

## Superior GRAPPA reconstruction with reduced g-factor noise using 2D CAIPIRINHA for 3D EPI

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**Introduction:** Segmented 3D EPI [1] offers multiple benefits over multi-slice 2D EPI sequence such as, higher sensitivity per unit scan time, absence of spin history artifacts and the possibility to accelerate in both the phase encode directions using partially parallel acquisitions (PPA). Recent studies have shown that in the context of fMRI studies, the fewer the number of segments used for forming 3D EPI dataset, the higher is the maximum temporal SNR (tSNR) achievable [2]. A higher PPA acceleration in the slice encode direction results in reduced number of segments used for volume acquisition using segmented 3D EPI, thus improving tSNR when operating in the physiologically dominated regime [2]. However, efficient GRAPPA [3] or SENSE [4] reconstruction is largely dependent on coil geometry in the direction in which phase encoding steps reduction is performed. 2D CAIPIRINHA [5] was proposed as a k-space sampling strategy, in which the phase encoding steps of 3D acquisitions are shifted along the slice encode direction in order to reduce the geometry factor (g-factor) noise amplification in the reconstructed images for a predefined total acceleration. In this study we demonstrate the ability to perform a CAIPIRINHA trajectory in a 3D EPI sequence.

**Method:** Figure 1 shows, for demonstration purposes, a few selected CAIPIRINHA and standard PPA sampling patterns, having the same  $R_y = 2$  and  $R_z = 6$  accelerations. Various datasets were acquired using CAIPIRINHA patterns ( $\Delta > 0$ ) and standard PPA patterns ( $\Delta = 0$ ) with 3D EPI pulse sequence.

A single volunteer was scanned (in accordance with the procedures approved by the local research ethics committee) on a 7T (Siemens, Germany) scanner equipped with a head only gradient system and 32Ch head Rx coil (Nova Medical Inc., USA). Imaging parameters: Transverse orientation, phase encode = A-P, matrix size =  $104 \times 104 \times 72$ , FOV = 210mm, resolution = 2mm isotropic, TE/TR = 30/70ms, FA = 20°, BW/pixel = 2828Hz, esp = 0.44ms, different  $R_y \times R_z = 1 \times 2, 1 \times 4, 1 \times 6$  and  $2 \times 6$  with varying  $\Delta$ s were used. A fully sampled dataset was acquired from which a central  $104 \times 32 \times 32$  matrix was used as calibration data required for GRAPPA reconstruction for all the subsequent acquisitions. Image reconstruction was performed on a standalone computer using MATLAB (The Mathworks, Inc.). The g-factor maps were calculated as described in [6].

**Results:** Figure (2) shows representative transverse and sagittal slices along with g-factor maps from each of the reconstructed datasets. As expected, 2D CAIPIRINHA patterns ( $\Delta = 2, 3$ ) provide improved reconstructions when using very large accelerations on one direction ( $R_z = 6$ ), thanks to the ability to use the coil sensitivities along the y-direction to compensate the reduced coil sensitivity variation in the z-direction. The g-factor noise with CAIPIRINHA patterns is substantially lower compared to that with standard PPA patterns. While CAIPIRINHA acquisitions (middle and bottom row) show superior reconstruction when compared to standard PPA acquisition (top row) with the same accelerations,  $\Delta = 2$  provides better image quality than  $\Delta = 3$ . This demonstrates that for a particular overall reduction factor, object shape, coil geometry and FOV, there are only few CAIPIRINHA patterns which offer the optimal point spread functions (PSFs) to exploit coil sensitivity variation to the maximum extent for PPA reconstruction [5].

Figure (3) shows representative transverse slices for  $1 \times 2$  ( $\Delta = 1$ ),  $1 \times 4$  ( $\Delta = 2$ ) and  $1 \times 6$  ( $\Delta = 2$ ) cases along with respective g-factor maps. As expected g-factor increases with increasing acceleration but 2D CAIPIRINHA helps in achieving image quality which is comparable to lower slice acceleration factors by reducing g-factor noise amplification.

**Discussion and conclusion:** 3D-EPI CAIPIRINHA was shown to exploit the coil sensitivity variations better, reducing g-factor noise in the reconstructed datasets, when compared to the standard PPA trajectories.

