SPatiotemporal ENcoded Spectroscopic Imaging (SPENSI) a New Approach for Multi & Single Scan Spectral Imaging

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Purpose: Develop a fast spectroscopic imaging sequence, immune to folding-in of peaks residing outside of the desired spectral width, and supporting *single-shot* 2D spatial / 1D spectral acquisitions optimized for an *a priori* known small subset of specified spectral peaks.

Methods: Instead of using time to monitor the FID leading to a spectrum, chemical shifts are encoded/decoded in this proposal by SPatio-temporal ENcoding (SPEN) principles underlying the ultrafast (single-shot) 2D NMR spectroscopy approach developed by our group[1,2]. Thus, after a slice-selective excitation, the SPEN Spectroscopic Imaging (SPENSI) method hereby introduced (Fig. 1a) imposes on the spins a phase evolution proportional to both the position and the chemical shift of the nuclei[2]: $\phi(\Omega) = C\Omega(z - z_o)$, where Ω is the chemical shift being sought, z is the position along the slice-direction vis-à-vis a reference z_o, and C is a known constant determined by the spatiotemporal encoding block. If this block were to be followed by an acquisition involving a constant gradient G_a along z, a signal $S(\Omega,t) \propto \int e^{i[(C\Omega+\gamma G_a t)z]}dz$ results, composed of a series of Ω-specific echoes chemically-shifted in time, and thus essentially identical to a spectrum. In the SPENSI proposal we assume that the Ω's being targeted are *a priori* known; a spectrum can then be optimally collected by employing solely a series of pre-calibrated G_a blips. Furthermore, incorporating these blips (along the slice/spectral dimension) into an EPI-like acquisition with a standard imaging readout (RO) gradient (Fig. 1a), yields a 1D-spectral / 1D-spatial 2D correlation. The information thus gathered is equivalent to that from echo planar spectroscopy imaging (EPSI), even if the SPENSI modality probes the spectral positions by gradient blips rather than by a time-encoding. By selecting in this manner a pre-targeted subset of spectral points, the resulting SPENSI acquisition becomes so efficient that it may be readily extended to an additional spatial dimension via its "looping" inside a Fast Spin-Echo-like acquisition (Fig. 1b), incorporating an additional phase-encoded dimensions. The resulting 3D fSPENSI variant is demonstrated both as a multi-shot scan, and as a "single-shot" scan, where in the latter we actually use only the odd phase encoding (PE) and two shots to overcome an even/odd issue along PE..

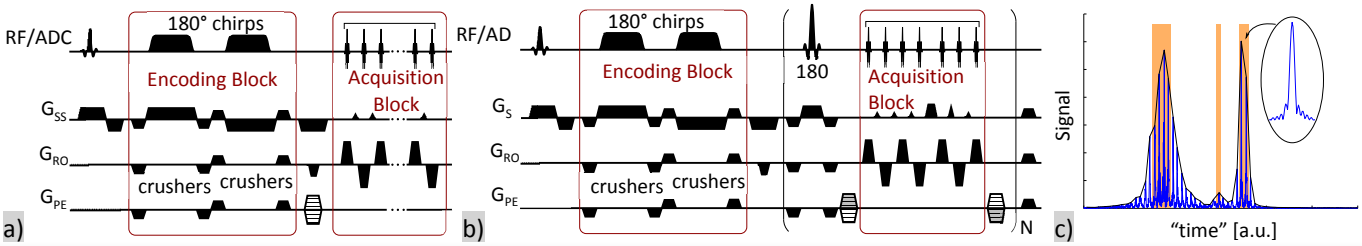

Figure 1: a) Basic SPENSI sequence for a full spectrum with one phase encoding point per excitation. b) Fast Spin Echo-like fSPENSI sequence, incorporating 6 "spectral" blips of different sizes to select up to 7 spectral peaks; notice that the acquisition block should be time reversed after each 180° pulse. c) A sample SPENSI signal without phase encoding ($\boldsymbol{k}_{PE} = \mathbf{0}$), each peak (in blue, see blow up) corresponds to the signal from a specific spectral point; the (black) envelope of the signal shows only 3 "peaks"; and the spectral subset targeted by the G_a blips in the single shot variant b) is marked by the colored orange background.

