

SSFP-based spectral editing for imaging of ^{19}F contrast agents

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Introduction

Steady-state free precession (SSFP) methods [1] have been proposed for non-proton MR imaging, which offer a high signal level and spectral selective properties [2]. In particular, imaging of ^{19}F contrast agents can benefit from SSFP techniques, because their complex multi-line spectra have a large chemical shift (CS) range and a low signal level in physiological concentrations. Recently, ^{19}F MRI has gained in importance for the detection and quantification of (anti-cancer) drugs or nano-particles with fluorine constituents [3]. In this paper, it is shown that multi-line spectra of clinically relevant ^{19}F contrast agents, in particular perfluoro-octyl-bromid (PFOB $\text{C}_8\text{F}_{17}\text{Br}$), can be purified by adjusting the SSFP dark-band frequency response. Weak spectral components, which predominantly cause image blurring, are eliminated. The remaining strong spectral components are separated and coherently combined for high SNR images. The method was evaluated in ^{19}F phantom experiments on a clinical 3T MR scanner.

Theory

Figure 1 illustrates the scheme for SSFP-based spectral editing. SSFP sequences show a frequency response (Fig.1 curve a) that is determined by sequence and relaxation parameters (flip-angle α , TR, offset frequency δf , T1, T2), as expressed analytically in [4]. The frequency distance of the dark bands is given by $\Delta f = 1/\text{TR}$. Parameters can be adjusted such that unwanted resonance lines coincide with the minima of the SSFP response. A compromise between signal level and number of CS components can be found if weak spectral lines are edited and strong lines are placed in the pass-bands. The PFOB spectrum consists of 7 spectral lines (2 strong, 5 weak). A selected frequency interval is shown in Fig.1, curve b (CF_2 line group around 0 ppm). For specific parameters ($\text{TR}=6.43$ ms, $\alpha=30^\circ$), the spectral lines at ± 550 Hz are suppressed (Fig.1c), while the two strong lines are not affected: CF_2 (0 ppm) and CF_3 (-40 ppm, not shown). The ± 100 Hz lines (around 0 ppm) remain. However, they do not lead to blurring effects for imaging pixel bandwidths $b > 200$ Hz. In a second step, the two strong components can be separated by Dixon-type imaging (2 echo times) and can be combined coherently after compensation of the CS by translation in the frequency encoding direction.

Experimental Methods

Phantom experiments were performed on a 3T whole-body scanner (Achieva, Philips Medical Systems) operated at 120 MHz for ^{19}F and using a transmit/receive coil ($\varnothing 14$ cm). A spherical phantom ($\varnothing 5$ cm) contained pure PFOB. Balanced 3D SSFP was applied in a FOV of 90 mm with 40 slices (2 mm) and $\text{TR}=6.43$ ms adjusted for spectral editing. CF_2 and CF_3 lines are out-of-phase for $\text{TE}=3.21$ ms and in-phase for $\text{TE}=3.14$ ms. The CF_2Br line (-58 ppm) was hardly excited due to the used RF excitation bandwidth. Additional shimming was applied to achieve the required homogeneity $\delta B_0 < 0.5$ ppm. Further imaging parameters: (Fig.2c/d): $\alpha=51^\circ$, resolution $\Delta x=1.4$ mm, $b=300$ Hz. (Fig.2e/f): $\alpha=31^\circ$, $\Delta x=0.7$ mm, $b=300$ Hz, two averages, 66 s scan time. (Fig.3a): $\alpha=25^\circ$, $\Delta x=0.7$ mm, $b=500$ Hz. (Fig.3b): 3D gradient echo sequence, $\alpha=15^\circ$.

