Determination of Optimal Fat Suppression in LOW-TIDE B-SSFP Imaging using Eigenvalue Analysis

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Introduction: Linear filter-based Optimal Window Transition to Driven Equilibrium (LOW-TIDE) is a preparation scheme for T2 weighting and intrinsic fat suppression with balanced SSFP imaging when partial Fourier encoding in the phase direction is used \([1]\). Both TIDE \([2]\) and LOW-TIDE use a \((\pi/2)-(TR/2)\) preparation pulse followed by a train of \(\pi\) \((180^\circ)\) excitation pulses. This is followed by a smooth ramp down to the final asymptotic flip angle train. The relationship between imaging parameters and fat suppression has previously only been determined through numerical simulations of the Bloch equations \([3]\). No inverse solution has been offered to predict the partial Fourier factor (PFF) necessary for fat suppression with a particular combination of imaging parameters. Here we explore a semi-analytical form (to determine optimal fat suppression) suitable for implementation in pulse programming software. The effective echo time to achieve optimal suppression can then be predicted and the partial Fourier factor (PFF) adjusted in a real-time fashion during scan prescription.

Materials and Methods: A 4-term Blackman-Harris window was used for ramp down to the final flip angle \([1]\). The exact characterization of fat signal evolution can only be predicted through numerical solution of Bloch equations \([3]\). However, it has been shown \([3]\) that signal evolution in b-SSFP can be considered to be a third order linear system that can be analyzed using eigenvalue decomposition. Accordingly, the magnetization at the \(k\)th iteration can be expressed as

\[ Q(k) = \Gamma \Gamma^{-1} Q(0) = \sum_{i=1}^{3} \beta(i) \lambda^k(i) \psi(i) \]

where \(\beta(i)\) is the component of \(Q(0)\) (steady-state signal) along each eigenvector, \(\lambda(i)\) is the \(i\)th eigenvalue and \(\psi(i)\) is the corresponding eigenvector of the matrix \(A=\text{P}_1 \text{C}_1 \text{R}_3 \text{P}_2 \text{C}_2\). \(\text{P}, \text{C}\) and \(\text{R}\) are the precession, relaxation and rotation matrices, respectively. If \(TE=TR/2, \text{P}1=\text{P}2\) and \(\text{C}1=\text{C}2\). Typically, only one of the eigenvalues is real and the transient response is purely exponential, rather than oscillatory. Figure 1 shows magnetization evolution as a function of off-resonance frequency. Fat off-resonance frequency for the parameters used is shown \((FS)\) while the red line shows the waveform follows that of the magnetization at the steady-state \((\text{SS})\) and other fat peaks. Although an asymptotic flip angle of \(90^\circ\) was used for the study, the analysis and results are valid for other asymptotic flip angles.

Results: Figure 3 shows the actual magnetization as calculated using numerical Bloch equations \((ns)\) and the fit \((an)\) using the piecewise model for three different prescriptions: (1) \(TR=5\)ms, \(10\ \pi\) and 30 ramp down pulses \((2) TR=3.5\)ms, \(5\ \pi\) and 25 ramp down pulses and \((c) TR=4.0\)ms, \(10\ \pi\) and 25 ramp down pulses. Figure 4 shows average fat signal measurements made across the three volunteers. For the three different protocols used, the PFE varied in small steps around the predicted optimal value. The predicted PFF value for a prescription is marked with ‘+’. Figure 5 shows perirenal fat in an abdominal image obtained with two different PFFs, one at the default value of 0.65 (left) and the other at optimal PFF=0.81 (right).

Discussion: Optimal intrinsic fat suppression requires adjustment of PFF based on prescribed imaging parameters. An algorithm that provides real-time feedback on the optimal value is presented here. The fat magnetization behaves similarly over a wide range of frequencies around the assumed fat peak at 217Hz for any given set of typical imaging parameters. Determining PFF at 217Hz provides robust fat suppression despite off-resonance and other fat peaks. Although an asymptotic flip angle of \(90^\circ\) was used for the study, the analysis and results are valid for other asymptotic flip angles.