Considerations on Startup Sequences in Interrupted Balanced SSFP Imaging at 3 Tesla

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Introduction:

Interrupted balanced steady-state free precession (IbSSFP) sequences for coronary MRA at 1.5T are state of the art due to high signal and excellent contrast between blood and myocardium. A preliminary study at 3.0T has shown reduction in both contrast and visualized vessel length using an IbSSFP sequence compared to a spoiled gradient echo sequence [1]. The reduced performance at 3.0T may be associated with increased B0-inhomogeneities and the corresponding transient artifacts. Several SSFP startup sequences to reduce the transient time and its associated artifacts have been proposed [2-7]. The goal of this study was to compare the different startup sequences for IbSSFP with regard to blood-muscle contrast and artifact generation in phase-encode direction due to transient signal oscillations.

Methods:

Different IbSSFP sequences were simulated using MATLAB (MATLAB, Natick, MA). Longitudinal and transversal magnetizations of a tissue matrix were calculated using the numerical solutions of the Bloch equations. The simulations incorporated phase encoding for spatial localization and field inhomogeneity. Three different startup sequences were investigated: Alpha-half-TR-half (AH) with (n-1) dummy excitations [2], linear flip angle sweep (LFA) [3,4] with n excitation steps using the c-TIDE formula [5], and the transition to driven equilibrium (TIDE) with 90°-TR-half and (n-1) excitation steps [5]; n being the number of startup steps. The following sequence parameters were used: TR = 5ms, FOV = 320mm, heart rate = 60bpm, blood was replaced every heart beat, 28 heart beats with 13 k-space lines applying a low-high k-space order were measured and k-space was zero filled to 512 data points.

Signal strength for contrast determination was simulated on-resonance using a tissue matrix composed of a blood (T1=1664ms, T2=141ms, ρ=0.95) and a cardiac muscle compartment (T1=1115ms, T2=41ms, ρ=0.7). All three sequences were simulated for flip angles ranging from 5° to 180° and n ranging from 1 to 120 with and without T2-preparation (90°-180°-180°-90°, TE=50ms).

Artifact signal in phase-encode direction was determined by simulating a tissue matrix composed of blood with 128 signal sources distributed over 1mm at the center of the FOV. The target signal was defined as the summed signal from the three center voxels of the reconstructed array, and artifact signal as the total signal minus the summed signal from the five center voxels. Figure 1 shows two exemplary simulations from the AH sequence with n=10. The relative target and artifact signal is defined as the ratio of each signal with the total signal measured on-resonant applying the same number of startups. The SSFP flip angle was 80°. Further simulations were performed with a reduction of all the applied flip angles by 10 and 20%, mimicking B1-inhomogeneities.

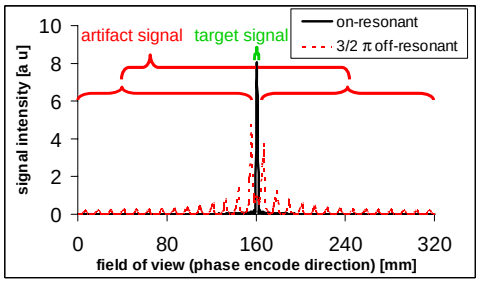

Figure 1: *Definition of target and artifact signal. Shown are the reconstructed signals from a 1mm big blood sample within a FOV of 320mm, black on-resonant and red with 3/2π dephasing over TR=5ms.*

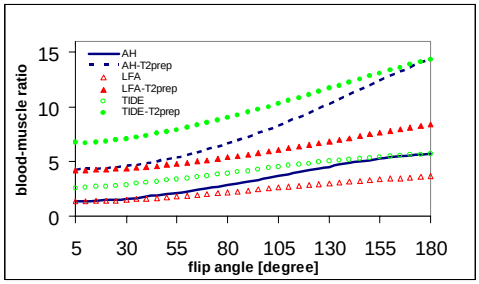

Figure 2: *Blood-muscle ratio depending on flip angle for the three different startup sequences, with or without T2-preparation.*

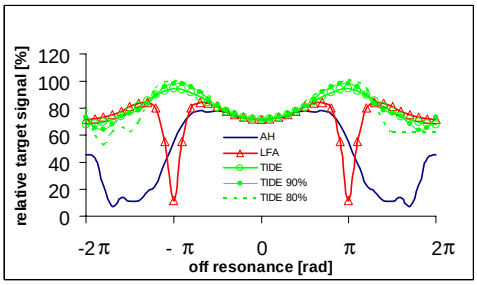

Figure 3: *Relative target signal depending on off resonance for the three different startup sequences and reduced B1 for the TIDE sequence. The number of startups was 10 and the flip angle 80°.*

