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3D Selective Pulse Design with Variable Spoke Trajectories for Parallel Excitation

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Abstract— **Three dimensional spatial selective RF pulse of practical length has been demonstrated using parallel transmission technique in Magnetic Resonance Imaging. Currently, spoke trajectory, which is a set of parallel k-space straight lines, is widely used for 3-D slab excitation to achieve sharp slice profile and a uniform or smoothly varying in-plane profile. The better control of in-plane profile mainly comes from an increased number of spokes. In this paper, we proposed three types of modified spoke trajectories for the 3-D tailored RF pulse design which traverse k-space more efficiently. Simulations are used to characterize the proposed trajectories.**

I. INTRODUCTION

Spatial tailored radio frequency (RF) pulses [1, 2] have been used to selectively excite a complicated two dimensional (2-D) pattern. However, long pulse durations prohibit the practical implementation of such pulses. With the help of multiple transmit channels, the duration of RF pulse can be shortened significantly. Several methods are proposed to design parallel excitation pulses under small-tip-angle approximation [3, 4]. Spiral [5] and EPI trajectory have been used to design 2-D tailored RF pulses followed by a conventional slice-selective 180° pulse. In many applications, a 3-D slice selective pulse is of more interest to achieve a sharp slice profile. Spoke trajectory [6], or so called fast k_z trajectory, has been introduced to design parallel excitation pulses that can generate sharp slice and a uniform or smoothly varying in-plane profile, e.g. a smoothly varying Gaussian function. These pulses can help to correct the B_o or B_1 inhomogeneity, which is particularly helpful in high-field MRI [7].

RF pulse design using spoke trajectory usually comes with two parts: the design of spoke trajectory and the design of RF pulse. The placement of spokes has been discussed in several previous publications. An intuitive way is to choose the locations where Fourier coefficients of the desired pattern has larger amplitude [8]. The number of spoke is determined empirically or based on simulations. Another method intents to find the most sparse distribution of spoke locations that can achieve excitation pattern within allowable error range [9].

With a chosen k-space trajectory, RF pulse can be designed using spatial domain method [10]. Alternatively, pulse on each spoke is assigned a fixed shape according to the slice profile, e.g. a Gaussian windowed Sinc function, but with different optimized weights. Depending on the complexity of the desired in-plane profile, the number of spokes range from 2 to 20 in order to control the in-plane profile orthogonal to the direction of spokes.

As the freedom of in-plane profile control using spoke trajectory solely comes from the placement and weighting of multiple spokes, it may not be the most efficient trajectory for 3D selective excitations. In some applications, the spoke at the center of k-space has a full length as determined by the desired spatial resolution, while all the other spokes are of half-length to reduce pulse duration. Also a single curved spoke [11] is proposed to twist the spoke in the k_x-k_y direction in order to mitigate in-plane inhomogeneity at high field with simultaneous slice selection. The result shyhhows that using the curved spoke, a more homogeneous excitation pattern has been achieved with some compromise of slice-selection profile. All these indicate the possibility of a more task-efficient variable spokes.

In this work, we studied three modified spoke trajectories: variable-length spoke, tilted spoke, and curved spoke. The performance of the three trajectories are characterized using simulations.

II. METHOD

In this section, the spatial domain RF design method for parallel excitation is introduced first. Then the role of k-space trajectory in the RF design process is discussed, and several kinds of modified spoke trajectories are proposed.

RF pulse design for parallel excitation

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Relationship between RF pulse and corresponding excited magnetization in NMR under time varying main field gradient is defined by the well-known Bloch equation. Because there is no analytical solution, the RF pulse cannot be solved for a specified excitation pattern with given gradient. However, under the small-tip-angle approximation, which assumes that the longitudinal magnetization remains constant, to express the excitation pattern as the Fourier transform of applied RF pulse as shown in Eq.(1).

