Improved RF Pulses for 3D SSFP with Minimised Off-Resonance Out-of-Slab Corruption

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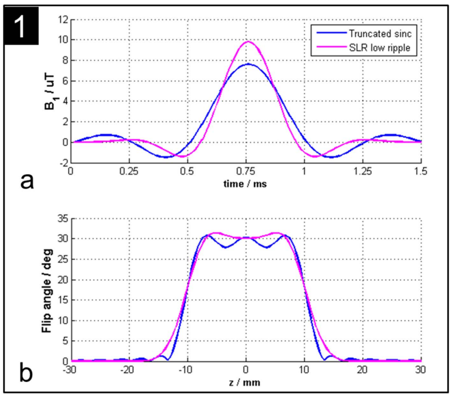
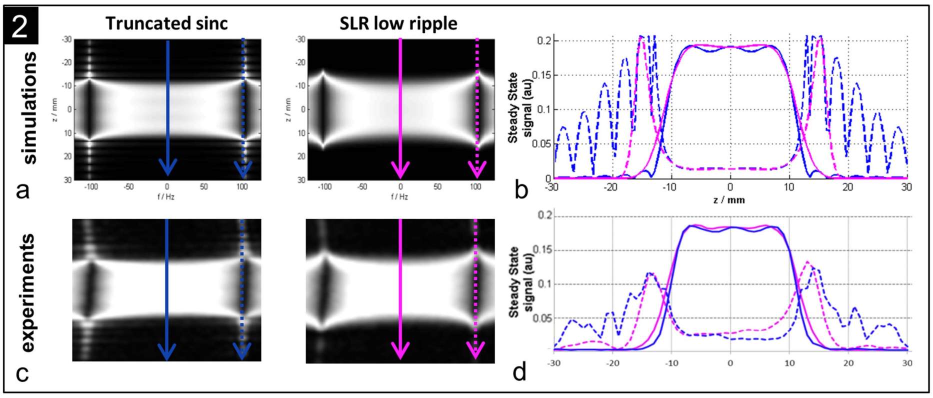
Introduction

Balanced SSFP provides excellent contrast and SNR efficiency, and is particularly well suited to cardiac applications - providing good discrimination between blood and myocardium. However, its familiar off-resonance characteristics are particularly problematic at higher field strengths, especially when imaging areas of flowing spins, such as within the heart. It is well known that 'black-band' artefacts arise at frequency offsets of ±1/(2TR). At these same frequencies however, if the flip angle is very low (typically <5°) the steady-state signal is actually very high. When using slice selective pulses, out-of-slice ripple manifests as very low but finite flip angles which result in very high signals originating outside the intended slice. These then fold back into the image, causing artefacts [1]. It is possible to suppress such artefacts by using pulses designed to have low out-of-slice ripple, with previous work focused on low time-bandwidth pulses suited to 2D SSFP applications [2]. 3D imaging with slab-selective pulses is more demanding of the slice profile, and off resonant out-of-slice effects are potentially worse given the difficulty in shimming extended 3D regions. Here we demonstrate a low-ripple pulse design that yields a suitable slab profile for 3D applications and minimise fold-in artefacts in the slice phase-encoded direction.

Methods

RF pulse design was performed using the VeSPA-RFPulse package [3] with the Shinnar-LeRoux (SLR) method with a target stopband ripple of 0.0001%, bandwidth = 6 kHz and duration = 1.5ms. This was compared with the default truncated sinc pulse used on the scanner for 3D SSFP sequences. Simulations of the SSFP steady-state slab profile were performed in Matlab. Bloch equation simulations were first performed to derive the flip angle profile of the pulse (assuming starting from thermal equilibrium). Steady-state predictions were then generated to correspond with these flip angles. Experiments were performed using a 10cm spherical phantom ($MnCl^2$-doped water giving a measured T2/T1 = 180/1075ms – similar to blood) on a 3T Philips Achieva scanner (Best, Netherlands). A 3D SSFP sequence with 1mm isotropic acquisition, TE/TR=2.4/4.8ms, FA=30 was used. The slab width was set to 20mm but encoded to 60mm so that signal outside the slab would also be resolved. Higher order shimming was performed, and then a 0.1 mT/m linear shim added to the Y-gradient to generate a field variation in the 1st phase-encode direction to mimic simulations.





Results & Discussion

Fig 1 shows the standard pulse (truncated sinc) vs new SLR designed low ripple pulse; both scaled to 30° and 1.5ms duration. The low ripple pulse is marginally less efficient and thus requires higher B1 to maintain the same pulse length. Fig 1b shows flip angle distribution from Bloch simulation revealing the low ripple pulse benefits from a flatter passband but slightly smoothed edge profile. Fig 2 shows the steady-state SSFP signal and corresponding profile plots from simulated (a,b) and experimental (c,d) results for flip angle distributions for on-resonance (solid lines) and 1/(2TR) off-resonance (dashed lines). There is good agreement between simulated and experimental data. The required uniform signal in slab is achieved. The off-resonance out-of-slice predictions appear to be slightly overestimated by the simulations, however this could partly be attributed to partial volume effects in the imaging (the phase changes rapidly here so cancellation is expected to be strong). Also a small but detectable off-resonance ripple still remains in the imaging of the SLR low ripple pulse, which is not predicted by the pulse design; further investigation is needed to determine the cause. It may be due to imperfections in the waveform generation of the pulse on the scanner. Nevertheless the pulse produced a significant improvement for suppressing fold-in artefacts in 3D SSFP imaging. Further improvement should be gained by shortening pulse duration and decreasing its peak amplitude using the time-optimal VERSE [4] approach.

Conclusion

We have used the SLR algorithm to design a pulse with very low out-of-slab ripple and demonstrated in simulation and phantoms that it should perform well for 3D SSFP imaging. The improved RF pulse shape has been shown to reduce the unwanted off-resonance SSFP signal originating far away from the intended passband, whilst also maintaining a good slab profile, both necessary for 3D SSFP applications.

References

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