A Spatial-Spectral Pulse Approach for Reduced FOV Excitation Using Second-Order Gradients

C. Ma[1], K. F. King[2], D. Xu[2], and Z-P. Liang[1]
[1]Electrical and Computer Engineering, University of Illinois, Urbana, Illinois, United States, [2]Global Applied Science Lab, General Electric Healthcare, Waukesha, Wisconsin, United States

INTRODUCTION: Spatially selective excitation finds wide applications in MR imaging/spectroscopy experiments. One popular example is slice selective excitation, which is often achieved using constant gradients and frequency-selective RF pulses. Multidimensional, spatially selective excitations can also be achieved using time-varying gradients and frequency-selective RF pulses [1-2]. However, to ensure sufficient coverage of excitation *k*-space, the RF pulses may be impractically long. Recent efforts to address this problem include the use of multiple RF transmit coils for parallel excitation [3-4]. This work investigates the use of high-order gradients for multidimensional, selective excitation. This work is complementary to the existing work on using nonlinear gradients for RF pulse design and for encoding in imaging [5-9].

METHOD: In source-free regions, magnetostatic fields are governed by Laplace's equation and can be decomposed as linear combinations of spherical harmonics (referred to as gradients) [10]. A zero-order gradient is a uniform field, and first-order gradients are linear gradients. In MRI, higher order gradients are usually available through shimming coils. For instance, the second-order gradients vary as $f = (\gamma/2\pi)\ [G_{Z2}(z^2-(x^2+y^2)/2)+G_{X2-Y2}(x^2-y^2)+G_{XY}\,xy+\ G_{YZ}\,yz\ +G_{XZ}\,xz]$, where G_{Z2}, G_{X2-Y2}, G_{XY}, G_{YZ}, and G_{XZ} are control variables. Note that a pure x^2+y^2 term does not exist since it does not satisfy Laplace's equation. Different from a linear gradient, a high-order gradient changes the resonance frequency nonlinearly in more than one spatial direction. Therefore, multidimensional, spatial selectivity can be achieved by a 1D frequency-selective RF pulse along with constant high-order gradients.

In this work, we focus on using second-order gradients and spatial-spectral pulses to excite a thin disk for reduced FOV imaging. We first illustrate the basic idea through a simple example. Suppose the target disk has a radius R and a thickness d (*i.e.* $|M_{xy}(x,y,z)|=1$, if $x^2+y^2 \leq R^2, |z| \leq d$; 0, otherwise). Conventional excitation approach would use multidimensional pulses with time-varying linear gradients to cover 3D excitation *k*-space (*e.g.* along a spoke trajectory), which could lead to a long pulse. In the proposed method, we adopt a spatial-spectral pulse approach to excite the disk in the presence of a constant second-order gradient (G_{Z2}). The spatial-spectral pulse is selective in two dimensions, *i.e.* selecting a thin slice in the slice-selection direction, z, and having a bandpass frequency response in the frequency direction, f. The corresponding 2D excitation *k*-space is covered by an oscillating linear gradient, G_z (k_z), and the constant second-order gradient G_{Z2} (k_f). In the selected slice ($|z| \leq d$), the resonance frequency offset is a function of the distance to the origin: $f=-(\gamma/4\pi)G_{Z2}r^2$, $r=(x^2+y^2)^{1/2}$, which holds well as along as the slice is a thin slice. As a result, the frequency selectivity of the spatial-spectral pulse is translated into the spatial selectivity in the radial direction, *i.e.* a bandpass frequency response results in a circular excitation region.

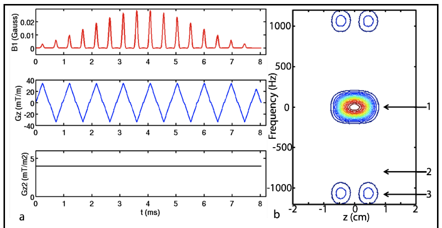

Fig. 1: a) Spatial-spectral pulse. b) Contour plot of the resulting excitation magnetization. The main peak **1** is centered at f=0 Hz. The maximum resonance frequency offset in the slice plane **2** is located at f=-852 Hz. The first replicate **3** is centered at f=-1075 Hz.

