Motion-compensated interleaved spiral acquisition for fMRI

H. Schmiedeskamp[1], M. Aksoy[1], G. H. Glover[1], and R. Bammer[1]

[1]Lucas Center, Department of Radiology, Stanford University, Stanford, CA, United States

INTRODUCTION – Typical fMRI acquisitions cannot reveal great detail about activated brain regions due to poor image resolution. At present, 64x64 voxels per slice is still the most commonly used acquisition matrix size for fMRI studies, leading to an in-plane resolution of 3.75 mm^2 with FOV = 24 cm. Increasing spatial resolution is very time consuming, e.g. doubling in-plane resolution increases signal readout time approximately by a factor of 4. Furthermore, an increase in resolution decreases image SNR. This can be problematic as BOLD-contrast is an inherently low-sensitive contrast mechanism. To overcome these challenges and the trade-off between acquisition time and image resolution, we propose combining a low-resolution spiral-in navigator trajectory with the acquisition of a higher-resolution interleaved spiral-out readout trajectory for motion-compensated multi-shot fMRI. Therefore, the navigator trajectory is used for two purposes: 1) for in-plane motion correction and realignment of multi-shot data, 2) for separate low-resolution fMRI analysis in order to extend functional analysis by a low-resolution dataset. Thus, the presented method facilitates high-resolution motion-corrected interleaved spiral-acquisition with additional low-resolution images to either mask high resolution data or to compare BOLD-activation acquired with two different image resolutions.

METHODS – fMRI images were acquired using a multi-echo spiral technique derived from [1]. A non-interleaved low-resolution spiral-in navigator trajectory was followed by a spiral-out readout trajectory acquired with higher resolution. In order to minimize T_2*-related signal dropouts during the signal readout and to maintain high temporal resolution, spiral-out trajectories were acquired in an interleaved fashion. Thus, readout times could be significantly reduced compared to non-interleaved acquisitions. Fig. 1 shows the pulse sequence used for the present study. The navigator images were acquired with a matrix size of 64x64, and in-plane resolution = 3.75x3.75 mm. The spiral-out trajectory was acquired in an interleaved fashion with N = 2 interleaves, a matrix size of 96x96, resulting in an in-plane resolution of 2.5x2.5 mm. The remaining acquisition parameters were TE/TR/flip = 35 ms/2000 ms/80°, FOV = 24 cm, slice thickness = 4.5 mm (skip: 1 mm), RBW = +/– 125 kHz, number of slices = 22. For this study, a visual stimulus (checkerboard with alternating contrast, frequency = 8 Hz) was combined with bilateral finger-tapping performed by the volunteers. Each on/off-cycle in the block-design fMRI paradigm was 18 seconds long. The entire experiment consisted of 9 off-cycles and 8 on-cycles, resulting in a total scan time of 5:06 minutes, excluding prescan and discarded acquisitions to reach a steady-state signal. All measurements were performed at 3T (gradients = 40mT/s and 150T/m/s) using an 8-channel head receiver coil. The voxel-wise temporal signal curve was correlated with a sinusoid function [2], and voxels with correlation coefficients r ≥ 0.5 were highlighted in functional maps. In order to reconstruct images from individual interleaves acquired with the spiral-out trajectory, we used a sliding window approach in which the missing k-space sampling points for each interleave were added from the subsequent time point to form fully sampled images. To counteract motion artifacts caused by misaligned interleaves – a general concern in interleaved EPI acquisitions – augmented generalized SENSE reconstruction [3] with correction for motion-induced altered coil sensitivities [4] was applied (Method 2A). Hereby, rotated and translated spiral arms were counter-rotated with respect to each other. Such rotation can cause gaps in k-space. Generalized SENSE reconstruction is applied to fill these motion-induced gaps to avoid undersampled k-space areas. This technique depends on parallel imaging reconstruction only for motion-correction purposes, therefore does not lower the spatial signal-to-noise ratio compared to non-interleaved acquisitions. In order to counter-rotate interleaved spiral trajectories in respect to each other, a non-interleaved spiral-in navigator was used for image realignment. In addition, the properties of the spiral-in navigator trajectory allowed the reconstruction of an additional fMRI time series with a lower matrix size of 64x64, adding additional information to the fMRI analysis (Method 1). For comparative reasons, the individual interleaves were reconstructed using the CG-SENSE-algorithm [5], therefore maintaining the temporal resolution of the acquisition in the fMRI analysis (Method 2B). For this purpose, sensitivity-maps for each time point were extracted from the corresponding navigator images.

