A novel, fast and adaptive trajectory in three-dimensional excitation k-space

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Introduction

In applications of three-dimensional (3D) small-tip selective excitation (e.g.: [1]), the excitation FOV and resolution requirements in the slice selection direction (z) are more stringent than those in the in-plane directions (x, y). Sampling strategies such as stack of spirals [1,2] are time-inefficient, and can lead to slice profiles that are susceptible to off-resonance distortion. We propose a novel trajectory in 3D excitation k-space [3] that traverses back and forth in the *kz* direction, while phase encoding in *kx-ky*. The *kx-ky* sample locations are computed adaptively, based on the 3D desired pattern. Our proposed trajectory is very time-efficient, and it provides good excitation accuracy, especially in the slice-selection direction. It leads to slice profiles that are less susceptible to distortion due to off resonance. It also eliminates aliasing slices due to sparse *kz* sampling by trajectories such as stack of spirals.

Method

The first trajectory design step is performing 3D FFT on the 3D desired pattern, with *coarse* resolutions in the *kx* and *ky* dimensions. Suppose that *kx-ky* is sampled at N locations, one can pick those N locations corresponding to the N largest values in

$$E(j,k)=\sum_{l=0}^{L-1}\left|D(j,k,l)\right|^2, \qquad j=0,\ldots,J\text{-}1 \text{ and } k=0,\ldots,K\text{-}1$$

where D is the 3D FFT of the desired pattern, and E is a coarse "energy distribution map" in *kx-ky*, obtained via collapsing the 3D distribution map along *kz*. FFT sizes along *kx* and *ky* (J, K) are design parameters which control the density of the phase-encoding locations.

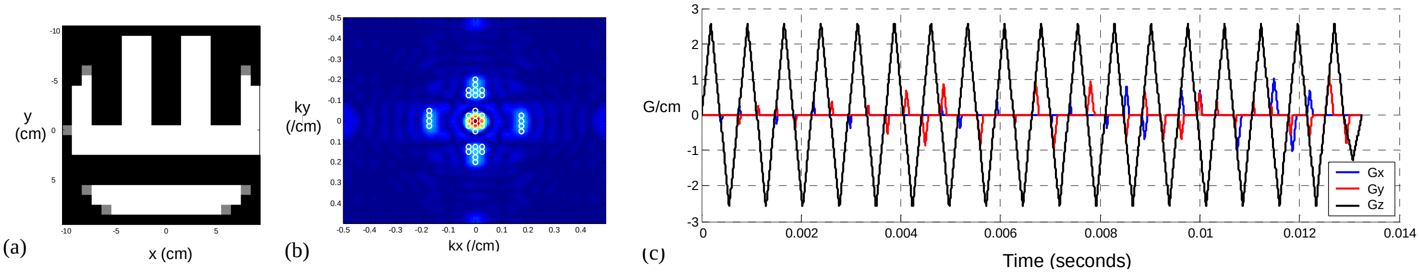

Fig. 1: (a) In-plane desired pattern. (b) kx-ky sample locations are determined based on the kx-ky energy distribution of desired pattern in excitation k-space. The locations are overlaid on top of the high-resolution energy distribution map. (c) Gradient waveforms leading to a trajectory that sweeps along kz and sample kx-ky locations adaptive to the desired pattern.

Gradient waveforms can then be designed accordingly. The Z gradient (*Gz*) oscillates, subject to the maximum gradient magnitude and slew rate constraints. It resembles the frequency-encoding gradient in echo-planar imaging (EPI), leading to upward and downward *kz* traversals. In between the traversals, phase encoding blips in the X and Y gradients (*Gx*, *Gy*) are applied to take trajectory toward the pre-computed *kx-ky* locations. The small *Gx* and *Gy* blips can overlap in time with the big *Gz* *b*lips (Fig. 1c). The complex RF pulse envelope is designed iteratively [4]. For fast computation, the iterative design utilizes *3D non-uniform fast Fourier transformation* (NUFFT) [5], and *time segmentation* analogous to [6] when off resonance is considered.

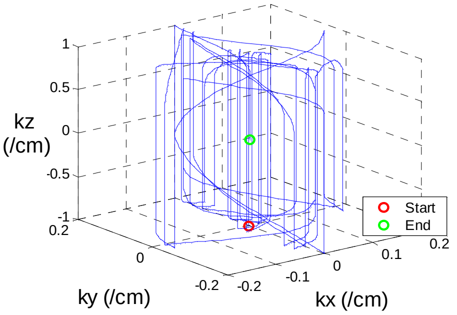

Fig. 2: 3D excitation k-space trajectory corresponding to gradients in Fig. 1(b).

Experimental results

A 3D RF pulse was designed iteratively using the proposed trajectory, without off resonance correction. The desired pattern had a Gaussian slice profile, with FWHM = 1 cm. In the transverse dimensions, resolution of desired pattern was 1 cm x 1 cm, and 40-point 2D FFT was performed (ie, J=K=40) for the adaptive process. 35 *kx-ky* locations were then picked as described above (Fig. 1b). Trajectory oscillated between kz = +/- 1 cm^{-1}. Constraints on the maximum gradient magnitude and slew rate were 4 G/cm and 15000 G/cm/s, respectively. These design parameters led to a pulse which was 13.25 ms long.

Resulting excitation pattern was imaged using a spin-echo sequence with spiral-out readout. The 180-degree pulse selected different slice locations within the 3D excitation pattern. The FOV in z was from -1 cm to 1.1 cm, with slice thickness = 3 mm. Fig. 3 shows acquired images of the 3D excitation pattern. No aliasing occurred in the through-plane dimension, and reasonably good in-plane accuracy was achieved. Because of the scarcity of phase-encoding locations, in-plane accuracy is susceptible to distortions due to off resonance and hardware imperfection. This problem can be alleviated by off resonance incorporation in the pulse design, or trajectory distortion estimation using a reference scan prior to trajectory design.

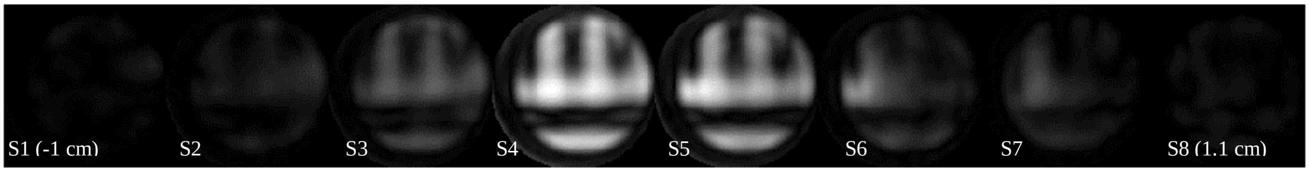

Fig. 3: Images of the 3D excitation pattern produced by the proposed trajectory and an iteratively designed RF pulse. Pulse length was 13.25 ms.

References

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