Fast ^{31}P Chemical Shift Imaging using SSFP Methods

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Abstract

High signal and short imaging times make SSFP methods good candidates for applications that intrinsically suffer from low signal such as low gamma nuclei imaging. A new CSI technique based on the SSFP signal formation has been implemented and applied to ^{31}P. The signal properties of the SSFP CSI method have been evaluated and the steady state signal of ^{31}P has been measured in human muscles. Due to the T2 and T1 signal dependence of SSFP the in vivo steady state signal mainly consists of PCr. Fast *in vivo* CSI of human muscle with sub-centimeter resolution and high SNR is demonstrated at 2T.

Introduction

A number of CSI sequences have been developed over the past years, mostly derived from fast imaging techniques. The sensitivity of these CSI methods is basically determined by the type of the underlying sequence. In most clinical applications of CSI a spoiled FLASH acquisition mode is used where the signal intensity of each repetitive experiment is determined by the Ernst formula (1,2). As an alternative approach we have implemented a steady-state free precession (SSFP) experiment which has been demonstrated to result in signal intensities far beyond that of spoiled techniques (3).

The goal of this work was to develop a new application of SSFP techniques for fast and highly sensitive SSFP-CSI.

Methods

All imaging and spectroscopy experiments have been performed on a 2T system (Bruker Medspec S200F Avance) equipped with an actively shielded gradient set (10 mT/m; 33 T/m/s). A double-tuned ^{1}H and ^{31}P quadrature birdcage resonator (inner diameter 38 cm) was used for ^{1}H imaging and shimming and for ^{31}P transmission. An actively decoupled single loop surface coil (diameter 10 cm) was used for ^{31}P reception. Experiments were performed on a ^{31}P-phantom containing two singlet resonances and on the gastrocnemius/soleus muscle of healthy volunteers.

The SSFP CSI sequence was derived from a regular SSFP-sequence. The read gradient was zero and the phase gradient was switched in the two directions perpendicular to the slice selection direction. The sequence parameters were FOV: 25.6*25.6 cm; slice-thickness: 40 mm; TE/TR: 6.6/13.2 ms; matrix 92*32*32; bandwidth 10kHz; flip angle: 45°.

In order to evaluate the steady-state signal distribution of the different ^{31}P metabolites, the sequence was modified to allow the acquisition of a steady state FID with a long acquisition time of 50 ms. Therefore, the read and phase gradients were turned off, and after 200 pulses with the short TR of 13.2 ms to reach the steady state, the long acquisition was started at the time of the echo-maximum. Fourier-transformation of this signal reveals the different frequency contributions to the steady state signal.

Results

The phantom measurements showed that for different settings of the system frequency the signal contribution of the two resonances in the steady state changed since the spectrum is shifted relative to the frequency response curve of the SSFP sequence, eventually suppressing one of the signals.

The FID and the SSFP *in vivo* spectra (Fig. 1a) show that the different resonances in the ^{31}P-spectrum are suppressed to a different degree due to their different T1/T2 ratio. The *in vivo* ^{31}P-SSFP signal mainly consists of PCr. A ^{31}P-SSFP-CSI image is shown in Figure 1b.

The SNR of the SSFP signal is approximately 15-20% of the fully relaxed FID signal. This matches the calculated signal intensity for a T2 of approx. 400 ms very well. Therefore, the theoretically predicted (4) high signal gain of 4 to 5 compared to FLASH based methods can be achieved.

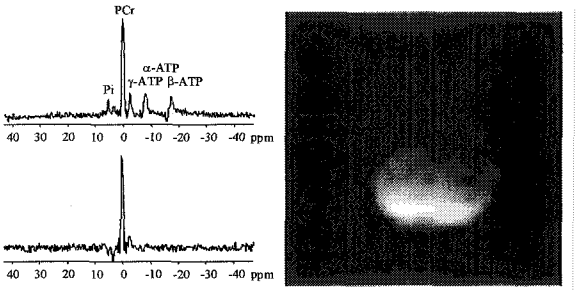

Fig. 1: (a) *In vivo* ^{31}P FID spectrum (top) and ^{31}P SSFP spectrum (bottom) of a human gastrocnemius/soleus muscle. In the SSFP signal PCr is the dominating resonance and (b) PCr resonance of the ^{31}P SSFP-CSI data set.

Discussion

The proposed new method for SSFP-(CSI) imaging offers a fast and efficient way to image low gamma nuclei such as ^{31}P. Compared to the FLASH-based ^{31}P-CSI technique, this method offers a high gain of SNR per unit time. The signal of conventional techniques, which read out the FID with sufficiently short echo time, is mainly given by the spin density and the T1 relaxation during the repetition time. For SSFP methods, however, the signal of the different metabolites is given mainly by the inherent T2/T1-contrast of the sequence as well as the off-resonance behavior. While the T1 relaxation times of all the ^{31}P metabolites are consistently high (5.0 to 7.6) (5), the T2 relaxation times vary considerably. A T2 of 435 ms for PCr and 240 for Pi has been reported and the apparent (including j-coupling effects) T2 of ATP has been measured to be between 8 and 40 ms (6). From these relaxation times the SSFP signal is expected to consist mainly of PCr and Pi (see Fig. 1a). Thus, the SSFP signal is spectrally selective in two ways. The resonance intensities are modulated by the SSFP frequency response (band pattern) depending on the TR and the system frequency and by the T2/T1 contrast depending on the metabolite under observation. The SSFP frequency response profile can also be exploited to suppress unwanted signals.

The SNR of the frequency selective image is even higher than predicted from the spectra since the CSI spectral resolution is smaller than the imaging bandwidth by a factor equal to the number of readout points. This is used to separate the signal of interest from the noise.

Possible applications for this new method are imaging experiments of low gamma nuclei. Fast PCr imaging of the myocardium could allow the assessment of the energetic status. However, many factors have to be evaluated before applying this methods routinely. Since the signal intensities depend on a multitude of parameters (SD, T1, T2, resonance frequency, system frequency, TR, flip angle, etc.) future studies will have to evaluate their interplay with pathologies of interest.

For the first time we have demonstrated the use of SSFP imaging and CSI sequences for efficient spatially encoded acquisition of ^{31}P-signals. The method shows a multifold improvement of SNR compared to conventional CSI.

References

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