MR contrast generated by altering parameters of adiabatic pulses: theoretical simulations and *in vivo* MRS results

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Introduction

Rotating frame relaxation rates ($R_{1\rho}$ and $R_{2\rho}$), measured during radiofrequency (RF) irradiation, are sensitive to molecular dynamics relevant for characterizing the functionality of the tissue *in vivo* especially at high magnetic fields. $R_{1\rho}$ and $R_{2\rho}$ can be "manipulated" by choosing different settings of the RF [1], thus leading to the generation of MR contrast. In the present work we focus on rotating frame relaxation methods based on adiabatic pulses [2,3]. Even if adiabatic relaxation methods have been already used to generate brain tissue contrast [4,5] and applied for the treatment monitoring of rat glioma [6], much work remains to be done to fully characterize the influence of adiabatic pulse parameters on the measured relaxation rate constants. The aim of this study is to explore how MR contrast can be created by using different pulse modulation functions, different maximum pulse amplitude (ω_1^{max}) or different bandwidth (*BW*) of the adiabatic pulse. Results from theoretical simulations and animal MRS experiments are presented.

Methods

Theoretical simulations. Relaxations rate constants during adiabatic rotation in the weak field approximation can be represented as an average of instantaneous time-dependent contributions due to the different relaxation channels. $R_{1\rho}$ and $R_{2\rho}$ were thus calculated separately for each time point, and the time average over the pulse time duration was then computed. We specifically considered the case of dipolar interactions in the fast motional regime, and the case of anisochronous exchange (*i.e.*, exchange between spins with different chemical shifts, $\delta\omega \neq 0$) in the fast exchange regime. The used time-dependent relaxation functions were detailed previously in [3]. Simulations were carried out using Matlab 7.3 platform.
Animals experiments. 2 rats - 1.7% isoflurane. *MRS*: Measurements were performed on a 9.4-T/31-cm magnet interfaced to Varian INOVA console. LASER (TE = 36 ms, TR = 5 s) was used to acquire spectra from a 4x7x4 mm^3 voxel localized in the rat brain. A train of adiabatic full passages (AFP) pulses of the Hyperbolic Secant family (HSn, n = 1 and 4; adiabaticity factor R = 20) was placed with no inter-pulse time intervals prior or after the coherent excitation by adiabatic half passage (AHP) pulse, leading to $R_{1\rho}$ or $R_{2\rho}$ relaxations, respectively. Other parameters: pulse time duration (T_p) = 6 ms or 3 ms, leading to *BW* = 3 or 6 kHz, respectively (in this case $\omega_1^{max}/(2\pi)$ = 3 kHz); $\omega_1^{max}/(2\pi)$ = 1.3 kHz or 4 kHz (in this case T_p =6 ms). The water signal intensity (SI) decay curves were measured when the number of AFP was incremented from 4 to 128.

Results and discussion

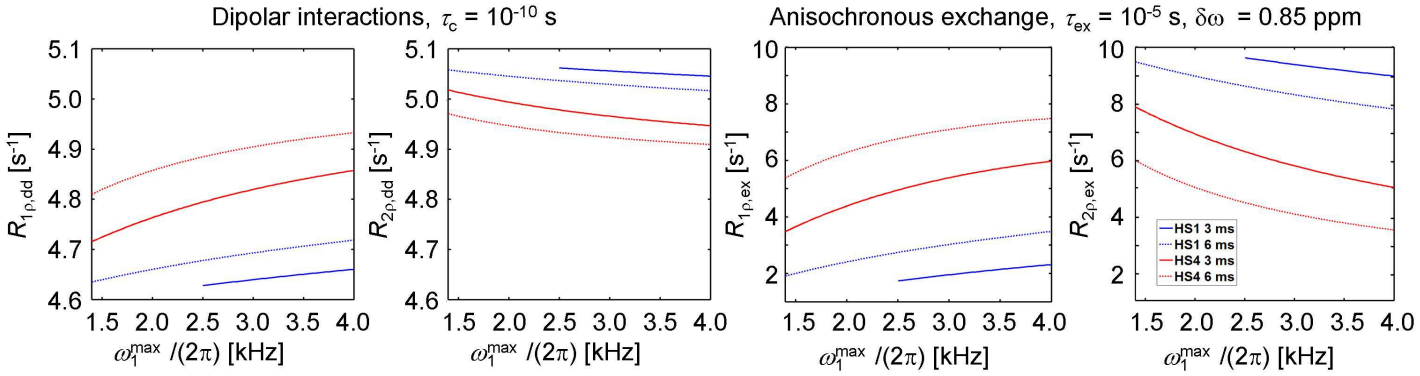

Table 1. Numbers are in s^{-1}, data from the rat brain at 9.4 T.

