Fully-Refocused Multi-Slice Ultrafast 3D MRI by Spatiotemporal Encoding

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Introduction. Single-shot acquisition sequences for 2D/3D imaging play key roles in a growing number of MRI applications. Echo Planar Imaging (EPI) [1] leads among these "ultrafast" experiments, even though its optimal signal sampling is often challenged by the presence of magnetic field inhomogeneities, chemical shift offsets, or sampling artifacts. Recent studies based on spatiotemporal encoding (SPEN) principles showed that many/all these challenges can be alleviated, particularly if implemented in a "full-refocusing" mode capable of eliminating T_2* effects [2]. This kind of encoding requires that the time periods elapsed between a spin-packet's excitation and its localized detection, be symmetrically placed around a 180˚ inversion pulse; the ensuing sequence displays a high robustness to all kind of frequency offsets/inhomogeneities. The present work extends this imaging modality from the single-slice acquisition form in which it has hitherto been implemented [3], by introducing a variety of new 3D multi-slice schemes. These new sequences employ either inversion or –for lower Specific Absorption Rate SAR)– stimulated echo pulses for performing the SPEN encoding, and are timed in ways that fulfill the demands of full-refocusing. In addition, a fully-refocused bi-axial 2D SPEN approach is presented. To maximize the quality of the resulting images super-resolved data processing [4] was customized as needed. The work confirmed the advantages of carrying out these new single-shot multi-slice 2D imaging modalities with *in vivo* animal and human scans performed at 3T and 7T.

Methods: A chirp pulse combined with a gradient imposes on the spins a quadratic phase that defines in its stationary point, the dominant region contributing at any given time to the observable Free Induction Decay (FID). SPEN exploits this FID to investigate an object's density: if the minimum of this parabola is shifted by an initial purging gradient of area $|k_{rg}| = \gamma G_{180} T_{180}$ (G_{180} is the gradient magnitude and the is T_{180} the chirp pulse duration) and the ensuing FID is monitored as a function of an acquisition time t while under the action of a gradient G_{acq} (gradient applied during acquisition), the sample's density $\rho(y)$ will be probed in a point-wise manner [2]. An image thus become available; not by FT but rather directly by the FID's magnitude As shown in [5], the condition to cover a full targeted FOV_y encoded by a 180˚ chirp is: $2 \cdot \gamma G_{180} T_{180} = \int_0^{T_{acq}} G_{acq}(t)dt$ (G_{acq}, T_{acq} being the acquisition gradient and duration). The position of this inversion pulse within the actual multi-slice sequence can in fact be manipulated; in this study we changed its placement so as to fulfill the demands imposed by full-refocusing. In such fashion any field inhomogeneity and/or offset effect experienced by a spin-packet will not influence the acquired signal, leading to images that are largely immune to T2* distortions. In abbreviated form, and skipping the readout dimension parameters which are as in conventional EPI, the new sequences that were here tested contained two arrangements of fully refocused sequences using 180° chirp pulse for hybrid encoding: a) $[90°_{ss}\text{-}\tau\text{-}180°_{chirp}\text{-ADC-}180°_{hard}]_{Nslices}$ and b) $[90°_{ss}\text{-}180°_{chirp}\text{-}\tau\text{-}180°_{hard}\text{-ADC}]_{Nslices}$ Two additional sequences that used stimulated echoes to reduce the SAR significantly, were also tested: c) $90°_{hard}\text{-}180°_{chirp}\text{-}\tau\text{-}90°_{hard}$ $-[90°_{ss}\text{-ADC}]_{Nslices}$, d) $90°_{chirp}\text{-}90°_{hard}$ $-[90°_{ss}\text{-ADC}]_{Nslices}$. Finally, a sequence with spatial encoding of both in-plane dimension using two 180° chirp pulses, was also tested: e) $[90_{ss}\text{-}180°_{chirp\ slow}\text{-}\tau\text{-}180°_{chirp\ fast}\text{-ADC}]_{Nslices}$ (when τ is the delay that is set to fulfill the fully refocusing, in this bi-SPEN sequence the two chirp pulses $180°_{chirp\ slow}$ and $180°_{chirp\ fast}$ encode two spatial dimensions and the quotation marks represent a loop versus acquired slices). The fully refocused conditions established for 180° chirp pulse sequences are: $T_{180}=\tau=T_{acq}/2$, comparing $T_{exc}=T_{acq}$ for 90° chirp pulse sequence. After a set of phantom experiments, in-vivo experiments on mice were conducted at 7T Varian VNMRS vertical imaging system using FOVs of 30x30x46 mm^3. A second set of experiments focused on brain imaging in human volunteers was collected on the 3T Siemens TIM TRIO clinical platform using a 4-channels brain coil.

