Highly dynamic k_T-points to minimize the B_1^+ inhomogeneity effects in T_2-weighted imaging at 7T

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Introduction:

At ultra-high field, the inhomogeneous distribution of the transmit magnetic field (B_1^+) can significantly impair the quality of turbo spin echo (TSE) sequences. In a previous study [1] the effect of the inhomogeneous B_1^+ distribution on T_2-weighted images was minimized by replacing each pulse of the TSE sequence by a single k_T-point pulse designed in the small tip angle (STA) regime (static k_T-points). Using the spatially resolved extended phase graph (SR-EPG) framework [2] to simulate the magnetization throughout the entire TSE sequence, dynamic k_T-points, where a specific k_T-point pulse is designed for each pulse of the sequence were proposed [3] to further improve the signal and contrast homogeneities in T_2-weighted imaging. In this work, the dynamic k_T-point design is revisited by allowing an increased flexibility for the optimization of the excitation pulse. The impact of the chosen cost function used in the optimization algorithm will also be discussed.

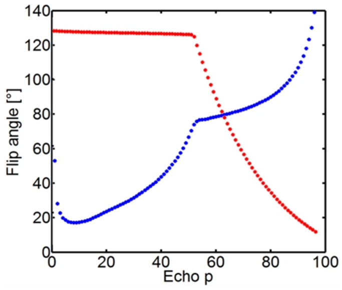

Fig. 1: *Train of flip angles (blue) optimized for a specific T_1/T_2 relaxation times such that a static pseudo steady state is maintained over a large number of echoes. The echo train (red) is presented in arbitrary*

Methods:

A healthy subject, who provided informed consent, was scanned on a 7T scanner (Siemens) equipped with a 32-channel receive coil (NOVA Medical). A B_1^+ map was obtained with the SA2RAGE [4] sequence for pulse designing purposes.
TSE sequence: TR/TE = 2.4s/280ms, echo train length (ETL)/echo spacing (ES) = 96/7.6ms, RF_{Dur} = 3.0ms, res. = 0.7mm isotropic, T_{acq} = 7min50s. The flip angle and echo trains used are presented in Fig.1. The echo train represents the amplitude of the signals $S^{theo} = [S^{theo}_1,\ldots, S^{theo}_{ETL}]$ that would be acquired given a perfectly homogeneous B_1^+ field.
The design of dynamic k_T-point pulses for the whole sequence was performed in four steps:

- **(1)** As its efficiency in refocusing pathways was demonstrated [1], a symmetric k_T-point pulse with n_{Ref} k_T-points was designed with the subject-specific B_1^+ profile. This pulse defined the k-space trajectory for all the refocusing pulses of the sequence.
- **(2)** An excitation pulse with n_{Exc} k_T-points was designed in the high tip-angle regime by using a linearization of the Bloch equations [5]. The sub-pulse amplitudes and phases as well as the k-space trajectory were optimized in a least squares sense in order to obtain an homogenous excitation but also to match the phase profile corresponding to the one of the refocusing pulse created in (1) such that the CPMG conditions are fulfilled.
- **(3)** The amplitudes and phases of all k_T-point sub-pulses of the first P1 refocusing pulses bringing the magnetization into static pseudo steady state (Fig. 1) were optimized together such that the echo profiles $S(\mathbf{r}) = [S_1(\mathbf{r}),\ldots,S_{P1}(\mathbf{r})]$ simulated using the SR-EPG match the theoretical signal $[S^{theo}_1,\ldots, S^{theo}_{P1}]$. Optimizations (1) and (2) defined the starting values of this optimization.
- **(4)** The remaining pulses of the sequence were optimized on a k_T-point pulse-by-k_T-point pulse basis. Once the sub-pulses of k_T-point pulse p were found, the SR-EPG states after it were calculated since they were needed to optimize the pulse p+1.

To reduce the computation time, the optimizations were performed by considering a subset of 500 voxels randomly selected from the subject-specific brain mask.

