Real-Time SSFP Transient Manipulation

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Introduction: Real-time balanced SSFP is an excellent technique for dynamic studies. It is a high-speed acquisition that provides increased SNR and improved contrast compared to other real-time acquisitions such as GRE. The dynamic nature of real-time imaging presents a challenge for the use of balanced SSFP sequences as imaging parameters can be drastically changed during the scan. This disturbs the steady state resulting in severe transient artifacts. Traditional catalyzation techniques are not tailored for real-time imaging being too slow or not solving all possible transitions. We have developed and compiled a set of transient manipulation methods optimized for real-time applications. Special consideration is to produce automatic and significant transient artifact reduction in the shortest possible time. We have classified the possible real-time disturbances and their impact on the steady state in four groups: 1) Steady state initialization that occurs at the beginning of an experiment and when the scan plane is modified. 2) Abrupt changes in flip angle by user request. 3) Changes in repetition time (TR) due to readout modifications and 4) modifications to RF phase.

Methods: Different methods have been previously demonstrated for transient reduction [1–4]. They are fast but effective in only a narrow spectral band [1] or slow with broadband effectiveness [2-4]. We propose a hybrid approach that improves broadband catalyzation when only few excitations are used. If the flip angle is increased in big discrete steps, significant transients remain for the central frequency bands. We can consider initialization as a special case of arbitrary changes in flip angle. If "a" is the current flip angle (0 for initialization) and "b" the target angle, then a correction pulse can be added at TR/2 to move the on-resonance spin magnetization to the steady-state direction corresponding to the next RF pulse. This correction is designed to be half the difference between the consecutive flip angles, (b-a)/2. In this manner, frequencies close to the central band are perfectly catalyzed while improving the response for the remaining spectrum. Figure 1 shows a pulse diagram when two correction pulses are used. This correction can also be interpreted as combining in a single pulse a magnetization storage pulse (back to Mz) with an a/2 preparation. To improve the transient reduction, the angle can be additionally changed in steps [3,4]. If only few steps are desired, then TR/2 correction is required as the intermediate transitions disturb the steady state.

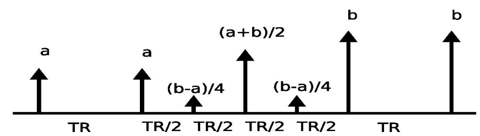

Figure 1: Flip angle transition sequence with correction pulses.

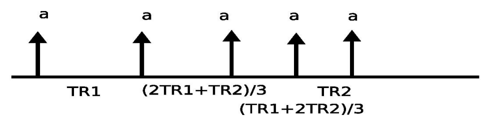

Figure 2: TR transition sequence. Consecutive TRs are smoothly changed.

For changes in the repetition time (TR), we can use the same approach as in the previous method. One can think of a combination of magnetization storage pulse (back to Mz) and a/2 preparation pulses into a new steady state. As both of these pulses have the same flip angle, they cancel, having a net effect of adding a transition TR that is the average duration between the previous and next repetition. As the steady state is very sensitive to phase changes [5], slowly varying the TR drastically improves the effectiveness of this technique. Figure 2 shows a pulse diagram where two intermediate transitions are used to mitigate transient response. This method effectively "ramps" the width of the TR's.

As it has been previously reported [5], the steady state is very sensitive to disturbances in the RF phase increment. For this reason, RF phase has to be incremented in small steps.

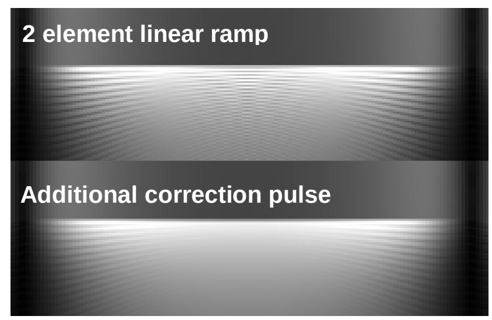

Figure 3: Spectrum vs time flip angle transition simulation (20 to 80 deg). Correction pulse minimizes transients for central bands.

Results and Discussion: Figure 3 shows a T1/T2 800/30 ms simulation of flip angle transition with additional correction pulses. On the top is a 3 element linear ramp during a 20 to 80 deg transition. The bottom image shows the result of adding correction pulses during the ramp. The problematic central band transients can be completely eliminated by the proposed method. Figure 4 shows the effect of changing the TR from 4 ms to 6 ms. The right image shows the elimination of transients after a 20-TR time ramp.

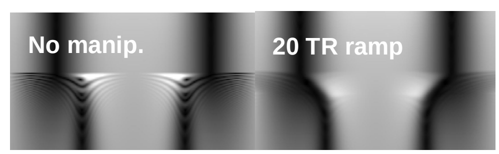

Figure 4: Spectrum vs time TR transition simulation.

A phantom experiment (T1/T2 1200/900 ms, TR = 4.2 ms, 30 Hz off-resonance) shows that the addition of the correction pulses greatly improves the signal behavior (figure 5).

We observed that a slightly bigger flip angle correction could reduce the transients for a broader spectrum without a significant degradation of the central bands. This is because in general the magnetization angle remains within a close range in the central band.

For flip angle changes, magnetization can be additionally scaled down to the final steady state value. A saturation effect can be accomplished by overshooting the transition and then returning to the new flip angle.

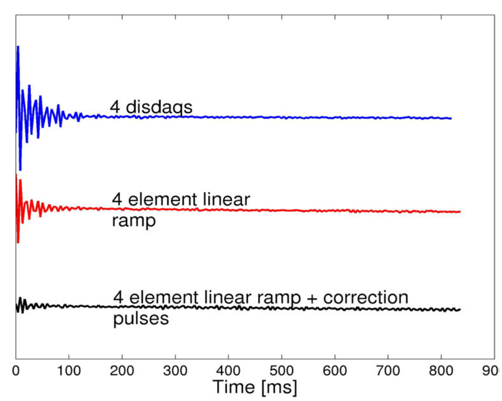

Figure5: Phantom experiment. Initialization transient after no catalyzation, 4 element ramp and ramp with correction pulses.

Conclusion: A simple an effective method has been presented to improve the transient response for application that cannot spend time in the catalyzation process. We have also classified and presented solutions for the most common transitions during a real-time experiment.

References: [1] Deimling M, et al. 2nd SMR, 495, 1994. [2] Hargreaves B, et al. Mag Res Med, 46:149, 2001. [3] Hennig J, et al. Mag Res Med, 48:801, 2002. [4] Le Roux, P. JMR, 163:23, 2003. [5] Foxall D, Mag Res Med, 48:501, 2002