Iterative spectral-spatial pulse design: Toward full use of design freedom

C-Y. Yip[1], S. Lee[1], J. A. Fessler[1,2], D. C. Noll[2]

[1]Electrical Engineering and Computer Science Department, University of Michigan, Ann Arbor, MI, United States, [2]Biomedical Engineering, University of Michigan, Ann Arbor, MI, United States

Introduction

Using standard spectral-spatial (SPSP) pulse design methods [1,2], a *true-null* design can be used to suppress fat signals via creating a spectral null-band at the fat resonance frequency offset, f_{cs}. It requires that the z gradient oscillates at $2f_{cs}$. Alternatively, an *opposed-null* design (with gradient oscillating at f_{cs}) creates secondary spectral peaks at f_{cs}, and fat suppression is achieved because of through-plane phase cancellation of the excited fat signals. The opposed-null design is often preferred for its relatively slow gradient oscillation that allows fine slice selection, but it is less robust because of partial cancellation due to non-uniform through-plane distribution of fat and B_0 inhomogeneity. We propose that using an iterative design method, a SPSP pulse can attain true null at f_{cs} even with gradient oscillating at f_{cs}, or at other frequencies lower than $2f_{cs}$. The new design will improve fat suppression in SPSP pulse applications that require thin and sharp slice selection.

Theory

Meyer et al. [1] expresses the spatial (z) excitation pattern at resonance frequency f as Fourier integral of a trajectory in the SPSP k-space (k_z-k_f space) weighted by a complex RF pulse, $b(t)$:

$$m(z,f) \approx i\gamma \int_0^T b(t)\, exp\,(ik_z(t)\cdot z + ik_f(t)\cdot f)\,dt \qquad (1)$$

in which $k_z(t)$ is given by backward integration of the z gradient waveform, and $k_f(t) = 2\pi(t - T)$, where T is the pulse duration. If we define $\mathbf{k}(t) = [k_z(t)\ k_f(t)]^T$, $\mathbf{r} = [z\ f]^T$, and discretize in both t and $\mathbf{r}$, we can express (1) as

$$\mathbf{m} \approx \mathbf{Ab}, \qquad (2)$$

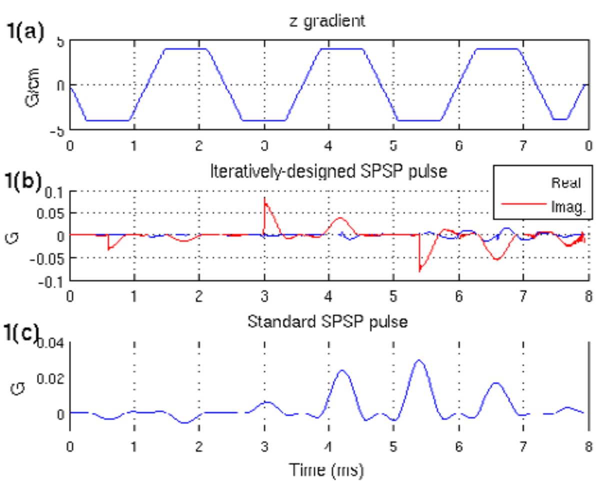
where the i,j-th element of $\mathbf{A}$ is given by $a_{ij} = i\gamma\Delta t \cdot exp(i\mathbf{k}(t_j)\cdot\mathbf{r})$, $\mathbf{m} = [m(\mathbf{r}_0) \ldots m(\mathbf{r}_{M-1})]^T$, and $\mathbf{b} = [b(t_0) \ldots b(t_{N-1})]^T$ are the SPSP pulse samples. Now, a SPSP pulse can be designed via minimizing the difference between $\mathbf{m}$ and a discrete desired SPSP pattern, $\mathbf{d}$:

$$\hat{\mathbf{b}} = \arg\min_{\mathbf{b}} \left\{ \|\mathbf{Ab} - \mathbf{d}\|_W^2 + R_1(\mathbf{b}) + R_2(\mathbf{Ab}) \right\} \qquad (3)$$

The desired pattern (Fig. 2a) specifies a slice profile in the pass-band centered at the water frequency (0 Hz), and a true null-band centered at f_{cs}. The region of interest (ROI), defined through binary weights in the diagonal matrix $\mathbf{W}$, covers *only* the pass-band and null-band (Fig 2a, enclosed by the dashed lines). Because excitation error is minimized only in the ROI, such ROI specification implies a large "don't care" region in z-f space, which the design can exploit for pass-band and null-band excitation accuracy. Regularization terms $R_1(\mathbf{b})$ and $R_2(\mathbf{Ab})$ can be devised to control pulse power and SPSP profiles (ripple magnitudes, transition width, etc), respectively. The minimization problem in (3) can be solved iteratively with conjugate gradient [3].

