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An Analysis of RF Pulse Apodization in Parallel Spatially Selective Excitation

Yinan Liu and Jim X. Ji
Department of Electrical and Computer Engineering, Texas A&M University

Abstract

This paper presents an analysis of the effect of RF apodization for parallel spatially selective excitation in MRI. Using the small tip-angle approximation and the k-space interpretation, the analysis shows that for multidimensional multi-channel parallel excitation, limited RF pulse duration can lead to ringing excitation artifacts, similar to the truncation artifacts. Proper weighting of RF pulses can significantly reduce these artifacts, which is important for restricting field of excitation with minimal side lobes. Simulation results using a four-channel system in 1-D and 2-D experiments were shown to verify the analysis.

I. INTRODUCTION

Multidimensional spatially selective RF (radio frequency) excitation can produce localized field of excitation (FOX) with designated excitation pattern, which has wide potential applications such as inner volume excitation, B1 field inhomogeneity correction, localized spectroscopy, and reducing susceptibility artifacts [1-4]. In using this technique, long RF pulses are needed to obtain high spatial definition of the excitation pattern which is jointly determined by the k-space trajectory traversed using gradient waveforms and the RF pulses. The long pulse duration not only reduces scan efficiency, but also lowers excitation performance due to the T2* effect.

Recently, parallel excitation has been proposed to shorten the RF pulse duration using a set of transmit array coils. This method, termed Transmit SENSE, in analogy to SENSE parallel acquisition imaging, utilizes the localized transmit sensitivity to allow the k-space be covered with increased gaps to achieve the desirable excitation pattern without aliasing [5,6]. To do so, the gradient waveform accompanying the RF pulse traverses a subsampled k-space trajectory. The use of multiple transmit coils, each driven by independent waveform, can compensate for the aliasing caused by subsampling the excitation k-space.

Nevertheless, in practice for both single-channel and multi-channel excitation, the RF pulse must be apodized, i.e., truncated in time, as the pulse derived from the desirable pattern usually has infinite time support. The discrete nature of RF pulse along the k-space trajectory implies aliasing lobes, i.e., the well-known Gibb's ringing,. In 1D case, it can lead to undesirable slice cross talk. Many optimal slice excitation methods have been proposed to apodize the RF pulse, which can improve the slice profile and minimizes this ringing effect [7-9]. In multidimensional excitation, particularly with parallel multi-channel transmit excitation, there is no rigorous analysis of the effects due to the RF apodization. Such analysis is critical for designing new method to alleviate or reduce the possible undesired effect.

In the following sections, we present an analysis of the RF weighting and apodization effects for parallel spatially selective excitation. Using the small tip-angle approximation and the k-space interpretation, the analysis shows that for spatially selective excitation using parallel transmit coils, RF truncation also lead to "ringing" artifacts, similar to the truncation artifacts. Proper apodization of RF pulses can significantly reduce these artifacts, which is important for restricting FOX with minimal side lobes. Simulation results using a four-channel system in 1-D and 2-D experiments were used to assist the analysis.

II. THEORY

Multidimensional spatially selective excitation

Base on the small-tip excitation approximation, Pauly showed that the transverse magnetization generated by a selective excitation pulse at the final magnetization time *T*, can be expressed as [1]

$$M(\mathrm{x}) = i\gamma M_o \int_0^T B_1(t) e^{i\mathrm{x}\times\mathrm{k}(t)} dt \qquad (1)$$

where γ denotes the gyro-magnetic ratio, M_o the equilibrium magnetization, and $B_1(t)$ the complex RF envelop. The vector $\mathrm{k}(t)$ describes the k-space trajectory defined by

$$\mathrm{k}(t) = -\gamma \int_t^T \mathrm{G}(\tau) d\tau \qquad (2)$$

If the trajectory does not cross itself, the time-dependent function $B_1(t)$ can be expressed in k-space as $\tilde{B}_1(k)\tilde{W}(k)$, where $\tilde{W}(\mathrm{k}) = \frac{\tilde{S}(\mathrm{k})}{\left|\gamma \tilde{G}(\mathrm{k})\right|}$

with $\tilde{S}(\mathrm{k})$ being the k-space sampling function which determines both the area and density of the k-space representation. Thus, Eq. (1) becomes

$$M(\mathrm{x}) = i\gamma M_o \int_{k\in trajectory} \tilde{B}_1(\mathrm{k})\tilde{W}(\mathrm{k}) e^{i\mathrm{xk}} d\mathrm{k} \qquad (3)$$

