Fast, focused fMRI at high spatial resolution: 3D-EPI-CAIPI with cylindrical excitation

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Target audience: Neuroscientists and MR physicists interested in fMRI with high spatiotemporal resolution.

Purpose: To increase spatial and temporal resolution in a 3D-EPI-CAIPI acquisition by limiting brain coverage with a 2-dimensional rf-pulse. Reduced matrix sizes in 3D-EPI are highly beneficial: 1) A lower number of acquired segments translates directly to gains in temporal resolution. 2) A lower number of excitations per acquisition reduces physiological noise contributions[1]. 3) A lower number of phase encoding steps can be traded for higher spatial resolution while keeping TE≈T_2^*(26-28ms at 7T).

Methods: The 3D-EPI-CAIPI sequence[2] was combined with a 2D-RF pulse selectively exciting a cylinder[3], as a minimal-SAR alternative to outer volume suppression[4]. Placing the cylinder along the read-out axis maximizes time benefits by allowing reduced matrix sizes in both phase-encoding directions.

Cylindrical excitation 3D-EPI-CAIPI was compared to standard slab selection 3D-EPI-CAIPI in 6 subjects at 7T to test for possible losses in tSNR or BOLD sensitivity due to the modified excitation profile (experiment 1). Shared parameters: FOV=200*200*120mm, 2mm isotropic voxels, TR/TR_{vol}/TE/α=55ms /1.1s/27ms/18^o. For cylindrical excitation: cylinder radius 25mm, alias 22cm.

In experiment 2, 3 datasets were acquired with reduced FOV for the cylindrical excitation to trade brain coverage for reduced distortions and physiological noise sensitivity. Parameters (slab selection): 1.5mm voxels, FOV=200*200*216mm, TR/TR_{vol}/TE/α= 60ms/0.96s/27ms /17^o,GRAPPA=6 and cylinder excitation: 1.5mm voxels, FOV=132*132*144 mm, TR/TR_{vol}/TE/α= 62ms/0.99s/25ms/17^o and GRAPPA=4. Cylinder radius 25mm, alias 22cm. Physiological data (cardiac and respiratory) was collected in both experiments for physiological noise removal using RETROICOR including cardiac rate[5] and respiratory volume[6].

An auditory stimulus (5s natural sounds, 15s silence alternated for 5 minutes, Sensimetric sound system) was used to test BOLD sensitivity in the inferior colliculus (IC) and medial geniculate nucleus (MGN) in both exp 1 and 2.

	Full brain standard	Full brain RETROICOR	Cylinder standard	Cylinder RETROICOR
#voxels IC	18	19	27	39
Max z-stat IC	4.6	5.2	5.6	6.4
#voxels MGN	47	45	76	97
Max z-stat MGN	4.4	5.4	6.1	7.8

Table 1. Average number of active voxels ($p<0.001$) and max z-stat in IC and MGN for experiment 1 (See Fig 1c/f). No significant differences (all $p>0.05$) were found.

