



Variable spacing Fast- $T_{1\rho}$ for the analysis of fast relaxing species at low-field

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ABSTRACT

$T_{1\rho}$ is a powerful analytical technique capable of probing motions on the timescale of molecular dynamics. Conventional $T_{1\rho}$ approaches are performed on high-field NMR magnets (typically > 2 T) and rely on step-by-step data acquisition, resulting in relatively long experiments and acquisitions that are affected by non-negligible internal gradient effects and strict Specific Absorption Rate limits. The work presented herein reports the development of novel one- and two-dimensional Fast- $T_{1\rho}$ pulse sequences on a 2 MHz benchtop NMR spectrometer. The developed method enables the observation of fast-relaxing species down to the millisecond timescale through application of a variably-spaced spin-lock duration array with delay spacings as short as 100 μ s. Fast- $T_{1\rho}$ and Fast- T_1 - $T_{1\rho}$ pulse sequences have been developed which show significantly faster acquisition relative to conventional $T_{1\rho}$, illustrated with a 6-fold and 25-fold reduction in experiment time respectively. These techniques were demonstrated to be robust and accurate with measured $T_{1\rho}$ values for bulk glycerol showing a maximum difference of 5.4% between Fast- $T_{1\rho}$ and conventional $T_{1\rho}$ experiments. The power of this method is exemplified through the simultaneous observation of multiple relaxation environments within a porous γ - Al_2O_3 sample imbibed with an ethanol:water mixture, where $T_{1\rho}$ relaxation rates of two orders of magnitude difference (2.4 ms to 370 ms) were captured.

1. Introduction

Relaxometry covers a wide suite of NMR spectroscopy techniques that provide insight into dynamic processes. Common approaches look at spin-lattice longitudinal (T_1) relaxation, spin-spin transverse (T_2) relaxation or combine them within correlation studies (T_1 - T_2 NMR) to gain additional insights into interactions within the chemical system [1]. A key limitation of these approaches is that relaxation is dominated by specific fixed frequencies: in the case of T_1 relaxation, the frequency of the external magnetic field ($\omega = \omega_0 = \gamma B_0$) and for T_2 relaxation both the frequency of the external magnetic field (ω_0) and an additional zero frequency component ($\omega = 0$ Hz) contribute. The ability to perform relaxation dispersion measurements, whereby the dominant relaxation frequency is varied, are very useful for probing motion on the molecular timescale [2,3]. Two main approaches have been developed to perform these types of experiments: Field Cycling (FC) instruments capable of varying B_0 during experiments [4,5] and spin-lattice relaxation in the rotating frame experiments, known as $T_{1\rho}$ [6].

$T_{1\rho}$ pulse sequences were first described in 1955 by Redfield [7], with the first MRI implementations being in the 1980s [8]. Within $T_{1\rho}$ experiments a radiofrequency (RF) pulse of set field strength, B_{SL} , is

applied during relaxation of the sample back to equilibrium. This B_{SL} field becomes the dominant relaxation frequency ($\omega = \omega_{SL} = \gamma B_{SL}$) [9]. Applied B_{SL} fields tend to cover a range from hundreds of Hz [10] to tens of kHz [11], though a specially designed NMR spectrometer was able to make use of a 110 kHz spin-lock frequency [12]. This frequency range results in $T_{1\rho}$ being sensitive to processes occurring on the millisecond to microsecond timescale. Owing to this, $T_{1\rho}$ has seen widespread application within medical imaging (for example looking at liver fibrosis [13], brain disease [14], and knee cartilage degradation [15,16]) and also within process control (such as the gelation of silica sol-gels [17,18]).

The key feature of a $T_{1\rho}$ pulse sequence is a low power, long duration spin-lock pulse (denoted as θ_y in Fig. 1(a)). The spin-lock pulse is applied in the same direction as the bulk magnetisation, preventing precession that would lead to loss of coherence and T_2^* relaxation. Instead, relaxation is dominated by the applied B_{SL} field and so the measured relaxation is $T_{1\rho}$ after a certain spin-lock duration (t_θ). By repeating the experiment at multiple spin-lock durations (each denoted by $t_{\theta i}$, where i indicates the current step), a $T_{1\rho}$ value for the sample can be calculated by fitting the integrated NMR data to Eq. (1), where

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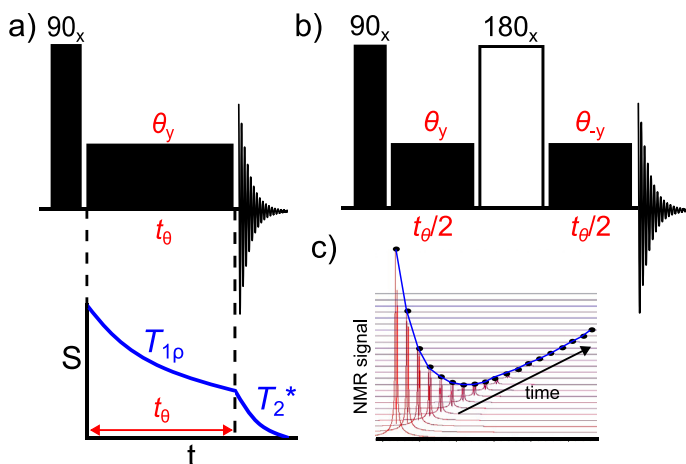


Fig. 1. (a) Original and (b) compensated $T_{1\rho}$ pulse sequences alongside (c) an example dataset analysed to produce a $T_{1\rho}$ relaxation time.

