A Simple Fat Suppression Method for Accelerated and Low-SAR 3D-EPI

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Target audience: MR physicists and sequence developers may be interested in the concept of the proposed method. Its application may be interesting for neuroscientists or neurosurgeons planning to perform fMRI experiments/studies with high spatial and temporal resolution, e.g. for precise presurgical planning [1].

Purpose: Recently, 3D echo planar imaging (EPI) has been proposed for isotropic, high-resolution fMRI [2]. Besides the possibility of performing partial Fourier (PF) and parallel imaging techniques in two phase encode (PE) dimensions, 3D-EPI generates reduced specific absorption rate (SAR) compared to conventional 2D-EPI. At ultra-high fields in particular, the application of either time-consuming fat saturation modules prior to each excitation or the use of special water-excitation pulses can however still exceed SAR limitations. Therefore we investigated the feasibility of using only a single, simple rectangular (RECT) RF excitation pulse with minimal time-demands and minimal SAR for water-selective (and spatially non-selective) excitation in 3D-EPI.

Methods: Off-resonance signal suppression is achieved by selecting a pulse bandwidth (via the pulse duration) such that the roots of the spectral response match the off-resonance. In the small tip angle approximation (STA) the spectral response corresponds to the Fourier transform of the pulse. A more general solution is preferred here which does not rely on the specific knowledge of the spectral response. In the (on-resonant) rotating frame of reference, off-resonant isochromats experience an effective excitation magnetic field that has a considerable longitudinal component in addition to the transverse B_1 component. Assuming a specific off-resonance, $\Delta\omega$, as shown in Fig. 1a the corresponding nutation frequency is $\Omega(t)=\sqrt{(\Delta\omega^2+\gamma^2 B_1(t)^2)}$, whereby γ is the gyromagnetic ratio and $B_1(t)$ is the time-varying RF envelope. For the off-resonance suppression condition the respective isochromats simply have to perform multiple (n) whole turns on the tilted cone of nutation during the pulse. Thus, in general: $\int\Omega(t)dt=2\pi n$. For RECT pulses with amplitude B_1 this is easily rearranged to the required pulse length, $\tau_n=2\pi n/\sqrt{(\Delta\omega^2+\gamma^2 B_1^2)}$. Substituting $\alpha=\gamma B_1\tau$ finally yields an expression for the "nth order" suppression pulse duration as a function of nominal (on-resonance) flip angle, α:

$$\tau_n=\sqrt{((2\pi n)^2-\alpha^2)}/|\Delta\omega| \qquad \text{(Eq. 1)}$$

While perfect suppression is only achievable for a specific off-resonance frequency it can be shown by simulations that the off-resonant steady state signal [3] corresponding to a relatively broad lipid peak centred about ~3.5ppm (chemical shift) is still significantly suppressed compared to the signal of a relatively broad brain tissue peak. **Experiment 1:** A low-resolution (3mm isotropic) 3D-EPI experiment with RF pulse durations increasing from 0.1ms to 6ms in steps of 0.1 ms was performed at 3 Tesla *in vivo* to validate the expected signal course (TE/TR=21.5ms/42ms, α=15°). **Experiment 2:** A blocked two-handed finger tapping fMRI experiment was performed at 3 Tesla using a high-resolution 3D-EPI protocol (1.5mm isotropic, GRAPPA R=2x2 in both PE directions, PF 6/8 in partition direction, TE/TR=32ms/62ms, volume TR_{vol}=2.6ms, bandwidth 1488 Hz/pixel, 54 repetitions, 3x[9TR_{vol} rest vs. 9TR_{vol} tapping], α=16°). A pulse duration of 2.4ms was selected. General linear model (GLM) fMRI analysis was performed using SPM8 (realignment to mean; using motion parameters as additional regressors; no smoothing).

Results: Fig. 1b shows isochromat trajectories for a typical fat off-resonance of 450Hz at 3T and varying pulse durations assuming α=90°. According to Eq. 1 a pulse duration of $\tau_1\approx$2150µs corresponds to 1st order fat suppression for that case. Fig. 1c shows magnitude images (left) from experiment 1 for selected pulse durations and the signal course (right) of representative voxels with pure "fat signal", pure "brain signal" and with both signals superimposed for all pulse durations performed. As expected the first two fat signal minima occur at approximately 2200 and 4400µs. Finally, from experiment 2, Fig. 1d shows activation patterns overlaid on the mean 3D-EPI image (p<0.05 (FWE)) which precisely follow the central sulcus.

