Published in final edited form as:
Med Phys. 1990 ; 17(1): 131–134.

Rapid measurement of T1 with spatially selective pre-inversion pulses

Elliot McVeigh, **Andrew Yang**, and **Elias Zerhouni**
Department of Radiology and Radiological Science, Johns Hopkins University School of Medicine, Baltimore, Maryland, 21205

Abstract

A method is described for rapidly obtaining a multipoint estimate of T1 from a sample that is homogeneous over a few millimeters. An image of the longitudinal recovery curve is produced through the application of successive “pre-inversion” slices that are perpendicular to the imaging slice. These pre-inversion pulses are analogous to pre-saturation pulses, but they are much thinner and the tip angle is 180°. The baseline for the recovery is measured from sections of the sample that have not been perturbed by the slice selective pre-inversion pulses. The existence of the baseline value and the lack of slice profile effects allows a quick T1 estimate (QT1) to be made with a simple linear regression algorithm. The QT1 values are found to correlate very well with T1 values measured with the scanner in “spectrometer” mode, for volumes as small as 5 × 5 × 5 mm. Possible applications are T1 estimates in homogeneous samples and tissues, and scouting the T1 range of a tissue to be measured with higher resolution volume localization techniques.

Keywords

magnetic resonance imaging; relaxation times; T1

I. INTRODUCTION

Estimating T1 with a series of inversion-recovery (IR) or saturation-recovery images presents some problems. Repetition rates on the order of 3-5 T1’s are required to measure the recovery curve most efficiently.[1,3] If shorter repetition times are used the baseline estimate becomes poor; this propagates noise into the estimate of T1. Simple linear regression algorithms cannot be used to fit slice selective imaging data because of the variation of tip angle through the slice produced by the interaction of the radio frequency (rf) pulses with the slice selection gradient.[4] Methods have been proposed to measure T1 rapidly using variable nutation angle.[5-7] Here we propose a new method for rapid IR data acquisition.

If the sample is homogeneous over a few millimeters, spatially selective pre-inversion pulses can be applied at different locations with different T1 values. When the resulting magnetization is imaged, the longitudinal recovery curve will be displayed as regions of different intensity. Figure 1 shows an image of a normal tibia with five pre-inversion pulses applied. The lower part of the figure is a profile through the bone marrow showing the magnitude inversion recovery curve mapped out by the five pulses. These intensities can be used with the baseline estimate from the noninverted magnetization to obtain a quick T1 (QT1) estimate with a simple linear regression procedure[8] applied to the data after logarithmic transformation. If it is not necessary to obtain an image, the IR data can be acquired in a “single-shot”, as will be described below.

II. QT1 PULSE SEQUENCE

The pulse sequence used to obtain the QT1 data is shown in Fig. 2. A sequence of slice selective pre-inversion pulses are applied at successive inversion times $TI_{1,2,...N}$, each with different spatial offsets, followed by a single spin-echo pulse sequence in an orthogonal plane. The spatial offsets can be obtained either by changing the transmitter frequency or modulating the amplitude of the carrier. The pre-inversion slices are perpendicular to the imaging plane, therefore an image of the inversion recovery response is produced. Refocussing gradients for the pre-inversion slices are not used because only the longitudinal component of the magnetization is of interest in these slices. The center of the pre-inversion slice can be resolved in the image; if the rf amplitude is adjusted so that the center of the slice has a tip angle of 180° this line can be used for an accurate T1 estimate. This eliminates the need for an algorithm to correct for the distribution of tip angles through the slice.[4]

The pulse sequence shown in Fig. 2 will produce parallel pre-inversion slices. The imaging time will depend on the TR used and the number of phase encoding steps. The orientation of the pre-inversion slices may be adjusted through the relative magnitudes of the gradient pulses. Rectilinear grids or radial patterns may be used if it is more appropriate for the specific sample. An advantage obtained by using the parallel pre-inversion slices with the readout gradient is that very thin pre-inversion slices can be resolved in a short time. In fact, if the 180° refocussing pulse is slice selective in the *y* direction, the T1 estimate can be obtained from a single projection of the selected line after the pre-inversion.[9]

The pulse sequence for this single-shot acquisition is shown in Fig. 3(a). A projection of a selected line of a uniform phantom is shown in Fig. 3(b). In this figure the projection gradient was 1 G/cm, and the 1.5-mm thick pre-inversion pulses spanned only 5 mm of the sample. Because this is a single-shot technique the magnetization is at its equilibrium value before the data is acquired. The majority of the time is spent on locating the volume from which the T1 will be measured from the images in the study.