$$m(\mathbf{x}) = i\gamma m_o \int_0^T b(t) e^{\mathbf{x}\cdot\mathbf{k}(t)} dt \qquad (1)$$

where m is the spatial pattern excited by RF waveform b, γ is the gyromagnetic ratio, m_o is the equilibrium magnetization magnitude, and T is the RF pulse length. The k-space trajectory $\mathbf{k}(t)$ is defined as the time-reversed integration of gradient waveform $\mathbf{k}(t) = -\gamma \int_t^T \mathbf{G}(\tau) d\tau$. Eq. (1) can be easily extended to the case of multiple channels for parallel excitation after incorporating spatial transmit sensitivity B_1^+ of the coils. By discretizing the formula, RF pulse design problem is transformed to an optimization problem:

$$\hat{\mathbf{b}}_{full} = \arg\min_{\mathbf{b}_{full}} \{ \left\|\mathbf{A}_{full}\mathbf{b}_{full} - m_{des}\right\|_{ROI}^2 + \beta\left\|\mathbf{b}_{full}\right\|^2 \} \qquad (2)$$

where $\mathbf{A}$ is the system matrix containing multiple channel transmit sensitivity and all elements in Eq.(1) except for RF pulse b.

As shown in Eq. (1), the excitation can be interpreted as RF power deposition along the specified k-space trajectory. Although the RF pulse is solved from the optimization problem, an improper trajectory may cause excitation artifact or high RF power which is prohibited by the specified absorption rate (SAR) constraint. Thus, it is desired to efficiently design variable trajectories.

Currently, most RF pulse design methods define a k-space trajectory first and then compute RF pulse using Eq. (2). Although some methods that can jointly design the RF pulse and k-space trajectory [9, 12], the k-space trajectory is usually limited to certain forms with a few free parameters to be optimized. So a k-space trajectory is still an interesting and open question. In the following, we explore three types of modified spoke trajectories, as shown in Fig. 1.

Modified spoke design

In the following discussion, the slice selection is assumed to be the z-direction and traditional spokes should be placed along the k_z direction.

I) *Variable length spoke:*

The control of in-plane profile using traditional spoke trajectory mainly comes from the increased number of spokes. However, the high frequency k_z component (high k_z) on spokes at high k_x-k_y may be insufficiently used as the nature energy distribution of 3D k-space. So the length of spokes, which are located further from the k-space center as shown in Fig.1 (a), can be shorter in order to reduce the trajectory length as well as pulse duration.

II) *Tilted quad-spoke*

As the high k_z at the high k_x-k_y may be inefficient as mentioned in previous spoke design, an intuitive idea is to tilt the spokes. By doing so, lower k_x-k_y can be traversed during low k_z as shown in Fig.1 (b). The four tilted spokes are center-symmetric and the slope is the only free parameter in this trajectory.

III) *Curved spoke*

The design motivations of curved spoke are quite straight forward: (1) k_x-k_y components are traversed in low k_z as much as possible to reduce slice selection artifact; (2) the trajectory should be center symmetric; (3) k-space center should be passed to most efficiently deposit RF power. So an amplitude modulated spring shaped curve is defined in Eq. (3).

$$\begin{aligned} k_x &= k_{\max}\sin(2\pi f\cdot t) \\ k_y &= k_{\max}\cos(2\pi f\cdot t),\ t\in[-1,1] \\ k_y &= bw_z\cdot t \end{aligned} \qquad (3)$$

where $k_{\max} = \arctan(\gamma t) * \exp(-t^2/2\sigma^2)$ is the amplitude envelope as shown in Fig.3 (c). The inverse tangent is used to push trajectory to go through k-space center and recover very fast by setting a large γ, and the Gaussian function make the trajectory spend less time at high k_z. So this curved spoke with pair-spin shaped envelope meets the desired properties well. However, there are three free variables in this trajectory definition, the number of turns f, the recovery rate of tangent function γ and the standard deviation of Gaussian function σ. And also before designing the pulse using this trajectory, points on this trajectory need to be rearranged to be equal-distant under maximum gradient and slew rate constraint.

