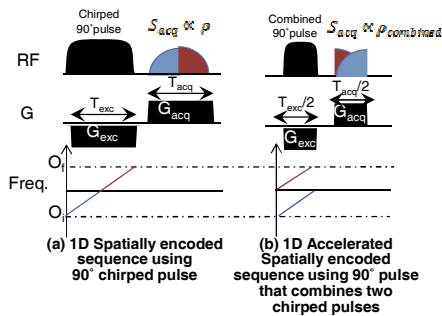# Parallel Imaging by Multi-band Spatiotemporal Encoding and a Combined Super-Resolved / SENSE Reconstruction

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Introduction. Recent studies described the potential of single shot methods based on spatiotemporal encoding (SPEN) principles [1,2] as alternatives to classical "ultrafast" scanning methods based on echo planar imaging (EPI) [3]. SPEN displays a high robustness to frequency offsets, particularly if implemented in a "full-refocusing" mode capable of eliminating T_2^* effects [4]. In addition, recent super resolution methods have been adapted to SPEN imaging [5] and demonstrated to afford a spatial resolution comparable to k-space imaging while substantially reducing the SAR and enhancing the sensitivity. An important step still needed to endow SPEN scanning with contemporary competitiveness, involves incorporating into the sequence the parallel imaging capabilities of modern scanners –without compromising the achievements of super resolution reconstruction. Given the differences between *k*-space encoding and SPEN –where the collected signal *is* the image– these two ingredients need to be carefully balanced. The present work demonstrates the use of multi-band chirp pulses applied in combination with a gradient, to simultaneously encode multiple partial field-of-views (pFOVs). This approach, already discussed in [6], is here combined with a super-resolved SENSE-based [7] method, to reconstruct the full FOV image using a-priori known spatially encoded point-spread-function and the receiver's channels sensitivity maps. The sequences implemented using 90° and 180° two-band chirp pulses, for single-slice and multi-slice scans. The performance of the new sequences and of their customized reconstruction algorithms were explored in phantoms and in human imaging scans at 3T.

Fig. 1- 1D SPEN Regular/ Accelerated Approaches

(a) 1D Spatially encoded sequence using 90° chirped pulse
(b) 1D Accelerated Spatially encoded sequence using 90° pulse that combines two chirped pulses

Methods. Figure 1 compares a regular 1D imaging sequence based on SPEN principles, with the kind of accelerated parallel sequences assayed in this work. The accelerated sequences contain an excitation pulse that incorporates multiple (N_{SP}) chirp pulses with bandwidth $G_{exc}FOV/N_{SP}$, and centers of mass frequencies that are shifted by $G_{exc}FOV/N_{SP}$ frequency increments from one another. This multi stationary-point encoding can be created by applying a pulse $P(t) = \sum_{n=0}^{N_{SP}-1} A_n e^{i \cdot 2\pi(\frac{\gamma G_{exc}FOV}{2T_{exc}}t^2 - \frac{\gamma G_{exc}FOV}{2}t + \frac{\gamma G_{exc}FOV}{N_{SP}}nt)}$, where $P(t)$ is the pulse's complex shape, N_{SP} is the number of bands / stationary points, G_{exc} and T_{exc} are the gradient and duration of the full FOV acquisition. The signals $S_j(t)$ detected in the subsequent multi-channel/coil acquisition can be expressed by the point-spread-function (A) to be involved in the super resolution reconstruction [4], and by the sensitivity maps of the channels C_j ($j=1..N_c$) according to

$$S_j(t) = \sum_{n=0}^{N_{SP}-1} \int_{FOV} A(t, y + \frac{nFOV}{N_{SP}}) \cdot C_j(y + \frac{nFOV}{N_{SP}}) \cdot \rho(y + \frac{nFOV}{N_{SP}}) dy.$$

This expression can be rewritten in matrix form and solved. Two parallelized Hybrid SPEN sequences were implemented on the basis of these concepts: one using the two-band 90° chirp pulse for the excitation, a 180° slice-selective pulse for achieving full refocusing, and an acquisition using a Cartesian k/SPEN sampling pattern, where the readout is encoded by k-space and the phase encoding direction serves as spatially encoded direction. A second sequence using a slice-selective excitation, a multi-band 180° SPEN-encoding pulse and acquisition parameters as before was also used; and concluded by a 180° hard pulse for rewinding. Experiments on phantoms and human volunteers were conducted at 3T Siemens TIM TRIO clinical platform using 4-channels brain and breast coils.

Fig.2 – Reconstruction comparison

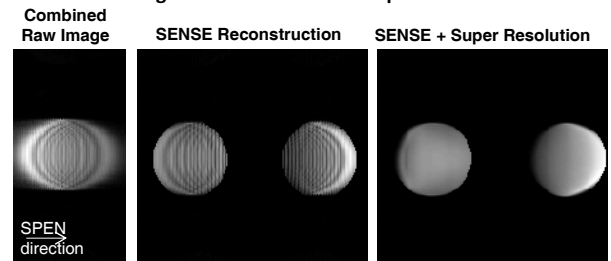Combined Raw Image   SENSE Reconstruction   SENSE + Super Resolution

Results. Figure 2 illustrates a phantom experiment using 4-channels breast coil, comparing reconstruction using the classical SENSE algorithm against SENSE combined with the Super Resolution method. It can be easily appreciated that the combined SENSE and Super Resolution delivers significant faithfulness gains in the object's reconstruction. Figure 3 shows a similar experiment carried out on a volunteer's brain scan, whose slice was chosen so as to afford heavily distorted EPI images near one of the ears. The figure compares multi-scan reference, EPI, fully refocused regular Hybrid SPEN, and finally the accelerated parallelized Hybrid SPEN using the 90° chirp pulse sequence under fully-refocusing conditions. The results clearly show that the Hybrid SPEN is less distorted then EPI, and that thanks to its shortened echo times the accelerated Hybrid SPEN has even smaller distortions as well as enhanced signal-to-noise. Important to note is Super-Resolution's capable handling of the "interface" between the various encoded bands, an artifact which was drastically larger when utilizing SPEN with a SENSE-based reconstruction but without Super Resolution.

Conclusions. This study demonstrates that Hybrid SPEN sequences implemented using multi-band pulses for accelerating the encoding and acquisition, can substantially enhance the resulting single-shot images. The implemented reconstruction combined Super Resolution with SENSE methods and showed reasonable reconstruction robustness. Parallel SPEN imaging can then be exploited for improving resolution or for enhancing sensitivity/ faithfulness due to shorter echo times.

Fig. 3 – Brain Imaging comparison – multi-scan reference, EPI , fully refocused regular and accelerated Hybrid SPEN

Multi scan   EPI   Hybrid SPEN   Accelerated Hybrid SPEN

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