in vivo Ultrafast Diffusion Imaging of Stroke at 21.1 T by Spatiotemporal Encoding

Jens T Rosenberg[1,2], Avigdor Leftin[3], Eddy Solomon[3], Fabian Calixto Bejarano[1], Lucio Frydman[1,3], and Samuel Colles Grant[1,2]
[1]*National High Magnetic Field Laboratory, The Florida State University, Tallahassee, FL, United States,* [2]*Chemical & Biomedical Engineering, The Florida State University, Tallahassee, FL, United States,* [3]*Chemical Physics, Weizmann Institute of Science, Rehovot, Israel*

Target Audience: Researchers and clinicians interested in rapid and susceptibility-free imaging in ischemic stroke.

Introduction: Two of the most pressing concerns in MRI have been the enhancement of image signal-to-noise and speed of image acquisition. The former has motivated a push to higher magnetic fields while the later issue has inspired other imaging techniques such as echo-planar imaging (EPI). Ironically, these techniques also can degrade image quality by means of susceptibility gradients and other artifacts that distort not only anatomical information but also the quantification of diagnostically relevant quantities, such as water diffusion. A new suite of super-resolved ultrafast single-shot spatiotemporally encoded (SPEN) imaging sequences [1] that are robust in the presence of high-field artifacts and offer high temporal resolution can address these concerns. This work implements diffusion weighted imaging (DWI) SPEN variants, and applies them to pre-clinical *in vivo* models of stroke assessed at the 21.1-T MR system at the National High Magnetic Field Laboratory (NHMFL). While providing the highest sensitivity available, this system challenges DW-EPI because of susceptibility artifacts and gradients that are prominent at the ultra-high field. This work compares *in vivo* diffusion quantification in ischemic stroke injuries of rats using SPEN-DWI, DW-EPI and DW spin-echo (SE) acquisition methods.

Purpose: To determine if diffusion-encoding spatiotemporally encoded imaging can provide more accurate quantification of in *vivo* ADC in stroke.

Methods: The SPEN-DWI sequence (Fig 1) were implemented on the 21.1-T, 900-MHz ultra-widebore magnet using a Bruker (Billerica, MA) Avance III spectrometer. The sequences are based on an EPI readout, with the 90° excitation substituted by a chirped pulse imparting the SPEN encoding while in the presence of a gradient [1]. For slice selection, a standard three-lobed 180° sinc pulse was used, with diffusion encoding gradients surrounding the pulse. Fully refocused SPEN signals were acquired with a 30-40 ms EPI readout covering a FOV of 32×32×2 mm using a matrix size of 100×100 and TR = 12 s. SPEN-DWI was obtained at six b-values (0, 200, 400, 600, 800 and 1000) along the principal axes. Post-processing of the SPEN-DWI datasets was carried out using MATLAB (MathWorks, Natick, MA) for echo alignment and the application of a super-resolution algorithm [1]. ADC maps were calculated in MATLAB incorporating all background gradient corrections for the SPEN-DWI sequence [3]. ADC data was acquired by 1 and 4 segmented DW-EPI. The EPI data were registered to the b_0 image of each diffusion direction using AMIRA (FEI Visualization Science Group, Burlington MA), and ROIs were drawn to cover the stroke and contralateral side. DW-SE images were acquired with 4 b-values to generate data with the same resolution and geometry within a reasonable time (1.5 h). Similar acquisition parameters were used for all experiments. For *in vivo* experiments, ischemic stroke was induced by middle cerebral artery occlusion (MCAO) and occluded for 1.5 h following reperfusion [2]. Four MCAO stroked rats and one control rats were scanned 24, 48 and 72 h after the induced stroke.

