Correction for Image Artifacts in T1ρ_{off}-weighted Imaging

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Introduction: T1 $_{off}$-weighted imaging provides useful clinical contrast with a lower SAR than T1 -weighted imaging in studies of cerebral ischemia and breast tumors (3-5), but is compromised by image artifacts, which are shown to be imperfections in the excitation flip angle. A pulse sequence for off-resonance spin locking is implemented which compensates for imperfections in the excitation flip angle through an off-resonance Solomon rotary echo (1,2,6). The off-resonance rotary echo alternates the frequency offset and phase of the RF transmitter during two equal duration spin locking pulses. MR images are shown demonstrating the effectiveness of the technique in agarose gel phantoms and in *in vivo* human brains at 3T *with a lower specific absorption rate (SAR) of radiation delivered to tissues.*

Method: Imaging was performed on a Siemens Trio 3T clinical imaging system equipped with a Bruker birdcage head coil. Volunteers were recruited and scanned following a pre-approved protocol by the IRB of the University of Pennsylvania. Imaging was performed using variations of a T1ρ_{off}-prepared fast spin echo sequence with the imaging parameters (TE_{eff}/TR = 13/2500 ms, 128x128 image matrix, FOV = 23 cm^2, slice thickness = 4 mm, ETL = 7, BW = 130 Hz/pixel, ω_{RF} = 400 Hz, spin lock excitation flip angle $\alpha = 65°$, spin lock duration TSL = 40 ms). Agarose (3%, 200 mM ^{23}Na) images were obtained similarly. (FOV = 15 cm^2).

Results: Phase inversion of the spin locking pulse ω_1 (±180°) on-resonance is shown to reduce artifacts in 3% agarose phantoms (Fig. 2). For example, if ω_1 is parallel to the *y*-axis during the first spin locking period, then ω_1 must be parallel to the -*y*-axis during the second spin locking period. Combined inversion of ω_1 and inversion of $\Delta\omega$, the transmitter offset frequency, is shown experimentally to reduce spin locking artifacts off-resonance (Fig. 2) This condition is called phase and frequency inversion. Magnetization is excited along the direction of the effective field with a hard pulse where it is spin locked by two phase and frequency symmetric spin locking pulses (+y, +$\Delta\omega$ and –y, -$\Delta\omega$). Consequently, the magnetization is stored along the z-axis with another hard pulse. During spin locking, the magnetization nutates first around the effective field (Fig. 1A) and is refocused during the second $\tau/2$ period by nutation in the opposite direction (Fig. 1B). Considering a single 500 Hz spin locking pulse delivered for 100 ms, the average SAR delivered with a TR = 3 s is approximately 2 W/kg, well under the 8 W/kg FDA mandated restriction in the head. For pulse sequences with shorter TR such as a T1ρ-weighted 3D GRE or balanced-SSFP, the average SAR can often surpass FDA limitations. For example, the average SAR delivered during a T1ρ-weighted 3D GRE with a TR = 300 ms is nearly 18 W/kg, but can be reduced to less than 8 W/kg by implementing a T1ρ_{off} sequence with ω_{eff} = 500 Hz, ω_1 = 325 Hz and $\Delta\omega_0$ = 380 Hz, or, alternatively, the total scan time could be reduced by lowering the minimum TRand to achieve identical SAR.

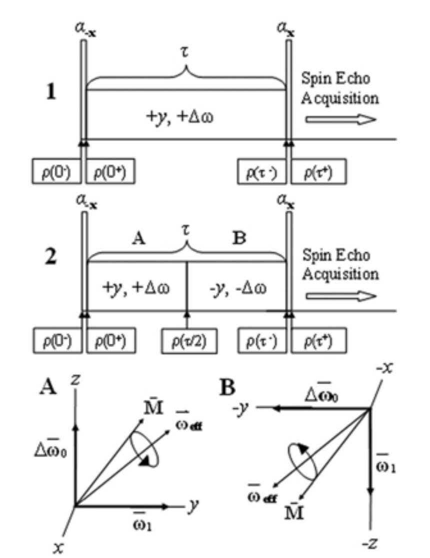

Fig. 1: Two preparatory pulse clusters for T1ρ_{off}-weighted imaging. In sequence 1, if the excitation flip angle is not the same as the angle of the effective field, the magnetization nutates and produces image artifacts, but in sequence 2, however, is refocused.

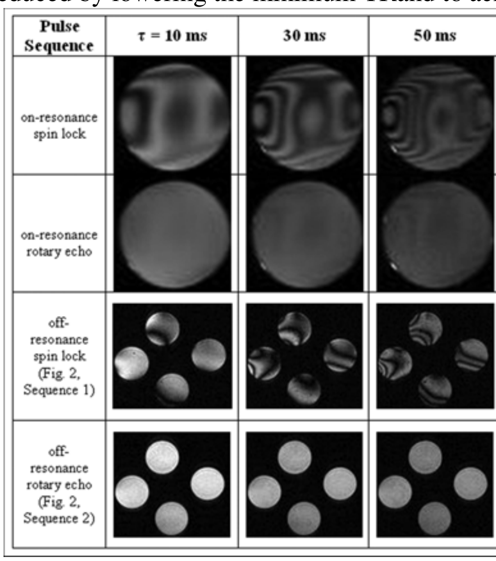

Fig. 2: Compensation for B1 inhomogeneity during on- (ω_{RF} = 0) and off-resonance (ω_{RF} = 400 Hz) spin locking in 3% agarose phantoms ($\alpha = 65°$, ω_1 = 400 Hz). Magnetization nutates about the effective field ω_{eff} and without both phase and frequency inversion, banding artifacts are severe.

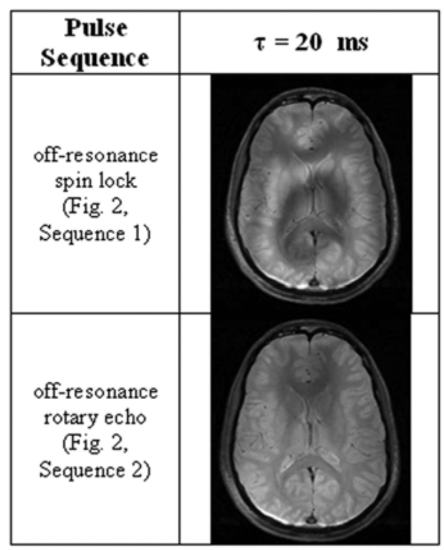

Fig. 3: T1ρ_{off}-weighted brain images obtained in a healthy volunteer on a Siemens Trio 3T clinical system with the following T1-off-weighting parameters ($\alpha = 65°$, ω_1 = 400 Hz, ω_{RF} = 400 Hz) using a fast spin echo readout sequence (TE_{eff} = 15 ms, TR = 2500 ms, 8 echoes per TR).

References: 1. Sears REJ. 1972;17(4):573. 2. Rhim WK, Pines A, Waugh JS. Physical Review B 1971;3(3):684-&. 3. Santyr GE, Fairbanks EJ, Kelcz F, Sorenson JA. Magn Reson Med 1994;32(1):43-51. 4. Grohn OH, Makela HI, Lukkarinen JA, DelaBarre L, Lin J, Garwood M, Kauppinen RA. Magn Reson Med 2003;49(1):172-176. 5. Fairbanks EJ, Santyr GE, Sorenson JA. Journal of Magnetic Resonance Series B 1995;106(3):279-283. 6. Soloman I. Rotary spin echoes. Physical Review Letters 1959;2(7):301-302.