III. SIMULATIONS AND RESULTS

Spoke length of the variable length 9-spoke trajectory is chosen proportional to the amplitude of corresponding Fourier coefficients of the in-plane pattern at the spoke location. The slope of the tilted spoke trajectory is chosen as $bw_z/\Delta k_x$. For the pair-spin enveloped curved spoke, $f = 0.5$, $\gamma = 40$ and $2\sigma = 1/4.7$ (cm^{-1}) have been used. It should be noted that the selection of parameters for different type of modified spokes should be optimized accordingly with analysis of target pattern.

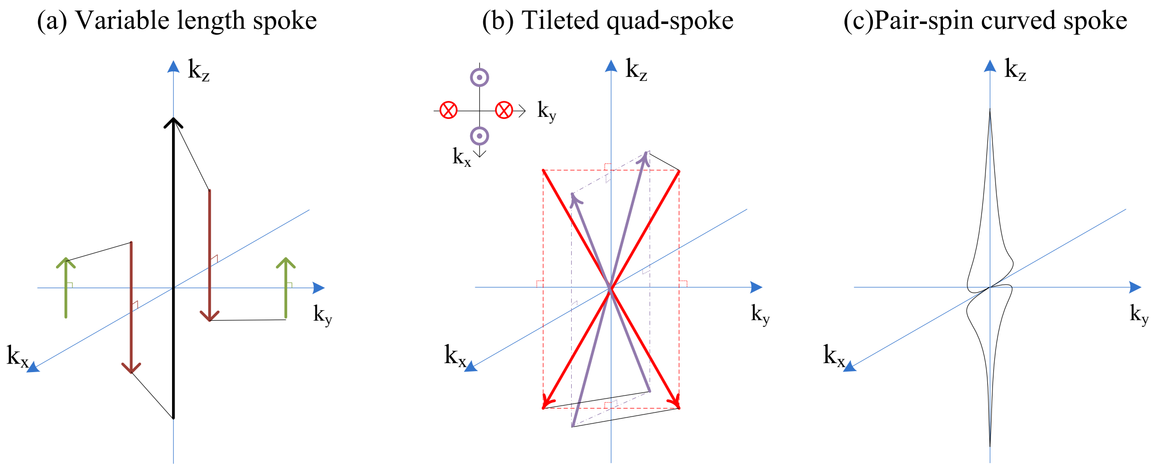

(a) Variable length spoke (b) Tileted quad-spoke (c)Pair-spin curved spoke

Fig.1 Illustrative exhibition of different modified spoke trajectories. The amplitude envelope of the curved spoke is given in (c)

Simulated coil field map was generated using the model of an 16-element array of planar pair coils [13] wrapped to a cylinder surface as shown at the right side of Fig.1 (a). Coil sensitivity of each channel was calculated according to Biot-Savart equation. The desired field of excitation are given as FOX_z= 30 cm, FOX_x = FOX_y = 20 cm. And the desired pattern is a uniform slab of thickness 4.7 cm as shown in Fig.2 (b) and (c). A volume resolution of $32\times32\times32$ (cm^3) is used.

RF pulses are then designed for each trajectory using the spatial domain method. Final 3D excitation pattern (tip angle map) is numerically simulated using a spinor domain representation of the Bloch equation [14]. All simulations are performed using MATLAB (Math Works, MA).

Simulation results with a uniform slab target using three introduced trajectories were given in Fig.3. Two profiles in cross directions of the 3D excited volume was provided to observe the through plane slab sharpness and in plane profile.

As expected, in this case as the target is uniform slab, there's no need for additional in-plane control and traditional spoke or variable length spoke provides the most uniform in-plane pattern with sharp slice edges according to the standard deviation of tip angles in the in-plane profile.

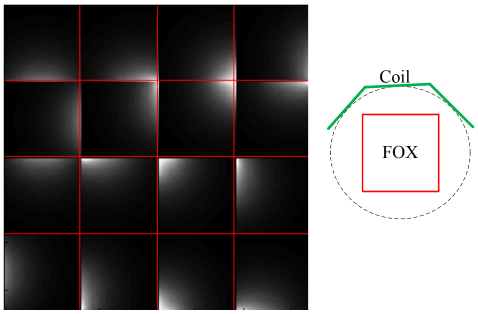
While the results of using a titled spoke and curved spoke are not so good as the traditional spoke. However, the curved spoke is essentially a single spoke and has the advantage of providing shorter pulse duration as provided in Fig.3.

