Sensitivity of Diffusion-Weighted-Steady State Free Precession to Diffusion Anisotropy

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Introduction Diffusion-weighted steady-state free precession (DW-SSFP) imaging has been shown to have a strong sensitivity to the self-diffusion of water within tissues. Since DW-SSFP acquires signal from multiple echoes simultaneously it requires only modest gradients and short imaging times, making it a promising option for high spatial and angular resolution diffusion imaging. Signal attenuation due to DW-SSFP, however, is no longer governed by a simple mono-exponential as in DW-spin-echo (SE) imaging and despite an extensive theoretical description of the DW-SSFP signal[1,2], the estimation of the diffusion coefficient (D) from SSFP data is not straightforward due to the complicated dependence of the signal[2]. Additionally, the question of how the DW-SSFP signal responds to anisotropic diffusion has, as of yet, not been addressed. This work characterizes the DW-SSFP signal attenuation in the context of 2D anisotropic diffusion and compares the results to the attenuated signal profiles from standard spin-echo (SE) diffusion imaging in order to better understand what challenges may be associated with diffusion tensor imaging (DTI) and/or tractography analysis using DW-SSFP MRI data.

Methods All simulations were done using Matlab 7.0 (Mathworks Inc.). Though the mean displacement of diffusing particles is described by an ellipse, the apparent diffusion coefficient (ADC) profile that is measured in DTI has a distinct peanut-shape that represents the variance of the final positions of all the particles along a given direction. A 2D ADC profile was simulated (Figure 1) with fractional anisotropy (FA) = 0.9, Trace (D) = 1.1 x 10^{-3} mm^2/s, such that diffusivities along the major and minor axes, λ_1 and λ_2 = 1.0 x $10^{-3}mm^2/s$ and 0.1 x $10^{-3}mm^2/s$ respectively. The analytical form of the ADC profile is : $D_\theta = \lambda_1\cos^2\theta + \lambda_2\sin^2\theta$, where D_θ represents the diffusivity along the projection at angle θ to the major eigenvector of the diffusion tensor[3] (Figure 1). Similarly, a diffusion-weighted attenuated signal profile was generated as: $A_\theta = I(bD_\theta)/I_0$ where A_θ represents the attenuated MR signal at an angle θ to the major diffusion axis, when diffusion-weighting is applied to the diffusion tensor defined by D_θ. I_0 is the non-diffusion-weighted signal (arbitrarily set to 1). For DW-SE imaging: $I_{SE}(b_{SE}D_\theta) = \exp(-b_{SE}D_\theta)$[4]. For DW-SSFP: $I_{SSFP}(b_{SSFP}D_\theta)$ is given by the equation described by Wu and Buxton[1,2]. Parameters used for SSFP signal simulations were: flip angle (α) = 10°, T_1 /T_2/TR = 780/90/30 ms, diffusion gradient amplitude (G) = 40 mT/m, duration of gradient pulse (τ) = 8 ms. These parameters are suitable for DW-SSFP imaging of white matter at 1.5 T.

Figure 1: ADC Profile (D_θ)

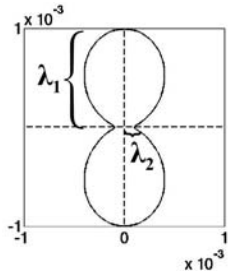


Figure 2: Attenuated Signal Profiles (A_θ)