Results: Sample results are shown in Figs. 2 and 3. Images are the root-mean-square of all acquired spectral points within the same "chemical" peak.

Discussion: Preliminary results are promising, exhibiting improved separation of spectral peaks at 14T –where the blips help to cope with the higher spectral bandwidth (Figure 2)– and allowing single shot 1D spectral / 2D spatial human breast exams at 3T, dealing with water, fat and silicone resonances in implants (Figure 3). Notice that unlike EPSI, SPENSI has: i) No folding-in of peaks from outside the targeted spectral bandwidth; ii) No problem of even/odd processing along the spectral dimension; iii) Great flexibility in setting up the bandwidth of the targeted spectrum or of the readout dimension, since spectral bandwidth is independent of echo-spacing; and iv) The possibility of sufficiently compressing a single-shot acquisition so as to incorporate additional spatial dimensions in an "EVI-like" fashion. In exchange for all these advantages SPENSI does in principle suffer from an SNR drop vs EPSI due to its lack of Fourier multiplexing along the spectral dimension. However, we find that the SNR per unit time can be regained and even exceeded for species with long T_2 s, by acquiring more than one row per spectral point within an acquisition. The SNR also benefits from the recurring refocusing pulses, even if this single-shot fSPENSI variant still suffers from "even/odd" PE issues, requiring two shots or a proper reference scan to avoid artifacts. The large spectral width accommodated by SPENSI also shows promise for hyperpolarized dynamic imaging in preliminary tests, characterized by their large spectral dispersion demands.

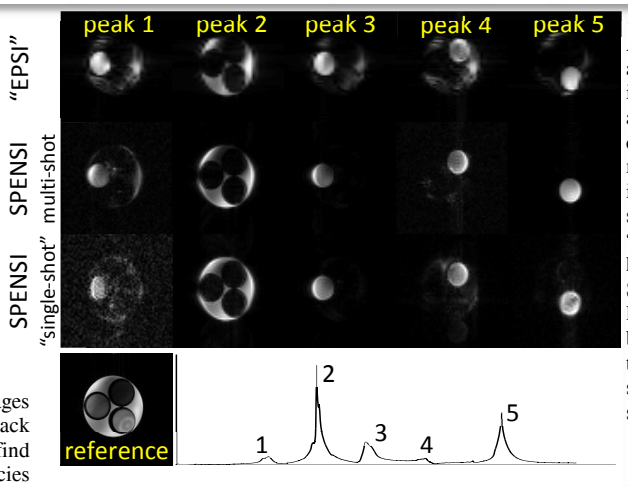

Figure 2: *Water*, Acetone, Cyclohexane, and Ethanol phantom imaged on a 14T animal magnet. Each column labeled by the matching peak number in the bottom 4kHz spectrum (PRESS). "EPSI" sequence used half the RO duration of SPENSI to achieve large enough spectral bandwidth. Shown on the bottom left is a spin-echo reference scan image.

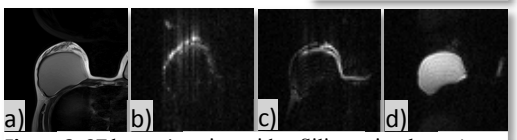

Figure 3: 3T breast imaging with a Silicone implant. a) turbo-SE reference image. b) Connective tissue, c) fat, and d) silicone images resolved by a "single-shot" fSPENSI scan on a healthy volunteer.

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References: *1.* Frydman L, Scherf T, Lupulescu A. The acquisition of multidimensional NMR spectra within a single scan. Proc Natl Acad Sci USA 2002; 99:15858–15862. *2.* Tal A, Frydman L. Single-scan multidimensional magnetic resonance. Prog Nucl Magn Reson Spectrosc 2010; 57:241-292.