On the perfomance of RARE, TRAPS and bSSFP in imaging of hyperpolarized compounds

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Introduction

Imaging of hyperpolarized nuclei such as DNP-polarized ^{13}C puts unique requirements on the pulse sequence, primarily because of the decay of the magnetization from the hyperpolarized state to thermal equilibrium; the latter is for ^{13}C as a low-sensitivity nucleus practically equal to zero. Consequently, the sequence needs to make use of this signal as long as possible in the sense of having the magnetization as less destroyed as possible by the appliance of RF-pulses and gradients. In this work, simulations of balanced SSFP (bSSFP), fast spin echo (RARE) and flip angle modulated fast spin echo (TRAPS) are compared with respect to their performance in imaging hyperpolarized nuclei. The sequences are assumed to be slice-selective and the signal is computed over the slice profile by integration of the Bloch equations.

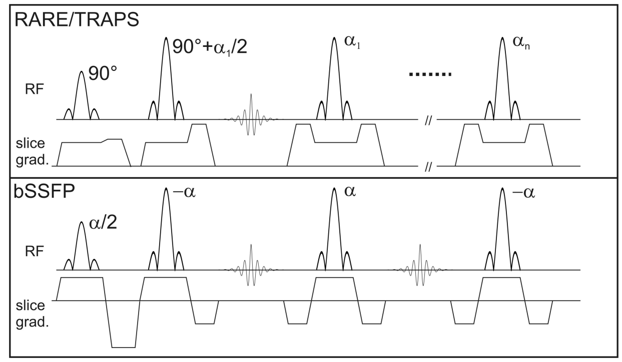

Fig.1: Basic sequence diagrams of RARE/TRAPS (top) and bSSFP (bottom). TRAPS employs varying flipangles of the refocusing pulses, for RARE the flip angle is constant. Both RARE and TRAPS prepare the signal close to the static pseudo-steady state by a 90°+ α/2-pulse [2]

Methods

Plots of the basic sequence diagrams concerning RF-pulses and gradient moments in slice direction of bSSFP and RARE/TRAPS [1] are displayed in Fig. 1. Gradients in readout direction and phase encoding direction are not displayed and are not used for the simulated signal of each sequence. This is justified by the fact that the target of the investigation was to obtain a k-space filter for each sequence that is multiplied on the k-space data obtained from 2D spatial encoding.

bSSFP employs an $\alpha/2$ $-\alpha$ α $-\alpha$ α $-\alpha$ … pulse train and gradient moments fully balanced during TR, while RARE and TRAPS both make use of spoiler gradients and differ only by the flip angle pattern. RARE employs a train of refocusing pulse with constant flip angle $\alpha=\alpha_i$ (i=1…n) of 180°. TRAPS ramps the flip angle from a low value 30° to 180° to and fro with a ramp length of 64 pulses (Fig. 2). Both RARE and TRAPS are operated in single-shot mode, e.g. the complete k-space information is sampled with a train of refocusing pulses after a single 90° excitation pulse. The flip angle for bSSFP was assumed to be 180°, as suggested for imaging of hyperpolarized nuclei [3]. The spoiler gradients for RARE and TRAPS set up a distribution of the magnetization over 4π during two consecutive refocusing pulses in the transversal plane over which needs to be summed. Only a single isochromat at on-resonance is regarded for bSSFP. The magnetization in hyperpolarized state was assumed to decay with T1=27s and T2=1.5 s over a total train of 1000 refocusing pulses spaced in time by 10 ms. The RF-pulses are hamming-apodized sinc-pulses with bandwidth*time=6.0. A number of 40 sub-slices along the slice profile were computed by integration of the Bloch equations. For each of these 40 sub-slices the signal of the simulated pulse train served as a 1D k-space filter for the k-space of simulated phantom data along one direction (which would be phase encoding direction in experiments), with matrix of 128*128 such that seven images could be reconstructed with the train of 1000 pulses. Gaussian noise was added to each of the k-spaces of the sub-slices. The final images for seven time frames were obtained after summing over the 40 sub-slices.