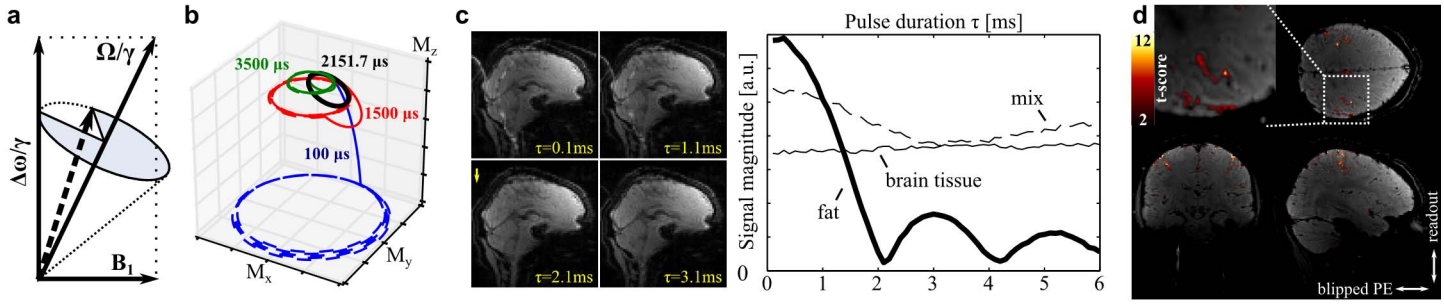

Fig. 1: ***(a)*** *Nutation of off-resonant magnetisation (dashed vector) during an on-resonant RF pulse (B_1).* ***(b)*** *Off-resonant isochromat trajectories during a nominal 90° excitation pulse (solid) and the following free-precession period (dashed) for several pulse durations (line colour). With the correct first order pulse duration a 450Hz off-resonant isochromat performs exactly one turn and thus has no transverse component upon start of the free precession.* ***(c)*** *Experimental verification of the proposed method: displayed are the signals of representative voxels (example images shown on the left) with brain and fat only magnetisation and with a superposition due to the fat-shift in PE direction (no actual mixture), respectively.* ***(d)*** *Accurately delineated activation from a two-handed finger tapping fMRI experiment superimposed to the mean high-resolution 3D-EPI image (1.5mm isotropic, no smoothing).*

Discussion: A basic mechanism for off-resonant signal suppression in 3D-EPI was discussed and verified *in vivo* at 3T. Even though only a near-optimal RF pulse duration was utilised for the finger tapping experiment, robust fat suppression was achieved rendering additional fat saturation obsolete. A rather short whole-brain TR_{vol} of only 2.6s at 1.5mm isotropic resolution and TE=32ms was thus possible (compared to $TR_{vol}\approx$3s with conventional fat saturation). Non-smoothed high-resolution fMRI analysis resulted in precisely delineated activation patterns which thus potentially allow for an accurate discrimination between brain areas.

Conclusion: The proposed method was demonstrated at 3T. The particular potential lies at even higher fields where optimal pulses become shorter (due to an increase of the absolute chemical shift), e.g. $\tau_1\approx$1ms at 7T or $\tau_1\approx$0.7ms at 9.4T. Together with decreasing echo times for optimal BOLD contrast (and using PF acquisition in blipped PE direction) volume repetition times of two seconds and less at 1.5 isotropic resolution are hence easily achievable. At the same time pulse durations of 1ms require rather low RF pulse amplitudes for typical (on-resonant) flip angles, which directly translates into very low SAR. It is, however, important to note that a decent shim is mandatory for an adequate performance of the proposed method without sacrificing brain signal.

References: [1] Rössler, K et al., J Neurol Neurosurg Psychiatry 76, 2005; [2] Poser, BA et al., NeuroImage 51, 2010; [3] Freed, DE et al., J Magn Reson 162, 2003