Improved BPE reconstruction using FOCUSS

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Introduction: Bunched Phase Encoding (BPE) is a new type of fast data acquisition method in MRI that takes advantage of zigzag k-space trajectories along the PE direction (Fig.1)[1,2]. Sampling frequency of BPE is higher than that of normal acquisition. Since BPE acquisition scheme is comparable to acquiring multiple PE lines in a single readout, the total number of TR cycles and hence the scan time can be reduced. A primary disadvantage of BPE is that images reconstructed using matrix inversion methods are sometimes affected by high levels of noise. Various efforts have been made to reduce noise and aliasing artifacts by modifying reconstruction methods. For example, recent studies of parallel imaging have demonstrated that regularization methods are useful to mitigate noise amplification [3-5]. However, these methods often may result in loss of spatial resolution or exhibit residual aliasing artifacts. The focal underdetermined system solver (FOCUSS) has recently been successfully adapted to undersampled projection reconstruction, spiral and dynamic imaging in MRI [6-8]. FOCUSS capitalizes on sparsity of image support and considerably reduces aliasing artifacts from undersampled k-space data. In this study, we present a novel framework to reduce SNR loss in BPE reconstruction. In our newly proposed technique, high frequency k-space data are processed using a combined method of regularization and FOCUSS to reconstruct images with reduced noise and aliasing artifacts. The newly proposed method is referred to as 'BPE-FOCUSS'. Images reconstructed using BPE-FOCUSS show substantially reduced noise from those reconstructed using a conventional BPE reconstruction method while no apparent aliasing artifacts are introduced. BPE-FOCUSS is quite useful and facilitates implementation of BPE in practice.

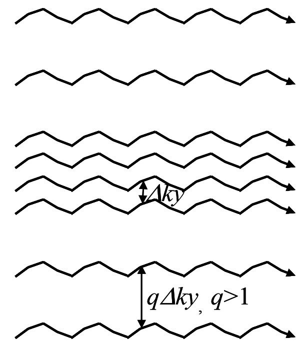

Fig.1. BPE-FOCUSS acquisition

Methods: BPE-FOCUSS acquires data in the central k-space to fulfill the Nyquist criterion, as shown in Fig.1, where q (>1) is a reduction factor of BPE and Δky is defined as $1/(FOV_y)$. This sampling method requires only short extension of acquisition time of BPE. Figure 2 shows a flow chart of BPE-FOCUSS. A low pass filter is first applied to the central data along ky direction. An inverse Fourier transform (IFT) is performed on these data to reconstruct a low resolution image. The rest of k-space data are decomposed to reconstruct an image with high spatial frequency components. In this step, matrix inversion is usually used. The inversion matrix can be constructed based on data locations along zigzag trajectories. Both low and high pass images are combined to create a final image. In BPE-FOCUSS, regularization and FOCUSS are taken advantage of when high frequency k-space data are decomposed. This process can be expressed as:

$$\rho = \rho_0 + \Theta R^H (R\, \Theta R^H + \lambda I)^{-1} d, \qquad \text{[Eq.1]}$$

where $\Theta = W W^H$,

and W is a diagonal matrix of which diagonal elements are $|\Delta\rho(1)|^{1/2}, |\Delta\rho(2)|^{1/2}, \ldots, |\Delta\rho(N)|^{1/2}$.

In Eq.1, ρ and ρ_0 are a final and a low pass images, respectively. d is high frequency k-space data. R is a decomposition matrix constructed based on data locations. λ is a regularization parameter. I is the identity matrix. In a weighting matrix W, the diagonal elements $\Delta\rho(i)$ represents estimated image values of high frequency components, and N is the total number of pixels in the image. In our experiments, $\Delta\rho(i)$ is computed from $R^H (R R^H + \lambda I)^{-1} d$ when λ is adequately small.

