Perturbed SSFP

K. W. Eberhardt[1], M. Schär[1], C. Barmet[1], J. Tsao[2], P. Boesiger[1], S. Kozerke[1]

[1]Institute for Biomedical Engineering, University and ETH Zurich, Zurich, Switzerland, [2]Central Technologies, Novartis Institutes for BioMedical Research, Inc., Cambridge, MA, United States

Introduction

Equidistant RF pulses of varying amplitude and phase have been presented for use of suppressing spectral regions [1] with possible subsequent combination of the images [2].

This work proposes a framework which allows designing small flip-angle pulse sequences for steady-state excitation to a desired frequency response. For this purpose, an approximate solution to the Bloch equations is derived with perturbation methods following ideas presented by Hoult for designing RF pulses [3].

Methods

Rapid small flip-angle pulse sequences with refocused gradients offer an alternative to frequency-selective pulses. To design these sequences, a model to predict the response of the system is required. It is shown that the steady-state response of the system can be linearly approximated very accurately at low flip angles. At these low excitation levels the response can be formed by weighting the frequencies of the flip-angle function.

Initial phantom measurements were carried out on a Philips 3T system (Philips Medical Systems, Best, The Netherlands) in a spherical water phantom with a gradient field along one axis to simulate a frequency range. A standard multi-frame balanced SSFP sequence was modified such that flip angles could be varied time-dependently according to predefined flip angle functions. As in SSFP, data are acquired between pulses with balanced gradients.

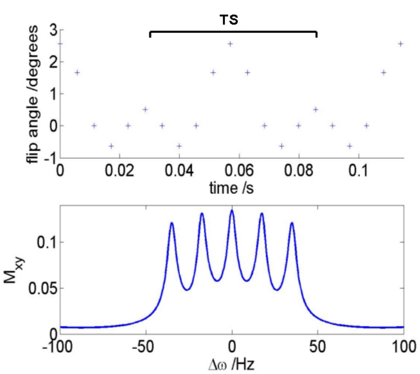

Figure 1: Top: An exemplary flip angle function, pulses applied about x-axis,

$$\alpha(t) = \alpha_0 \sum_{j=-2}^{2} \cos(2\pi \cdot 17.5 \cdot j \cdot t) \sum_{k=0}^{\infty} \delta(t - k \cdot TR)$$

Bottom: Frequency response in steady-state at t=n·TS, parameters: T1=2s, T2=0.1s, TR=5.7ms, α_0=0.7° and TS = 0.057s.

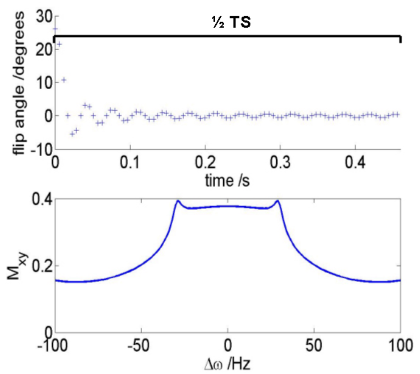

Figure 2: Pulse sequence (top) and excitation profiles (bottom) in the steady-state. The peaks occur at the frequencies of the excitation function.

$$\alpha(t) = \alpha_0 \sum_{j=-25}^{25} \cos(2\pi \cdot 1.3 \cdot j \cdot t) \sum_{k=0}^{\infty} \delta(t - k \cdot TR)$$

with α_0=0.7° at t = n·TS + TE, TE = TR/2 with parameters: T1=2s, T2=0.1s, TR=5.7ms, α_0=0.7° and TS = 0.87s.

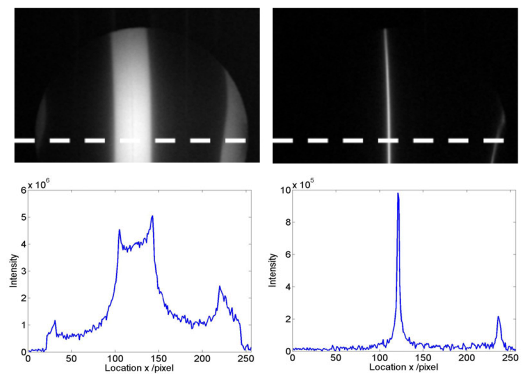

Figure 3: Phantom experiment demonstrating the principle. The left image shows the absolute value of the sum of all peaks. The right image shows the 23rd peak illustrating the capability to resolve small spectral ranges. The bottom row depicts corresponding profiles along the dashed line as indicated.

Results and Discussion

The second order solution of the transverse magnetization $M_{xy}=M_x+iM_y$, when applying driving functions $\omega_D(t)$ with a periodicity TS, is:

$$M_{xy}(\omega,t) \approx M_0 \sum_{\Omega} C_{\Omega}\left(e^{i\Omega t} - e^{-\frac{t}{T_2}+i\omega t}\right), \text{ with } C_{\Omega} = \omega_{\Omega}\left[\frac{\omega-\Omega}{\frac{1}{T_2{}^2}+(\Omega-\omega)^2} - i\frac{\frac{1}{T_2}}{\frac{1}{T_2{}^2}+(\Omega-\omega)^2}\right] \text{ and } \omega_D(t) = \sum_{\Omega}\omega_{\Omega}e^{i\Omega t}$$

The solution consists of a series of peaks at frequencies Ω, weighted by their Fourier coefficient ω_Ω. The second exponential in M_{xy} is the transient behavior which decays with T2, whereas the first exponential characterizes the rotation of the forced response.

Sampling of k-space repeatedly every TR over the sequence periodicity TS allows one to separate the C_Ω-peaks via a discrete Fourier transform, thereby extracting the spectral information of the imaged object with a very high frequency-resolution in the order of 1/T2. The simulated sequence signal-to-noise ratio reaches the level of steady-state free precession sequences in the peak-regions of excitation.

Figures 1 and 2 show the excitation profile of α(t) calculated by rotational and relaxation matrices. The comparison of this solution with the perturbation solution reveals high agreement in the frequency response. Figure 3 demonstrates the feasibility of the proposed method by exciting 51 peaks in the spectrum of which each one can be reconstructed separately.

Conclusion

The sequences enable the acquisition of tight frequency intervals, thus allowing a tradeoff between the resolved spectral area for imaging time without sacrificing resolution at high signal and very low SAR. A new approach to frequency-selective imaging has been presented.

References

[1] Vasanawala SS et al., MRM 1999; **42**; 876-883 [2] Vasanawala SS et al., MRM 2000; **43**; 82-90 [3] Hoult DI, JMR 1979; **35**; 69-86