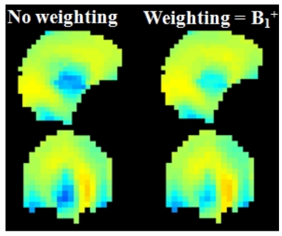

Fig. 2: *Improvement of the signal homogeneity at k-space center obtained by introducing a weighting factor corresponding to the B_1^+ profile in the cost function.*

Cost function considerations: In optimizations (3) and (4), a gradient descent algorithm was used to minimize the following cost function

$$CF = \sum_{n=1}^{n_p} \left(\left| tol \cdot S_n^{theo} e^{i\bar{\phi}} - S_n^c(\vec{r}) \right| \cdot B_1^+(\vec{r}) \right)^{pow}$$

with n_p the number of pulses in the optimization, c the current iteration and pow a power factor used to penalize more the regions of the echo distributions $S^c(\mathbf{r})$ which are highly different from the expected signal S^{theo}. The average phase $\bar{\phi}$ over the n_p echoes calculated at iteration c-1 was introduced to ensure a smooth phase transition from one echo to the next, which improved the quality of the data acquired (not shown). As suggested in [2], the tolerance factor tol, was used to provide more flexibility to the optimization process. The subject-specific B_1^+ profile was used as a weighting factor such that the importance of very low B_1^+ regions for which the algorithm cannot provide a correction are downplayed. The validity of the proposed methodology was demonstrated by comparing TSE images acquired with dynamic k_T-points with images acquired with static k_T-points and standard hard pulses (no k_T-point).

Results and discussion:

In this work, the following parameters were used in optimizations (1) to (4) and when evaluating the cost function: n_{Ref} = 3, n_{Exc} = 5, P_1 = 9, tol = 0.9 and pow = 4.5. The importance of having the B_1^+ profile as a weighting factor is illustrated in Fig.3 where the signal homogeneity across the brain is improved when the weighting term is considered. When not using the weighting term, the optimization efforts regarding the correction of low B_1^+ regions created a hole in the center.

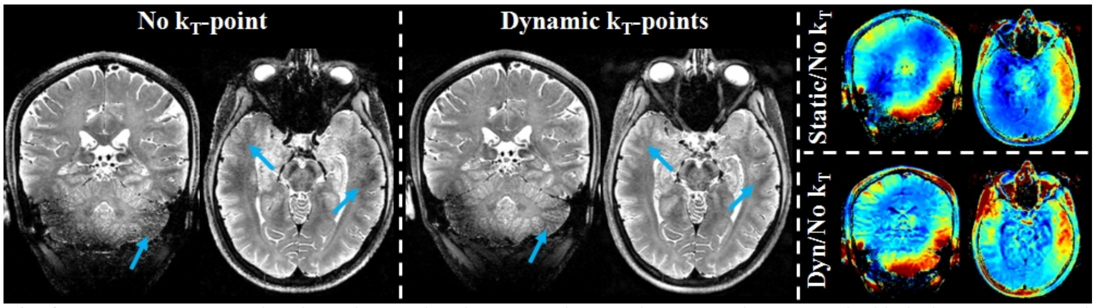

Fig. 3: *TSE images acquired without (left) and with (center) dynamic k_T-points. Blue arrows highlight brain regions with significant improvements. The maps on the right correspond to the ratios of the images acquired with static (top) and dynamic (bottom) k_T-points in respect to the image acquired with the standard hard pulses.*

The signal and contrast homogeneities are improved throughout the image when using dynamic k_T-points (Fig. 3), particularly in the cerebellum and the temporal lobes (blue arrows). Ratio images on the right side of Fig. 3 emphasize the improvement in signal homogeneity obtained when going from static to dynamic k_T-points. Indeed, the ratio dynamic/no k_T-point displays higher corrections on the temporal lobes as well as on the cerebellum.

Conclusion:

It was demonstrated that the effect of the B_1^+ inhomogeneity observed at high field can be largely minimized by replacing the original hard pulses of a TSE sequence with variable flip angles by dynamic k_T-point pulses even in the absence of parallel transmission. More flexibility in the design was provided by considering more k_T-points and an independent k-space trajectory for the excitation pulse. It was also shown that choosing carefully the cost function used in the gradient descent algorithm dramatically improves the quality of the acquired T_2-weighted images.

References: [1] Eggenschwiler et al, MRM 71, 2014, [2] Malik et al, MRM 68, 2012, [3] Eggenschwiler et al, ISMRM meeting, 2014, [4] Eggenschwiler et al, MRM 67, 2012, [5] Eggenschwiler et al, ISMRM meeting, 2013.

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