Chapter 5

Transient Reduction in Steady-State Sequences

In many MR imaging sequences the recorded signal is the steady-state signal, which forms as a result of numerous periods of excitation and relaxation. For imaging, the steady-state signal has the desirable condition that it does not change from one excitation to the next, and thus avoids the image artifacts that would otherwise result. Depending on sequence parameters and relaxation times, the magnetization can take many sequence repetitions before the steady state is reached. This can take as long as a second or more, and both increases imaging time and complicates magnetization-prepared or cardiac-gated imaging techniques. This chapter discusses potential methods of “catalyzing,” or speeding the evolution of the steady state.

The transient response of steady-state sequences was described in Section 4.2.1. A snapshot of the magnetization vector after each excitation shows that the transient magnetization rotates around the real-valued eigenvector as it decays. This results in an oscillation in the measured signal that decays in amplitude with time. The DC signal level approaches a steady state exponentially. Figure 5.1 shows an example of possible transient signal responses for refocused-SSFP imaging.
Chapter 5. Transient Reduction in Steady-State Sequences

Figure 5.1: The signal magnitude (a) and phase (b) both oscillate during the transient response of refocused-SSFP sequences. Oscillations in both magnitude and phase can cause artifacts in images.

The oscillatory signals shown in Fig. 5.1 are not usable for imaging as they would result in serious artifacts, such as ghosting in 2DFT or EPI imaging, and streaking in spiral or PR imaging. Normally, steady-state imaging methods acquire image data only after the steady state is reached. However an alternative is to generate a sequence that manipulates the magnetization directly to its steady-state value. Such methods have been previously proposed by Deimling and Heid [72], and Nishimura and Vasanawala [73]. This chapter focuses on a more complex method that takes into account the nature of the transient response and its dependence on resonant-frequency.
5.1 Other Catalyzing Methods

Image artifacts can arise due to the transient response to steady state [74–76]. Since the original catalyzing idea presented by Deimling and Heid [72], several other solutions have recently been proposed [73, 77, 78].

Deimling and Heid [72] originally presented a simple method that greatly reduces oscillation in the transient response of refocused-SSFP imaging sequences. Their idea has been used for fat suppression [79, 80] and for $T_1$-measurement [81]. The technique, referred to here as “half-tip catalyzation,” consists of simply adding an additional RF pulse that precedes the first $\alpha$—tip of the SSFP sequence by a time of TR/2, as shown in Fig. 5.2. This RF pulse rotates the magnetization non-selectively through an angle of $\alpha/2$. The axis of rotation is chosen such that the spins at a certain frequency (where signal is high) are tipped very close to their equilibrium position.

![Diagram](image)

Figure 5.2: In the sequence presented by Deimling and Heid [72] a pulse tips the magnetization by an angle of $\alpha/2$ where $\alpha$ is the flip angle used in the SSFP sequence. The $\alpha/2$-pulse precedes the first tip of the SSFP sequence by TR/2.

The “half-tip” catalyzing method shown in Fig. 5.2 can be modified to a general “ramp” catalyzing method as shown in Fig. 5.3 [73]. $N$ catalyzing tips have amplitude increasing linearly from $\alpha/(N + 1)$ to $\alpha N/(N + 1)$ are separated in time by TR, and phases match the phase of the RF pulses in the refocused-SSFP sequence. As the length of the ramp, $N$, is increased, the range of resonant frequencies over which the catalyzation is effective increases.
Figure 5.3: In the sequence presented by Nishimura and Vasamawala [73] a sequence of $N$ RF pulses with linearly increasing tip amplitude precedes a normal refocused-SSFP sequence. All pulses are spaced apart in time by TR. In this example, $N = 4$.

### 5.2 Spectrally-Selective Methods

The steady-state magnetization for given sequence parameters is a function of relaxation times and resonant frequency. This dependence, combined with limitations of pulse design as well as practical system considerations, means that it is impossible to perfectly manipulate magnetization to the steady state. The method described here uses the analysis of Chapter 4 to design a sequence that puts the magnetization into a state where the residual transient response is small. This approach treats the magnitude and direction of the magnetization vector separately. First the magnitude scaling scales the equilibrium magnetization vector to approximately its steady-state length. Then a direction-selection pulse rotates the magnetization so that the transient magnetization lies along the real-valued eigenvector, thus eliminating transient signal oscillation.

