Improved off-resonance correction for *segmented* spatially selective excitation pulses to achieve large excitation bandwidth

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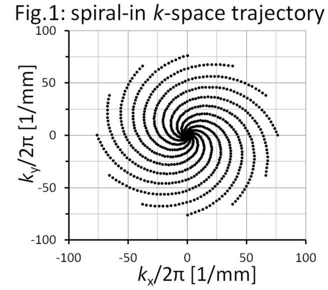
Purpose: Recent studies explored the feasibility of spatially selective excitation (SSE) to create arbitrarily shaped voxels for MRS, using parallel transmission (pTx) to shorten the RF pulses and segmentation of the *k*-space trajectory to increase the excitation bandwidth [1,2]. The small tip angle (STA) approach provides a fast algorithm to calculate SSE pulses. Here, we describe a new way to handle the B_0 off-resonance term in the design algorithm for pTx SSE pulses [3][4]. This permits to design segmented SSE pulses as a single pulse including off-resonance correction and to carry out the segmentation afterwards. The modification allows to calculate segmented SSE pulses with large bandwidth by simultaneous optimization for multiple frequencies for improved pattern fidelity even for large off-resonances.

Fig.1: spiral-in *k*-space trajectory



Methods: The segmented SSE pulse calculation is based on a STA algorithm similar to [4]. The *k*-space trajectory (12 segments, 710µs RF duration each) from Fig.1 and B_1^+ maps of an agarose phantom (L=20cm, Ø=19cm) measured with a 3T transmit-array (Siemens) and an 8 channel Tx/Rx coil were used. The transverse magnetization $M(\boldsymbol{x})$ created by a pTx pulse of duration T can be approximated by [4]:

$$M(\boldsymbol{x}) = \mathrm{i}\gamma M_0 \sum_{c=1}^{R} S^c(\boldsymbol{x}) \int_0^T B_1^c(t) e^{\mathrm{i}\,\boldsymbol{k}(t)\cdot\boldsymbol{x} + \mathrm{i}\Delta\omega(\boldsymbol{x})[t-T]} dt \quad . \qquad (1)$$

S^c is the transmit sensitivity of coil element c, B_1^c the corresponding RF pulse, *k* the *k*-space trajectory and Δω the off-resonance frequency. For segmented SSE the pulse is designed as a single pulse and only segmented afterwards. The transverse magnetization fully relaxes between RF pulse segments, such that in the STA regime the condition $M(\boldsymbol{x}) = \sum_{s=1}^{N} M_s(\boldsymbol{x})$ is inherently fulfilled [1]. M_s is the magnetization created by the RF pulse of segment *s* = [1,…*N*]. In order to incorporate off-resonances correctly, Eq.1 needs to account for the fact that the true pulse duration after segmentation will be *T*/*N*. Introducing the parameter *s*, Eq.1 can then be written as:

$$M(\boldsymbol{x}) = \mathrm{i}\gamma M_0 \sum_{s=1}^{N} \sum_{c=1}^{R} S^c(\boldsymbol{x}) \int_{T\frac{s-1}{N}}^{T\frac{s}{N}} B_1^c(t) e^{\mathrm{i}\,\boldsymbol{k}(t)\cdot\boldsymbol{x} + \mathrm{i}\Delta\omega(\boldsymbol{x})\left[t-T\frac{s}{N}\right]} dt.$$

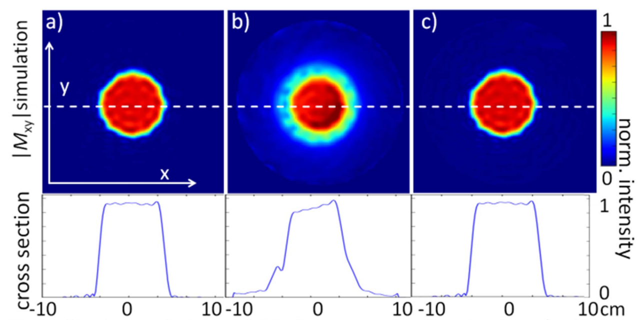


Fig.2: Bloch simulations of M_{xy} for segmented excitation a) without, and b) with 800Hz off-resonance , c) with corrected off-resonance.

In addition to off-resonance correction, this modification permits to supplement the bandwidth enhancement, which is the primary reason for segmented pulses in the first place. To this end, the STA design equation $\boldsymbol{P} = \boldsymbol{A}\,\boldsymbol{B}$ is expanded by concatenating a series of *n* matrices **A** with different off-resonance frequencies, thus optimizing the SSE pulse for a single target pattern ***P*** at different frequencies simultaneously without increasing its duration. The computation time increases proportional to *n*.

Results: Bloch simulations for each segment were performed and a complex summation yields the excitation patterns presented in figures 2 and 3. With the proposed modification the artifacts (Fig.2b) introduced by off-resonances (here 800 Hz) can be compensated (Fig.2c) to restore the original pattern fidelity without B_0 inhomogeneities (Fig.2a). Figure 3 shows SSE simulations based on (a) a conventional, segmented RF pulse, (b) a RF pulse optimized for ±800 Hz B_0 variation in steps of 400 Hz and (c) a phantom MR measurement using the optimized pulse. While the new pulse design (b) requires some more power to achieve the same flip angle and sacrifices some pattern fidelity on-resonance, it gives a constant excitation pattern over a wide frequency range with improved fidelity for large off-resonance.

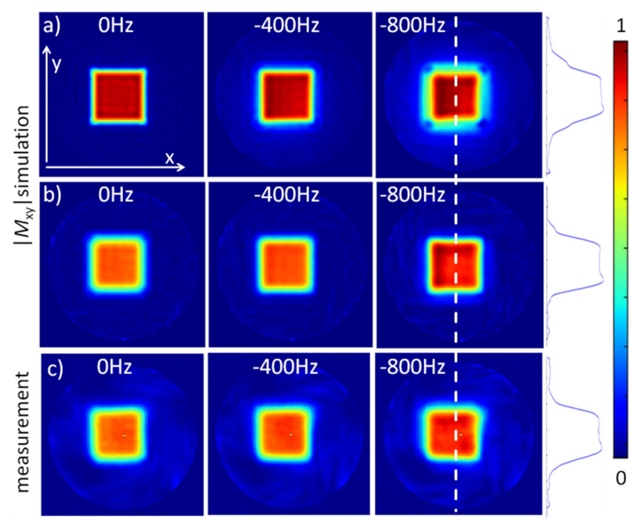


Fig.3: off-resonance performance of segmented SSE for a) standard calculation, b)& c) off-resonance optimized pulse

Discussion/Conclusion: An easy to implement and computationally affordable modification to existing STA pulse design algorithms was proposed offering superior off-resonance correction for *segmented* pTx SSE pulses. Using this correction term a constant excitation pattern was achieved over a large range of off-resonance frequencies, which is specifically desirable when using these segmented SSE pulses for voxel localization in MRS. With this approach in the plane of the 2D SSE pulses, the frequency dependent voxel displacement due to the chemical shift artifact, which is a significant problem in (ultra)high field MRS with standard localization schemes, is completely absent for weakly coupled spins, for which the Bloch equations hold. A (conventional) slice selection in the third dimension is still required, however, for full localization.

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[3] Yip,C. et al.,(2005),MRM,54:908-917 [4] Grissom, W. et al.,(2006), MRM,56:620-629