Analysis of Diffusion-Weighted SSFP Signal with Computer Simulation

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NTRODUCTION: A major advantage of Diffusion-Weighted Steady State Free Precession sequence (DW-SSFP) over the conventional Diffusion-Weighted Spin Echo (DW-SE) is reduced scan time due to the shorter diffusion preparation. High diffusion weighting can be achieved with the relatively short spin preparation because the weighting develops over many TR's. Consequently, the DW-SSFP signal depends on extrinsic parameters, such as TR, flip angle, diffusion gradient geometry, and on intrinsic parameters, such as T1, T2, and diffusion coefficient. Because of these dependencies, the DW-SSFP signal in the pulsed gradient experiment has not been characterized by an exact analytical solution. Kaiser *et al.* developed expressions for the constant gradient DW-SSFP experiments [1] that were later refined by Freed *et el* [2]. Wu and Buxton developed an approximation to the pulsed gradient DW-SSFP signal [3], and others used the extended phase graph (EPG) method by decomposing signals with multiple different coherent pathways [4]. Here, we model DW-SSFP signal using the Bloch equation simulation which functions in flexible diffusion environment and compare it with the EPG method and the approximate solution given by Wu and Buxton [3]. Preliminary phantom validation data is also presented.

MATERIALS & METHODS: *Bloch Equation Simulation*: Figure 1 depicts the basic Bloch simulation module. A number of spins are initialized and undergo RF pulse excitation, precession, and relaxation for each cycle. In order to simulate diffusion and flow, a diffusion and flow motion block is included. After one cycle, both magnetization and displacement, M(r, t) are updated and accumulated in memory with a time increment, Δt. Here, RF pulse excitation is assumed to occur instantaneously, and rising/decay time for gradients is also ignored. The simulation used 15,000 spins and a time increment Δt=0.1ms. Net magnetization is computed at each TE by averaging over all the spins. The simulations were run for a sufficient number of TR's to reach a steady state (>200). The simulation was conducted in MATLAB and took about 15 minutes for 200 TRs with TR=25ms.

Extended Phase Graph Simulation: EPG states, [F+, F-, Z], are initialized and after RF pulse excitation each EPG state propagates during a period of relaxation over a specific interval with or without a diffusion-encoding gradient. The diffusion effect is given as a weighted attenuation on every EPG state as a linear operation.

Phantom Experiments: A basic DW-SSFP sequence (Fig 2) was used to collect a series of 2000 echoes on a spherical agar phantom (T1/T2 = 967.54ms/50.20ms) on a 1.5T system (Signa HDx, GE Healthcare). Scan parameters: TR=25ms, diffusion gradient amplitude G =5G/cm and diffusion gradient width tau=5ms.

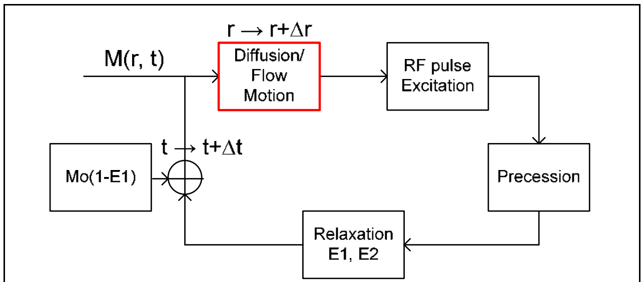

Figure 1. A unit cycle for Bloch equation simulation in diffusion environment for unit time, Δt. The red block represents random motion from diffusion. ($E1 = \exp(-\Delta t/T1)$, $E2 = \exp(-\Delta t/T2)$)

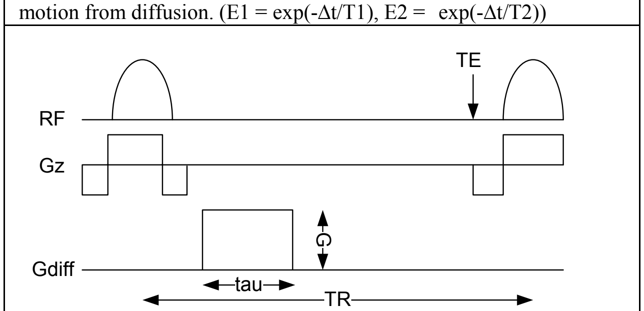

Figure 2. Sequence for diffusion-weighted (DW) SSFP. The echo is detected right before the next RF pulse.

