

# Flow Effects in Balanced Steady State Free Precession Imaging

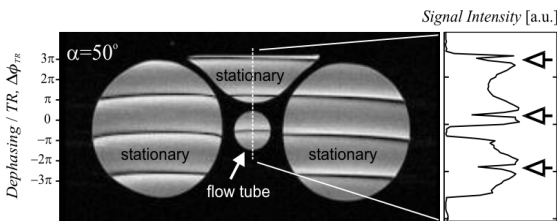
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**Synopsis:** An analysis of the effect of flow on 2D fully balanced Steady State Free Precession (SSFP) [1] imaging is presented. For various through-plane flow waveforms and flow rates transient and steady-state SSFP signal intensities in the presence of steady and pulsatile flow were simulated using a matrix formalism based on the Bloch equations. For accurate modeling of SSFP signal intensities it is crucial to include properties such as imperfect slice profiles and, more importantly, 'out-of-slice' contributions to the signal. Both simulations and experiments show that there can be considerable flow related changes in SSFP signal intensity resulting from frequency-dependent signal contributions from flowing spins that have already left the slice but still influence the SSFP signal.

**Methods:** The temporal evolution of the magnetization was calculated using a train of equally spaced RF-pulses (constant  $TR$ ,  $T_2$  and  $T_1$ ) and a matrix formalism similar to [2,3]. All simulations were performed for a set of 100 spin ensembles, each with different dephasing/ $TR$  (including two banding artifacts at  $\pm\pi$ ). Modeling of in-flow was performed by subdividing the imaging slice into thin sub-slices and, for each  $TR$ , shifting the magnetization vectors according to spin motion. The total SSFP signal intensity in each  $TR$  was calculated by forming the complex sum over all sub-slices. It is necessary to include two additional effects, imperfect slice profile and 'out-of-slice' contributions, as these play a significant role in the transient and steady state signal intensities. Phantom and volunteer studies were performed on a 1.5T system (Signa CV/i, GE, Milwaukee, WI) with a k-space segmented cine SSFP pulse sequence ( $\alpha=10^\circ-70^\circ$ ,  $TE=1.9\text{ms}$ ,  $TR=4.1\text{ms}$ ,  $FOV=20\text{cm}$ , matrix =  $256 \times 256$ , slice thickness =  $5\text{mm}$ ,  $BW=\pm 125\text{kHz}$ ). A flow pump was used to generate both pulsatile and steady flow in a cylindrical tube with gadolinium doped water ( $T_1 = 79\text{ms}$ ,  $T_2=67\text{ms}$ ) surrounded by structures with stationary fluid. Velocity profiles were measured using a phase contrast (PC) sequence ( $\alpha=20^\circ$ ,  $TE=3.5\text{ms}$ ,  $TR=8.4\text{ms}$ ). To analyze the sensitivity of the SSFP signal to off-resonance effects and its consequence on in-flow effects, one gradient axis was purposely misbalanced by slightly reducing the area of the readout refocusing lobe to create spatially dependent frequency offsets. Figure 2 shows the phantom with linearly varying dephasing/ $TR$  along the readout direction and a banding artifact centered in the flow tube. In the absence of flow, the magnitude images demonstrate typical SSFP signal modulation. To calculate the SSFP steady state signal response for each pixel inside the flow tube a pixel-by-pixel estimate of the spin replacement rate (derived from the velocity profiles measured with PC-MRI) and frequency offset were generated.

