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Rotating frame relaxation during adiabatic pulses vs. conventional spin lock: simulations and experimental results at 4 T

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Abstract

Spin relaxation taking place during radiofrequency (RF) irradiation can be assessed by measuring the longitudinal and transverse rotating frame relaxation rate constants ($R_{1\rho}$ and $R_{2\rho}$). These relaxation parameters can be altered by utilizing different settings of the RF irradiation, thus providing a useful tool to generate contrast in MRI. In this work, we investigate the dependencies of $R_{1\rho}$ and $R_{2\rho}$ due to dipolar interactions and anisochronous exchange (i.e., exchange between spins with different chemical shift $\delta\omega \neq 0$) on the properties of conventional spin-lock and adiabatic pulses, with particular emphasis on the latter ones which were not fully described previously. The results of simulations based on relaxation theory provide a foundation for formulating practical considerations for in vivo applications of rotating frame relaxation methods. Rotating frame relaxation measurements obtained from phantoms and from the human brain at 4 T are presented to confirm the theoretical predictions.

Keywords: Rotating frame relaxations; Spin lock; Adiabatic pulses; Dipolar interactions; Anisochronous exchange; MR contrast

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1. Introduction

Rotating frame relaxation rate constants, $R_{1\rho}$ and $R_{2\rho}$, characterize relaxation during radiofrequency (RF) irradiation when the magnetization vector $\vec{\mathbf{M}}$ is aligned along or perpendicular to the direction of the effective magnetic field ($\vec{\mathbf{B}}_{eff}$), respectively. $R_{1\rho}$ and $R_{2\rho}$ reflect the features of the spin dynamic processes and depend on the properties of the RF irradiation [1–4]. The latter feature creates the possibility to "manipulate" the measured $R_{1\rho}$ and $R_{2\rho}$ by choosing different settings of the RF irradiation, thus leading to the generation of MR contrast [5,6]. Whereas the spin–lattice relaxation rate constant R_1 is sensitive to dynamic processes close to the Larmor frequency ($\omega_0/(2\pi)$), which is in the order of megahertz for standard in vivo applications, in the majority of cases the rotating frame relaxations are additionally sensitive to fluctuations close to the effective frequency [$\omega_{\mathrm{eff}}/(2\pi)$, where $\omega_{\mathrm{eff}}=\gamma\ B_{\mathrm{eff}}$ and γ is the gyromagnetic ratio], which is in the order of kilohertz. The enhanced sensitivity of $R_{1\rho}$ and $R_{2\rho}$ to molecular dynamics in the kilohertz range makes rotating frame relaxations a practical tool for gaining information about water spin dynamics and interactions with endogenous macromolecules [7]. Application of these methods holds great potential for addressing several biological questions, especially at high magnetic fields.

A typical method to measure $R_{1\rho}$ and $R_{2\rho}$ is the conventional spin-lock (SL) experiment, where a continuous-wave (CW) pulse is applied on- or off-resonance (for review, see Ref. [4]). In the presence of the CW pulse, relaxations due to different relaxation channels, such as dipolar interaction and exchange, are well investigated [3,8]. Advances in RF pulse design and experimental capabilities have led to the routine use of pulse sequences based on adiabatic RF pulses for in vivo applications [9]. Rotating frame relaxation experiments can also be performed with adiabatic pulses [10]. Although the theoretical investigation of rotating frame relaxations during adiabatic RF pulses has been recently extended [10,11], much work remains to be done to characterize the influence of the experimental parameters on the measured relaxations.

The aim of the present work was to describe the effects of different RF irradiation parameters on either CW SL or

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adiabatic $R_{1\rho}$ and $R_{2\rho}$, due to dipolar interactions in the weak field limit (i.e., fast motional regime) and in the presence of anisochronous exchange (i.e., exchange between spins with different chemical shifts, $\delta\omega\neq 0$) in the fast exchange regime (FXR). Specifically, the simulations presented here exploit the dependencies of $R_{1\rho}$ and $R_{2\rho}$ on (i) the amplitude and direction of the effective field during the CW SL pulse, and (ii) the pulse length, bandwidth and RF peak amplitude during adiabatic rotation. Finally, the effect on relaxations introduced by different pulse modulation functions of adiabatic pulses is discussed, and a practical perspective of rotating frame relaxation methods for in vivo applications is provided. Experimental results obtained from phantoms and from the human brain at 4 T are presented to confirm some relevant theoretical predictions.

