T1rho and Steady-State MRI: The Odd Couple

W. R. Witschey[1], S. Mangia[2], S. Michaeli[2], M. Garwood[2], R. Reddy[3], J. Hennig[1], and M. Zaitsev[1]

[1]Medical Physics, University Medical Center Freiburg, Freiburg i. Breisgau, Baden Württemberg, Germany, [2]CMRR, University of Minnesota, Minneapolis, MN, United States, [3]CMROI, University of Pennsylvania, Philadelphia, PA, United States

Purpose

If one similarity can be drawn between spin locking and fast, steady-state imaging it is this: lots of radiofrequency (RF) irradiation, all the time. This educational e-poster explores some interesting and useful relationships between the conventional spin locking pulse and pulsed RF methods commonly used for steady-state free precession (SSFP). We will provide answers to questions like: Can a FLASH sequence be used to quantify spin lattice relaxation in the rotating frame (T1ρ) without magnetization preparation? Can spin locking acquire balanced SSFP-like images with less radiation deposition? What is the physical mechanism that determines the steady-state in these two techniques? By attempting to answer these questions, we hope to provide fresh insights about spin locking and fast imaging to appeal to the interested novice or the MRI expert.

Outline of Content

Introduction to Spin Locking: We first review the basic T1ρ experiment, using continuous wave spin locking pulses of varying duration and amplitude along with the methods used for quantification of the T1ρ relaxation time constants (1). The observed T1ρ dispersion, or variation in T1ρ relaxation time as a function of RF field strength, will be analyzed using the random field model. It has been shown that the adopted acquisition strategy can have an effect on the measured relaxation times because of variation in echo amplitude throughout the readout train (2). To minimize these errors, the effect of several acquisition strategies and k-space trajectories are analyzed. In particular we examine radial and Cartesian trajectories and spoiled gradient echo methods.

Spin Locked SSFP: A method was recently introduced to generate spin lock contrast in the steady-state (3). This sequence provides a clear link between basic SSFP contrast and continuous wave spin lock (see Fig. 2). The basic implementation of this method adjusts the phase of the transmitter and receiver to match the accumulated phase of the spin during the free precession period. The steady-states of the sequence are shown for limits when the pulse duration is equivalent to the TR (the pseudo-cw case), instantaneous (conventional SSFP), and for a range of intermediate durations (the general case).

Mechanisms of T1ρ Relaxation: Basic mechanisms of T1ρ relaxation *in vivo* will be summarized and briefly explored, including dipole-dipole nuclear relaxation between like spins modulated by nuclear rotation, residual dipolar coupling, cross relaxation, chemical exchange, and spin diffusion through magnetic field gradients. Increasing the amplitude of the applied locking field generally attenuates each of these relaxation mechanisms. Using a dispersion model of chemical exchange and dipole-dipole relaxation effects, the exchange rate and dipolar relaxation rate can be estimated in the low-frequency regime (0-2.5 kHz, Fig. 3).

Spoiling: Artifacts are a confounding issue for quantification of all bSSFP sequences and therefore a method subvoxel spoiling slSSFP-FID and –ECHO are presented. The impact of the spoiling gradients on the steady-state magnetization is shown. The effect of this condition on T1ρ contrast is considered.

Power Requirements: slSSFP image contrast is closely related to the phase alternating bSSFP contrast, but the steady-state can be maintained with sufficiently lower power. bSSFP requires a linear relationship between the magnetization orientation and the flip angle, whereas the orientation of the magnetization in slSSFP is directed along effective field and controlled by the ratio of the RF amplitude and the frequency offset.

Simulation Methods: Methods to simulate conventional bSSFP, slSSFP are explained and illustrated using (A) a Runge-Kutta numerical integration of the Bloch equations, (B) orthogonal, rotation matrix formulation, and (C) product operators. A summary of the pulse sequence and magnetization trajectory for various initial and steady-state conditions and over a range of interaction frequencies and spoiling conditions is shown.

Summary

Through a close examination of the unusual similarities between spin locking and bSSFP, this educational e-poster hopes to teach the basic methods of the spin lock experiment in MRI, the underlying mechanisms for T1ρ relaxation in vivo and illustrate the considerable contrast variation, sensitivity to mechanisms of low-frequency nuclear relaxation like residual dipolar coupling, chemical exchange and cross-relaxation that can be achieved using a very common steady-state sequence.

References: (1) Sepponen, et al. J Comput Assist Tomogr 9(6):1007-11(1985). (2) Witschey, et al. J Magn Reson Imaging 28(3):744-54(2008). (3) Witschey, et al. Magn Reson Med 62(4):993-1001.(2009)

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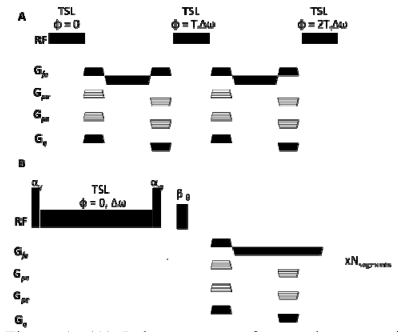

Figure 1: (A) Pulse sequence for steady-state spin locking (slSSFP). The off-resonance spin lock is interrupted briefly for periods of frequency and phase encoding. It is necessary to update the phase of the spin locking pulse to match the accumulated spin phase during free precession period. (B) Conventional T1ρ-prepared turboflash sequence for fast 2D or 3D acquisition of spin locked signals.

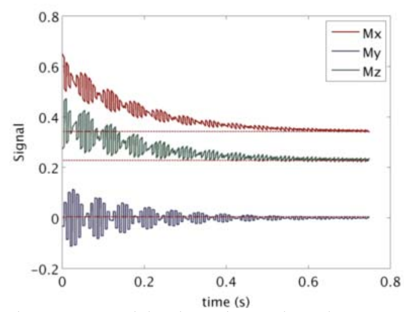

Figure 2: Demodulated transient and steady-states of an off-resonance pulsed spin locking RF sequence. Considerable signal can be sustained in the steady-state off-resonance nearly approximating the cw case (asymptotic line).

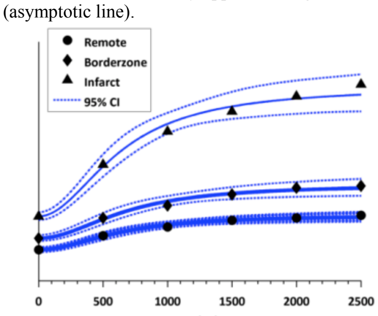

Figure 3: T1ρ dispersion in swine myocardium following acute myocardial infarction (T1ρ, ordinate). The dispersion was fit to a single Lorentzian model of 2-site chemical exchange and nuclear dipole-dipole relaxation between like spins modulated by rotational motion.