Optimization of pulsed saturation for CEST imaging in standard clinical MR scanners

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Introduction:

Chemical Exchange Saturation Transfer (CEST) provides a new type of contrast for MR imaging. Recently, different saturation and readout schemes have been proposed for CEST imaging with the purpose to maximize the effect [1-3]. Especially in clinical applications, hardware limitations or safety regulations restrict full exploitation of the potential of CEST. In particular the pulse length provided by whole-body scanners prevents sufficiently long continuous wave (cw) irradiation to drive magnetization into steady state. We propose an effective pulsed saturation scheme for CEST which avoids common limits of clinical MRI hardware and reduces SAR.

Theory:

In magnetization transfer (MT) experiments, an MT pulse is applied off-resonant from the water proton frequency to saturate a spin pool that can transfer magnetization to water protons. Concerning the effects of off-resonance irradiation on the magnetization, several models for pulsed MT have been investigated, in particular CW Power Equivalent (CWPE) [4] or intervals of cw irradiation with interleaving free precession periods [5, 6].

If pulse trains are used for MT instead of cw irradiation, a frequency-selective component adds to the frequency response of the off-resonance pool which leads to a distribution of energy around the center frequency of the single pulses (similar to the effect of composite RF pulses such as 1331). Concatenation of RF pulses can improve the magnetization transfer effect. The response in the frequency domain is obtained by Fourier transformation (FT) of the entire pulse train (envelope function $B_1(t)$). Additionally, the excitation bandwidth of the pulse train can be verified in ^{1}H NMR spectra upon excitation of an off-resonant spin pool. Thus, parameters like pulse shape, pulse width (τ_D), or interpulse delay (τ_I) can be calculated in order to maximize the saturation efficiency of the CEST pulse train while staying within given hardware and safety limits.

Asymmetry of z-spectra is given by $MTR_{asym}(\delta ppm) = S_{Sat}(-\delta ppm)/S_0 - S_{Sat}(+\delta ppm)/S_0$; S_0 being the unsuppressed water signal and $S_{Sat}(\delta ppm)$ being the remaining water signal after saturation at δppm with respect to water. In a solution which only contains to 2 exchanging pools, MTR_{asym} is a direct measure of the generated CEST effect.

Materials & Methods:

Experiments were performed on MR tomographs (Magnetom; Siemens Healthcare, Erlangen, Germany) with B_0 = 1.5 T, 3 T, and 7 T using 90°-pulse-acquire (FID) without spatial encoding and the standard head coil (1.5 and 3 T) or an 8-channel Tx/Rx head coil (7 T). The saturation scheme consisted of a train of Gaussian-shaped RF pulses (number of pulses: 5 to 40). Each pulse was followed by spoiler gradients in x-, y- and z-direction. The amplitude as well as the polarity of gradients was varied between subsequent saturation pulses. Model solutions: Creatine (Cr, 50 mM) was dissolved in PBS at pH 7.4 and served as CEST agent. Bovine serum albumin (BSA) was dissolved in phosphate buffered saline (PBS) at pH 7.4 to mimic MT-like macromolecular behaviour. Data analysis was performed using own code in Matlab 7 (The Mathworks, Natick, MA, USA).

Results and Discussion:

A series of pulses (Fig. 1a) generates a spectral excitation range that is split into peaks around the center frequency of the pulses (Fig. 1b). As the bandwidth of the pulse train is proportional to its duration (t_{sat}), extensive saturation will enhance spillover effects. Maximizing saturation power and t_{sat} are appropriate measures to drive the magnetization of the CEST pool into a saturated steady state. Repeating RF pulses under exploitation of the longest possible width for a single pulse in combination with an appropriate choice of other parameters, like pulse shape, τ_I, and number of pulses per train, can generate effective saturation. Simulations showed that the most efficient combination of parameters was a series of 5 pulses with τ_D = 99 ms and τ_I = 100 ms. The long τ_I leads to a small separation between the peaks in the frequency spectrum at reduced mean SAR which is a function of the RF duty cycle. B_1 of the train was calculated on the basis of the CWPE method and attained values of 1-5 µT in experiments with the Cr solution. Fig. 2 shows an ^{1}H spectrum of the BSA solution demonstrating a non-uniform distribution of spin excitation as a result of pulsed saturation. The efficiency of the suggested saturation scheme was verified at three different B_0 and compared with other combinations of saturation parameters. The maximum MTR_{asym} measured at 1.9 ppm in the Cr solution was 15.8 % at B_0 = 1.5 T, 28.5 % at 3 T, and 40.9 % at 7 T where the suggested saturation scheme generated the largest effect among all schemes examined (B_{1_CWPE} = 2 µT). The results demonstrate the expected benefit of high B_0 due to prolongation of T_1 and provision of a higher spectral resolution. Thus, less RF spillover to neighbouring pools occurs which is favourable if the saturation bandwidth is already large due to the structure of the saturation scheme. However, SAR is still a limiting factor for CEST experiments at $B_0 \geq$ 3 T.

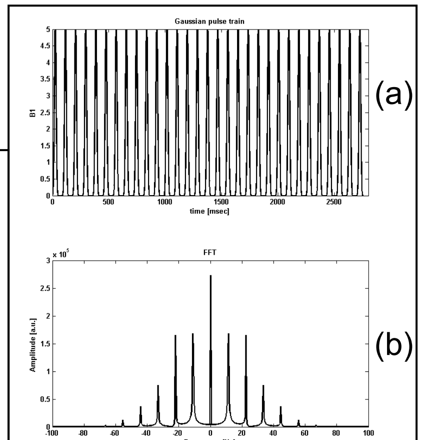

Fig. 1: (a) Train of 30 Gaussian-shaped RF pulses with amplitude B_1 = 5 µT. (b) The excitation is split over a range of 120 Hz around the offset frequency of the pulses.

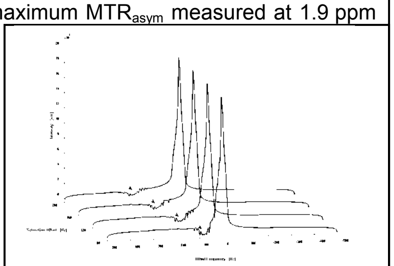

Fig. 2: Effects of the saturation pulse train of Fig. 1 on the ^{1}H spectrum of BSA model solution. Spin excitation occurs over a wide range around the offset frequency of the pulses visible as dips (arrows) in the macromolecular background signal.

Conclusion:

Saturation efficiency in CEST experiments was maximized by spectral analysis of different pulse trains and subsequent choice of appropriate measurement parameters. The simulation was verified in experiments with model solutions. Energy deposition over a narrow frequency bandwidth is the key factor in pulsed saturation transfer experiments.

References:

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