Off-Resonance Dependent Slice Profile Effects in Balanced SSFP Imaging

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Introduction: Fully Balanced steady-state free precession (bSSFP, TrueFisp, FIESTA, Balanced FFE) is a fast imaging technique with high signal-to-noise efficiency and excellent blood-tissue contrast [1]. Little has been reported, however, on the influence of off-resonance effects on the true underlying slice profile of bSSFP imaging [2]. Since short TRs are crucial for artifact free SSFP imaging, short rf-pulses are generally used resulting in non-ideal flip angle distributions along the slice direction. Due to the frequency response function of the bSSFP sequence, measurements that are not on resonance result in broadened effective slices profiles with different, off-resonance dependent, shapes and consequently signal intensities. In this study, bSSFP slice profile effects and their dependence on off-resonance were investigated based on and bSSFP signal simulations of phantom data as well as blood and tissue.

Methods: ***Slice Profile Measurements:*** All phantom experiments were performed on a 1.5T Espree MR-system (Siemens, Erlangen, Germany) using a phantom with T_1=300 ms and T_2=261 ms. Data were acquired using a 3D SSFP Sequence with a small dephasing momentum added to the phase encoding gradients in order to generate literarily varying off-resonance frequencies. Further imaging parameters were as follows: flip angle = 60 degree, TR = 2TE = 5 ms, FOV = 233x233x128 mm³, 10 averages, slab thickness = 128mm, 32 slices/slab. Slice and readout gradient were executed along the same direction to permit direct imaging of the slice profile as a function of off-resonance frequency.

Slice Profile simulations: For all SSFP signal simulations, a train of equally spaced rf-pulses with constant flip angle and alternating rf-phase was assumed. Based on the Bloch equations, the evolution of the SSFP magnetization was recursively determined by three independent matrix operations corresponding to rf-excitation (α-rotations around x), dephasing per TR ($\Delta\Phi$/TR rotation around z) and a matrix/vector combination representing T2-decay and T1-relaxation. The bSSFP-slice profile was simulated with the same parameters (flip angle 60°, TE = 5 ms, T_1=300 ms, T_2=261 ms, 910 µs sinc shaped rf-pulse with two side lobes) as for the phantom measurements.

The measured slice profiles were normalized to the maximum and to the full width at half maximum (Figure 2, top left, FWHM) of the simulated slice profiles at $\Delta\Phi$/TR=0. Near the band, effective slice thickness was defined as the distance between the outer borders of the first two peaks at half maximum (Figure 2, top right). Further, the off-resonance dependence of effective slice thickness and the integral of the slice profile signal magnitude (i.e. bSSFP signal intensity) were simulated for blood (T_1=1000 ms, T_2=150 ms at 1.5T) and myocardium (T_1=700 ms, T_2=40 ms at 1.5T) for different flip angles

Results: Results for the measured (right) and simulated (left) bSSFP slice profiles for α=60° are shown in figure 1. From figure 1 and it is evident that signal distribution across the imaging slices and effective slice thickness are substantially altered for different frequency offsets. Note that at or near banding regions ($\Delta\Phi$/TR = +/- π) both the simulated and measured slice profiles demonstrates substantial signal contributions outside the imaging slice. Direct comparison of slice profiles (figure 2, top) and correlation analysis (figure 2, bottom) indicate that simulation can accurately reproduce off-resonance dependent bSSFP slice profile effects over a wide range of off-resonance frequencies with somewhat limited agreement at the band. As a result, simulations can be utilized to predict bSSFP slice profile effects for more realistic relaxation times. Simulation results for blood and tissue are summarized in figure 3 and clearly show a substantial variation of bSSFP signal intensity as well as an increase of effective slice thickness of up to 80% if on-resonance and near band regions are compared. The integral over the slice profile magnitude increases close to the band.

Discussion: The off-resonance frequency dependent bSSFP slice profile broadening and signal variation have been demonstrated in phantom experiments and numerical calculations. Simulated and measured slice profiles show similar shapes and demonstrated excellent agreement. Discrepancies between measurements and simulations were most prominent in and near off-resonance frequency bands which exhibit the strongest signal variations. Improved simulations including additionally measured field maps into the simulation process may improve the results at the bands.

Nevertheless, measurements and simulation illustrate that bSSFP suffers from considerable off-resonance dependent slice profiles. Simulations for blood shows that the effective slice thickness can increases by more than 80% close to the off-resonance frequency bands. Integrated slice profile magnitude (figure 3) indicate that the bSSFP signal might increase close to the band due to the out-of-slice excitation. However, for the calculations the SSFP signal phase dependency has to be included in the calculations.

