Original Research

k-t-Space Accelerated Myocardial Perfusion

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Purpose: To investigate the performance of the recently introduced spatiotemporal parallel imaging technique called parallel MRI with extended and averaged generalized autocalibrating partially parallel acquisitions (GRAPPA) kernels (PEAK-GRAPPA) for myocardial perfusion measurements.

Materials and Methods: A study with 11 patients with myocardial infarction was performed to compare nonaccelerated perfusion imaging, i.e., fully acquired *k*-space data, with the results of conventional GRAPPA and PEAK-GRAPPA with a net acceleration factor of 2.4 to 3.4. Signal time courses reflecting the passage of the contrast agent bolus in different regions of the heart were evaluated for these different reconstruction methods.

Results: Reconstruction with PEAK-GRAPPA demonstrated considerably improved image quality compared to conventional GRAPPA. In addition, signal time courses for PEAK-GRAPPA demonstrated an excellent agreement compared to full *k*-space data, which is necessary for an accurate qualitative and quantitative assessment of myocardial perfusion.

Conclusion: Qualitative and quantitative results of patient measurements illustrate that the temporal fidelity of nonperiodic processes such as myocardial perfusion are preserved with PEAK-GRAPPA up to net acceleration factors of more than 3 while showing a superior image quality compared to conventional GRAPPA and a sliding-window reconstruction.

Key Words: parallel MRI; GRAPPA; dynamic imaging; myocardial perfusion; cardiac imaging
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FIRST-PASS CONTRAST-ENHANCED myocardial perfusion MRI was first introduced in 1990 (1). Since then, a number of technical improvements of the acquisition sequences have enhanced its clinical practicability (2). However, even modern implementations still suffer from incomplete coverage of the left ventricle or low spatial resolution. A further acceleration of data acquisition would therefore provide a great benefit by increasing left-ventricular coverage and/or spatial resolution (3).

To reduce total acquisition times or increase spatiotemporal resolution, parallel imaging techniques such as sensitivity encoding (SENSE) and generalized autocalibrating partially parallel acquisitions (GRAPPA) have been introduced (4,5). A number of studies have shown that the application of parallel imaging to dynamic MRI is highly promising. By incorporating the temporal domain into the reconstruction process, higher reduction factors can be achieved and the temporal and spatial resolution can be considerably improved. In temporal SENSE (TSENSE) (6) and temporal GRAPPA (TGRAPPA) (7), a time-interleaved acquisition scheme allows for a direct merging of adjacent time frames to build a fully-encoded reference data set as sensitivity information or autocalibration signal. A drawback of this approach is related to the increase of noise and a low-pass filter effect of the dynamic information, especially for higher reduction factors and the case in which consecutive dynamic images vary strongly. In contrast, advanced techniques such as *k-t*-SENSE and *k-t*-broad-use linear acquisition speed-up technique (BLAST) (8), *k-t*-GRAPPA (9), and parallel MRI with extended and averaged GRAPPA kernels (PEAK-GRAPPA) as an extension of *k-t*-GRAPPA (10) directly incorporate the temporal information into the reconstruction process, allowing for an enhanced reconstruction quality or a further speed-up of data acquisition in dynamic imaging since these techniques can be treated as a combination of the conventional parallel imaging methods (GRAPPA and SENSE) and sliding-window techniques. *k-t*-BLAST and *k-t*-SENSE are suitable for motion processes determined by compactness of object representation in *x-f*-space (8). It was recently shown that *k-t*-SENSE accelerated myocardial perfusion is feasible as a nonperiodic motion because perfusion imaging shows transient signal changes with a confinement of dynamic object portions along *x* (11).

Recently, the PEAK-GRAPPA spatiotemporal parallel imaging technique was introduced (10). PEAK-GRAPPA is based on an extended spatiotemporal uniform GRAPPA kernel geometry in combination with temporal averaging of sets of coil weights obtained over *k-t* space. The use of such a uniform kernel geometry leads to a decreased artifact level, as well as to strongly decreased reconstruction times (10).

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The purpose of this study was to apply the PEAK-GRAPPA technique to myocardial perfusion measurements in order to evaluate its potential for accelerating dynamic nonperiodic processes. Image quality and temporal evolution of regional myocardial signal were analyzed and compared for different reconstruction algorithms in a study with 11 patients. Besides the fully acquired *k*-space image, further image reconstruction included conventional GRAPPA, PEAK-GRAPPA, and a sliding-window reconstruction. Signal time courses were evaluated in a region within the left and right ventricular blood chamber and the myocardium. Furthermore, the relative error within a region of interest (ROI), and the signal-to-noise ratio (SNR) within an ROI in the left ventricle were calculated.