S_0 and S_i are the initial signal and signal after a spin-lock of duration $t_{\theta i}$ respectively:

$$S_i = S_0 e^{-\frac{t_{\theta i}}{T_{1\rho}}} \quad (1)$$

Many improvements have been made to the $T_{1\rho}$ pulse sequence focused on reducing artifacts and signal loss during spin-lock pulse application. These developments have led to the common usage of a compensated $T_{1\rho}$ pulse sequence (Fig. 1(b)) which features B_1 compensation through use of a rotary-echo spin-lock (the spin-lock pulse is divided into two sections of equal duration and opposite phase) and B_0 compensation through use of a 180° refocusing pulse and phase cycling [16,19].

One disadvantage of the standard $T_{1\rho}$ approach is that each experiment performed only collects data for a single spin-lock duration. To build up a relaxation decay curve, and thus calculate the $T_{1\rho}$ values for a system, an additional acquisition is required for each spin-lock duration investigated (Fig. 1(c)). Therefore, as the number of required datapoints is increased, the experiment duration increases in step.

Recent advances within $T_{1\rho}$ pulse sequences have mainly focused upon improving acquisition speed. This has led to the development of faster techniques that utilise off-resonance spin-lock pulses such as Spin-Lock Adiabatic Field Cycling Imaging (SLOAFI) [20,21] and sequences that couple with fast imaging techniques (such as fast spin-echo sequences [22,23], compressed sensing [24,25], or echo planar imaging [26]). For on-resonance $T_{1\rho}$ experiments, a significant reduction in experiment duration was first reported in 2023 by the research group of Telkki with the development of the SPICY (SPIn lock CYcle) $T_{1\rho}$ pulse sequence on a 600 MHz (14.1 T) NMR spectrometer [27]. Within this sequence, a loop is utilised to enable repetition of a constant duration spin-lock and single-point signal acquisition. This pulse sequence reduced experiment time by an order of magnitude when compared to standard $T_{1\rho}$ sequences (with a single scan obtained in 16 s rather than 4.2 min). Further advances by that research group have seen the development of fast $T_{1\rho}$ 1D imaging [27] and of 2D $T_{1\rho}$ sequences (both IR-SPICY and Ultrafast IR-SPICY [28]).

One limitation observed when performing on-resonance $T_{1\rho}$ experiments with high-field NMR spectrometers is RF power. The relatively long pulse durations combined with the RF power required to overcome local field gradients and spin-lock the sample can limit the experimental timescales that can be explored, especially when Specific Absorption Rates (SARs) need to be considered to prevent substantial heating of the experimental subject [29]. One solution is to transition to a weaker magnetic field strength, which will reduce the overall power requirements of the $T_{1\rho}$ experiment [30] and also help to minimise

artifacts from B_0 and B_1 magnetic field inhomogeneities [31]. Due to a recent resurgence in the use of low-field (≤ 2 T) NMR spectrometers, there is a wide range of benchtop systems available for relaxometry measurements [32,33]. While these spectrometers sacrifice resolution and sensitivity, they come with the additional advantage of being cryogen-free which improves safety, affordability and portability [34,35]. Owing to these features, these spectrometers have seen widespread applications across industrial processes, such as cement drying [36], probing fluid motion within porous media [37,38] and in assessing food quality [39,40]. While $T_{1\rho}$ experiments have seen some limited application on low-field NMR instruments (namely around the early 2000s within the fields of articular cartilage degradation [41,42] and porous media wettability [43]), there is no current literature focused on implementing a single-shot on-resonance $T_{1\rho}$ approach upon modern benchtop NMR spectrometers.

When designing a single-shot $T_{1\rho}$ approach, another limitation to consider is the minimum spin-lock duration able to be accessed. To be able to obtain $T_{1\rho}$ information about multiple relaxing species, the spin-lock duration used is limited by the slowest relaxing species and the number of steps that can be performed. Therefore observation of fast relaxing species, namely on the millisecond timescale, can prove difficult due to the limited sampling of datapoints at short spin-lock durations [28].

