High-Resolution 3D-fMRI at 9.4 Tesla with Intrinsically Minimised Geometric Distortions

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Target audience: The demonstration of a 3D-EPI sequence segmented in both phase encode dimensions for minimised geometrical distortions at 9.4 Tesla may be of particular interest for MR physicists and sequence developers as well as neuroscientists specialised on ultra-high field MRI.

Purpose: Echo-planar imaging (EPI) is one of the most regularly employed MRI pulse sequences in the neurosciences, most prominently for functional imaging (fMRI). Even at low and moderate field-strengths EPI suffers from susceptibility-related artefacts such as geometric distortions and signal drop-outs. At ultra-high magnetic field strengths such artefacts worsen dramatically due to an absolute increase of susceptibility-differences at tissue interfaces and cavities. Increasing the effective bandwidth in "blipped" phase encode dimension (PE bandwidth) is an effective means to reduce geometric distortions [1]. Alternatively (or in addition) post-processing correction methods have been suggested. However, such methods usually require time-consuming extra calibration scans or field map acquisitions followed by extra post-processing of typically large data sets. This work demonstrates the feasibility and the limitations of fMRI at 9.4 Tesla with Intrinsically minimised geometric distortions utilising a strongly accelerated 3D-EPI sequence [2] with segmented acquisition in phase encode (PE) and partition (3D) dimension.

Methods: A self-written 2D-EPI sequence was adapted for a multi-shot 3D-EPI sequence according to Ref. [2]. Ramp sampling, parallel imaging and "in-plane-multi-shot" acquisition were inherited from the 2D-version and then supplemented for 3D *k*-space acquisition. In-plane segmentation is specifically required for the external GRAPPA [3] reference scans with PE bandwidth identical to the subsequent imaging scans. It additionally facilitates short echo times (TE) desirable at ultra-high fields for optimal BOLD contrast. The schematic in Fig. 1a demonstrates 3D *k*-space trajectories without and with in-plane segmentation. **Experiment 1:** A visual stimulation fMRI experiment was performed on a 9.4 Tesla human MRI scanner (Siemens, Erlangen) using a 3-fold in-plane segmented 3D-EPI whole-brain protocol (spatially non-selective excitation, 710µs rectangular pulse duration) with very short TE=13.5ms (FOV=210x210x144mm^3, 1.5mm isotropic voxel size, readout bandwidth 1553Hz/pixel, GRAPPA R=2x2 in PE and 3D, no partial Fourier, TR/TR$_{vol}$=26ms/3.75s, nominal flip angle 11°). Readout and phase encode direction were superior-inferior and anterior-posterior, respectively. A home-built, cylindrical 8-channel coil was used for excitation and signal reception. The RF-shim was focused on the visual cortex. The fMRI block paradigm consisted of 6 alternating epochs of rest (fixation cross) and flickering checkerboard stimulation, each for 22.5s=6TR$_{vol}$. **Experiment 2:** A two-handed finger-tapping fMRI experiment was performed at 9.4T, this time using slab-selection in anterior-posterior direction and employing a non-segmented echo-planar readout in the coronal plane with a longer TE=23ms (FOV=180x180x90mm^3, 1.5mm isotropic voxel size, readout bandwidth 1543Hz/pixel, GRAPPA R=2 in PE, no partial Fourier, TR/TR$_{vol}$=45ms/2.7s, nominal flip angle 12°). The fMRI block paradigm consisted of 6 alternating epochs of rest (fixation cross) and visually cued two-handed finger tapping, each for 21.6s=8TR$_{vol}$. Both experiments were analysed using SPM8 (realigned, non-smoothed, 6 motion parameters as additional regressors, p<0.001).

Results: Fig. 1b and c show activation patterns (colour-coded t-scores) from experiment 1 and 2 overlaid on the respective mean magnitude images. In Fig. 1b only very subtle geometric distortions are visible due to 3-fold in-plane segmentation. The zoomed excerpts (bottom) show that the activation accurately follows occipital grey matter as expected for a visual stimulation experiment. The mean magnitude image from the reduced-FOV experiment 2 without in-plane segmentation exhibits more geometrical distortions in the blipped PE direction (left-right) which would certainly require correction if alignment to an anatomical reference was desired. Nevertheless, the activation patterns precisely delineate the central sulcus as expected from the finger tapping experiment.