MATERIALS AND METHODS

Data Acquisition

All measurements were performed on a 1.5T system (Espree; Siemens Medical Solutions, Erlangen, Germany) using a 12-channel thorax coil. The human studies were approved by the local ethics committee and informed consent was obtained from all subjects.

Myocardial perfusion measurements were performed in 11 patients (mean age = 69 years, range = 58–87 years) with known or suspected myocardial infarction using a saturation recovery fast low-angle shot (FLASH) sequence (TR = 3 msec, flip angle = 15°). During each heartbeat, three short-axis slices (basal, midventricular, and apical) with a slice thickness of 8 mm were acquired with a matrix size of 78 × 256. Data acquisition was started directly after the injection of Gd-contrast agent (Multihance; Bracco) at a flow of 4 mL/second and covered a period of 50 heartbeats. Since diagnosis was focused on delayed-enhancement images, no application of a stress-inducing substance was performed.

Image Reconstruction

For conventional GRAPPA, sliding-window, and PEAK-GRAPPA reconstructions, *k*-space lines along the phase-encoding direction were removed retrospectively from the fully acquired *k*-space data. Line removal was incrementally shifted by one *k*-space line for subsequent time frames. For all time-frames the *k*-space center consisted of a predefined number of N_{ACS} reference lines. The resulting *ky-t*-space sampling pattern is illustrated in Fig. 1.

PEAK-GRAPPA uses a uniform three-dimensional (3D) kernel (two encoding *kx*, *ky* directions and one temporal dimension) for each reduction factor *R* (10). The coil weights are independently determined for each time frame (by shifting the kernel with an increment of 1 in the *kx*- and *ky*-directions over the reference lines). All weights are subsequently averaged to generate a single set of coil weights for the reconstruction of the entire *k-t*-space. For the reconstruction of the missing *k*-space lines, the kernel including the averaged weights is then shifted by an increment of R/2 in the *ky*-direction and *R* in the *t*-direction across *k-t*-space. The kernel size in the *kx*-direction was *bx* = 5 for PEAK-GRAPPA. Conventional GRAPPA was reconstructed with a kernel size of *bx* = 5 in the *kx*-direction and *by* = 2 in the *ky*-direction.

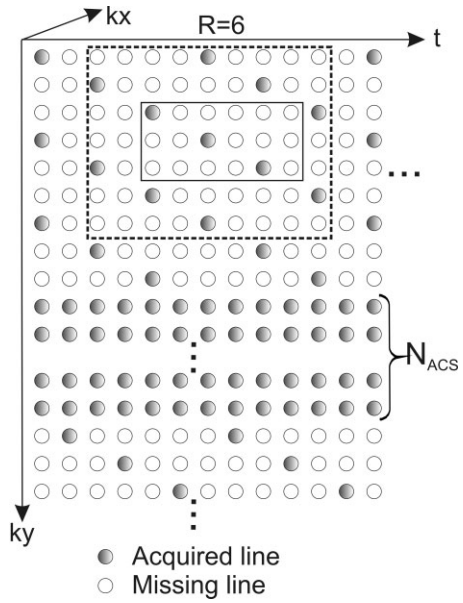

Figure 1. Time-interleaved acquisition scheme in the *ky-t* domain for an outer reduction factor of *R* = 6.

Calculations were performed with 24 and 12 reference lines leading to net acceleration factors of R_{net} = 2.4 and 3.4, respectively, with 78 *ky*-lines and an outer reduction factor of *R* = 6. For all reconstruction algorithms, the reference lines were copied back into the data matrix after reconstruction to preserve the temporal dynamics already existent in the acquired data. Image reconstruction was performed using in-house-built reconstruction algorithms (MATLAB; The MathWorks, Natick, MA, USA) on a standard PC.

Data Analysis

Signal time courses in a basal slice were evaluated in three different ROIs: the blood pool of the left and right ventricles and a user-defined area in the myocardium of the left ventricle showing no observable perfusion deficit. For patients showing reduced signal intensity in infarcted regions compared to normal regions, an additional signal time course was determined in an ROI in the injured myocardium. A correlation analysis for the signal time courses was performed between the fully acquired *k*-space reconstruction and PEAK-GRAPPA in the three different ROIs for all 11 patients.

