Extending GRAPPA kernels to 4D: application on time-resolved 3D phase contrast imaging

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Introduction: Improved scanner performance (gradients, CPU, RAM) and recent methodological development enable multi-dimensional data acquisition such as time-resolved 3D phase contrast imaging with three-directional velocity encoding [1]. However, these methods suffer from long acquisition times while aiming for high temporal / spatial resolution and thus hampering their use in clinical routine. To speed up acquisition times for 3D data acquisition, parallel imaging techniques have been introduced [2]. To further reduce scan time in time-resolved imaging, dynamic parallel imaging techniques have been developed such as kt-SENSE and kt-BLAST [3], kt-GRAPPA [4], and PEAK-GRAPPA [5] as an extension of kt-GRAPPA. Previous applications of these methods focused on time-resolved 2D imaging. It was the aim of this work was to extend spatio-temporal PEAK-GRAPPA acceleration to reconstruction for time-resolved 3D phase contrast data acquisition to fully exploit data redundancy along all spatial and temporal directions.

Methods: Time resolved three-directional, three-dimensional phase contrast measurements of the aorta were performed in a healthy volunteer on a 3 T Siemens Trio system using a 12 channel thorax coil. Imaging parameters were as follow: matrix 160 x 120 x 48 (spatial resolution 1.6 mm isotropic), flip angle = 7°, TR = 4.9 ms, temporal resolution = 50 ms, venc = 150 cm/s. Acquisition duration was about 45 min during free breathing using navigator gated respiratory control.

PEAK-GRAPPA as an extension of kt-GRAPPA is characterized by a uniform kernel geometry in combination with temporal averaging of coil weights [5]. A 3D-kernel (kx,ky,t) was used for reconstruction while determining coil weights from Ny_{ACS} lines for the kz=0 partition (Fig.1). For a further reconstruction modality the kernel was extended to 4D (kx, ky, kz, t) with a pre-defined number of Ny_{ACS} and Nz_{ACS} reference lines (Fig.2) determining the net acceleration factor R_{net}. For comparison, conventional parallel imaging using GRAPPA was also performed.

Image reconstruction was performed in Matlab. K-space lines were removed retrospectively from the fully acquired k-space data according to the sampling patterns as illustrated in Fig.1 and Fig.2. Reference lines were copied back into the data matrix after reconstruction to preserve the temporal dynamics already existent in the acquired data. Velocity time courses were evaluated in a small ROI in the descending aorta. Global root-mean-square error (RMSE) of magnitude images averaged over all partitions and time frames was determined. Furthermore, a correlation analysis of pixel-wise velocity values for the peak velocity time frame of the segmented aorta was performed between the fully acquired k-space reconstruction and GRAPPA / PEAK-GRAPPA reconstruction types.

Results: Magnitude and phase difference images encoded along the foot-head direction (vx) for a systolic time frame in Fig.3 show the strongly enhanced quality of PEAK reconstruction (R_{net}=7.2) compared to conventional GRAPPA (R_{net}=2.4). Velocity time courses in Fig.4 show the excellent agreement of the PEAK recon types compared to the full k-space data. Note that the use of true 4D kernels provide improved results compared to the 3D-kernel reconstruction (yellow) which showed increased deviations in peak velocities. Pixel-wise correlation of systolic velocities is plotted in Fig.5 for the PEAK reconstruction with a 4D-kernel for R_{net}=7.2. RMSE and correlation analysis of velocity values are summarized in Table 1.

	R	R_{net}	N_{ACS}	RMSE [%]	r2
GRAPPA	4	2.4	24*48	22.6	0.38
PEAK 3D-kernel	8	7.2	12*8	8.7	0.95
PEAK 4D-kernel	8	7.2	12*8	8.1	0.93
PEAK 4D-kernel	12	9.5	12*8	10.4	0.89

Table 1: Reduction factor R, net acceleration factor R_{net}, number of ACS lines in ky and kz, root-mean-square error and pixel-wise correlation coefficients for different reconstruction modalities – conventional GRAPPA, PEAK-GRAPPA with 3D- and 4D-kernel configurations.

