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Journal of Magnetic Resonance 173 (2005) 169–174
JMR Journal of Magnetic Resonance
www.elsevier.com/locate/jmr

Increasing the speed of relaxometry-based compartmental analysis experiments in STEAM spectroscopy

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Received 8 July 2004; revised 30 November 2004
Available online 20 January 2005

Abstract

In this work we present a method for improving the speed of spin–spin relaxation time (T_2) measurements for compartmental analysis in stimulated echo localized magnetic resonance spectroscopy without reducing the sampling density. The technique uses a progressive repetition time (TR) to compensate for echo time (TE) dependent variations in saturation effects that would otherwise modulate the received signal at short TRs. The method was validated in T_2 studies on 10 young healthy subjects in spectroscopic voxels localized along either the right or left Sylvian fissure ($2 \times 2 \times 1.5$ cm^3, 10 ms mixing time (TM), 2048 data points, 819.2 ms acquisition time). The TR was automatically adjusted so that TR–TM–TE/2 was kept constant as the TE was incremented. Compared to long TR T_2 experiments, the progressive TR technique consistently replicated the T_2 relaxation times and reference signals of the tissue water compartment while reducing the data acquisition time by more than 50%. The percent error was on average less than 2% for estimates of T_2 and S_0 for the tissue water, an indication that the progressive TR technique is a useful method for determining the tissue water signal for internal referencing.

Keywords: MRS; Transverse relaxation; T_2; Spin–spin relaxation; Spin–lattice relaxation

1. Introduction

Voxel segmentation is an integral part of the quantitation process of single-voxel in vivo ^{1}H magnetic resonance spectroscopy (^{1}H MRS) [1–3]. In ^{1}H MR brain spectroscopy, internal and external referencing schemes use spin–spin relaxometry to separate the volume contributions of tissue water and cerebral spinal fluid (CSF) in a localized volume-of-interest (VOI) to obtain a referencing signal for the calculation of the metabolite concentrations [1–7]. In internal schemes, the tissue water component serves as a reference, while in external schemes the CSF component serves as a measure of CSF partial volume. In the latter case, the CSF component is referenced to an external standard to calculate the tissue volume within the VOI. The presence of both CSF and tissue water within the VOI require a moderate-to-high sampling density to accurately separate the differential relaxation effects of the water compartments. In addition, the long spin–lattice relaxation time (T_1) of CSF typically requires long repetition times to minimize the effects of magnetization saturation on the spin–spin relaxation time (T_2) measurements. These conditions necessitate sparse sampling of the T_2 curve in clinical examinations to minimize patient scan times. Minimal sampling schemes have poor precision and accuracy [8]. In this work, we present a time efficient relaxation measurement technique that uses a variable repetition time (TR) and the acquisition of multiple relaxation curves to reduce the scan time for a stimulated echo (STEAM) spectroscopic T_2 experiment while preserving a high sampling density.

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doi:10.1016/j.jmr.2004.12.001

2. Materials and methods

2.1. A progressive repetition time

A common method for measuring T_2 in in vivo ^{1}H MRS is the repetitive single-echo technique, where the TR is sufficiently long to allow the longitudinal magnetization to fully recovery between repetitions [9]. We will henceforth refer to this method as the fully relaxed T_2 technique. The technique yields a signal S_{XY} from the transverse magnetization that varies as a function of the echo time (TE) as:

$$S_{XY}(\mathrm{TE}_n) = \sum_{m=1}^{M} S_{0\_m} \exp\left(-\frac{\mathrm{TE}_n}{T_{2\_m}}\right), \tag{1}$$

where the summation allows for M different relaxation compartments with various signal contributions S_{0_m}. In the spectroscopic brain model, M is generally restricted to two, CSF and tissue water [1–7]. If the TR is less than five times the T_1 of CSF, then Eq. (1) must be modified to include T_1 saturation effects. For the STEAM sequence, this inclusion yields the familiar equation (Fig. 1) [10–13]:

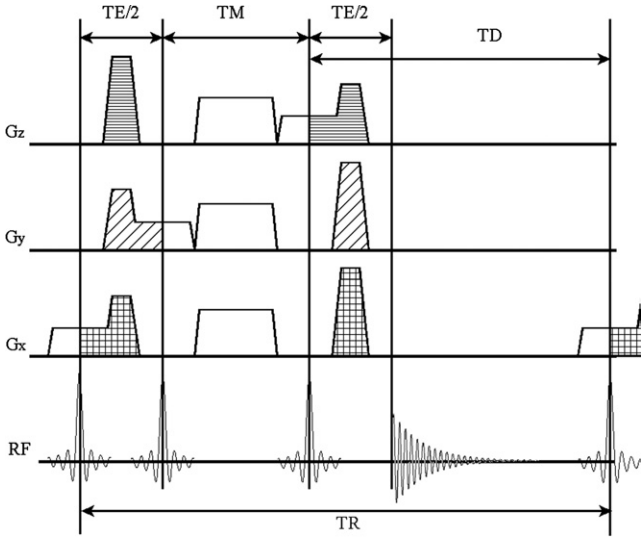

Fig. 1. Schematic of the stimulated echo localization sequence. The mixing time (TM) and delay time (TD) are kept constant throughout each progressive TR experiment. The time interval between the sets of concatenated gradients (positioned before and after the TM period) is kept constant as the TE increases to minimize TM-dependent diffusion-weighting. The concatenation of the refocusing gradient of the first slice-select gradient with the TE spoiler gradient is removed after the dead time during the first TE/2 interval becomes equal to or longer than the length of the RF pulse. This procedure minimizes the diffusion effects from the first slice-select gradient, especially at long echo times, since the rephasing gradient can be applied immediately following slice selection at long echo times.

$$S_{XY}(\mathrm{TE}_n) = \sum_{m=1}^{M} \frac{S_{0\_m}}{2}\left[1 - \exp\left(-\frac{\mathrm{TD}_{n-1}}{T_{1\_m}}\right)\right] \times \exp\left(-\frac{\mathrm{TE}_n}{T_{2\_m}} - \frac{\mathrm{TM}}{T_{1\_m}}\right), \tag{2}$$

where $\mathrm{TD}_n = \mathrm{TR}_n - \mathrm{TM} - \mathrm{TE}_n/2$, and the intervals for TR, TM, and TE/2 are defined in Fig. 1. If Eq. (2) is to be employed for T_2 measurements in a similar fashion as Eq. (1), then the following three conditions must be satisfied: (i) TM must be kept constant, (ii) diffusion-related signal attenuation must also be constant or negligible [14], and (iii) the focus of this work, TD must be kept constant by progressively changing the TR with the TE so that saturation effects are also kept constant. Thus representative T_2 curves of Eqs. (1) and (2) will differ in intensity but not in decay rate.

Compared to the fully relaxed T_2 technique, a relaxometry experiment with a short and progressive TR will yield estimates of the T_2 and T_1-weighted S_{0_m} values. To obtain the true reference S_{0_m} values needed in metabolite concentration calculations, two progressive TR relaxometry experiments with different TD values must be performed so that Eq. (2) can be employed. Although this requires two sets of data, because the minimum TR for a fully relaxed T_2 experiment in the brain is 9 s or greater, T_2 experiments with a progressive TR can be performed considerably faster.

2.2. Relaxometry experiments

To validate the progressive TR technique, spectroscopic relaxometry data were collected from 10 healthy young volunteers using STEAM (4 men/6 women, mean age: 23.5 ± 3.9 years, range: 18–33 years). All experiments were performed on a 1.5 T Magnetom Sonata whole-body MRI system (Siemens Medical Systems, Iselin, NJ) using a standard Siemens circularly polarized proton head coil. Human studies were performed under protocols approved by the institutional review board and with the signed and informed consent of each participant. Each participant underwent a fully relaxed T_2 experiment with TM/TR = 10 ms/11 s, a homospoil saturation recovery (HSR) T_1 experiment [15], two progressive TR T_2 experiments (Table 1), and then a repeat of the fully relaxed T_2 experiment, in that order. The second fully relaxed T_2 data were collected to determine whether a participant had significantly moved during the scan.

The HSR sequence was created by inserting a variable delay time between a three-pulse frequency-selective water suppression preparation sequence and the first slice-selective RF pulse in the STEAM sequence. The progressive TR T_2 sequence was created by inserting variable delay times in the TE/2 periods and at the end of the sequence. The variable delay