To quantitatively compare image quality among fully acquired *k*-space data, conventional GRAPPA, PEAK-GRAPPA, and sliding window, the relative error (the square root of the sum of squares of the intensity difference divided by the square root of the sum of squares of the reference image) within an ROI encompassing the heart was determined for all reconstruction types. Furthermore, SNR was calculated for all patients in an ROI encompassing the left ventricle. To account for the well-known spatial dependency of SNR in parallel imaging, SNR was calculated by averaging and subtracting two

different time frames. SNR was determined by dividing the mean value within the ROI of the averaged image by the standard deviation in the identical ROI in the subtracted image. Only pairs of time frames with a temporal distance of the reduction factor $R = 6$ were used for SNR calculation because time frames reconstructed within the target boundary of a kernel show an influence on the SNR due to an introduction of temporally correlated noise (10). Time frames 2 and 8 were chosen for SNR calculation to use frames before the arrival of the contrast agent bolus. The first frame was not used due to the signal changes related to the transition into the steady state of the gradient-echo sequence.

RESULTS

All patient examinations were performed successfully. Two patients showed a myocardial perfusion deficit with decreased subendocardial signal intensity in the perfusion images. Results of the myocardial perfusion imaging are shown in Figs. 2–6. Figure 2 depicts the perfusion images in a basal slice before the arrival of the contrast agent bolus in the heart (a), after the bolus arrival in the right ventricle (b) and the left ventricle (c), and the signal enhancement within the myocardium (d). Images are shown for the fully acquired *k*-space data, sliding-window, PEAK-GRAPPA, and conventional GRAPPA reconstructions with 12 reference lines and an outer reduction factor of $R = 6$ ($R_{net} = 3.4$). The image quality of PEAK-GRAPPA reconstruction is only slightly reduced compared to the full *k*-space reconstruction, whereas the sliding-window reconstruction exhibits some more distinct artifacts as indicated by the subtraction images ("full data" minus "sliding window" in the third column, and "full data" minus "PEAK-GRAPPA" in the fifth column). Images reconstructed with conventional GRAPPA demonstrate poor quality due to the high reduction factor.

The exemplary signal time courses in Fig. 3 (same patient as in Fig. 2) demonstrate the dynamics of the contrast agent bolus within the three different ROIs in the right ventricle (upper right), the left ventricle (lower left), and the myocardium (lower right). For each ROI the time courses are plotted for the fully acquired *k*-space (blue), sliding-window (pink), PEAK-GRAPPA (yellow), and conventional GRAPPA (turquoise) with 12 reference lines and an outer reduction factor of $R = 6$ ($R_{net} = 3.4$). The time courses for full *k*-space, sliding-window, and PEAK-GRAPPA reconstructions exhibit an excellent agreement in all ROIs, whereas time courses derived from the conventional GRAPPA images demonstrate strong signal deviations.

The difference of the signal time courses in a patient after myocardial infarction in two ROIs in infarcted myocardium with a lack of perfusion (see arrows) and in healthy myocardium is presented in Fig. 4. Time courses are plotted for the fully acquired *k*-space data and the PEAK-GRAPPA data with 12 reference lines and