In the design process, one needs to specify a constant second-order gradient (G_{Z2}) and a spatial-spectral pulse (Fig 1a.) The RF waveform is in the form of $b_1(t)=b_{\text{spec}}(t)b_{\text{spat}}(t)$, where $b_{\text{spec}}(t)$ is a minimum-phase SLR pulse that defines a bandpass spectral response, and $b_{\text{spat}}(t)$ is a chain of subpulses that define spatial selectivity [1]. The design process includes three sequential steps: 1) the oscillating gradient waveform of period T and the subpulse of $b_{\text{spat}}(t)$ are designed to satisfy the slice selection requirement; 2) since the magnetization response to a spatial-spectral pulse has a main peak at f=0 and periodic replicates at $f=\pm n/T$, $n=1,2,\cdots$ [11], the magnitude G_{Z2} is chosen such that no excitation replicate would appear in the imaging object; 3) a minimum-phase SLR pulse $b_{\text{spec}}(t)$ of bandwidth $(\gamma/2\pi)G_{Z2}R^2$ and length $N\times T$ (resulting an oscillating linear gradient waveform of N periods) is designed. More generally, it can be shown that arbitrary thin elliptical disks at arbitrary locations can be achieved with an appropriate combination of zero-, first- and second-order gradients. The proposed method can also be easily extended to the case of using time-varying second-order gradients (if available), where common multidimensional RF pulses [2] need to be designed instead of spatial-spectral RF pulses.

RESULTS: The proposed method was used to design an RF pulse (shown in Fig. 1a) that excited a thin disk of 4 cm radius and 0.9 cm thickness in a cylinder phantom of 10 cm radius with a 30° flip angle (shown in Fig. 2a). The slice gradient waveform was an oscillating triangle waveform of 8 periods, resulting in a 7.9 ms RF pulse. With G_{Z2}=4 mT/m^2, the bandwidth of the desired spectral response was 273 Hz. For comparison, a spoke trajectory based RF pulse of the same length was designed using a recently proposed method [12] that jointly designs the RF pulse and spoke locations. Bloch equation simulation was used to calculate the resulting magnetization for the designed RF pulses. Compared to the spoke trajectory based RF pulse (Fig. 2c), the proposed method (Fig. 2d) produced much smaller excitation outside the desired excitation region, which is more desirable for reduced FOV imaging. The difference can be better appreciated in the excitation profile plot (Fig. 2b), where the proposed method produced a more accurate profile with much sharper transition and smaller side lobes.

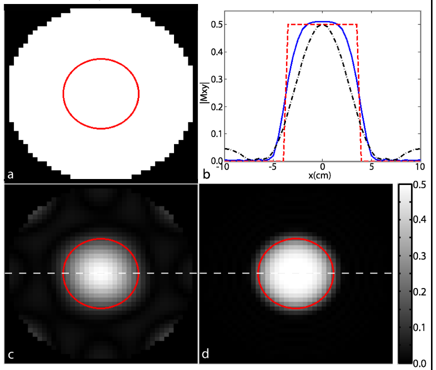

Fig. 2: a) The desired excitation pattern (indicated by a red circle) in the slice plane. c) $|M_{xy}|$ by the spoke trajectory based RF pulse. d) $|M_{xy}|$ by the proposed RF pulse. b) The excitation profiles along the dashed lines: red dashed line: the desired profile; blue solid line: the proposed method; black dash-doted line: the spoke trajectory based RF pulse.

CONCLUSION: This paper presents a method to design RF pulses for reduced FOV excitation using second-order gradients and spatial-spectral pulses. The benefits lie in the fact that using second-order gradients, a 2D spatial-spectral pulse can be used to excite a thin disk (a 3D pattern). This dimension reduction leads to significantly improved excitation accuracy (for a given RF pulse length) and/or much shorter pulses compared to conventional 3D multidimensional RF pulses.

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