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-bromide (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 SFFP-based spectral editing. SSFP sequences show a frequency response (Fig.1 curve a) that is determined by sequence and relaxation parameters (flip-angle $\alpha$, TR, offset frequency $\delta$, 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 (TR=6.43 ms, $\alpha=30^\circ$), the spectral lines at $\pm550$ 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 $\pm100$ Hz lines (around 0 ppm) remain. However, they do not lead to blurring effects for imaging pixel bandwidths $>$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 ($\phi=0.7$ mm). A spherical phantom ($\phi=5$ cm) contained pure PFOB. Balanced 3D SSFP was applied in a FOV of 90 mm with 40 slices (2 mm) and TR=6.43 ms adjusted for spectral editing. CF$_2$ and CF$_3$ lines are out-of-phase for TE=3.21 ms and in-phase for TE=3.14 ms. The CF$_2$Br line (-58 ppm) was hardly excited due to the used RF excitation bandwidth. Additional shimming was applied to achieve the required homogeneity ($B_0<0.5$ ppm). Further imaging parameters: (Fig.2c/d): $\alpha=51^\circ$, resolution $\Delta x=1.4$ mm, $\text{b}=300$ Hz. (Fig.2e/f): $\alpha=31^\circ$, $\Delta x=0.7$ mm, $\text{b}=500$ Hz. (Fig.3b): 3D gradient echo sequence, $\Delta x=15^\circ$.

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 $\text{C}_8\text{F}_{17}$, single resonance line). Band structure (a) and 180° phase steps (b) are clearly visible. SSFP spectral editing removes the $\pm550$ 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 $\pm550$ 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 T2(*)-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 twofold gain in signal level as compared to a spoiled gradient-echo sequence was achieved. 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