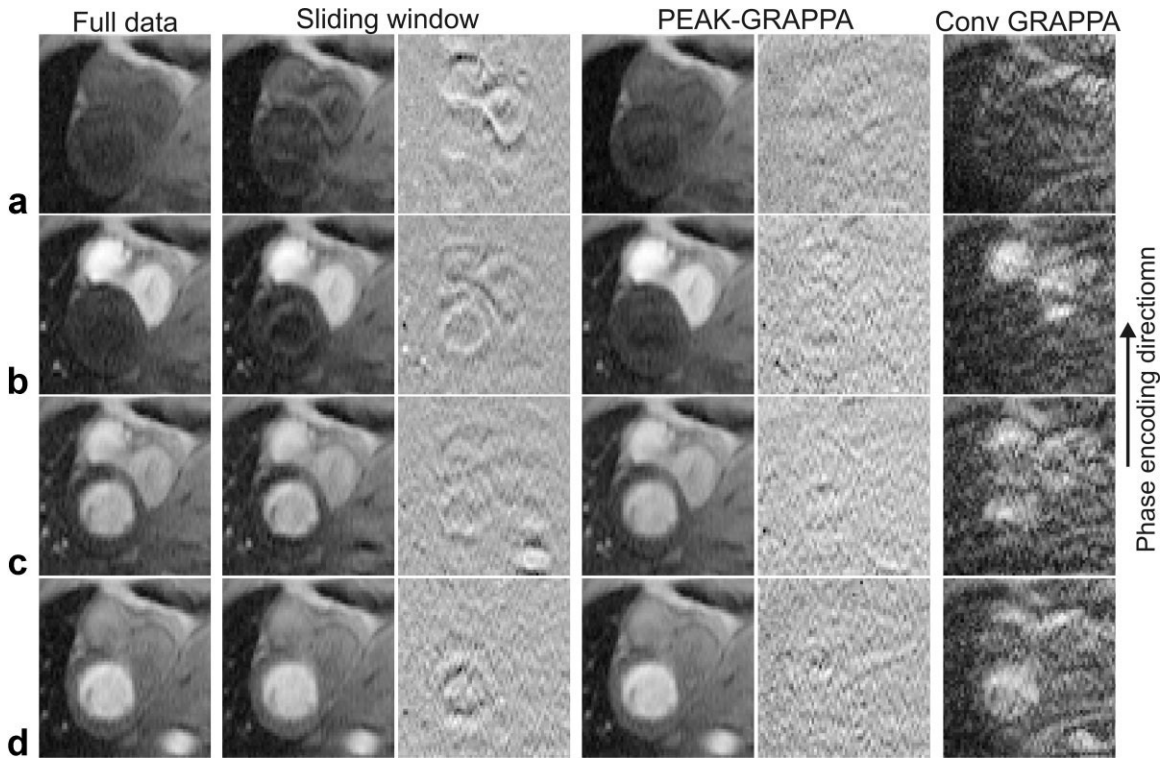

Figure 2. Perfusion images in a basal slice for four characteristic time frames after injection of contrast agent: before the arrival of the contrast agent bolus in the heart (**a**), signal enhancement in the right ventricle (**b**), signal enhancement in the left ventricle (**c**), and signal enhancement of myocardium. The magnitude images reconstructed with fully acquired *k*-space (first column), sliding-window (second column), PEAK-GRAPPA (fourth column), and conventional GRAPPA (last column) are shown. The third and fifth columns show the subtraction of the full data image from the sliding-window and PEAK-GRAPPA images, respectively. An outer reduction factor of $R = 6$ and 12 reference lines were used, leading to a net acceleration factor of $R_{net} = 3.4$.