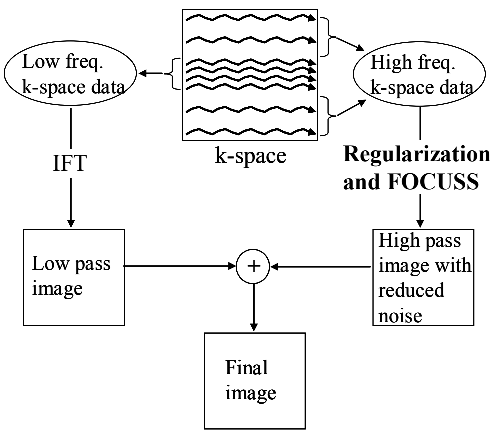

Fig.2. Flow chart of BPE-FOCUSS

MR experiments were performed to test BPE-FOCUSS using a 1.5 Tesla Siemens Sonata Scanner. A resolution phantom was scanned using a FISP sequence with TE/TR=10.0/20.0ms in this experiment. The target image matrix size was 256 x 256. A zigzag trajectory we designed consisted of 128 oscillations. Reduction factor was set to two, i.e. q=2. The central 15% of k-space was acquired with the Nyquist criterion fulfilled, i.e. the total number of TR cycles was 147(=256/2+19).

Results: Figure 3 (a-c) show images reconstructed from the high frequency data. (a) is reconstructed using a conventional matrix inversion method. (b) is reconstructed using a matrix inversion method with a large regularization parameter ($\lambda=10^{5.5}$). (c) is reconstructed using BPE-FOCUSS ($\lambda=10^{-5.5}$). As seen, although noise in (b) is reduced from that in (a), aliasing artifacts appear in (b). However, noise in (c) is significantly reduced from that in (a) while no apparent aliasing artifacts are observed in (c). Figure 3 (d-f) are final reconstructed images corresponding to Fig.3(a-c), respectively. As expected from images (b) and (c), both (e) and (f) achieve noise reduction from (d) while preserving spatial resolution. However, (e) is affected by non-negligible aliasing artifacts. These aliasing artifacts are considerably reduced in (f). The measured SNR of (f) is comparable to that of (e). They are approximately 2.2 times higher than the measured SNR of (d).

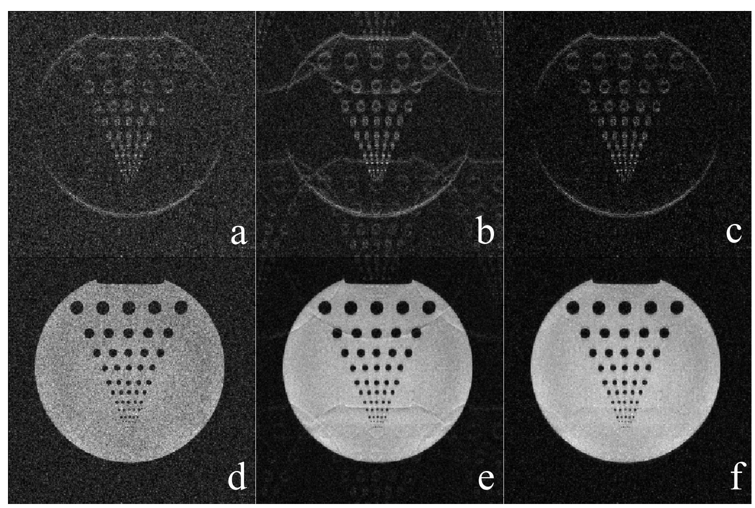

Fig.3. Reconstructed images

Discussion and Conclusions: In BPE, image SNR depends on various factors, e.g. reduction factor, the number and an amplitude of oscillations for each zigzag trajectory, and zigzag wave pattern. In general, for the same reduction factor, when the number and/or an amplitude of oscillations are increased, SNR of the image is increased [1]. However, it is often difficult to increase these values due to limited gradient performance. BPE-FOCUSS does not require to change gradient waveforms from BPE although it needs to acquire several additional PEs at the k-space center. The basis of FOCUSS algorithm is sparsity of image support [6-8]. In fact, images reconstructed from high frequency k-space data are usually sparse enough. Furthermore, performance of FOCUSS algorithm often depends on 'initial estimates' with which the algorithm starts. When we reconstructed Fig.3(c), image values of Fig.3(a) were used to construct a matrix W. In other words, 'a good estimate' is available for BPE-FOCUSS since it is provided by a conventional BPE reconstruction method. These are the reasons why BPE-FOCUSS can successfully be applied to BPE data. The newly proposed BPE-FOCUSS is a quite useful fast data acquisition method that improves image quality from BPE.

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