Flow Suppression Effect in Dual Steady States Acquisition

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Introduction: Dark blood contrast mechanisms are essential for cardiovascular imaging applications like tissue characterization (e.g., acute infarct), RV dysplasia (e.g., fatty infiltration) and atherosclerotic plaque characterization. The most common dark-blood technique is based on double-inversion recovery (DIR) magnetization preparation [1], yet, the prohibitive scan time prevents many applications such as screening for atherosclerotic plaques from entering the clinical setting. Previously, we presented a rapid dark-blood (dual steady states) vessel-wall imaging method that could be combined with TrueFISP imaging [2]. The current work aims to investigate the development of very rapid methods for flow suppression by using an analytic model for moving spins in a 2D SSFP sequence; it builds on the earlier work by Markl [3] and the previously reported dual-steady state method. Our work combines incoming spins with unsaturated magnetization, establishment of an out-of-slice spoiled steady state signal proximal to the imaging slice, a SSFP signal from the imaging slice and out-of-slice contributions generated by spins that have left the image slice but still contribute signal because of the zero gradient moments of SSFP acquisitions. Animal imaging trials were performed to provide *in vivo* experimental validations of simulation results that confirm rapid flow suppression effect.

Methods: The dual steady states SSFP sequence acquires relatively high signal amplitude for static spins with fully refocused gradients along all three imaging axes over each repetition time (TR); it also achieves signal attenuation for moving spins by varying the phase (i.e. RF spoiling) of the saturation slab which is located adjacent to the imaging slice (Fig 1). To enhance the contrast between the moving and static spins, we established two different steady state equilibriums which correspond to FLASH-like magnetization for incoming moving spins and TrueFISP contrast for stationary spins in the imaging plane. The out of slice slab signal is further reduced by using a non-zero slice selection gradient moment at the echo time for slab spins.

Analytic expressions for the resulting rotation matrices and magnetization distributions have been generated using Mathematica (Wolfram Research, Inc., Champaign, IL.) with plug and continuous flow assumptions. Based on the Bloch equations, the SSFP signal behavior is determined by three matrices corresponding to RF excitation, dephasing per TR and a matrix representing T1 relaxation and T2 decay. Blood velocity is indicated by the percentage of unsaturated spins that flow into the image slice within each TR. Spins are followed through the saturation slab, into the imaging slab at a partially saturated magnetization due to experiencing multiple RF pulses, through the imaging slice and out where only gradient activity is encountered. Solutions are also obtained for spins stationary within the imaging slice. Plots of signal from flowing spins and spins within the imaging slice are obtained as a function of off-resonance frequency. According to current protocol (TR/TE/Thickness=2/4/5mm), an inflow rate equal to 20% corresponds to a blood flow velocity of 25cm/second. To verify simulation results, three Watanabe heritable hyperlipidemic (WHHL) rabbits (mean age: 26 months) underwent magnetic resonance imaging of the abdominal aorta using a 1.5 T MR system (Sonata, Siemens Medical Solutions, Erlangen, Germany) for *in vivo* image using a dual steady state pulse sequence comparable to that used in the simulations .

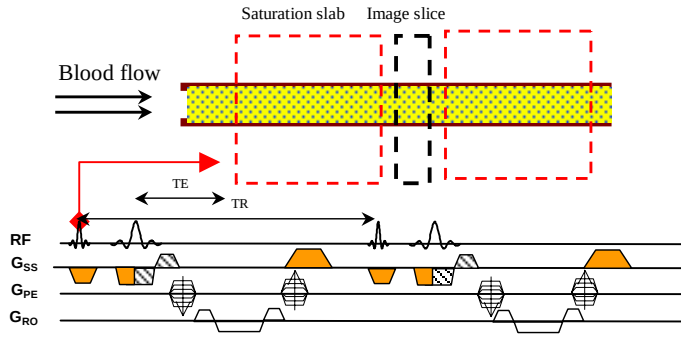

Figure1. Pulse sequence diagram for dual steady states flow suppression sequence. During each sequence cycle we apply FLASH-like saturation pulse prior to image slice and the refocused gradient (shaded regions) to achieve fully balance for zero gradient moment which is followed the condition of TrueFISP for static spins and diverse phase for moving spins.