RESULTS & DISCUSSION: Figure 3 demonstrates the evolution of the DW-SSFP signal to steady state as simulated by Bloch simulation, EPG, and phantom experiment. In general, the Bloch simulation results correspond well to the EPG method confirmed by the phantom experiments as well. For large flip angles (>90°), there is excellent agreement between the two models, whereas the signal fluctuates somewhat in the low flip angle range. In Figure 4 the steady state signal of the Wu-Buxton model, EPG method and Bloch equation simulation are compared over the full range of flip angles. As expected from the previous work [2], the Wu-Buxton model is inaccurate at low flip angles. This is because more coherent pathways are created at low flip angles as a weighted sum of spin echo (SE) and stimulated echo (STE), and the Wu-Buxton model does not consider all possible pathways.

CONCLUSION: In this study, a Bloch equation simulation that included the effects of diffusion agreed well with the EPG method and is confirmed from the phantom experiment. The EPG method is highly efficient in time aspect, but the Bloch simulator has more flexibility to include the effects of flow and general motion. In the absence of an analytical solution for the DW-SSFP signal, these simulations can give insight into the way in which the signal evolves to the steady state and its dependencies. A better understanding of these effects is critical to the use of DW-SSFP imaging in quantitative imaging applications. Future work will focus on phantom validation and application of these simulation results to quantitative DWI in vivo.

REFERENCES: [1] Kaiser et al J Chem Phys 1974. [2] Freed et al. J Chem Phys 2001. [3] Wu and Buxton. JMR 1990. [4] Weigel et al JMR 2010.
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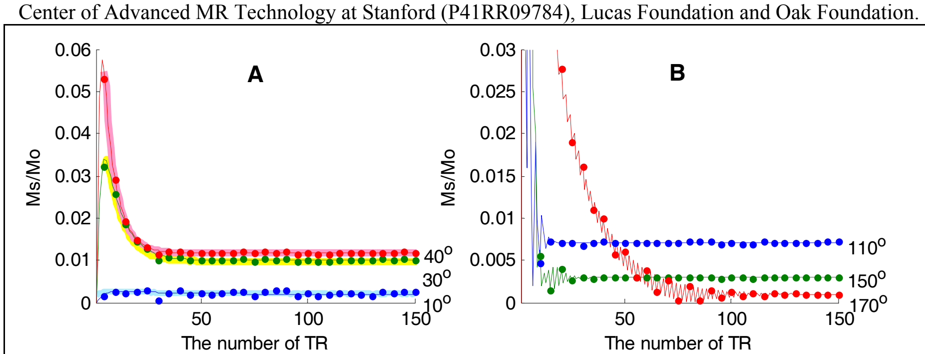

Figure 3. The DW-SSFP echo magnitude with different flip angles (A: 10°, 30°, 40°, and B: 110°, 150°, 170°). The EPG method is shown as a narrow solid line, the Bloch simulation as a dot marker, and the phantom experiment as a bold solid line in figure 1A.

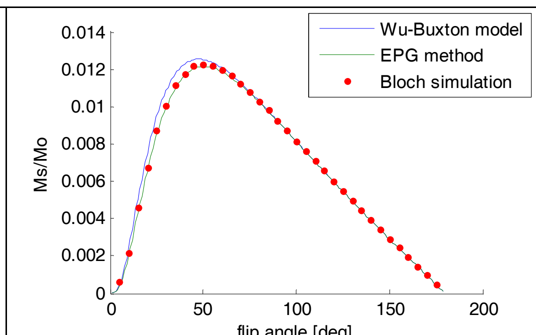

Figure 4. Comparison of the steady-state signal with the Wu-Buxton Model, the EPG method, and the Bloch simulation.