Diffusion tensor imaging with 1mm isotropic resolution using a dual-echo steady-state method at 3T

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Target audience. The aim of this work is to investigate the applicability of the dual-echo steady-state (DESS) sequence with diffusion weighting gradients to measure the anisotropic water diffusion in biological tissue. It is of great importance to the DTI community as well as researchers in the field of diffusion MRI.

Purpose. Diffusion tensor imaging (DTI) is a widely used MRI technique for the study of the anisotropic diffusion of water in biological tissue. Diffusion-weighted spin-echo single shot echo planar imaging (DW-SE-EPI) is commonly used for DTI due to its rapid imaging capability. Unfortunately this technique suffers from poor spatial resolution (typically 2 mm isotropic resolution) and does not allow for short echo-time (TE) acquisition. The DW-DESS sequence appears to be a promising alternative to DW-SE-EPI [1] and has recently emerged as a possible approach for quantifying proton isotropic diffusivity *in vivo* in knee cartilage [2,3], for example. In this sequence, diffusion weighting is controlled by applying a conventional spoiler gradient between the gradient recalled echo (S^+) and the time-reverse gradient echo (S^-). These additional gradients may be applied in the frequency encoding (FE), the phase encoding (PE) or slice selection directions (SL) independently, thus enabling sensitivity to anisotropic diffusion. In this work, we evaluate the potential of DW-DESS for the investigation of anisotropic diffusion using DTI with 1 mm isotropic resolution at 3T.

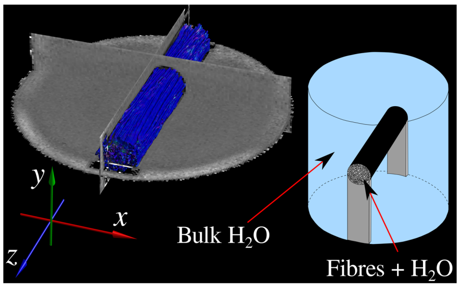

Figure 1. Right: schematic representation of the anisotropic diffusion fibre phantom; left: fibre tractography based on the DTI analysis from the DW-DESS pulse sequence, obtained with the help of the ExploreDTI toolkit [9].

Methods. A dedicated anisotropic diffusion fibre phantom [4] (Fig. 1) was scanned on a 3T Trio Tim (Siemens, Erlangen, Germany) equipped with a 12-array head coil using the DW-DESS sequence with slab-selective excitation. In order not to disturb the imaging process [5], the diffusion gradient momentum $I_d^{(\mathrm{diff})}$ (T.m^{-1}.s) applied in the direction d (i.e., FE, PE, SL) must be an integer multiple of the imaging gradient momentum $I_d = 2\pi/(\gamma\delta_d)$, where δ_d is the imaging resolution in the direction d. Subsequently, the vectors (I_{RO}, I_{PE}, I_{SL}) and ($I_{\mathrm{RO}}^{(\mathrm{diff})}$, $I_{\mathrm{PE}}^{(\mathrm{diff})}$, $I_{\mathrm{SL}}^{(\mathrm{diff})}$) are denoted respectively by I and $I^{(\mathrm{diff})}$. Thus, the b-value for this pulse sequence is defined as $b = \left(\gamma I^{(\mathrm{diff})}\right)^2 TR$. Protocol parameters for DW-DESS were: TR/TE = 25/5 ms, FA = 20°, BW 180 Hz/pixel, matrix size 200×200×64, FOV 200×200×32 mm^3, 12% slice oversampling and 2 min acquisition time. The sequence was repeated 30 times with $I^{(\mathrm{diff})}/I = (0, n, \pm n)$, $(n, 0, \pm n)$, $(n, \pm n, 0)$ with $n = 1,\ldots,5$ (frame of reference shown in Fig. 1). Thus, the b-values reached with this sequence were in the range (0-60) s/mm^2. Precise estimation of T_1 and T_2 in the bulk water region and in the fibre region was performed. Finally, the AFI sequence [6] (TR_2/TR_1 = 5, TR_1+TR_2 = 60 ms, FA = 45°) was applied in order to assess the actual B_1^+ profile. In order to settle the ground truth for DTI, the conventional DW-SE-EPI sequence was carried out with the following protocol parameters: TR/TE = 3000/82 ms, b = 0, 500, 1000 s/mm^2, 30 field gradient directions and 4 repetitions. The apparent diffusion coefficient maps (D_{app}) for each gradient direction used in the DW-DESS sequence were evaluated by fitting the model proposed by Freed et al. [7] to the signals S^+ and S^- with known T_1, T_2 and an initial value for B_1^+ provided by the AFI data. The apparent diffusion tensor and related rotationally invariants, such as mean diffusivity (MD) and fractional anisotropy (FA), were subsequently evaluated as described by Basser et al [8]. The directionally colour-coded FA (colour FA) was obtained as well.