Equation (3) shows that the excitation profile M is the

Fourier transform of the weighted RF pulse along the k-space trajectory. After discretization, Eq. (3) becomes

$$M\left(\mathrm{x}_p\right)=i\gamma M_o\sum_q \tilde{B}_1\left(\mathrm{k}_q\right)\tilde{W}\left(\mathrm{k}_q\right)\exp\left(i\mathrm{x}_p\mathrm{k}_q\right)\Delta\mathrm{k} \qquad (4)$$

where x_p and k_q represent the sampling grids in the spatial and k-space domain, respectively.

Truncation effect on a single coil excitation

From Eq.(3-4), it is clear that the RF pulse, as well as the k-space trajectory, must be finite in time duration in practice. This is equivalent to applying a time window $\tilde{h}\left(\mathrm{k}(t)\right)$, which has finite time support and constant unit amplitude. This can be generalized to arbitrary apodization window, which gives the weighting $\tilde{h}\left(\mathrm{k}_q\right)$. According to Fourier transform property, multiplying in the k-space domain results in a circular convolution in spatial domain. In matrix form, the convolution can be approximated as

$$M_{trun}=H\cdot M \qquad (5)$$

where H is a circular convolution "blurring" matrix. Equations (6) show that in single coil case, apodization of RF pulse, i.e., truncation in k-space, will result in convolution of the ideal slice excitation profile with a kernel in spatial domain, as shown in previous literature [10].

Truncation effect in multi-channel parallel excitation

Transmit SENSE is a recently proposed parallel transmission method, where the spatially selective RF pulse is applied using array coils driven by independent RF channels. In analogy to parallel reception, the channel sensitivities provide a localization effect complementary to those induced by gradient waveform. This makes it possible to use a undersampled k-space trajectory, which in turn reduces the duration of the RF pulses [5]. Let L be the number of transmit coils with known, arbitrary, complex sensitivity profiles S_l , $l=1,2,...,L$, each having a excitation profile M_l within the FOX. The ideal total excitation pattern M_{tot} can be expressed as

$$M_{tot}=\sum_{l=1}^{R}S_l M_l \qquad (6)$$

where S_l is a $N\times N$ diagonal matrix with the sensitivity value for each spatial location as the diagonal elements. N is the length of the profile.

Taking the truncation effect into consideration， M_l should be substituted by M_{trun} in Eq (5) and the excitation profile becomes:

$$M_{tot}=\sum_{l=1}^{L}diag\left\{S_l\right\}\cdot\left(H\cdot M_l\right) \qquad (7)$$

In transmit SENSE, the k-space trajectory is under-sampled by a factor of *R*. That is to say, the excitation profile from the *l*-th coil will be aliased

$$M_{alias,l}=U\cdot M_{trun,l} \qquad (8)$$

where U is the aliasing matrix. With this aliasing, the acquired excitation pattern based on Eq. (7) is

$$M_{tot}=\sum_{l=1}^{L}diag\left\{S_l\right\}\cdot M_{alias,l} \qquad (9)$$

Substituting (6) and (9) into (10), we get

$$M_{tot}=\sum_{l=1}^{L}diag\left\{S_l\right\}\cdot U\cdot(H\cdot M_l) \qquad (10)$$

Equation (10) indicates that the desired excitation pattern of each channel will be convolved with a "non-ideal" kernel, which corresponds to the Fourier transform of the truncation function, producing "side lobes". The resulting pattern with side lobes will be aliased, then weighted by the transmit sensitivity. With this insight, it is clear that it may be desirable to apply an appropriate apodization function (rather than rectangular function as the simple truncation case) to minimize the undesirable artifacts.

