Optimization of Spin-Lock Parameters for Chemical Exchange Imaging Contrast Enhancement by Maximizing Asymmetric Magnetization Transfer Ratio: A Theoretical Study

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Target Audience: MRI physicist, radiologist, radiographer, medical imaging researcher.

Purpose: Chemical exchange (CE) process between water and labile macromolecules provides a novel MR image contrast mechanism and is mostly performed by using chemical exchange saturation transfer (CEST) [1]. Spin-lock technique, traditionally applied for the study of relaxation time (T1ρ) or relaxation rate (R1ρ) in the rotating frame, can also be used for CE imaging besides CEST [2]. Maximizing of CE-based image contrast is of great importance for in vivo CE imaging because it is often very small, particularly at lower field strength for fast exchange. In this study, optimized spin-lock frequency (FSL) and spin-lock time (TSL) were theoretically investigated for CE processes with different proton exchange rates to maximize the asymmetric magnetization transfer ratio (MTR_{asym}) by using a two-pool $R_{1\rho}$ relaxation model beyond fast-exchange limit [3] based on Bloch-McConnell equations.

Methods: Z-spectrum acquired by using spin-lock technique for CE imaging (CESL) was simulated based on a two-pool $R_{1\rho}$ relaxation model beyond fast-exchange limit (Eq.1) and could be analytically expressed as shown in Eq.2. The asymmetric populations of on-resonance pool a (like water) and off-resonance pool b (at 3ppm) were p_a and p_b (p_a+p_b=*1* and p_a>>p_b). and k and B_1 denote off-resonant frequency of pool *b*, chemical exchange rate and spin-lock field strength respectively. For all simulations, population-averaged T1 and T2 were set as 1500ms and 80ms, respectively.

$$R_{1\rho} = R_1\cos^2\theta + R_2\sin^2\theta + \frac{p_a p_b \delta^2 k \sin^2\theta}{\omega_1^2+\delta^2+k^2} = R_1\cos^2\theta + (R_2+R_{ex})\sin^2\theta \quad \text{where } \theta = \arctan(\omega_1/\delta) \text{ and } \omega_1 = 2\pi\gamma B_1 = 2\pi FSL \qquad (1)$$

$$\frac{M}{M_0} = \left(1-\frac{R_1\cdot\cos\theta}{R_{1\rho}}\right)\cdot e^{-R_{1\rho}\cdot TSL} + \frac{R_1\cdot\cos\theta}{R_{1\rho}} = \left(1-\frac{R_1\cdot\cos\theta}{R_1\cos^2\theta+(R_2+R_{ex})\sin^2\theta}\right)\cdot e^{-(R_1\cos^2\theta+(R_2+R_{ex})\sin^2\theta)\cdot TSL} + \frac{R_1\cdot\cos\theta}{R_1\cos^2\theta+(R_2+R_{ex})\sin^2\theta} \qquad (2)$$

An optimal FSL was defined as the FSL that maximizes the MTR_{asym} at 3ppm for a specific proton exchange rate k and a fixed TSL. Optimal FSLs for exchange rates from 10/s to 5000/s (step:10/s) and TSLs from 20ms to 600ms (step:20ms) at 3T and 9.4T were numerically searched within the FSL range of 1Hz to 4000Hz (step:1Hz).

Results: Simulated Z-spectra and MTR_{asym} for fixed TSL=100ms and varying FSL were plotted in Fig.1a and the dependence of MTR_{asym} at 3ppm on FSL was shown in Fig.1b. MTR_{asym} does not increase monotonically with FSL and the maximum MTR_{asym} is achieved at the FSL=524Hz, close to CE rate *k*. Z-spectra and MTR_{asym} for varying TSLs at the fixed FSL=200Hz were plotted in Fig.1c and MTR_{asym} at 3ppm with regard to TSL is depicted in Fig.1d. MTR_{asym} increases monotonically with TSL and approaches the maximum value asymptotically. The optimal FSLs and the corresponding maximal MTR_{asym} at 3ppm were depicted in Fig. 2 for 9.4T (a, b) and 3T (c, d), respectively. Maximum MTR_{asym} acquired with optimal FSL is generally larger at 9.4T than at 3T. Larger maximum MTR_{asym} can be obtained for low k with longer TSL. For both 9.4T and 3T, optimal FSL is much dependent on *k* when TSL is shorter than 100ms. Higher FSL is preferable to maximize MTR_{asym} for high proton exchange rate. For a certain *k*, when a longer TSL is applied, the value of optimal FSL reduces. In short, low FSL and long TSL is sensitive to detect slow CE processes while high FSL and short TSL is useful to probe fast CE process.

