An Interleaved Spatial-Spectral Pulse for Imaging Large Chemical-shift Components

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Introduction Ultra-high field MR brings large chemical shift in terms of resonant frequency displacement. For example, the difference frequency of water/fat on a 7T system is 1013 Hz. Taking advantage of this large chemical shift, Ivanov et al. developed a simple yet effective fat suppression technique for 7T (1). However, this method only works with spin echo sequences. Conventional fat-saturation pulses are sensitive to B1 inhomogeneity and yield high SAR value, both of which are not in favor of ultra-high field systems. In comparison, spatial-spectral (SPSP) pulse offers better resilience to B1 inhomogeneity (2, 3). However, large chemical shift translates into high gradient oscillation frequency, which renders SPSP pulses minimum slice thickness penalty and eddy current artifacts. In this work, we propose the use of interleaved spatial-spectral pulses with lower gradient oscillation to improve slice selection and reduce eddy currents.

Theory and Method The design process of interleaved spatial-spectral pulses can be divided into two steps. The first step is to design an ideal SPSP pulse with an unlimited gradient slew rate as shown in Fig 1(a). Therefore, all the gradient sublobes are perfect rectangles. The second step is to separate the ideal SPSP pulse into 3 different pulses. As shown in Fig 1 (b-d), the 1st pulse consists of all the (3i+1)th subpulses of the ideal pulse, the 2nd pulse consists of all the (3i+2)th ones, and so on, i=0,1,2…etc. With the RF pulse separation, 2/3 of the original rectangular gradient sublobes are played with zero RF deposition, which could be replaced with any gradient waveform as long as they return to the same point in the excitation k-space (4). To reduce eddy currents, these gradients are replaced by the attack and decay of trapezoidal sublobes, and other gradients remain constant when the RF subpulses are on, as illustrated by dashed lines in Fig 1 (b-d). In this way, the excitation k-space is filled in an interleaving pattern after 3 repetitions. Coherent addition of the raw data of three acquisitions completes the k-space.

For demonstration purpose, the chemical shift (f_{cs}) is set to 1 kHz, similar to water and fat's frequency difference on a 7T system. The opposed-null design was used, with water placed on resonance and fat at the asymmetric secondary peak for signal suppression: $T = 1/f_{cs} = 1/1kHz = 1$ *ms.* Therefore, each ideal gradient sublobe is 500 μs in duration. For spatial selection, using a conventional maximum gradient amplitude *Gmax* (40 mT/m) and sinc-shaped time-bandwidth product (*TBW*) of 2 RF subpulses, the minimum slice thickness **Δz** is: $\Delta z = TBW/(\gamma/2\pi)(T/2)Gmax = 2/(42.58\ MHz/T *0.5\ ms*40\ mT/m) \approx 2.35\ mm$, suitable for most applications. For spectral selection, the overall pulse is synthesized using an SLR algorithm with minimal phase and the following parameters: TBW=4, bandwidth=333 Hz. Therefore, the ideal spatial-spectral RF pulse is 12 ms long with 24 oscillating gradient sublobes. By separating the ideal pulse into 3 groups of pulse, the corresponding maximum gradient slew rate is 80 mT/m/ms, which could be easily implemented with conventional gradient systems.

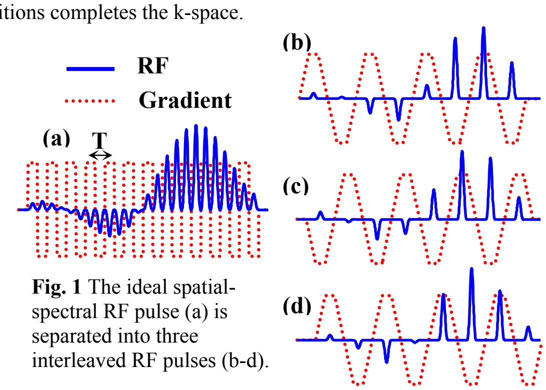

Fig. 1 The ideal spatial-spectral RF pulse (a) is separated into three interleaved RF pulses (b-d).