	$R_{1\rho}$ HS1	$R_{2\rho}$ HS1	$R_{1\rho}$ HS4	$R_{2\rho}$ HS4
ω_1^{max} = 1.4 kHz	6.1 ± 0.2	17.6 ± 0.9	8.8 ± 0.2	15.8 ± 0.8
ω_1^{max} = 4.0 kHz	6.3 ± 0.1	16.3 ± 0.7	10.1 ± 0.3	13.1 ± 0.4
T_p = 3 ms	9.0 ± 0.1	18.4 ± 0.8	9.0 ± 0.1	15.3 ± 0.3
T_p = 6 ms	10.1 ± 0.3	17 ± 1	17 ± 1	13.6 ± 0.6

Figure 1. Simulations of $R_{1\rho}$ and $R_{2\rho}$ due to dipolar interactions or anisochronous exchange, as a function of ω_1^{max} during HS1 (blue) and HS4 (red) pulses, with T_p = 3 ms (solid lines) or 6 ms (dashed lines), corresponding to *BW* = 6 kHz or 3 kHz, respectively. τ_c and τ_{ex} are the rotational and exchange correlation times, respectively. Additionally, the population of the sites undergoing exchange was 0.5. Only ω_1^{max} values which guarantee adiabaticity are considered. $\omega_0/(2\pi)$ = 400 MHz.

Simulations (Figure 1) showed that the contrast generated by HS1 and HS4 pulses in presence of dipolar interactions or anisochronous exchange, defined as ($R_{1,2\rho,dd,ex}$(HS4) - $R_{1,2\rho,dd,ex}$(HS1))/$R_{1,2\rho,dd,ex}$(HS1), depend on ω_1^{max} and *BW*. Note that different *BW* were obtained by changing T_p at constant R value; however, if the R value was adjusted to match *BW* for different T_p, $R_{1,2\rho,dd,ex}$ (and consequently the contrast) would become independent of T_p. With the adopted choices of RF settings and intrinsic relaxation parameters, the contrast was found to be larger for anisochronous exchange compared to dipolar interactions at similar ω_1^{max}, and was generally larger for $R_{1\rho}$ compared to $R_{2\rho}$. In addition, it always resulted: $R_{1\rho}$(HS1) < $R_{1\rho}$(HS4), while $R_{2\rho}$(HS1) > $R_{2\rho}$(HS4). Whereas for dipolar interactions both $R_{1\rho}$ and $R_{2\rho}$ contrasts increased with ω_1^{max}, for anisochronous exchange only the $R_{2\rho}$ contrast increased with ω_1^{max}, but the $R_{1\rho}$ contrast decreased. Similarly, for dipolar interactions both $R_{1\rho}$ and $R_{2\rho}$ contrasts decreased with *BW*, but for anisochronous exchange only the $R_{2\rho}$ contrast decreased with *BW*, while the $R_{1\rho}$ contrast increased. Data from the rat brain (Table 1), measured with RF parameters similar to those used for simulations, showed that the contrast increased with ω_1^{max}, decreased with *BW*, and was not substantially different for $R_{1\rho}$ compared to $R_{2\rho}$. These findings indicate that *in vivo* the anisochronous exchange is not the dominant exchange relaxation channel; in fact, *in vivo* water is known to be involved in isochronous exchange processes, which where not considered here for the theoretical predictions.

Conclusions. MR contrast can be generated with adiabatic pulses by using different pulse modulation functions, different ω_1^{max} and different *BW* of the adiabatic pulses. The influence of these parameters on the rotating frame relaxation rate constants depends on the relaxation channel and on the motional regime. This may provide a possibility to separate relaxation mechanisms *in vivo*.

References: Abergel and Palmer Concepts Magn Reson A 2003;19A(2):134. [2] Garwood and DelaBarre JMR 2001;153:155. [3] Michaeli et al. Curr Anal Chem 2008;4:8 [4] Michaeli et al. MRM 2005;53:823 [5] Michaeli et al. JMR 2006;181:138 [6] Sierra et al. MRM 2008;59:1311. **Acknowledgments**: BTRR - P41 RR008079, P30 NS057091, R01NS061866 and R21NS059813.