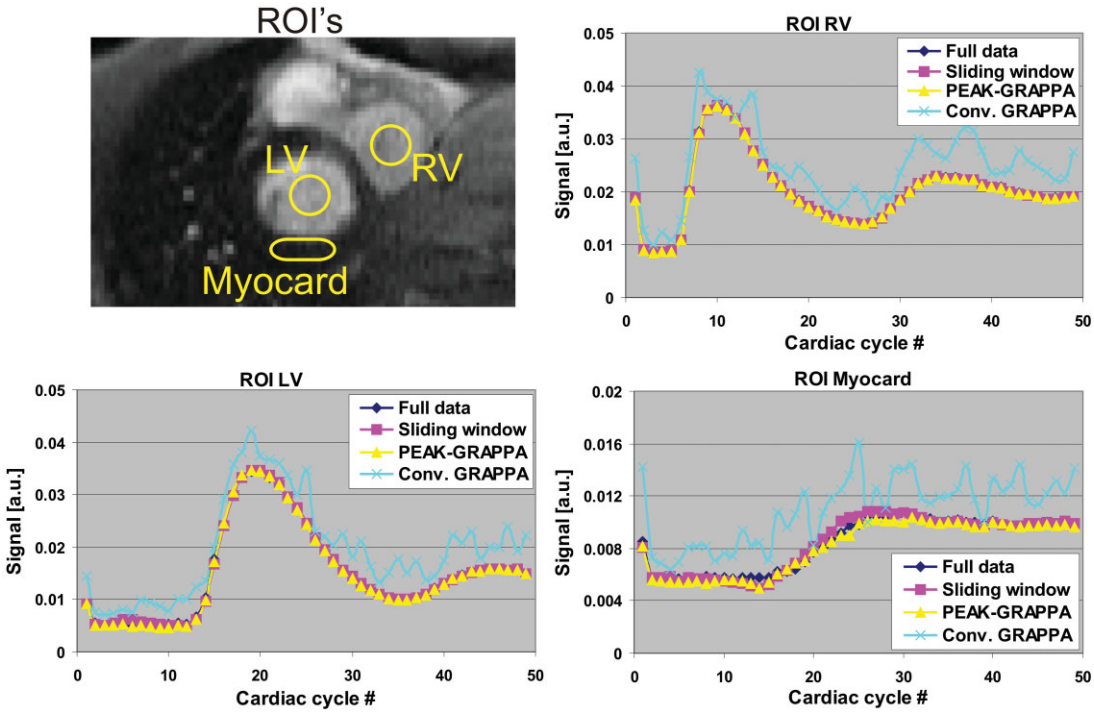

Figure 3. Signal time courses in a patient in three different ROIs: the contrast agent bolus arrives first in the right ventricle (upper right), then in the left ventricle (lower left), and finally in the myocardium (lower right). For each ROI the time courses are plotted for fully acquired *k*-space (blue), sliding-window (pink), PEAK-GRAPPA (yellow), and conventional GRAPPA (turquoise). An outer reduction factor of $R = 6$ and 12 reference lines were used, leading to a net acceleration factor of $R_{net} = 3.4$.

$R = 6$ ($R_{net} = 3.4$), demonstrating a very good agreement. The corresponding magnitude images demonstrating the signal decrease in the infarcted region are shown for the fully acquired *k*-space reconstruction (left) and the PEAK-GRAPPA reconstruction (right).

Figure 5 shows correlation plots of all patients (50 temporal values × 11 patients = 550 data points) between the fully acquired *k*-space data and PEAK-GRAPPA data for the signal time courses within the small myocardial ROI. Using 24 reference lines, a very good agreement is observed and even for 12 reference lines only minor deviations are present, as indicated by the fit parameters and the correlation values R^2 of the linear regression.

The relative error within an ROI encompassing the heart is summarized in Table 1 for conventional GRAPPA, sliding-window, and PEAK-GRAPPA each reconstructed with 24 and 12 reference lines. As expected, the most distinct deviation from the full *k*-space data reconstruction is provided by the conventional GRAPPA reconstruction. PEAK-GRAPPA exhibits an improvement of about 20% compared to sliding window for both reconstructions with 24 and 12 reference lines.

The results of the SNR analysis are summarized in Fig. 6, which shows the SNR values averaged over all patients with their standard deviations. Compared to full *k*-space data, the SNR values of PEAK-GRAPPA are only slightly reduced, whereas the SNR of conventional GRAPPA reconstruction shows a strongly decreased SNR. The sliding-window reconstruction also exhibits a slight decrease in SNR compared to full *k*-space data that can be explained by the use of two different time

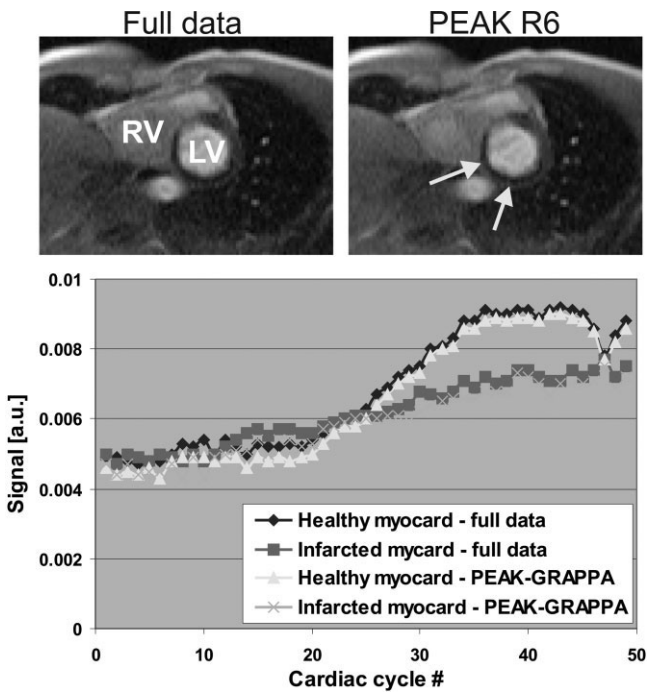

Figure 4. Signal time courses in a patient after myocardial infarction in two small ROIs in infarcted myocardium with a lack of perfusion (see arrows), and in healthy myocardium for the fully acquired *k*-space data and the PEAK-GRAPPA data with 12 reference lines and $R_{net} = 3.4$. The magnitude images demonstrating the signal decrease in the infarcted region are shown for the fully acquired *k*-space reconstruction (left) and the PEAK-GRAPPA reconstruction (right).