The interleaved spatial-spectral pulses were implemented in a 2D gradient echo (GRE) sequence (TE/TR = 15/150 ms, 15 cm FOV, 1 slice, 5 mm thickness, 192*192 matrix, 3 excitations, total acquisition time: 86 s). To demonstrate the spatiospectral response, the GRE sequence was modified as in (5) to image a cylinder filled with doped water on a 3T Siemens scanner. The result was compared to the Bloch equation simulated response. To illustrate the fat suppression, the interleaved SPSP pulses were compared to a standard non-spectrally selective pulse in a water/oil phantom scan on a 7T Siemens scanner.

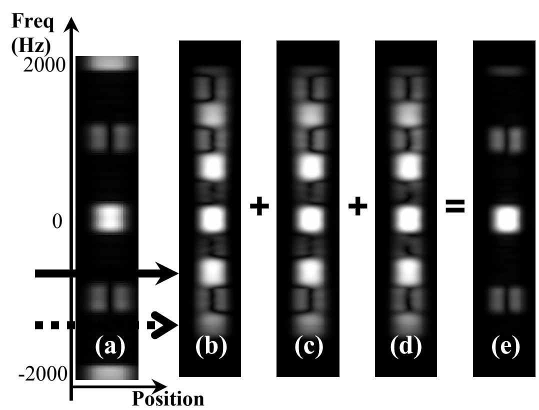

Fig. 2 The Bloch simulation (a) agrees with the measured spatiospectral response (b-e). (b), (c), and (d) are generated by RF pulses showed in Fig.1 (b), (c), and (d), and adding the three complex images yields (e).

Results Fig. 2 shows the Bloch simulation and experiment result of the spatiospectral response of the interleaved spatial-spectral pulses. As designed, the interleaved SPSP pulses were able to select in both spatial and spectral dimensions. By placing the fat frequency at opposed null, the fat signal was suppressed by the interleaved SPSP pulses, as demonstrated in the phantom images in Fig. 3.

Conclusion and Discussion In this work, we demonstrate the design of an interleaved spatial-spectral pulse for selective excitation of large chemical shift components. By filling the excitation k-space in three repetitions, the gradient oscillation is decreased by 3-fold, hence maximizing the area under gradient sublobes. Therefore, a minimum slice thickness could be achieved with moderate gradient slew rates. Applications of this pulse include selective excitation of water or fat on 7T, and spectrally selective phosphocreatine imaging (6).

Since three excitations are used to complete the k-space, the total scan time increases by a factor of three. But it should be noted that there is no reduction in the signal-to-noise (SNR) efficiency. Therefore, this method is best suited for low SNR cases where a number of averages are used to improve SNR, such as phosphocreatine imaging (6). In Fig. 3(b), there is some residue fat signal at the edge of the oil phantom. This is because the oil bottle has a contoured shape. Since that fat signal is cancelled by antisymmetric phase of the secondary peak, the uneven edge results in incomplete cancellation. On the other hand, the fat frequency could be placed at the symmetric sidelobes (Fig.2, arrow and dash arrow), and linear superposition of the three acquisitions would generate water-only and fat-only images. Schick used a similar 2-shot method for simultaneous water and fat imaging (7). This is the excitation counterpart to the three-point Dixon technique for water/fat decomposition (8). Our future work includes correcting the B0 inhomogeneity in image reconstruction, and applying the interleaved spatial-spectral pulses to simultaneous PCr and β-ATP metabolic imaging.

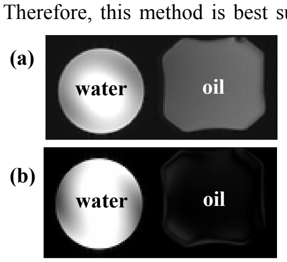

Fig. 3 Phantom images acquired on a 7T system. Compared to a standard spatial selective pulse (a), the interleaved spatial-spectral pulses successfully suppressed the fat signal as shown in (b).

Reference

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Acknowledgement

Ministry of Science and Technology of China (2005CB522800, 2009IM030900, and 2010IM030800), National Nature Science Foundation of China (90820307)