Fast dynamic parallel phase contrast MRI with high acceleration factors and optimized SNR

B. A. Jung[1], M. Honal[1], P. Ullmann[1], F. Staehle[1], J. Hennig[1], and M. Markl[1]

[1]Dept. of Diagnostic Radiology - Medical Physics, University Hospital, Freiburg, Germany

Introduction: Time-resolved phase contrast (PC) MRI is important for many clinical applications and requires fast data acquisition. In order to increase spatiotemporal resolution or reduce total acquisition times, parallel imaging techniques such as kt-SENSE, kt-BLAST [1] and kt-Grappa [2] have been introduced. For kt-BLAST/ kt-SENSE it has been shown that high reduction factors of the order of R=8 may introduce discrepancies in the measured velocities in PC MRI [3]. Generally, all techniques suffer from decreased SNR and/or increased temporal blurring with increasing acceleration factors. In this study, a method called PEAK-Grappa (Parallel MRI with Extended and Averaged Grappa Kernels) was applied to phase contrast MRI for the evaluation of blood flow in the thoracic aorta. PEAK-Grappa is based on an extended spatiotemporal Grappa kernel in combination with temporal averaging. Qualitative and quantitative results of in-vivo experiments illustrate that the temporal fidelity of time-resolved flow measurements are preserved while SNR was considerable improved compared to conventional Grappa. Most noticeable, the integration of the temporal domain into estimated Grappa reconstruction in conjunction with temporal averaging even permitted imaging with enhanced SNR compared to full k-space reconstruction without temporal averaging.

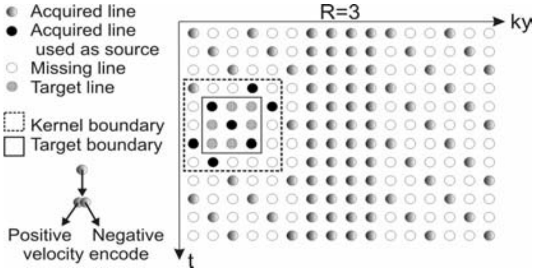

Fig.1: Data acquisition in ky-t space with reference lines and the PEAK-Grappa kernel with its source and target lines for R=3.

Methods: A uniform spatiotemporal 3D Grappa kernel (kx, ky direction and time dimension) was defined for every reduction factor as shown in Fig.1 for R=3. For each spatiotemporal kernel location, spatial and temporal Grappa weights were estimated using the fully acquired central *k-t*-space. Subsequent averaging of weights resulted in a single unique 3D Grappa kernel for the reconstruction of the entire k-t space. For the reconstruction this kernel is shifted by an increment of R in *ky*- and *t*-direction over *k-t*-space, with a kernel size in kx-direction *bx*=5. Such a uniform kernel was chosen since different kernels for different *k-t*-data points might lead to systematic errors and hence artifacts in image reconstruction. All reconstructions were performed with 24 reference lines, such that the true acceleration factor is smaller than the reduction factor (e.g. for R=8, 96 ky-lines and 24 reference lines the acceleration factor is 2.91). After reconstruction of the missing k-space lines the reference lines were copied back into the data matrix. For conventional Grappa, a border with zeros is typically placed around the kx-ky-space to permit the reconstruction of outer k-space lines. For PEAK-Grappa, the border also includes the time direction where central k-space lines contribute to the weight calculation and hence generate image artifacts for the first and last time frames. To compensate for these effects, the last time frames were copied to the beginning and vice versa. To account for the spatial dependency in parallel imaging, SNR was calculated by averaging and subtracting two adjacent time frames (end-diastolic frames) and by dividing the mean signal intensity in a ROI of the averaged image by the standard deviation in the identical ROI in the subtracted image.

Aortic flow measurements were performed on a 3T Trio (Siemens, Germany) in a healthy volunteer using an 8 channel thorax coil and a k-space segmented Cine gradient echo phase contrast sequence (TR=4ms) with a temporal resolution of 24 ms (34 cardiac frames, 32 heartbeats breath-hold). The matrix size was 96 x 256, velocity encoding was performed with a through-plane *venc* of 1.5 m/s. Data processing was performed in Matlab (The Mathworks). To evaluate the performance of different reconstruction methods, fully acquired k-space data sets were used to compare the following reconstruction algorithms: standard (full k-space), conventional Grappa with reduction factors from R2-R6, and PEAK-Grappa data with reduction factors R2-10.

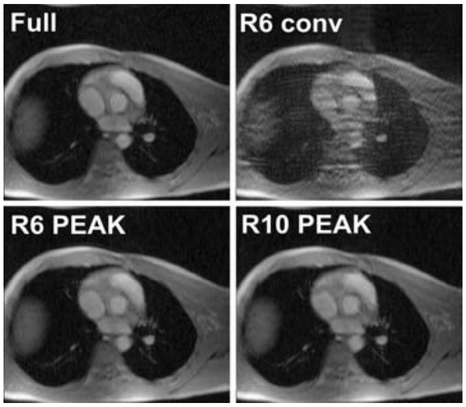

Fig.2: PC magnitude images of systolic time frame.

