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k_T-spokes: combining k_T-points with spokes to ease ramp pulse design for TOF slab selection with parallel transmission at 7T

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SYNOPSIS

TONE pulses counteract blood saturation through the imaged slab in TOF sequences, but their ramp profile is hampered by RF inhomogeneities at UHF. On the other hand, k_z-spokes are known to compensate for in-plane B_1^+ heterogeneities in slice or slab selection. However, their design doesn't address thru-slab heterogeneities. To address them, a new pulse type called "k_T-spokes" is introduced. As TONE pulses, k_T-spokes efficacy is demonstrated with pTx at 7T in comparison with mere equivalent k_z-spokes.

INTRODUCTION

MR angiography Time-Of-Flight (TOF) sequences are sensitive to blood saturation effects as blood traverses the imaged slab in the human head, preventing the visualization of the whole arterial network. One efficient way to compensate for this saturation has been the use of ramp or TONE RF pulses, with thru-slab ascending flip angle (FA) profiles [1, 2]. However, at UHF, in large-slab selection, B_1^+ heterogeneities hamper fidelity to the specified FA pattern [3]. Previously, we addressed this issue by combining parallel transmission (pTx) and double spoke ramp excitations [4]. The study demonstrated the efficiency of a spoke waveform design addressing the full three-dimensional problem as opposed to the traditional spokes which only mitigate the FA in-plane variations [5]. Yet because of the large number of unknowns (waveform complex data-points for each spoke and every channel), the optimization of tailored "3D-spokes" takes a rather long time (~20-30 min), not quite compatible with clinical routine. In the present work, a simpler spoke type is introduced, called "k_T-spoke", whose design takes only a few seconds while still considering the slab 3D B_1^+ distribution.

METHODS

The conventional spoke method optimizes the (k_x, k_y)-locations of consecutive selective excitations in the transmit k-space [5]. In the context of a mere uniform slab excitation, k_T-spokes additionally allow the placement of the spoke centers in different (but nearby) k_z-locations, thereby relaxing the degree of freedom needed for thru-slab homogenization. This method is equivalent to a k_T-points pulse design [6] where the target ROI is limited to the slab of interest, and where square subpulses are eventually replaced by kz-spokes, i.e. sinc-like waveforms played along with their selection gradient. Thus the only difference between spokes and k_T-spokes is the presence of z-gradient blips in between RF subpulses. In the context of TONE pulses, for both conventional spokes and k_T-spokes, the FA ramp profile was obtained by replacing the sinus-cardinal waveform by the inverse Fourier transform of the desired FA ramp. More precisely, the Fourier transform of an apodized sinc with TBW=10 was multiplied by the latter before transforming it back. Only triplets of spokes are considered in this study. The pulse design was formulated as a SAR- and power-constrained Magnitude Least Squares problem that jointly optimized the magnitude and phase of each spoke on every channel of a pTx system, as well as the spoke placement in transmit k-space [7,8]. The Small Tip Angle approximation was used to build the k-space encoding matrix in the optimization problem. Yet full Bloch equation simulations were run in the end to predict the slab FA maps and compute errors with respect to the desired ramp profile. Experiments were performed on 5 volunteers (who signed an IRB-approved informed consent) using a 7T scanner (MAGNETOM, Siemens Healthcare, Erlangen, Germany) and an 8-Tx/Rx head array (RAPID Biomedical GmbH, Rimpar, Germany). B0 and B1-maps of all subject brains were acquired with 5-mm resolution (B1-maps obtained from the XFL sequence [9]). Prior to the study, the k_T-spoke performance was evaluated on a spherical water phantom with the AFI sequence [10] to corroborate the FA Bloch simulations (Figure 1). A FA-ramp from 10° to 30° was targeted with three bipolar spokes of 1 ms each. First, a comparison between conventional spoke and k_T-spoke performances was carried out from simulation of the FA maps. Then, for either spoke strategy and only for the 5th subject, the computed composite pulse was integrated into a pTx TOF sequence with the following parameters: TR = 20 ms, TE = 4 ms, resolution = 0.4x0.4x0.5 mm, FOV = 200x200x60 mm, GRAPPA = 2, partition partial Fourier = 6/8 and TA = 6 min. To evaluate the angiograms, a Maximal Intensity Projection (MIP) was performed on the TOF native images.

