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 (α/2)-(TR/2) preparation pulse followed by a train of π (180°) 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

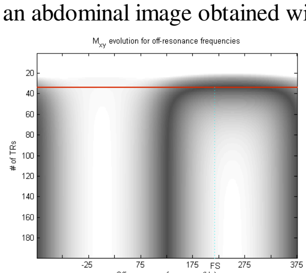
$$Q(k) = \Gamma \Lambda^k \Gamma^{-1} Q(0) = \sum_{i=1}^{3} \beta(i)\lambda^k(i)\upsilon(i)$$

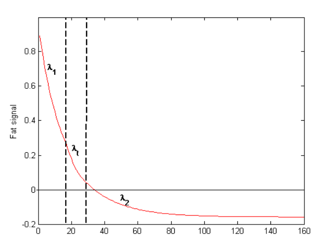
where *β(i)* is the component of *Q(0)* (steady-state signal) along each eigenvector, λ(i) is the i^{th} eigenvalue and υ(i) is the corresponding eigenvector of the matrix $\mathbf{A=P_1C_1R_\alpha P_2C_2}$. **P**, **C** and **R** are the precession, relaxation and rotation matrices, respectively. If TE=TR/2, **P1=P2** and **C1=C2**. 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 signal "null" point over a range of off-resonance frequencies. The magnitude response beyond the null point recovers to an asymptotic value. The real isochromat signal (imaginary is zero) is smooth and decays to a steady-state value. Figure 2 shows that the fat signal (off-resonance=217Hz) typically can be divided into three zones. An analysis of the eigenvalues and eigenvectors at each step reveals the value to be constant during the time the waveform follows pure T2 decay (λ_1). This is followed by a segment where the eigenvalues and eigenvectors change (labeled λ_t) while they transition to a final constant eigenvalue (λ_2) segment of the curve. A semi-analytical solution can be devised based on two piecewise curves based on λ_1 and λ_2. From empirical observations, the duration of the first curve was determined to be ~T2 of fat (53ms at 1.5T). Thus, the magnetization could be described by

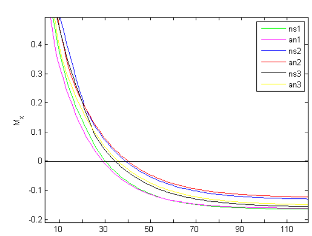
$$f(n) = (1 - M_{ss})\lambda_1^n + M_{ss}, \quad n = 1,\ldots\ldots, M \qquad (2) \qquad\qquad f(n) = c\lambda_2^{n-M} + M_{ss}, \quad n = M+1,\ldots\ldots, N \qquad (3)$$

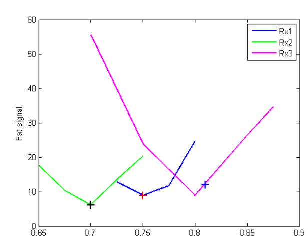
where $Mss = \mathbf{(I - A)^{-1}B}$ is the steady-state signal. $\mathbf{B= P_1C_1R_\alpha D_2+D_1}$; $\mathbf{D_1=D_2=(I - C)}[0\ 0\ 1]^T$. M=(T2$_{fat}$*b/TR) (b is inversely related to ramp length) and *N* is the maximum encoding step number. The solution then involves determining the eigenvalue at two different steps: (a) n(TR)=1, α=π° and (b) at steady-state (α=final asymptotic flip angle) in addition to determining the steady-state signal. The PFF is fixed at (yres/2+L)/yres where $f(L)=M_{SS}/2$ from eq. (3). The algorithm was implemented in pulse programming software to establish the optimal PFF interactively. Three volunteers were scanned with an IRB approved protocol on a Philips 1.5T Achieva scanner with three different prescriptions employing different ramp lengths and with different PFFs varied around the optimal PFF as estimated by the implemented algorithm.

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=5ms, 10 π and 30 ramp down pulses (2) TR=3.5ms, 5 π and 25 ramp down pulses and (c) TR=4.0ms, 10 π 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 (r).

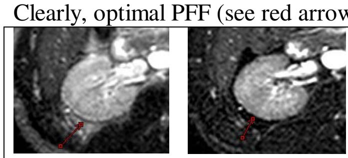








Clearly, optimal PFF (see red arrows) is essential to achieving good fat suppression.



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° was used for the study, the analysis and results are valid for other asymptotic flip angles.

References: [1] N. Gai et al., *ISMRM*, 2007: 1642. [2] J. Hennig et al., *MRM.*, 48: 801-809 (2002). [3] B. Hargreaves et al., MRM, 46 : 149-158 (2001).