2. Theoretical overview

2.1. Properties of the effective magnetic field during SL vs. adiabatic rotation

During the CW SL pulse, $\overrightarrow{\mathbf{B}}_{eff}$ is tilted from the quantization axis z' (i.e., the longitudinal axis of the first rotating frame) by the angle α (Fig. 1A), defined as:

$$\alpha = \tan^{-1}\left(\frac{\omega_1}{\Delta\omega}\right), \tag{1}$$

where ω_1 is the amplitude of the SL pulse in radian per second and $\Delta\omega = (\omega_0 - \omega_{\mathrm{RF}})$ is the frequency offset in radian per second. The amplitude of the effective frequency ω_{eff} is given by:

$$\omega_{\mathrm{eff}} = \sqrt{\omega_1^2 + \Delta\omega^2}. \tag{2}$$

During an adiabatic pulse, both amplitude and frequency are typically modulated (Fig. 2A). In the present study, we use adiabatic pulses of the hyperbolic secant (HSn) family [9,12,13]. The amplitude of HSn pulses is given by:

$$\omega_1(t) = \omega_1^{\max}\mathrm{sech}\left(\beta\left(2t/T_{\mathrm{p}} - 1\right)^n\right), \tag{3}$$

where $\omega_1^{\max}$ is the maximum value of $\omega_1(t)$ in radian per second, β is a truncation factor ($\mathrm{sech}(\beta)=0.01$), T_{p} is the pulse duration, $t \in [0,\ T_{\mathrm{p}}]$ and $n=1$ and 4 for HS1 and HS4 pulses, respectively. With respect to the carrier frequency ω_{c}, i.e., the center frequency in the bandwidth (BW) of interest, the frequency modulation for HS1 pulse is given by:

$$\omega_{\mathrm{RF}}(t) - \omega_{\mathrm{c}} = A\tanh\left(\beta\left(2t/T_{\mathrm{p}} - 1\right)\right), \tag{4}$$

and for the HS4 pulse it is given by:

$$\omega_{\mathrm{RF}}(t) - \omega_{\mathrm{c}} = A\int_0^t \sec\mathrm{h}^2\left(\beta\left(2t'/T_{\mathrm{p}} - 1\right)^4\right)\mathrm{d}t', \tag{5}$$

where A is the amplitude of the frequency sweep in radian per second, with the bandwidth of the pulse being $\mathrm{BW}=2A$. One fundamental property of the adiabatic pulse is the time–bandwidth product given by:

$$R = \left(AT_{\mathrm{p}}\right)/\pi. \tag{6}$$

From Eq. (6), it is evident that at a given T_{p} settings, the amplitude of the frequency sweep (A) is determined by the R

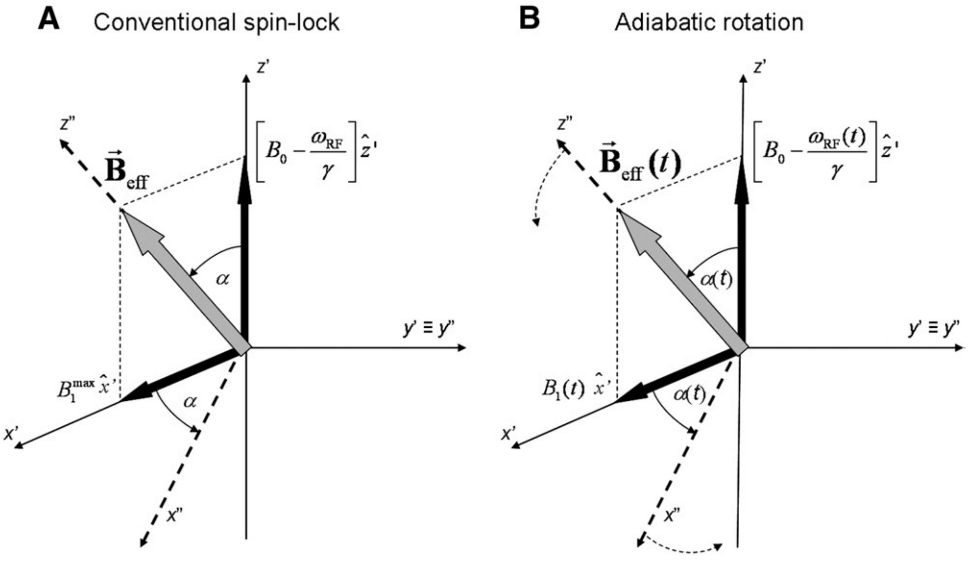

Fig. 1. Effective magnetic field during conventional SL pulse (A) and during adiabatic rotation (B). The effective magnetic field ($\overrightarrow{\mathbf{B}}_{eff}$) is the vector sum of the RF-generated magnetic field $B_1\boldsymbol{x}'$ and a longitudinal field component $[B_0 - \omega_{\mathrm{RF}}/\gamma]\,\boldsymbol{z}'$. In the first rotating frame, $\overrightarrow{\mathbf{B}}_{eff}$ is kept in the $x'z'$ plane, since the frame rotates around z' ($\equiv z$) with frequency ω_{RF}. In the second rotating frame, z'' is aligned with the direction of $\overrightarrow{\mathbf{B}}_{eff}$, and therefore this frame is tilted compared to z' by the angle α. The magnitude and the direction of $\overrightarrow{\mathbf{B}}_{eff}$ are kept stationary in the first rotating frame during the conventional SL pulse, whereas they are time dependent during the adiabatic rotation, since $\overrightarrow{\mathbf{B}}_{eff}$ is a function of the amplitude and frequency modulation functions.