RESULTS

Regarding the 3D FA maps from the numerical simulations, k_T-spokes showed an improvement of the slab profile for all subjects compared to conventional spokes (Figure 2). The FA Root Mean Square Error with respect to the prescribed ramp and normalized to the slab-center FA (NRMSE) was improved by 15% in average with the k_T-

spoke method (Table 1). The MIP performed on the 5th volunteer showed a significant enhancement of the depiction of the distal arteries compared to the acquisition made with a flat FA= 20° justifying the benefit of a ramp excitation (Figure 3). According to the simulation, the fidelity of the ramp generated by the k_T-spoke design ensured a more accurate control of the blood saturation compensation compared to the 3-spoke excitation. Indeed the contrast was slightly better and some additional arteries was restored (Figure 3).

CONCLUSION

The clinically-viable k_T-spoke design succeeds in counteracting the B_1^+ heterogeneities along the z-axis, particularly in wide off-centered slabs as shown here. Moreover this study demonstrates the benefit of FA-ramped k_T-spokes for blood saturation compensation at 7T by enhancing distal arteries visualization.

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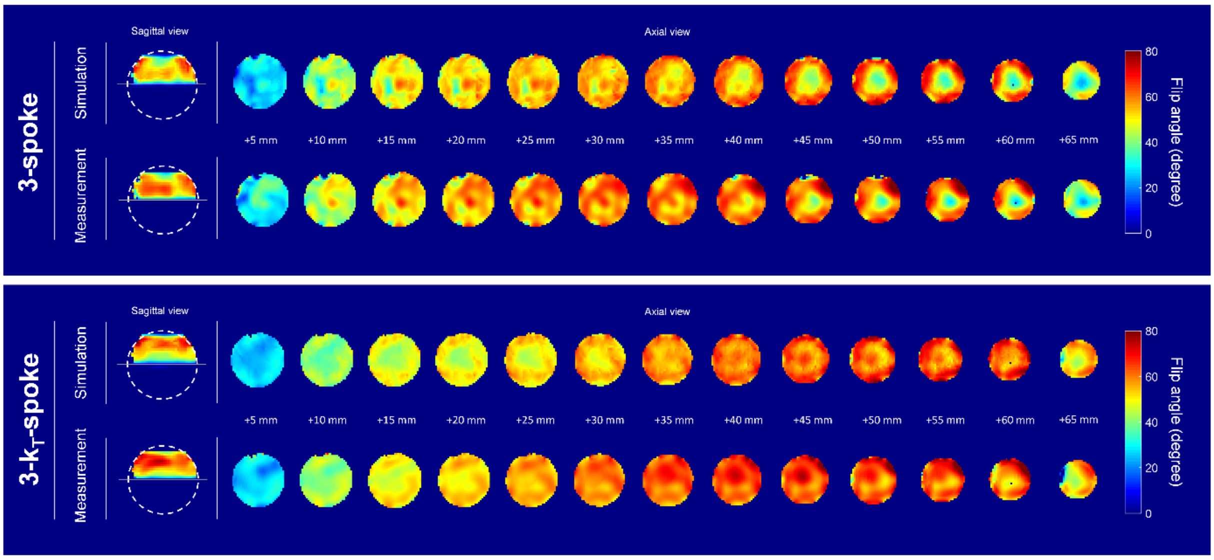


Figure 1: Agreement between FA simulation and measurements with 3-spoke and 3-k_T-spoke excitations targeting FA=45° to 75° in a 50-mm slab of a 160-mm spherical water phantom: this validates the simulations performed in this study. The range of desired FA was around 60° because the AFI sensitivity is optimal for these values.

