Generalized Blipped CAIPI for Interleaved EPI Diffusion Weighted Imaging

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Target audience: Researchers interested in diffusion weighted and fast MR imaging.

Purpose: Controlled aliasing in parallel imaging (CAIPI) as a kind of multiband technique can better utilize the coil sensitivity information for slice separation [(1)]. Recently, blipped CAIPI has been widely used to accelerate single shot EPI diffusion and BOLD imaging [(2)]. Compared with single-shot technique, multi-shot EPI diffusion techniques can provide higher spatial resolution together with reduced geometric distortions, but relatively long acquisition time is needed [(3)]. Thus combination of multi-shot EPI and blipped CAIPI may achieve the advantages of both. In this study, a generalized blipped CAIPI sequence and reconstruction framework for interleaved EPI is first proposed and implemented. Then the generalized interleaved blipped CAIPI EPI is applied for DWI imaging and the performance is compared with single-shot blipped CAIPI EPI.

Methods: ***Sequence design:*** According to the theory of CAIPI, an extra phase accumulation along ky direction in k-space is needed to introduce the in-plane FOV shift [(1,2)]. For *N*-shot blipped CAIPI EPI to generate the FOV/M shift, a generalized calculation for the desired extra phase $\varphi_{ky',n}$ at ky' in each shot can be described as

$$\varphi_{ky',n} = \{[n-1+(ky'-1)\times N]\ mod\ M\}\times 2\pi/M-(M-1)\pi/M,$$

where M is the multiband acceleration factor, N is the total shot number, n is the shot index, $ky' = 1,2,3\ldots$ is the phase encoding index in each shot. Three kinds of gradient blips are added in slice direction to generate the desired $\varphi_{ky',n}$, as shown in Fig. 1. For simplicity, only the sequence diagram of 2-shot blipped CAIPI spin echo (SE) EPI with *M*=3 is shown. 1) A gradient blip (G_1) is added at the beginning of each shot to reduce voxel tilting artifacts [(2)]; 2) A gradient blip (G_2) is then added to introduce the corresponding phase of the first ky' line of each shot; 3) A block of gradient blips (G_3) are added to introduce the phase increment between adjacent two ky' lines. For each shot, the G_3 block consists of M gradient blips, with each gradient area corresponding to the $\varphi_{ky'}$ increment of the adjacent two ky' lines in each shot, which can be calculated as $A_i = \left(\varphi_{ky'_i,n} - \varphi_{ky'_{i-1},n}\right)/\gamma$, where $1 \le i \le M$ and γ is the gyro-magnetic ratio. The G_3 block repeats until the end of each shot. For different shots, G_1 keeps constant, while G_2 and G_3 change with the corresponding $\varphi_{ky',n}$ changes. ***Reconstruction:*** A 3D reconstruction framework is used for the slice separation, in which multiband acceleration is viewed as an undersampling of "MB 3D" k-space [(4)]. The "MB 3D" k-space takes the blipped gradients as kind of kz encoding in traditional 3D sampling. Considering the phase inconsistency between different shots for DWI images, the full k-space from each shot is individually reconstructed with 2D GRAPPA. Then the separated images from each shot are modulus-averaged to generate the final image. A fully sampled SE EPI "MB 3D" k-space is acquired and the central 64×3 (ky×kz) lines are used for weighting matrix estimation. ***Imaging procedure:*** All MRI experiments were performed on a Philips 3T scanner using a 32-channel head coil. To perform multiband excitation, conventional slice-selective RF pulses were frequency modulated and summed. 3 slices separated by 30 mm were simultaneously excited with FOV/3 shift. Both single-shot (TE=92 ms) and 2-shot (TE=86 ms) SE EPI DTI imaging for the human brain were performed as the following: FOV=230×230 mm^2, matrix size=141×141, slice thickness=4 mm, TR=3s, partial Fourier=6/8. The DWI images with b=600 s/mm^2 in 6 direction were acquired.

