SIR-EPI Diffusion Imaging for 3-fold faster scan time to enable trade-offs in slice coverage and Gradient duty cycle reduction.

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Introduction: Diffusion imaging with HARDI techniques places high demands on gradient performance and data acquisition times, with human brain studies requiring often long scan times of greater than 30 minutes. The use of high b-values encoded with lengthy high amplitude gradient pulses increases the gradient duty cycle and the resistive heat loss in the coils ultimately places limitation on the data acquisition, either in maximal b-value or the maximum number of slices encoded within the TR repetition. Simultaneous Image Refocused (SIR) EPI has been demonstrated with two echoes per switched gradient read period in EPI for nearly a factor of 2 reductions in HARDI imaging time. Here, we develop and evaluate SIR with two and three echoes per read period (SIR-2, SIR-3) for faster scan times, greater slice coverage and reduced gradient duty cycle, a means to overcome limitations in HARDI imaging.

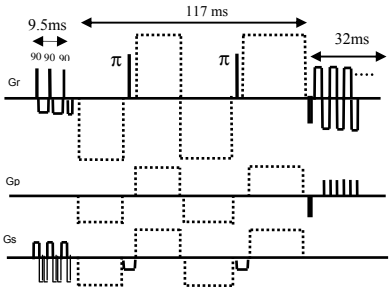

Fig.1. SIR-3 Pulse sequence diagram with b = 5000 (dotted lines= diffusion pulses) for one SIR set of 3 slices.

Methods: Experiments performed on a 3T scanner (Siemens Trio) with 40 mT/m maximum gradient, 200 slew rate, 12 and 32 channel coils. Four normal volunteers were imaged under institutional guidelines. Parallel imaging using GRAPPA factor 2 was applied in all studies. The acquisitions had the following parameters; TR/1900-2700ms, TE/135ms, BW/1185Hz/px, 30slices/TR, final image matrix/64*64, total acquisition time SIR-2 11.46min, SIR-3 8.46min, and nominal image resolution/ 3.0mmx3.0mmx3.5mm. The conventional EPI DWI images used TR/5900ms, TE/140ms, and BW/1390 Hz/px in which the TR was the minimum allowed by the gradients. The SIR-EPI DWI pulse sequence is shown in Fig. 1, in which the time between 90^{O} RF pulses is 4.6 ms. The phase encoding was performed identically for all slices for the center of k-space, k_o occurring on the same readout period, therefore, for SIR-2 there was a 4.6ms offset from the Hahn SE (HSE) time for one slice, whereas in SIR-3 there was 0ms, 4.7ms and 9.5ms offsets from HSE time for adjacent groups of 3 slices. A simple approach to eliminate these differences is with additional phase encoding pulses, discussed below, is in progress but not yet implemented in these results.

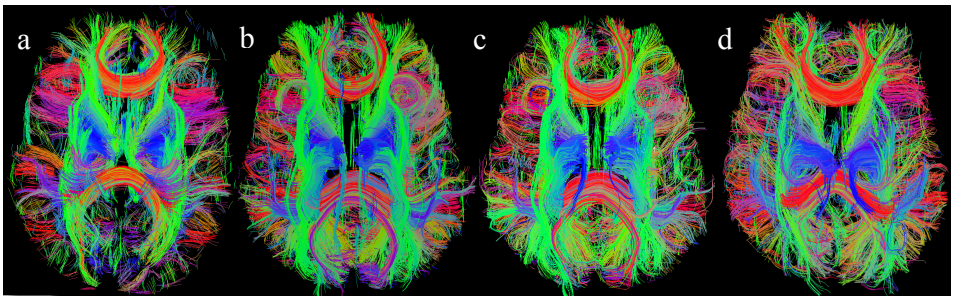

Fig.2. DSI images acquired with **a**) conventional EPI in 25.3 min **b**) SIR-2 in 11.46 min, **c**) SIR-3 in 11.46 min with reduced gradient duty, **d**) SIR-3 EPI in 8.46 min.

Results: Fig. 2 shows DSI reconstructed images using conventional EPI, SIR-2, and SIR-3 EPI in scan times of 25.3 min(TR = 5900ms), 11.46min(TR = 2700ms) and 8.46 min(TR = 1900ms), respectively. The SNR measured in respective source images showed general decrease in SNR with greater SIR factor, as measured in b-value of 1000 in the centrum semiovale white matter, 3.42 (SIR-2) and 2.82 (SIR-3). In SIR-2 there was a 5-6% variation in signal intensity between the two simultaneously read slices and in SIR-3 there was a 15-20% difference.

