Artifact and Noise Suppression in High Resolution GRAPPA Imaging

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Introduction

GRAPPA (GeneRalized Auto calibrating Partially Parallel Acquisition) has been used to increase spatial resolution in a limited imaging time with an RF coil array for spatial encoding (1). Coil sensitivity is exploited to reconstruct missing phase encoding lines from a reduced data set. However, high-resolution images reconstructed by GRAPPA suffer from residual aliasing artifacts and amplified noises when a least squares fitting in the coil sensitivity calibration is applied to highly fluctuating data along the phase encoding direction. In this work, we propose a modified fitting approach to reduce the residual aliasing artifacts and noises. Variable-density (VD) sampling trajectories along the phase encoding direction are optimized to reduce high frequency smoothing filtering inherent in GRAPPA reconstruction.

Theory

In GRAPPA, the central region of each coil k-space is sampled at the Nyquist rate, while the outer k-space is reduced by an outer reduction factor (ORF). The reconstruction algorithm consists of several steps (1): 1) Coil weights are calculated by a least squares fitting using auto calibration signal (ACS) lines of a target coil and measured lines around them over all coils, 2) The missing lines of the target coil k-space are calculated by multiple blockwise reconstructions using the coil weights obtained in step 1), 3). The multiple reconstructions for a missing line are combined in a weighted average to generate the final reconstructed line. The weights used in step 3) are computed by the goodness of fit for the ACS lines, 4) A Fourier transform is applied to generate each coil image after the missing lines are reconstructed, 5) All of the coil images are combined using a root sum of squares reconstruction.

In high-resolution imaging with GRAPPA, each coil k-space is sampled with a higher ORF (= 3 or 4) than 2, since more Nyquist sampled central lines can be acquired under the same imaging time. These high-energy low frequency lines contribute to suppressing aliasing artifacts as well as improving signal-to-noise ratio in the final reconstructed image. However, residual aliasing artifacts and amplified noises occur when the least squares fitting in steps 1) and 3) is applied to highly fluctuating ACS data in signal intensity along the phase encoding direction. In GRAPPA, only low-signal high frequency lines are reconstructed. Therefore, if the ACS lines around the highest signal echo are included in the fitting process, significant errors are propagated to the high frequency region.

To avoid this problem, each coil k-space is segmented along the frequency encoding direction to localize high signal echo region from low signal region (Fig. 1). The least squares fittings in steps 1) and 3) exclude the ACS lines around the highest signal echo in the segmented k-space by the following two ways: a) A part of ACS lines in the upper shaded region in Fig. 1 are used to calibrate the coil weights to reconstruct the missing lines in the upper k-space, and b) The step a) is repeated using a part of ACS lines in the lower shaded region in Fig. 1 to reconstruct the missing lines in the lower k-space. Each coil k-space is reconstructed segment by segment along the frequency encoding direction.

GRAPPA reconstruction is equivalent to applying smoothing filtering in the high frequency region along the phase encoding direction. It results in blurring when k-space is sampled with a high ORF (= 3 or 4), since more filtering is applied in the high frequency region. To reduce this blurring, the outer k-space is sampled with ORFs of 2 and 4 under the same imaging time, increasing the number of measured high frequency lines while reducing the number of the Nyquist sampled lines in the central region of k-space.

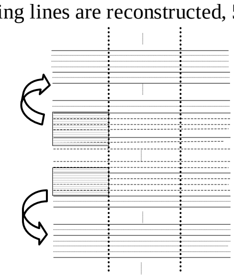

Fig. 1. A modified fitting for coil calibration with ORF of 2 and 4. (solid: measured line, dotted: missing line, dashed: ACS line)

Methods

A high-resolution coronary artery image (250x512, 270x380 mm^2 FOV, 3mm thickness) was acquired using an ECG triggered segmented 3D true-FISP (2) at Siemens 1.5T Sonata scanner with 7 coils posterior and anterior to heart. The fully acquired k-space data was decimated off-line by VD sampling scheme. Four images were generated by: a) the root sum of squares reconstruction with full acquisition (reference), b) GRAPPA with ORF of 4 (125x512), c) GRAPPA using the modified fitting with ORF of 4 (125x512), and d GRAPPA using the modified fitting with ORFs of 2 and 4 (125x512). The least squares fitting profiles of reconstructed signals along the phase encoding direction were presented with the profile of measured signals.

