Accelerated 3D EPI using 2D blipped-CAIPI for high temporal and/or spatial resolution

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Target audience: MR physicists and Neuroscientists

Purpose: Improved volumetric EPI reconstruction for neuroscience applications

Introduction

3D EPI can offer advantages over 2D EPI when operating in the thermal noise regime (high spatial resolution) [1,2,3]. Furthermore, considerable reductions in volume acquisition times can be achieved by parallel acceleration along the secondary (k_z) phase encoding direction. Similar to the recently proposed simultaneous multislice (SMS) EPI[4,5] this increases BOLD fMRI sampling rates and reduces the vulnerability to physiological fluctuations**,** and ultimately increases BOLD sensitivity[3]. Conventional SENSE or GRAPPA along the two phase-encoding directions is independently limited by the coil sensitivities along the two dimensions. Furthermore, the g-noise is greatest at the center where both aliases overlap. **We propose 2D blipped-CAIPIRINHA[5,6] to lift these limitations, to achieve a higher undersampling factor, and to gain full flexibility how to utilise it.**

Theory

2D CAIPIRINHA ("CAIPI")[6] has been developed for optimal exploitation of the FOV and coil encoding: strategic sampling of the partial k-space controls the alias so as to distribute it over the FOV. A prominent feature of CAIPI is that it can exploit coil sensitivities in one direction to undersample along another. The conventional notion of an in-plane (AF_{PE}) and through-plane acceleration factor (AF_{3D}) is therefore lost, and the reconstruction characterized by total undersampling/acceleration AF_{tot} and a "CAIPI pattern". For one-shot-one-line methods (e.g. FLASH) the pattern does not affect scan time, which follows AF_{tot}. In the proposed 3D EPI acquisition the entire k_y-k_z plane is acquired per shot, thus the flexibility added by CAIPI does impact on scan time: The total undersampling capability can be invested to **(a) reduce the number of EPI shots[7] , (b) reduce the number of lines per shot[8], or (c) any desired tradeoff between the two[8]. We demonstrate each of these cases with AF_{tot} = 16.**

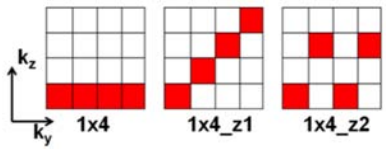
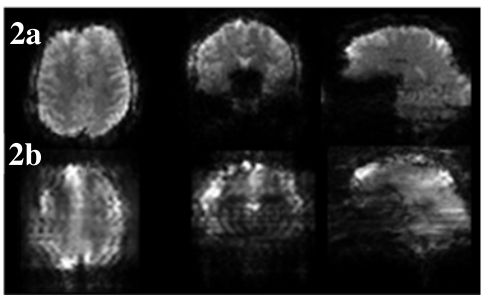
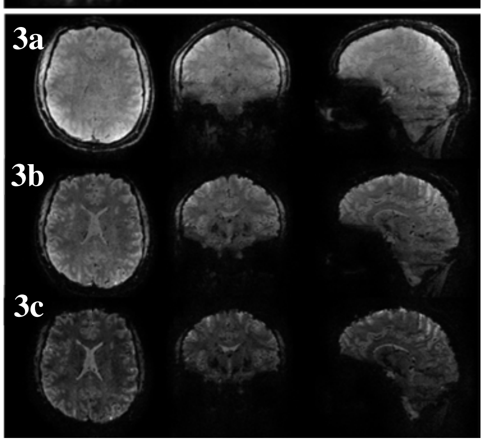


Fig 1: CAIPI patterns for AF_{tot}=4, expressed with k_z shift.
1x4 relies fully on coil sensitivities along z
1x4_z1 can reconstruct with sensitivities in z **OR** y alone
1x4_z2 can reconstruct with sensitivity in z alone





