Spatiotempral Encoding (SPEN) for Fast and Robust Magnetic Resonance Imaging (MRI) and spectroscopy (NMR): Principles and Applications

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1. Introduction

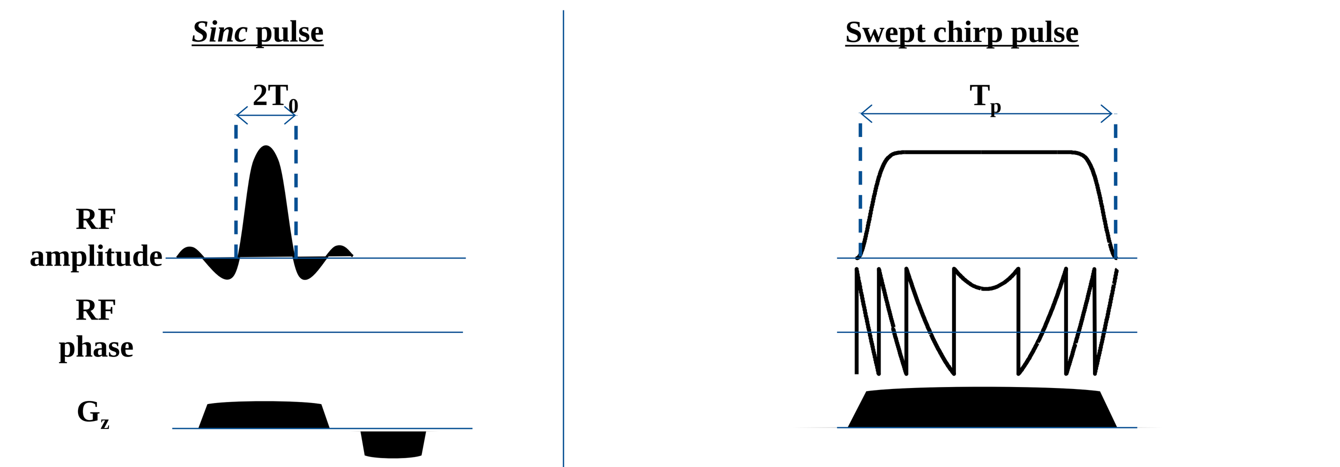
Magnetic resonance spectroscopy (NMR) and imaging (MRI) are safe and highly versatile modalities, based on fundamental concepts in quantum spin physics. Although highly informative and useful, NMR and MRI are intrinsically slow, usually requiring several minutes per scan (i.e., to deliver a 3D set of images). Faster imaging is possible, but typically suffers from image artifacts and is less robust. **Our group is developing a new approach to collecting magnetic resonance data from nuclear spins, which is both faster and more robust than existing alternatives. This poster highlights some of the new opportunities that our method has opened in the field of MRI.** Our new method is based on a special spatiotemporal encoding (SPEN), where radiofrequency (RF) pulses are applied in conjunction with suitably timed magnetic field gradient waveforms. A specialized signal processing is needed to process these data. The application of the new sequences to different important problems such as diffusion measurements to diagnose cancer, and functional MRI (fMRI) to monitor brain activities, are described below.

2. SPEN: swept chirp pulses and gradients

MRI: Spin precession frequency is linear with local magnetic field: $\omega(\vec{r}) = \gamma B(\vec{r})$

1. Apply a magnetic field gradient G_y: $\vec{B} = G_y y\hat{z}$ (linear in y pointing along $\hat{z}$). $\Rightarrow \omega(y) = \gamma G_y y$
2. Apply RF pulse with linearly varying frequency in time: $\omega_{\mathrm{RF}} = \gamma G_y L\left(\frac{t}{T_p} - \frac{1}{2}\right)$
3. At each moment a different "spin" along is effected
4. Results in a parabolic phase along the gradient's dimension $\phi(y) = ay^2 + by + c$.
5. Parabolic phase can be shifted by applying a gradient $\tilde{G}_y$ for a specified time.