Figures 5.4 and 5.5 show the magnitude-scaling and direction-selection catalyzation approach. The magnitude-scaling stage uses a frequency-selective RF pulse to place the desired magnetization length, $|\text{M}_{\text{SS}}|$, along the longitudinal axis. A crusher gradient then spoils the transverse magnetization, leaving only the longitudinal component. The direction-selection stage takes the scaled magnetization and rotates it to the desired direction and attempts to correct for any errors from the magnitude-scaling stage.
Chapter 5. Transient Reduction in Steady-State Sequences

Figure 5.4: The magnitude-scaling process rotates the initial magnetization $M_0$ (a) so that the residual component along the z-axis is equal to $|M_{ss}|$, as in (b). A crusher gradient leaves only the z-component of the magnetization (c), so that ideally it is scaled to its steady state length.

Figure 5.5: Direction selection can start with an imperfectly scaled magnetization, $M_I$, as in (a). This magnetization is rotated in (b) to $M_{des}$, which differs from $M_{ss}$ along the real-valued eigenvector of the matrix $A$. The magnetization will then decay along $v_r$ to $M_{ss}$ (c). In the case where either $v_r$ lies along $M_{ss}$, or when $|M_I| = |M_{ss}|$, the direction selection simply rotates the magnetization from the z-axis to the steady-state direction.
Chapter 5. Transient Reduction in Steady-State Sequences

The magnitude-scaling and direction-selection pulses are complicated by the fact that the steady-state magnetization vector, as well as the direction of the eigenvectors of the matrix \( A \) vary considerably with the resonant frequency. The pulses must be designed to be spectrally selective so that they simultaneously catalyze the steady state for all resonant frequencies.

### 5.2.1 Magnitude Scaling

Ideally, simply rotating the magnetization to the desired direction will eliminate oscillations in the transient response of steady-state sequences. However, there are several reasons for first performing some type of magnitude scaling. First, the magnitude can be slow in decaying to the steady-state value. Second, small errors in direction are amplified by the magnitude difference resulting in type of oscillations that the direction selection is designed to reduce. Third, for SSFP sequences magnitude-scaling pulse can improve the performance of the direction-selection pulse described below. Fourth, in SSFP sequences, the on-resonance magnetization transient is large, but steady-state magnitude is small. Nulling this magnetization eliminates this transient behavior.

The sequence used for magnitude scaling depends on the steady-state magnetization length. A spectrally-selective tip followed by a crusher pulse results in spectrally-selective scaling of the magnetization and leaves all magnetization along the \( z \)-axis (Fig. 5.4). The cosine of the tip angle should be approximately equal to the steady-state magnetization length.

It is possible to design spectrally-selective RF pulses to approximate any profile, as will be discussed subsequently. For SSFP, a simpler design is achieved by noting that \( |M_{SS}| \approx a |\sin (\pi \Delta f_{TR})| \). This magnetization profile is easily generated with the sequence shown in Fig. 5.6, which results in the scaled magnetization, \( M_{mag} \), as

\[
M_{mag} = \begin{bmatrix}
0 \\
0 \\
\sin \psi \sin (\pi \Delta f_{TR})
\end{bmatrix}
\]  
(5.1)
where $\psi$ is the tip angle of the first pulse of the sequence.

![Diagram](image)

Figure 5.6: The spectrally-selective magnitude-scaling sequence first tips the desired peak magnetization into the transverse plane through an angle $\psi$. After TR/2 the 90° pulse brings this magnetization along the longitudinal axis. A crusher pulse spoils remaining transverse magnetization.

After the magnitude scaling pulse is known, the direction-selection pulse can be designed.

### 5.2.2 Direction Selection

The ideal catalyzing sequence directs and scales the magnetization to be equal to $M_{SS}$. In this section we consider what is the best way to direct magnetization from a starting point, $M_t$. The general case of arbitrary $M_t$ is treated, although $M_t$ is typically directed along the $M_x$ axis, following magnitude scaling or some type of magnetization preparation.

