# Simultaneous Multi-slice Flyback Echo Planar Imaging with Auto-calibration

Kangrong Zhu[1], Adam Kerr[1], and John M Pauly[1]
[1]*Stanford University, Stanford, California, United States*

**Purpose:** Simultaneous multi-slice parallel imaging techniques, such as CAIPIRINHA [1] and Blipped-CAIPI [2], usually need external calibration scans for image reconstruction. Internal auto-calibration for such slice-accelerated acquisitions can be performed if the reconstruction is conducted in the 3D k-space instead of the 2D k-space [3]. In this work, we develop an auto-calibrating data acquisition scheme in the 3D k-space for simultaneous multi-slice Echo Planar Imaging (EPI).

**Methods:** For $N_s$ simultaneously excited slices, Blipped-CAIPI [2] uses positive and negative $G_z$ blips to alternate the phase between successive slices among $N_s$ different states: $(2\pi/N_s) \times [-(N_s-1)/2, -(N_s-1)/2+1, ..., +(N_s-1)/2]$. Since these phase states correspond to the $N_s$-point DFT of the excited slices, the 2D k-space data acquired in Blipped-CAIPI can be reformulated into a 3D k-space data set [3], as illustrated in Fig. 1a. In our proposed ACME (Auto Calibrating Multiband EPI) technique, $G_z$ blips are also utilized to step through $k_z$, but the need for external calibration scans is eliminated by the fully sampled auto-calibration signal (ACS) in the central k-space area, as illustrated in Fig. 1b. If there is little variation of the receiving coil sensitivity along the slice select direction, the undersampling pattern in Fig. 1a and Fig. 1b lead to similar conditions for the reconstruction problem. With only intra-slice aliasing, the undersampling pattern in Fig. 1b has an advantage over that in Fig. 1a by restricting the EPI related ghosting artifacts only to slices which contain the sources of the ghosting. The indices on the sampled points in Fig. 1b indicate the acquisition order of the samples if a one-shot acquisition were used. This acquisition order is picked to smooth the signal decay in the 3D k-space. Fig. 1c displays the gradient waveforms for the undersampling pattern in Fig. 1b. In practice, a multi-shot interleaved acquisition with echo time shifting is used instead of one-shot acquisition to shorten the echo train length.

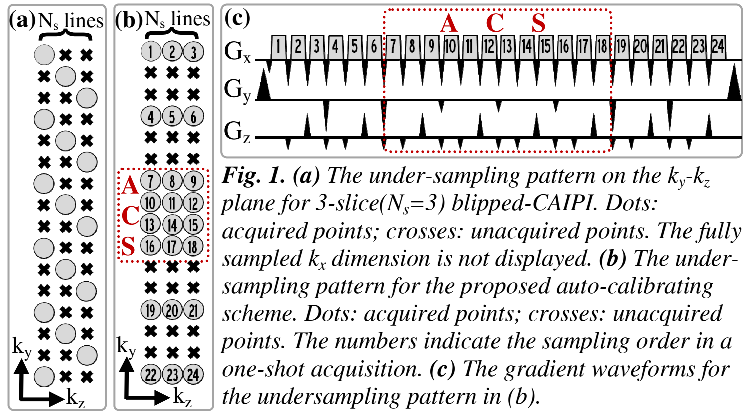


***Fig. 1. (a)** The under-sampling pattern on the $k_y$-$k_z$ plane for 3-slice($N_s$=3) blipped-CAIPI. Dots: acquired points; crosses: unacquired points. The fully sampled $k_x$ dimension is not displayed. **(b)** The under-sampling pattern for the proposed auto-calibrating scheme. Dots: acquired points; crosses: unacquired points. The numbers indicate the sampling order in a one-shot acquisition. **(c)** The gradient waveforms for the undersampling pattern in (b).*

Three fold slice-accelerated brain images of a healthy volunteer were acquired on a 1.5T GE scanner using an 8-channel head coil with a multi-shot flyback EPI GRE sequence. Scan parameters were TR/TE/α/matrix/slice thickness/multislice slice spacing/echo train length = 500ms/30.32ms/20°/96×96/3mm/45mm/8. The total number of points acquired on the $k_y$-$k_z$ plane and the number of interleaves in the acquisition ($N_{total}/N_{intl}$) were 162/21 for ACME and 96/12 for Blipped-CAIPI. Both ACME and Blipped-CAIPI images were reconstructed by 2D-GRAPPA [3, 4] using the same kernel size ($k_x \times k_y \times k_z$ = 7×4×3) and calibration area size ($k_x \times k_y \times k_z$ = 96×34×3). The internal ACS lines for ACME were included in the reconstructed images. The Blipped-CAIPI data was reconstructed twice using two different external fully sampled calibration data sets. One of the fully sampled data sets well matched the slice-accelerated data, while the other fully sampled data set was acquired after the subject rotated his head for about 26 degrees and therefore does not match the slice-accelerated data.

