In Vivo Single-Scan 3D Spectroscopic Imaging by Spatiotemporal Encoding

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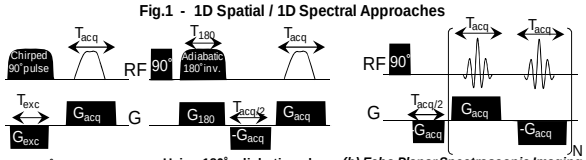
Introduction: A major challenge faced by spectroscopic imaging methods is their high dimensionality, which may lead to long acquisition times that limit their use. "Single-shot" strategies –foremost among them Echo Planar Spectroscopic Imaging [1]– alleviate this time constrain. Although a powerful aid, EPSI's echo trains face limitations related to their demand for rapidly oscillating gradients. Among EPSI's alternatives is a recent proposal for performing ultrafast imaging in multiple dimensions, using spatiotemporal encoding (SPEN) principles. In these methods, closely related to quadratic phase excitation approaches first discussed in imaging contexts by Kunz and Pipe [2-3], spins are excited sequentially in space –for instance with the aid of a chirped 90˚ RF pulse [4]. The acquired data in such experiment carries the spatial information, and its phase modulation that can convey the chemical shift offsets. This information is actually built-in into SPEN experiments, i.e., it is encoded at no extra cost in the experiment's complexity. Ref. [5] discussed a possibility to recover such additional chemical shift dimension based on a filtering procedure, although with severe compromises in the ensuing spatial resolution. The present study alleviates this limitation, and proves it in a human scanning setting.

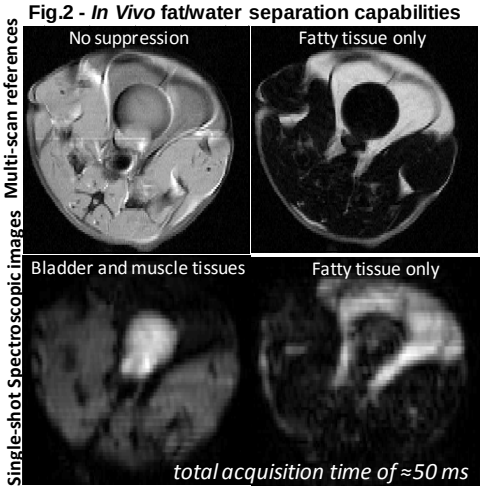
Purpose: This work extends the super-resolution (SR) algorithm for SPEN-based single-scan [6] to extract spectroscopic images, capable of dealing with the mentioned resolution as well as with relatively high Specific Absorption Rate (SAR) limitations associated with the previous proposals. This work demonstrates in-vivo 7T animal abdomen fat-water imaging and human 3T breast fat-water imaging. This work demonstrates the potential of these new sequences to extract both spatial and spectral information in DNP- and in metabolic-oriented settings.

Fig.1 - 1D Spatial / 1D Spectral Approaches



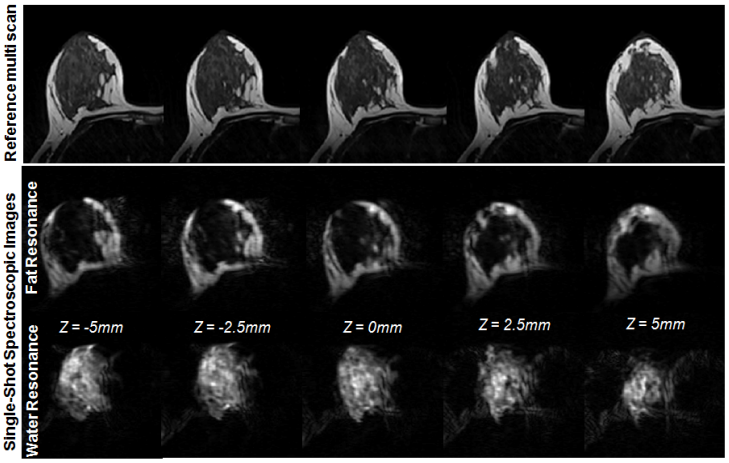
Methods: Fig.1 compares how SPEN and EPSI approaches obtain 1D spectral plus 1D spatial correlations in one scan. SPEN's simpler requirement is only a sufficiently long acquisition time to resolve among chemically inequivalent peaks which is for Fig.1a sequence with 90° chirp pulse defined as $T_{acq} > \frac{G_{exc}}{(G_{exc} - G_{acq})\Delta\nu}$ (where $G_{exc}, T_{exc}, G_{acq}, T_{acq}$ are the gradients magnitude and duration of the excitation pulse and acquisition and Δν is the resolved chemical shift). The new Extended Super-Resolution formalism hereby introduced exploits these sequences and relations, and can be summarized in the following expression: $\left| S(t_i) = \sum_{q=1}^{Q} S_q(t_i) = \sum_{q=1k=1}^{Q} \sum_{k=1}^{M} A(t_i, y_k, w_{cs}^q)\rho^q(y_k) \right|_{i=1..N}$. This can be rewritten in matrix form as $S = A_{ext}[\rho^1 .. \rho^Q]$ ($S(t)$ – measured signal, $q=1..Q$ – chemical sites, $k=1..M$ – spatial reconstructed points, $i=1..N$ – acquisition points ρ^q – spin density of each chemical site, y_k - spatial location, φ_{exc} – phase imparted by the excitation, $k(t) = \gamma \int G_{acq}(t')dt'$, w_{cs} - chemical shifts, A_{ext} is the extended point-spread-function matrix**).** Multi-slice 2D spatial plus 1D spectral versions of the pulse sequence in Fig.1 left were developed using slice-selective excitation pulses, spatial encoding using 180° adiabatic chirp pulses combined with a gradient and accomplished by echo planar Cartesian acquisition pattern. For multi-slice sequence a rewinding 180° pulse is required, to reduce SAR, 180° hard pulse was used.

Fig.2 - *In Vivo* fat/water separation capabilities



Results: A SPEN animal experiment at 7T targeting the inferior abdomen of a mouse is shown in Fig.2. The figure illustrates the abilities of the new single-shot sequence and of its associated SR-processing procedure to get good resolution with a faithful reproduction of the spatial features for both chemical sites, while the cross-talk between the two contributing spectral signals is minimal. The above example, executed at 7 T, involved a fat/water separation of approximately 1000 Hz. An additional set of images is shown in Fig. 3, with two peaks at ~420Hz separation were resolved in the highly inhomogeneous environment of the human breast imaging. This experiment was conducted at 3T Siemens TIM TRIO clinical system using 4 channels breast coil, a multi-slice scan was acquired, extracting two separated images and compared to a reference multi-scan.

Fig.3 - Comparison between five slices collected by a multi-scan gradient echo sequence against the two spectroscopically-resolved images afforded by the SPEN-based procedure



Conclusions: The results presented in this study validate the use of SPEN-based techniques as valuable additions to the existing toolkit available to reconstruct spectrally-resolved 3D images in a sub-second fashion. The ensuing spectroscopic data displays high spectral resolution and spatial definition. The resulting methods could find valuable applications, including breast imaging, characterizations of fatty tissues –particularly those involved in organs that due to breathing, pulsation or beating, experience substantial motions like liver and kidney. Another important direction of these methods is dynamic imaging aimed at experiments like fMRS, DNP.

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