The magnetization will decay without oscillation if the transient is directed along a real-valued eigenvector of the A-matrix. The desired magnetization, $M_{des}$, satisfies

$$M_{des} = M_{SS} + a\mathbf{v}_r$$

under the constraint that

$$|M_{des}| = |M_t|$$

where $\mathbf{v}_r$ is a real-valued eigenvector of the A-matrix, and $a$ is a scalar. The relationship between $M_t$, $M_{SS}$, $M_{des}$ and $\mathbf{v}_r$ is shown in Fig. 5.5a-b. Ideally, $M_{des}$
could be achieved for every $T_1$, $T_2$ and $\Delta f$, but $T_1$- and $T_2$-selective RF pulses would have a very long time duration.

In many sequences, $M_{ss}$ and the $v_r$-direction are not very sensitive to $T_1$ and $T_2$, although they are highly sensitive to off-resonance frequency, $\Delta f$. Using Eqs. 5.2, 5.3 and 4.7, it is possible to obtain $M_{des}(\Delta f)$, the desired magnetization as a function of $\Delta f$. Next, a frequency-selective RF pulse is designed to achieve the desired magnetization direction. The RF pulse is designed using the Shinnar–Le Roux (SLR) selective pulse design algorithm [82]. The SLR algorithm provides a structured approach to obtain an RF pulse from a desired profile of rotation angles (both elevation and azimuthal angle). The details of this pulse design are included in Sections 5.2.3 and 5.3. The SLR algorithm designs a pulse that is non-causal; it assumes that the time-origin can be shifted, usually by a refocusing gradient. To “refocus” resonant frequency differences, a 180° refocusing pulse is included in the design and the desired magnetization is achieved at the resulting spin echo.

As previously discussed, for a large range of off-resonance frequencies, the real-valued eigenvalue is often close to 1 and the angle between $M_{ss}$ and $v_r$ is very small. In this case, the direction pulse simply attempts to rotate $M_I$ to the direction of $M_{ss}$.

### 5.2.3 Shinnar-Le Roux Pulse Design

Pulse design using the Shinnar-Le Roux (SLR) algorithm is described in detail in [82]. The SLR algorithm allows design of more precise pulses than simpler “small-tip-angle” approaches [83]. Both methods attempt to generate a profile of tip angle as a function of resonant frequency. The primary component of SLR pulse design is the selection of two polynomials, referred to as $A(z)$ and $B(z)$ as in [82]. The secondary component uses the SLR transform to generate a practical RF pulse from the two polynomials.
Chapter 5. Transient Reduction in Steady-State Sequences

Selection of $A(z)$ and $B(z)$ Polynomials

The polynomials $A(z)$ and $B(z)$ used in SLR pulse design are defined as

\[
A(z) = \sum_{n=0}^{N-1} A_n z^{-n} \quad (5.4)
\]

and

\[
B(z) = \sum_{n=0}^{N-1} B_n z^{-n} \quad (5.5)
\]

Beginning with the flip angle profile, $\theta(\Delta f)$, and the azimuthal angle profile, $\phi(\Delta f)$, the goal is to select $A(z)$ and $B(z)$ with $z = e^{i\pi \Delta f / TR}$ such that

\[
A(z) = \sum_{n=0}^{N} A_n z^{-n} = \cos \theta / 2 \quad (5.6)
\]

\[
B(z) = \sum_{n=0}^{N} B_n z^{-n} = e^{i\phi} \sin \theta / 2 \quad (5.7)
\]

The desired profiles $\phi(\Delta f)$ and $\theta(\Delta f)$ are periodic in $\Delta f$ with a period of $2/\text{TR}$. This periodicity in $2/\text{TR}$ arises as a result of the magnitude scaling pulse.

Taking sampled versions of $A(z)$ and $B(z)$,

\[
\hat{A}_k = A(z)\big|_{z = e^{i\pi k TR / N}} \quad (5.8)
\]

and

\[
\hat{B}_k = B(z)\big|_{z = e^{i\pi k TR / N}} \quad (5.9)
\]

where $k$ is an integer with $0 \leq k < N$ and $-1/\text{TR} < \Delta f < 1/\text{TR}$, then a discrete Fourier transform of $\hat{A}_k$ and $\hat{B}_k$ gives the coefficients $A_n$ and $B_n$ of $A(z)$ and $B(z)$.

