Fast Quantitative Double Echo Steady State Diffusion Imaging

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Introduction. Single-shot EPI techniques are commonly used for diffusion-weighted imaging (DWI) but offer rather poor spatial resolution and coverage for species with short T_2, such as for the musculoskeletal system. Recently, compelling results were reported based on a semi-quantitative characterization of cartilage function and repair (1,2) with diffusion-weighted steady state free precession (dwSSFP). Quantification of diffusion effects with SSFP, however, is generally hampered by its prominent sensitivity on relaxation times.

In this work, a new and *truly diffusion-weighted* (i.e., relaxation time independent) SSFP technique is introduced using a double-echo steady state approach (*true-dw*DESS). We will show that the signal attenuation from diffusion becomes independent on relaxation with respect to the SSFP Echo-FID signal ratio, similar to what was proposed by Cho et al using bipolar gradients (3). As a result, quantitative SSFP DWI can be performed in the *very-rapid-pulsing regime* (that is with $TR \ll T_2$) which offers substantially increased SNR and scanning efficiency. Finally, high-resolution quantitative DWI is demonstrated for human articular cartilage in the knee joint at 3.0T.

Theory. For quantitative DWI, at least two SSFP scans need to be performed: one with (labeled '*diff*', $G\tau >> 0$) and one without (labeled '0', $G\tau \sim 0$) additional dephasing (but with essentially identical other sequence parameters, such as *TR*, flip angle, etc). The signal reduction from diffusion of the FID (S^+) and Echo (S^-) paths depend not only on diffusion (D), but also on relaxation ($T_{1,2}$), dephasing ($G\tau$), repetition time (TR) and flip angle (α),

$$s^{\pm} := \frac{S^{\pm}_{diff}}{S^{\pm}_{0}},\ s := \frac{S^{-}_{diff} \cdot S^{+}_{0}}{S^{-}_{0} \cdot S^{+}_{diff}},\ \text{where } S^{\pm}_{0,diff} = S^{\pm}_{0,diff}(D, T_{1,2}, G\tau, TR, \alpha) \qquad [1]$$

Diffusion effects are evaluated based on the model by Freed et al (4), since prominent coupling between higher order modes in the *very-rapid-pulsing regime* leads to considerable deviations between experiments and common SSFP diffusion theory (5). For quantification of the diffusion coefficient D, the signal attenuation was parameterized by a quadratic function for any given set of external parameters (TR, $G\tau$, α). This allows for the fast assessment of the diffusion constant from a quadratic equation.

Materials & Methods. All measurements were performed at 3T (Siemens Verio) and simulations, data analysis and visualizations were done using Matlab 2007b. A diffusion-weighted double-echo steady-state (*true-dw*DESS) sequence was implemented (see Figure 1) which allowed the simultaneous acquisition of signal from both lowest order modes (FID and Echo) separated by variable amounts of spin dephasing ($G\tau$) within any *TR*. SSFP imaging protocols are given in the corresponding figure caption.

Results & Discussion. The sensitivity of the SSFP-Echo (s^-), the SSFP-FID (s^+) and of the Echo-FID signal ratio (s^-/s^+) is shown in Figure 2 over a large range of $T_{1,2}$ times. As expected, the FID and the Echo show a pronounced $T_{1,2}$ sensitivity, reflecting the need of proper relaxation information, if quantification of diffusion effects with SSFP is desired. This is in contrast to the predicted sensitivity of the echo ratio which proves to be is largely inert to variations in relaxation times. In summary,

$$\partial_{T_{1,2}} s^{\pm} \neq 0 \ \text{ and } \ \partial_{T_{1,2}} s \approx 0 \qquad [2]$$

Theoretical findings are confirmed by measurements on aqueous probes over a broad range of $T_{1,2}$ times (Fig. 2). Finally, high-resolution quantitative (non-navigator corrected) DWI with *true-dw*DESS is demonstrated to be feasible *in-vivo* for patellar cartilage in the knee joint (see Figure 3). Moreover, the non-diffusion-weighted double echo scan can additionally be used to generate the frequently acquired diagnostically relevant DESS contrast. Thus, for most clinical MSK protocols, only one additional scan has to be performed.