Results: As shown in Figure 2, flow signal in a standard TrueFISP acquisition shows significant (and resonance-offset angle dependent) enhancement; this is associated with both the in-flow effects (additional influx of unsaturated magnetization) (Fig. 2a) and the out-of-slice contribution, previously reported by Markl and provided here for comparison. The out-of-slice contribution is provided by spins that yield gradient echoes even after leaving the imaging plane due to the balanced gradient structure (Fig. 2b) [3]. Fig. 2c and d demonstrate significant flow signal reduction (below that of stationary spins) and similar stationary tissue signal amplitude when a dual steady state sequence is used. *In vivo* images obtained with both standard TrueFISP and the dual steady states sequence depicted in Fig 1 are displayed in Fig3. Fig. 3a shows a standard TrueFISP acquisition in the abdomen of WHHL rabbit. Figures 3b, c and d were acquired by placing the saturated slab superior, inferior, and both superior and inferior to the image slice. All images demonstrate the blood flow signal attenuation with the dual steady states sequence. Note the excellent suppression of inflowing spins and consistent True-FISP contrast for stationary tissue.

Discussion: This study suggests that establishing different steady states for static and moving spins offers great promise in rapid dark-blood imaging, as shown here for evaluation of the vessel lumen. In this study, we have shown that the dual steady states sequence has the desirable dark-blood contrast within extremely short acquisition time of 3.3seconds. Good agreement has been achieved between analytic simulation results and in vivo experiments that confirm the partial saturation of the inflow signal (via out-of-slice spoiled SSFP signal generation) allows significant variation between the moving and static spins. The in-flow effect could be further reduced by designing a better slice excitation profile in order to place the saturation slab and image slice as close as possible to avoid flow signal re-growth in the posterior saturation region. The analytical tool created allows adjustment of all aspects of the pulse sequence, including RF tip angles, RF phases, dephasing intervals, flow rate, TR, TE, etc. Future research can now explore modifications of the basic sequence to achieve further improvements in flow suppression. This work provides confirmation, by both simulation and experiments, that modest adaptations of the basic TrueFISP structure can prevent unwanted "bright blood signal" within the vessels, while simultaneously preserving the contrast and speed advantages of this well established rapid imaging method.

References: [1] Edelman, R. et al., Radiology, 1991:181:655-660. [2] Dale, B. et al. Proc. Intl. Soc. Mag. Reson. Med., 2003:11: 453
[3] Markl, M. et al. Magn Reson Med, 2003:50:892-903

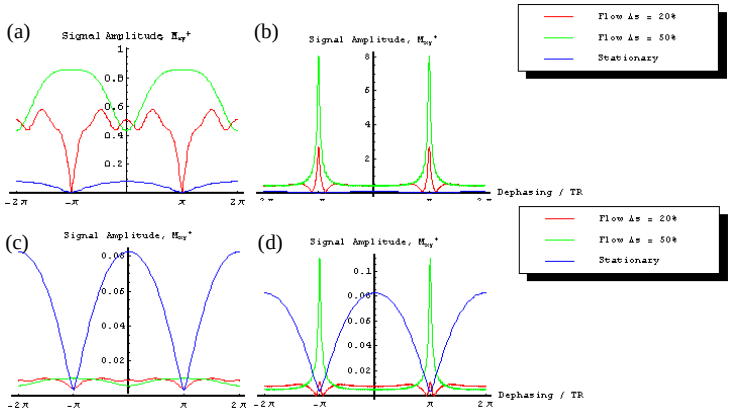

Figure 2. Static and moving spins signal behavior vs. dephasing per each TR which were simulated by (a) standard TrueFISP with in-flow effect (b) standard TrueFISP with in-flow effect and out-of-slice contribution (c) dual steady states sequence with in-flow effect (d) dual steady states sequence with in-flow effect and out-of-slice contribution. (TE/TR/FA-slab/FA-slice/T1/T2=2/4/90°/60°/1000/150ms)

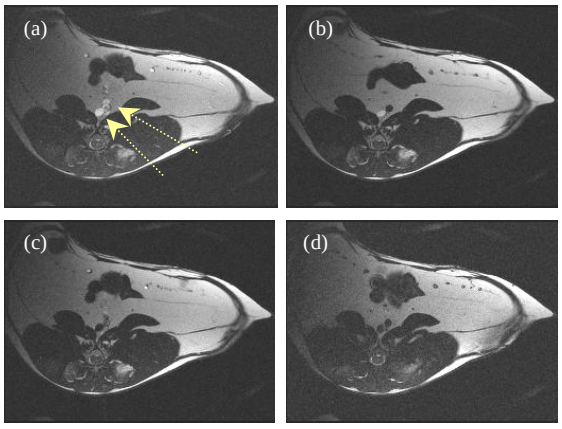

Figure 3. WHHL rabbit abdominal aorta wall image using (a) standard TrueFISP (b) Dual steady states sequence with arterial saturation (c) Dual steady states sequence with venous saturation (d) Dual steady states sequence with arterial and venous saturation
FA-slab90° /FA-slice60°/TE3.6/TR8.8/192X256/NEX2/Time 3.3 sec