Fast Frequency Mapping with Balanced SSFP: Theory and Application to Proton-Resonance Frequency Shift Thermometry

K. Scheffler[1]

[1]Dept. Medical Radiology, MR-Physics, University of Basel, Switzerland

Introduction

Based on the temperature-dependent chemical shift coefficient of water protons, the phase of rapid FLASH or segmented EPI with TE between 4 ms to 30 ms is typically used to calculate temperature maps (1). For T_1-weighted FLASH short TR may increase signal saturation, and reduce SNR and phase accuracy. Here, the use of multi echo, balanced SSFP (b-SSFP) (2) is proposed as a new method for rapid measurement of frequency maps. The signal amplitude and evolution after excitation is analyzed and compared for spoiled FLASH and b-SSFP under different conditions such as relaxation times and local microscopic field inhomogeneities.

Simulations and Experiments

For FLASH, the highest possible, initial signal amplitude after excitation S(TE=0) is given by $S_E = M_0\sqrt{(1-E_1)(1+E_1)}$. For b-SSFP, S(TE=0) depends on TR/T_1, TR/T_2, and dephasing Δ within TR. For Δ=0 and using an optimized flip angle of $\alpha_{opt} = \arccos((E_1 - E_2)/(1 - E_1E_2))$ the maximal signal of $S_{bSSFP} = S_E/\sqrt{1-E_2^2} > S_E$ can be obtained ($E_{1,2}$ equals $e^{-TR/T1,2}$) (3). Thus, at TE=0 and Δ=0 b-SSFP gives a higher signal than FLASH for any combination of T_1 and T_2. After excitation the signal evolution S(TE=0…TR) is influenced by T_2 relaxation and static dephasing (T_2\`, diffusion-related dynamic averaging effects are ignored here). To simulate $T_2$\` relaxation a Lorenzian distribution of off-resonance frequencies was assumed. For FLASH, S(TE) is an exponential decay. For b- SSFP, parts of the frequency distribution (width of ±1/2TR centered at ±2n/TR, n=0,1,…) are refocused at TE=TR/2 with zero phase while other parts (width of ±1/2TR centred at ±(1+2n)/TR, n=0,1,…) are refocused at TE=TR/2 with a phase of π, yielding a destructive contribution to the overall echo signal (4). Figure 1a shows a numerical calculation of S(TE), corresponding measurements with a nine-echo b- SSFP, FLASH, and S^--SSFP are shown in Fig. 1b.

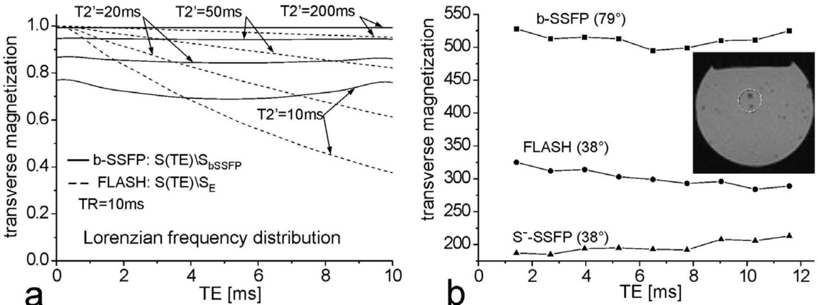

Fig. 1: Simulation a) and measurement b) of signal evolution between excitation pulses for Lorenzian frequency distribution.

Results

Experiments have been performed on Gd-doped ultrasound gel phantoms using a 1.5 T Siemens Sonata system. The warming of the injected, cooled gel (4°C) into the gel at room temperature (23°C) is depicted in Fig. 2. The temporal resolution was 1.89 s/image using a matrix size of 128^2, FOV of 130 mm, slice thickness of 5 mm, and α=85°. Every 15th temperature map is displayed, corresponding to a temporal separation of about 28 seconds.

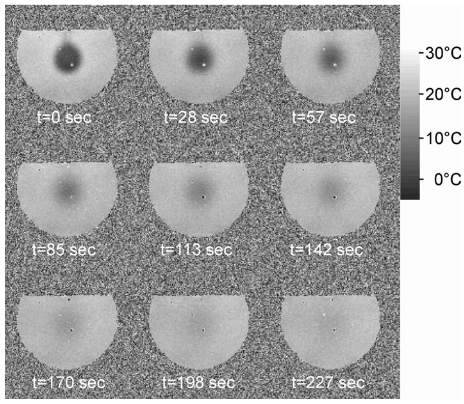

Fig. 2: Temperature maps depicting the warming of injected, cooled gel.

Conclusion

Multi echo b-SSFP exhibits a high SNR and short acquisition time, which can be used for time-resolved temperature/frequency mapping. Simulations and measurement (Fig. 1) demonstrate that even with a relatively brought Lorenzian frequency distribution b-SSFP shows a smaller dephasing-related signal loss than FLASH. In addition, the initial signal amplitude S(TE=0) is higher for b-SSFP than for FLASH for all combinations of T_1 and T_2. However, beside effects of microscopic field inhomogeneities, b-SSFP is additionally sensitive to the macroscopic field distribution, appearing as bandings or signal drops at multiples of 2π. At these locations SNR may easily fall below that of FLASH. Thus, a potential limitation of the presented technique is the quality of the global magnetic field homogeneity. Short T_2* values within the ROI or imaging voxel have a less significant effect on the signal amplitude. In contrast to FLASH b-SSFP offers the possibility to use short TR without generating signal saturation, making it useful for real-time temperature mapping.

References

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