On The Cause of Transient Off-resonance Stopbands in TIDE bSSFP Imaging

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Introduction

Transition Into Driven Equilibrium balanced steady-state free precession sequence (TIDE bSSFP) [1] has been shown to exhibit an intrinsic fat suppression [2, 3]. This phenomenon was described to come from the appearance of an off-resonance signal null or transient stopbands [3]. In experience, fat suppression remained although TIDE preparations of various TIDE-specific parameters were used **(Fig. 1)** [2, 3, 4]. This study is devoted to the analysis of the mechanism of the signal nulling using simulation and analytical derivation. Experimental validations were also performed.

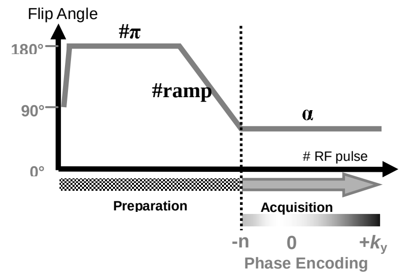

FIG. 1. The flip angle scheme of the TIDE preparation and the bSSFP readout. There exist three TIDE-specific parameters, including **#π**: the number of 180° pulses; **#ramp**: the number of the down-ramping pulses; **α**: the constant flip angle of bSSFP readout.

Theory

Simulating the time curves for M_{xy} and M_z of various dephasing angles θ, we found the θ = 360° curves resemble those of inversion recovery (IR). Such an evolution goes from –z to +z, passing through a zero at a time similar to inversion time (TI) in IR **(Fig. 2)**. The magnetizations of both θ cases eventually converge to the same steady state, since conceptually θ = 0° should be the same as θ = 360°. However, the two cases differ at the TR/2 period of the TIDE preparation: the precession angle of the θ = 360° magnetization is only 180°. Without loss of generality, we illustrate this process with a simple TIDE-preparation scheme: 90°→TR/2→135°→TR→α = 90° as in Ref. [1], and the initia1 relaxation is neglected in this short TIDE-preparation phase **(Fig. 3)**. After the preparation, the θ = 360° magnetization goes to a location $\mathbf{M_1^-}$ on the α/2-cone in –z octants, while the θ = 0° one goes to another $\mathbf{M_1^-}$ on the α/2-cone in +z octants. The prepared $\mathbf{M_1^-}$ of the θ = 0° case is basically the same as that in half-angle-half-TR TrueFISP [6, 7]. The minus sign in $\mathbf{M_1^-}$ simply marks it as before RF pulsing.

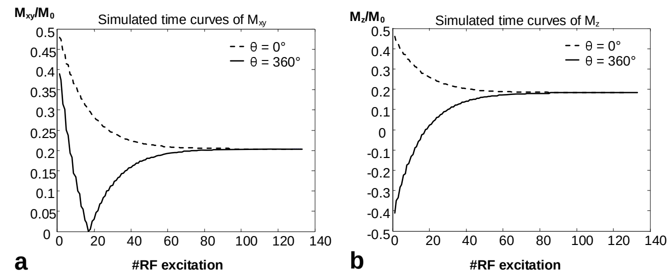

FIG. 2. Simulated time curves of (a) M_{xy} (b) and M_z after the TIDE-preparation phase. The dotted line in both plots is the evolution of a magnetization of dephasing angle θ = 0°, whereas the solid line is that of a magnetization of θ = 360°.

Following the same formalism in Ref. [5], we use rotation matrices $\mathbf{R}_\alpha$ around the x-axis for α-angle RF pulses and $\mathbf{P}_\theta$ around the z-axis for precession in a dephasing angle θ, as well as a relaxation matrix **E** during TR and a vector $\mathbf{e}M_0$ related to T_1 recovery. The RF phase alternation is equivalent to adding another 180° rotation to $\mathbf{P}_\theta$, i.e. we denote it as $\mathbf{P}_{\theta+\pi}$. The transient magnetization $\mathbf{M_N^-}$ between the initial $\mathbf{M_1^-}$ and the steady-state $\mathbf{M_\infty^-}$ can be written as

$$\mathbf{M_N^-} = \mathbf{T}^{N-1}\mathbf{M_1^-} + (1+\mathbf{T}+\mathbf{T}^2+\ldots+\mathbf{T}^{N-2})\mathbf{e}M_0 = \mathbf{T}^{N-1}\mathbf{M_1^-} + (1-\mathbf{T}^{N-1})(1-\mathbf{T})^{-1}\mathbf{e}M_0,$$