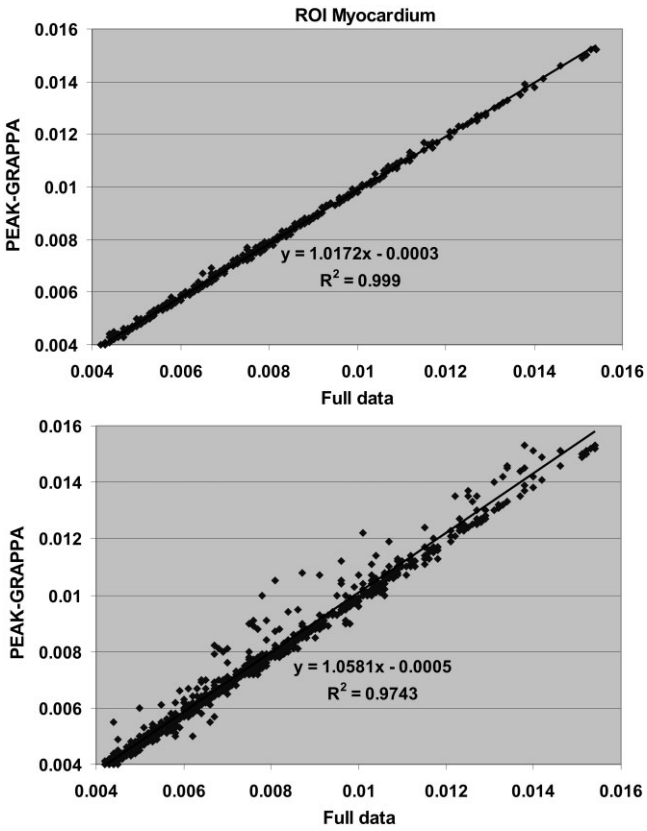

Figure 5. Correlation between the fully acquired *k*-space data and PEAK-GRAPPA data for the signal time courses in the myocardial ROI for all 11 patients. Upper graph: 24 reference lines; lower graph: 12 reference lines.

frames for SNR calculation offering possible signal fluctuation and thus a decreased SNR. A paired *t*-test exhibits a significant decrease in SNR ($P < 0.01$) for conventional GRAPPA reconstructions, whereas no significant decrease can be observed for PEAK-GRAPPA and sliding window.

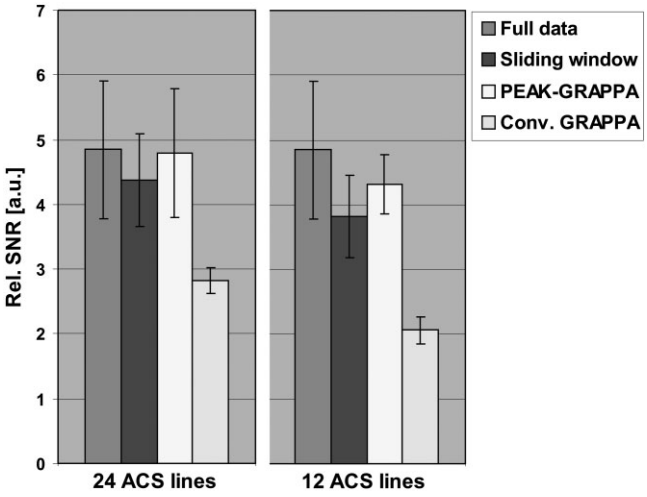

Figure 6. SNR analysis within the myocardial region averaged over all patients for full *k*-space data, sliding-window, PEAK-GRAPPA, and conventional GRAPPA reconstruction.