Herein, novel Fast- $T_{1\rho}$ and Fast- T_1 - $T_{1\rho}$ pulse sequences are introduced that enable facile observation of fast-relaxing species within a multi-component system. The single-shot nature of the method developed enables rapid data acquisition relative to conventional $T_{1\rho}$ approaches. These pulse sequences are developed on a benchtop 2 MHz NMR system, marking the first implementation of single-shot on-resonance $T_{1\rho}$ experiments at low-field within the currently available literature. Initial experiments focus on the optimisation of the pulse sequence and benchmarking with a bulk glycerol sample to ensure that robust relaxation information is able to be obtained. The developed techniques are then applied to an ethanol:water binary mixture imbibed within a porous γ - Al_2O_3 pellet to probe the ability of the method to resolve multiple $T_{1\rho}$ components within a system. Within this example, the ability to resolve relaxation components down to millisecond timescales is highlighted.

2. Experimental

2.1. Materials and sample preparation

Glycerol (Sigma Aldrich) was used as received and dispensed into a sample vial for analysis. For porous media samples, the γ - Al_2O_3 pellets used were purchased from Alfa Aesar in the form of 1/8" cylindrical extrudates. The γ - Al_2O_3 pellets were prepared for imbibition by drying overnight in a 95°C oven. Following drying, the pellets were soaked in the required imbibition fluid overnight. Prior to analysis, the γ - Al_2O_3 pellets were removed from the remaining solvent and dried using filter paper to remove any extra-pellet liquid. The imbibition fluid used in this study was a 50:50 (v/v) ethanol:water mixture. For this mixture, $\geq 99.8\%$ ethanol (Fischer Chemicals) was used.

2.2. NMR methodology

All benchtop NMR experiments were carried out on a 51 mT (2.18 MHz) Geospec 2-75 Rock Core Analyser (Oxford Instruments, UK) held at $(35.0 \pm 0.1)^\circ\text{C}$ and operated using RINMR software. A 4.2 kHz spin-lock frequency (θ_y), corresponding to 20% of the maximum RF power for the spectrometer, was used for all experiments. Comparison studies with conventional $T_{1\rho}$ experiments were performed using the compensated $T_{1\rho}$ pulse sequence shown in Fig. 2(a).

During development of the following pulse sequences, a constraint within the RINMR software used meant that the maximum spin-lock pulse duration able to be implemented was 100 ms. To overcome this

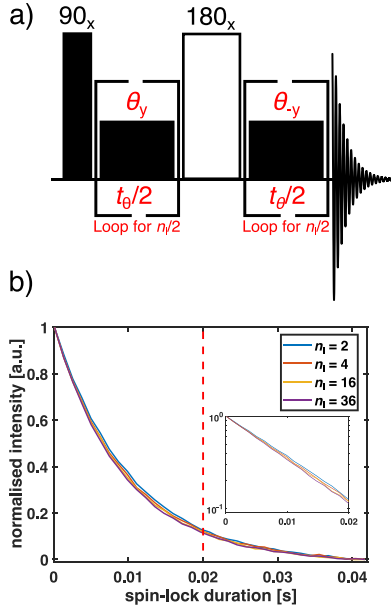


Fig. 2. (a) $T_{1\rho}$ pulse sequence incorporating hard pulse chains for spin-lock pulses and (b) comparison between glycerol $T_{1\rho}$ relaxation curves collected with n_1 loops with a logarithmically-spaced inset focused on the initial 20 ms of relaxation.

limitation, the $T_{1\rho}$ pulse sequence were altered to allow for hard pulse trains (of length n_1) to be used within each spin-lock pulse (Fig. 2(a) shows this adaptation for the compensated $T_{1\rho}$ experiment). To ensure that these additional pulses had a minimal impact on the calculated $T_{1\rho}$ values, experiments featuring $n_1 = 2, 4, 16$ and 36 were conducted (with $n_1 = 36$ allowing for a maximum spin-lock duration of 3.6 s). The experiments were conducted with bulk glycerol using 35 steps between 100 μ s and 42 ms with 4 scans per step and a repetition time of 3 s. The results, given in Fig. 2(b), gave $T_{1\rho}$ values of 9.69, 9.46, 9.23 and 9.07 ms for $n_1 = 2, 4, 16$ and 36 respectively, with all values having an experimental error of <0.15 ms. From these experiments, a maximum deviation of 0.62 ms is observed between the $n_1 = 2$ and $n_1 = 36$ datasets. The origin of this deviation is due to additional spin-lock interruptions from the switching between each pulse within the hard pulse train. The higher n_1 , the more overall T_2^* relaxation will affect the observed signal.

The 6.4% reduction in $T_{1\rho}$ value was deemed an acceptable trade-off so as to allow long spin-lock durations to be accessed on the spectrometer. All further pulse sequences contain the hard pulse train modification but this has been omitted for clarity. Unless otherwise stated, a value of n_1 of 4 has been used in all further experiments.