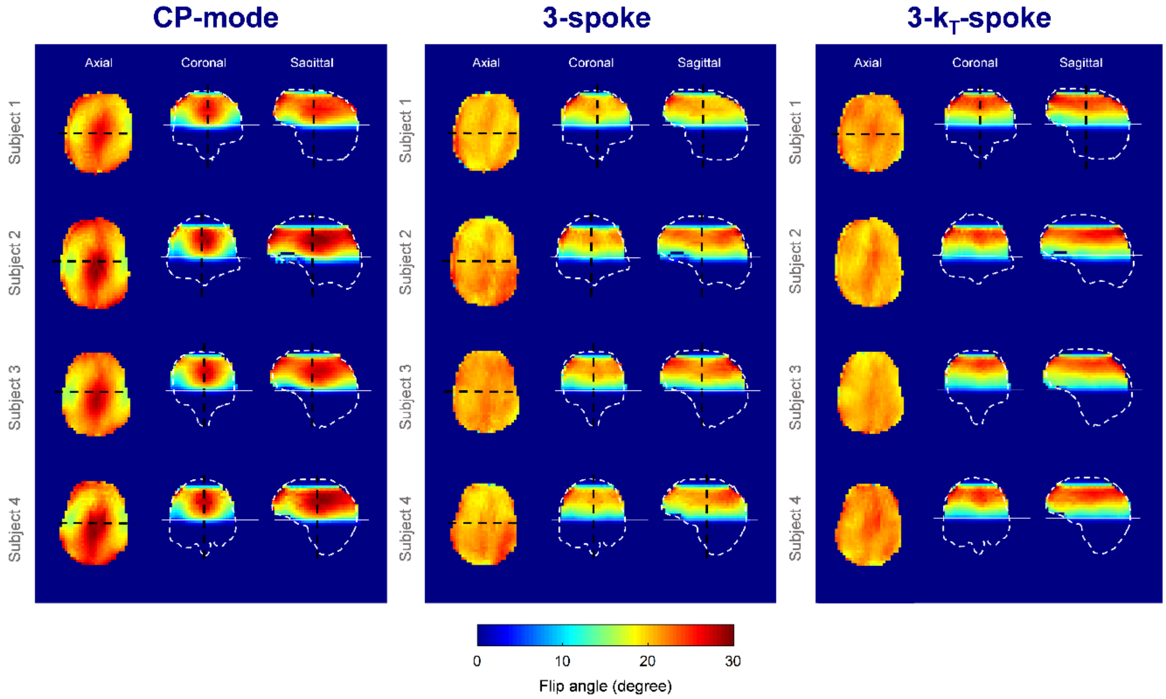
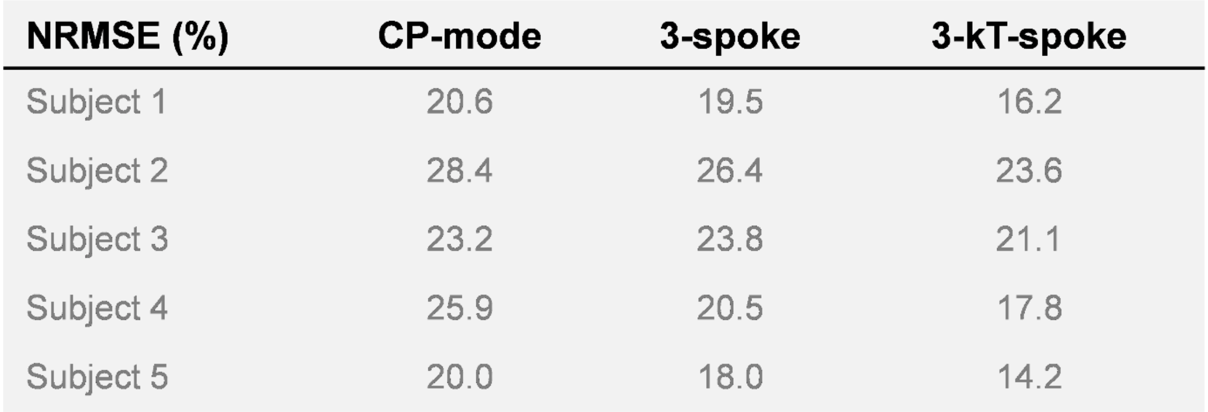


