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 $\frac{1}{4}$ 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-d) $|H(f)| \leq (a+d)$, and $(\theta-d\theta) \leq H(f) \leq (\theta+\theta\theta)$ using the piecewise linear constraints as shown. In addition the transition band behavior can likewise be limited to $|H(f)| \leq 1$ as in Fig. 1b. In practice, we choose linear constraints tangent to the unit circle at $\theta_k = 2\pi k/N, k = 1...N$ 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.

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.