

Target-Pattern-Informed Variable-Density Trajectory Design for Low-SAR Pulse Design in Parallel Transmission

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Target audience: RF engineers and MR physicists. **Purpose:** Since the introduction of parallel transmission (pTX), a large effort has been spent towards SAR-constrained RF pulse design. The majority of approaches use sophisticated optimization schemes to control global and local SAR explicitly (1-4). However, for highly parameterized RF pulses, e.g. spiral spatially selective pulses (SSP) these optimization schemes can be computationally intensive and hence hardly applicable in clinical use. Variable-density trajectories have also been shown to reduce global SAR (5), but leave space for the optimal distribution and intensity of the k-space sampling density. The Fourier transform (FT) of the target magnetization pattern was reported for being beneficial to determine custom k-space sampling locations (6-8), but an algorithm for SSPs has not been demonstrated so far.

The aim of this work is to introduce a variable-density k-space trajectory metric, which is **target pattern driven (TD)** and directly computed to inherently reduce RF hardware demands without any additional optimization steps or iterations. The metric proves to be very beneficial with respect to local and global SAR performance. The proposed TD design is compared to the commonly used equal- and variable-density (ED and VD) trajectories varying the TX acceleration factor. For this purpose, an elaborate simulation study was conducted for 3D spatially selective stack-of-spiral pulses (SOS).

Methods: The proposed trajectory design TD computes a TX k-space sampling distribution metric Θ based on the combination of a) the FT of the target magnetization pattern (T) and b) a spatial spectral window function (W). Hence, Θ combines the principle TX energy distribution in k-space according to Parseval's theorem in a) and an optimized balancing between RF energy deposit and spatial TX accuracy via b). In practice, the algorithm firstly detects local k-space "energy hotspots" of T, i.e. TX k-space locations of relevance. Then the TX k-space is sub-segmented such that each segment contains one single hotspot. Finally, Θ is achieved by scaling each segment to the corresponding W segment. Based on Θ , the distribution and intensity of the k-space sampling density of an arbitrary k-space trajectory can be determined. Potential benefits of the TD design are shown for SOS pulses exciting a heart-shaped target pattern (Fig.1a) with 30mm isotropic resolution in dependence of different TX acceleration factors within the low-flip-angle regime. The simulations were based on the anatomy model HUGO (Visible Human Project, National Library of Medicine) with 2 mm resolution and 32 unique tissue types. B1⁺ maps for an 8-ch 3T whole-body multi-channel TX array and SAR calculations were performed using CST Microwave Studio (CST AG, Darmstadt, Germany). RF pulse design followed the approach of (9) and was run on an 18x30x35 grid with FOV = 342x548x228mm³. In SOS TD design the distribution of the spirals along k_z, the sampling density per spiral and the allocation of TX acceleration factors along the spirals were calculated according to Θ . W was set to a Hanning window. In comparison, SOS trajectories with equal density (ED) and fixed variable density (VD) similar to (5) were designed. SOS trajectories were stepwise accelerated in-plane and along z by reducing the number of spiral rounds per spiral (R_{XY}) and total number of spirals (R_Z). For evaluating the respective excitation performance, the spatial fidelity (RMSE), the RF peak voltage and RF power, global and local SAR were assessed. Except for RMSE, all metrics were normalized to the ED design. Note that for a reasonable comparison, all SOS designs were computed to match the same trajectory length and same RMSE.

Results/Discussion: Some exemplary SOS designs are shown in Fig. 1b-d. Performance results for all designs and all TX acceleration factors are depicted in Fig. 2a-e. In numerical Bloch simulations (Fig. 2f) TX aliasing effects in slice selection direction can be clearly observed resulting in blurring and degraded spatial accuracy. For all scenarios, the proposed TD design (top row) has the lowest RF hardware demands, global and local SAR values at constant spatial excitation error. Particularly, the average RF peak voltage (RF power) gets reduced by 57(59)% compared to ED and 49(54)% compared to VD design. The average global SAR (local SAR) reduction adds up to 64(77)% less than ED and 54(71)% less than VD. Thus, TD SOS pulses can be calculated more efficiently and can be further accelerated compared to the other designs, which is important in order to stay within RF hardware limits and for minimizing off-resonance effects.

