interference of the 16 B_1^+ fields). Dynamic B1 shimming[8] was applied in all 4D flow acquisitions, toggling between B1 Shim sets for navigator (NAV) and imaging pulse (IMG). NAV was always acquired with 'B1Eff' while IMG was acquired with 'B1Hom', except in one scan in subject 2 where 'B1Eff' was used for IMG for comparison. Scan parameters for the 4D flow sequence[9] were: 132x192x32 matrix, resolution 1.8x1.8x2.4 mm^3; temporal resolution = 38 ms, TR/TE = 4.75ms/2.3ms, GRAPPA R = 2, velocity sensitivity: 150 cm/s. In one subject we applied kt-GRAPPA[10], increasing the acceleration factor R from 2 to 5 and thus reducing imaging time from 16:04min to 9:50min. Imaging parameters were kept identical. 4D flow data were pre-processed to correct for noise, eddy currents and velocity aliasing, and to calculate a 3D PC-MR angiogram (MRA) from the velocity data, as previously described[11]. 3D segmentations of the thoracic aorta geometry were created for each subject based on the 3D PC-MRA data (MIMICS, Materialise Inc., Belgium). Segmented aorta geometry and 4D flow velocity data were imported into commercial software (Ensight, CEI, Inc. Apex, NC) for 3D blood flow visualization and quantification of net flow and peak velocity in AAo, Arch and DAo

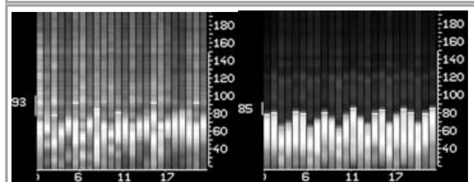

***Fig.2:** Navigator signal before (left) and after (right) efficient B_{1+} shimming on the diaphragm.*

***Table 1**: Net Flow and peak velocity derived from all acquired data sets at 3 representative analysis planes.*

		Net Flow [ml/cycle]			Peak Velocity [m/s]		
Method	**Volunteer**	**AAo**	**Arch**	**DAo**	**AAo**	**Arch**	**DAo**
Homog. shim	Vol.1 scan1	67.50	37.81	30.76	1.06	0.53	0.69
	Vol.2 scan1	62.39	53.85	46.00	1.34	1.10	1.01
	Vol.3	96.12	77.93	67.63	1.26	0.98	0.99
	Mean	**75.34**	**56.53**	**48.13**	**1.22**	**0.87**	**0.90**
	Std	**14.84**	**16.49**	**15.13**	**0.12**	**0.25**	**0.15**
k-t Grappa	Vol1 scan2	70.73	32.28	26.94	0.99	0.48	0.62
	Mean Vol 1	**69.12**	**35.05**	**28.85**	**1.03**	**0.51**	**0.66**
	Std Vol 1	**1.62**	**2.77**	**1.91**	**0.04**	**0.03**	**0.04**
Efficient Shim	Vol.2 scan2	58.40	47.91	41.62	1.26	1.13	1.00
	Mean Vol 2	**60.40**	**50.88**	**43.81**	**1.30**	**1.12**	**1.01**
	Std Vol 2	**2.00**	**2.97**	**2.19**	**0.04**	**0.01**	**0.01**

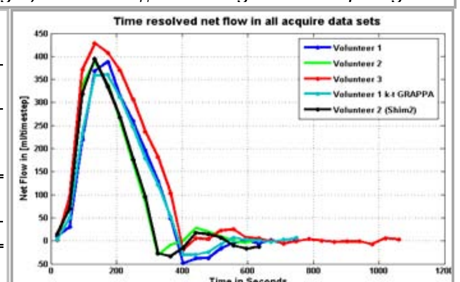

***Fig.3:** Time-resolved net flow for all volunteers and comparative methods*

RESULTS. Fig.1a displays a localizer through the thoracic aorta before and after 'B1Hom' shimming. The signal void resulting from destructive B_1^+ interference was effectively removed (see white arrows) and CV value was improved from 49.4% to 8.3% within a ROI containing AAo, Arch and DAo. The initial set of B1 phases for the diaphragm (Fig 1b) did not achieve sufficiently high flip-angles for suitable navigator signals (Fig2a), and increasing RF voltage was not feasible. However, applying the 'B1Eff' shim solution enabled navigator triggering (Fig1a+b), rising transmit efficiency from 27% to 88% in the target ROI (see red circle in Fig.1b). Quantitative results from all subjects are summarized in Table 1. Vol. 1 showed lower values, particularly for the Arch and DAo, which was in agreement with a higher regurgitant fraction of 19.3%/23.4% (Arch/DAo) compared to vol. 2 with 2.3%/0.4% and vol. 3 with 1.7%/3.5%. The average underestimation of net flow by kt-Grappa acceleration versus standard Grappa was 7.4% and for peak velocity 9.4% (see Table 1). The time-resolved net flow curves (Fig 3), were similar (light/dark blue curves). Using a 'B1Eff' shim solution for IMG did not result in quantitative differences, however, due to resulting stronger variations of B_1^+ the image segmentation of the aorta was more challenging, particularly in the Arch. Thus, 'B1Hom' shim, although less B1+ efficient seems preferable. In all subjects robust streamline visualization (Fig4) was achieved, justifying quantification results.

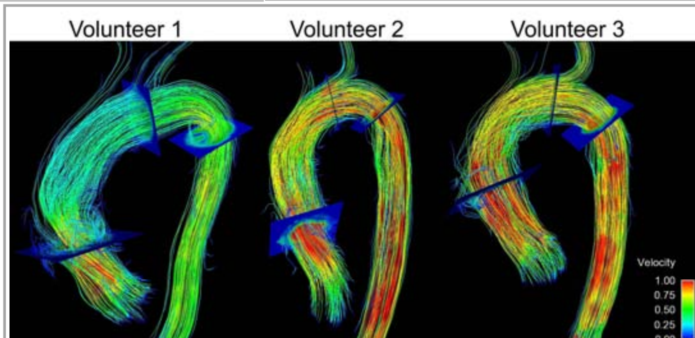

***Fig.4:** Streamlines in all three volunteer data sets acquired with dual shimming and standard GRAPPA at the time point of maximum velocity (peak systole). The streamlines were created with 300 emitters at the AAo and the Arch planes in forward and backward direction*

DISCUSSION+CONCLUSION. Successful 4D flow MRI data acquisition, 3D flow visualization and flow quantification in the human thoracic aorta at 7T was demonstrated. B1 shimming was essential for both, navigator and excitation pulse. Robust imaging performance was achieved with values corresponding to findings at 3T. Similar results for kt-Grappa as to standard Grappa showed potential for further acceleration and/or higher resolution.

ACKNOWLEDGMENTS: NIH P41 EB015894, S10 RR026783, R21-EB009138, NIH NHLBI grant R01HL115828. KECK Foundation, DFG SCHN 1170/2-1, SIR Foundation Pilot Research. **REFERENCES** 1) Markl, JMRI 36:1015. 2) van Ooij, MRM 69:868 3) Wiesinger, MRM 52:953 4) Vaughan, MRM 46:24 5) Metzger, MRM 59:396 6) Snyder, MRM 61:517 7) Van de Moortele, ISMRM 2009:367 8) Metzger, MRM 69:114 9) Barker, DOI: 10.1002/mrm.24962 10) Schnell, DOI 10.1002/mrm.24925 11) Bock, ISMRM. 2007:3138