Blipped-CAIPI Spiral for Simultaneous Multi-Slice BOLD fMRI

Benjamin Zahneisen[1], Benedikt A. Poser[1], Thomas Ernst[1], and V. Andrew Stenger[1]
[1]*Department of Medicine, John A. Burns School of Medicine, University of Hawaii, Honolulu, Hawaii, United States*

Introduction: Sub-second whole brain fMRI is advantageous since it resolves cardiac and respiratory temporal signal fluctuations, virtually freezes head motion, increases statistical power, and allows the detection of subtle HRF shifts or delays. Recently, the "blipped-CAIPI" EPI method [2] was introduced as a means to reduce the g-factor penalty in simultaneous multi-slice (SMS) imaging by distributing the aliasing energy more evenly in the image domain. However, the approach is limited to Cartesian trajectories with their unique fold-over artifact. Here, we present a new framework for SMS imaging based on 3D Fourier encoding of simultaneously excited slices. We show that the blipped-CAIPI approach can be generalized to non-Cartesian trajectories and SENSE-like reconstructions, and present a new design for blipped-CAIPI spiral trajectories. Spirals have a more efficient gradient utilization and shorter readouts are possible.

Theory:

By placing N voxels symmetrically around $N=R_{SMS}$ simultaneously excited slices (separation Δz in Fig.1), Fourier sampling in slice direction is given by $\Delta K_z = 1/FOV_z=1/(N*\Delta z)$ and $k_{max} = N/2*\Delta K_z$. The through-plane and in-plane directions span a 3D k-space that can be sampled by arbitrary trajectories. Achievable acceleration then solely depends on the encoding properties of the coil array along a specific direction. Starting with a slew-rate optimized *spiral-in* design (S_{max}=135T/ms) [1], gradient blips in slice direction are added after each full spiral rotation in order to distribute the samples evenly in the 3D k-space (Fig.2). The blip moment and pattern (number & distribution) depend on the number of slices and their separation.

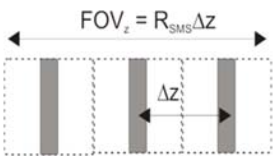

Fig 1: SMS imaging geometry (R_{SMS}=3)

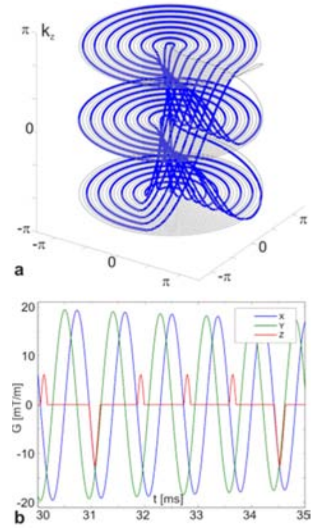

Fig 2: Blipped spiral in a) with blip locations relative to the xy-gradient shapes in b).

Methods: SMS excitation was performed by replicating a sinc-shaped excitation pulse R_{SMS} times and applying frequency shifts corresponding to the slice separation prior to complex summation. Visual stimulation was performed by presenting a flickering checkerboard for 5s followed by 10s rest (4x). During visual stimulation subjects (n=3) were asked to perform bilateral finger tapping. The HRF delay was found by shifting the BOLD model in a GLM-analysis in steps of TR spanning ±10TR. Non-Cartesian SENSE-like image reconstruction was based on minimizing the cost function $f(x)=||Ax-b||^2$ with respect to *x*, where *x* is the unknown image, *b* is the measured data and *A* describes the measurement process (coil sensitivities, off-resonance map, k-space trajectory) using time segmentation for off-resonance correction. All experiments were performed on a 3T scanner (Tim Trio, Siemens) using a 32 channel head coil array. Coil sensitivities and off-resonance map were derived from a short GRE prescan.

Results:

Fig.3a displays a whole brain acquisition (R_{SMS}=7, 3x3x3mm^3, 35slices,TE=30ms,TR=200ms) acquired in 200ms. The readout time per shot was 35ms resulting in minor blurring after off-resonance corrected reconstruction. For Figs.3bc (R_{SMS}=8, 2x2x2mm^3, 48slices,TE~38ms,TR=333ms) the HRF delay and the highest T-value (T>3.8) for the combined visual/motor task of a single subject are overlaid on the first time frame. Due to the inherent reaction time for the finger tapping task a mean delay of 900ms relative to the onset of the visual cortex can be observed. Fig.4 displays the average time courses of activated voxels for the motor and the visual cortex with the relative shift of the BOLD responses.