The RF pulse that results from the SLR transform needs to be sufficiently short that $T_1$ and $T_2$ relaxation are not significant. The RF pulse length generally increases
as the number of coefficients of $A(z)$ and $B(z)$ increases. This is the standard tradeoff of filter design where the accuracy with which a frequency response can be obtained depends on the length of the filter; in order to achieve an arbitrary frequency response perfectly, the filter duration would need to be infinite. This tradeoff demands some method of truncating the $A(z)$ and $B(z)$ polynomials. As with frequency response design, there are several ways to do this.

The simplest method of truncating $A(z)$ and $B(z)$ is to effectively low-pass filter the desired tip profile. This is done by keeping only the dominant central coefficients of $B(z)$ and a corresponding number of coefficients of $A(z)$. A second method is to use some form of weighted least-squares fit. The $N$ coefficients of $A(z)$ and $B(z)$ are chosen such that the difference between the discrete Fourier transform of the coefficients and the desired profile is minimized in a least-squares sense. The steady-state magnitude profile is a good choice for a least-squares weighting function.

**SLR Transform and RF Pulse Implementation**

Once the $A(z)$ and $B(z)$ polynomials have been chosen, the SLR transform gives the appropriate RF pulse. An example of this pulse design is given in Section 5.3.

To achieve the phase profile for which the RF pulse is designed usually requires a refocusing pulse, as the net linear-phase component in the desired response is zero. A $180^\circ$ refocusing pulse is appended to the end of the RF pulse, to effectively move the time origin to a point after the RF pulse. In addition to providing a spin-echo, this pulse also reverses the magnetization along the $z$-axis. However, if the $M_{des}(f)$ profile is rotated by $180^\circ$ before the SLR pulse design, this corrects for the effect of the refocusing pulse. The $180^\circ$ “pre-rotation” is along the same axis as the refocusing pulse.
Chapter 5. Transient Reduction in Steady-State Sequences

5.3 Catalyzing Pulse Design Example

This section gives an example of the entire design of a spectrally-selective magnitude-direction catalyzing sequence for refocused-SSFP with a flip angle of 60°, TR=8 ms and TE=4 ms. The design is for bottled water, which has relaxation times of $T_1=2000$ ms and $T_2=1300$ ms.

The first phase of the design is to calculate the steady-state magnetization over the range of frequencies from $-1/\text{TR}$ to $1/\text{TR}$, using Eq. 4.7. After this, the magnitude-scaling and direction-selection portions of the sequence are designed separately. The range $-1/\text{TR}$ to $1/\text{TR}$ is used as this is the period that arises from the magnitude-scaling pulse. More periods of the spectral response can be included in the design, but their effect is not significant.

5.3.1 Magnitude Scaling

The design of the magnitude-scaling pulse simply applies a least-squares fit to the steady-state magnetization magnitude to determine the parameter $\psi$ in Eq. 5.1. For the sequence parameters above, $\psi = \cos(57°)$. Figure 5.7 shows the actual steady-state magnitude and the fit using Eq. 5.1.

5.3.2 Direction Selection

The direction-selection pulse is designed using the SLR algorithm described in Section 5.2.3. First the “target direction” as a function of frequency is calculated over the frequency range from $-1/\text{TR}$ to $1/\text{TR}$, for the point $\text{TE} = \text{TR}/2$. For refocused-SSFP, this intuitively simplifies the design by the fact that at $\text{TE} = \text{TR}/2$, the steady-state magnetization lies completely in a vertical plane. The result is that the azimuthal angle of the target direction does not vary, and a single tip axis may be used over the entire frequency range. The angle of the target direction from the $z$-axis is shown in Fig. 5.8a.
Figure 5.7: The magnitude-scaling design determines the parameter $\psi$ in Eq. 5.1 by using a least-squares fit to the actual steady-state magnetization magnitude. The dashed line and solid line show the actual and fitted profiles respectively.

Note that this design method can still be used if the azimuthal angle does vary with frequency—the tip profile will then be complex. Also, if a point $TE$ is chosen arbitrarily with $0 < TE < TR$, then the design method produces the same RF pulse, as the phase difference from the point $TE = TR/2$ is a linear phase term.