IV. CONCLUSION AND DISCUSSIONS

In this work, we studied three types of modified spoke trajectoris for of 3-D spatial selective RF pulse design in parallel excitations. The preliminary simulations show that all three types of trajectories are capable of achieving 3-D uniform slab pattern and the pulse duration is relatively shorter with curved spoke when in-plane desired pattern is more smoothly varying.

For a more complicated in-plane target, the performance may vary a lot with different choices of spoke parameters and need to be optimized accordingly which is not discussed in this paper and will be part of our future work.

(a) In-plane coil sensitivities of the 16-ch array



(b) Desired slice profile (c)Desired in-plane profile

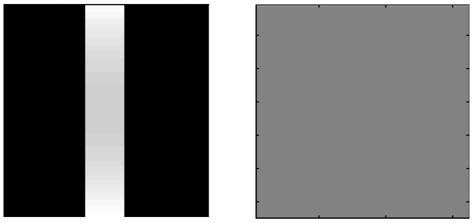


Fig.2 Coil sensitivities and desired pattern

V. ACKNOWLEDGEMENT

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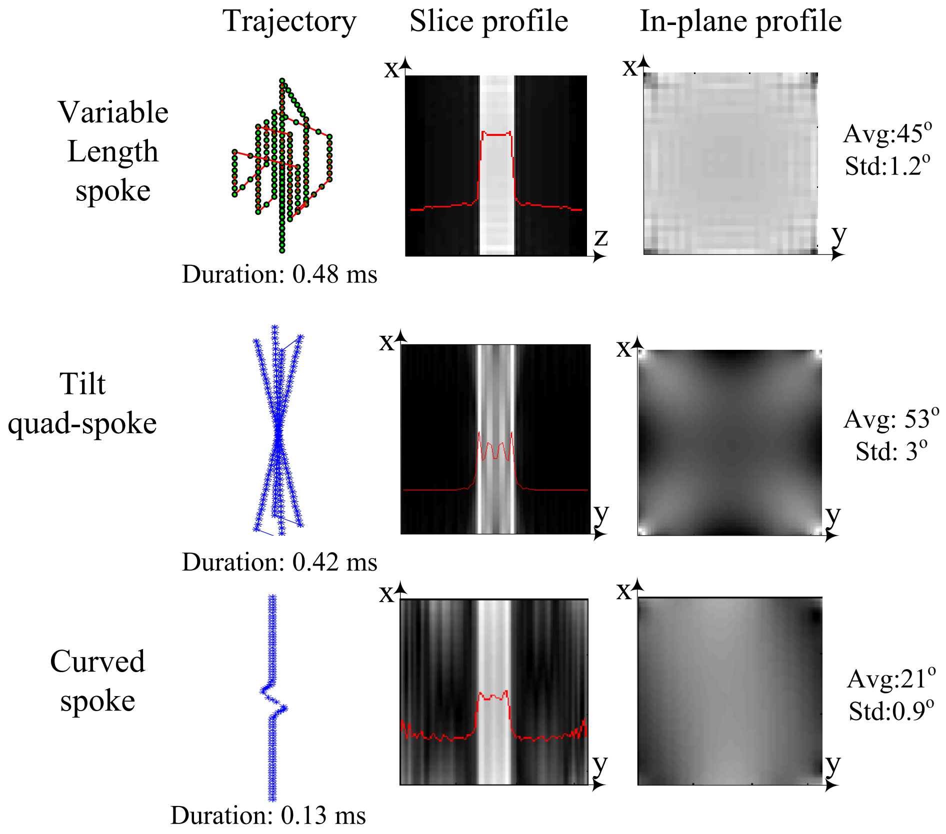

Fig.3 Modified spokes with corresponding excited slice profile and in-plane pattern.