Data processing was performed within MATLAB. Analysis of 1D relaxation data was carried out using mono- and bi-exponential fitting for the single component (glycerol) and multi-component (ethanol:water mixture) systems respectively. For analysis of 2D relaxation data, inverse Laplace transformation (ILT) of the signal was used to generate $T_{1\rho}$ and T_1 distributions for the system. The ILT routine used was developed by Reci et al. [44] and is based upon Tikhonov regularisation.

3. Results and discussion

3.1. Single-shot Fast- $T_{1\rho}$

A set of 1D (Fast- $T_{1\rho}$, T_1 -Suppressed Fast- $T_{1\rho}$) and 2D (Fast- T_1 - $T_{1\rho}$) single-shot $T_{1\rho}$ pulse sequences have been developed as part of this research. Discussion of this work is split into pulse sequence development (Sections 3.1.1 and 3.1.2 for 1D and 2D pulse sequences respectively)

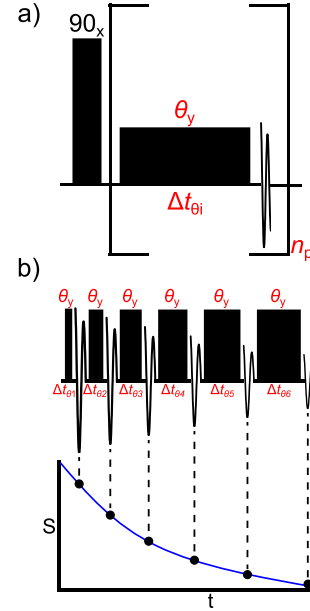


Fig. 3. (a) Fast- $T_{1\rho}$ pulse sequence alongside (b) a cartoon representation of the variable spacing of spin-lock durations.

and then application to a binary mixture system (Section 3.2). For succinctness, discussion of the developed T_1 -Suppressed Fast- $T_{1\rho}$ pulse sequence is reserved for Section 3.2.2 where it can be demonstrated effectively for a system containing multiple components.

3.1.1. 1D Fast- $T_{1\rho}$

A novel single-shot approach (Fast- $T_{1\rho}$) was developed for the benchtop NMR instrument to allow for acquisition of all $T_{1\rho}$ datapoints within a single experiment (Fig. 3(a)), taking inspiration from the CPMG pulse sequence for single-shot T_2 acquisition [45] and the SPICY method for single-shot $T_{1\rho}$ measurements [27]. In this experiment, a loop consisting of a spin-lock pulse followed by acquisition of a single complex datapoint (collecting only magnitude information) is performed. Unlike alternative $T_{1\rho}$ pulse sequences, the duration of the spin-lock pulse is actively updated within the acquisition loop, allowing for the delay spacing to be constantly updated within a single experiment (Fig. 3(b)). For this initial implementation, B_0 and B_1 compensation through a 180° spin-echo was omitted to reduce the total number of interruptions to the spin-lock pulses. As stated previously, transitioning to a 2 MHz magnet will reduce the presence of artifacts due to B_0 and B_1 inhomogeneities and so the requirement for compensation is reduced at this weaker magnetic field strength.

The ability to update the spin-lock duration during the experiment allows for non-linear sampling of the $T_{1\rho}$ data which can be very beneficial when attempting to capture multiple relaxation times with different magnitudes. The approach used to implement a specific array of spin-lock durations within the Fast- $T_{1\rho}$ pulse sequence is given below for both conventional linear and logarithmic datapoint spacing. In both instances, the first step requires the calculation of the overall spin-lock duration that occurs prior to each acquisition step ($t_{\theta i}$). For this, user inputs of number of datapoints (n_p), minimum spin-lock duration ($t_{\theta 1}$, down to a minimum value of 100 μ s within this study) and maximum spin-lock duration ($t_{\theta np}$) are required. $t_{\theta i}$ values for both linear (Eq. (2)) and logarithmic (Eq. (3)) spacings can then be calculated:

$$t_{\theta i} = t_{\theta 1} + \frac{(t_{\theta np} - t_{\theta 1})}{n_p - 1}(i - 1), \quad (2)$$

$$\log(t_{\theta i}) = \log(t_{\theta 1}) + \frac{\log(t_{\theta np} - t_{\theta 1})}{n_p - 1}(i - 1). \quad (3)$$