Conclusion. Combination of both lowest order SSFP echo paths is able to cancel the otherwise prominent relaxation time dependence of diffusion in each mode to generate truly diffusion weighted SSFP scans that can be used for quantification.

References. **1**. Mamisch TC et al. Eur J Radiol 2008;65(1):72-79. **2**. Friedrich KM et al. Eur J Radiol 2010; 73(3):622-628. **3**. Cho MH, Proc. ISMRM 1989(S2), p. 911. **4**. Freed DE et al, J Chem Phys 2001; 119(9):4249-4258. **5**. Bieri O et al. Proc ISMRM 2010, p. 1631.

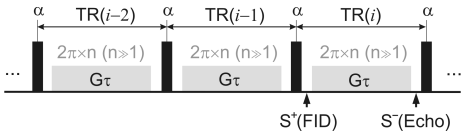

Figure 1: A diffusion sensitivity to SSFP paths is induced with large dephasing moments ($2\pi \times n$/voxel, with $n >> 1$).

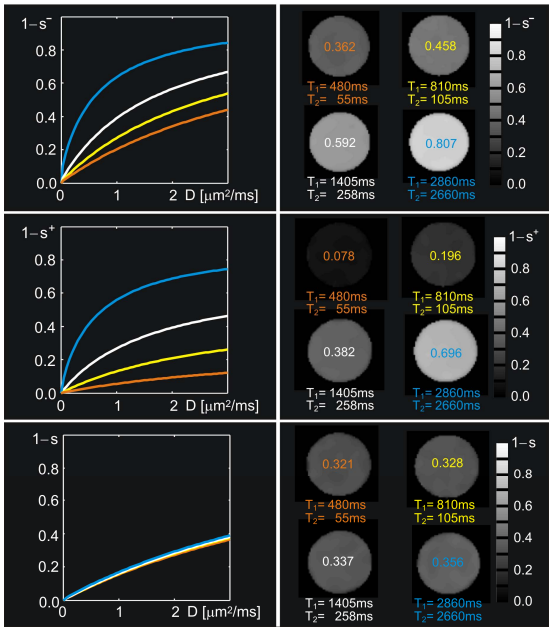

Figure 2: Sensitivity of the SSFP signal on diffusion and relaxation (see Eq. [1]). (top) SSFP-Echo. (middle) SSFP-FID. (c) True-dwDESS. (Imaging: TR = 13.5ms, BW = 558Hz/Pixel, $\alpha = 25°$, dephasing $G\tau = 150$ mT/m·ms along slice selection, $320 \times 160 \times 16$ matrix with $0.6 \times 0.6 \times 2.0 mm^3$ resolution. Aqueous probes with 0…0.25mM $MnCl_2$).

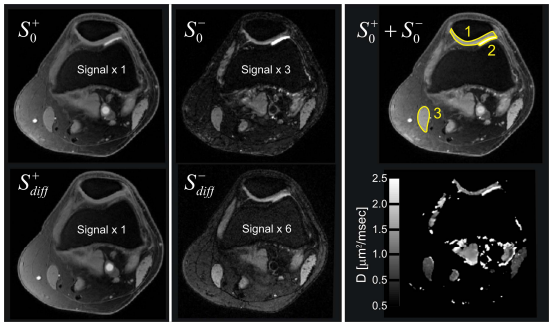

Figure 3: High-resolution in-vivo quantitative DWI using true-dwDESS. For patellar cartilage, D = 1.34 ± 0.29 μm^2/msec (ROI1); for synovial fluid D = 2.86 ± 1.21 μm^2/msec (ROI2); and for muscle D = 0.74 ± 0.16 μm^2/msec (ROI3) is found. (Imaging: TR = 15ms, BW = 210Hz/Pixel; water selective excitation with $\alpha = 15°$, dephasing $G\tau = 150$mT/m·ms along slice selection, $320 \times 320 \times 16$ matrix with $0.6 \times 0.6 \times 2.0 mm^3$ resolution. Four averages were taken and the DWI scan was completed within approximately 4 minutes.