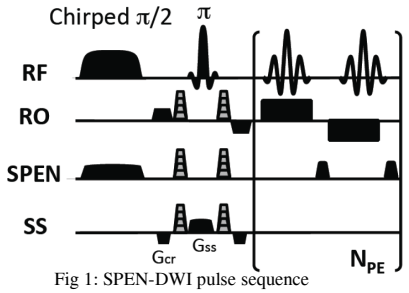

Fig 1: SPEN-DWI pulse sequence

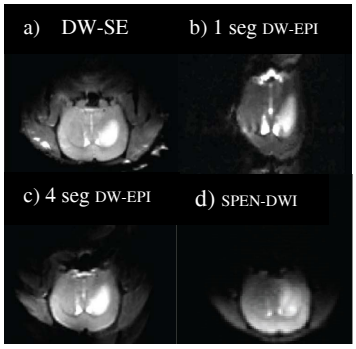

Fig 2: Representative images of the four respective sequences used

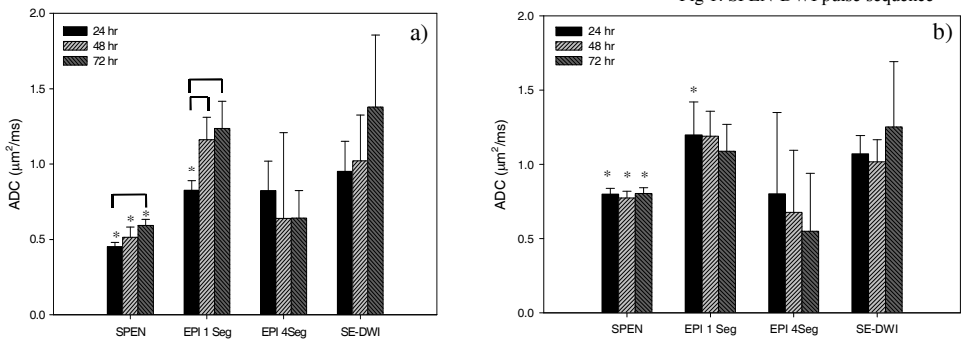

Fig 3: ADCs for each time point and sequence on the stroke (a) and contralateral side (b). Brackets indicate significance between time point for each scan while * indicates significance between ipsi- and contralateral hemispheres as determined by ANOVA and Tukey's post hoc test ($p<0.05$).

Results and Discussion: Fig. 2 shows representative magnitude images for each of the acquisition techniques. At 21.1 T, the SPEN-DWI sequence is immune to susceptibility artifacts that are particularly strong in non-segmented DW-EPI using similar acquisition parameters. The artifact-free SPEN-DWI reveals a large hyperintense stroke region characteristic of toxic edema and swelling associated with the MCAO. Significant decreases in ADCs were evident for SPEN-DWI and DW-EPI 1-shot at 24 h only. EPI artifacts at this field strength fail to provide consistent results and overestimated ADC values, which impacted significance of EPI ADCs over the evolution of the stroke. The DW-SE provides the best quality images but the required acquisition time (1.5 h) severely restricts measurements to a reduced number of b-values and displays higher variations in ADC, likely due to motion during the acquisition.

Conclusions: The quality of the SPEN-DWI and resulting ADC maps make this form of single-shot acquisition a clear choice for comprehensive, high-throughput *in vivo* stroke studies at ultra-high fields and/or heterogeneous signal regions.

Acknowledgement: All work has been conducted in accordance with FSU Animal Care and User committee. Funding provided by the NSF and National High Magnetic Field Laboratory (DMR-0654118), the User Collaboration Group Program (to SCG), the American Heart Association (10GNT3860040), ERC Advanced Grant (246754 to LF), a Helen Kimmel Award for Innovative Investigation (to LF), Kamin-Yeda Grant Israel (711237 to Lf), DIP Grant Germany (710907 to LF), and NSF IRFP and Fulbright (to AL).

References: [1] Ben-Eliezer N. *et al* Magn. Reson. Med. 2010;63. [2] J.T. Rosenberg, *et al.* Cytotherapy 2013;15(3) [3] E. Solomon *et al.* J Magn Reson 2013;232.