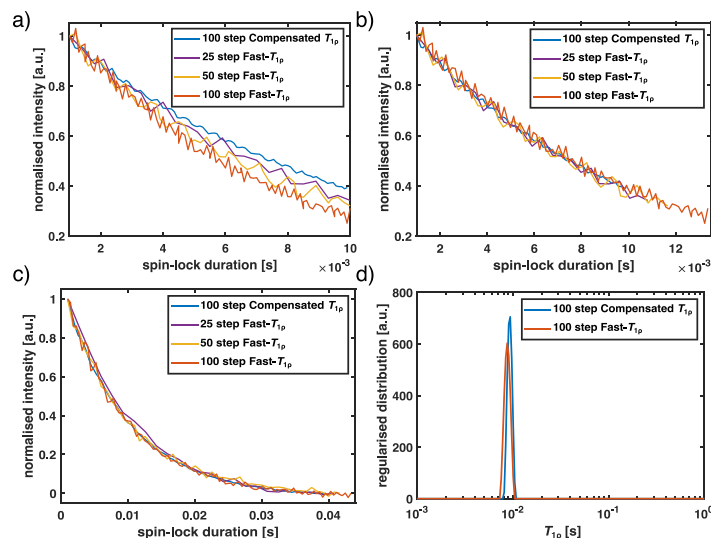


Fig. 4. $T_{1\rho}$ relaxation of glycerol measured by compensated $T_{1\rho}$ (100 steps) and Fast- $T_{1\rho}$ (25, 50, 100 steps) over 10 ms (a) without and (b) with deadline correction, and (c) measured over 40 ms with deadline correction with (d) a direct $T_{1\rho}$ distribution comparison for the 100 step experiments performed.

The next step of the calculation accounts for any previous spin-lock within the loop. As each spin-lock is performed sequentially rather than independently, the actual duration of each spin-lock (Δt_{θ_i}), except for the initial step, is dictated by the difference between each step (Eq. (4)). Δt_{θ_i} is then divided by the value of n_i chosen for the experiment. The value of n_i required is dictated by the maximum value of Δt_{θ_i} (i.e. if the maximum Δt_{θ_i} is 400 ms, $n_i = 4$ is the minimum requirement to meet the 100 ms hard pulse limitation of the spectrometer):

$$\Delta t_{\theta_i} = t_{\theta_i} - t_{\theta_{i-1}}. \quad (4)$$

A benefit of rapid single-shot acquisition using Fast- $T_{1\rho}$ is that experimental time is decoupled from the number of spin-lock durations examined. This means that up to an x -fold speed increase can be achieved, where x is the number of $T_{1\rho}$ steps performed. In situations where high-throughput of samples is not necessary or low-concentration species are present, this time-saving enables an increased number of scans as to maximise the signal-to-noise ratio (SNR) for the dataset.

Initial testing of the Fast- $T_{1\rho}$ pulse sequence was performed on a bulk glycerol sample using different acquisition step sizes (n_p), focused on only the first 10 ms of relaxation. For all $T_{1\rho}$ experiments performed a linearly-spaced array of spin-lock durations between 1 ms and 10 ms were used, with a repetition time of 500 ms. The Fast- $T_{1\rho}$ pulse sequence was repeated with 25, 50 and 100 steps, with 64 scans each (giving a total acquisition time of 32 s). For comparison, a compensated $T_{1\rho}$ experiment was performed with 100 steps, each with 4 scans, with a total acquisition time of 3.3 min. Compared to the compensated $T_{1\rho}$ experiment, a 6.2-fold experimental time reduction is achieved with the Fast- $T_{1\rho}$ experiment even with the acquisition of 16 times more scans.

From the acquired datasets (Fig. 4(a)) a trend is evident that increasing n_p reduces the observed $T_{1\rho}$, with the measured values for glycerol being (8.5 ± 0.4) , (7.9 ± 0.3) and (6.9 ± 0.2) ms for 25, 50 and 100 steps respectively. This trend with n_p is due to a key difference between Fast- $T_{1\rho}$ and conventional $T_{1\rho}$; in the case of Fast- $T_{1\rho}$, each acquisition carries a fixed duration of spectrometer deadline (to allow for sufficient ringdown in the coil prior to detection and for datapoint acquisition). Therefore, each subsequent datapoint is offset by the sum of all previous spectrometer deadline periods. Accounting for this additional delay (fixed at 34 μ s for each acquisition) within the spin-lock duration array results in strong alignment of the individual datasets (Fig. 4(b)) with $T_{1\rho}$ values being corrected to (9.3 ± 0.4) , (9.4 ± 0.3) and (9.5 ± 0.2) ms.

The experiment was then repeated using a maximum spin-lock duration of 40 ms (all other parameters were identical to before) to capture the complete $T_{1\rho}$ relaxation of the glycerol sample. Following correction, the resulting relaxation decay curves (Fig. 4(c)) give $T_{1\rho}$ values of (9.2 ± 0.3) , (9.2 ± 0.2) and (8.8 ± 0.2) ms for the Fast- $T_{1\rho}$ experiment with 25, 50 and 100 steps and (9.29 ± 0.08) ms for the compensated $T_{1\rho}$ experiment. This corresponds to differences of 1.1%, 1.1% and 5.4% relative to the compensated $T_{1\rho}$ experiment, indicating that while there is a slight decrease in value observed with Fast- $T_{1\rho}$ when larger values of n_p are selected, there is overall a very strong agreement between the two different techniques. A good overlap was also observed in the regularised distribution of $T_{1\rho}$ values obtained via ILT (Fig. 4(d)) for both 100 step datasets. Overall, this shows that this technique carries a high accuracy, highlighting that this method can be used with a negligible loss in data quality.