**Results:** Whole brain imaging can be performed using the proposed ACME technique (Fig. 2a). The overall image qualities of the ACME technique (Fig. 2b) and the Blipped-CAIPI technique (Fig. 2c) are similar, but the ACME images have higher SNR due to the inclusion of the internal ACS data. The different undersampling patterns of ACME and Blipped-CAIPI result in different artifacts in the reconstructed images. In ACME, the ghosting of the eyeball caused by motion during the EPI readout is mostly restricted to the slice containing the eyeball (Fig. 2b). In Blipped-CAIPI, however, the ghosting of the eyeball appears in a slice not containing the eyeball (Fig. 2c), which may hamper future analysis of the unaliased images. Mismatch between the external calibration scan and the accelerated scan may further degrade the image quality of Blipped-CAIPI (Fig. 2d). The ACME images and the Blipped-CAIPI images have slightly different distortions due to the different sequence timings.

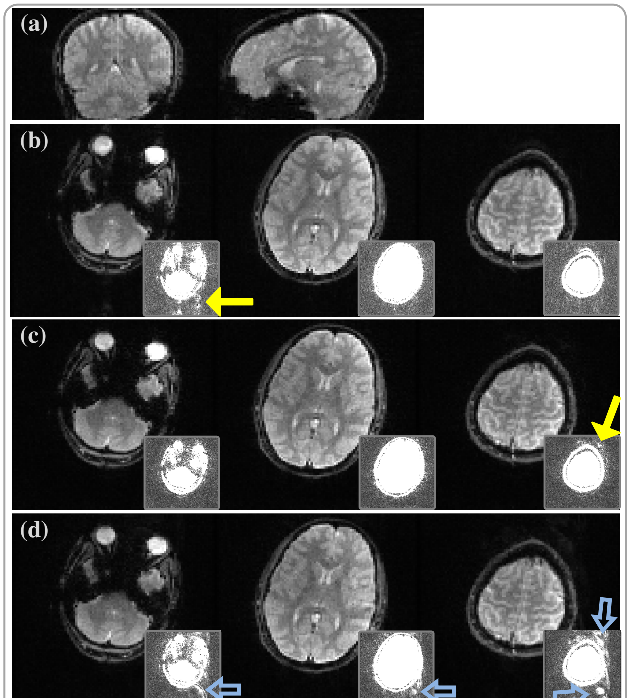


***Fig. 2.** Reconstructed images from 3× slice-accelerated multi-shot flyback EPI acquisitions. **(a)** Reformatted coronal and sagittal views from the proposed ACME technique. **(b)** A group of 3 unaliased slices from the ACME technique. To highlight the artifacts in the background, the max intensity in the display window of the inset images is adjusted to about 5% of the max image intensity. The ghosting of the eyeball (solid yellow arrow) is mostly restricted to the slice containing the eyeball. **(c)** The 3 unaliased slices from Blipped-CAIPI, when the external calibration scan well matched the accelerated scan. The ghosting of the eyeball (solid yellow arrow) appears in a slice not containing the eyeball. **(d)** The 3 unaliased slices from Blipped-CAIPI, when artifacts (hollow blue arrows) arise from the mismatch between the calibration and the accelerated data.*

**Discussion and Conclusion:** Both Blipped-CAIPI and ACME techniques can perform whole brain imaging using simultaneous multi-slice EPI acquisition. Unlike the Blipped-CAIPI technique, the proposed ACME technique does not need any external calibration scans and therefore has minimum artifacts caused by the mismatch between the calibration data and the accelerated data. If the ACS data is included in the reconstructed k-space, the ACME images will have higher SNR than Blipped-CAIPI images. The undersampling pattern of ACME is helpful in limiting the ghosting artifacts introduced by motion or flow to slices containing the sources of the ghosting.

**References:**
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