Variable Flip Angles and Echo Train Lengths in Segmented 3D-EPI at 3 and 7 Tesla

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Target Audience: MR physicists and neuroscientists with an interest in high-resolution functional imaging at normal and at ultra-high field strengths.

Purpose: To increase the signal sensitivity (temporal SNR/√acquisition time) of high-resolution functional MRI by means of two novel segmented 3D-EPI modifications[1]: the use of variable flip angles (vFA) and, optionally, the use of variable echo train lengths (vETL) facilitated by employing elliptical k-space subsampling[2]. While vFA has the potential to increase the base signal-to-noise ratio, vETL leads to shorter volume repetition times. The methods are simulated and validated by means of high-resolution acquisitions at 3 and at 7 Tesla.

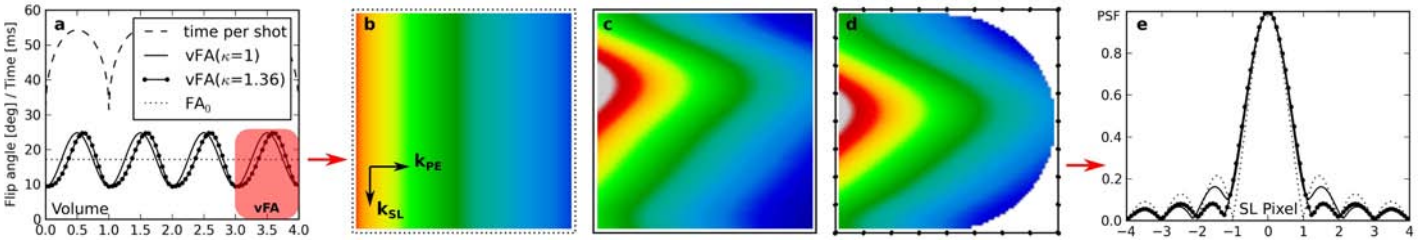

Fig. 1 *Most relevant simulation parameters (a), corresponding signal distributions in k-space (MTF) with constant FA_0 (b), vFA (c) and skewed vFA (κ>1) combined with vETL (d). (e) shows corresponding point spread functions along the secondary phase encoding direction (SL).*

Methods - Simulations: Extended phase graph[3,4] simulations were performed to obtain representative MR signal distributions over the k-space (modulation transfer function, MTF) for a typical gradient echo 3D-EPI[1] protocol. Gray matter (3T) relaxation times, T_1=1400ms, T_2=80ms, T_2*=35ms, and linear chronologic order of both primary (PE, inner loop) and secondary (SL, outer loop) phase encoding steps was assumed. Either a constant flip angle (Ernst angle), FA_0, or variable flip angles according to a heuristic periodic function centered about FA_0 are used for excitation: $vFA(t) = FA_0(1 - \delta \cos(2\pi\, t^{\kappa}))$, where t is the fraction of the imaging volume acquired. The parameter δ in [0,1] and the skew factor, κ>0, can be chosen freely, whereby the latter is determined from $\kappa(t_{max})=-\log(2)/\log(t_{max})$, with t_{max} indicating where vFA peaks (cf. Fig. 1 a). In addition the ETL is allowed to vary according to Fig. 1 d, which results in a reduced volume repetition time. **Experiments:** The vFA and vETL features were implemented into a custom, segmented 3D-EPI sequence running on a Siemens (Erlangen, Germany) Magnetom Skyra (3T) and Magnetom 7T scanner, both utilizing a 32 channel head array for signal reception. At 3 Tesla a healthy male subject was scanned using three different 1.5mm isotropic resolution protocols: with a constant flip angle of 19° (cFA), using vFA (FA_0=19°, δ=0.45) and using the same vFA + vETL (TR reduction from 2500 to 2350ms). In all cases 2x2-fold parallel imaging (PI) acceleration and 6/8 partial Fourier (PF) acquisition in SL direction was employed (t_{max}=0.45 such that the MTF would approximately coincide with the k-space center in SL direction). Sagittal slice orientation allowed for quick water excitation by means of a single rectangular pulse[5] per shot. Two additional high resolution scans were performed at 7T with the same subject to compare 3D-EPI using the proposed vFA method at 0.75mm isotropic resolution (256x256x208 matrix, sagittal, whole brain coverage, PI 3x2, PF 6/8x6/8, TR=6084ms, nominal FA_0=19°, δ=0.45, t_{max}=0.45) to a similar protocol using a vendor-provided 2D-EPI sequence that employs the slice-blipped CAIPI technique[6] for slice acceleration (0.75mm in-plane resolution, 0.8mm slice thickness, sagittal, max. 126 slices ~ 2/3 brain coverage, PI 3, MB 2, PF 6/8, TR=4880ms, nominal FA=80°). RF transmission was performed using a birdcage coil surrounding the receive array. For all experiments voxelwise temporal SNR was calculated from the magnitude data as tSNR=AVG/STD, whereby 200 time points were used at 3T and 60 time points were used at 7T.