This is particularly important for fast imaging application because outer-FOX side lobes will be aliased to FOV causing artifacts. This is a tradeoff between side lobe suppression and transition width. Apodization may lead to wider transition in edges of excitation patterns, although it may significantly reduce outer-FOX side lobes.

III. Computer Simulations

In this section, computer simulations are presented to verify the analysis in the previous section.

Phantom design

One-dimensional and two-dimensional excitation pattern as shown in Fig 1 were used in the simulation.

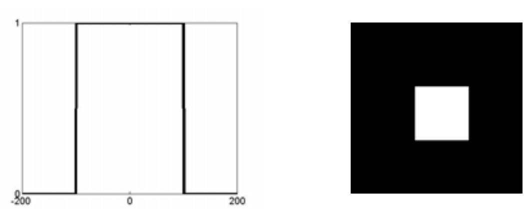

Fig 1. (left) 1D excitation pattern with 4-cm-wide pattern in a FOX of 8 cm; (right) 2D excitation pattern of the size of 3 cm in a FOX of 10-cm.

One-dimensional parallel excitation with 4-coils

The RF pulses for each coil were computed according to the image domain solution described by Katscher in [5] with a reduction factor R = 2. The sensitivity maps are shown in Fig 2. In excitation pattern was computed using a Bloch Simulator with small angle approximation. The parameters used in simulation are: gradient G = 100 Gauss/cm, pulse duration 2 ms, total sinc side lobes 4, time step size 1/128 ms, spatial points 256 within a FOV of 8 cm.

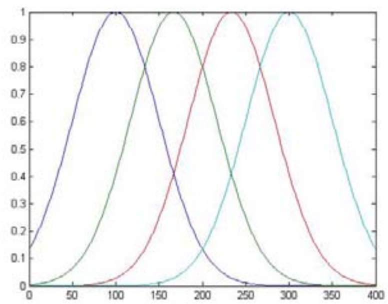

Fig 2. Simulated Gaussin sensitivity maps of the 4 transmit coils. All channels are assumed to have zero phases, free of noise. The variation of the Gaussin window is 1/8 of the FOX.

Then the "ideal" RF pulses were truncated with two apodization windows, rectangular and Hamming windows, to keep 1/4 central portion. The actual excited profile was computed according to equation (11). There are significant ringings in the excitation pattern when the rectangular window was used, as shown in Fig. 3 (a). With the Hamming apodization function, the ringing artifacts were well suppressed, although the FOX edges were slightly blurred.

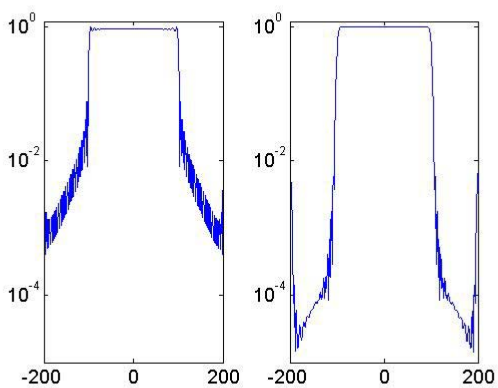

Fig 3. Truncation effect on a 1D rectangular profile excited using 4 parallel transmit coils: (left) with a rectangular apodization function; (right) with a hamming apodizaiton function.

Two-dimensional parallel excitation with multiple coils

In this experiment, we simulated a 4-channel linear phased array with complex sensitivity maps as in Fig 4.

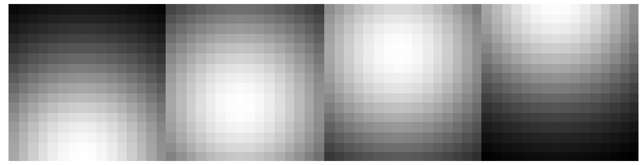

Fig 4. Simulated sensitivity maps (magnitude) for linear phased array with 2D Gaussian profiles. Sensitivity phase was assumed to be zero.

