SPECTRAL-SPATIAL SELECTIVITY USING SPATIOTEMPORAL ENCODING

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Introduction: Spectral-spatial (SPSP) pulses [1] have proven useful for a variety of purposes such as fat suppression [2] and the fast imaging of hyperpolarised metabolites [3]. In SPSP pulses, a radio-frequency (RF) waveform is played in synchrony with an oscillating gradient and spatial selectivity usually relies on amplitude modulations. Compared to pure amplitude modulations, a frequency modulation results in additional contributions to the phase [4], which may be regarded as detrimental. Recently, these contributions have been identified as a form of *spatiotemporal encoding* (SPEN) that can be exploited for NMR imaging and spectroscopy [5]. Here we show that spatiotemporal encoding can also be used to *add spectral selectivity to a pair of spatially selective frequency-swept pulses*. The result of this is a SPEN-based SPSP selectivity that does not require fast oscillating gradients, but rather simple manipulation (Fig. 1a).

Conventional multi-slice acquisition schemes can be used in conjunction with this spectral/spatial component (e.g., fat & water) images can be obtained simultaneously. These principles are illustrated with phantom experiments at 7T and human volunteers imaging at 3T.

Methods: Excitation by a linearly frequency-swept (chirp) pulse leads to a phase of the form [5]:

\[
\phi(z) = \gamma T_p z - \frac{\Delta\omega}{2} T_{\text{chirp}} (z - z_0^0) - \frac{1}{2} \frac{\Delta T}{L} (z - z_0^0)^2 + \phi_0
\]

where \(T_p\), \(G_o\), \(\Delta\omega\) are the duration, the gradient amplitude and the bandwidth of the pulse; \(\Omega\) is an additional frequency offset, \(L\) is the length of the selected slice, \(z_0\) is the width and the center of the excited region, respectively; \(e^{i\phi_0}\) corresponds to all the \(z\)-independent contributions. The quadratic term in eq. (1) can be removed by a subsequent frequency-swept refocusing pulse [6]. Earlier examples of this approach for slice selection used parameters that also remove the chemical-shift-dependent linear phase [7,8]. If opposite gradients are used during excitation and refocusing, however, the chemical-shift dependent linear phase will remain as a through-slice dephasing after the refocusing pulse. This will lead to a signal cancellation for all off-resonance chemical species, but a suitable and *a priori* known additional gradient can progressively wound up these individual species into phase. This “unwinding” can be modified throughout acquisition by an additional gradient pulse; its mechanism is illustrated in Fig. 1a. In order to experimentally assay this principle, quadratic-phase SLR pulses designed with a modified algorithm adapted from Ref. [9] were used, to obtain an improved phase and spatial selectivity. Shaped excitation pulses can also be obtained with a Fourier design. A pulse that addresses a region of length \(L\) and imparts a quadratic phase \(\frac{1}{2}\Delta\omega T_e/(x-a)L^2\) consists of an approximately linear frequency sweep of duration \(T_e\); the duration \(T_e\) chosen by the operator should be shorter than the actual duration of the pulse \(T_e\). Phantom experiments were performed at 7T on a Varian VNMRS 300/89 vertical microimaging system (Varian Associates, Palo Alto, CA) using a Millipede® probe, with a water/fat phantom consisting of two tubes, one filled with water and one filled with oil. Spin-echo images were acquired using a quadratic-phase Fourier pulse for excitation (\(T_e = 16\) ms, \(T_r = 8\) ms) and a quadratic-phase SLR pulse for refocusing (\(T_e = 10\) ms, \(T_r = T_e/2\)). Both pulses had a bandwidth of 10.5 kHz. An additional refocusing pulse was used for slice selection. Imaging of human volunteers was performed at 3T on a Siemens Tim Trio clinical system (Siemens Healthcare, Erlangen, Germany) using a four-channel breast coil. Spin-echo EPI images were acquired using slice-selective quadratic-phase SLR pulses for excitation (\(T_e = 9.6\) ms, \(T_r = 5.6\) ms) and refocusing (\(T_e = 6\) ms, \(T_r = T_e/2\)) with an additional band-pass filter in the readout direction. Fat & water images were obtained with the default sequence that uses an SPSP pulse for selective water excitation and a linear-phase refocusing pulse. Other parameters were kept identical: slab thickness: 5 mm, TE: 48 ms, FOV: 22 x 22 cm²; matrix size: 64 x 64. Simultaneous water and fat imaging was obtained following the SPEN-based SPSP pulse by adding gradient blips of alternating sign in the slice-selection dimension during the phase-encoding blips of the EPI waveform (slice thickness:10 mm, TE: 99 ms). Separate Fourier transformation of the odd and even echoes then yields a water and a fat image, respectively. Pulse generation and image processing were done offline using Matlab® (The Mathwork, Natick, MA).

Results and discussion: The simultaneous spatial and spectral selectivity that can be achieved by the SPEN-based SPSP approach is illustrated in Fig. 1, using a pair of frequency-swept pulses in the readout domain. As opposite gradients are used during excitation and refocusing, the fat echo is displaced outside the acquired region of k-space (Fig. 2a). Note that the mechanism here to result in SPEN-based SPSP selectivity (Fig. 1a) is entirely distinct from that of SPEN pulses: signal suppression results from through-slice dephasing of off-resonance species, and no fast oscillating gradients are involved. Figure 2a shows how this SPEN-based SPSP selectivity can be used for fat suppression in a spin-echo EPI experiment, with an example of breast imaging. The high bandwidth of the frequency-swept pulses ensures a minimal chemical-shift displacement [7,8]. The sweep’s duration was chosen to ensure full fat through-slice dephasing and thereby signal cancellation. Because fat is only excited within the targeted slice and coherently dephased, a gradient lobe in the slice selection dimension can be used to put fat in phase and dephase water. Fig. 2b shows how this mechanism can be used to obtain a water and a fat image in a single EPI scan, with half the field of view in the phase-encoding dimension. This approach is compatible with multi-slice imaging, a work that is currently in progress.

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Fig. 1: (a) Pair of quadratic-phase pulses with opposite gradients for SPEN-based spatial/spectral selectivity. Phantom experiments at 7T: (b) spatial selection profile; (c) no selectivity; (d) spatial selectivity; (e) spatial/spectral selectivity.

Fig. 2: Breast spin-echo EPI at 3T. (a) Fat-suppressed images obtained using the SPEN-based SPSP selectivity (left) or an SPSP pulse for selective water excitation (right). (b) Simultaneous water/fat imaging in a single scan using the SPEN-based SPSP selectivity.