## Diffusion-Weighted MRI by **SP**atiotemporal **EN**coding (SPEN): Analytical Description and in vivo Validations מכוז ויצמז למדע WEIZMANN INSTITUTE OF SCIENCE

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## **1. Introduction**

Diffusion-weighted (DW) MRI tends to be of limited use in regions suffering from large magnetic field or chemical shift heterogeneities, which severely distort the EPI images on which DW MRI usually relies. In this study we propose novel DW sequences based on **SP**atio-temporal **EN**coding (SPEN), which overcome such shortcomings owing to SPEN's inherent robustness to offsets<sup>1</sup>. As these experiments involve the combined application of frequencyswept pulses and magnetic field gradients, the Stejskal-Tanner<sup>2</sup> derivation of the b-values for the basic pulsed-gradient spin-echo (PGSE) experiment, is no longer valid: in addition to diffusion-sensitizing gradients, SPEN's gradients and swept RF fields impose additional spatiallydependent diffusion weightings. These effects, as well as potential cross-talk terms between the diffusion-sensitizing and SPEN gradients, are

#### **1D Conventional SE 1D SPEN 90**<sup>0</sup> Chirped **90**<sup>0</sup> RF/ ADC Phase $\varphi$ δ δ Ga

## SPEN is a single-shot imaging technique based on the sequential excitation of the spins in the presence of an excitation gradient (Ge). As a result of SPEN's nonuniform temporal excitation, the phases $\varphi$ evolved by different spin-packets (red and purple) in Spin-Echo (SE) and in SPEN experiments incorporating a PGSE diffusionweighting module, will be different and so will be their local phase dispersion.

To deal with such complexities, Shrot and Frydman<sup>3</sup> presented a description extending Karlicek and Lowe's<sup>4</sup> proposal, to relate diffusion effects with the general form taken by the spins' evolution phases at any time t. The combined SPEN/PGSE attenuation A for a given diffusion coefficient D is thus expressed in terms of the spatial derivatives of position-dependent spin evolution phases:

2. SPEN-based DW MRI: Basic Physical Description

$$A(t,z_o) = \exp\left[-D \cdot b(t,z)\right] = \exp\left[-D \cdot \int_0^t K_{local}^2(t',z_o)dt'\right] = \exp\left[-D \cdot \int_0^t \left(\frac{d\varphi(t',z_o)}{dz}\right)^2 dt'\right]$$
[1]

This expression can be extended to 3D diffusion-encoding / imaging cases, where one could draw the

effective b-value acting in a SPEN diffusion MRI scan.

## **3. SPEN-based DW MRI: Analytical Results for Model Experiments**

Three novel single-scan 2D DW SPEN (dSPEN) imaging schemes were developed<sup>5</sup>: a single-slice, single-shot sequence involving encoding by a chirped 90° excitation pulse (A), and two multi-slice sequences (B and C) involving encoding by a swept 180° adiabatic inversion. Shown below is the analytical b-value derived for the simplest case, (A):



# **4. Solution Phantom Validations**

As experimental validation of the attenuation functions, we illustrate two single-shot dSPEN experiments conducted on a water sample (pulse sequences A and B on the left).

### ADC maps derived from these dSPEN experiments lead to:

- Uncorrected maps (b<sup>PGSE</sup>) based on solely the predictions of (i) the Stejskal-Tanner<sup>1</sup> formalism (panels 3A and 3D and dashed lines in panels 3C and 3F). Notice the fictitious spatial dependence apparent in water's D-values.
- Corrected maps (bexact): Taking into account all effective (ii) gradient events including SPEN imaging gradients as derived from Eq. (1) (panels 3B and 3E and solid lines in panels 3C and 3F): *leads to the correct D coefficients*

uncorrected corrected



### 5. Monitoring Isotropic and Anisotropic Diffusion by SPEN MRI

Fresh celery positioned parallel to the magnet's main axis was scanned using dSPEN, SE EPI and gradient-echo multi-scan MRI sequences. The greater signal attenuation parallel to the celery vascular bundles, relative to the perpendicular direction, reflects larger molecular displacements which is indicative of diffusion anisotropy.



#### Fresh Celery – MR images



FOV 28x22mm with resolution of 0.4×0.3×3 mm

The ADC values of the celery vascular bundles were 1.7x10<sup>-3</sup>  $mm^2s^{-1}$  and  $1.5x10^{-3} mm^2s^{-1}$  for the SPEN and SE EPI, respectively.

[1] N. Ben-Eliezer, Y. Shrot, L. Frydman, High-definition, single-scan 2D MRI in inhomogeneous fields using spatial encoding methods, Magn. Reson. Imaging 28 (2009) 77-86.

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dSPEN scans were collected on excised swine spinal cords. Fractional anisotropy (FA) maps were generated such orthogonal that the diffusion measurements were considered as  $\lambda 1$ ,  $\lambda 2$ and  $\lambda 3$  respectively. Differences between the white and gray matter of the spine are by all ultrafast clearly evidenced experiments. Good agreement is observed between the FA values arising from the DW SE EPI sequence, and those derived from all the different dSPEN imaging modalities.

#### **Ex-vivo Swine Spinal Cord – FA map**



FOV 20mm with resolution of 0.28×0.28×1 mm

## Conclusions

The present study focuses on the potential arising upon using SPEN as a diffusion technique, based on the combined use of gradients and swept pulses. The developed formalism evaluates the actual b-values characterizing the combined effects of all gradients and RF pulses. The validations of dSPEN as a reliable ultrafast diffusion measurement tool, bodes well for further uses of this method to target other challenging organs, and for extensions to higher-field preclinical and clinical measurements.

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