A multi-kernel approach for reducing inter-slice image ghosting in simultaneous multi-slice EPI

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Introduction: Simultaneous multi-slice (SMS) EPI using parallel imaging (1-5) allows for a significant increase in the temporal sampling rate of fMRI and the number of diffusion directions that can be obtained per unit time in diffusion imaging. Nonetheless, the unaliasing problem is difficult for closely spaced simultaneously excited slices, resulting in a high noise penalty (g factor) and unaliasing artifacts. A blipped-CAIPI acquisition scheme (6) was recently proposed to mitigate this issue by creating an inter-slice image shift between simultaneously acquired slices to increase the distance between the aliased voxels and thereby significantly reduce g-factor penalty and artifact. This method applies a phase cycled blipped slice-select gradient simultaneously with the PE_y blips. Such scheme eliminates the "tilted voxel" problem of previous blip schemes aimed at introducing slice shifts in EPI. (3) The slice-GRAPPA algorithm (6) was proposed as a method to unalias the blipped-CAIPI multi-slice datasets. In this work, we show that the presence of spatially varying field inhomogeneities and eddy currents can result in significant aliasing artifact from inter-slice image ghost leakage. A modified slice-GRAPPA reconstruction technique is proposed to mitigate this issue.

Method: Field inhomogeneities and eddy currents can create slice-specific FOV/2 ghosting artifacts in multi-slice acquisitions. If the ghost correction is performed prior to slice-GRAPPA separation on the collapsed slices (using information from the navigator lines of the slice collapsed acquisition), then only the slice-group average ghost is corrected (we term this the "standard" correction). To correct for slice-specific ghosts, Moeller et al (4) applied a residual ghost correction to each imaging slice after slice separation (using information from the navigator lines of a reference scan acquired one slice at a time). We termed this correction the "tailored" ghost correction. In our experience, the tailored ghost correction does not fully remove the ghost artifact in blipped-CAIPI acquisitions. Figure 1 shows the performance of the standard and tailored ghost correction schemes in a 3xSMS SE-EPI acquisition with FOV/2 interslice image shift and 4cm slice gap (Fig.1A) acquired on a Siemens Tim Trio scanner with a 32ch head array. Here slice-GRAPPA is used for slice separation. Figure 1B,C, and D shows the *percentage signal error* image of the unaliased center slice. With the standard ghost correction scheme, the center unaliased slice (Fig. 1B) exhibits significant inter-slice ghost artifacts originating from the top slice, which does not get mitigated by the tailored ghost correction method (Fig. 1C). This example illustrates that a small level of ghost from a high intensity region of the top slice can cause a large signal change in the voxels with lower intensity in the center slice. This issue is particularly prominent for blipped-CAIPI acquisition with FOV/2 inter-slice shift, where the ghost from the top imaging slice lands in the middle of the FOV of the center slice.

The inter-slice ghost artifact is caused by imperfect separation of the single slice data from the collapsed data through the use of a single GRAPPA kernel set in the slice-GRAPPA algorithm. This algorithm fails to *simultaneously* remove the top slice image and its ghost during the reconstruction of the center slice. To illustrate this point, figure 1E shows the application of a GRAPPA kernel to the even and odd lines (blue and yellow) of the collapsed k-space data in the presence of even/odd phase imperfection which might arise when the 3-slice average phase correction is applied in a case where different corrections are needed for each slice. Figure 1F shows the differences in the kernel coverage in the un-warped k-space for the odd and even lines. Note: the kernel coverage will actually be different for each slice of the collapsed image since the amount of eddy current warping is different in each slice. To address the different warping sense of the even and odd lines, we propose the use of a different GRAPPA kernel for the odd and the even lines to effectively unalias the imaging slices and eliminate inter-slice ghost artifact. The first kernel set is estimated using the even lines fitting of the pre-scan calibration data and then applied on the collapsed data to generate the even lines data of the individual slice. The second kernel set is generated and apply in a similar way on the odd data lines. Both kernel sets are estimated from the pre-scan dataset after a slice-group average phase corrections from the reference lines of the SMS acquisition.

The ghost correction would normally be performed prior to the gridding operation. Here, the slice-group average ghost correction based on the navigator of the SMS data is applied prior to the gridding process (this was done for all the ghost correction cases in figure 1). However, the slice specific ghost correction can only be applied after the slice-GRAPPA operation, which needs to be performed on gridded k-space data.

Results: Figure 1 assesses the artifact burden of the 3xSMS acquisitions with 3 different ghost correction methods. Figure 1B, C and D show a ratio image of the conventional single-slice prescan data and the unaliased SMS image of the center slice. Either the standard ghost correction (B), the tailored ghost correction (C) or the tailored ghost correction + two GRAPPA kernel approach (D) was used. The table in figure 1G tabulates the mean and standard deviation of the artifact, and the percentage of pixels that has more than 10% signal error for all three ghost correction techniques. Combining the tailored correction and the multiple kernel approach significantly lowers the aliased ghost. For example, the standard ghost correction method results in 30% higher mean artifact level increases in the number of pixels with more than 10% signal error by more than 3 fold.

Conclusion: The aliasing of the ghosts from other imaging slices can be particularly problematic in SMS acquisitions, particularly when blipped-CAIPI scheme is used since the ghost is shifted into the center of the FOV. In this work, we demonstrate a multiple kernel approach to reducing the inter-slice image ghost artifact in the slice-GRAPPA reconstruction of SMS acquisition.

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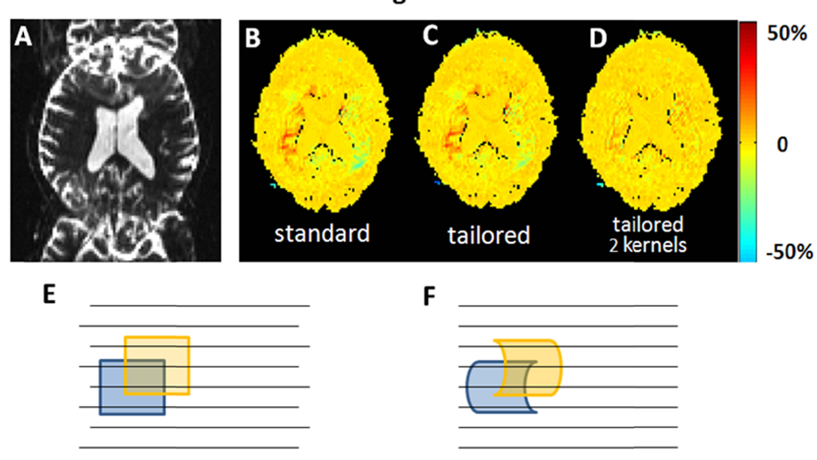
FIG. 1 Artifact with different ghost correction methods



G	%Error: Mean +/- Std	Pixels with > 10% error
Standard	2.6+/-3.5	4.5%
Tailored-Ghost	2.4+/-3.26	3.5%
Tailored-Ghost with 2kernels	1.97+/-2.3	1.4%