

# Blipped CAIPIRHINA for simultaneous multi-slice EPI with reduced g-factor penalty

K. Setsompop<sup>1,2</sup>, B. A. Gagoski<sup>3</sup>, J. Polimeni<sup>1,2</sup>, T. Witzel<sup>1</sup>, V. J. Wedeen<sup>1,2</sup>, and L. L. Wald<sup>1,2</sup>

<sup>1</sup>Radiology, A. A. Martinos Center for Biomedical Imaging, Massachusetts General Hospital, Charlestown, MA, United States, <sup>2</sup>Harvard Medical School, Boston, MA, United States, <sup>3</sup>EECS, Massachusetts Institute of Technology, Cambridge, MA, United States

**Introduction:** The acquisition of simultaneous slices using EPI with either wideband methods (1-3) or parallel imaging multi-slice methods (4-7) has the potential to increase the temporal sampling rate of fMRI or the number of diffusion directions obtained per unit time in diffusion imaging (DI). Unlike conventional parallel imaging with EPI, which does not significantly increase the number of slices per second, simultaneous multi-slice methods do not undersample the data, instead they alias simultaneously excited slices. This leads to an R fold reduction of time and an SNR reduction given simply by the g factor, rather than  $g\sqrt{R}$ . Thus, the same data is acquired in significantly shorter time, providing the potential to increase the SNR per unit time for high-resolution whole-head fMRI, or DI where TRs  $\gg T_1$  are generally required.

With parallel imaging methods, the unaliasing problem is difficult in closely spaced simultaneously excited slices, resulting in high g factors. Unfortunately, the traditional CAIPIRINHA scheme (5) for introducing a FOV/2 shift in the phase direction of alternate slices utilizes RF phase cycling of the excitation pulses and is not applicable to single-shot EPI. A method to use a set of constant slice-select gradient blips ( $G_z$ ) simultaneously with the EPI phase encoding blips ( $G_y$ ) to achieve CAIPIRINHA-style shifts (6) introduces undesirable “tilted voxel” problem similar to the wideband methods (1-3). Here, we introduce a blipped CAIPIRINHA scheme where the blips in the slice-select gradient are cycled in amplitude to impart a phase on each line of kspace that produces the modulation needed for the CAIPIRINHA shift scheme, but does not accrue significant phase over the EPI readout, eliminating “tilted voxel” problem and its spatial resolution filtering effect.

**Theory:** In ref. (6), to achieve an inter-slice image shift in the PE direction, gradient blips in the slice-select direction ( $G_z$ ) are introduced simultaneously with the conventional EPI  $G_y$  blips. The addition of constant amplitude  $G_z$  blips results in a rotation of the phase encode direction into the slice direction rendering slice and PE directions non-orthogonal (the gradients vectors add), resulting in the undesirable pixel tilt artifact. The tilt-effect produces a voxel blurring artifact (6), where the phase shifts introduced to the  $k_y$  lines cause through-plane dephasing within each excited slice. An initial  $G_z$  pre-wind gradient refocuses the dephasing at the center of kspace, but the dephasing accumulates for high  $k_y$  lines introducing a blurring filter in the y direction of the image. To address this, we developed a novel  $G_z$  blipping scheme that provide an inter-slice image shift (e.g. of FOV/2), but does not produce a phase accumulation in  $k_y$ , and thus eliminates the through-plane dephasing and associated blurring/voxel tilt artifact. In this strategy, subsequent  $G_z$  blips act to un-wind the through-plane dephasing of the previous blip as well as producing the required phase shift between the adjacent slices needed for the inter-slice image shift. By replacing a constant phase accumulation across  $k_y$  with back-and-forth jumps, we eliminate the accumulation of through-plane dephasing and its associated blurring filter. The scheme is shown schematically in Fig. 1 for FOV/2 and FOV/3 image shift cases.

**Methods:** We tested our blipped CAIPIRINHA acquisition on two volunteers using Siemens TIM Trio scanner with a 32-channel head array coil. A slice-GRAPPA reconstruction technique similar to that used in ref. (7-8) was implemented. The method was demonstrated with (i) 3 simultaneously acquired multi-slice SE-EPI acquisition which utilizes R=3 slice-Grappa, and (ii) 6 simultaneously acquired multi-slice GE-EPI acquisition which utilizes R=3 slice-Grappa together with Simultaneous Image Refocusing (SIR) (9) to achieve an extra R=2 multiplicative acceleration factor. Additionally, R=2 inplane-Grappa was employed to counteract lengthen echo-spacing due to SIR (~50% longer esp was required) providing a net 50% improvement in susceptibility induced distortion. Because of the inplane acceleration, an intra-slice image shift of  $\frac{1}{4}$  rather than  $\frac{1}{2}$  FOV was used to prevent voxels with same in-plane (x,y) locations of adjacent image slices from overlapping. The parameters for the two acquisitions were: (i) slice-Grappa inter-slice gap = 40mm; FOV = 208x208x120 mm; Partial Fourier =  $\frac{3}{4}$ ; matrix = 104x78x20; resol= 2mm iso; TR/TE = 3s/96 ms; for (ii) slice-Grappa inter-slice gap = 40mm; FOV = 208x208x120 mm; Partial Fourier =  $\frac{3}{4}$ ; matrix = 104x52x10; resol= 2mm iso; TR/TE = 0.77s/33 ms; Flip angle = 51.8° (Ernst angle). All RF pulses were designed using SLR algorithm (10) with frequency modulation and summation to produce simultaneous multi-slice excitation. Verse (11) was applied to reduce SAR while keeping each RF pulse to within 4 ms.

**Results:** Fig. 2 shows results of 3x slice-Grappa SE-EPI: Fig. 2A. left: coronal and sagittal views of the unaliased 3D stack of slices, right: an unaliased slice group. Fig.2B. left: blipped-CAIPIRINHA folded images, right: Retained SNR (1/g) calculated via pseudo-multiple replica method(12) Fig.2C. left: non-blip folded images, right: Retained SNR. The retained SNR from blipped CAIPIRINHA acquisition is substantially higher than the non-blip case. In some regions the retained SNR is greater than unity indicating some noise cancellation in the reconstruction process as previously demonstrated in low R inplane Grappa acquisition (13). Note that in order to perform the same inter-slice image shift acquisition using method in ref. (6), voxel tilt would cause signal from one voxel to smear over ~3.5 voxels. Fig. 3 shows results from 6x multi-slice GE-EPI, left: coronal and sagittal

views of unfolded slice stack, center: a set of 6 unaliased slices from 2 SIR multislice groups (red and yellow), right: Retained SNR of blipped and non-blip acquisitions from a representative slice. Again blipped CAIPIRINHA acquisition results in substantially higher retained SNR. Noted that as a result of short TR, low contrast between gray and white matter can be observed. **Conclusion:** In this work we introduced blipped CAIPIRINHA EPI acquisition and demonstrated its associated low g-factor penalty and 3x acceleration of the slices per second of acquisition. Given the benefit achieved, this method could help enable fast high-resolution whole-head fMRI and HARDI/Q-ball and DSI style diffusion imaging acquisitions.

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