Direct Design of 2D Pulses using Matrix Inversion

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Introduction

Multi-dimensional RF pulses are used in special applications like targeted excitation or spectrally-spatially selective excitation [1,2]. A recent application is metabolic imaging of hyperpolarised 13C compounds, where a single metabolite is excited spectrally selective in a single slice, and subsequently sampled with a single-shot imaging readout such as EPI or spirals [3,4]. Commonly, spectral-spatial pulses are designed in a so-called separable design, by first choosing a suitable gradient trajectory, and designing a 1D spectral and a 1D spatial filter function and finally combining this into the actual 2D pulse, possibly using a correction function [3]. In this work, we introduce a simple 2D pulse design by direct matrix inversion, which helps to reduce sideband artefacts. Exemplary spectral-spatial pulses as well as 2D pulses with a quadratic phase are designed which can be used for efficient CSI encoding using SPEN [5].

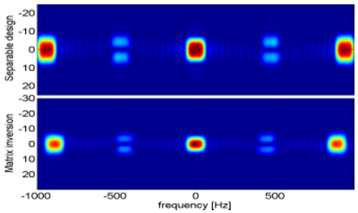

Fig. 4: Comparison between separable design (top) and direct 2D design (bottom).

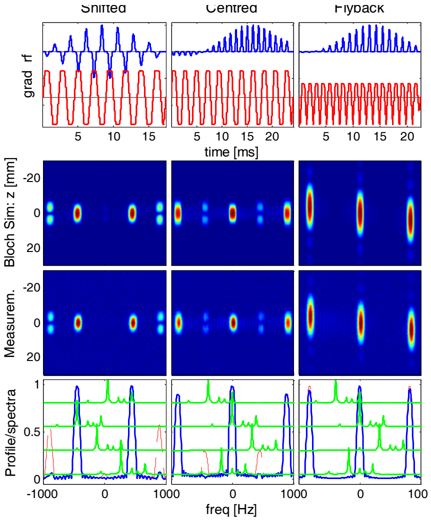

Fig. 1: SPSP pulse (top), its 2D profile simulated and measured and its profile (maximum or cross-section) in combination with the Pyr spectrum (bottom). Minimum slice thickness on 13C were 8mm, 8mm and 14mm, for shifted, centred and fly-back pulses, respectively (g_{max}=40mT/m, s_{max}=150T/m/s).

Methods

The direct 2D RF pulse design follows the following steps. First, a suitable gradient trajectory is designed, constrained by maximum gradient strength, slewrate and (for Cartesian trajectories) number and duration of sub-lobes. The latter determines time-bandwidth products in both domains and also the position of side-lobes stemming from the coarse discretisation along the spectral dimension. Then the according k-space trajectory is calculated by integrating the gradient trajectory and for the spectral dimension taking the reversed time. The 2D target profile b_m is chosen with the given time-bandwidth products and the desired fractional transition widths. The profile is discretised, leading with the small-tip-angle approximation to the following RF encoding matrix: $A_{m,n} = \exp(-2\pi i(f_{1,m}k_{1,n} + f_{2,m}k_{2,n}))$, where $f_{1,m}$ and $f_{2,m}$ denote the discrete frequencies along the two dimensions. To determine the actual RF pulse coefficients ρ, the following equation has to be inverted: $A\rho = b$. In this work, it is solved in a linear least squares sense by computing $\rho = (A^TA)^{-1}(A^Tb)$. This typically takes ≤ 1 min on a current computer.

Results and Discussion

Three spectral-spatial pulses with different properties were designed. The left pulse in Fig. 1 has its main excitation lobe shifted to the first side lobe, hence yielding a large and clean stopband. This middle pulse in Fig. 1 has a centred main lobe with bi-directional and the right one with flyback gradient modulation. All pulses are optimised for [1-13C]pyruvate and its downstream metabolites, and are suitable for exciting all four resonances selectively with minimal contamination from the other peaks. As shown in Fig. 3, the k-space for spectral-spatial pulses is not fully Cartesian, hence leading to additional errors in the separable design. For the left pulse, the target profile was shifted to the location of the first sidelobe artefact, which enables a high suppression at zero frequency. This effect is similar to inverting every other lobe in the separable design [6], however achieving higher suppression levels at zero frequency due to full consideration of the non-equidistant k-space (Fig. 3). The regular centred pulse (Fig. 1 middle) also enables higher suppression of the N/2 artefact (see Fig 4 for a comparison to a pulsed from a separable design). For the pulse with the fly-back gradient trajectory, it is possible to completely eliminate the artefact with the 2D design approach due to equidistant k-space sampling (Fig. 3).

Another class of 2D pulses are shown in Fig. 2. On the left is a 2D spatial pulse with Cartesian k-space sampling and a quadratic phase overlaid to the horizontal direction. On the right is a 2D spatial pulse designed with a spiral gradient trajectory and a quadratic phase along both spatial dimensions. The amount of quadratic phase was chosen according to Eq. 19 in [7]. Possible application for this kind of pulses is spatio-temporal encoding (SPEN) [5], where the spins are excited spatially subsequently with a frequency sweep; the spectral information can be extracted from the phase information. The SPEN encoding used in [5] uses a slice-selective excitation and a quadratic-phase (i.e. frequency swept) inversion, which can be combined to a single pulse, as shown in Fig. 2 (left). In combination with a spiral gradient trajectory, this could enable even faster CSI encoding.

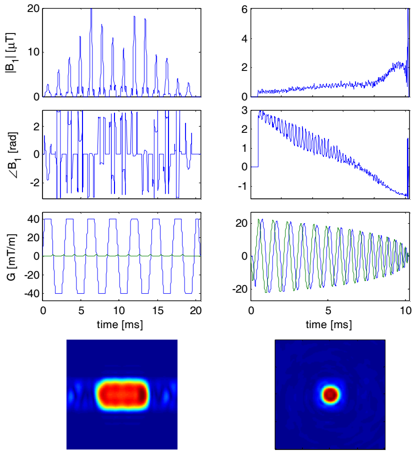

Fig. 2: 2D spatial pulses with an overlaid quadratic phase, left with a Cartesian and right with a spiral gradient trajectory.

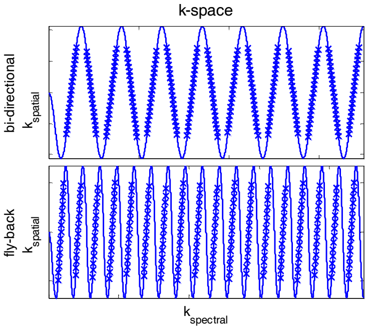

Fig. 3: k-space for spectral-spatial pulses with bi-directional gradients (top), which are more sampling efficient, but lead to a zig-zag curve k-space, and thus pronounced, intermediated sidelobes. Fly-back (bottom) gradients are more robust towards gradient delay artefacts. The k-space is skewed, but still equidistant. Hence, it is possible with direct 2D design to completely eliminate the first sidelobe.

References

[1]Pauly J, et al.JMR81,43(1989).
[2]Meyer CH, et al. MRM15,287(1990).
[3]Cunningham CH, et al. JMR193,139(2008).
[4]Schulte RF, et al. MRM early view(2012).
[5]Ben-Eliezer N, et al. NMRB10,1191(2011).
[6]Zur Y, et al. MRM43,410(2000).
[7]Schulte RF, et al. JMR166,111(2004).

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