Figure 2: FA Bloch simulations for 3-spoke, 3-k_T-spoke excitations and in Circularly-Polarized (CP) mode targeting a FA ramp profile from 10° to 30° in a 65-mm off-centered slab. Note how the tailored excitations improved the fidelity of the resulting FA with respect to the CP-mode. Moreover, the 3-k_T-spoke achieved a better profile for each subject compared to 3-spoke excitations.



NRMSE (%)	CP-mode	3-spoke	3-kT-spoke
Subject 1	20.6	19.5	16.2
Subject 2	28.4	26.4	23.6
Subject 3	23.2	23.8	21.1
Subject 4	25.9	20.5	17.8
Subject 5	20.0	18.0	14.2

Table 1: Final FA-NRMSE in the slab of interest obtained from numerical simulations (cf. Figure 2). The FA-NRMSE evaluated the RMS error of the in-slab Bloch-simulated FA from the desired FA ramp pattern.

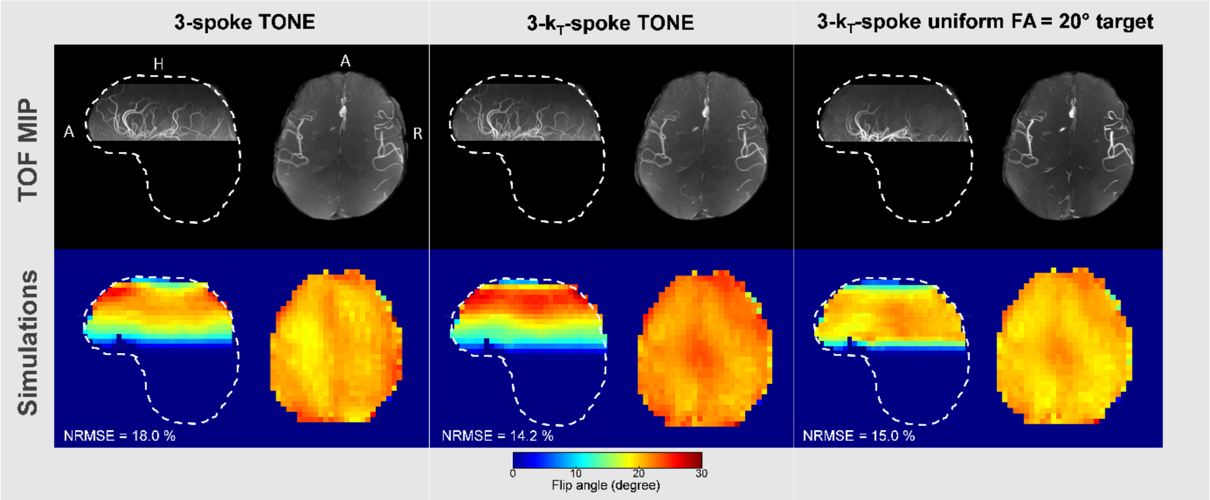


Figure 3: TOF MIPs and their associated FA Bloch simulations for 3-spoke and 3-k_T-spoke excitation in a 65 mm off-centered slab. Here again, the 3-k_T-spoke excitation achieved a better ramp profile (FA from 10° to 30°) for this subject than 3 spokes. Note the effect of blood saturation compensation compared to the 3-k_T-spoke acquired with a constant slab target FA = 20° (right sub-figure).