Designing Variable Flip Angle Refocusing Trains to Optimize Resolution, Signal-to-Noise, and RF Power

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Varying the flip angle of the refocusing RF pulses in a RARE (Fast/Turbo Spin Echo) pulse sequence has been demonstrated as a means to address high RF power deposition [1,2,5,8-11] and MTF distortion due to relaxation [4,6,8]. If the first few flip angles are carefully controlled so as to suppress oscillatory signal behavior and establish pseudo-steady-state (PSS) conditions [1,2,5], the resulting signal level is maximized for a given terminal flip angle α. PSS conditions may be maintained while varying the flip angle throughout the pulse train [4,6,8-11]. By doing so, the produced signal may be prospectively "shaped" (at least for a specific species) to match some target function [4,6,8,10].

Signal levels may also be retrospectively corrected to compensate for relaxation (of a specific species) [3,7] and/or to correct for unwanted signal modulation due to varying the refocusing flip angle [11]. Here we show a desired MTF may be achieved by a combination of *prospectively* varying the flip angle and *retrospectively* correcting the data. A framework is developed to quantitatively compare various flip angle variation strategies on equal terms—at equivalent RF power and resolution. It is shown that prospective and retrospective means, used appropriately in conjunction, can achieve higher SNR at a given power level and resolution than either individually.

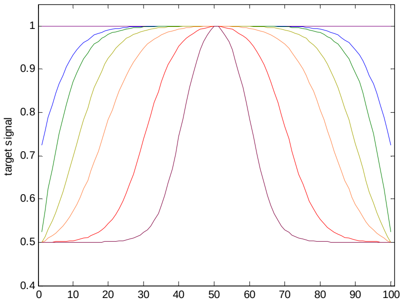

Figure 1: target signal functions

Methods

An exhaustive search of all flip angle combinations is impractical, but insight may be gleaned by studying a family of target signal functions and analyzing their relationship to SNR and power. Here, we examine target functions that range from sharply peaked in the center of k-space to flat, as shown in Figure 1. By varying the amplitude of the target signal function, various flip angle schedules may be generated with different RF power levels. Power (relative to 180° pulses), P, for each flip angle schedule is calculated according to

$$P=\frac{1}{N\pi^2}\sum_{i=1}^{N}\alpha(i)^2 \tag{1}$$

where $\alpha(i)$ is the nutation by RF pulse i and N is the total number of pulses. As an example, Figure 2 shows a family of flip schedules, all of which operate at 10% power, and Figure 3 shows the signal they each produce in the design species (T1=1000ms, T2=100ms). As a reference, the gray curves correspond to a 10% power, constant-flip train.

If the signal profile produced by the flip train is not equivalent to the desired MTF, a correction filter is applied:

$$f(i)=\frac{mtf(i)}{s(i)/s_0} \tag{2}$$

where s(i) is the expected signal for echo i, s_0 is the expected signal for the zero-order phase encode, and mtf(i) is the MTF function value at echo i. By convention, the MTF for the zero-order phase encode is unity.

The filter acts on noise as well as signal. The impact on relative SNR may be computed as

$$SNR_{rel}=\frac{SNR}{SNR_{base}}=\frac{s_{k=0}}{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(f(i))^2}}=\frac{1}{\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{mtf(i)}{s(i)}\right)^2}} \tag{3}$$

where SNR_{base} is the signal-to-noise ratio in the absence of relaxation and flip angle variation. When correcting the signal profile to match a desired MTF, signal throughout the pulse train affects SNR, not just signal in the center of k-space.

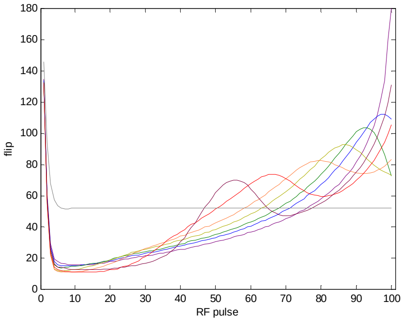

Figure 2: flip schedules for 10% power

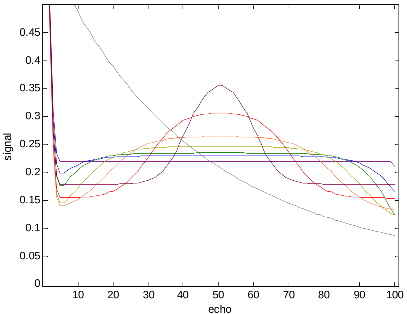

Figure 3: signal produced in design species

Results

Cases were considered for a variety of echo train lengths and target species. Figure 4 presents a case where a 100-echo train was designed for a species with T1=1000, T2=100. The MTF function was designed to be relatively flat and only apodized at the edges of k-space in order to preserve resolution while suppressing Gibbs' ringing artifacts – equivalent to the green curve in Figure 1.

Figure 4 shows relative SNR as a function of relative power. The target signal functions that were more sharply peaked than the MTF (yellow to red) were found to be less SNR efficient at any given power level. Target signal matching the MTF (green) or flat (purple) were both found to be good choices, but the optimal setting was found when the target function was between these; a target equal to the square-root of the MTF (blue) was the most optimal design considered. This was found to be generally true for a variety of MTF's and target species considered.

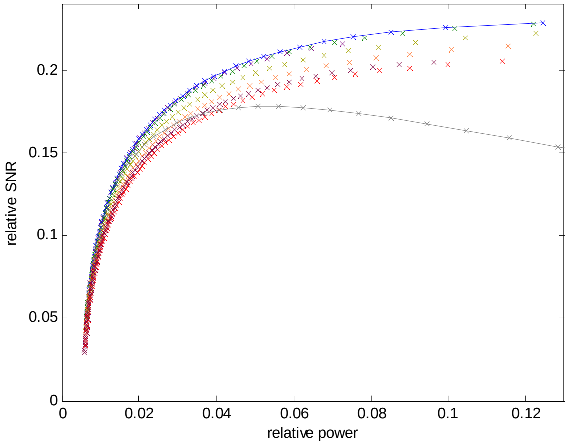

Figure 4: relative SNR as a function of relative power

Discussion

Numerous strategies for continuously varying the refocusing flip angle during the course of a fast-spin-echo readout train have previously been described. By correcting the signal data to match a desired MTF, one can control for the effect of flip angle variation on resolution, and therefore directly compare differing strategies in terms of SNR/power.

This analysis demonstrates that a flip angle schedule designed to generate a relatively flat signal profile, (in particular, one in which the profile shape equals the square-root of the MTF), produces higher SNR at any given power setting than flip angle schedules designed to generate signal profiles more peaked in the center of k-space.

References

1. Glover, Proc SMRM 1991, p1242; **2**. LeRoux, MRM 30:183 (1993); **3**. Zhou, JMRI 3:803 (1993); **4**. Schäffter, Proc SMR 1994, p27; **5**. Alsop, MRM 37:176 (1997); **6**. Mugler, Proc ISMRM 2000, p687; **7**. Busse, MRM 44:339 (2000); **8**. Busse, Proc ISMRM 2001, p1790; **9**. Hennig, MRM 49:527 (2003); **10**. Hennig, MRM 51:68 (2004), **11**. Busse, MRM 51:1031 (2004)