On the Accuracy of Diffusion Models for fast low-angle short-TR SSFP-Echo (FLASH-DW SSFP)

O. Bieri[1], C. Ganter[2], and K. Scheffler[1]
[1]Radiological Physics, University of Basel Hospital, Basel, Switzerland, [2]Department of Diagnostic Radiology, Technical University Munich, Munich, Germany

Introduction. Several models have been developed for the description of diffusion in steady-state free precession (SSFP) sequences (1-4) being based on the seminal work of Kaiser, Bartholdi and Ernst (KBE)(1). In MRI, besides semiempirical approaches, such as the work of Le Bihan et al. (2), the extension of the KBE ansatz to pulsed gradient SSFP by Wu and Buxton (3) is generally well accepted. However, only recently, Freed et al (4) pointed out that the famous KBE ansatz (1) is wrong under certain circumstances and can lead to large errors especially in the most diffusion sensitive regime. In this work, we present a new approach for quantitative diffusion imaging with a fast low-angle short-*TR* (FLASH) diffusion-weighted (DW) SSFP sequence as displayed in Fig. 1. The accuracy of diffusion models is assed in-vitro and in-vivo.

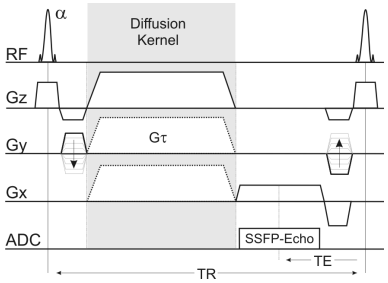

Fig. 1: Sequence scheme for diffusion-weighted (DW) SSFP-Echo.

Materials & Methods. Measurements were performed on a 3T system (Siemens Verio). All simulations, data analysis and visualizations were done using Matlab 2007b. SSFP diffusion experiments were performed in 3D on a spherical phantom (1.25g $NiSO_4 \times 6H_2O$ in 1000g H_2O) with T_2/T_1=260ms/290ms and on articular cartilage (T_2/T_1= 50ms/1200ms) of the human knee joint.
In-vitro flash-DW SSFP protocol: 64×64×32 matrix with 192×192×96mm^3 FOV (resolution: 3×3×3mm^3). A *TR* of 14ms (BW=240Hz /Pixel) was used with a flip angle α=10°–90° in combination with and without a diffusion moment Gτ of 100 mT/m·ms and 200 mT/m·ms in all three spatial directions (G_x, G_y, G_z).
In-vivo flash-DW SSFP protocol: 448×448×16 matrix with 160×160×48 mm^3 FOV (resolution: 0.35×0.35×3.0mm^3) with a *TR*=15ms (BW=210Hz /Pixel) and a water selective RF pulse with α = 14° with and without Gτ=100mT/m·ms along all orthogonal directions. Image encoding was accelerated by using 6/8 partial Fourier (phase direction) and parallel imaging factor of 2. The scan was completed within approximately 6 minutes (4×1min38sec/scan).
Quantification: For quantification of the diffusion constant D, the signal attenuation $\Delta s = 1 - S_{x,y,z}/S_0$ as a function of D given by the Freed and Buxton model was parameterized by a quadratic function for any given value of T_1, T_2, *TR* and α. This allows for the fast assessment of the diffusion constant from a quadratic equation.

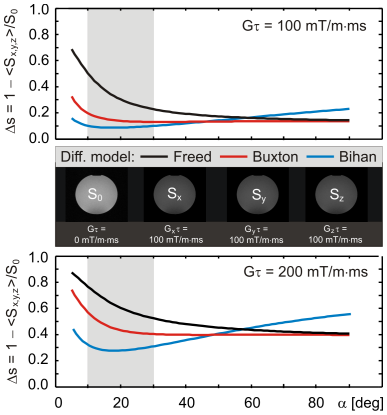

Fig. 2: Predicted signal attenuation for DW-SSFP with Gτ=100mT/m·ms (top) and Gτ = 200 mT/m·ms (bottom) as a function of the flip angle α for water with a T_2/T_1=260ms/290ms and a diffusion constant D=2.4μm^2/ms.

