Complex Multiband Spectral-Spatial RF Pulse Design for Hyperpolarized C-13 Applications

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Introduction: Spectral-spatial RF pulse design is challenged by requirements of high spectral bandwidth, sharp spatial profiles, short excitation times and peak B_1 constraints. These design issues are especially prevalent when designing pulses for ^{13}C metabolites that have significant spectral dispersion and gyromagnetic ratio ¼ that of protons[1,2]. An approach for spectral-spatial RF design that addresses these issues in a systematic manner has been previously developed[3,4], and is extended here to support complex spectral phase profiles. We also demonstrate that allowing the excitation phase to vary between different spectral bands can result in peak B_1 reduction.

Methods: The spectral-spatial design begins as illustrated in Fig. 3b with the spectral profile specification. This profile includes only the bands of interest, and does not specify the response elsewhere. The minimum-time gradient lobes that meet the specified spatial time-bandwidth requirements subject to system constraints are first designed, thus determining the maximum spectral sampling frequency F_{max}.

Spectral sampling frequencies F_s in the range of 0 to F_{max}, are then evaluated to determine those which do not result in an aliasing of the spectral specifications that would be inconsistent (e.g. different amplitude or ripple). For each feasible sampling frequency F_s, gradient sublobes with the corresponding duration are redesigned.

A minimum-time complex-coefficient filter that meets the spectral requirements for each F_s is then determined using an FIR filter design method based on convex optimization and spectral factorization[5]. The advantage of the convex optimization approach over a complex Parks-McClellan multiband design is that the power in the transition bands can be explicitly minimized, thereby reducing the power of the RF pulse. This method has been further extended here to permit a complex band specification as shown in Fig. 1a: $(a\text{-}d) \le |H(f)| \le (a+d)$, and $(\theta\text{-}d\theta) \le H(f) \le (\theta+d\theta)$ using the piecewise linear constraints as shown. In addition the transition band behavior can likewise be limited to $|H(f)| \le 1$ as in Fig. 1b. In practice, we choose linear constraints tangent to the unit circle at $\theta_k = 2\pi k/N$, $k = 1 \ldots N$ with $N = 36$.

For peak B_1 reduction, we search a coarse grid (30° spacing) of varying excitation phase for each spectral band to determine the spectral filter with the minimum peak magnitude. After testing all feasible F_s, the pulse that best meets the design criteria is chosen.

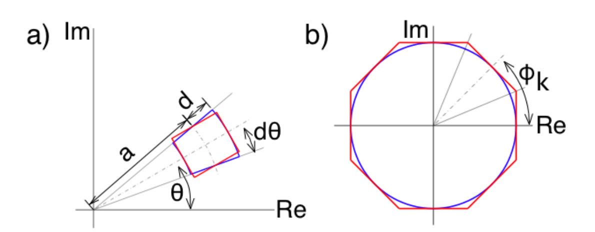

Figure 1: The piecewise linear constraints approximating the (a) in-band specification and (b) transition-band magnitude limit for H(f) are shown in red, with ideal specifications in blue.

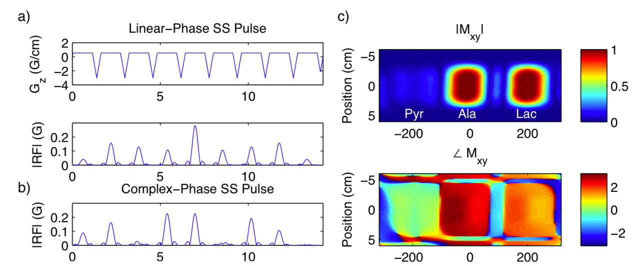

Figure 2: (a) Gradient, |RF| waveforms for a 14.2-ms linear-phase spectral-spatial pulse with 5°/90°/90° flip angles for pyr/ala/lac. (b) |RF| waveforms for complex-phase spectral-spatial pulse when spectral bands have excitation phase 0°/150°/90° showing a 20% reduction in peak B_1. (c) Spectral-spatial profile of (b).

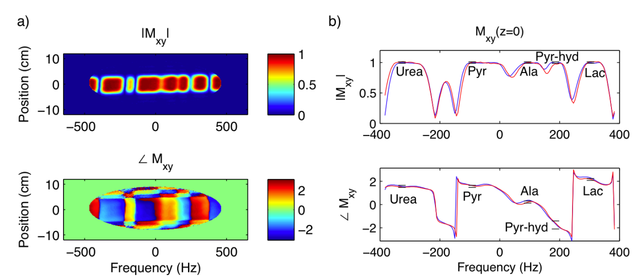

Figure 3: (a) Experimental validation of complex spectral-spatial profile on a GE Signa 1.5-T scanner. Spectral frequencies are emulated with an X gradient shim. (b) Experimental (red) and simulated (blue) spectral profiles show both magnitude and phase agreement.

Results: Figure 2 illustrates how the peak B_1 for a multiband excitation with flip angles of 5°/90°/90° for pyruvate, alanine and lactate can be reduced by 20% when allowing the spectral bands to have relative excitation phase 0°/150°/90°. Figure 3 shows the experimental validation of a pulse designed to provide the specific spectral phase profile required for a MAD-STEAM experiment[6]. This particular spectral phase profile is necessary to ensure signal from metabolites produced during the mixing time will be in quadrature to signal from metabolites present at the time of STEAM encoding.

Discussion and Conclusions: A novel approach for multiband spectral-spatial design has been presented that iterates over feasible spectral sampling frequencies to determine the best design according to minimum-time, B_1 or power criteria. FIR filter design based on convex optimization minimizes the energy in transition and don't-care regions, and can provide complex spectral responses. Optimizing the relative phase between spectral bands is shown to be able to reduce the peak B_1 of the RF pulses by up to 20% in one case.

References: [1] Golman *et al.,* Academic Radiology, 13(8):932-42, 2006. [2] Chen *et al.,* Proc. ISMRM p587, 2006. [3] Kerr *et al.*, Proc., ISMRM p226, 2008. [4] Larson *et al.*, J Magn Reson, 194(1):121–127, 2008. [5] Wu *et al.,* Dec. and Control, Proc. 35th IEEE, 1:271-6, 1996. [6] Larson *et al.*, JMR, Oct. 2012. *(In press, available online.)* [Acknowledgement: This work partly supported by NIH R01 EB007588, NIH P41 RR09784.]