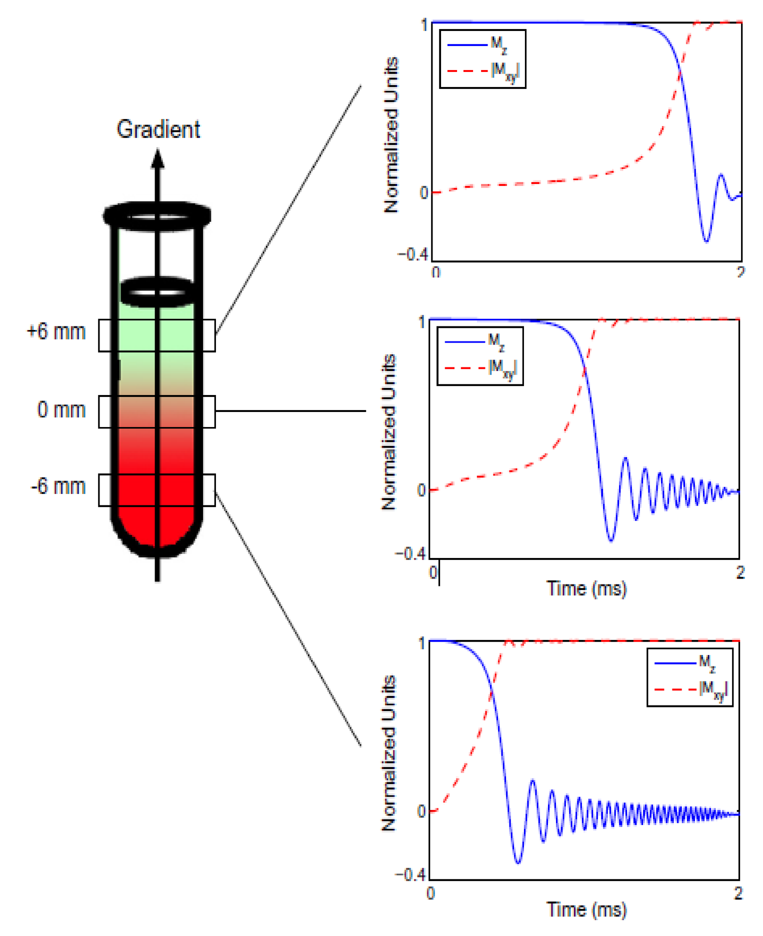
Sweep chirp pulse vs *sinc*



-Amplitude shape defines the frequency selectivity.
-Constant phase.
-Pulse duration defines the bandwidth

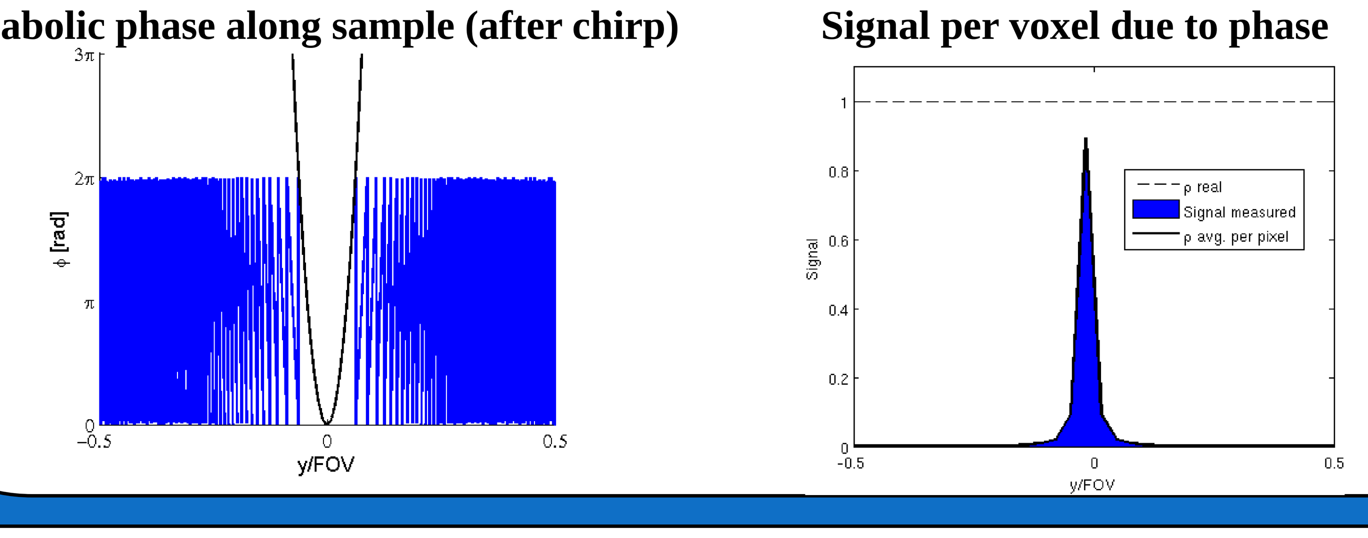
-Constant amplitude.
-Phase modulation defines the linear frequency dependence and the frequency selectivity.
-Pulse duration does not define the bandwidth

