Targeted MRSI via Fully-Refocused Spatiotemporal Imaging and Polychromatic Spectral Pulses (PC-SPEN)

Zhiyong Zhang[1, 2]; Lucio Frydman[1]

[1]*Department of Chemical Physics, Weizmann Institute of Science, Rehovot 76100, Israel;* [2]*Department of Electronic Science, Xiamen University, Xiamen, Fujian 361005, China;*

Introduction

Magnetic resonance spectroscopic imaging (MRSI) plays numerous roles in contemporary research. Recently, SPatiotemporal ENcoding (SPEN) [1] provides an alternative to EPI with similar acquisition durations, resolution and sensitivity parameters while providing enhanced immunity to artifacts such as B_0 inhomogeneities and susceptibility effects. Particularly robust are fully-refocused SPEN experiments [2], providing a voxel-by-voxel refocusing of all frequency shifts in the sample along the PE domain. While this removes all shift information, we have recently shown how polychromatic (PC) pulses targeting a priori resonances, can be used to phase modulate and eventually separate peaks from different sites [3]. In this study, this Fourier Encoding based on PC 180° pulses is combined with fully-refocused SPEN experiments, to provide a PC-SPEN MRSI sequence that is both efficient and robust for the rapid acquisition of spectroscopic images.

Methods

The PC-SPEN MRSI sequence is shown in Fig. 1a. The PC 180° pulse following the adiabatic sweep 180° pulse and timed as indicated, provides full refocusing [2] while addressing N resonances of interest according to $PC_m = \sum_{m=1}^{N} P_n^{180}(\Omega_n) e^{i\pi mn/N}$, where $0 \le n \le N\text{-}1$, m is a scan index among $M \ge N$, and $P_n^{180}(\Omega_n)$ is a selective 180° pulse centered at the frequency of the n-th resonance, Ω_n. This manipulation behaves as Fourier encoding, imparting a phase modulation $e^{i2\pi mn/N}$ into n-th chemical shift component in m-th scan. After Fourier transforming these scans' signals, all chemical shifts – as well as their images – are separated. Moreover, this PC pulse restores to equilibrium all spins that were not targeted by the initial slice-selective excitation, enabling multi-slice spectroscopic imaging. Notice that, for the different decoded image components there will a chemical shift miss-registration along SPEN's low-bandwidth dimension, which can be corrected using the corresponding chemical shift information. All the SPEN images are processed with a referenceless super-resolution (SR) reconstruction algorithm [4].

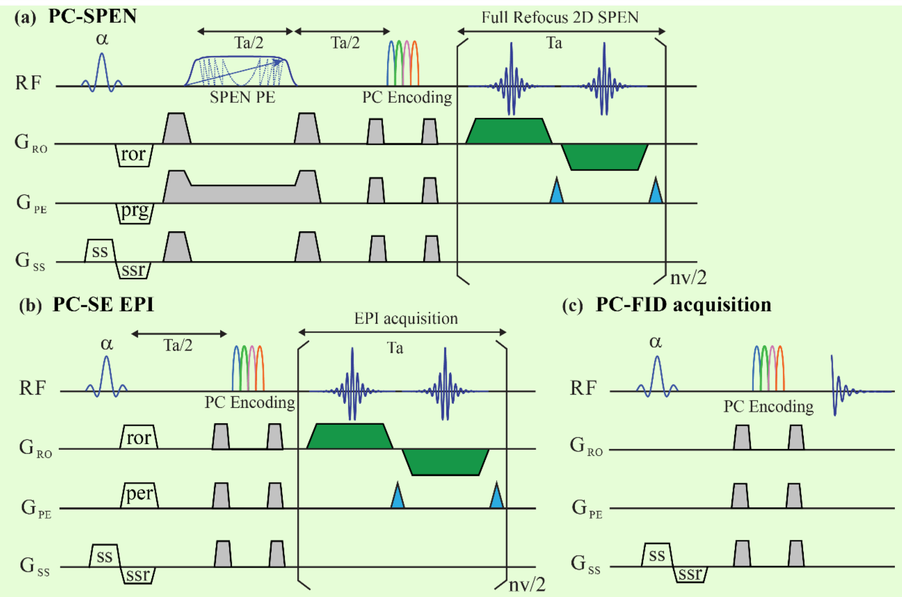

Fig. 1 (a) PC-SPEN sequence, using a phase-modulated polychromatic (PC) pulse in SPEN sequence, in order to enable the separation of the spectral peaks. (b) Analogous PC-SE EPI sequence, replacing SE-EPI's refocusing 180˚ pulse with a PC counterpart. (c) Purely spectroscopic PC-FID sequence using a PC pulse following a slice selection.