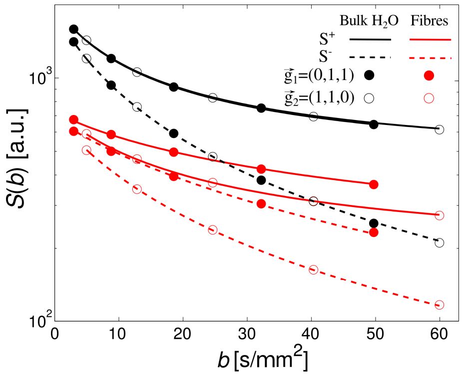

Figure 2. S^+ (solid lines) and S^- (dashed lines) signals from the DW-DESS sequence for two field gradient directions (filled and empty circles) and two ROIs, one in the bulk water (black) and the other in the fibres (red).

Results. Fig. 2 shows the S^+ and S^- averaged over two ROIs placed in the bulk water (black) and the fibre regions (red), for 2 field gradient directions (filled and empty circles). The fit of the S^+ and S^- echoes are represented by the continuous and the dashed lines, respectively. Fig. 3 shows a comparison of MD (a,d), FA (b,e) and Colour FA (c,f) from the DW-SE-EPI (a-c) and DW-DESS (d-f) sequences.

Discussion. The signal attenuations shown in Fig. 2 indicate a good sensitivity of DW-DESS data to diffusion (especially S^-) and a good agreement with Freed's model [7]. Due to anisotropic water diffusion in fibre, the measured signal attenuation depends on the gradient direction in the fibre region whereas it is not the case in the bulk water. MD, FA and colour FA maps obtained with the DW-DESS and the DW-SE-EPI protocols are in good agreement. An image artefact could be observed in the DW-DESS MRI data when the field gradient direction possesses a non-zero component along the y direction (see Fig. 1). This artefact, which propagates into the quantitative maps, is likely to be due to mechanical vibrations and is being further investigated.

Conclusion. This work demonstrates the feasibility of performing DTI with high resolution at 3T using a novel DW-DESS protocol. A dedicated data analysis algorithm is currently under development, which is expected to further improve the quantitative accuracy of the MD and FA estimation based on DW-DESS MRI data. We are currently working on the implementation of such protocol for *in vivo* brain imaging. To achieve this, several optimizations are being investigated (reduction of TR and reduction of the number of acquired b-values).

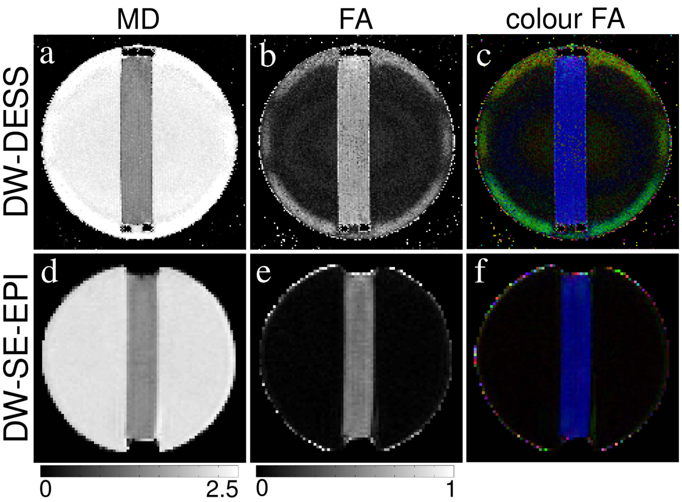

Figure 3. The maps of MD (a,d), FA (b,e) and Colour FA(c,f) from the DW-DESS (a,b,c) and the conventional DW-SE-EPI (e,f,g) pulse sequences. MD values are reported in µm^2/ms.

References. [1] Gras V, et al. ESMRMB 2013; 26:299-300; [2] Staroswiecki E, et al. Magn Reson Med. 2012; 67:1086-1096; [3] Bieri O, et al. Magn Reson Med. 2012; 67:691-700; [4] Farrher E, et al. Magn Reson Imaging. 2012; 30:518-526; [5] Sobol W, et al. J Magn Reson Imaging 1996; 6:384-398; [6] Yarnykh et al. Magn Reson Med. 2007; 57:192-200; [7] Freed D, et al. J Chem Phys. 2001; 115:4249-4258; [8] Basser P, Magn Reson Med. 1998; 39:928-934; [9] Leemans A, et al. Proc. Intl. Soc. Mag. Reson. Med. 2009; 17:3537.