Spatial and time dependence of the spin magnetization



Signal due to parabolic phase Signal=Image

Parabolic phase along sample (after chirp) **Signal per voxel due to phase**



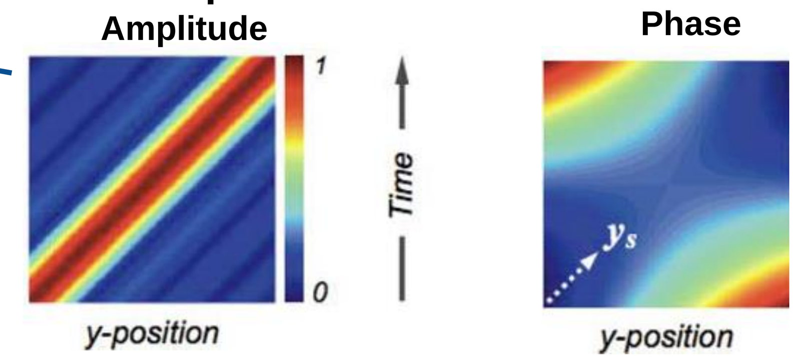
3. Image Reconstruction

Signal acquired is typically low resolution with internal inconsistencies. Post processing is required for a final high-resolution image.

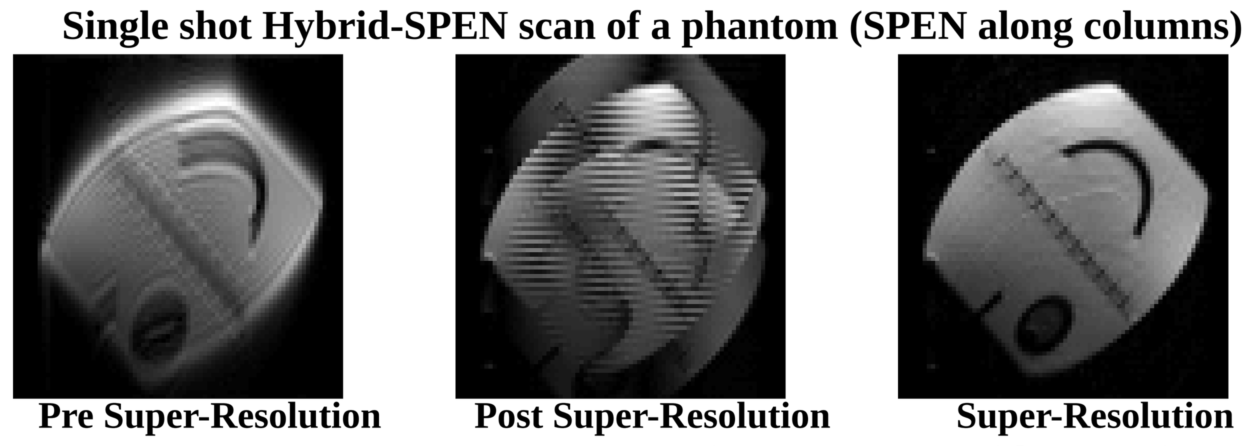
$$\vec{S}(t) = \hat{A}(y,t)\rho(y)$$

Signal ("pre super-resolution") — Object

"super resolution" matrix $\hat{A}$



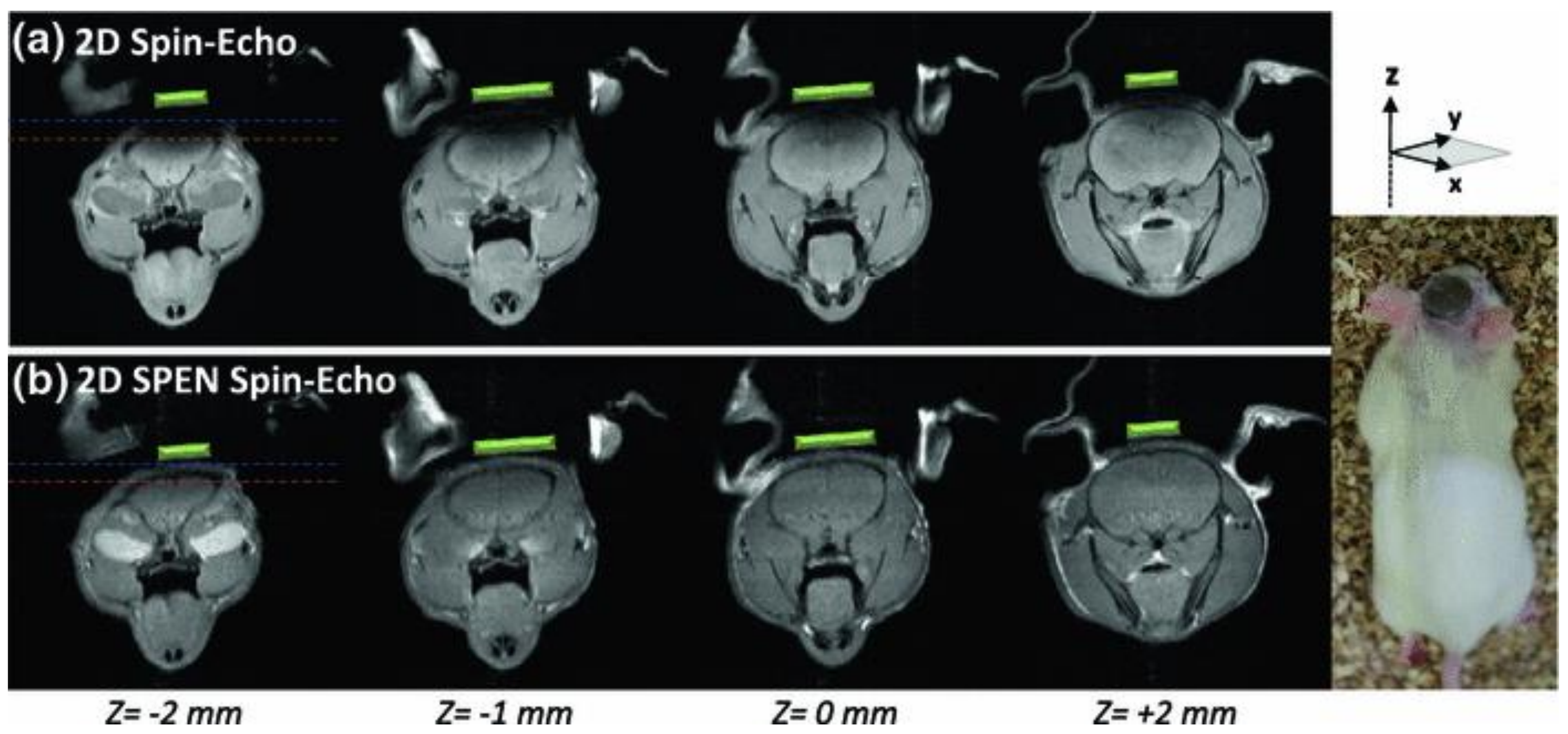
Single shot Hybrid-SPEN scan of a phantom (SPEN along columns)