Results. The theoretical signal attenuation in SSFP-Echo for water (D=2.4μm^2/ms at room temperature with T2/T1=260ms/290ms), as achieved with short TR (15ms), is displayed in Fig. 2 as a function of α and for low diffusion moments of Gτ =100 mT/m·ms and Gτ =200 mT/m·ms, respectively. For reasons of completeness, we show the semiempirical theory according to Le Bihan as well, although the theory is not correct for short TR and low flip angles. It can readily be observed that the three models predict considerable differences in Δs. In the limit of large excitation angles (α ~ 90°), the Freed and Wu-Buxton model converge but especially at lower flip angles, the Freed model predicts considerably stronger diffusion effects than the Wu-Buxton model, whereas the Le Bihan model shows completely different signal attenuation properties.

Discussion & Conclusion. For clinical relevance, DW-SSFP should have an easy setup, with high SNR and short acquisition times. Although for TR ~ 1.5T2, diffusion effects become independent on T2, especially SNR is very poor as a result of the long TR. In addition, sensitivity to bulk motion increases with increasing TR and diffusion moments and motion correction was needed for successful estimation of D from DW-SSFP (5). Thus from practice, a different setup for DW SSFP is desirable: (i) low flip angles have the advantage that (a) echo formation occurs primarily from longitudinal paths and thus sensitivity to bulk motion is reduced, (b) SNR is increased, and (c) sensitivity to diffusion is increased requiring lower diffusion moments with reduced motion artifacts; (ii) short TR has the advantage that (a) SNR is increased, (b) sensitivity to bulk motion is reduced and (c) enables fast 3D image acquisitions. The feasibility of high resolution with FLASH-DW SSFP is demonstrated in-vivo for human articular cartilage in Fig. 4.

References. (1) Kaiser et al. J. Chem. Phys. 1974; 60:2966. (2) Le Bihan et al. MRM 1989; 10:324. (3) Wu & Buxton. J. Magn. Reson. 1990; 90:243. (4) Freed et al. J. Chem. Phys. 2001; 115(6):4249. (5) Miller et al. MRM 2004; 51(2):394.

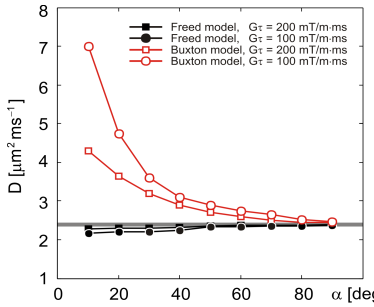

Fig. 3: Diffusion constants in water derived from the Freed (black) and Wu-Buxton (red) model as a function of α with a TR=15ms and for Gτ =100, 200 mT/m·ms.

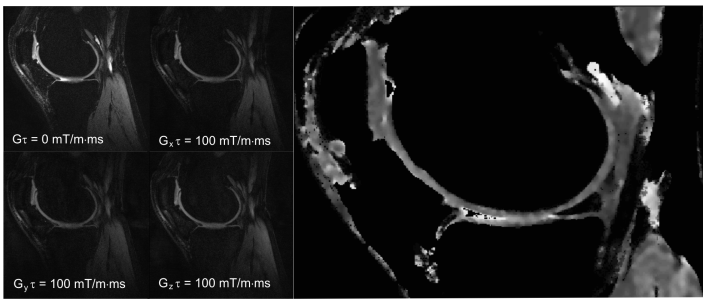

Fig. 4: In-vivo assessment of the diffusion constant of human articular cartlage using flash-DW SSFP (imaging parameters are given in the text). Derived diffusion constants are: D=1.6±0.2μm^2/ms (Freed model) and D=2.3±0.3μm^2/ms (Wu-Buxton model).