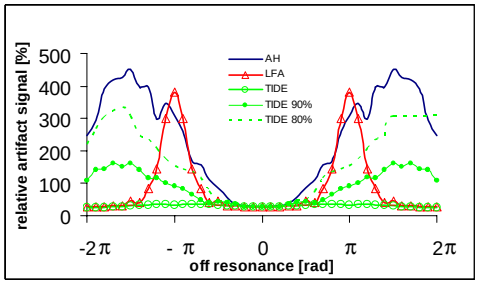

Figure 4: *Relative artifact signal depending on off resonance for the three different startup sequences and reduced B1 for the TIDE sequence. The number of startups was 10 and the flip angle 80°.*

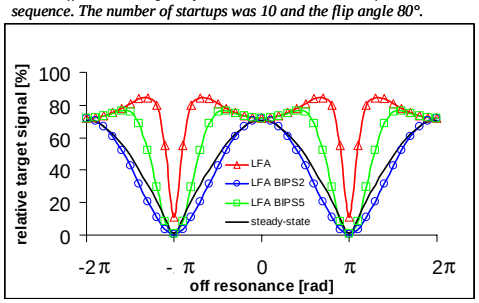

Figure 5: *The relative target signal depending on off resonance for the LFA startup sequence with or without binomial pre-saturation (2 or 5 pulses) compared to the balanced SSFP steady state after 1200 startups.*

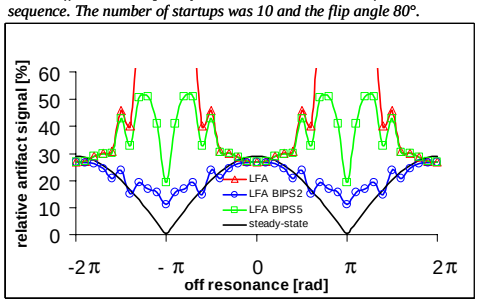

Figure 6: *The relative artifact signal depending on off resonance for the LFA startup sequence with or without binomial pre-saturation (2 or 5 pulses) compared to the balanced SSFP steady state after 1200 startups. Note the different scale of the graph compared to Fig. 4.*

Results:

Blood signal (not shown) and blood-muscle ratio (Fig. 2) both increase with increasing flip angle. T2-preparation improves the blood-muscle ratio. Application of high flip angles is limited by SAR and the desire for short TR.

The relative target signal (Fig. 3) shows a constant level covering an off-resonance interval of [-.8π, .8π] for all startup sequences. Both LFA and TIDE are periodic over 2π, while AH has a periodicity over 4π. The relative artifact signal (Fig. 4) is low in an off-resonance interval of [-.6π, .6π] for all sequences. Both AH and TIDE with inhomogeneous B1 show a 4π periodicity, while LFA is 2π periodic.

Discussion:

Assuming a TR of 5ms, the field inhomogeneity of the slice should therefore not exceed 120Hz. However, at 3.0T this is only possible for a region of interest (ROI) using localized shimming. Surrounding tissue with higher field inhomogeneity will then cause transient artifacts. To prevent these artifacts from outside the ROI, the artifact signal can be pre-saturated in the LFA sequence. Foxall used a similar approach to scale longitudinal magnetization before the LFA startup [7]. Fig. 5 and 6 show that applying a 2 pulse (45°-(-45°)) binomial pre-saturation (BIPS2) as suggested by Foxall leads to a state very close to the final bSSFP steady-state. For coronary MRA, however, this is suboptimal, as a broad constant target signal is warranted. This may be achieved by a 5 pulse binomial pre-saturation (BIPS5).

In summary, there are characteristic differences when considering startup schemes for IbSSFP sequences as used in coronary MRA relative to sequences operating in the steady-state. Based on the simulations presented, the LFA scheme in conjunction with suppression bands at the darkband resonances is favored as it provides most homogenous excitation across the off-resonance range encountered. The TIDE scheme, even though it has the best off-resonance performance under ideal conditions, is compromised in the presence of B1 inhomogeneity, which is expected at high field systems.

References:

[1] Kaul MG, Proc. 12th ISMRM, p.1874, 2004. [2] Deimling M, Proc. 2nd ISMRM, p. 495, 1994. [3] Nishimura DG, Proc. 8th ISMRM, p. 301, 2000. [4] Deshpande VS, MRM **49**:151-157, 2003. [5] Hennig J, MRM **48**:801-809, 2002. [6] Hargreaves BA, MRM **46**:149-158, 2001. [7] Foxall DL, US Patent #20040095138.