The net tip is the result of magnitude scaling and direction selection. As mentioned in Section 5.2.3, a $180^\circ$-refocusing pulse is appended to the end of the SLR pulse. Thus the desired tip of the SLR pulse must be chosen such that the effect of the magnitude-scaling pulse followed by the SLR pulse and the $180^\circ$-refocusing pulse tips the magnetization to the target direction. Magnitude scaling effectively inverts off-resonant frequencies between $-1/TR$ and $0$. Thus to find the desired tip, the target direction is first rotated by $180^\circ$. Next the angle of the magnitude-scaled magnetization is subtracted, leaving the desired tip shown in Fig. 5.8b.
Figure 5.8: The net tip profile, or elevation angle of the steady-state magnetization (a) is combined with the effects of magnitude-scaling and the 180°-refocusing pulse to give the desired tip (b). The spectrally-selective SLR pulse is designed to achieve the tip profile shown in (b).

The desired tip is $\theta$ in Eqs. 5.6 and 5.7. For SSFP with TE = TR/2, $\phi$ in these equations is zero at all frequencies. The sampled profile of $\theta(f)$ provides $\hat{A}_k$ and $\hat{B}_k$, which are then Fourier transformed to give the coefficients of $A(z)$ and $B(z)$. The dominant 5 coefficients of $A(z)$ and $B(z)$ are shown in Figs. 5.9(a) and 5.9(b). The SLR transform is then used to calculate the RF pulse, shown in Fig. 5.9(c).

The SLR RF pulse shown in Fig. 5.9(c) is combined with the magnitude scaling pulses and a 180°-refocusing pulse to form the catalyzing sequence shown in Fig. 5.10. The spacing of the discrete RF pulses of TR/2 results from the fact that the tip profile, $\theta$ extends over a range of 2/TR. The use of the discrete Fourier transform to calculate the $A(z)$ and $B(z)$ effectively makes the assumption that the $\theta$ profile is periodic, which in fact is true for steady-state sequences and results in the discretized RF pulse.

The performance of the entire catalyzing sequence can be determined using a Bloch-equation simulation. Figure 5.11 shows the individual components of the actual steady-state magnetization, and the catalyzed magnetization over the frequency
Figure 5.9: The coefficients of the $A(z)$ (a) and $B(z)$ (b) polynomials are truncated to five coefficients. The SLR transform uses these polynomials to determine the RF pulse (c), which consists of five discrete tips.
Figure 5.10: The spectrally-selective catalyzing sequence is based on eigenvector analysis and the steady-state magnetization. The first two pulses perform magnitude scaling, while the remainder serves to selectively tip the magnetization to the desired direction. The flip angle in degrees is shown for each pulse, along with the axis of the tip in a rotating coordinate frame. The regular refocused-SSFP tip pulses begin at 5TR, so the cost of the catalyzing sequence is 5TR.
range from \(-1/\TR\) to \(1/\TR\). The catalyzing sequence performs quite well, leaving maximum deviations of \(0.05 |\mathbf{M}_0|\) from the steady-state magnetization.

![Graphs](image)

Figure 5.11: The entire catalyzation sequence was simulated over the resonant frequency spectrum. Individual magnetization components, \(M_x\) (a), \(M_y\) (b), and \(M_z\) (c) are shown. In each case the dashed line represents the desired (actual steady-state) magnetization while the solid line shows the profile achieved by simulating the catalyzation sequence.

### 5.4 Experimental Methods

The design methods described in the preceding section were used to design a catalyzing sequence for refocused-SSFP imaging. This catalyzing sequence is compared
Chapter 5. Transient Reduction in Steady-State Sequences

with a “half-tip” method described by Deimling and Heid [72], both in simulations and by implementing them on an MR scanner.

In a typical SSFP sequence, the axis of rotation of the RF pulses is cycled by \( \pi \) radians on each tip so that on-resonant spins are in the center of the passband of the SSFP spectral response. To simplify analysis here, all pulses in the SSFP sequence are about the same axis, and the center of the SSFP passband is actually at an off-resonant frequency of \( 1/2 \)TR. The phase of the catalyzing pulse in the half-tip method is adjusted to be \( \pi/2 \) out of phase from the other tips accordingly. Note that phase cycling is equivalent to simply changing the center frequency used to modulate the RF pulses and demodulate acquired signal.