Such effects have to be taken into account for routine clinical imaging where off-resonance dependent slice profile effects may result in a substantial difference between selected and true slice thickness or may even lead to spatially varying slice profiles and signal intensities across the bSSFP image.

References: [1] Oppelt A. et al. Electromedica 54:15, 1986
[2] Lu W. and Hargreaves B. Proc. Intl. Soc. Mag. Reson. Med. 14 (2006)

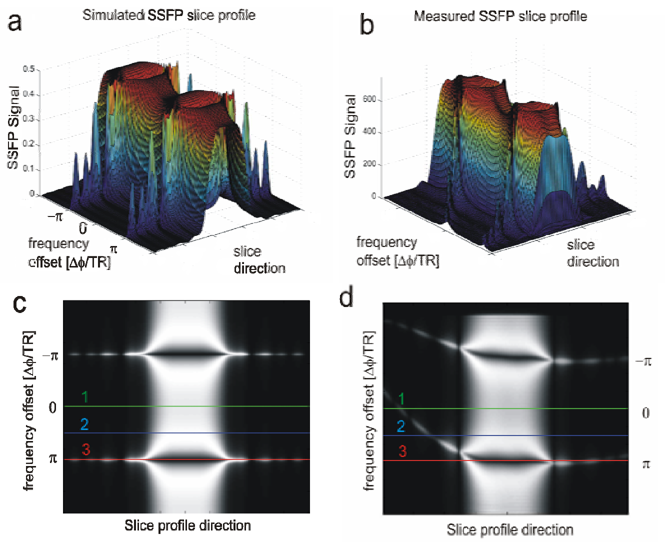

Figure 1: Simulated (a, c) and measured (b, d) 3D-images of bSSFP slice profiles for a flip angle of 60°. The lines indicate where cross-sections of the slice profiles were compared: on-resonance (1), at an off-resonance frequency of π/2 (2), and at an off-resonance frequency of π (3). See also figure 2.

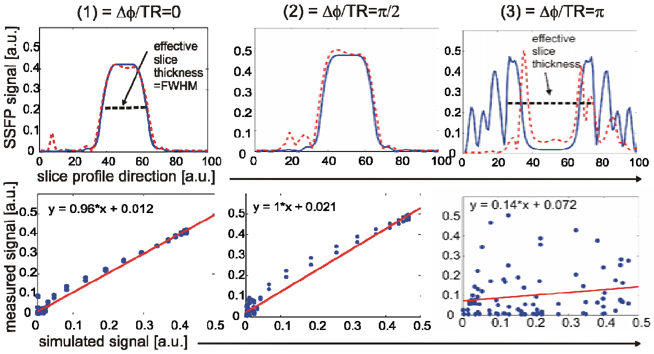

Figure 2: **Top:** Cross-sections through the simulated (blue, solid line) and measured (red dashed line) slice profiles for α=60° on resonance (1), at off-resonance of π/2 (2) and π (3). **Bottom:** linear correlation of measured and simulated data for the same frequency offsets

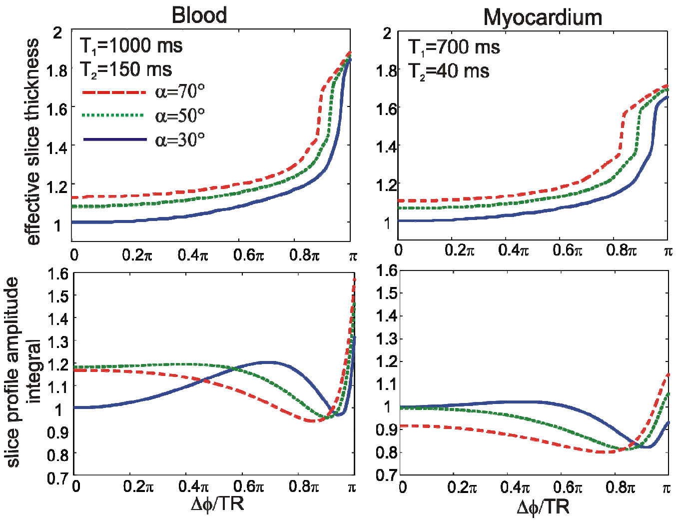

Figure 3: Simulated effective slice thickness (top) and corresponding bSSFP signal intensity (bottom) as a function of off-resonance frequency for different relaxation times for blood and myocardium and three different flip angles. The simulated effective slice thickness and signal intensities were normalized to values on-resonance for α=30°.