Conclusions: The target-pattern-driven trajectory (TD) design offers substantial improvements in RF hardware efficiency and global and local SAR performance. The TD approach can be applied to arbitrary trajectories and is computed directly. In contrast to previous methods that explicitly constrain SAR by the optimizer (1-4), the TD design inherently reduces the RF energy deposition and clearly tends to lower both global and local SAR without any additional computational expense. In other words, the TD design still allows further RF hardware and SAR improvements by a redesign of the TX trajectory on top of other sophisticated optimization schemes.

References: [1] Brunner D (2010). MRM 63(5):1280-1291. [2] Lee J (2011). MRM 67(6):1566-1578. [3] Guérin B (2012). Proc. ISMRM 20:0642. [4] Guérin B (2012). Proc. ISMRM 20:2215. [5] Liu Y (2008). MRI 26(8):1122-1132. [6] Yip C (2006). MRM 56(5):1050-1059. [7] Cloos M (2011). MRM 67(1):72-80. [8] Malik S (2011). MRM 67(5):1303-1315. [9] Setsompop K (2008). MRM 60(6):1422-1432.

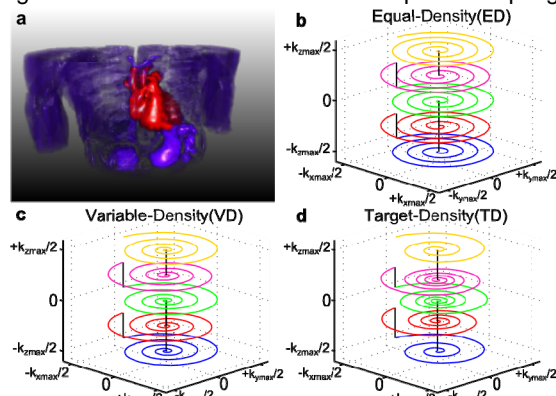


Figure 1: a Heart-shaped target pattern (red) used in the study. b-d Different exemplary SOS trajectory designs for TX acceleration factors $R_{XY}=1.8$, $R_Z=1.6$.

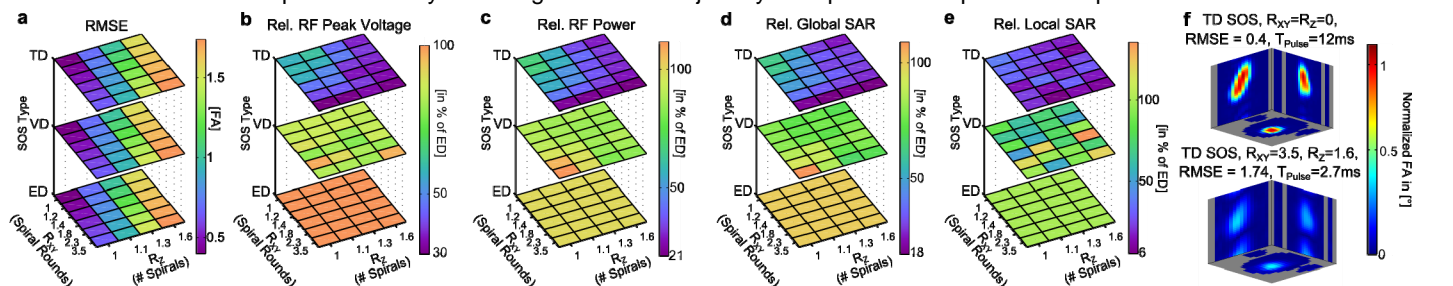


Figure 2: a-e Performance metrics for different stack-of-spiral designs in dependence of TX accelerations factors R_{XY} , R_Z . b-e are given in percent to the ED design. f Flip angle maps of non- and highly accelerated TD stack-of-spiral pulses.

References: [1] Brunner D (2010). MRM 63(5):1280-1291. [2] Lee J (2011). MRM 67(6):1566-1578. [3] Guérin B (2012). Proc. ISMRM 20:0642. [4] Guérin B (2012). Proc. ISMRM 20:2215. [5] Liu Y (2008). MRI 26(8):1122-1132. [6] Yip C (2006). MRM 56(5):1050-1059. [7] Cloos M (2011). MRM 67(1):72-80. [8] Malik S (2011). MRM 67(5):1303-1315. [9] Setsompop K (2008). MRM 60(6):1422-1432.