if we define $\mathbf{T} = \mathbf{P}_{\theta+\pi}\,\mathbf{E}\,\mathbf{R}_\alpha$. One can find that $\mathbf{M_\infty^-} = (1-\mathbf{T})^{-1}\mathbf{e}M_0$ as N→ ∞. Therefore we have $\mathbf{M_N^-} = \mathbf{T}^{N-1}\mathbf{M_1^-} + (1-\mathbf{T}^{N-1})\,\mathbf{M_\infty^-}$ or $(\mathbf{M_N^-} - \mathbf{M_\infty^-}) = \mathbf{T}^{N-1}(\mathbf{M_1^-} - \mathbf{M_\infty^-})$. The last expression is an eigenvector equation since the evolution is along a constant direction, and then we have $(\mathbf{M_N^-} - \mathbf{M_\infty^-}) = \lambda^{N-1}(\mathbf{M_1^-} - \mathbf{M_\infty^-})$, with λ being the eigenvalue $\lambda \approx e^{-TR/T1}\cos^2\alpha + e^{-TR/T2}\sin^2\alpha$ [6]. The θ = 0° case is equivalent to the result in Ref. [6]. However for the θ = 360° case, we can rewrite it as $\mathbf{M_N^-} = \mathbf{M_\infty^-} - \lambda^{N-1}(\mathbf{M_\infty^-} - \mathbf{M_1^-})$, analogous to the inversion recovery: $M_z(t) = M_0 - e^{-t/T1}(M_0 - M_z(0))$, but in a discrete-time system fashion.

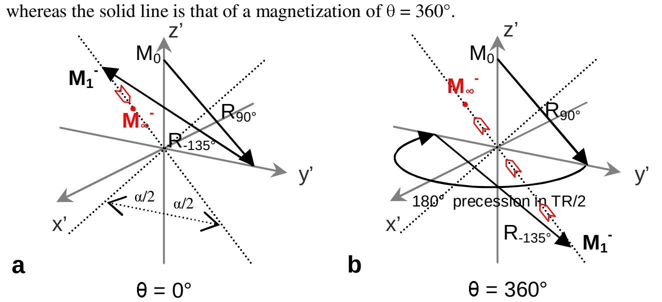

FIG. 3. An illustration showing the difference between magnetizations of dephasing angle (a) 0° and (b) 360° during the TR/2 period after the initial 90° pulse of the TIDE preparation (90°-TR/2-135°-TR). After the preparation, the bSSFP pulsing of α flip angle drives the initial magnetization $\mathbf{M_1^-}$ along the α/2-cone to the destination, i.e. the steady-state magnetization $\mathbf{M_\infty^-}$. The two evolutions are different: one from +z octants, and the other from –z octants.

Materials and Methods

Simulation was based on Bloch equation using MATLAB software. Scans of a soy-bean oil phantom were performed to validate the theoretical characteristics of the stopbands. The images were acquired on a 3.0T system (Siemens Trio, Erlangen, Germany). TIDE-specific parameters in both studies were #π = 1, #ramp = 14, and α = 70°. We used TR/TE = 6.8/3.4 ms and matrix size 128×128. Half-Fourier function was applied. Additional linear shim gradient of 200 μT/m was applied to visualize the stopbands and the passbands.

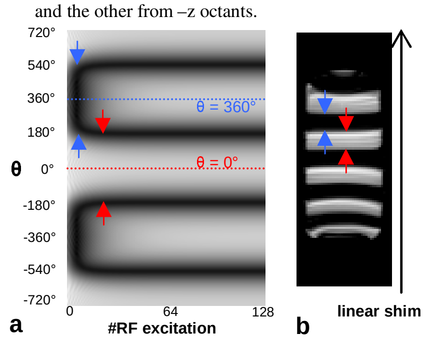

FIG. 4. (a) The simulated plot of signal intensity evolution versus the off-resonance dephasing angle; (b) The TIDE image of a soy-bean oil phantom with addition linear shim gradient (200 μT/m) demonstrates the width of the stopband (blue arrows) is equivalent to that of the passband (red arrows), matching the theoretical prediction.

Results

Fig. 4 shows the results from the simulations and the experiments. The transient stopband (blue arrows) shows up after the end of TIDE-preparation phase with a bandwidth approximately equal to that of the passband (red arrows). The passband and the transient stopband are symmetric about θ = 0° and θ = 360°, respectively. Timing of transient stopband in the experiments matches the theoretical prediction.

Discussion and Conclusion

In this study, we demonstrated the θ = 360° magnetization evolves in a fashion analogous to inversion recovery (frequency-selective IR-like evolution). An intrinsic fat suppression results when placing the frequencies of the lipid protons around θ = 360° and choosing a correct timing to sample [2, 3]. The explanation here applies to other θ angles passing the stopbands, despite the presence of oscillations. Signal oscillations when θ is other than 0° or 360° may result in ghosting. In conclusion, we have analyzed the mechanism of the intrinsic fat suppression with a simple theoretical model. This model may contribute to the estimation of water and lipid signals during the TIDE evolution.

References

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