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Rapid determination of the RF pulse flip angle and spin–lattice relaxation time for materials imaging

Igor V. Mastikhin*

Department of Physics, MRI Centre, University of New Brunswick, P.O. Box 4400, Fredericton, Canada E3B 5A3

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Abstract

For samples with T_1s longer than 10 s, calibration of the RF probe and a measurement of T_1 can be very time-consuming. A technique is proposed for use in imaging applications where one wishes to rapidly obtain information about the RF flip angle and sample T_1 prior to imaging. The flip angle measurement time is less than 1 s for a single scan. Prior knowledge of the RF flip angle is not required for the measurement of T_1. The resulting time savings in measuring the values of flip angle and T_1 are particularly significant in the case of samples with very long T_1 and short T_2^*. An imaging extension of the technique provides RF flip angle mapping without the need for incrementing the pulse duration, i.e., RF mapping can be performed at fixed RF amplifier output.

Keywords: Long T_1; Short T_2^*; Flip angle; MRI; B_1 mapping; Pure phase encode; SPI; Materials

1. Introduction

Rapid determination of the RF flip angle and the spin–lattice relaxation time, T_1 is highly desirable in an MRI experiment. The RF flip angle and sample T_1 define the level of the signal saturation and thus characterize the image contrast and/or resolution of the MR images [1,2].

Traditionally, one cannot measure T_1 without first calibrating the RF probe, i.e., determining which RF pulse duration will rotate the net magnetization by a required flip angle.

One usually determines the 180°-pulse length by incrementing the pulse duration to find the minimal FID signal or by observing the inversion of the spectral line. The FID acquisition is repeated several times as the RF pulse duration is changed, with a longitudinal magnetization recovery delay of $5T_1$ between the repetitions. If the sample T_1 is long, this method requires a considerable time. One can also apply a train of pulses so that the rotation of the net magnetization can be measured via the pulse nutation frequency [3,4]. However, this method requires that T_2^* be longer than at least n times the probe dead time, where n is the number of pulses applied. Another, more important problem in nutation experiments for samples with $T_1 \gg T_2^*$ is appearance of "nonlinear but periodic distortions" [5] caused by incomplete relaxation. Therefore, for samples with T_2^* lifetimes shorter than hundreds of microseconds, this method is hard to implement.

NMR methods for determination of T_1 can be classified into two groups, "slow" and "rapid" methods, according to their measurement time. In slow methods, such as inversion-recovery, the measurement time of one data scan is determined by the relaxation delay TR and is of order of $5mT_1$, where m is the number of data points in the relaxation curve. In rapid methods such as progressive saturation [6], fast inversion recovery [7], and single-scan methods [8], the measurement time of one data accumulation is of the order of T_1.

* Fax: +1 506 4534581.
E-mail address: mast@unb.ca.

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The technique proposed here, for rapid determination of RF flip angle and T_1, is a modification of fast single-scan methods. The new technique has advantages in measurement of very long T_1 (>10 s), yielding significant time savings.

I also propose an imaging extension of this technique for RF field mapping. If one is interested in measuring the RF field distribution in a sample with conductive elements, or any sample that produces a significant B_0 shift, frequency-encoding MRI methods will not work well: time evolution artifacts will distort the resulting images [9]. Pure phase encode methods such as SPI (single point imaging) methods are immune to time-evolution image artifacts ([10,11]), and thus should be utilized for RF field mapping in such samples.

One can map the RF field distribution by acquiring a series of images with an increment of the RF pulse duration. This is not always possible in the case of SPI, as the pulses are applied in the presence of magnetic field gradients, and only a part of the sample may be excited. For small RF probes, as utilized for NMR spectroscopy, it is possible to generate very short 180° RF pulses, less than several microseconds in length. For 6–20 cm diameter RF probes that are typically in use for imaging, the duration of the 180° pulse can be several dozens of microseconds. This is too long to ensure broadband sample excitation and therefore one is restricted in the range of useable RF pulse lengths. The proposed technique permits RF field mapping at fixed RF amplifier output, without the need to increment the RF pulse duration.