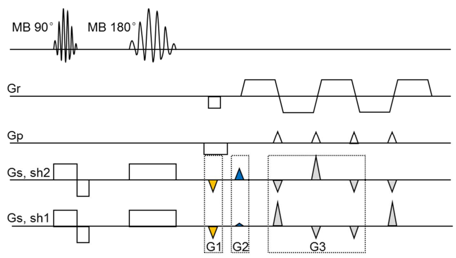

Fig. 1 The sequence diagram of 2-shot blipped CAIPI SE EPI with MB=3. Gradients in slice direction in all shots (sh1 - 2) were shown.

Results: The DTI images and FA maps from both single-shot and 2-shot SE EPI with MB=3 were shown in Fig. 2. The corresponding FA maps from single-shot and 2-shot SE EPI DTI with single band excitation were taken as reference.

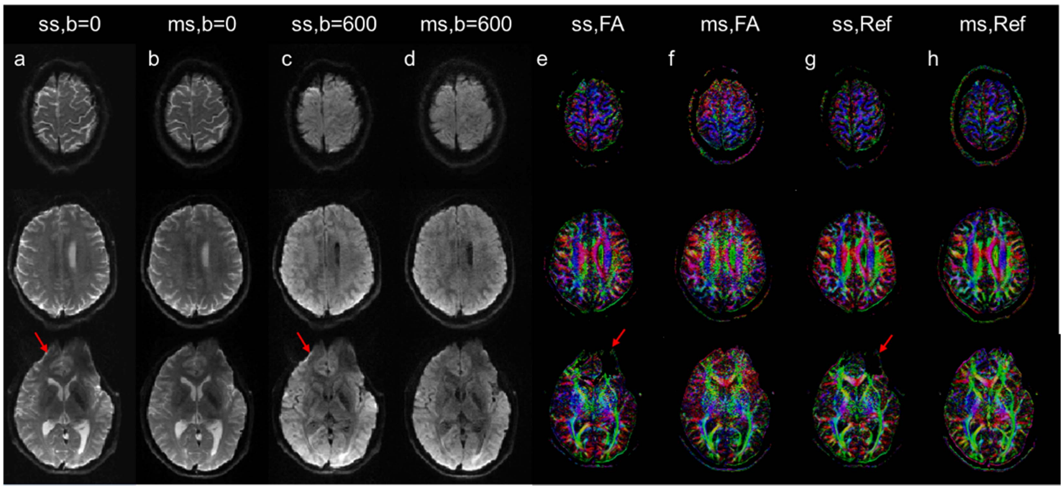

Fig. 2 DTI images with blipped CAIPI acceleration factor M=3. (a) b=0 with single-shot (ss) EPI; (b) b=0 with multi-shot (ms) EPI; (c) b=600 s/mm^2 with ss-EPI, one direction (d) b=600 s/mm^2 with ms-EPI, one direction; (e) FA maps with ss-EPI; (f) FA maps with ms-EPI; (g) FA maps from single band excitation with ss-EPI as reference; (d) FA maps from single band excitation with ms-EPI as reference. Image distortions from ss-EPI were indicated with red arrows.

Discussion: As shown in Fig. 2, compared with single-shot blipped CAIPI EPI with the same resolution, multi-shot blipped CAIPI EPI shows fewer geometric distortions (red arrows). Besides, the multi-shot blipped CAIPI EPI has shown comparable FA maps with single band excitation, though FA maps from multiband excitation was a little noisy. This is because for multi-shot blipped CAIPI EPI DTI, since phases are inconsistent for different EPI segments, 2D GRAPPA was performed shot by shot in this study. Thus relatively far neighboring points were used to reconstruct each unacquired data, leading to noise amplification. An optimized reconstruction algorithm and phase correction method will be involved in the future study.

Conclusion: In this study, a generalized blipped CAIPI for interleaved EPI has been proposed and implemented. The proposed method has achieved fewer distortions than single-shot blipped CAIPI EPI and comparable FA maps with single band excitation. With both the advantage of low distortion of multi-shot EPI and accelerated imaging acquisition with blipped CAIPI, this method can be valuable for fast high resolution DWI or DTI in the future.

References: 1. Breuer FA, et al. MRM 2005. 2. Setsompop K, et al. MRM 2012. 3. Bammer R, et al. Radiology 1999. 4. Zahneisen B, et al. MRM 2014.