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Multidimensional excitation pulses based on spatiotemporal encoding concepts

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ABSTRACT

The understanding and control of spin dynamics play a fundamental role in modern NMR imaging, for devising new ways to monitor an object's density as well as for enabling the tailored excitation of spins in space. It has recently been shown that by relying on spatiotemporal encoding (SPEN), new forms of single-scan multidimensional NMR spectroscopy and imaging become feasible. The present study extends those imaging developments, by introducing a new class of multidimensional excitation pulses that relies on SPEN concepts. We focus in particular on a family of "hybrid" 2D radiofrequency (RF) pulses that operate in both direct and reciprocal excitation space, and which can spatially sculpt the spin magnetization in manners that are beyond the reach of sequential 1D pulse shaping. These SPEN-based 2D pulses are compatible with a majority of single- and multi-scan imaging techniques. Like the corresponding SPEN-based hybrid 2D acquisitions, these pulses can benefit from a high robustness against field inhomogeneities and/or offset effects that affect their *k*-space-based counterparts. These properties are analyzed, and illustrated with numerical simulations and model experiments.

1. Introduction

Selective pulses play numerous roles in nuclear magnetic resonance (NMR). In spectroscopy they help simplify the information content and can increase sensitivity [1,2]. In NMR imaging (MRI) they are widely used to limit the extent of the spatial region from which the observed NMR signals originate [3]; for similar reasons they are integral component of spatially localized *in vivo* spectroscopic measurements [4]. All such experiments usually seek to delineate a slice or a voxel in space, and utilize for this selective RF pulses applied in the presence of magnetic field gradients. Each pulse will then address selectively a slab within the sample, leading to slice-, line- or cube-shaped spatial excitations. In many instances, however, more complex 2D or 3D regions of interest (ROIs) are sought. These may attempt targeting the shape of a particular organ [5–7], exciting selected chemical components with a pre-defined spatial location within the sample [8,9], or endowing complex geometries with pre-set excitation phases that compensate for magnetic field inhomogeneities [10–12]. Such multidimensional spatial or spectral–spatial selectivity often requires more sophisticated strategies than what can be achieved within the context of simple 1D frequency-selective pulses; they call for the use of so-called multidimensional RF schemes [13–15].

An essential component in the design of frequency-selective pulses in one or more dimensions is the Fourier relationship that, in the limit of small excitation angles, relates a time-dependent B_1 field with the spectral distribution excited as a function of frequency [2]. Walks in reciprocal spaces enable an extension of this and other classic RF selectivity concepts, from one to multiple dimensions. These "excitation *k*-spaces" [14] provide a unified description relating the shape of the RF waveform as a function of time, with the properties that can be excited from the spins along *n* spatial dimensions. Most modern multidimensional pulse-design approaches build upon this excitation *k*-space [16,17], and its associated Fourier properties. Also built around Fourier-based *k*-space concepts is the contemporary explanation of a majority of MRI experiments [18,19]. Walks through *k*-space, for instance, underlie the operation of echo-planar imaging (EPI) approaches capable of delivering multidimensional spatial profiles in a single-scan. Although a majority of single-scan MRI experiments exploit such *k*-space concepts to define the features that will characterize the image being sought [3], a number of alternatives to EPI exist in ultrafast multidimensional MRI [20–25]. Owing to their ability to probe the spin response throughout a multidimensional space in a single scan, these alternatives might also constitute a basis for the design of multidimensional spatial or spatial/spectral excitation pulses. One such non-EPI scanning method, dubbed spatiotemporal encoding (SPEN), relies on measuring the NMR signal in "direct" rather than in reciprocal space. SPEN

Abbreviations: EPI, echo-planar imaging; SPEN, spatiotemporal encoding; RF, radio-frequency; ROI, region of interest; FT, Fourier transform; RO, readout; SS, slice selection; PE, phase encoding.

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operates by generating a spin response that at any given instant throughout the signal acquisition carries only contributions from a very localized region of the sample. This approach has been shown to benefit from robustness against the effect of undesirable frequency offsets – arising, for example, from chemical shifts or magnetic susceptibility differences [26].

In this article, we demonstrate that spatiotemporal-encoding concepts can lead to a novel class of multidimensional pulses, the operation of which is distinct from that of *k*-space-based pulses. This demonstration proceeds in two stages. We begin with a description of how a spatiotemporal, sequential excitation of arbitrary 1D spin profiles can be imparted in both continuous and discrete manners. We then consider 2D analyses focusing on a number of options, and in particular on a "hybrid" 2D approach whereby spins are excited along one spatial dimension based on discretized SPEN concepts and along an orthogonal dimension based on standard *k*-space approaches. Both calculations and experiments demonstrate that the ensuing pulses, which can be seen as operating in both direct and reciprocal spaces, are compatible with SPEN-based as well as with conventional *k*-space-based NMR imaging. In the latter, more usual case, attention is placed on a self-unfolding property of these new pulses that endows them with a high robustness against field inhomogeneities and/or chemical shift offsets.