Another important achievement to highlight is that spin-lock duration spacing, Δt_{θ_i} , for the 100 step experiment is 100 μ s. This is two orders of magnitude shorter than the 12 ms minimum spin-lock duration reported by Tolkkinen et al. [28] and as such allows for the analysis of fast relaxing species that were previously difficult to capture. The ability of the method to manage these short duration spin-locks is also beneficial when implementing non-linear spin-lock duration arrays, such as logarithmic spacing, where the difference between initial acquisition steps can be on the micro- to millisecond timescale.

3.1.2. 2D Fast- T_1 - $T_{1\rho}$

The Fast- $T_{1\rho}$ technique was further developed into a multidimensional Fast- T_1 - $T_{1\rho}$ pulse sequence (Fig. 5(a)). This pulse sequence is based upon the IR-CPMG pulse sequence commonly used for T_1 - T_2 experiments [46] and follows a similar design to the linearly-spaced single-shot T_1 - $T_{1\rho}$ pulse sequence designed by Tolkkinen et al. [28]. Here, the CPMG train has been replaced by the Fast- $T_{1\rho}$ acquisition loop to encode the required $T_{1\rho}$ information. The Fast- T_1 - $T_{1\rho}$ pulse sequence was tested using glycerol with 25 $T_{1\rho}$ steps between 1 and 40 ms and 25 T_1 steps between 1 and 100 ms, each with 32 scans and a recycle delay of 2.5 s to give a total experiment time of 34 min. This is a 25-fold time saving when compared to using conventional $T_{1\rho}$ (13.9 h experiment) which is a significant improvement and ensures that long experiment time issues, such as spectrometer lock drift, are negligible. Results are shown for 2D spectra collected using both linear (Fig. 5(b)) and logarithmic (Fig. 5(c)) spacing of spin-lock durations. In both cases, a clear single cross-peak is identified, centred at $T_1 = 13$ ms

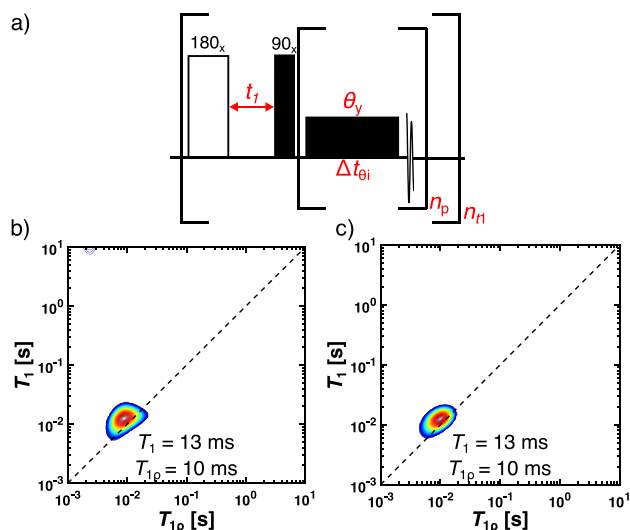


Fig. 5. (a) Fast- T_1 - $T_{1\rho}$ pulse sequence alongside T_1 - $T_{1\rho}$ spectra for glycerol recorded using (b) linear and (c) logarithmic $T_{1\rho}$ delay spacing.

and $T_{1\rho} = 10$ ms, as expected from the single relaxation environment of the glycerol sample. The absence of any spurious peaks within the 2D spectra is a good indicator that the Fast- $T_{1\rho}$ acquisition loop has a negligible impact on the quality of data being obtained (there are no fast-relaxing cross-peaks present, which could indicate an additional source of signal loss). Similarly, the near identical appearance of both 2D spectra is strong evidence that there are no artifacts associated with implementing a non-linear spacing array within the Fast- $T_{1\rho}$ acquisition loop.

3.2. Application: Ethanol:water binary mixture imbibed in γ - Al_2O_3

3.2.1. Fast- $T_{1\rho}$ and Fast- T_1 - $T_{1\rho}$ analysis

To demonstrate the power of variable spacing for $T_{1\rho}$ experiments, a binary mixture of ethanol:water (50:50, v/v) imbibed in γ - Al_2O_3 was prepared. Previous studies have highlighted the ethanol:water binary mixture as an interesting system for probing competitive adsorption and surface interaction strengths in porous media [47]. Within this binary mixture there are two NMR environments: a fast-relaxing labile OH environment with contributions from both the water and ethanol molecules and a relatively slow-relaxing CH_n environment associated with the alkyl chain of the ethanol molecule (there is not enough resolution at 2 MHz to separately resolve the CH_2 and CH_3 moieties).

The sample was initially analysed using 1D Fast- $T_{1\rho}$ and T_1 experiments to establish sensible parameters for the 2D Fast- T_1 - $T_{1\rho}$ experiment. Fast- $T_{1\rho}$ experiments with linear and logarithmic spacing were performed with 50 steps, 64 scans, $n_1 = 24$ and a repetition time of 5 s (giving a total acquisition time of 5.3 min) with the obtained relaxation curves given as Figs. 6(a) and (b) respectively. From these studies, T_1 parameters of 0.1 ms - 3 s and $T_{1\rho}$ parameters of 0.1 ms - 2 s were extracted. The 2D Fast- T_1 - $T_{1\rho}$ experiment was performed with 50 steps in each dimension, with 32 scans per step and a repetition time of 6 s to give a total experiment time of 2.6 h. The resulting 2D spectra are shown for both linear (Fig. 6(c)) and logarithmic (Fig. 6(d)) spacing.

From the collected datasets it is evident that the expected bi-exponential decay is observed for the system, with two degrees of magnitude difference between the fast relaxing OH environment and slow relaxing CH environment. The moiety responsible for the predominant signal decay observed are highlighted by the blue and orange datapoints respectively in Fig. 6. When linear spacing is used, only the CH environment is able to be positively identified with a $T_{1\rho}$ of (350 ± 40) ms. There is also evidence of a second faster-relaxing environment

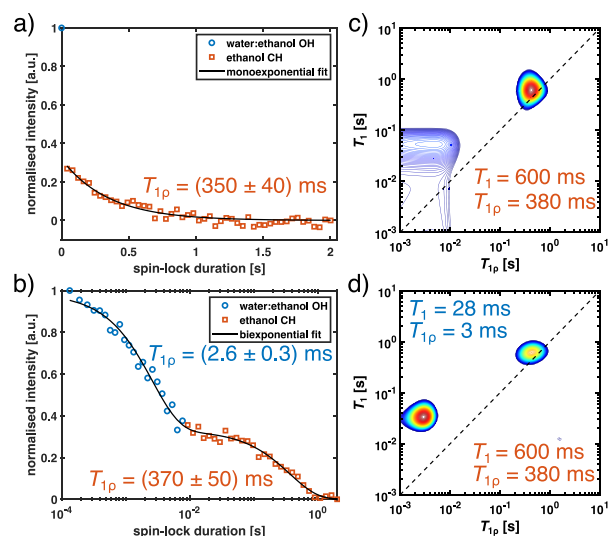


Fig. 6. 1D Fast- $T_{1\rho}$ decay curves and 2D Fast- T_1 - $T_{1\rho}$ spectra for a sample of γ - Al_2O_3 imbibed with ethanol:water (50:50, v/v) using (a, c) linear spacing and (b, d) logarithmic spacing of $T_{1\rho}$ delays. For all plots, colour has been used to indicate the predominant moiety responsible for the signal, either the labile OH of water and ethanol (blue) or the ethanolic CH (orange).

in the form of a high initial intensity for the 1D experiment and a broad secondary peak centred around $T_{1\rho} = 10^{-3}$ s in the 2D experiment. However, it is impossible to extract any quantitative relaxation information about this environment from these linearly-spaced data.

When implementing the logarithmic variable spacing, there is an increased weighting of datapoints collected at short $t_{\theta i}$ values - with over 20 datapoints being recorded before a cumulative spin-lock duration of 10 ms is reached. As a result, a good distribution of datapoints between the fast- and slow-relaxing $T_{1\rho}$ environments is achieved. This results in values of (2.6 ± 0.3) and (370 ± 50) ms to be measured for the OH and CH environments respectively. This improvement is also reflected in the 2D spectrum collected, where both relaxation environments are clearly identifiable and well resolved from one another.

3.2.2. T_1 -Suppressed Fast- $T_{1\rho}$ analysis

For more complex mixtures, especially those where cross-peak overlap is a potential issue, it can be beneficial to suppress certain environments to simplify analysis and individually resolve components. To this end, a T_1 -Suppressed Fast- $T_{1\rho}$ pulse sequence was implemented (Fig. 7(a)).

Within this pulse sequence, the delay following the initial 180° inversion is fixed at a T_1 value that equates to zero signal for one environment. This T_1 value is termed $T_{1\text{Null}}$ and can be calculated using Eq. (5):

$$T_{1\text{Null}} = T_1 \times \ln(2). \quad (5)$$

To determine $T_{1\text{Null}}$ for each environment within the ethanol:water binary mixture, the measured T_1 values of 28 ms and 600 ms (taken from Fig. 6) were used. Using Eq. (5), this gave $T_{1\text{Null}}$ values of 19 and 416 ms. Using these values as initial guesses, exploratory T_1 -Suppressed Fast- $T_{1\rho}$ experiments were performed until optimal signal cancellation was obtained for each environment. This gave optimised $T_{1\text{Null}}$ values of 18 and 400 ms respectively. An example of the desired suppression is given in Fig. 7(b) where all datapoints except the initial point (representing signal from the fast-relaxing OH environment) are centred around zero and so no signal from the slow-relaxing CH environment is being recorded.

Using this approach, linearly-spaced $T_{1\rho}$ data for both the OH environment (Fig. 7(c), $T_{1\rho} = (2.4 \pm 0.2)$ ms) and slow relaxing CH

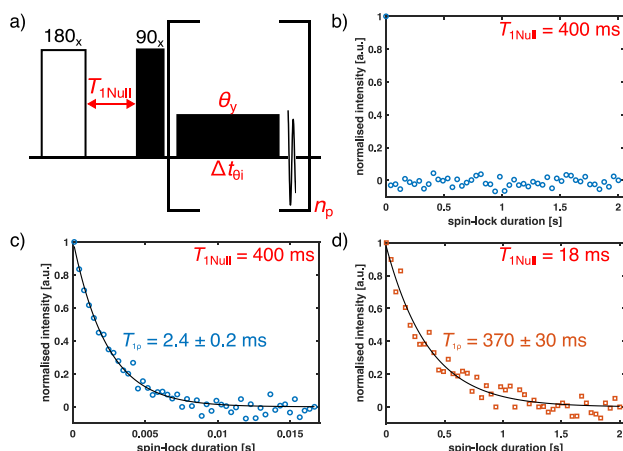


Fig. 7. (a) T_1 -Suppressed Fast- $T_{1\rho}$ pulse sequence alongside relaxation decay curves for a sample of γ - Al_2O_3 imbibed with an ethanol:water mixture (50:50, v/v) using a $T_{1\text{Null}}$ value of (b, c) 400 ms and (d) 18 ms. (b, d) capture $T_{1\rho}$ relaxation over 2 s while (c) captures $T_{1\rho}$ relaxation over 15 ms.

environment (Fig. 7(d), $T_{1\rho} = (370 \pm 30)$ ms) are easily obtained. By individually processing each relaxation environment, as the other is suppressed, all datapoints are dedicated to a single component within the mixture. This also enables a mono-exponential function to be applied, reducing the number of fitting parameters, which overall improves the accuracy of the calculated $T_{1\rho}$ values obtained.

4. Conclusions

In this work, a novel Fast- $T_{1\rho}$ pulse sequence which enables the application of variable spin-lock durations was designed and implemented on a 2 MHz benchtop NMR spectrometer. This technique carries a significant decrease in $T_{1\rho}$ data acquisition times compared to conventional compensated $T_{1\rho}$ experiments, with a theoretical maximum improvement matching the number of $T_{1\rho}$ steps performed within the experiment. This faster acquisition is achieved with a minimal loss of experimental accuracy, with the measured $T_{1\rho}$ of glycerol reducing by only 5.4% between a 100 step Fast- $T_{1\rho}$ and compensated $T_{1\rho}$ experiment. These two features make this approach suitable for processes where dynamic changes or transient species need to be captured and for high-throughput applications.

The key features of this Fast- $T_{1\rho}$ pulse sequence are the implementation of non-linear variable delay spacings between subsequent $T_{1\rho}$ steps and the ability to access down to 100 μs spin-lock durations. These improvements allowed for the simultaneous observation of multiple relaxation environments in a γ - Al_2O_3 sample imbibed with an ethanol:water mixture using both 1D (Fast- $T_{1\rho}$, T_1 -Suppressed Fast- $T_{1\rho}$) and 2D (Fast- T_1 - $T_{1\rho}$) NMR techniques. The ethanolic CH environment gave a $T_{1\rho}$ value of (370 ± 30) ms while the labile OH environment gave a $T_{1\rho}$ value of (2.4 ± 0.2) ms - demonstrating the ability of this technique to effectively capture species with relaxation parameters that are two orders of magnitude apart.

As demonstrated within the presented work, the developed low-field Fast- $T_{1\rho}$ method has clear applicability in the understanding of multi-component systems. Characterisation of the behaviour of species confined within the pore spaces of porous media is essential to understand their behaviour under standard industrial conditions; NMR relaxometry pulse sequences are able to offer unique insights into these optically-opaque systems. Potential fields where Fast- $T_{1\rho}$ could be an invaluable additional method in the relaxometry toolkit include catalysis [48,49], the storage and transport of both liquids [50] and gases [51] and in understanding the mechanisms and long-term implications of CO_2 sequestration [52–54]. There is also scope to further

develop the Fast- $T_{1\rho}$ technique through coupling of the pulse sequence to previously-developed 1D image acquisition approaches [55] thereby enabling spatial resolution for examining heterogeneous systems.

CRediT authorship contribution statement

Alastair D. Robinson: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Jordan A. Ward-Williams:** Resources, Methodology. **Matthias Appel:** Writing – review & editing, Resources, Funding acquisition. **Andrew J. Sederman:** Writing – review & editing, Supervision, Conceptualization. **Mick D. Mantle:** Writing – review & editing, Supervision, Conceptualization. **Lynn F. Gladden:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

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Data availability

Data will be made available on request.

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