Table 1
Results for the Relative Error Within an ROI Encompassing the Left and the Right Ventricle Averaged Over All Cardiac Cycles and Patients for Different Reconstruction Types: Conventional GRAPPA, Sliding Window, and PEAK-GRAPPA for 24 and 12 Reference Lines

Regional error (%)	24 reference lines ($R_{net} = 2.4$)	12 reference lines (Rnet = 3.4)
Conventional GRAPPA	21.6	52.9
Sliding window	7.2	10.5
PEAK-GRAPPA	5.9	8.4

DISCUSSION

The results of this study demonstrate that the combination of the recently introduced *k-t*-space related PEAK-GRAPPA method with time-resolved myocardial perfusion MRI provides robust image quality and high SNR efficiency with only minor temporal blurring compared to reconstruction of fully acquired *k*-space data. The integration of the temporal domain into the 3D PEAK-GRAPPA kernel helps to preserve dynamics within the signal time courses and thus permits accurate quantification of perfusion-related signal changes (12) even for high acceleration factors, as demonstrated by the analysis of signal time courses in Figs. 3–5.

The *k-t*-space related PEAK-GRAPPA technique improved SNR compared to the conventional GRAPPA reconstruction while maintaining high image quality. The observed SNR optimization is a result of the inclusion of temporal information for the estimation of coil weights and reconstruction of missing *k*-space data. Moreover, GRAPPA weight averaging effectively exploits temporally uncorrelated noise in different time frames and results in optimized SNR performance compared to other parallel imaging techniques (10).

Due to the small matrix size in the phase-encoding direction in this study, the true acceleration factor remained relatively small despite the high reduction factor of $R = 6$ in the outer *k*-space regions. Nevertheless, the results of the time-course analysis and the presented image quality indicate that PEAK-GRAPPA may be used to increase spatial resolution in myocardial perfusion images, resulting in a higher true acceleration factor.

A drawback of parallel imaging reconstruction that incorporates the temporal domain into the reconstruction process is related to breathing, which can introduce artifacts in the reconstruction process due to an error in the coil weight estimation. Figure 7 shows a data set of a patient with very distinct respiration motion between successive time frames to demonstrate the introduction of such artifacts. In this example, the PEAK-GRAPPA reconstruction shows more reconstruction artifacts compared to the sliding-window reconstruction (both images reconstructed with 12 reference lines), as indicated by the arrows. However, in all 11 patients the mean error averaged over all 50 time frames was decreased with PEAK-GRAPPA compared to the sliding-window reconstruction.

Further limitations of this study are related to the investigation of only the basal slices without determin-

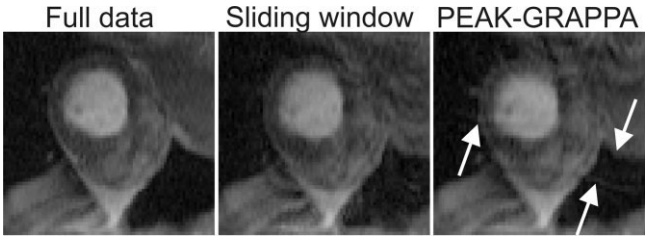

Figure 7. Images of a data set of a patient with a very distinct breathing pattern between successive time frames, demonstrating respiration-induced artifacts due to changing coil weights. In this special case, PEAK-GRAPPA exhibits more artifacts compared to the sliding-window reconstruction (both images reconstructed with 12 reference lines).

ing quantitative perfusion parameters such as time-to-peak, signal upslope, and peak signal. The presented SNR analysis demonstrates only the rough SNR performance because the determination of noise is limited by calculating the standard deviation in an ROI and might be affected by signal fluctuations and breathing motion. An improved SNR analysis might be provided by reconstructing data that are acquired with zero flip angle reflecting only the noise behavior.

The presented study demonstrates the feasibility of using the *k-t*-space related PEAK-GRAPPA technique for application to nonperiodic motion processes. The technique works well for myocardial perfusion, which is characterized by strongly varying consecutive dynamic images during free breathing. As a result, the application of the technique to other dynamic processes with less motion, such as renal, tumor, or cerebral perfusion, is highly promising. In particular, EPI sequences may benefit from shorter effective echo times due to shorter echo train length resulting in a reduced T2* decay.

Initial approaches have been presented to create data acquisition strategies and GRAPPA kernels for static multislice or volumetric data (13–15). Such approaches offer the potential to further accelerate time-resolved 3D data acquisition in the third spatial domain, i.e., an extension of the introduced 3D PEAK-GRAPPA kernels to 4D configurations (three spatial directions and the temporal domain). Time-resolved angiography (16) as a 3D nonperiodic process is a potential application that may benefit from such extended kernel configurations in order to overcome limitations in temporal or spatial resolution associated with the breathhold capabilities of patients.

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