Simulation of Diffusion Weighted SSFP: Time to Reach the Steady State and Effects on Anisotropic Diffusion

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INTRODUCTION: One of the major advantages of Diffusion-weighted steady state free precession (DW-SSFP) is that we can reduce data acquisition time by using a short repetition time (TR) and still retain high sensitivity to diffusion. However, to guarantee signal consistency, data acquisition should not begin until the magnetization reaches a steady state. Previous work has provided insight into the complex dependencies of the steady state signal on physical and imaging parameters but, so far, an analytical description of the pulsed gradient DW-SSFP experiment has not been developed [1,2,3,4]. Consequently, an extended phase graph (EPG) method [5,6] is used here to quantify the time taken to reach steady state. In EPG the signal is analyzed by decomposing it into separate coherence pathways. In this study, we use EPG to quantify the dependence of the time taken to reach steady state on multiple parameters. Also we simulate the case of switching the diffusion-encoding direction (as is done in DTI) with an anisotropic tissue such as white matter.

MATERIALS & METHODS: Since an explicit expression does not exist for describing DW-SSFP signals, a simulation is performed instead that uses the EPG method. The sequence used is a balanced SSFP sequence in addition to an unbalanced diffusion gradient immediately after RF excitation, and the echo is detected right before the next RF pulse. First, we define the steady state as a number of TR, n_o, when the absolute value of the first order difference of every echo is less than 10^{-4} as shown below,

$$|\,\text{Echo}\,(n+1) - \text{Echo}\,(n)\,| < 10^{-4} \quad \text{for all } n \geq n_o.$$

The intrinsic parameters are modeling brain tissues: White Matters (WMs) with two different diffusion coefficients $D_\perp$=500μm^2/s and $D_\parallel$ = 1500μm^2/s representing its orientation into perpendicular and horizontal direction, and Cerebrospinal Fluid (CSF) with D_{csf} = 3200μm^2/s. T_1/T_2 values used here are 800ms/100ms for WM and 2,300ms/2,200ms for CSF respectively [7]. With these tissue parameters, we run a simulation to determine the time to reach steady-state. The simulation varies *TR* from 15ms to 50ms, and flip angle from 5° to 175°. A second simulation was performed in which the diffusion direction was alternated from an orientation parallel to the simulated white matter fibers to an orientation perpendicular to them.

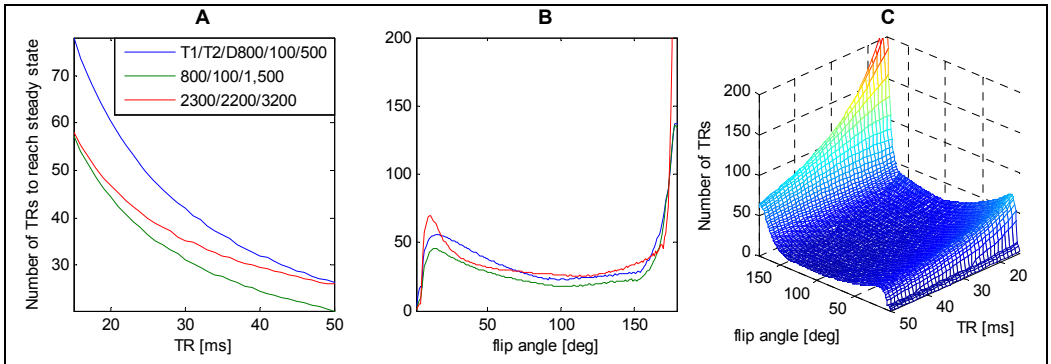
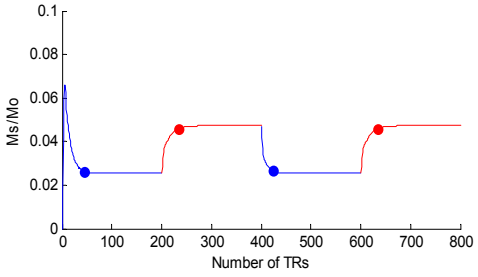


Figure 1. Number of TRs required to reach steady state is simulated with two different parameters, *TR* and flip angle. Flip angle 30° is used for varying *TR* (fig 1a), *TR* = 25ms for varying flip angle (fig 1b), and $T_1/T_2/D$ = 800/100/1500 for varying TR and flip angle (fig 1c).

RESULTS & DISCUSSION: The time to reach steady state is plotted versus *TR* and flip angle in Figure 1. As expected, the echo number decreases as *TR* becomes longer (fig 1a). Note that under the same T_1 and T_2 value, the different diffusion sensitivity is nearly linear with the time to reach steady state given a fixed flip angle of 30°. Figure 1b shows the time to reach steady state changes as the flip angle is varied. Except for extremely small and large flip angles, the time to reach steady state does not vary much with T_1, T_2, and diffusion coefficients. Combining figures 1a and 1b, figure 1c illustrates that for flip angles between 50 and 150 degrees, the flip angle is the dominant parameter that determines the time it takes to reach the steady state. However, *TR* has the most effect on the time to reach steady state under the very small and large flip angles. Figure 2 demonstrates the effect of switching the diffusion encoding direction on the steady state signal. The table shows the number of TRs required to reestablish steady state after each gradient direction change. For applications with multiple diffusion-encoding directions such as DTI, it is critical to know the time required to reestablish steady state after switching the gradient direction.



	Echo number
zero state → $D_\perp$	56
zero state → $D_\parallel$	44
$D_\perp$ → $D_\parallel$	25
$D_\parallel$ → $D_\perp$	34

Figure2. Echo magnitude when diffusion encoding direction changes from parallel to perpendicular direction vice and versa. Each dot represents the time to reach the steady-state given $D_\perp$=500μm^2/s and $D_\parallel$ = 1500μm^2/s.

CONCLUSION: In this study, we demonstrate how different parameters affect the time to reach steady state. If we can estimate the time to reach steady state we can minimize distortion on the image, ensuring stable signal acquisition. Furthermore, we demonstrated the disruption of the steady state in anisotropic tissue by switching the diffusion encoding direction.

REFERENCES: [1] Kaiser et al J Chem Phys 1974. [2] Wu and Buxton. JMR 1990. [3] Freed et al. J Chem Phys. 2001. [4] McNab et al. MRM 2010. [5] Scheffler Conc. Magn. Reson. 11 (1999) [6] Weigel et al JMR 2010. [7] Magnetic Resonance Imaging Physical Principles and Sequence Design, Wiley-LISS, ISBN 0-471-35128-8

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