Method and results

We compare the SPSP excitation patterns of iterative and standard pulse designs, assuming a 3T system with maximum gradient and slew rate being 4 G/cm and 15000 G/cm/s, respectively. The goal is to design a SPSP pulse for fat suppression (f_{cs} = -420 Hz), and 30-degree water excitation (0 Hz) in a sharp 2-mm slice. Such demanding slice specification dictates an opposed-null design with slow gradient oscillation at 420 Hz (Fig. 1a). The standard SPSP pulse is designed with a sinc envelope in k_z and a minimum-phase Shinnar-La-Roux envelope in k_f (Fig. 1c). As expected for an opposed-null design, Bloch simulation of the SPSP pattern excited by the standard pulse reveals secondary peaks around -420 Hz, which are asymmetric about $z = 0$ (magnitude shown in Fig 2c). For the iterative design, the desired pattern (Fig. 2a) is defined with FOV = 15 cm x 2000 Hz and matrix size 750 x 500, whereas the ROI (Fig. 2a, enclosed by dash lines) covers 150 Hz-wide bands centered at 0 and -420 Hz. Using the same gradient waveform, the iterative method produces a SPSP pulse (Fig. 1b) in 50 CG iterations, with computation acceleration based on [4]. The iteratively designed pulse leads to a true null band at -420 Hz (Fig. 2b), while attaining pass-band slice selectivity comparable to the standard.



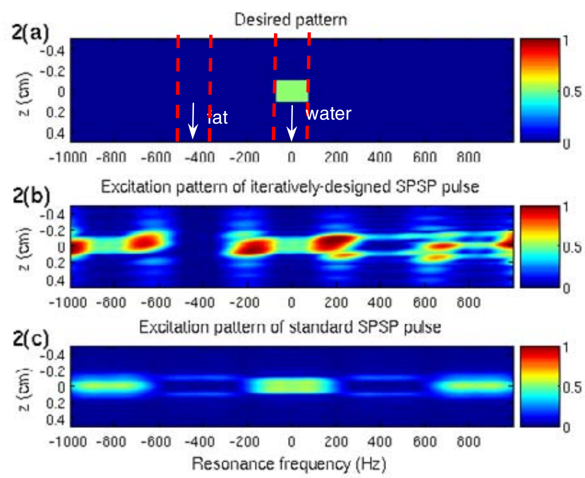


Fig. 1a-c: The z gradient waveform, and SPSP pulses designed iteratively or using envelopes in k_z and k_f. Note that the iterative design is complex.

Fig. 2, a: Normalized desired pattern (shown in a 1-cm window). Interior of dash lines represents the ROI (pass-band and null-band). b-c: SPSP patterns excited by pulses in Fig. 1b-c.

Discussion

The hallmark of the iterative SPSP pulse design is a full use of design freedom, via exploiting the complex nature of RF pulses and the fact that usually only a selective set of frequency bands are of design interest. Under demanding slice specifications, the extra freedom can be used to create a true null at the fat frequency even with slow gradient oscillation. It is potentially useful in MR systems with low-performance gradients, or at high field strengths in which the water-fat spectral separation is wide. The iterative approach can potentially lead to other benefits in different MR applications of SPSP pulses. For example, it can provide flexible and precise control in spectral editing for spectroscopy or spectroscopic imaging.

References

1. Meyer CH et al., MRM(15), 1990
2. Zur Y et al., MRM(43), 2000
3. Yip CY et al., MRM(54), 2005
4. Fessler JA et al., IEEE TSP(53), 2005

Supported, in part, by NIH grant R01DA015410-01