Results: Results of time-resolved 2D PC MRI at the level of the thoracic ascending and descending aorta are shown in Fig.2-4. Fig. 2 depicts magnitude images for a systolic time frame reconstructed with full k-space data (a), conventional Grappa with R=6 (b), PEAK-Grappa with R=6 (c), and PEAK-Grappa with R=10 (d). The conventional Grappa reconstruction leads to strong image artifacts whereas the PEAK-Grappa reconstruction exhibits excellent image quality for R=6 and even R=10 with only minor blurring. Quantitative analysis of image quality is displayed in Fig.3 which shows the SNR variation as a function of the reduction factor for three different ROI's in the chest muscle (ROI anterior), near the spine (ROI posterior) and the right atrium. As expected, the SNR for conventional Grappa decreases with increasing reduction factors. Conversely, due its inherent temporal averaging properties, PEAK-Grappa reconstructions results in considerable increased SNR for reduction factors up to R=6. The SNR behavior shows fluctuations for higher reduction factors that might be explained by the spatial dependency of the SNR from the coil characteristic g-factor. To further analyze the effect of high reduction factors on the temporal dynamics of the measured blood flow velocities, mean velocities in the cross-sectional area of the aorta ascendens were evaluated (Fig. 4). The velocity time courses of the full k-space data and the PEAK-Grappa data for R=6 show an excellent concurrence (Fig.4 left). In contrast, velocity values for the conventional Grappa reconstruction reveal strong discrepancies especially for peak velocities during systole. The effect of even higher reduction factors on the measured velocity time courses is shown in Fig.4, right, for PEAK-Grappa data from R7 to R10. Excellent agreement with the full k-space time course even for acceleration factors as high as R=10 can clearly be appreciated with only minor deviations in systolic peak velocities (2.8% for R=10).

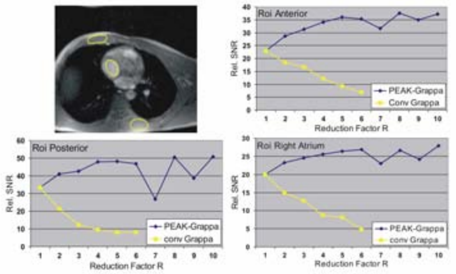

Fig.3: SNR behavior dependent on reduction factor R in three ROI's for conventional and PEAK-Grappa.

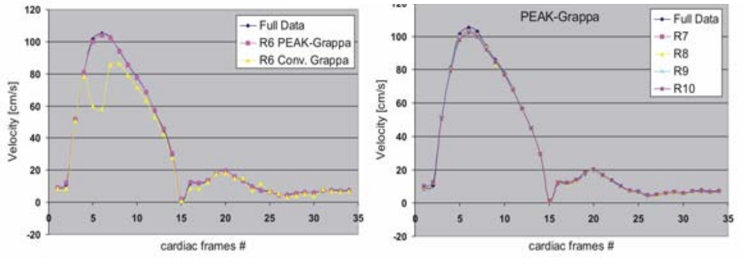

Fig.4: Velocity time courses in the aorta ascendens. Left: Full data (blue), PEAK-Grappa (pink) R6 and conventional Grappa R6 (yellow) reconstruction. Right: Full data and PEAK-Grappa reconstructions for reduction factors from R7 to R10.

Discussion: PEAK-Grappa in combination with time-resolved 2D PC-MRI provides robust image quality for high reduction factors up to 10 while maintaining or even increasing SNR compared to the full k-space reconstruction. The observed SNR optimization is a result of the averaging process included in the weight estimation used to define a single Grappa kernel for the entire k-t-space. Grappa weight averaging effectively exploits temporally uncorrelated noise in different time frames and results in considerably optimized SNR performance compared to other parallel imaging techniques while minimizing temporal blurring. Moreover, the integration of the temporal domain into the 3D PEAK-Grappa kernel helps preserving hemodynamics of blood flow in phase contrast imaging and permits accurate flow quantification and peak velocity measurements even for high acceleration factors. Since the standard deviation of the signal phase is inversely proportional to the SNR of the magnitude images, the noise of the phase images in PEAK-Grappa is also strongly decreased. The presented method offers high potential for the acceleration of measurements with long scan times such as 3D flow measurements with 3-directional velocity encoding [5].

References: [1] Tsao et al. *MRM* 2003; 50:1031-42. [2] Huang et al. *MRM* 2005; 54:1172-84. [3] Griswold et al. *MRM* 2002; 47:1202-10.
[4] Baltes et al. *MRM* 2005;54:1430-38. [5] Markl et al. *JCAT* 2004; 28:459-68.