Spiral rapid diffusion tensor imaging sequence on a 7T small bore magnet: application on traumatic rat brain

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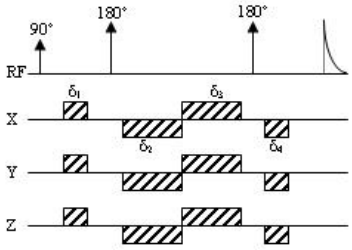
Introduction

Implementation of a very accurate fast Diffusion Tensor Imaging (DTI) sequence on a high field small bore magnet is a challenge since Fractional Anisotropy (FA) mapping requires high precision. The aim of this work was to implement a fast DTI sequence on a 7T small bore magnet with different calibration stages in order to assess the accuracy and precision of Apparent Diffusion Coefficient (ADC) and FA measurements. Our gradient system suffers from the generation of eddy currents and in order to minimize their influence, a Twice Refocused Spin Echo (TRSE) sequence [1] was implemented. Spiral scanning was preferred to EPI since it offers several advantages for DTI studies such as insensitivity to motion [2]. In this work, the implemented sequence was applied to *in-vivo* traumatic brain injury in rats to map the FA indices.

Material and methods

Experiments were implemented on a Magnex 7T small-bore system with 12 cm diameter equipped with shield gradients (G_{max} = 200 mT/m). TRSE sequence (Fig. 1) was calibrated using the signal of polybutadiene: $CH\text{-}CH_2$, a polymer with very slow diffusion coefficient (D = 10^{-15} mm^2.s^{-1}). Calibrations were performed in Diffusion Weighted Spectroscopy (DWS) and were compared to those obtained with the classical Stejskal-Tanner Spin Echo (Pulsed Gradient Spin Echo: PGSE) sequence. According to the very slow diffusion coefficient of the polymer, the application of a diffusion gradient factor *b* in the range of 100 to 2000 s/mm^2 should not induce any signal attenuation in DW Spectra in the absence of eddy currents. The diffusion gradient scheme used the following six gradient combinations ([3] dual gradient optimized scheme): (X,Y,0), (X,0,Z), (0,Y,Z), (X,-Y,0), (X,0,-Z) and (0,-Y,Z). DWS on polymer was performed using independently each of these six diffusion gradient orientation. The objective of these calibrations was to find, for a given echo time (TE), the optimum sequence parameters (δ_1,δ_2,δ_3 and δ_4) which may correspond to none signal attenuation. Signal reproducibility during two hours was also tested on polybutadiene.

Fig. 1: Diffusion Weighted Spectroscopy TRSE sequence.



DTI experiment was achieved on a water phantom and on celery in order to validate diffusion coefficient and anisotropy indices measurements. Images were acquired using an analytically designed interleaved variable-density (VD) spiral readout trajectory [4]. This trajectory normally starts in the slew-rate-limited region and ends in the amplitude-limited region at maximal gradient amplitude of the system. Imaging parameters were, *FOV* = 50 mm for a matrix size of 128x128 (K_{max} = 1280 m^{-1}: limit of our system), 8 interleaves with number of samples = 2486 and sample time = 2µs, given an acquisition time of 4.9 ms per spiral. This value seemed to be a good compromise between the insensitivity to the signal T_2 decrease and the noise effects due to the spectral bandwidth. 4 averages were necessary to make an EXORCYCLE phase cycling and 5 slices (1.5 mm thick) were acquired. *In-vivo* DTI studies were performed on the brain of three groups of rats: a healthy group, a trauma group (n = 4) and a control group (n = 4) using a *b*-value of 500s/mm^2. In the trauma group, diffuse traumatic brain injury was induced according to the impact acceleration model, inducing cellular brain edema [5]. Here, DTI measurements were obtain at 4h30 post-trauma. The Mann-Withney test was used to compare groups of data (*: p<0.05).