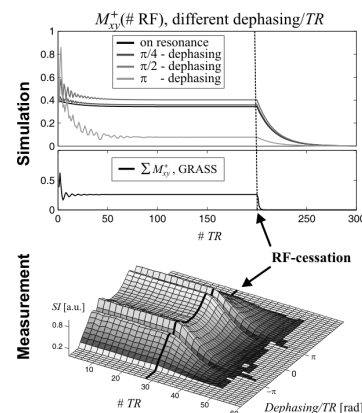
**Results:** Phantom experiments with steady flow showed considerable flow related changes in SSFP signal intensity at dephasing/ $TR$  of odd multiples of  $\pi$  (i.e. at banding artifact) while regions near on-resonance demonstrate only slight changes. Significant and more than five fold increase in signal enhancement was found. Comparison with simulations indicate that those signal changes are related to flowing spins that already left the imaging slice ('out-of-slice' contributions). Figure 2 illustrates the origin of those signal contributions in an analogous physical situation by investigating the evolution of magnetization in a static object with paused RF-excitation but continued gradient activity. With standard pulse sequences the signal is expected to cease once RF-excitation ends. With SSFP this is not the case. Both measurement and simulation demonstrate the  $T_2$ -dependent persistence of the SSFP signal even after RF-cessation. In addition, a noticeable increase in variation of the signal phase for different frequency offsets was found. Consequently, GRASS type pulse sequences decay much faster since the signal is the complex average over all frequency offsets (non-zero gradient area over a single  $TR$ ). Signal contributions after suspended RF-excitation are quickly reduced by complex averaging of spins with different phases. Balanced SSFP, on the other hand, continues to generate signal (figure 2, comparison of the GRASS and SSFP). Spin isochromats flowing out of the imaging slice experience similar conditions. Although spins leaving the slice do not experience additional RF-excitation, gradient activity is not confined to the region of excitations and is therefore still seen by previously excited spins. Remaining transversal 'out-of-slice' magnetization can thus still contribute to the total SSFP signal, effectively by broadening the slice thickness. To validate the simulation, detailed comparisons for pixel wise signal intensities (figures 3) were performed. Normalized measured and simulated signal intensities are displayed as 3D surface (top row) and contour plots (bottom row) and demonstrate that characteristic features of the signal enhancement patterns can be reproduced by the simulations with high accuracy. By contrast, simulations that exclude the 'out-of-slice' phenomenon were unable to reproduce signal variations observed in the experiments. In addition, excellent agreement is seen for pulsatile flow (figure 4). On-resonance spins mostly remain in a steady state while signal originating from regions at or near the band demonstrate large cyclic signal changes with the same periodicity as the in-flow waveform.



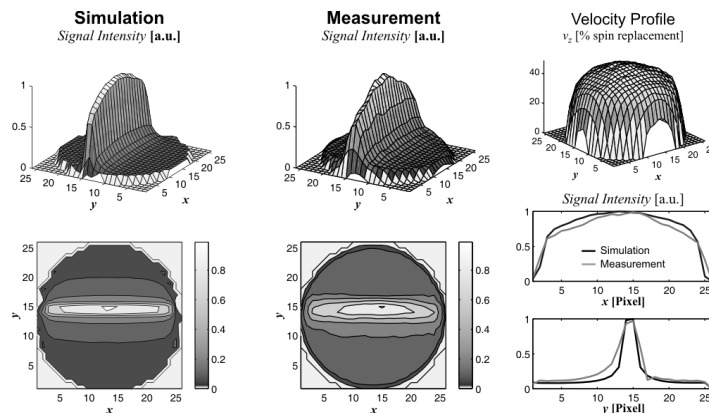
**Figure 1:** SSFP images of the experimental setup. The flow tube in the center (solid arrow) is surrounded by static objects. Purposely introduced frequency offsets result in equally spaced banding artifacts (signal drop-off, open arrows) corresponding to dephasing/ $TR$  of odd multiples of  $\pi$ .

**Discussion:** Excellent agreement between theory and measurement validate our computer simulations and assumptions of the factors that contribute to the in-flow effects of SSFP. It is evident that our computer simulations are also well suited for the portrayal of pulsatile flow waveforms and related periodic SSFP signal changes. Of particular importance, spins that have left the imaging slice can have a major effect on the total signal. It is essential to include 'out-of-slice' contribution into the simulation process to permit a correct description of the influence of flow onto the SSFP signal. Measurements, simulations and additional human studies verify that SSFP imaging has considerable flow related signal changes which are strongly dependent on off-resonance effects. Consequently, 'out-of-slice' contributions effectively increase slice thickness non-uniformly as a function of local through plane velocity and frequency offset.

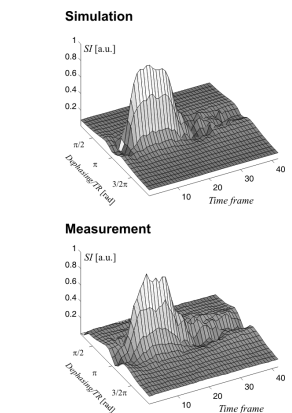
**References:** [1] Carr HY. Physical Review 1958;112(5):1693-1701, [2] Scheffler K. Concepts in Magnetic Resonance 1999;11(5):291-304 [3] Hargreaves BA, Vasanawala SS, Pauly JM, Nishimura DG.. Magn Reson Med 2001;46(1):149-58.



**Figure 2:** Simulated and measured SSFP signal evolution for RF-cessation and continued gradient activity.



**Figure 3:** Comparison of measured and simulated signal intensities in the flow tube for steady flow. Top right: measured velocity profile used for simulations. Note the strong signal enhancement at the tube center.



**Figure 4:** Measured and simulated signal intensities (SI) as a function of dephasing/ $TR$  for pulsatile flow.