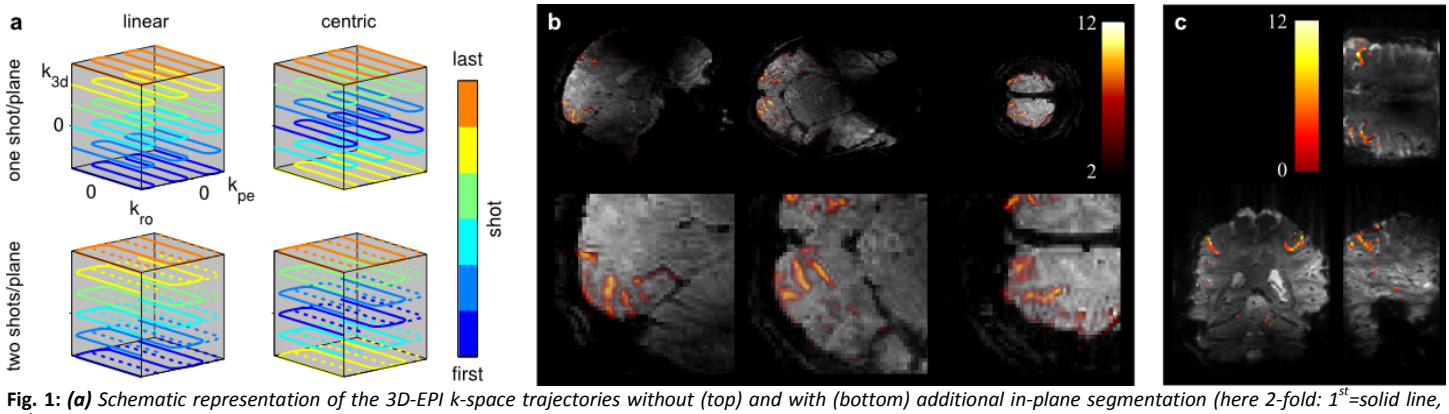

Fig. 1: ***(a)*** *Schematic representation of the 3D-EPI k-space trajectories without (top) and with (bottom) additional in-plane segmentation (here 2-fold: 1st=solid line, 2nd=dotted line). (b) Activation (t-scores) as a result from experiment 1 overlaid on the mean magnitude image; bottom row: zoomed excerpts. (c) Activation (t-scores) as a result from experiment 2 with reduced FOV overlaid on the mean magnitude image.*

Discussion: A 3D-EPI sequence has been implemented which, in addition to parallel imaging and partial Fourier acquisition, features segmentation in phase encode and partition encode dimension. Its feasibility for high-resolution fMRI at 9.4 Tesla has been demonstrated by means of basic block design fMRI experiments. It has been shown that additional in-plane segmentation provides intrinsic geometric distortion minimisation to an acceptable level.

Conclusions: 3D-EPI allows for truly isotropic high-resolution whole-brain fMRI feasible even at 9.4 Tesla. Additional in-plane segmentation reduces geometric distortions significantly and helps to achieve short echo times for optimal BOLD-contrast (further investigations required). However, it should be noted that physiological noise increases with the number of shots required to fill a complete *k*-space volume [4]. This can lead to pronounced image artefacts, for example in critical regions near the skull base. Further investigations are required to compare fMRI using 3D-EPI to alternative techniques such as multi-band 2D-EPI (e.g. [5]). It can be expected that a general recommendation cannot be made but rather a choice depending on target parameters such as the spatial and temporal resolution. With 3D-EPI, for instance, specific absorption rate (SAR) limitations are much less likely to be exceeded than with multiband and conventional 2D-EPI.

References: [1] Hennel, F, Concepts Magn Reson 9, 1997; [2] Poser, BA et al., NeuroImage 51, 2010; [3] Griswold, MA et al., Magn Reson Med 47, 2002; [4] van der Zwaag, W et al., Magn Reson Med 67, 2012; [5] Setsompop, K et al., Magn Reson Med 67, 2012