Results

The usefulness of this PC-SPEN MRSI approach is demonstrated on a metabolite phantom (Fig. 2) and in vivo water-fat separation imaging at 7 T (Figs. 3 and 4). (See captions for details) The phantom is composed of three tubes containing separate choline (III: Cho, 50 mM), N-Acetyl-L-Aspartic acid (II: NAA, 250 mM) and sodium lactate (I: Lac, 125 mM) solutions, immersed in a fourth, 15 mm diameter water tube.

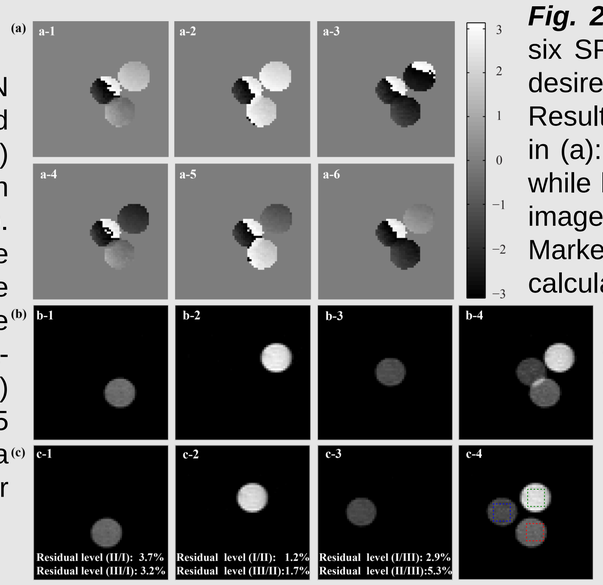

Fig. 2 Implementing PC-SPEN MRSI in the phantom (a) six SPEN images modulated by PC pulses imparting the desired FT encoding on three metabolic components. (b) Results arising from an inverse FT of the 6 images shown in (a): panels b-1~3 show the first three decoded images, while b-4 is a sum image. (c) Idem as (b), but after the (b) images were corrected by shift-derived miss-placements. Marked by squares in (c-4) are regions of interests for calculating the residual cross-talk level. Scan parameters: FOV = 20×20 mm^2; matrix size = 64×64; slice thickness = 4 mm; Ta = 24.6 ms; bandwidth of the 180˚ adiabatic encoding pulse = 4.88 kHz; PC pulse duration = 20 ms; PC phase increments M = 6; repetition time TR = 2 sec. Total scan time was 25 min, including the averaging of 128 PC-encoded experiments for SNR improvement.