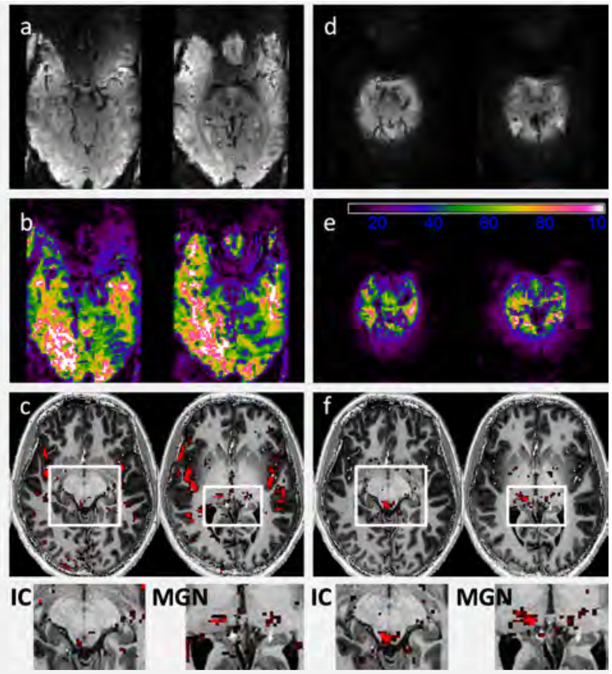

Figure 1. Example subject exp 1. (a-c) full excitation data (d-f) cylinder excitation data. (a,d) example slices, (b,e) tSNR maps, (c,f) activation maps with responses for auditory task ($p<0.001$) inserts show the inferior colliculus (IC) and medial geniculate nucleus (MGN).

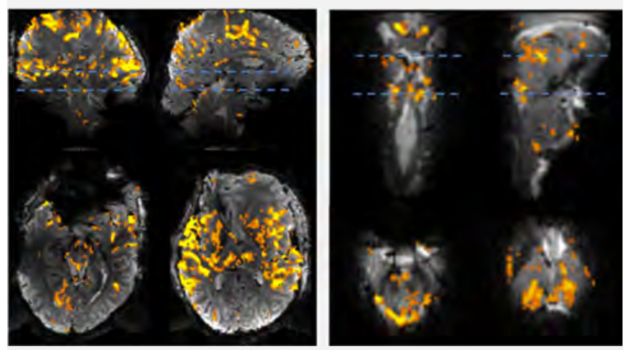

Figure 2. Experiment 2. Example auditory activation maps ($p<0.001$), post-retroicor, overlaid on echo planar images. Coronal, sagittal and 2 axial planes (IC and MGN) for slab (left) and cylinder (right) excitation.

Results: Cylindrical excitation resulted in very low residual signal outside the intended region of interest (Fig 1d). The modified rf-pulse resulted in a 60% increase in SAR, which was nonetheless below 20% of the SAR limit because of the small α used at short TR. Temporal SNR within the cylinder (central region in Fig 1d), was a little, but not significantly higher in the cylindrical excitation data (34±2 vs 31±2). After motion correction and smoothing (2mm FWHM) the difference increased (68±4 vs 62±5), although it remained non-significant (paired t-test, $p=0.2$). For all 6 subjects in exp 1, significant ($p<0.001$) BOLD signal changes were found in the IC, and for 5/6 bilaterally in the MGN (Fig 1c/f). There was no significant difference in either the number of active voxels or the maximum z-scores in IC/MGN, although both showed a trend for higher BOLD sensitivity in (a) cylinder excitation data and (b) after physiological noise removal with retroicor (Table 1).

Reducing the FOV and GRAPPA factor (exp 2) led to stronger BOLD responses in the IC and MGN and markedly reduced distortion (Fig 2).

Discussion: The small increase (10%, $p=0.2$) in temporal SNR seen in the cylindrical excitation data is probably due to both the exclusion of physiological noise from non-excited areas and the improved efficiency of the motion correction step. The motion parameters showed clear respiratory-induced fluctuations, indicating that, at 1s $TR_{vol,}$ some respiratory signal is removed in the realignment step. The resulting higher z-scores and #active voxels found in the retroicor-cleaned cylindrical data was, however, not significant due to inter-subject variability. The GRAPPA=4 cylindrical excitation data in exp 2 shows that a reduction of FOV can also be used to improve anatomical fidelity of the functional data.

Conclusion: Use of the cylindrical excitation pulse did not reduce tSNR or BOLD sensitivity within the region of interest when all other parameters were kept constant. 3D-EPI-CAIPI with cylindrical excitation can be used to acquire fMRI data with reduced distortions and physiological noise contributions, which can also be traded for higher spatiotemporal resolution.

References: 1) van der Zwaag et al, 2012, MRM; 2) Narsude et al, 2014, ISMRM; 3) Reynaud et al, 2014, MRM; 4) Heidemann et al, 2012, MRM; 5) Chang et al, 2009; 6) Birn et al, 2008