Fig.1 – 7T phantom experiment –multi-scan reference, multi-slice EPI and fully refocused Hybrid SPEN

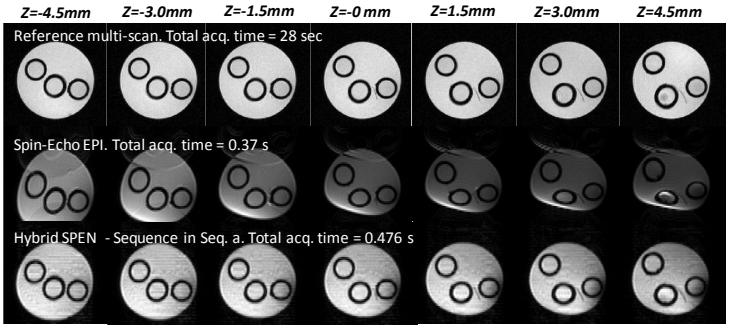
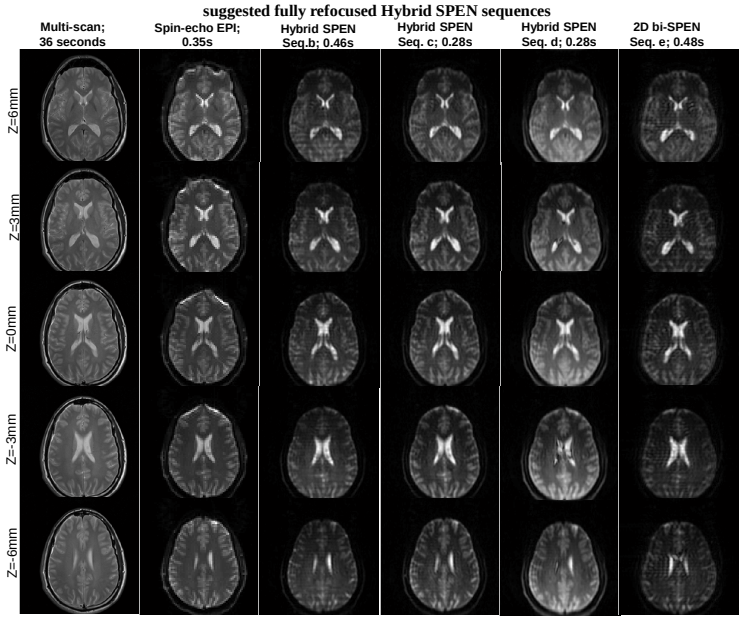


Fig.2 – 3T human brain imaging – comparing multi-scan reference, multi-slice EPI and all suggested fully refocused Hybrid SPEN sequences



Results. Figure 1 illustrates 7T phantom experiment by comparing multi-scan, multi-slice EPI and Hybrid SPEN seq.a. High robustness of the SPEN sequence is evident versus EPI scan. Fig. 2 displays 3T volunteer brain imaging comparing all suggested sequences.

Conclusions. The resulting experiments demonstrate that Hybrid SPEN can serve as practical 3D imaging alternatives to EPI. If suitably timed to achieve full ΔB_o and chemical shift refocusing, all the new experiments here introduced evidenced significant advantages in terms of dealing with field distortions and heterogeneities along the single-scan "slow" dimension. The sensitivity and resolution of all the new SPEN sequences was very competitive thanks to the use of suitable super-resolution methods. The stimulated echo sequences decreased SAR to levels comparable –and in fact even lower– than those involved in spin-echo EPI.

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