Results and Discussion

Figure 2a/b illustrates the SSFP frequency response for ^{19}F MRI, using an offset gradient (0.45 mT/m) to map the frequency to a spatial dimension (contrast agent Crown-Ether C_9F_{18} , single resonance line). Band structure (a) and 180° phase steps (b) are clearly visible. SSFP spectral editing removes the ± 550 Hz parts of the 0 ppm group (Fig.2c, CF_3 not excited for clarity). If the frequency is offset by 35 Hz (Fig.2d), the main line is suppressed and the ± 550 Hz lines appear, which points out the off-resonance sensitivity of the SSFP method. The suppression is strong even at low flip angle and for T_2^* -broadened lines, because the SSFP phase changes by 180° at the dark-bands and leads to destructive interference of low and high frequency parts of the resonance line (c.f. Fig.1). Purified two-line images are shown in Fig.2e/f. The TE difference allows to separate the CS components, and a single image can be obtained by CS compensation and complex summation (not shown). In addition, spatial resolution was improved by reduction of blurring effects. A more than two-fold gain in signal level as compared to a spoiled gradient-echo sequence was obtained by the SSFP method (Figure 3). The SSFP-based signal gain in the spectral components depends on individual T1 and T2 relaxation parameters [2].

Conclusion

SSFP based imaging of ^{19}F contrast agents offers remarkable features for imaging without CS artifacts at a high signal level, which is essential for detection and quantification of low concentrations for molecular imaging in vivo. Spectral editing reduces the complexity of chemical shift effects, while the SSFP sequence leads to an improved signal level. Off-resonance sensitivity requires further studies and strategies for future applications.

References

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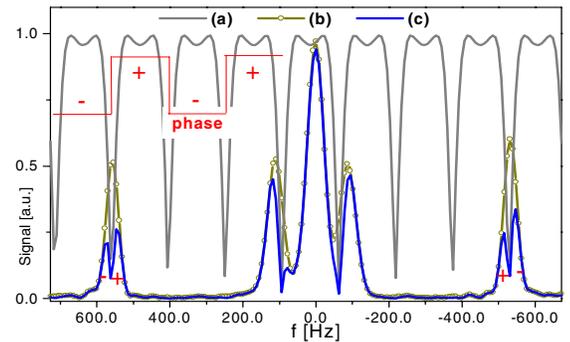


Figure 1: SSFP based spectral editing scheme. A sub-set of Perfluoro-octyl-bromide resonance lines (CF_2) is shown. TR is matched such that unwanted spectral lines are suppressed by the SSFP frequency response. 180° phase steps at the dark-bands aid to eliminate spectral lines.

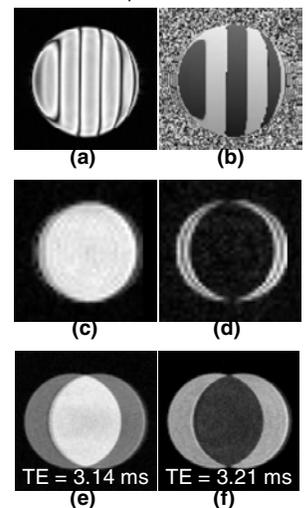


Figure 2: ^{19}F SSFP imaging examples. Modulus (a) and phase (b) images visualize the dark-band structure (Crown-Ether). Spectral editing of a multi-line PFOB spectrum depends on offset frequency shifts of 35 Hz from (c) to (d). Purified two-line images of PFOB show constructive (e) or destructive (f) addition.

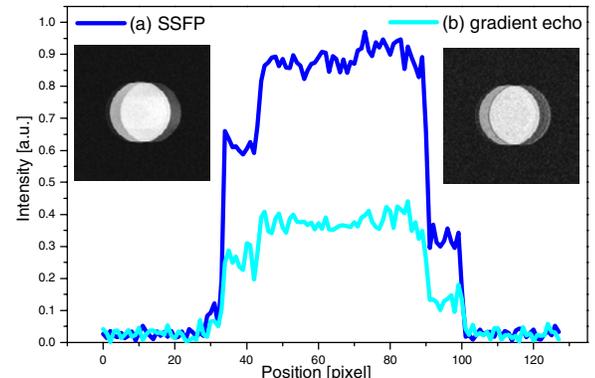


Figure 3: ^{19}F SSFP and gradient-echo imaging. 4 chemical shift components are obtained in SSFP with a higher signal (a) than achievable with all 6 components in the gradient-echo acquisition (b).