Discussion:

The 3D Fourier k-space formalism provides a comprehensive understanding of SMS imaging and allows for non-Cartesian and further optimized blipped EPI sequences and their reconstruction methods. We have shown that the blipped-CAIPI EPI approach can be generalized to non-Cartesian spiral trajectories and SENSE- like parallel imaging reconstruction. Up to 8 slices can be acquired simultaneously for a total "blipped-CAIPI" spiral readout time of 35ms, which is approximately 2/3 the acquisition time of a comparable blipped-CAIPI EPI acquisition matched for coverage. Sub-second (TR<333ms) whole brain fMRI with 2mm spatial resolution is demonstrated in a combined visual and motor task. The volume acquisition time for more moderate spatial resolution (3x3x3mm) fMRI can be as low as 120ms using 3 shots with R_{SMS}=11 at the cost of some image quality degradation (not shown).

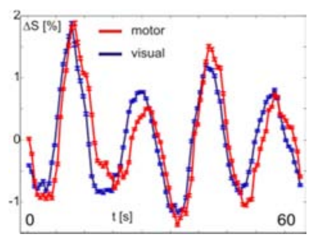

Fig 4: Mean BOLD responses in motor/visual areas

[1] Boernert P et al., *Magn Reson Med* 2000;44:479-484.
[3] Setsompop K et al., *Magn Reson Med*, 67(5):1210–1224, May 2012.
[2] Breuer F et al., *Magn Reson Med*, 53(3):684–691, Mar 2005.

This work is part is supported by grants #1R01 DA021146, 8 G12 MD007601-26, #R01DA019912, #R01EB011517, and #K02DA020569

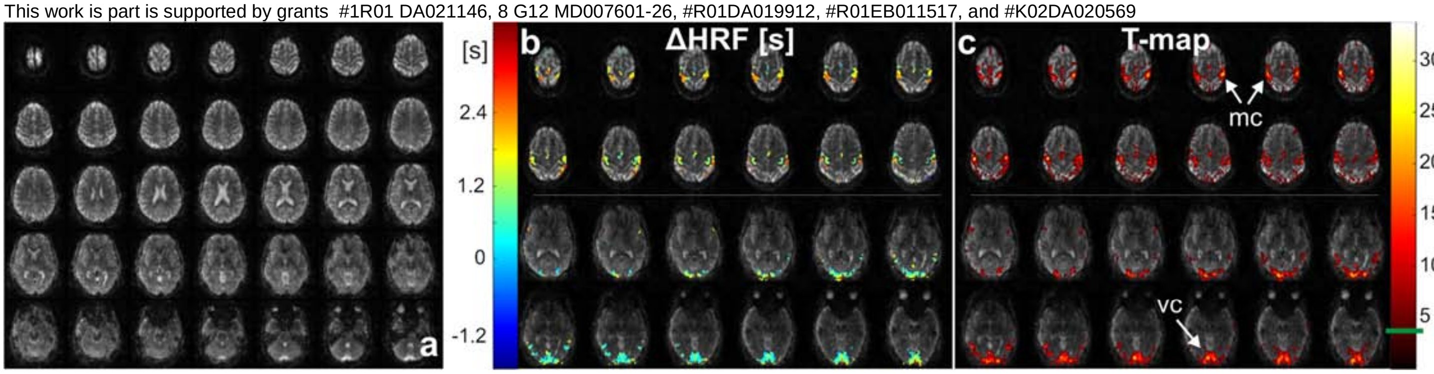

Fig 3: a) 200ms full brain acquisition (3x3x3mm,35slices) using a blipped spiral readout with R_{SMS}=7. b) HRF delay map based on shifting the GLM model function in steps of TR. c) T-map (T>3.8) corresponding to the optimal delay. Only the bottom and top 12 slices are shown (2x2x2mm at TR=300ms,R_{SMS}=8).