2. Theory

2.1. RF spatial sculpting using SPEN concepts in one dimension

NMR imparts 1D spatial selectivity by applying a shaped RF waveform in unison with an external magnetic field gradient. In typical excitation schemes RF pulses address all the frequency elements within a targeted ROI simultaneously; in SPEN-oriented excitation pulses, spins across the sample will be addressed sequentially by the combined action of the magnetic field gradient and of a frequency-swept RF. In the simplest description of these

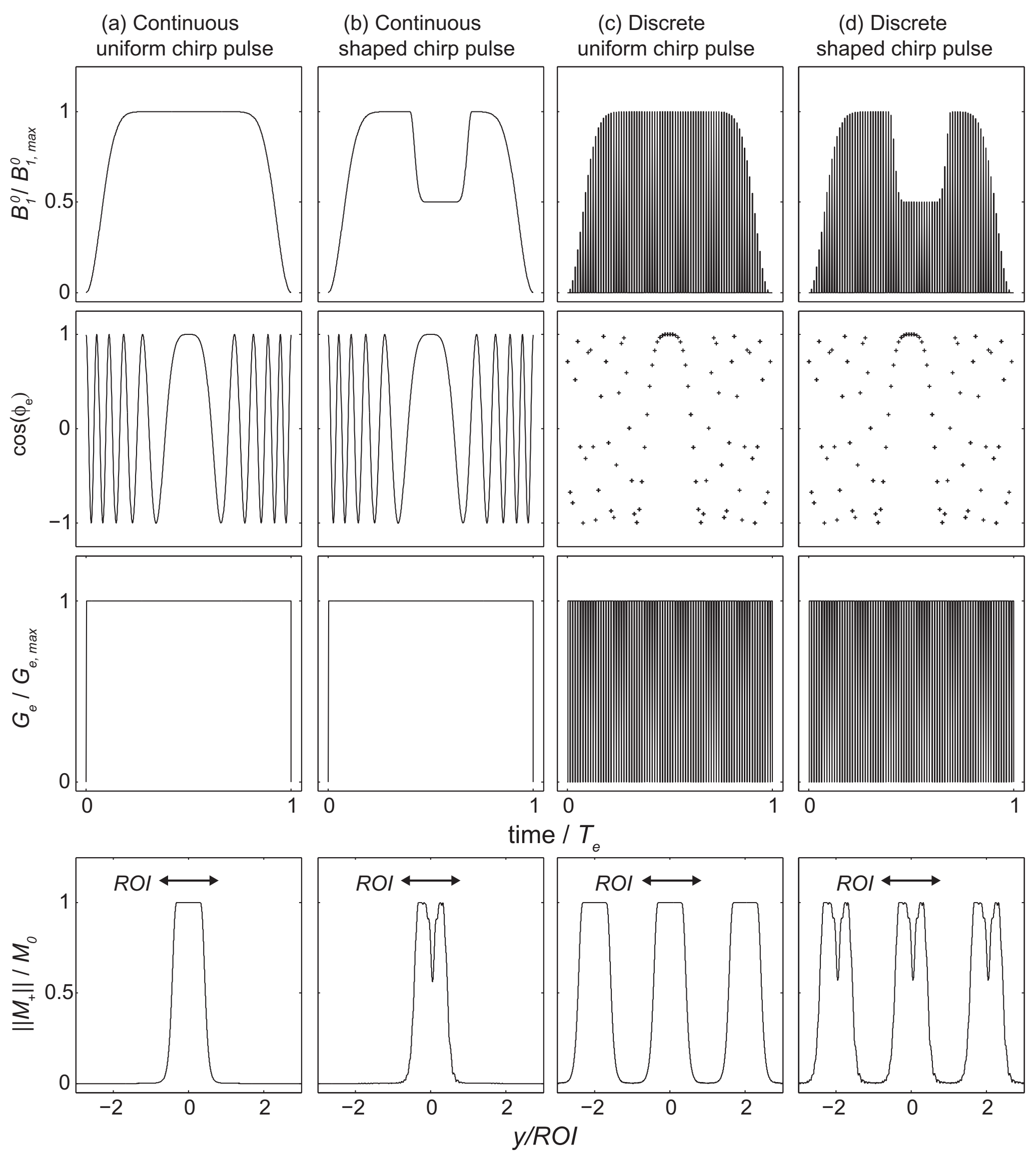

Fig. 1. One-dimensional excitation in direct space using a linearly frequency-swept pulse. Examples are given for a region of interest of length ROI, indicated by a double arrow, and of uniform (a and c) or shaped (b and d) amplitude, excited using either a continuous (a and b) or a discretized (c and d) pulse. In each case, the RF amplitude, the RF phase and the gradient amplitude are shown in the first, second and third row respectively. The magnitudes of the transverse magnetization at the end of the pulse, calculated using Bloch simulations, are shown in the fourth row. The time-bandwidth product of the pulses are $Q = 40$ for all cases; the discretized pulses use $N_e = 80$ steps, resulting in the excitation of periodic sidebands with a replication length of (N_e/Q)ROI = 2ROI.