NONLINEAR PHASE CORRECTION OF MULTI-SHOT DIFFUSION WEIGHTED EPI USING PARALLEL IMAGING ESTIMATED PHASE CYCLED RECONSTRUCTION (PIPCR) METHOD

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Target audience: Researchers with an interest in diffusion weighted multi-shot EPI reconstruction may benefit from this study.

Purpose: Multi-shot echo-planar imaging (msEPI) has advantages in obtaining better quality images with high spatial resolution and less distortion when comparing to single-shot EPI (ssEPI). However, msEPI is sensitive to subject motion, in particular in the application of diffusion imaging. The effect of a tiny motion will be amplified by diffusion-sensitizing gradients and will produce ghosting artifact due to phase variations from shot to shot [1]. To correct the inter-shot phase errors, a phase shift for each EPI shot can be measured by a spiral navigator technique [2]. Various reference-scan-free methods were also proposed to estimate the constant and linear phase errors for ghosting correction [3, 4]. Most recently, a phase cycled reconstruction (PCR) procedure was introduced to make 2D phase correction in msEPI more efficient [5]. The original PCR method uses a search algorithm to find the optimal phase compensation for phase errors between the odd and even echoes. In principle, the inter-shot phase errors of diffusion weighted msEPI can also be corrected by PCR method. However, in practice, the pulsing of cerebrospinal fluid (CSF) produces irregular and nonlinear inter-shot phase shift, which requires much more searching variables of PCR method and will result in time consuming or even infeasible to directly apply PCR method for diffusion weighted msEPI reconstruction. To resolve these problems, in this report, an efficient parallel imaging estimated phase cycled reconstruction (PIPCR) method is introduced and its result in correcting arbitrary inter-shot phase errors of diffusion weighted msEPI is demonstrated.

Methods: The original PCR method finds the best compensating phase via a search algorithm. In an alternative method, the phase map of each msEPI shot can be extracted from the undersampled data itself. One shot of diffusion weighted msEPI data is a subset of a full *k*-space which is modulated by an extra phase φ_r, where *r* (=1,2,…,*R*) is the *r*th shot of the total number of *R* shots: $S_r=\mathrm{FT}\{\rho\exp(i\varphi_r)\}_r$, and ρ is the image without the phase variation. The subset data S_r can also be treated as a parallel imaging (PI) data with undersampling factor *R*, so the estimated image of the *r*th shot can be reconstructed from S_r using various PI techniques, such as SENSE and GRAPPA: $\hat{I}_r=\mathrm{PI}\{S_r\}$, and the phase of the *r*th shot can be extracted from the estimated image: $\hat{\varphi}_r=\angle(\hat{I}_r)$. Since PI reconstruction introduces extra noise, in particular in the case of high accelerator factor *R*, the phase maps are polluted by random noise and need to be smoothed. The smoothing procedure can be performed either in image or k-space domains. In the end, these phase maps are utilized as the inter-shot phase compensation for PCR msEPI reconstruction. A flowchart of a typical GRAPPA-based PIPCR reconstruction method is shown in Figure 1.

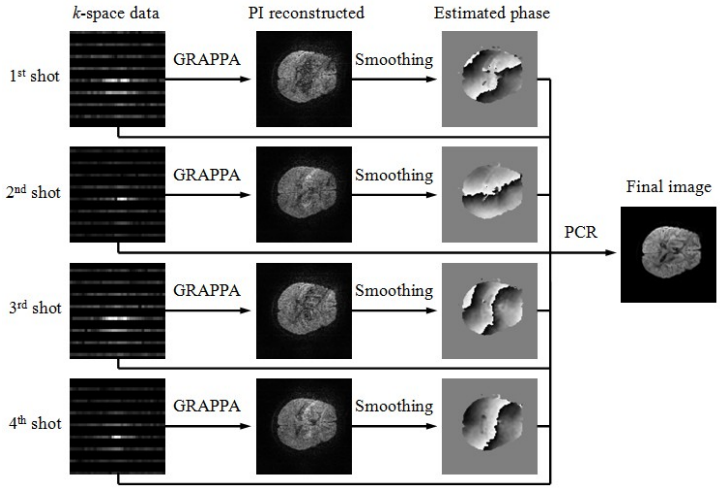

Figure 1. Flowchart of the proposed PIPCR method.

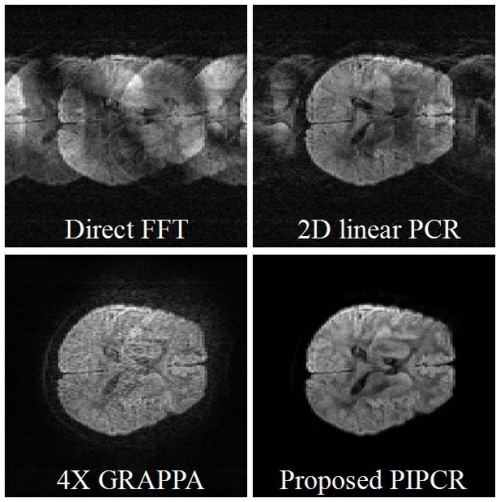

Figure 2. Images obtained from a diffusion msEPI data set using different reconstruction methods.

Results and Discussion: Figure 2 shows images obtained from a human brain diffusion weighted msEPI data set using different reconstruction strategies. The diffusion *b*-value=600s/mm^2 and multi-shot number is *R*=4. The image generated from direct FFT of the *k*-space data set suffers severe ghosting artifacts; the image produced by the 2D linear phase PCR method is still impaired by residual artifacts; the average image reconstructed from four undersampled msEPI data using GRAPPA technique is ghost free but bears severe noise amplification. The image produced by our newly developed PIPCR method illustrates high imaging quality with the absence of residual artifacts and noise amplification.

Conclusion: PIPCR is a fast and robust multi-shot EPI reconstruction technique and it is extremely powerful in generating artifact-free diffusion images with high spatial resolution.

Reference: [1] Butts et al., MRM 1996;35:763-770; [2] Butts et al., MRM 1997;38:741-749; [3] Lee et al., MRM 2002;47:812–817; [4] Zhang and Wehrli, MRM 2004;51:621–624; [5] Chen et al., MRM 2011;66:1057–1066.