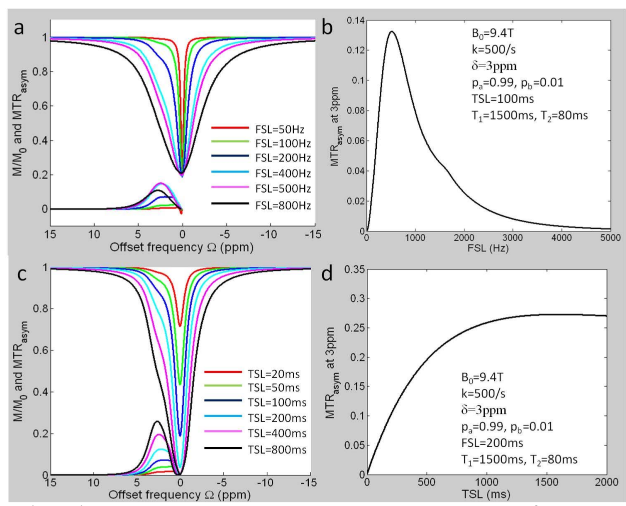

Fig.1. Simulated Z-spectra and MTR_{asym} (a, c) and the dependence of MTR_{asym} at 3ppm on FSL (b) and TSL (d).

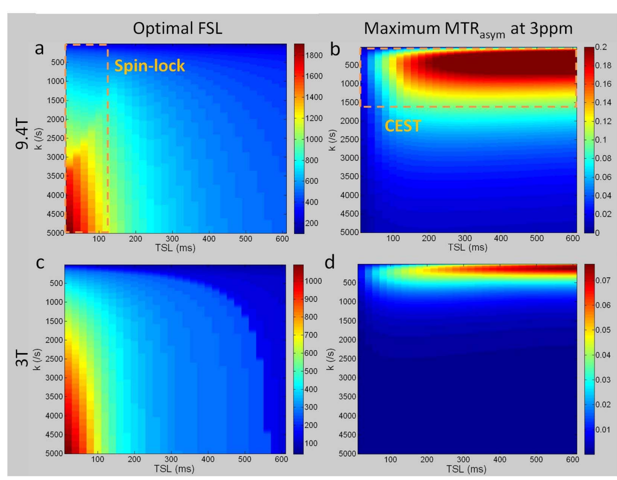

Fig. 2. Optimal FSL and maximal MTR_{asym} at 3ppm for different proton exchange rates k and different TSLs at 9.4T and 3T.

Discussion: CEST is normally described sensitive to slow or intermediate CE processes, while spin-lock technique is considered more sensitive to probe fast CE processes. The dash blocks in Fig.2 well illustrate the traditional applicable areas for CEST and SL respectively. Since Bloch-McConnell equations forms the theoretical basis for both CEST and CESL, these two techniques should be compatible and could be applied alternatively. According to Fig. 2, imaging of fast CE is still challenging, particularly at clinical field strength because the maximum MTR_{asym} is still very small (generally <5%) even after optimization. SAR and hardware performance restriction should also be considered for MTR_{asym} maximization at 3T.

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References: [1] van Zijl, PC, et al, MRM 2011, 65:927-948; [2] Jin T, et al, MRM 2011, 65:1448-60; [4] Trott O, et al, JMR 2002, 154:157-160.