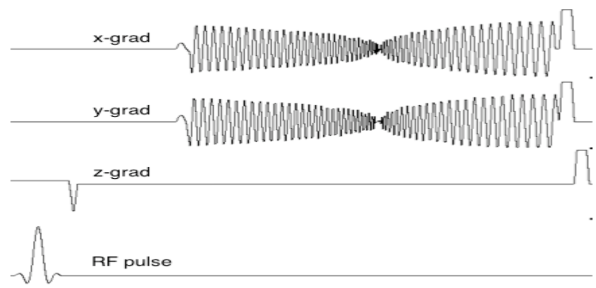

Fig.1: Spiral pulse sequence used in this study with spiral-in navigator trajectory and spiral-out readout trajectory, both acquired with the same echo time. The spiral-out trajectory was acquired in an interleaved fashion to facilitate higher image resolution.

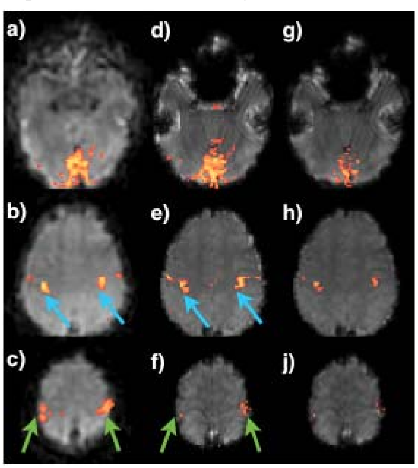

Fig.2: Images showing functional activity in the visual cortex (top row), as well as in the motor cortex (middle and bottom row) for: (a-c) spiral-in navigator, (d-f) spiral-out sliding-window reconstruction, (g-j) spiral-out SENSE-reconstruction.

RESULTS – Fig. 2 shows resulting BOLD-fMRI maps from a male volunteer, with fMRI analysis performed on the navigator images (Method 1, Fig. 2a-c), the interleaved images reconstructed using the sliding window approach (Method 2A, Fig. 2d-f), and the interleaved images reconstructed with CG-SENSE (Method 2B, Fig. 2g-j). Most functional activity was detected in the low-resolution navigator images due to higher overall SNR. In the upper part of the motor cortex (Fig. 2c vs. Fig. 2f/j), neuronal activity that is hardly visible in either method 2A or 2B (green arrows) could be detected with method 1 using the given threshold for r. On the other hand, method 2A revealed more detailed activation patterns in the lower part of the motor cortex, adding more precise information about the true location of neuronal activity (blue arrows). Using the CG-SENSE reconstruction algorithm for all interleaves, substantially less functional activity was detected compared to the sliding-window reconstruction using a fully sampled k-space.

DISCUSSION – The present study showed larger overall sensitivity to changes in the BOLD signal using sliding-window reconstructed interleaved spiral trajectories, compared to SENSE-reconstruction of individual interleaves. This is explained by temporal averaging used in method 2A, allowing for reconstruction of fully sampled k-space data for each time point, whereas method 2B suffered from enhanced noise caused by parallel imaging reconstruction of undersampled data. The sliding-window approach therefore allows higher image resolution without reduced BOLD-sensitivity caused by parallel imaging reconstruction. Method 2A showed fMRI maps similar to the ones retrieved from the navigator images acquired with each interleave, except for missing functional activity in those parts of the motor cortex, where correlation of the BOLD-signal to the stimulus was relatively low even in the navigator images. The sliding-window approach applies temporal smoothing to the interleaved dataset, lowering temporal resolution compared to non-interleaved image acquisition. This is due to the fact that half of the k-space sampling points come from the preceding time point, while the other half is sampled with the same temporal resolution than the acquisition of each interleave. When increasing the resolution and the number of interleaves further, functional activity detected in the navigator images could serve as mask for the analysis of the high-resolution dataset by rejecting voxels without functional activity detection in navigator data. Thus, high-resolution data can be masked for false-positive activation when lower correlation thresholds or larger temporal smoothing due to an increase in the number of interleaves are applied.

REFERENCES: [1] Glover *et al.* MRM 46:515-522 (2001), [2] Lee *et al.* MRM 33:745-754 (1995), [3] Bammer *et al.* MRM 57:90-102 (2007), [4] Aksoy *et al.* Proc. ISMRM 2008, p3111, [5] Pruessmann *et al*, MRM 46:638-651 (2001) – **ACKNOWLEDGEMENTS**: NIH (2R01EB002711, 1R01EB008706, 1R21EB006860, P41RR09784), Lucas Foundation, Oak Foundation.