Multiband Spectral-Spatial Design for High-Field and 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 challenging requirements are especially prevalent for high-field applications, as well as when imaging hyperpolarized C-13 metabolites with significant spectral dispersion and a gyromagnetic ratio ¼ that of protons [1,2]. A novel approach to spectral-spatial RF design is presented that addresses these issues in a systematic and optimal manner.

Methods and Results: The spectral-spatial design begins as illustrated in Fig. 1b with the specification of the desired spectral profile. This profile includes only the bands of interest as in [3], and does not specify the response elsewhere. The minimum-time gradient sublobe is then designed that meets the specified spatial time-bandwidth subject to system constraints and the specified fraction of the gradient lobe ramps allowed for versed RF excitation [4]. The following gradient lobe is then either a replica of opposite polarity (for echoplanar designs) or a minimum-time rewinder (for flyback designs). This gradient design determines the maximum spectral sampling frequency F_{max}.

A range of spectral sampling frequencies F_s from 0 to F_{max} is then evaluated to determine if the specified spectral profile extends outside the spectral bandwidth, and if so, whether the aliased specifications are self-consistent. For each valid sampling frequency F_s, minimum-amplitude gradient sublobes with the corresponding duration are designed.

Minimum-time complex-coefficient linear-phase or minimum-phase filters that meet the spectral requirements for each F_s are 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-McLellan multiband design as used in [6,7] is that the power in the transition bands can be explicitly minimized, thereby reducing the power of the RF pulse. It should be noted that the linear-phase design is truly linear-phase unlike in [3].

For each spectral filter corresponding to a given F_s, the composite spectral-spatial pulse is designed with correction for the non-uniform k_z-t sampling as in [8] to eliminate chemical-shift misregistration within the Nyquist bandwidth. This technique also prevents degradation of the off-center spectral profile for echoplanar or opposed-null spectral-spatial designs. For flyback pulses, this approach has been further extended to support large-tip designs using a 2D SLR approach similar to that in [9]. After testing all feasible F_s, the pulse that best meets the design criteria (be it minimum-time, minimum peak B_1 or minimum power) is chosen.

Results: Figure 1 illustrates the design and validation of a 13.4-ms linear-phase spectral-spatial pulse targeting metabolite products of hyperpolarized C-13 pyruvate on a GE Excite 3T scanner (4 G/cm, 15 G/cm/ms). This pulse excites lactate, alanine and bicarbonate by 90°, while exciting pyruvate by only 3°, thus leaving the pyruvate hyperpolarization largely undisturbed. Figure 2 illustrates the validation of the spectral-spatial profile obtained by imaging a water phantom with the spectral-spatial gradient on Y, and an additional constant gradient on X to mimic the effect of off-resonant spins. Figure 3 presents a minimum-phase spectral-spatial multiband design targeting lactate-only excitation at 3T. Stopbands of 0.002 are obtained for pyruvate and bicarbonate even though they are outside the nominal spectral bandwidth.

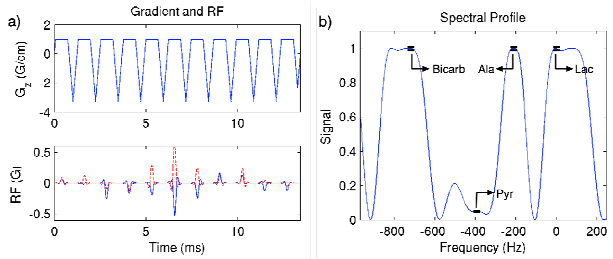

Figure 1: a) Flyback gradient and RF (real/imaginary) waveforms for a linear-phase multiband spectral-spatial pulse targeting metabolic products of C-13 labeled pyruvate at 3T. b) Excitation spectral profile as determined with a Bloch simulator, including original multiband specfication (in black). Lactate, alanine and bicarbonate products are all excited by 90°, while pyruvate is excited by only 3°.

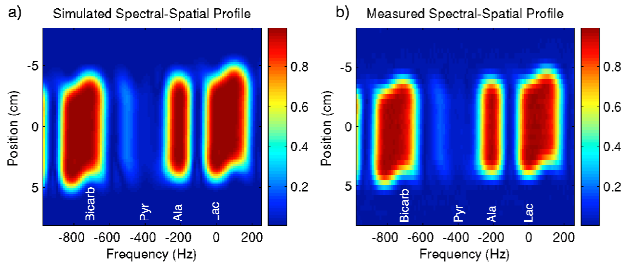

Figure 2: Simulated and measured spectral-spatial profiles of the multiband excitation pulse showing excellent agreement. A spatial time-bandwidth of 6 and slice thickness of 8 cm was specified. Note the excellent chemical-shift registration within the spectral Nyquist bandwidth of -765 to +45 Hz.

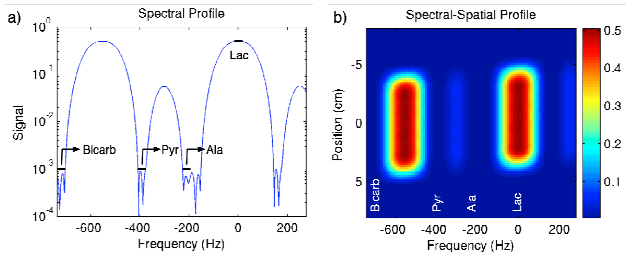

Figure 3: a) Spectral profile of 15.2-ms minimum-phase spatial-spectral excitation designed for lactate-only excitation of 30° at 3T. b) Spectral-spatial profile of the lactate-only excitation. The spectral bandwidth of the excitation was 552 Hz, centered on lactate. A spatial time-bandwidth of 8, and slice thickness of 8 cm was specified. Pyruvate and bicarbonate resonant frequencies are outside the effective bandwidth, but the design ensures the aliased frequencies are still suppressed.

Discussion: 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 true linear-phase or minimum-phase spectral responses. Chemical-shift misregistration correction has also been extended to large-tip flyback designs. Example designs appropriate for spectroscopic imaging of C-13 pyruvate metabolites or C-13 lactate imaging at 3T are presented and validated.

References: [1] Golman *et al.,* Academic Radiology, 13(8):932-42, 2006. [2] Chen *et al.,* Proc. ISMRM p587, 2006. [3] Yip *et al.*, Proc. ISMRM p2998, 2006. [4] Conolly *et al.*, JMR 78(3):440-58, 1988. [5] Wu *et al.,* Dec. and Control, Proc. 35th IEEE, 1:271-6, 1996. [6] Schricker *et al.*, MRM 46:1079-87, 2001. [7] Cunningham *et al.,* MRM 53:1033-39, 2005. [8] Cunningham *et al.*, Proc. ISMRM p72, 2007. [9] Pauly *et al.,* MRM 29:776-82, 1993.
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