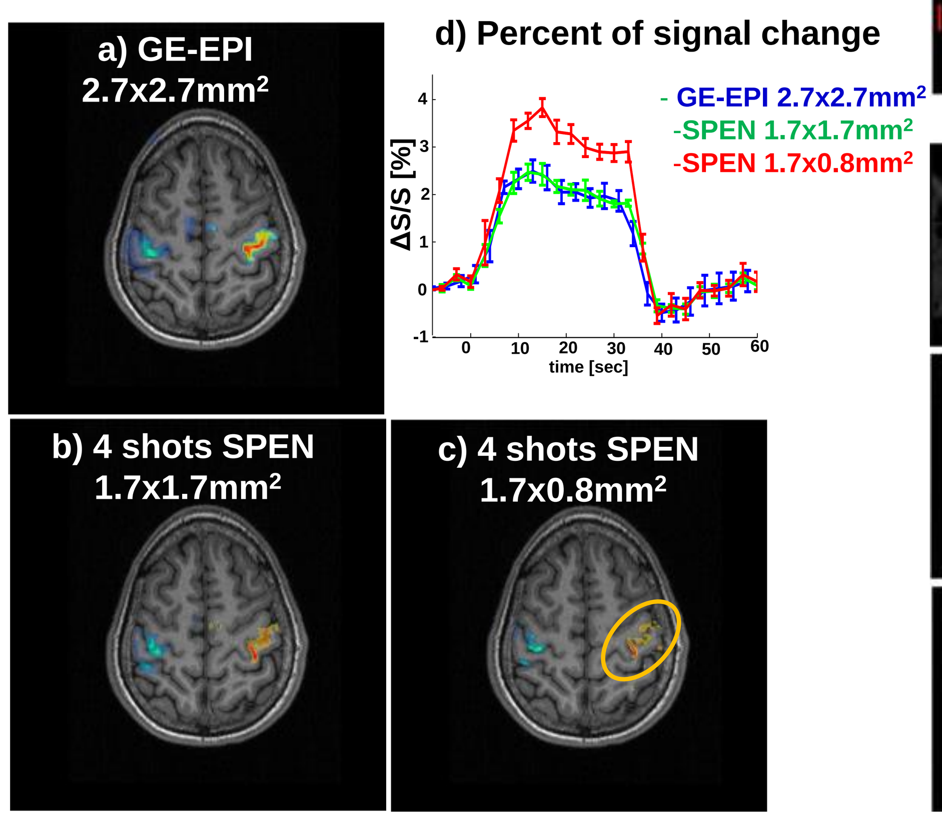
Pre Super-Resolution **Post Super-Resolution no correction** **Super-Resolution with corrections**

4. Some of our Ongoing Applications

Imaging Near Metallic Impalants (7T microimaging):