III. EXPERIMENTAL RESULTS

All measurements were obtained at a field strength of 1.5 using a SIGNA system (GE Medical Systems, Milwaukee). Four solutions of $CuSO_4$ dissolved in distilled water at different concentrations (3, 4, 6, 8 mM) were used as samples to compare the accuracy of the QT1 fit with “spectrometer” T1 values.

A. Measurement of T1 in “spectrometer mode”

The “spectrometer” T1 values were obtained with the SIGNA using inversion recovery sequences without imaging gradients. The whole-body transmitter coil was used to produce the broadband 180° (800μs) and 90° (400μs) rf pulses. The signal was received with a 3-in. circular coil placed around the 15-ml disposable centrifuge tube (Corning Glassware Inc.) sitting vertically at the isocenter of the magnet. The pulses were tuned by adjusting the transmitter attenuation of an 800-μs pulse and reading the free induction decay 1 ms after the pulse. The transmitter attenuation was adjusted to within 0.1 dB to find the zero crossing, indicating a 180° flip angle. The full width of the magnitude spectrum at half-maximum was 20 Hz, indicating that the sample was well within the bandwidth of the rf pulses. The repetition time was set at $\sim$ 10T1; the TI values used were chosen so that the recovery curve was evenly sampled over the entire dynamic range. The receiver attenuation was adjusted to match the dynamic range of the analogue-to-digital converter with the dynamic range of the input signal for each TI value. It was assumed that the magnetization followed a recovery curve given by the following equation:

$$s(\mathrm{TI}) = Mo[1 - (1 - \cos\theta)\exp(-\mathrm{TI}/T1)]. \quad (1)$$

The T1 was estimated from a grid search for a minimum over chi-squared(T1, *Mo*, θ) run on a SUN/4 (Sun Microsystems). For all data, θ had a value between 178.5°-180° at the chi-squared minimum. Figure 4 shows the data from the 4 mM solution with the predicted values from the fit shown as solid points connected with a line. This plot demonstrates the accuracy with which T1 can be measured with the imager in "spectrometer" mode.

B. Measurement of T1 with the QT1 sequence

The QT1 data was obtained from four samples in a single scan. The image is shown in Fig. 5. This figure illustrates the efficiency of the method at measuring T1 in homogeneous samples. The image profile software available on SIGNA was used to measure the intensity of the signal from the center of each pre-inversion slice. The pre-inversion slices had TI times of 25, 125, 225, 325, and 425 ms. The intensities in the image represent the magnitude of the magnetization, therefore, the short TI points appear bright. Data points with intensities close to zero may present a problem when determining their phase. The data obtained in this study did not present this problem.

The QT1 estimate from the data was made using a linear regression of data obtained from the transform:

$$s'(\mathrm{TI}) = \log[1 - s(\mathrm{TI}) / Mo], \tag{2}$$

with baseline, *Mo*, determined from the noninverted part of the sample, and the sign of *s*(TI) determined by minimizing the error in the fit. The slope of the regression line is -1/T1. The advantage of this method is that a T1 estimate can be obtained immediately using a handheld calculator. The correlation of the QT1 values with the "spectrometer" T1 values is shown in Fig. 6. Table I gives the values obtained with each method. The data in this table fits a line with slope 1.05, intercept at - 12.8 and a correlation coefficient of > 0.999.

It is important that the pre-inversion slices do not overlap. For T1 estimates in small volumes this requires high-resolution imaging or projections and thin preinversion slices. In order to test the accuracy of the measurements as a function of the resolution, a series of T1 measurements were obtained from the 4 mH $CuSO_4$ solution in which the pre-inversion slices were made progressively thinner, and closer together. The width of five pre-inversion slices was adjusted between 6 and 1.5 mm, and the separation adjusted between 10 and 2.5 mm. The readout gradient was 1 G/cm, which was large enough to resolve the center of the pre-inversion slices. [Figure 3(b) shows an example using three 1.5-mm pre-inversion slices.] The T1 estimates were constant to within 1.5%.

IV. DISCUSSION

The high degree of correlation between the QT1 values and the "spectrometer" T1 values of the samples shows that the method is accurate. Because the data is obtained over a volume of $\sim$1 cm^3, the application of the technique *in vivo* will be limited to measuring T1 in tissues that have homogeneous volumes of this order. Skeletal muscle, myocardial muscle, fat, liver, spleen, large tumors, and bone marrow are examples of such tissues.