Results

Compared with the reference image (Fig. 2a), residual aliasing artifacts and amplified noises were observed when the ACS lines with high signal echoes are included in the least squares fitting process (Fig. 2b). The artifacts and noises were significantly reduced by the modified fitting approach (Fig 2c). The exclusion of the high signal ACS lines in the least squares fitting yielded more smoothly reconstructed profiles in the high frequency region along the phase encoding direction (Fig. 3). However, a blurring occurred with ORF of 4 (Fig.2c,e). The blurring was reduced by optimizing sampling trajectories with ORF of 2 and 4 in the outer k-space (Fig. 2d,f).

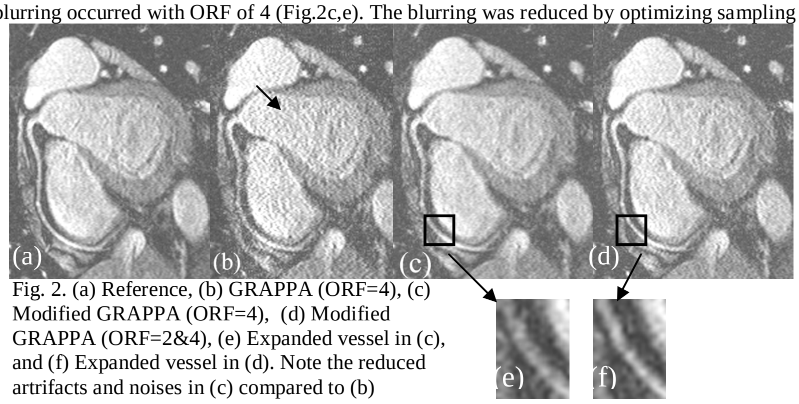

Fig. 2. (a) Reference, (b) GRAPPA (ORF=4), (c) Modified GRAPPA (ORF=4), (d) Modified GRAPPA (ORF=2&4), (e) Expanded vessel in (c), and (f) Expanded vessel in (d). Note the reduced artrifacts and noises in (c) compared to (b) and higher sharpness of vessel in (f) compared to (e).

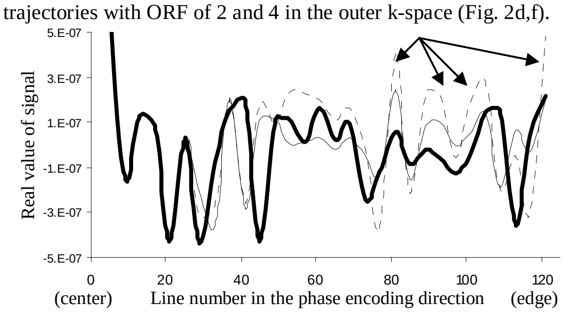

Fig. 3. Least squares fitting profiles of reconstructed signals with measured signals along the phase encoding direction (thick solid: measured, dotted: the original fitting, thin solid: the modified fitting). Note the overestimated signals in high frequency region (arrows) result in the amplified noises in Fig. 2 (b)

Discussion & Conclusions

The coil weights are calibrated inaccurately if the least square fitting includes the ACS lines around the highest signal echo. It yields large deviation of reconstructed signals in the high frequency region along the phase encoding direction. As a result, residual aliasing artifacts and amplified noises are observed. The artifacts and noises are significantly reduced by the least square fitting excluding the high signal ACS lines. The blurring in GRAPPA with high ORF (= 4) is decreased by optimizing VD sampling trajectories with ORFs of 2 and 4 reducing the smoothing filtering in the high frequency region.

References :

(1) Griswold et al, MRM 47:1202-1210 (2002). (2) Deshpande et. al. MRM 46: 494-502 (2001).