Dynamic kT-points: a new concept to improve T2-weighted imaging at 7T
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Introduction:
T2-weighted images are widely used for the diagnosis of brain diseases involving gray- and white-matter lesions such as multiple sclerosis. The increased SNR available at high field strengths (≥7T) should provide higher spatial resolution; however, the inhomogeneous distribution of the RF field (B1+) causes undesirable signal and contrast variations of GM/WM across the brain. In a previous study1, high quality whole brain T2-weighted imaging was achieved by combining short 3D tailored RF pulses (kT-points)2 with a variable flip angle TSE (SPACE3) sequence. A single kT-point pulse was designed in the STA regime to replace all the sequence pulses (here referred to as static kT-point design). In this work, a specific kT-point pulse is designed for each pulse of the sequence (dynamic kT-point design) in order to further improve T2-weighted imaging homogeneity.

Methods:
Two healthy subjects, who provided informed consent, were scanned on a MAGNETOM 7T scanner (Siemens AG Healthcare Sector, Erlangen, Germany) equipped with a 32-channel head coil (NOVA Medical, USA). Protocols: B1+ map – SA2RAGE4 sequence: TR/TD/TD2 = 2.40/0.0054/1.8s, res. = 3.4x3.4x0.0mm3, matrix = 64x64x48, TEn = min55s. TSE sequence: TR/TE = 2s/100ms, echo train length (ETL)/echo spacing (ES) = 57/4.16ms, RF Dur = 1.40ms, res. = 0.85x0.85x0.85mm3, matrix = 256x256x176, IPAT = 3, TEn = 6min30s.
The k-space trajectory defining the kT-point positions was determined by designing a first kT-point pulse in the STA regime using the SOLO algorithm5 fed with the subject-specific B1+ profile. This first estimation was used as a starting point for subsequent optimizations. The k-space trajectory was maintained throughout the entire sequence. The Spatially Resolved Extended Phase Graph (SR-EPG) formalism6 including kT-point pulses was used to simulate the signal across the TSE sequence. When considering a sequence of ETL pulses made of N kT-points each, the goal is to optimize the amplitude Ai,j and phase φi,j of each sub-pulse of the kT-points (i (1=N) and RF pulses (j (0-ETL) in order to make the signal throughout the sample S(r) as close as possible to the expected signal Stheo (cf. Fig. 1) for all echoes across the sequence (dynamic kT-point design).
The optimization problem was split into two parts: initial ramp – transition towards static pseudo-steady state7 (blue part in Fig. 1) and maintenance of signal homogeneity throughout echoes in pseudo-steady state (red part in Fig. 1). For the initial ramp, the amplitudes Ai and phases φi (with j=0-10) were optimized simultaneously using a gradient descent algorithm8 using a magnitude least squares (MLS) cost function. The second part of the sequence was optimized on a kT-point pulse-by-kT-point pulse basis. For each pulse optimization, the amplitudes and phases of the previously optimized kT-point pulse are used as an initial guess. To reduce computation time, optimizations were performed on voxels belonging to a subject-specific brain mask calculated using a homebuilt software.
The SR-EPG framework was subsequently used to simulate the signal throughout the TSE train for: (1) standard hard pulses; (2) static kT-point pulses; (3) dynamic kT-point pulses. The quality of each approach was evaluated in terms of signal fidelity (∥S(r)-Stheo∥) for each echo) and signal homogeneity (standard deviation throughout each simulated S(r) map). In (2) and (3), 5 kT-points were used for each sequence pulse.

To support simulations, TSE images acquired with kT-point pulses designed statically and dynamically were compared with images acquired with standard hard pulses (no kT-point).

Results and discussion:
The curves presented in Fig. 2a and 2b show the improvement provided by the dynamic kT-points over the static kT-point design and the approach without kT-point in terms of both echo train fidelity and homogeneity. It can be seen that the solution resulting from the use of 3 dynamic kT-points is comparable to the one obtained with 5 kT-points in the static regime. Moreover, for the same RF duration, the sequence designed with 3 dynamic kT-points outperformed the one with 5 static kT-points by more than 50% in terms of SAR. Despite the increased homogeneity obtained using a higher number of kT-points, measured images were acquired using 3 kT-points to keep the RF duration shorter than 1.5ms within the SAR limits. The differences "static - no kT-point" and “dynamic - no kT-point” calculated for the measured TSE images (Fig. 3 a,c,e) are in close agreement with the ones obtained using the SR-EPG at k-space center (Fig. 3 b,d,f,h) for both subjects. This shows that the state of the magnetization throughout the TSE sequence can be reliably understood with SR-EPG simulations including static and dynamic kT-points. TSE images acquired without and with dynamic kT-points are shown in Fig. 3 i-j. High improvements in signal and contrast homogeneity are seen in the cerebellum, brain center and over sinuses (blue arrows) when using dynamic kT-points.

Conclusion:
The very good agreement between simulations and experimental data demonstrates that including kT-points in the SR-EPG formalism provides a new degree of freedom to control the magnetization distribution in a TSE sequence with variable flip angles leading to T2-weighted images with high level of signal and contrast homogeneity at 7T. This methodology will now be translated to parallel transmission where the advantages are expected to be greater thanks to the increased number of degrees of freedom associated with the different transmit channels.


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