Results and discussion

According to DWS calibrations on polymer, the most accurate diffusion parameters were determined: for *TE/TR* = 50/2500 ms they were found $\delta_1 = \delta_4 = 3.5$ ms and $\delta_2 = \delta_3 = 7.5$ ms with G_{diff} = 25 to 160 mT/m for respectively *b*-value = 100 to 2000 s/mm^2. Fig. 2 shows results of DWS on the polymer. The first graph shows results obtained with PGSE sequence where diffusion gradients are applied in the six spatial directions of diffusion gradient scheme. The second graph shows the same experiment obtained with the TRSE sequence. The TRSE sequence with the established diffusion parameters gives less than 2% attenuation with *b* in the range of 0-1000 s/mm^2 and less than 7% with *b* in the range of 1000-2000 s/mm^2, whereas PGSE gives more than 70% along (X,Y,0) for *b* = 500 s/mm^2. Diffusion values obtained with TRSE-DTI sequence from water phantom (*D* = 0.0023 mm^2/s at 25°C and FA = 0.07) and from celery ($D_\perp$ = 0.0006 and $D_{//}$ = 0.0015 mm^2/s) are in accordance with published results [6]. ADC obtained on rat brain are also in accordance with published results for grey (GM) and white matter (WM): ADC = 0.0009 mm^2/s with FA = 0.25 in GM and ADC = 0.0009 mm^2/s with FA = 0.8 in WM [7]. These results validate the implemented method and allow us to apply it on traumatic brain injury in rats. Fig. 3 represents a spiral diffusion weighted image on traumatic rat brain at *b* = 100 s/mm^2. In spiral DW image, no retrospective motion correction [4] was needed and the contrast allowed analyze of the different brain structures. Results show a significant decrease of the ADC in the cortex in the trauma group: 0.0007 ± 1e-4 *vs* 0.0009 ± 3.4e-5 mm^2/s in the control group (p = 0.009). These results suggest that cellular edema is predominant following diffuse traumatic brain injury. Furthermore, FA values in the cortex are significantly (p = 0.009) lower in control group (FA = 0.27 ± 0.04) than in trauma group (FA = 0.40 ± 0.05). Since the used *b*-value is low, signal in diffusion experiments are predominantly due to extracellular water. The presence of cellular edema is known to induce an increase of cellular water content producing cellular swelling which could be responsible for a more anisotropic extracellular space. These results are unexpected and other investigations will be necessary to interpret it.

Fig. 2: Eddy currents effects with PGSE (a) and TRSE (b) sequence: Signal attenuation on a polymer in terms of b-value for each axe pair of the diffusion gradient scheme.

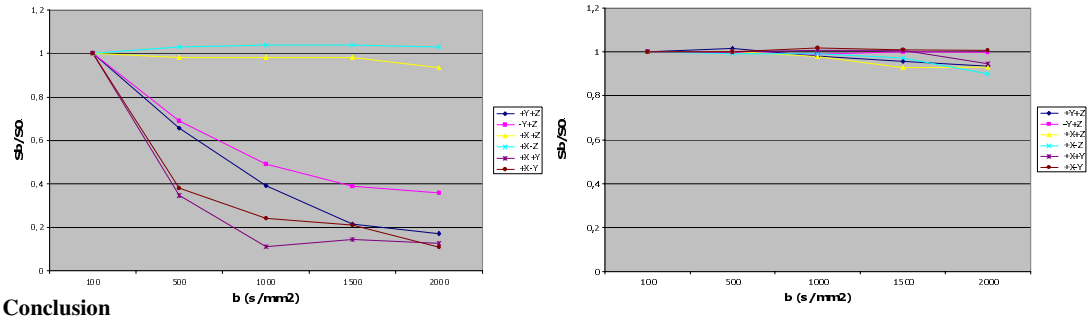
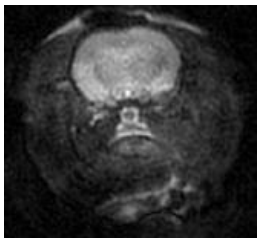


Fig.3



Conclusion

In this work we have validated the feasibility of the TRSE spiral sequence in our 7T system. This implemented sequence is demonstrated to be sensitive enough to measure modifications of FA in grey matter of rats following diffuse traumatic brain injury. Future research will be performed to optimize FA measures in traumatic rat brain by increasing the number of diffusion gradients orientations. To our knowledge, this was also the first time *in-vivo* Diffusion Tensor Variable Density Spiral Imaging results were reported on rat brain at 7T.

[1] T. G. Reese *et al.*, MRM (2003). [2] E. Fieremans *et al.*, Proceeding ISMRM 2005. [3]S. Skare *et al.*, JMR (2000). [4] C. Liu *et al.*, MRM (2004). [5] H. Lahrech *et al.*, Proceeding ESMRMB 2005. [6] C. Beaulieu, NMR Biomed. (2002). [7] S. Borietus *et al.*, Magma (2004).