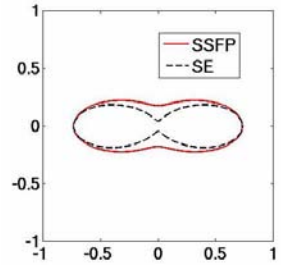


Figure 3: Different SSFP echo pathways

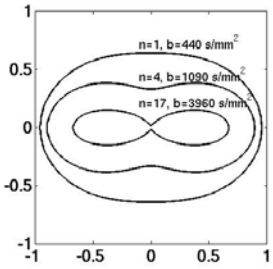


Figure 4:Echo Pathway vs. SSFP signal

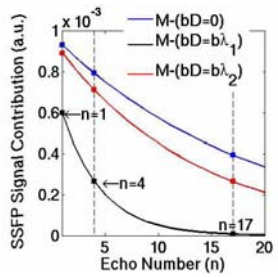


Figure 4:Changing FA

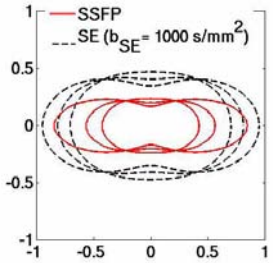


Figure 6: Changing τ

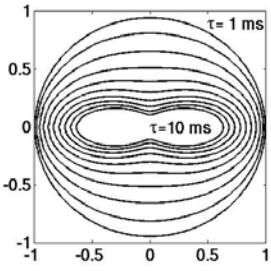


Figure 7: Changing α

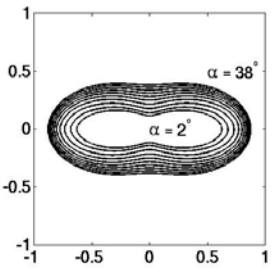


Figure 8: Changing T_1

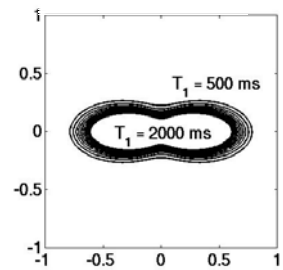


Figure 9: Changing T_2

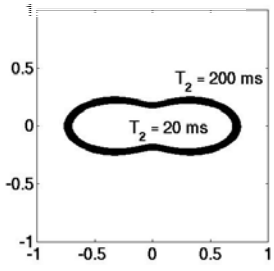
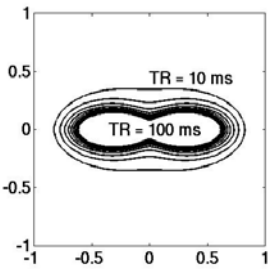


Figure 10: Changing TR



Results and Discussion DW-SSFP and DW-SE A_θ profiles with matched signal attenuation along the minor diffusion axis are displayed in Figure 2. Very different gradients are required to achieve the same amount of signal attenuation in DW-SSFP and DW-SE imaging. In Figure 2, the DW-SSFP A_θ profile represents a diffusion weighting from one 8 ms gradient pulse at 40 mT/m per TR, whereas the matching DW-SE A_θ represents b_{SE}=3112s/mm^2. The DW-SSFP A_θ profile is shaped differently, with less narrowing at the principle diffusion axis. The lessened narrowing at the principle diffusion axis can be understood by considering the shape of attenuated signal profiles for individual echo pathways that contribute to the SSFP signal. Figure 3 displays DW-SSFP profiles (using Buxton's two echo approximation[2]) for stimulated echoes (STEs) with echo number, n=1, 4 and 17, where echo number equals the number of longitudinal periods prior to echo formation. Lower echo numbers represent a shorter mixing time (i.e. fewer longitudinal periods prior to echo formation). While the DW-SSFP A_θ profiles for larger echo numbers have much stronger signal attenuation they contribute less to the overall SSFP signal as shown in Figure 4. The weighted summation of 'single echo' A_θ profiles such as those depicted in Figure 3 (each individually governed by exp(-bD)) results in a fundamentally different shape than that of DW-SE. Despite this difference in shape, the DW-SSFP A_θ profile morphs similar to DW-SE A_θ profile (Figure 5) when FA changes from 0.1 (innermost) to 0.5 and 0.9 (outermost). SSFP parameters were also changed one at a time to demonstrate how the shape of the DW-SSFP signal attenuation varies with each of: 1 ms < τ < 10 m s (Figure 6), 2° < α < 38° (Figure 7), 500 ms < T_1 < 2000 ms (Figure 8), 20 ms < T_2 < 200 ms (Figure 9) and 10 ms < TR < 100 ms (Figure 10). Sensitivity of the DW-SSFP signal to anisotropic diffusion changes with gradient duration, flip angle, T_1, T_2 and TR but it appears to scale and change in a consistent manner. In addition, it is relatively insensitive to T_1 and T_2 (Figures 8 & 9), even across a wide range of time constants. This inspires confidence that despite the complicated SSFP signal dependence, diffusion tensor analysis should still be possible. It is clear, however, that a new formalism will be required to extract information about the diffusion tensor (or other anisotropy models) from DW-SSFP data. While the DW-SSFP signal is dominated by short STEs (low echo number), the anisotropy contrast is contributed by the long STE components (high echo number) and thus it may be of interest to find ways to isolate these longer STEs. Modeling the DW-SSFP signal in the context of anisotropic diffusion is an important first step towards extending DW-SSFP imaging data to diffusion tensor imaging and/or tractography.

Acknowledgments and References Funding provided by the Royal Academy of Engineering, EPSRC and the Charles Wolfson Charitable Trust. (1) Wu EX, Buxton RB. JMR. 90:243-253 (1990). (2) Buxton RB. MRM. 29:235-243 (1993). (3) Callaghan PT et. al. Biophys J. 28:133-141 (1979). (4) Torrey HC. Phys. Rev. 104:563-565 (1956).