The QT1 estimate will be affected by nonuniform rf tip angles and nonuniform receiver sensitivity over the volume containing the pre-inversion pulses. The receiver sensitivity can be modelled mathematically or measured with a uniform phantom; an algorithm can then be used to remove its effect.[10] The nonuniformity in the tip angles can be kept to a minimum by keeping the spatial extent of the pre-inversion slices small with respect to the size of the transmitter coil. When transmitting with a whole-body quadrature coil, tip angle nonuniformity over the volume containing the pre-inversion-slices was not a problem.

A possible application of the QT1 sequence is to scout the T1 range of a tissue that will be measured with volume localization techniques. For example, if an accurate T1 measurement is desired in bone marrow, a single-shot QT1 estimate can be performed in a volume chosen from the scout images. From the QT1 estimate the sampling protocol for the higher resolution volume localized T1 estimate may be determined. This will help maximize the accuracy of the final volume localized T1 estimate.

V. CONCLUSIONS

A technique has been described for the acquisition of multipoint IR data using slice selective pre-inversion pulses. An image of the IR curve can be made, or the IR data can be obtained in a single shot from a selected line. Using a standard clinical scanner, estimates for T1 can be obtained over volumes as small as $5 \times 5 \times 5$ mm, using a baseline measurement and three data points. The existence of the baseline measurement and the absence of slice selection effects permit the use of a simple linear regression algorithm for the T1 fit.

References

1. Granot J. Optimization of spin-lattice relaxation-time measurements: statistical analysis by stochastic simulation of inversion recovery experiments. J. Magn. Reson 1983;53:386–379.
2. Kurland RJ. Strategies and tactics in NMR imaging relaxation time measurements I. Minimizing relaxation time errors due to image noise-the ideal case. Magn. Reson. Med 1985;2:136–158. [PubMed: 3831683]
3. Crawley AP, Henkelman RM. A comparison of one-shot and recovery methods in T1 imaging. Magn. Reson. Med 1988;7:23–34. [PubMed: 3386519]
4. Rosen BR, Pykett IL, Brady TJ. Spin lattice relaxation time measurements in 2D NMR imaging: corrections for plane selection and pulse sequence. J. Comput. Assist. Tomog 1984;8:195–199.
5. Gupta RK. A new look at the method of variable nutation angle for the measurement of spin-lattice relaxation times using Fourier transform NMR. J. Magn. Reson 1977;25:231–235.
6. Wang HZ, Riederer SJ, Lee JN. Optimizing the precision in T1 relaxation estimation using limited flip angles. Magn. Reson. Med 1987;5:399–416. [PubMed: 3431401]
7. Fram EK, Herfkens RJ, Johnson GA, Glover GH, Karis JP, Shimakawa A, Perkins TG, Pelc NJ. Rapid calculation of T1 using variable flip angle gradient refocused imaging. Magn. Reson. Imag 1987;5:201–208.
8. Bevington, PR. Data Reduction and Error Analysis for the Physical Sciences. McGraw-Hill; New York: 1969. p. 92-118.
9. Maudsley AA. Multiple-line-scanning spin density imaging. J. Magn. Reson 1980;41:112–126.
10. McVeigh ER, Bronskill MJ, Henkelman RM. Phase and sensitivity of receiver coils in magnetic resonance imaging. Med. Phys 1986;13:806–814. [PubMed: 3796476]

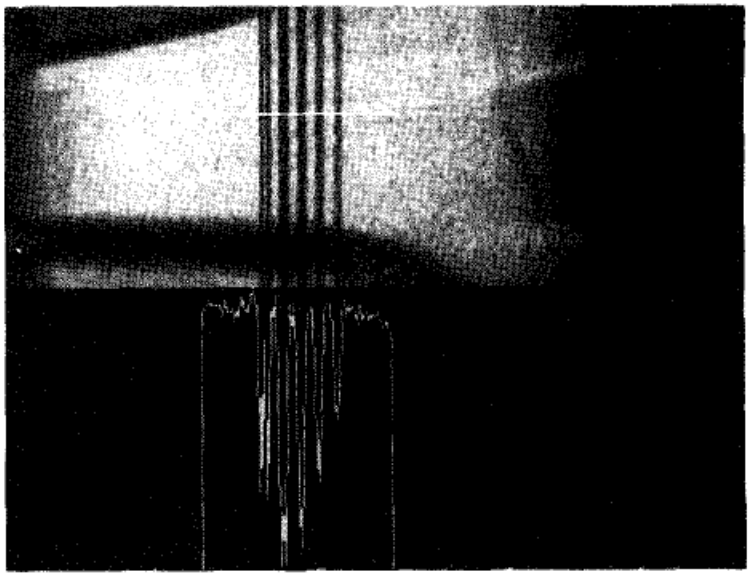

Fig 1.
A coronal image of the tibia of a normal volunteer. The magnitude of the longitudinal recovery curve is obtained by plotting a profile through the pre-inversion regions.