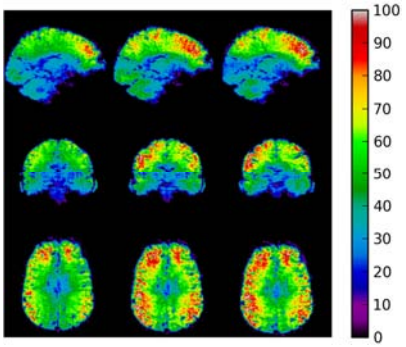

Fig. 2: *Temporal SNR maps obtained at 3T (from left to right: cFA, vFA, vFA+vETL).*

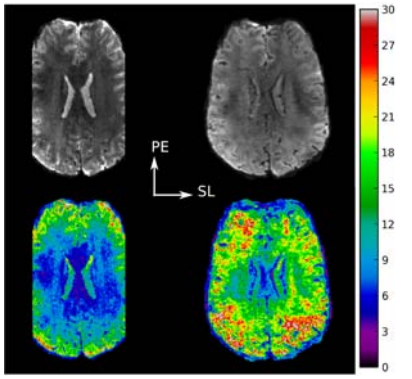

Fig. 3: *Representative axial slice of magnitude images (top) and tSNR maps (bottom) obtained at 7T. Left: 2D-EPI with slice-blipped CAIPI[6]. Right: 3D-EPI with vFA.*

Results: Figure 1 e shows the effect of vFA on the point spread function (PSF) in SL direction corresponding to the MTFs shown in Fig. 1 b-d as result of simulations with constant FA_0 (b, dotted), vFA with 45% variation (c, solid) and skewed vFA ($\kappa(t_{max}$=0.6)=1.36) with 45% variation + vETL (solid with points). The latter results in 36% SNR increase with only little PSF broadening (rather moderate apodization). Fig. 2 confirms an increase of tSNR from cFA to vFA and shows no tSNR loss when minimizing the TR by means of vETL. Fig. 3 shows at 7T a clear tSNR advantage of 3D-EPI with vFA and $(750\mu m)^3$ voxels over the slice-blipped CAIPI 2D-EPI with $800x750x750\mu m^3$ voxels.

Discussion: The simulations and experiments show an increase of (t)SNR with negligible PSF broadening as hypothesized. However, increasing the base SNR_0 by means of vFA is only useful at high spatial resolutions or large acceleration factors, i.e. as long as one resides in the thermal noise dominated regime[7] whereas reducing the volume TR is beneficial in any case.

Conclusion: Two new features, variable flip angles and variable echo train lengths (using an elliptical k-space acquisition), have been implemented into segmented 3D-EPI and have been shown to increase signal sensitivity at 3T and at 7T (higher SNR and shorter TRs at the same time). At 7T whole brain coverage with $(750\mu m)^3$ voxels can be realized with higher tSNR than with a corresponding protocol based on a slice-blipped CAIPI 2D-EPI sequence.

References: [1] Poser et al., NeuroImage 52, 2010; [2] Bernstein et al, J Magn Reson Imaging 14, 2001 [3] Hennig, Concepts Magn Reson 3, 1991; [4] Scheffler, Concepts Magn Reson 11, 1999; [5] Stirnberg et al., Proc. Intl. Soc. ISMRM 21, 2013; [6] Setsompop et al., Magn. Reson. Med. 67, 2012; [7] Triantafyllou et al., NeuroImage 55, 2011