An interleaved multi-shot scheme involving self-refocused single-scan SPEN that is immune to in-plane movement and phase shifts

Rita Schmidt[1], Amir Seginer[1], and Lucio Frydman[1]
[1]*Chemical Physics, Weizmann Institute of Science, Rehovot, Israel*

Introduction. Echo Planar Imaging (EPI) [1] is MRI's standard when considering ultrafast applications. Recent studies have shown the benefits of relying on single-shot spatiotemporal encoding (SPEN) upon imaging regions that are challenging: this ultrafast technique can reduce magnetic field inhomogeneity distortions, cope with restricted FOVs and deliver chemical shift information, at no additional expense [2-4]. The present work demonstrates that SPEN can also exhibit substantial motion immunity, even when executed in interleaved multi-shot schemes. Interleaved or segmented EPI is well known for its abilities to improve SNR or resolution [5] and increase robustness against ΔB_0, but it can suffer from ghosts, artifacts or blurring related to the multi-scan reconstruction. These artifacts can be partially eliminated by phase correction based on a reference scan, but reference scans often fail to overcome transient events. It is here shown that unlike what happens in EPI, multiple shots of interleaved SPEN MRI data can be co-processed to generate common full FOV images, without ghosts and without requiring navigator or extra reference scans. This results from SPEN's direct-space imaging nature: since no FT-derived aliasing is involved, a phase correction enabling the joint processing of data stemming from different SPEN scans can be estimated, along the lines proposed for the referenceless, ghost-free reconstruction of single shot SPEN images [6]. In this manner, not only can transient phase shifts between scans be eliminated, but also in-plane movements of an object between shots can be corrected. The end result of all this is an image with no artifacts and with a better SNR (and/or resolution) than single-shot counterparts. This can be particularly valuable in functional and diffusion MRI, as well as in real time imaging applications. Preliminary tests confirm the advantages of this approach on phantom and human scans, including functional MRI experiments performed at 3 T.

Fig.1 – Interleaved multi shot SPEN sequence

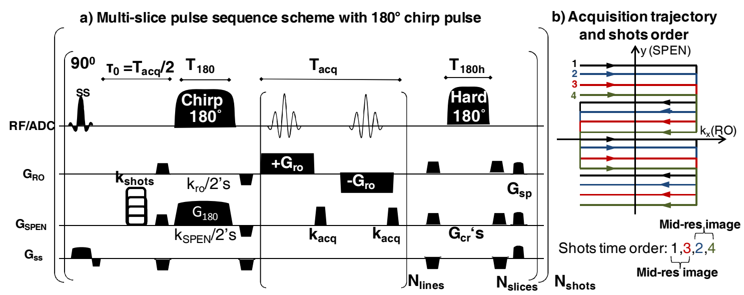
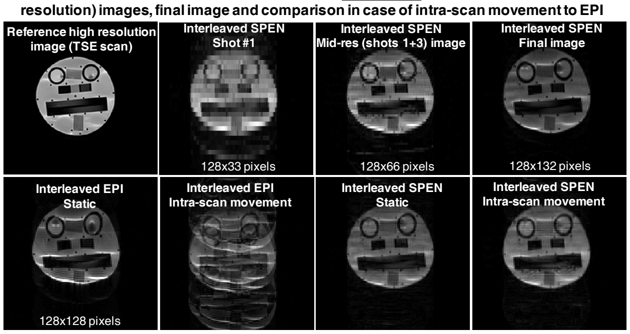
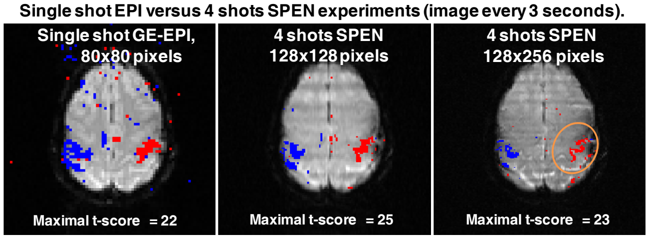


Fig.2 – Interleaved 4 shots SPEN on phantom. No aliasing in the intermediate (lower resolution) images, final image and comparison in case of intra-scan movement to EPI



Methods. The new interleaved multi-shot SPEN scheme hereby proposed (Fig. 1) includes 90° or 180° chirp pulses acting in unison with a gradient for spatiotemporal encoding; these impart a parabolic phase that is later moved through the FOV during the acquisition by a corresponding gradient [2]. To implement an interleaved scheme with N_{final} image pixels in N_{shots}, the gradients in the SPEN direction were designed so as to move the individual scans' parabolic phases by $k_n^{shot} = n \cdot \lambda \cdot \gamma G_p T_p / N_{final}$, where n=1..$N_{shots}$ is the shot index, and with the steps in the SPEN acquisition dimension being $\Delta k_{acq} = \frac{\lambda \cdot \gamma G_p T_p}{(N_{final}/N_{shots})}$ (λ=1 or 2 for 90° or 180° chirp pulse, respectively). Figure 1 illustrates the 180° chirp pulse encoding case, with a multi-slice option. The data reconstruction along the SPEN dimension to yield the final (as well as intermediate) image(s) was performed using a Super Resolution algorithm, representing the signal as $S = A\rho$, where ρ is the spin density profile and A is the point-spread-function that corresponds to the chirp pulse and acquisition parameters [7]. The bandwidth of the pulse and the refocusing timing conditions [2,8] will define the scan's level of immunity to B_0 inhomogeneities; as can be seen in Fig. 2, the multi-shot scheme shows an even higher ΔB_0 immunity than its single shot counterpart. Notably, no effects arise in these instances even from inter/intra-scan movement. The reconstruction method for N_{shots} involves: i) applying a positive/negative readout gradient phase correction for each shot [6]; ii) applying a phase correction between shots leading to a mid-resolution image reconstruction (e.g., scans 1+3 and 2+4 in Fig.2); iii) correct phase incongruences among these various mid-resolution images, iv) perform a final super-resolved image reconstruction. The method can be generalized to any number of shots and can include spatial co-registration and motion correction, as was performed in Fig.2 example in case of movement of the object between the shots. In addition, functional MRI experiment with finger tapping motor stimuli (30 seconds for each hand, 4 minutes total) were performed, and single shot GE-EPI (TE=30 ms, TR=3 sec) was compared against four-shots SPEN experiments using the sequence in Fig.1 with appropriate delays before acquisition for T_2^* weighting of 30 ms, a TR=750 ms (final image every 3 sec) and a flip angle of 60°. Phase correction, registration and reconstruction, as well as the functional maps, were calculated from the GE-EPI and multi-shot SPEN data using MATLAB custom written code. The phantom and brain human volunteer experiments were performed on a 3 T Siemens TIM TRIO clinical platform using a 4-channels brain coil.

Fig.3 – Functional activation maps (|t|>5) overlay for a motoric stimuli. Single shot EPI versus 4 shots SPEN experiments (image every 3 seconds).



Results. Fig. 3 shows functional activation maps overlaid on the single shot EPI and on four-shots SPEN experiments. Notice the latter is with higher spatial resolution compared to the single shot EPI. The results demonstrate similar t-score values; however, in the case of the higher resolution image achieved by four-shots SPEN t-scores overlay follows more precisely the anatomical region of activation (marked by an orange circle).

Conclusions. The resulting experiments demonstrate that interleaved multi-shot SPEN can be exploited for achieving higher SNR, better resolution and less sensitivity to motion artifacts at no expense in the effectiveness of the data acquisition.

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