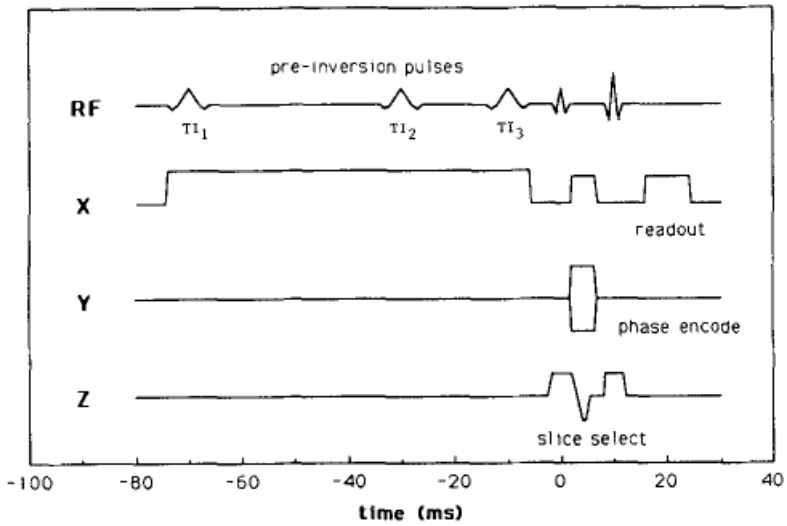

Fig 2.

The pulse sequence used to obtain QT1 data. Slice selective pre-inversion pulses are applied at times TI_i. In this figure three such pulses are applied with the slice selection in the "readout" direction. The orientation of the pre-inversion pulses can be adjusted using the gradient pulses.

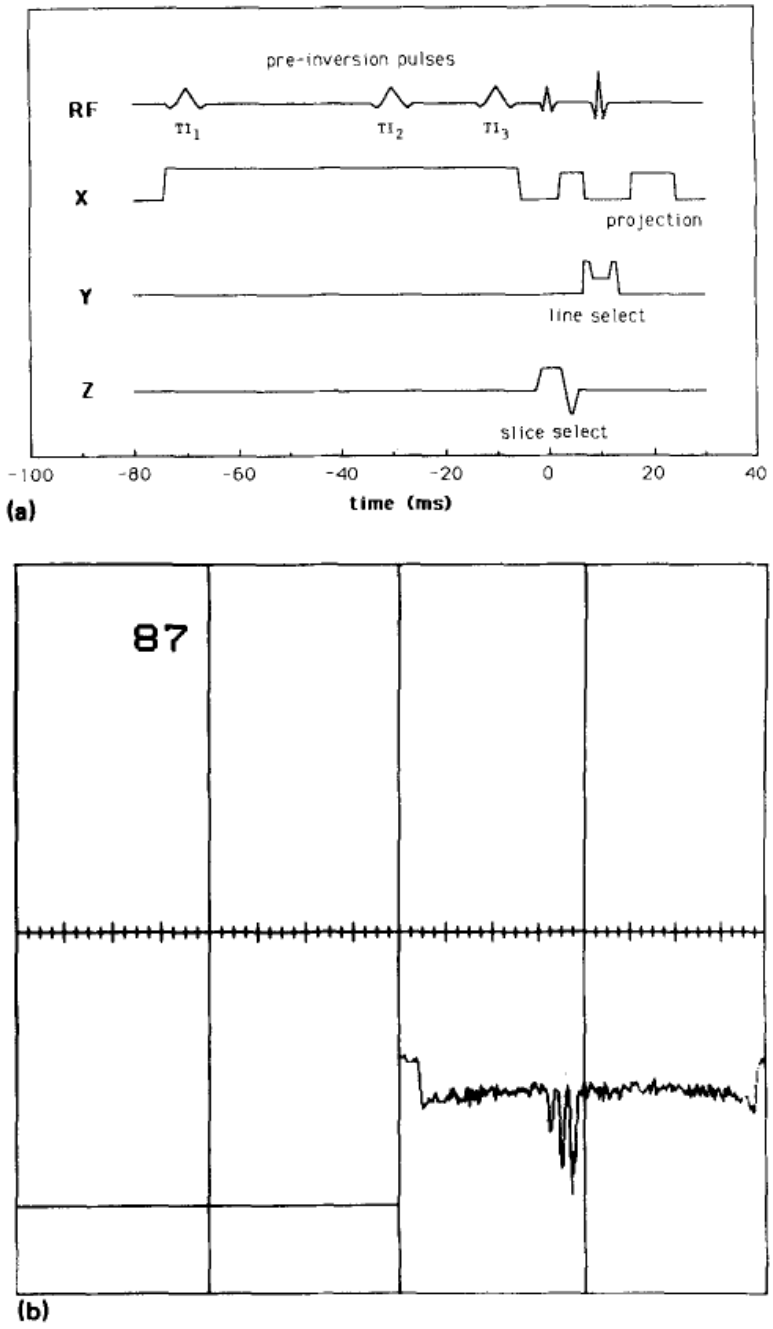

Fig 3.