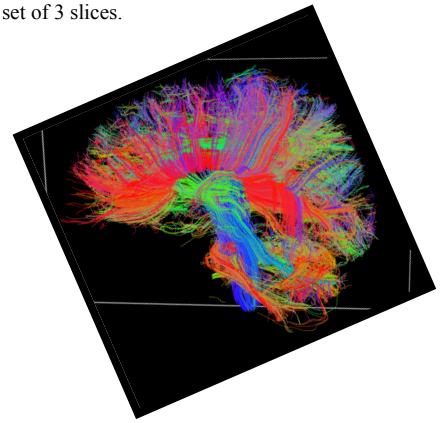

Fig.3. SIR-3 EPI used to increase slice coverage from 30 to 39 slices in TR of 2600ms.

Fig 3 shows application to increase slice coverage from 30 in SIR-2 to 39 in SIR-3 within a TR/2600ms. Fig.2 shows application to reduce gradient duty cycle using SIR-3 to obtain the same number of 30 slices as SIR-2 in TR/2700ms but with a 33% reduced number of diffusion gradient pulses from SIR-2 and 66% reduction from conventional EPI in Fig.2a. The images shown are not exactly in the same rotational orientation accounting for different appearance in some fiber tracts.

Discussion: The overall anatomical fiber bundles are represented in these similar quality DSI images with an approximately 3 fold scan time reduction using SIR-3. It is perhaps more important that the SIR EPI acquisitions provide new ability to optimize with trade-offs in scan time, SNR, and gradient duty cycle currently limiting HARDI imaging techniques. For example, use of stronger gradient amplitudes of 70 mT/m obtainable in some head gradient inserts and potentially up to 300 mT/m in future designed gradient coils will ultimately be limited by resistive heating losses, and therefore the use of multiplexed diffusion imaging techniques such as SIR EPI or other techniques such as 3D GRASE and Multi-banded RF pulses will be useful.

There are several areas of further improvement for the SIR SE sequences presented here, namely the use of G_p pulses between the 90^{O} RF pulses to offset k_o of different slices to fall onto their respective HSE times for reduced susceptibility. The use of 180^{O} refocusing pulses in these SIR SE EPI sequences reduces susceptibility signal loss that would greater with longer echo trains in GE SIR EPI. The use of parallel imaging greatly reduces the echo train length to reduce image distortions. The TE, M-factor, BW and TR differences are calculable effects on SNR, while susceptibility artifacts and distortions appear predictably similar between all images, Fig.4.

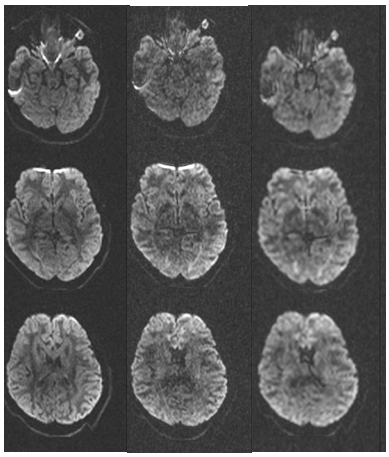

Fig.4 Comparison of distortion and susceptibility artifacts at b-1000 with 3 of 30 slices shown: **Left**) EPI, **middle**) SIR-2 EPI, **right**) SIR-3 EPI. The major differences are in T2 contrast from later TEs. There is similar susceptibility signal loss artifact, identifiable in top images of temporal lobe and frontal lobe rectus gyrus and there are similar distortions.

Conclusion: We have presented factors of 2 to 3 time reduction in HARDI image acquisitions by means of the first demonstration of SIR-3 EPI diffusion imaging. Rather than simply reducing scan time, SIR EPI sequences may be useful to obtain higher resolution or larger slice-axis field of view by acquiring more slices per TR or instead for controlling heat limitations using high b-values by reducing the gradient duty cycle that can become too high in HARDI acquisitions.

References: 1) Feinberg, Reese, Wedeen, MRM 2002, Jul;48(1):1-5.; 2) Reese et al 2009 JMRI Mar;29(3):517-22. ; 3) Gunther, Feinberg, Magn Reson Med. 2005 Sep; 54(3):513-23.