2. Method

2.1. Measurement of flip angles

The pulse sequence is a train of n RF pulses with flip angle α and the repetition time TR (Fig. 1). In order that transverse magnetization decays completely pulse to pulse, the TR is set so that $\mathrm{TR} \gg T_2$ of the sample. In the following discussion we consider solely effects of multiple pulses on longitudinal magnetization.

A single data point is acquired at time t_p after each pulse. The measured signal is

$$S \propto M_z \sin\alpha \exp(-t_p/T_2^*), \tag{1}$$

where M_z is the longitudinal magnetization before the pulse. After n pulses, n data points will be collected. α and t_p are merely scaling factors because they are the same for all n RF pulses, and the evolution of M_z with RF pulsing can be determined.

At time TR after the first RF pulse, the longitudinal magnetization M_z is equal to

$$M_z = M_0 \cos\alpha \exp(-\mathrm{TR}/T_1) + M_0(1 - \exp(-\mathrm{TR}/T_1)). \tag{2}$$

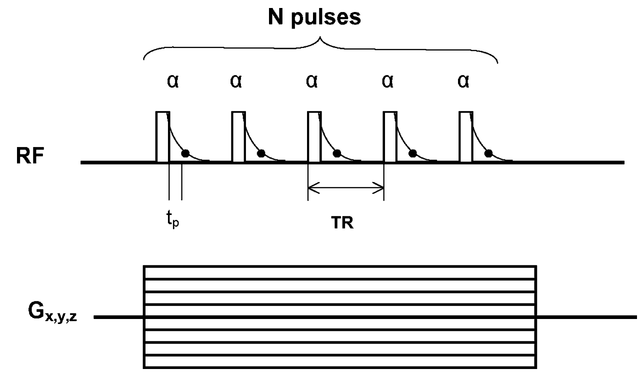

Fig. 1. The pulse sequence for RF flip angle and T_1 measurements is a train of N RF pulses. A single data point is acquired at time t_p after each pulse. In the imaging extension of the sequence, magnetic field gradients are added, similar to an SPI pulse sequence. N RF pulses are applied for each gradient value. N images are acquired which represent the signal decay due to RF pulsing and T_1 relaxation, with the same spatial information.

The longitudinal magnetization M_{zn} after the nth RF pulse is given by Eq. (3) [2,12]:

$$M_{zn} = M_0 C^n E^n + M_0(1 - E)\frac{1 - C^n E^n}{1 - CE}, \tag{3}$$

where $E = \exp(-\mathrm{TR}/T_1)$ and $C = \cos\alpha$. As the number of pulses increases, the value of the longitudinal magnetization approaches a steady-state magnetization

$$M_{st} = M_0 \frac{1 - E}{1 - CE}. \tag{4}$$

Eq. (3) can be rearranged in the following form:

$$\begin{aligned} M_{zn} - M_{st} &= (M_0 - M_{st}) \exp(-n\mathrm{TR}/T_1 + n \\ &\quad \times \ln(\cos\alpha)) \\ &= (M_0 - M_{st}) \exp(-n\mathrm{TR}/T_{app}), \end{aligned} \tag{5}$$

where T_{app} is defined as [11]

$1/T_{app} = 1/T_1 - \ln(\cos\alpha)/\mathrm{TR}.$

Using the definition of the Ernst angle as $\alpha_E = \mathrm{Arccos}\ \exp(-\mathrm{TR}/T_1)$, Eq. (5) can be rewritten as:

$$\ln\left(\frac{M_{zn} - M_{st}}{M_0 - M_{st}}\right) = -n\frac{\mathrm{TR}}{T_{app}} = n \ln(\cos\alpha \cos\alpha_E) \tag{6}$$

The RF flip angle and the sample T_1 determine the evolution of the longitudinal magnetization towards the steady state. The Ernst angle is a measure of the T_1 impact on the longitudinal magnetization decay for a given TR, in Eq. (6). Information on both the flip angle and T_1 is contained in the product of cosines, $\cos\alpha \cos\alpha_E$. Thus by finding this product, one can extract information on α and T_1.

According to Eq. (6), the longitudinal magnetization decay can be fit to an exponential function $\exp(-kn)$, where n is the number of RF pulses and the decay constant k is: