MULTIBAND ARBITRARY-PHASE SLR RF PULSE WITH GENERALIZED FLIP ANGLE VIA CONVEX OPTIMIZATION

Hong Shang[1,2], Peder E.Z. Larson[1,2], Adam B. Kerr[3], Galen Reed[4], Adam Elkhaled[1,2], Jeremy W. Gordon[1], Cornelius von Morze[1], Michael Lustig[5], and Daniel B. Vigneron[1]

[1]*Radiology and Biomedical Imaging, UCSF, San Francisco, California, United States,* [2]*UCSF-UC Berkeley Graduate Program in Bioengineering, San Francisco/Berkeley, California, United States,* [3]*Electrical Engineering, Stanford University, Stanford, California, United States,* [4]*HeartVista, Menlo Park, California, United States,* [5]*Electrical Engineering and Computer Science, UC Berkeley, Berkeley, California, United States*

Purpose RF pulse performance can be improved when the desired profile is sparse and a multiband profile is specified, for example, in the application of HP ^{13}C imaging or certain regions in ^{1}H spectra. Furthermore the phase profile constraint can be eliminated in certain cases, such as saturation pulses, thus improving flexibility in pulse design. For example, pulse duration can be shortened or the transition bandwidth can be sharper. In this work, a systematic approach was developed for the design of multi-band, arbitrary-phase, generalized-flip-angle RF pulses with flexible trade-off of optimizing different characteristics. The FIR filter design was solved by convex optimization. Two different pulses demonstrate proof of concept.

Methods The Shinnar-Le Roux (SLR) algorithm is a powerful tool for large tip angle selective excitation RF pulse design (1). Design of a multiband RF pulse has no additional difficulties for the SLR algorithm itself; instead, it requires a more sophisticated FIR filter design as the beta polynomial in SLR algorithm. Such a FIR filter can be designed via spectral factorization and convex optimization (2-3). The advantage of the convex optimization approach over Parks-McClellan equi-ripple filter design is the flexible trade-off among different characteristics to be optimized by defining a multi-objective function, or adding constraints if they are also convex (such as total energy or stopband attenuation). Some characteristics are quasi-convex, such as transition bandwidth or pulse duration, which can be optimized with bisection search. This method is implemented in Matlab and we are creating an open source distribution of the software used.

Application 1: An excitation RF pulse for balanced SSFP (bSSFP) hyperpolarized (HP) ^{13}C 14T MRI was designed for shortest duration. At 14T the spectral separation (between pyruvate, lactate, alanine) is far enough such that a spectrally selective pulse can be used in bSSFP to excite metabolites individually. A RF pulse with short duration is desired to reduce TR and minimize banding artifacts and total scan time. A multiband RF pulse was designed to excite only pyruvate (120°). For each compound, a frequency range of [-50Hz 50Hz] is specified, due to the shimming capability and bSSFP banding artifact (TR = 10ms). A standard linear-phase SLR pulse was used as comparison.

Application 2: A dualband saturation RF pulse for ^{1}H MR spectroscopy at 3T. A flip-angle larger than 90° is often used for these saturation pulses to offset rapid T1 dependent signal recovery (4). A dualband spectral saturation pulse was designed for suppression of both water (90°) and glutamine/glutamate/NAA (120°) without perturbing peaks in between and minimizing transition bandwidth.

For both applications, numerical Bloch simulations were used to test the RF pulse profile. MR experiments with a water phantom were performed on a 3T clinical MRI scanner (GE Healthcare, Waukesha, WI, USA) to validate the 1H 3T pulse.