Discussion: By including additional dimension such as kz and t in the PEAK-GRAPPA reconstruction process, considerably improved image quality and quantitative accuracy of functional data can be obtained compared to conventional GRAPPA even for net acceleration factors of up to 10 as indicated by the velocity time course and correlation coefficients. Furthermore, reconstruction errors are very sensitive to the kernel configuration as can be seen in the velocity time courses of the 3D and 4D recon with identical R_{net}. The results clearly demonstrate the importance of including all available dimensions for fitting the missing k-space lines and illsuatrate the high potential to accelerate multi-dimensional data acquisition such as 7D flow measurements for the investigation of vascular hemodynamics. More detailed investigations are necessary in order to determine optimized acquisition and kernel configurations in multi-dimensional acquisition space.

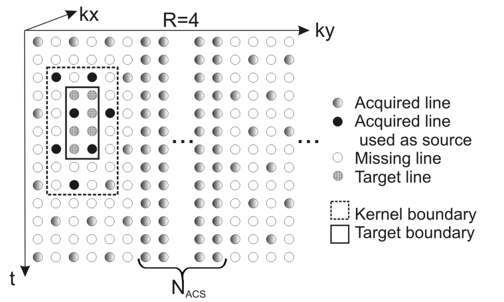

Fig.1: 3D-Peak-kernel (kx,ky,t) with its source and target points for a reduction factor of R=4.

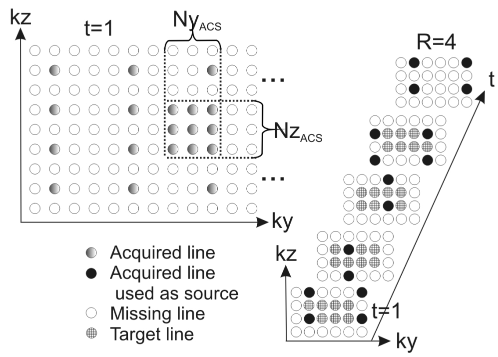

Fig.2: 4D-PEAK-kernel (kx,ky,kz,t) with its source and target points for a reduction factor of R=8.

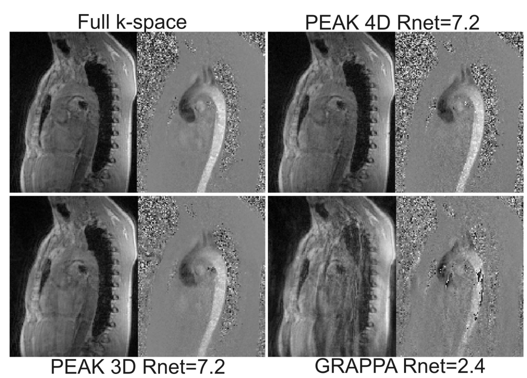

Fig.3: Magnitude and phase difference images (vx) for one slice during systole (4th frame).

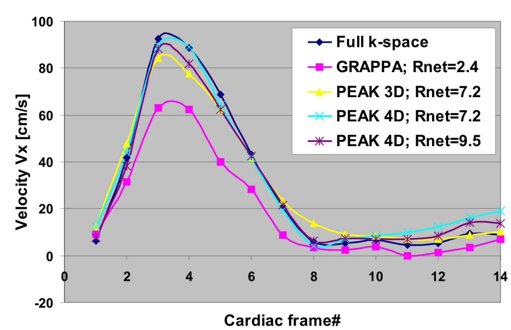

Fig.4: Velocity time courses in a small region-of- interest in the descending aorta for different reconstruction types.

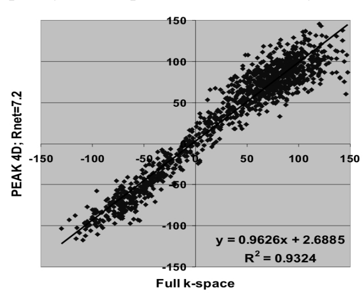

Fig.5: Exemplary plot of pixel-wise velocities of full k-space data vs. PEAK-GRAPPA with a 4D-kernel with R_{net}=7.2.

References: [1] Markl et al.*JMRI* 2003;17:499-506. [2] Breuer et al *MRM* 2006;55:549-55. [3] Tsao et al. *MRM* 2003;50:1031-42. [4] Huang et al. *MRM* 2005;54:1172-84. [5] Jung et al. *JMRI* 2008; 28:1226-32.