Methods

CAIPI-enabled 3D multi-echo EPI was implemented on a Siemens 7T with 32ch head coil: **The EPI readout is either modulated by Δk_z-blips (for $AF_{3D} \geq AF_{PE}$), or successive k_z-planes are shifted by Δk_y and appropriate echo shifts (for $AF_{3D} < AF_{PE}$).** Human scans were in accordance with IRB protocols. We demonstrate thee choices at AF_{tot}=16: **1) High temporal resolution** (3.0mm voxels, 64x64x64 matrix, CAIPI 1x16_z6, TE=19ms, TR_{shot}=37ms, TR_{vol}=148ms; normal GRAPPA 1x12 as reference); **2) High spatial resolution, multi-echo** (0.8mm voxels, 240x240x208 matrix, CAIPI 16x1_y4 (→4x4_z1) TE=9/22/35ms, TR_{shot}=47ms, TR_{vol}=7330ms); **3) an intermediate choice** (0.8mm voxels, 240x240x208 matrix, CAIPI 4x4_z2 TE=19ms, TR_{shot}=49ms, TR_{vol}=1911ms; normal GRAPPA 4x4 as reference).

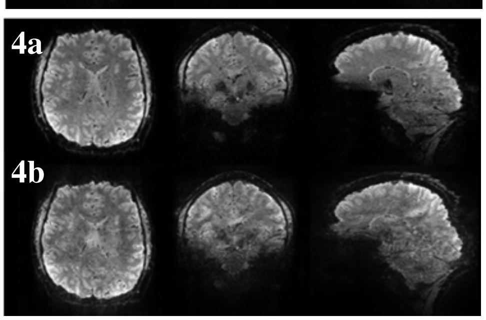
Results

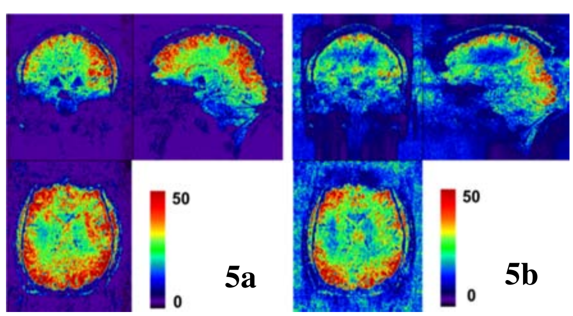
Fig 2: High temporal resolution. 3mm iso resolution at **volume TR=148ms** acquired with CAIPI 1x16_z6 (2a) and regular GRAPPA 1x12 (2b). k_x-k_y planes are fully sampled, resulting in distortion. Regular GRAPPA clearly fails due to its inability to use in-plane coil sensitivities for through-plane acceleration.

Fig 3: High spatial resolution, multi-echo. CAIPI 16x1_4y provides maximal in-plane acceleration, hence high spatial resolution with negligible distortions due to the short **echo train of 12ms**. Images were simultaneously acquired at TE=9/22/35ms (3a,b,c). The 16x1_4y CAIPI pattern is equivalent to 4x4_z1. Regular 16x1 GRAPPA does not produce a recognisable image and is hence not shown.

Fig 4: in-plane and through-plane acceleration. 4x4_z2 CAIPI (4a) appears much less blurry than the regular 4x4 GRAPPA scan (4b). Through-plane acceleration allows a very reasonable **volume TR=1.9s** while in-plane distortions (along A-P) remain acceptable.

Fig 5: tSNR maps of the 4x4 scans, computed over 25 volumes. The CAIPI data (5a) shows less background noise, and greater stability as a proxy for reduced g-noise, than the regular GRAPPA (5b). This is most apparent near the centre where all aliasing in the regular GRAPPA overlaps.





Discussion and Conclusion

The flexibility of CAIPI 3D EPI has been illustrated and good image quality and tSNR were observed with AF_{tot}=16. Practical use may warrant more modest choices. All coil encoding can be utilised along one phase- encode direction, but it also yields higher SNR than regular GRAPPA when sharing between both.

An interesting next step is the comparison to blipped-CAIPI 2D SMS-EPI with slice-GRAPPA reconstruction[4] which can turn in-plane coil sensitivities into through-plane acceleration in same way, but it cannot exploit through-plane sensitivities for additional in-plane acceleration as here shown with volumetric CAIPI.

References

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