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: the use of variable flip angles (vFA) and, optionally, the use of variable echo train lengths (vETL) facilitated by employing elliptical k-space subsampling. 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.

Methods - Simulations: Extended phase graph simulations were performed to obtain representative MR signal distributions over the k-space (modulation transfer function, MTF) for a typical gradient echo 3D-EPI protocol. Gray matter (3T) relaxation times, T₁ = 1400ms, T₂ = 80ms, T* = 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), FA₀ or variable flip angles according to a heuristic periodic function centered about FA₀ are used for excitation: vFA(t) = FA₀(1 – δ cos(2πt)), where t is the fraction of the imaging volume acquired. The parameter δ in [0,1] and the skew factor, κ, can be chosen freely, whereby the latter is determined from FA₀ = FA₀(1 – δ cos(2πt)), with the skew factor, κ, 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 (FA₀=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 (tₚ=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 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 FA₀=19°, δ=0.45, tₚ=0.45) to a similar protocol using a vendor-provided 2D-EPI sequence that employs the slice-blipped CAIPI technique 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 FA₀=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.

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 FA₀ (b, dotted), vFA with 45% variation (c, solid) and skewed vFA (κ =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 (750µm)³ voxels over the slice-blipped CAIPI 2D-EPI with 800x750x750µm³ voxels.

Discussion: The simulations and experiments show an increase of tSNR with negligible PSF broadening as hypothesized. However, increasing the base SNR, i.e. 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 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 (750µm)³ voxels can be realized with higher tSNR than with a corresponding protocol based on a slice-blipped CAIPI 2D-EPI sequence.