A spectrally-selective catalyzing sequence was designed with a total duration of 5TR, as described in Section 5.3. The transient response of the SSFP sequence was simulated for a species of \( T_1 = 2000 \) ms, \( T_2 = 1300 \) ms. Simulations were performed for a SSFP sequence with no catalysis, with half-tip catalyzation and finally with the spectrally-selective catalyzation method describe here.

A 3D SSFP sequence with options for both catalyzing schemes described above was implemented on a GE Signa 1.5 T scanner with CV/i gradients (up to 40 mT/m and 150 T/m/sec slew rates). Experiments were performed using a 500 ml bottle of spring water (Crystal Geyser) with relaxation times \( T_1 \) and \( T_2 \) of 2000 ms and 1300 ms respectively. The bottle was placed with its longitudinal axis along that of the scanner to reduce susceptibility artifacts. A quadrature transmit/receive head coil (GE Medical Systems) was used to provide relatively good \( B_1 \) homogeneity. The sequence used gradient amplitudes up to 40 mT/m gradients and slew rates up to 120 T/m/s.

The experimental SSFP sequence, as shown in Fig. 5.12, used non-selective RF pulses with 60° tip angle, with the tip applied about the x-axis in the rotating coordinate frame. Images were acquired using TR = 8 ms and TE = 4 ms. A 2 ms readout along the axis of the bore was used, with phase-encoding in the other two directions for a voxel size of \( 0.5 \times 8 \times 8 \) mm\(^3\). A linear (shim) gradient was
applied along the longitudinal axis to produce a frequency variation of approximately 3 Hz/mm, or 1.5 Hz/pixel.

Figure 5.12: A experimental pulse sequence was used to validate the different catalyzing methods. An optional catalyzing sequence is followed by 256 repetitions of a standard SSFP sequence with the same phase-encode gradients. After a recovery of 12 s, the sequence is repeated. A readout at the end of the catalyzing sequence can be used to check the catalyzed magnetization.

To record the spatially-resolved transient response, phase-encode gradients were kept constant for 256 repetitions of the SSFP sequence (preceded by an optional catalyzing sequence). This was followed by a 12 s recovery time to allow magnetization to return to equilibrium before the next phase encode was acquired. The experiment was repeated three times: first with no catalyzing sequence, next with the half-tip catalyzation and finally with spectrally-selective catalyzation.

For each of 3 catalyzing options, and for each of 256 repetitions, 3D images were reconstructed using a custom reconstruction program. The image data were then rearranged to view the transient response for individual voxels along the longitudinal
Chapter 5. Transient Reduction in Steady-State Sequences

axis. The frequency corresponding to each voxel was determined using the phase of the signal from the first excitation of the uncatalyzed SSFP sequence.

The same refocused-SSFP sequence was used to show the effects of the transient response in 2D images. After an optional catalyzing sequence, the y-axis phase encode was incremented on each excitation, but the z-axis phase encode was kept constant. After a 12 s recovery time, the catalyzing sequence and y-axis phase encodes were repeated for a different z-axis phase encode. Images were acquired for all three catalyzing options described above, and also for the case where 250 repetitions were applied instead of a catalyzing sequence. In all cases, a small gradient lobe in the direction of the readout was used to simulate off-resonance. For each TR/2, a gradient lobe was included to give a 4 Hz/mm or 1.6 Hz per pixel in the readout direction.

5.5 Results

All results are shown for SSFP sequences with no catalyzation, half-tip catalyzation and spectrally-selective catalyzation. Figures 5.13a-e show the simulated transient response for the three cases at five different off-resonant frequencies. The periodic spectral SSFP response in Fig. 5.13f shows the positions of each of the off-resonant frequencies. Figures 5.14a-e show the experimentally-measured transient response for the same three cases.