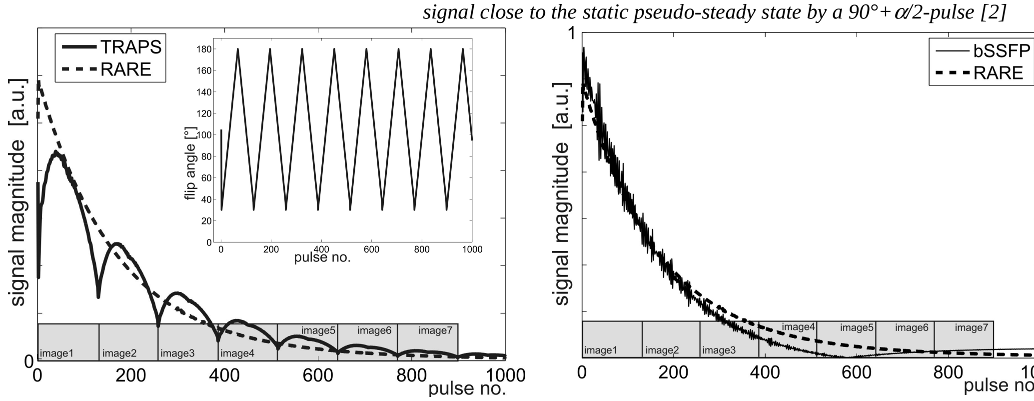

Fig.2: Comparison of the signal intensity of TRAPS, RARE and bSSFP assuming an underlying decay (T1=27s, T2=1.5s) of a hyperpolarized magnetization. Images during seven time frames (shaded regions) were reconstructed with the displayed curves as k-space filters. The left panel depicts also the flip angle pattern used for TRAPS.

Results

Fig 2 shows the decay of hyperpolarized magnetization for the three discussed sequences according to the described simulation procedure. Note the oscillations in the bSSFP signal, these are not observed for RARE and TRAPS as the signal consists of a sum over fully dephased magnetization due to the spoiler gradients. TRAPS shows significantly higher signal at later time points in comparison with RARE, due to the increased contribution of stimulated echoes whose signal is temporarily stored longitudinally and decays with the longer T1 rather than with T2 [1]. The simulated images (Fig. 3) show artefacts for bSSFP due to the oscillations, while RARE and TRAPS show equally well SNR at early time points. At later time frames, the SNR of TRAPS images is superior to the SNR of the RARE images.

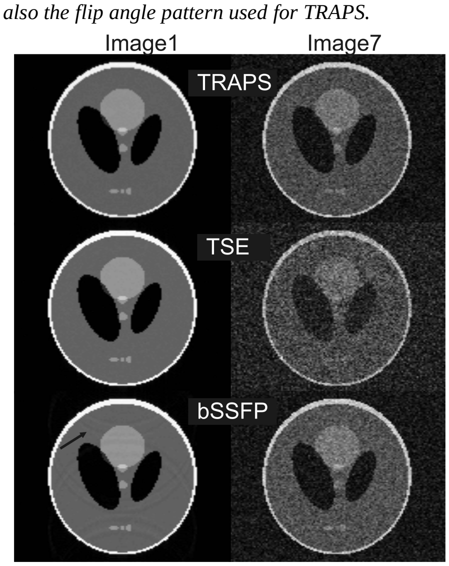

Fig.3: Simulated images for the 1st and 7th timeframe. In comparison with TRAPS, bSSFP shows ghost artefacts (arrow) and TSE yields lower SNR at later timeframes.

Conclusion

According to our simulations, TRAPS is promising to become a standard imaging module for hyperpolarized nuclei, as it superior to bSSFP and RARE in SNR and artefact performance. This statement is also supported by the fact that off-resonance can lead to severe artefacts for bSSFP imaging of hyperpolarized nuclei, in contrast to fast spin echo [4]. The simulated signal behaviour is currently under experimental verification.

Literature

[1] Hennig et al.,MRM 49:527-535(2003) [2] Hennig et al.,MRM 44:983-985(2000) [3] Svensson et al., MRM 50:256-262(2003) [4] Leupold et al., Proc. ISMRM 2007, p.1310