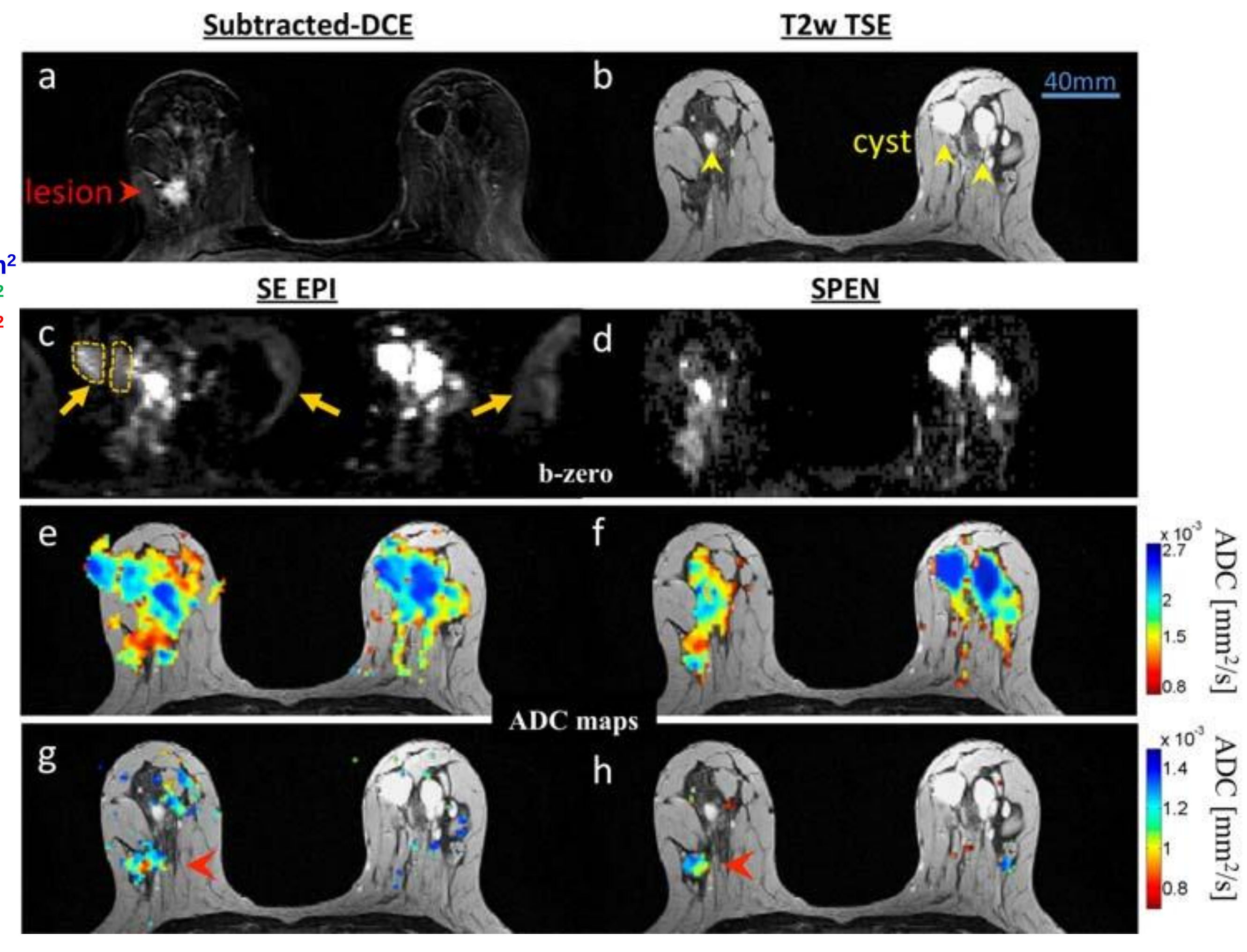


Functional SPEN MRI – Motor Activation Monitored in the Human Brain (3T) :



fMRI based on motor stimuli including all fingers tapping for 30 seconds, interleaving right and left hands for a 5 minutes total study duration (5 pairs of stimuli blocks).

Breast Cancer Patient – Detection of malignancies by SPEN-based Diffusion Imaging (3T) :



Comparison between images derived from SE-EPI and single-slice SPEN scans of a patient with IDC. Red arrowheads indicate the cancer; yellow arrowheads indicate the cysts; dashed orange regions highlight the folding of cysts and fat

Results presented above from the following references:

Ben-Eliezer N., Irani M., Frydman L. Super-Resolved Spatially-Encoded Single-Scan 2D MRI. MRM; 63:1594–1600, 2010.
Ben-Eliezer N., Solomon E., et al. Fully refocused multi-shot spatiotemporally encoded MRI: robust imaging in the presence of metallic implants. MAGMA; 25(6): 433-442, 2012.
Schmidt R., Seginer A., Frydman L. An interleaved multi-shot scheme involving self-refocused single-scan SPEN that is immune to in-plane movement and phase shifts. Proc. Intl. Soc. Mag. Reson. Med. 22 (2014).
Seginer A., Schmidt R., et al. Referenceless reconstruction of spatiotemporally encoded imaging data: Principles and applications to real-time MRI. MRM; 72:1687–1695, 2014.
Solomon E., Nissan N., et al. Overcoming Limitations in Diffusion-Weighted MRI of Breast by Spatio-Temporal Encoding. MRM; 2014; doi: 10.1002/mrm.25344.
Tal A., Frydman L. Single-scan multidimensional magnetic resonance. Prog. Nucl. Magn. Reson. Spectrosc.; 57: 241–292, 2010.

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Conclusions: **Ultrafast and fast SPEN acquisitions can offer a new alternative with an improved robustness to B_0 inhomogeneity. In-vivo animal and human imaging studies promise valuable gains in functional and diffusion MRI as well as other applications.**