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 selectivity. In addition, two-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]:

$$\phi(z) = \gamma G_e \frac{T_e}{2}(z - z_c) - \frac{1}{2}\Delta\omega T_e\left(\frac{z - z_c}{L}\right)^2 - T_e\Omega\left(\frac{z - z_c}{L}\right) + \phi^0 \quad (1)$$

where T_e, G_e, $\Delta\omega$ are the duration, the gradient amplitude and the bandwidth of the pulse; Ω is an additional frequency offset, considered here to result from a chemical shift; L and z_c are the width and the center of the excited region, respectively; ϕ^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 bring these individually-wound species into phase. This "unwinding" can be modified throughout acquisition by an additional gradient lobe; 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 $\frac{1}{2}\Delta\omega\, T'_e((z-z_c)/L)^2$ 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'_e = 8 ms) and a quadratic-phase SLR pulse for refocusing (T_r = 10 ms, $T'_r = T'_e/2$). Both pulses had a bandwith 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'_e = 5.6 ms) and refocusing (T_r = 6 ms, $T'_r = T'_e/2$). Both pulses had a bandwith of 4.5 kHz. Reference 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: slice thickness: 5 mm, TE: 48 ms, FOV: 22 x 22 cm^2; 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 Mathworks, Natick, MA).

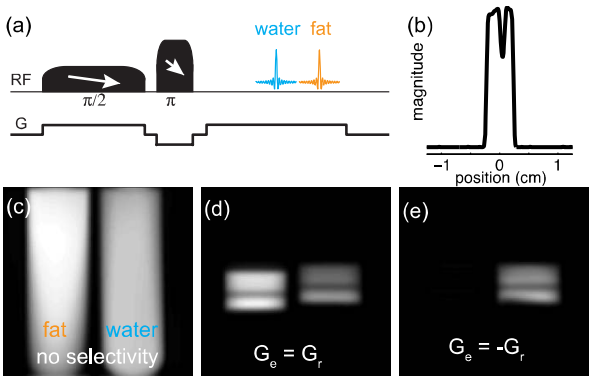

Fig. 1: (a) Pair of quadratic-phase pulses with opposite gradients for SPEN-based spatial/spectral selectivity. Phantom experiments at 7T: (b) spatial selection profile; (c) no selectivity; (d) spatial selectivity; (e) spatial/spectral selectivity.

Results and discussion: The simultaneous spatial and spectral selectiviy 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 dimension. As opposite gradients are used during excitation and refocusing, the fat echo is displaced outside the acquired region of k-space (Fig.1c). Note that the mechanism underlying SPEN-based SPSP selectivity (Fig. 1a) is entirely distinct from that of SPSP 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.

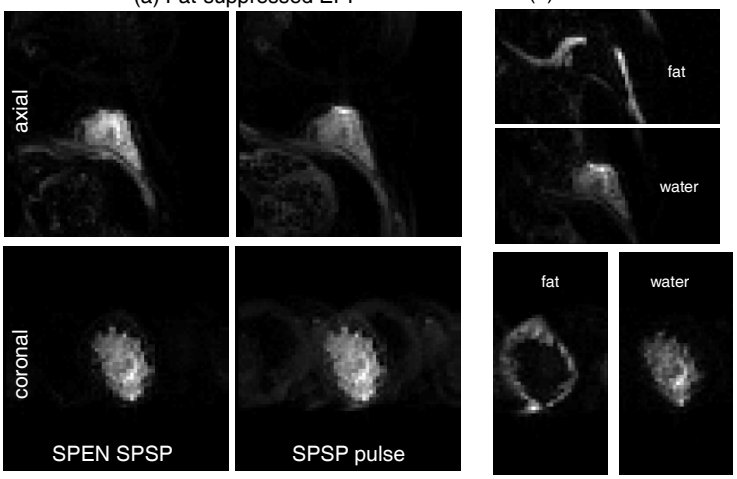

Fig. 2: Breast spin-echo EPI at 3T. (a) Fat-suppressed images obtained using the SPEN-based SPSP selectivity (left) or an SPSP pulse for selective water excitation (right). (b) Simultaneous water/fat imaging in a single scan using the SPEN-based SPSP selectivity.

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References: [1] C. H. Meyer *et al.*, Magn. Reson. Med. 15 (1990) 287; [2] Y. Zur, Magn. Reson. Med. 43 (2000) 410; [3] A. Z. Lau *et al.*, NMR Biomed. 24 (2011) 988; [4] M. Garwood and L. DelaBarre, J. Magn. Reson. 153 (2001) 155; [5] A. Tal and L. Frydman, Prog. Nucl. Magn. Reson. Spectrosc.57 (2010) 241; [6] D. Kunz, Magn. Reson. Med. 3 (1986) 377; [7] P. Balchandani *et al.*, Magn. Reson. Med. 67 (2012) 1077; [8] J.-Y. Park and M. Garwood, Magn. Reson. Med. 61 (2009) 175; [9] P. Balchandani, J. Pauly and D. Spielman, Magn. Reson. Med., 64 (2010) 843.