A spiral trajectory with time-bandwidth product of 4 was used. The spiral k-space trajectory was sub-sampled in the radius direction, effectively reducing the RF pulse time by a factor of R=2. The apodization window shown in Fig 5 was applied to weigh the RF pulse. As the spiral starts from outer k-space and ends in the center of the k-space, this is effectively a symmetric Gaussian weighting centered at the k-space center.

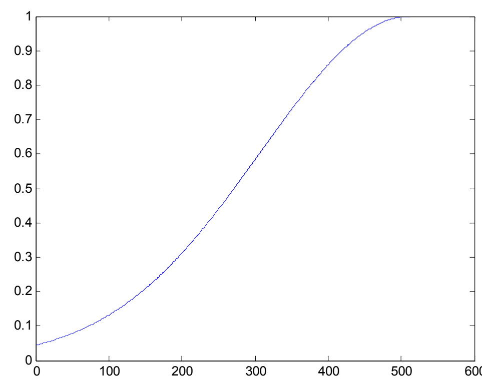

Fig 5. Hanning apodization window for 2D spatially selective excitation. Note that the horizontal index represents the time-sequential discretized k-space trajectory points.

Figure 6 shows the excitation patterns produced using a Bloch simulator, for both rectangular window and Gaussian window. The parameters used in simulation are: gradient G = 100 Gauss/cm, pulse duration 2 ms, time step size 1/128 ms, spatial points 16x16 within the FOV. Clearly, the excitation profile looked more homogeneous within the ROI, since the apodization significantly reduced the ringing artifacts, although the spatial resolution was reduced.

The fluctuations, i.e., standard deviation, within the square in the center were calculated and shown in the following table. The Gaussian apodization improved the homogeneity within the area, though the edges are less sharp.

without apodization	with Gaussian apodization
0.1268	0.1155

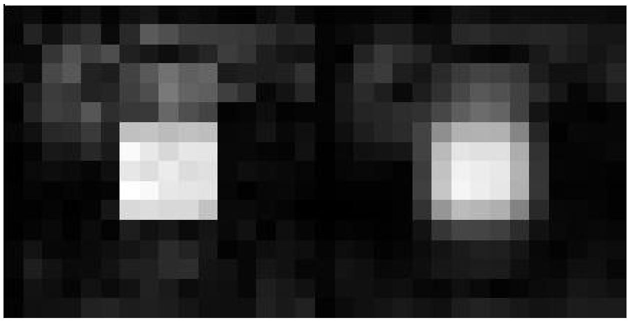

Fig 6. Truncation effect on a 2D excitation profile with the 4-channel transmit coils: (Left) truncated with rectangular window; (Right) truncated with Gaussion apodization shown in Fig. 5.

IV. DISCUSSION

In this study, we analyzed and demonstrated the truncation effects of spatially selective multidimensional RF pulses in parallel transmission. The analysis shows that truncation artifacts exist due to the convolution of the desired excitation pattern with apodization window spectrum. By applying proper apodization windows, the side lobes could be suppressed. An important insight is that for parallel excitation such as transmit SENSE, using appropriate apodization in addition to k-space trajectory weighting can significantly lower side lobes. This is critical for application relying on limiting FOX but not exact resolution of excitation pattern. For example, in fast imaging applications with limited FOX, it is not important to have very sharp transition from excitation to unexcited regions. Rather, it is desirable to have better inhomogeneity in the excited regions and suppression of the side lobes. For certain symmetric excitation patterns (rectangular, circular, oval shaped patterns), there exist equiripple 2D apodization filters, which gives optimal side-lobe suppression and homogeneous excitation patterns. Interestingly, this may be integrated for the design of large-tip-angle parallel excitation. Both issues will be explored in future research.

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