In simulations and experiments, both catalyzing methods perform well for frequencies around 62 Hz, corresponding to 0.5/TR. For frequencies around 0 Hz or ±125 Hz, where the nulls in the spectral response occur, the oscillations are large and slow to decay when the half-tip method is used, or when no catalyzation is used. For frequencies around -62 Hz, spectrally-selective catalyzation demonstrates significantly reduced transients compared to half-tip catalyzation. This is because the half-tip catalyzing scheme tips magnetization in the correct direction for only one half of the resonant species, and in the wrong direction for the other half.
Figure 5.13: The transient response was simulated for five different resonant frequencies (a-e). For each frequency, the transient response is shown for standard SSFP (top), SSFP with spectrally-selective catalyzation (middle) and SSFP with Deimling and Heid’s half-tip method (bottom). The simulated steady-state signal plotted as a function of frequency (f) shows the positions of the five frequencies of the other plots.
Figure 5.14: The transient response was measured experimentally for five different resonant frequencies (a-e). For each frequency, the transient response is shown for standard SSFP (top), SSFP with spectrally-selective catalyzation (middle) and SSFP with Deimling and Heid’s half-tip method (bottom). The experimentally-measured steady-state signal is plotted as a function of frequency (f), showing the positions of five different frequencies.
Chapter 5. Transient Reduction in Steady-State Sequences

The transient effects of both catalyzing schemes are very similar between the simulations and the experimental results. A major difference between the simulations and the experimental results is that the oscillations in experimental transient responses die out more quickly. This effect can be attributed to the frequency variation over a single voxel with a small gradient applied. Consider the monochromatic response to be an oscillation superimposed on a low frequency decay. The frequency of the oscillation increases with resonant frequency, but both the low frequency decay and the direction of the magnetization are less sensitive to resonant frequency. When the signals from a range of frequencies are summed with a sinc(x) weighting to form a voxel as done by the discrete Fourier transform, the resulting effect is a rectangular windowing or weighting on the oscillatory component, causing it to die out more quickly. This effect has been tested by varying the voxel size along the direction of the shim gradient and noting that the transient oscillations die out in a time inversely proportional to the voxel size (and thus the frequency variation over a voxel). Recently, this effect itself was suggested as an effective means for reducing transient oscillations [77].

Images acquired using the same three options are shown in Fig. 5.15. A fourth image shows the result when all imaging is done after a steady state has been reached by waiting enough excitations before acquisition. As with the transient response plots, half-tip catalyzation performs well for one half of the resonant frequencies, but not for the other half. The alternating bright and dark bands arise because the half-tip approach tips the magnetization in the wrong direction for half of the resonant frequencies. Image artifacts are severe around regions where the steady-state signal nulls occur when no catalyzation is used as well as when the half-tip method is used. The spectrally-selective catalyzing technique eliminates all artifacts and produces images that are very similar to images obtained after the steady-state has been obtained naturally. The darker region at the right side of the image in Fig. 5.15 is most likely due to the $B_1$-sensitivity of this method, described in the next section.
Figure 5.15: Images were obtained using a standard SSFP imaging sequence using no transient response reduction method (a), spectrally-selective catalyzation (b), the half-tip catalyzation presented by Deimling and Heid (c), and 250 excitations to establish steady state prior to imaging (d). The readout and phase encode directions are as shown. A small additional gradient causes the resonant frequency to vary with position, about 4 Hz/mm over the 20 cm field-of-view.
Chapter 5. Transient Reduction in Steady-State Sequences

5.6 Discussion

The spectrally selective catalyzation method reduces both oscillations and exponential decay in the transient response. The results show that the theory presented is applicable to real imaging sequences. The method uses two stages, magnitude scaling and direction selection. A magnitude-scaling pulse performs a frequency-selective partial-saturation to scale the magnetization close to its steady-state length. The direction-selection pulse then manipulates the magnetization to the appropriate direction for its frequency. The overall sequence attempts to simultaneously catalyze the transition to steady state for all resonant frequencies.

The robustness of this method can be illustrated by quantifying the amplitude of transient oscillation as a fraction of the passband signal magnitude, as a parameter is varied. For spectrally-selective catalyzation, the oscillation was calculated for frequencies varying over a full period of off-resonant frequency using simulations and \( T_1/T_2 = 2000/1300 \) ms. The mean, standard deviation and maximum oscillation amplitudes as fractions of the signal were 8.4%, 5.0% and 16.8% respectively. These numbers are significantly lower than those calculated for the same case but without a catalyzing sequence: A mean, standard deviation and maximum of 92%, 24% and 111% respectively.