While higher PPA acceleration along the slice direction benefits 3D EPI acquisition by improving tSNR due to reduced number of segments used to form the 3D EPI dataset, use of CAIPIRINHA further enhances this benefit by aiding PPA reconstruction to reduce g-factor noise amplification. Lower volume TR ( $TR_{\text{volume}}$ ) allows a better characterization of physiological signal fluctuations facilitating the removal of such unwanted signal fluctuations from the BOLD signal of interest in fMRI studies. A total acceleration of  $12 \times$  ( $R_y = 2, R_z = 6$ ) with 32Ch coil was used to acquire whole head coverage in 700ms  $TR_{\text{volume}}$  with acceptable image quality. To reduce  $TR_{\text{volume}}$  further, partial Fourier could provide further acceleration (1.33x) in the slice encode direction to achieve  $TR_{\text{volume}}$  of 560ms with the same whole brain imaging protocol. The minimum segment TR ( $TR_{\text{segment}}$ ) used was restricted in the above study by  $R_y = 1$  case. With  $R_y = 2$ , minimum  $TR_{\text{segment}}$  used could have been 50ms which in turn should have allowed, along with partial Fourier in the slice direction, whole brain coverage in  $\sim 400$ ms.

Unlike simultaneous multi-slice CAIPIRINHA which comes at the expense of increased SAR for higher acceleration in the slice direction, 2D CAIPIRINHA does not impact SAR of the sequence and can readily be implemented in 3D EPI to achieve fast high-resolution whole-head MRI at ultra- high fields.

**References:** [1] Poser, B.A., et al., Neuroimage, 2010. 51: p. 261-6. [2] van der Zwaag, W., et al., Magn Reson Med, 2011. [3] Griswold, M.A., et al., Magn Reson Med, 2002. 47: p. 1202-10; [4] Pruessmann, K.P., et al., Magn Reson Med, 1999. 42: p. 952-62; [5] Breuer, F.A., et al., Magn Reson Med, 2006. 55: p. 549-56; [6] Robson, P.M., et al., Magn Reson Med, 2008. 60: p. 895

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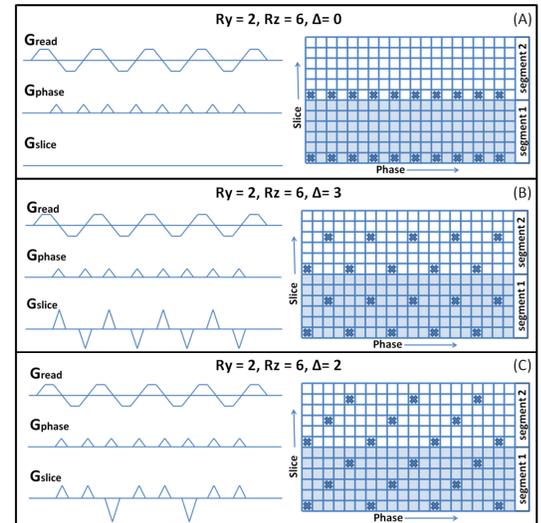


Figure 1: Read, phase and slice gradients for  $R_y \times R_z = 1 \times 6$  case with different  $\Delta$  shifts (A=0, B=3, C=2) in the slice encode direction for one sampling row  $K_y$  to the next. Corresponding k-space sampling patterns are also shown. All points belonging to a particular segment are acquired during a single readout echo train. Missing k-space points are empty squares whereas filled squares are acquired k-space points. Note that the length of the echo train is kept unchanged.

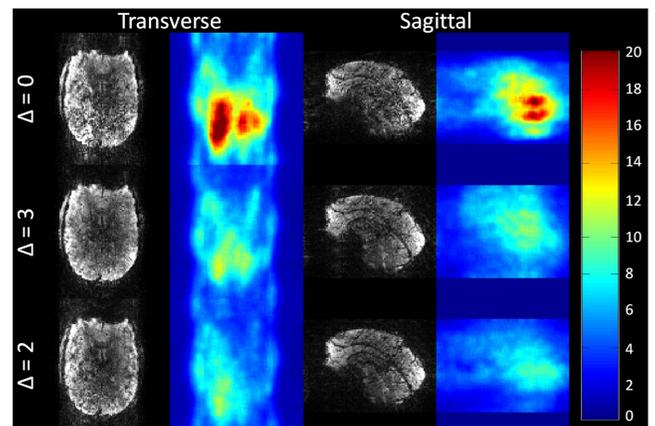


Figure 2: Sagittal images with corresponding g-factor maps. Images with varying  $\Delta$  are shown.  $R_y \times R_z = 2 \times 6$ .

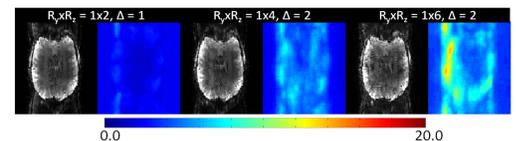


Figure 3: Transverse slices for varying slice acceleration factor and CAIPIRINHA shifts ( $\Delta$ ).