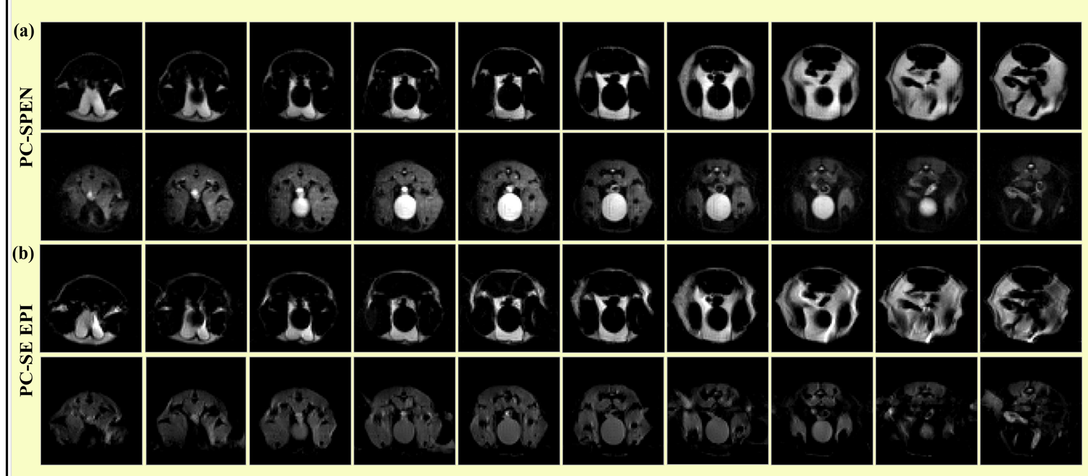

Fig. 4 In vivo fat/water separation comparisons of the PC-SPEN and PC-SE EPI multi-slicing methodologies, as applied to abdominal mouse investigations at 7T. (a) Water/fat separation from 10 slices arising from a PC-SPEN sequence with M = 3. (b) Idem but from a PC-SE-EPI sequence. Common parameters of these images were as in Fig. 3; the total scan duration for the PC-SPEN scan was 30 sec, while the PC-SE-EPI scan required 60 sec (the additional time stemming from EPI's reliance on reference scans for joint co-processing of even/odd phase-encoded lines). It shows more robustness of PC-SPEN to distortions

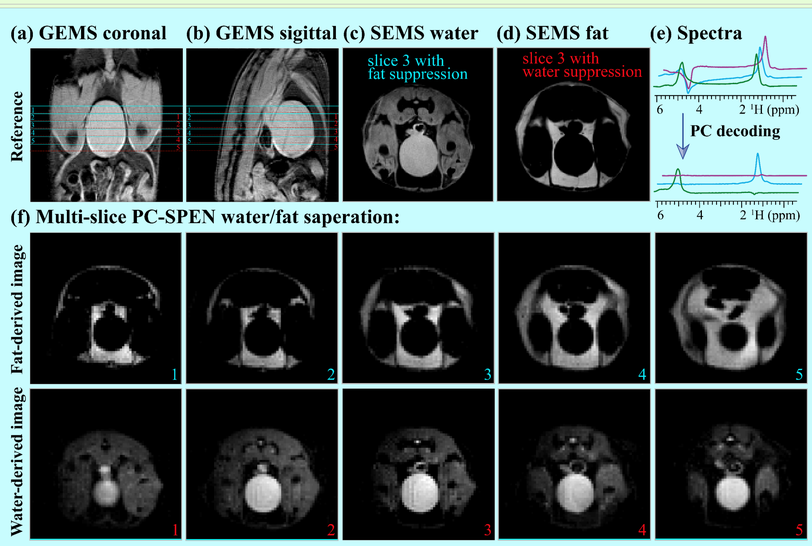

Fig. 3 *In vivo* fat/water separation using the PC-SPEN methodology, applied to abdominal mouse imaging at 7T. (a, b) Scout images for the 5-slice selection, the water-derived slices are marked in red lines while the fat-derived slices are marked in green lines. (c, d) The 3rd multiscan spin echo references involving fat suppression (c) and water suppression (d). (e) The spectra acquired using the sequence with slice selection pulse followed by PC pulses in three scans and well-separated spectra after applying a Fourier transform (PC decoding) on the encoded spectra. (f) The water/fat separation using PC-SPEN sequence, applied to the 5 slices. Common parameters of these images: FOV =40 × 40 mm^2; slice thickness = 2 mm; bandwidth of chirped pulse =10.9 kHz; PC pulse duration = 5 ms . The total scan time for PC-SPEN is 15 sec using 3 scans with PC phase modulation. The edges' decay along SPEN dimension in PC-SPEN images is due to the chirp encoding profile has rising and falling edges.

Conclusion: The PC-SPEN MRSI provides a robust technique to map multiple chemical shift images with high time efficiency.

Acknowledgments: This research was funded by Israel Science Foundation grant 795/13, by ERC PoC Grant #633888, by the Kimmel Institute for Magnetic Resonance (Weizmann Institute), and by the generosity of the Perlman Family Foundation. ZZ is thankful for financial support from the China Scholarship Council (201306310056).

References: [1]. A. Tal, L. Frydman, Prog. Nucl. Magn. Reson. Spectrosc., 2010, 57:241-292. [2]. R. Schmidt, and L. Frydman, Magn. Reson. Med., 2014, 71:711-722. [3]. Z.Y. Zhang, P. Smith and L. Frydman, J. Chem. Phys. 2014, 141:.194201. [4] A. Seginer, R. Schmidt, A. Leftin, et al., Magn. Reson. Med., 2014, 72:1687-1695.