Dynamics of ^{23}Na during balanced steady-state free precession

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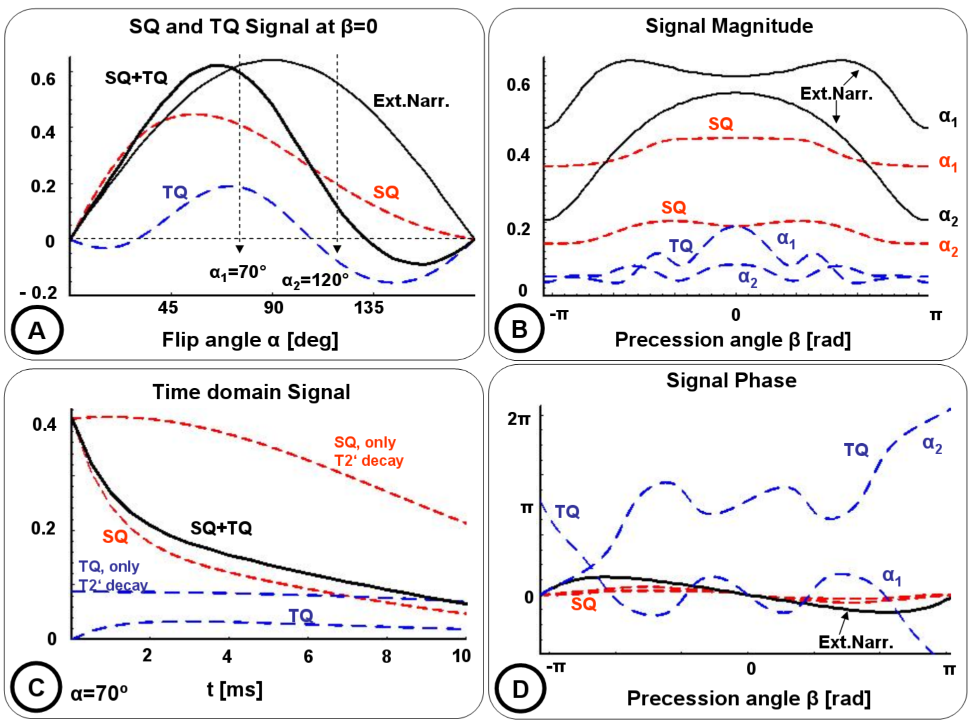
Introduction

Due to its high SNR efficiency and interesting contrast properties, balanced steady-state free precession methods (bSSFP) have become relevant for many applications. Beyond their use for 1H imaging, bSSFP is used for imaging and spectroscopy with X-nuclei, e.g. ^{31}P and ^{23}Na. For a spin 1/2 system, the dynamics of the magnetization vector during bSSFP is qualitatively and quantitatively understood. An analogous understanding is missing for ^{23}Na and spin 3/2 systems in general. This is insofar important since in the presence of quadrupolar interaction, a spin 3/2 system exhibits biexponential relaxation and the formation of multiple quantum coherences (MQC), and should therefore reveal different dynamics than a spin 1/2 system. For example, the formation of MQC could be an important contrast mechanism to distinguish signal from the intra- and extracellular compartment in myocardial tissue. The purpose of this work was therefore to investigate the dynamics of ^{23}Na under bSSFP conditions.

Methods

We chose a numerical implementation to compute the density operator σ in the steady state. To this end, the formalism employing the symmetric and antisymmetric combinations of the spherical tensor operators, $T_{lm}(s)$ and $T_{lm}(a)$, respectively [1,2,3], was implemented as a Mathematica script. The sequence consisted of R.F. pulses with constant flip angle α and free quadrupolar relaxation plus Larmor precession in between. We focus here on the results obtained with alternating R.F. pulse phase and quadrupolar frequency $\omega_Q=0$. Starting with the equilibrium magnetization, the algorithm repeatedly applied the sequence to σ. The steady state was considered to be reached when the condition $|(\sigma_n-\sigma_{n-1})|/|\sigma_n| < \varepsilon = 10^{-4}$ was fulfilled. The signal amplitude in the steady state was taken as $T_{11}(s)+T_{11}(a)$ and $T_{31}(s)+T_{31}(a)$, immediately after the excitation pulse, for single and triple quantum signal, respectively. The time domain signal was computed by Fourier transformation of the signal contributions in the frequency domain, weighted by a Gaussian distribution of off-resonant spins corresponding to a T_{2s}^* of 7ms. Relaxation times were T_{2f}=1ms and T_{2s}=17ms; the relaxation times of all other coherences were computed according to the model in [2].



Figs. A through D: SQ signal is shown with a red, finely dashed and TQ signal with a blue, coarsely dashed line. The TR is 10ms. Curves of the steady state signal in the extreme narrowing-limit ($T_{2f}=T_{2s}$=17ms) are drawn with a solid line. β is the precession angle of off-resonant spins between two consecutive R.F. pulses.

References

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Results

MQC are excited at a TR of about 30ms and below. In contrast to SQ signal in the extreme narrowing limit, SQ and TQ signal show contributions of sin(2α) in the flip angle domain (fig. A). There are regimes in the α domain where the phase profile shows refocussing behavior, but also regimes with a defocussing phase profile (figs B and D). T_2' decay of SQ time domain signal (fig C) reveals an echo which occurs ealier than TR/2. Echo formation is not as distinctly observed in the T_2' decay of TQ time domain signal (fig C). Because of the short T_{2f} and T_{2s}, T_2 decay is the predominant relaxation mechanism.

Summary and Discussion

Outside the extreme narrowing limit, i.e. in the presence of quadrupolar coupling and long correlation times, ^{23}Na bSSFP signal reveals a characteristic flip angle dependency and off-resonance profile. TQ signal is excited to a considerable extent. These dynamics differ significantly from spin 1/2 dynamics and could possibly be used for an alternative multiple quantum filtration technique.