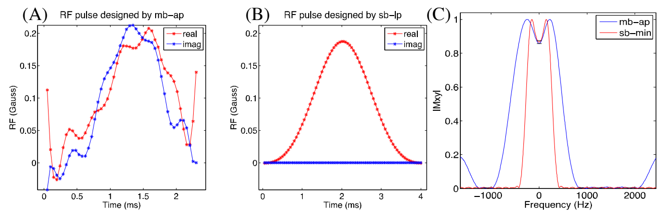

Figure 1. Multiband arbitrary-phase spectral selective RF pulse (mb-ap) for balanced SSFP ^{13}C imaging at 14T (A), compared to a standard single-band linear phase RF pulse (sb-lp) (B). Bloch simulation of profile with defined multiband specification (in black) (C).

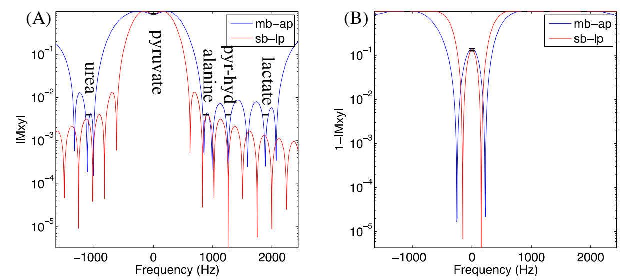

Figure 2. Simulated spectral profile of both pulses as in figure 1 but with logarithmic scale. Predefined multiband specification is plot together in black.

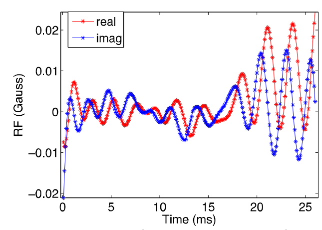

Figure 3. Multiband saturation pulse for suppression of both water (90°) and glutamine/glutamate/NAA(120°) for ^{1}H MRS at 3T.

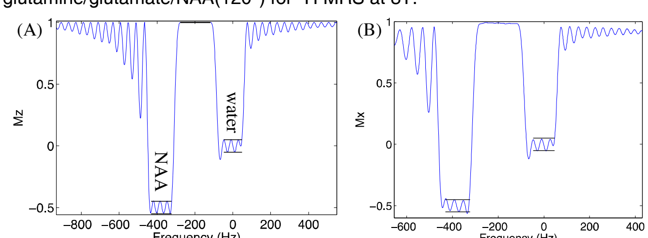

Figure 4. Bloch simulation of the spectral profile for the ^{1}H spectroscopy saturation pulse (A). The measured spectral profile (B) agrees well with the simulated results. The defined multiband specification is highlighted in black.

Results For the balanced SSFP spectrally selective excitation pulse, the multiband pulse is illustrated in Fig 1 (A). Its pulse duration was just 2.3ms with the same profile for the region of interest, compared to a standard 4ms linear phase SLR pulse in Fig 1 (B). Bloch simulation of pulse profiles is shown in Fig 1(C) and Fig 2. The shorter pulse has increased total power by 1.59 and increased peak amplitude by 1.49, but is still within the system limit. For the dualband saturation pulse (application 2, Fig. 3), Bloch simulation and measured profile are shown in Fig 4. A transition width of 44 Hz was achieved, ~20% sharper than a standard SLR single-band pulse.

Discussion A framework for general RF pulse design was developed based on convex optimization. This algorithm can create RF pulses with a multiband magnitude profile, arbitrary phase profile and generalized flip angle. Spectral sparsity was exploited to further optimize characteristics such as duration, transition width, peak B1 amplitude and SAR with flexible trade-off among them. Example designs for excitation RF pulses for bSSFP ^{13}C 14T MRI and a dualband saturation RF pulse for ^{1}H MR spectroscopy at 3T were developed and evaluated.

References [1] Pauly, John, et al. Medical Imaging, IEEE Transactions on 10.1 (1991): 53-65. [2] Kerr, A. B., et al. Proceedings of the 16th Annual Meeting of ISMRM, Toronto. 2008. [3] Wu, Shao-Po, et al. Applied and Computational Control, Signals, and Circuits. Birkhäuser Boston, 1999. 215-245. [4] Bernstein, Matt A., et al. Handbook of MRI pulse sequences. Elsevier, 2004.