The spectrally-selective catalyzing sequence was designed for one combination of \( T_1 \) and \( T_2 \). Two properties allow such a sequence to be useful. First, in steady-state sequences, the species with shorter relaxation times have a shorter transient response and do not need catalyzing. Second, the eigenvector directions tend to be much less sensitive to relaxation times than they are to frequency. It follows that the transient response is smooth even where the scaled magnetization length is very different from the steady-state length for a given combination of relaxation times. A simulation was used to find the initial oscillation magnitude for \( 200 \) ms < \( T_1 < 3000 \) ms, \( 0.1T_1 < T_2 < 0.9T_1 \) and over all frequencies using spectrally-selective catalyzation. The mean, standard deviation and maximum values of the oscillation as a fraction of the passband signal were 7.9%, 4.6% and 17% respectively, showing that the method
Chapter 5. Transient Reduction in Steady-State Sequences

is not very sensitive to $T_1$ and $T_2$ variation. These numbers are similar but slightly lower than the numbers calculated for the single $T_1$ and $T_2$ of distilled water. The fact that they are slightly lower is probably due only to a very slight variation in eigenvector direction with $T_1$ and $T_2$, and is not significant.

Design of frequency-selective pulses is partly an art. The ideal trade-off between pulse duration and accuracy of the profile will probably depend on the application, and on the relaxation times. The approach discussed is fairly structured, using the SLR algorithm, which can be used to design both the magnitude-scaling and direction-selection pulses (although the magnitude-scaling pulse tested here was a simpler design.)

One problem where this method could be improved is the sensitivity of catalyzing sequence to $B_1$ variation. In the half-tip sequence presented by Deimling and Heid, the catalyzing tip angle is one half of the tip angle used in the standard sequence. Thus this method will be insensitive to $B_1$ variation. The spectrally-selective method, on the other hand, is quite sensitive to errors in $B_1$ of more than about $\pm 5\%$. For $B_1$ variations of $\pm 5\%$, the initial oscillation was calculated over the complete frequency range. The oscillation as a fraction of signal has a mean, standard deviation and maximum of 15.6\%, 10.2\% and 35\%. It is likely that this sensitivity to $B_1$ variations can be reduced with more careful pulse design. This problem is left as future work.

The spectrally-selective catalyzing method is based entirely on free precession, like the signal in a refocused-SSFP sequence. In steady-state sequences where gradient pulses are not completely rewound, the same catalyzing method can still be used, providing that the phase accrual due to gradients in the catalyzing sequence appropriately mimics that of the steady-state sequence.

As an example, this sequence can be used in gradient-recalled acquisition in steady state (GRASS) sequences. Each RF pulse in the catalyzing sequence would be followed by a gradient with 50\% of the area of the spoiler pulse used in the GRASS sequence for gradient spoiling. This corresponds to the fact that in the
The magnitude scaling part of this sequence is useful when a particular tissue of interest will have a steady-state magnetization lower in magnitude than its initial magnetization. This is frequently the case, except in situations where the initial magnetization is actually a different steady state [70, 71]. However, magnitude scaling is also very useful because it suppresses the signal at frequencies where the amount of oscillation is large. Magnitude scaling followed by either Deimling and Heid's sequence or the ramped pulse sequence presented by Nishimura and Vasanawala in [73] has been simulated. In both cases, the magnitude scaling significantly reduces the amount of oscillation near the signal nulls. Alternatively, a non-selective saturation pulse has been used to help catalyze the response of spoiled gradient-recalled echo imaging in [84].

Direction catalyzing has widespread application in situations where imaging during the transient response is useful [79, 81, 85]. It may also be useful in catalyzing the transition between different steady states, as in [70, 71]. A direction-selection pulse will reduce transient oscillation, leaving an exponential transient signal magnitude that can be used in conjunction with other preparatory sequences to obtain desirable contrast.

5.7 Summary

The transient response of steady-state sequences can be a limiting factor on scan time, or can otherwise cause artifacts in images. A spectrally-selective catalyzation method that consists of first scaling the magnetization magnitude, then rotating the magnetization toward the steady-state direction has been designed and tested. The method drastically reduces the oscillations in the transient response and allows images to be acquired immediately. Compared with other methods, this method simultaneously catalyzes the steady state across all resonant frequencies, making it robust to off-resonance effects.