(a) The pulse sequence for the single-shot acquisition of QT1 data. The phase encoding gradient is now a line selection gradient. (b) A projection of a homogeneous phantom with three pre-inversion pulses applied. The field-of-view is 8 cm (readout gradient of 1 G/cm). The pre-inversion pulses are 1.5 mm wide and separated by 2.5 mm giving a total span of 5 mm.

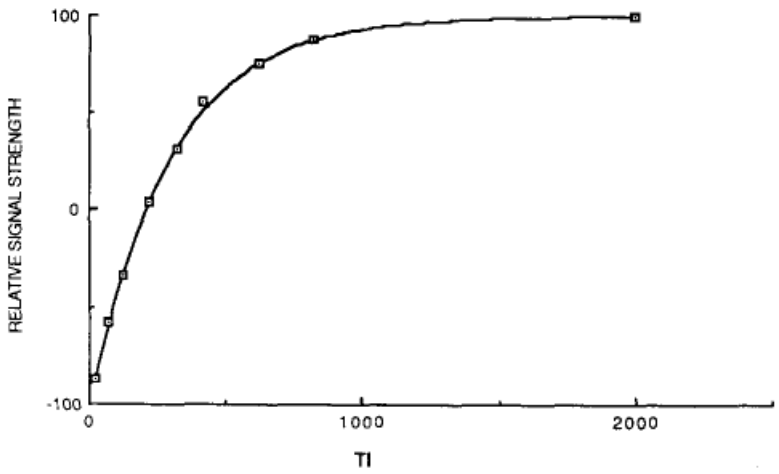

Fig 4.

A plot showing the data used to obtain the "spectrometer" T1 values. The open squares are the data, the line represents the values predicted by the fit.

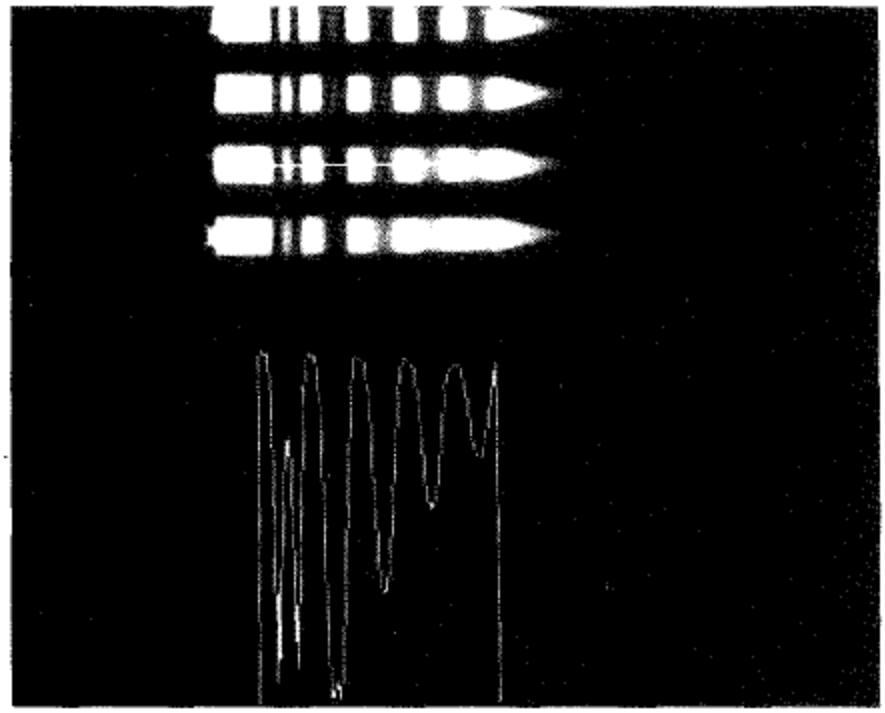

Fig 5.
A QT1 image of four sample tubes with different concentrations of $CuSO_4$. Five parallel pre-inversion slices show the different longitudinal relaxation in each solution.

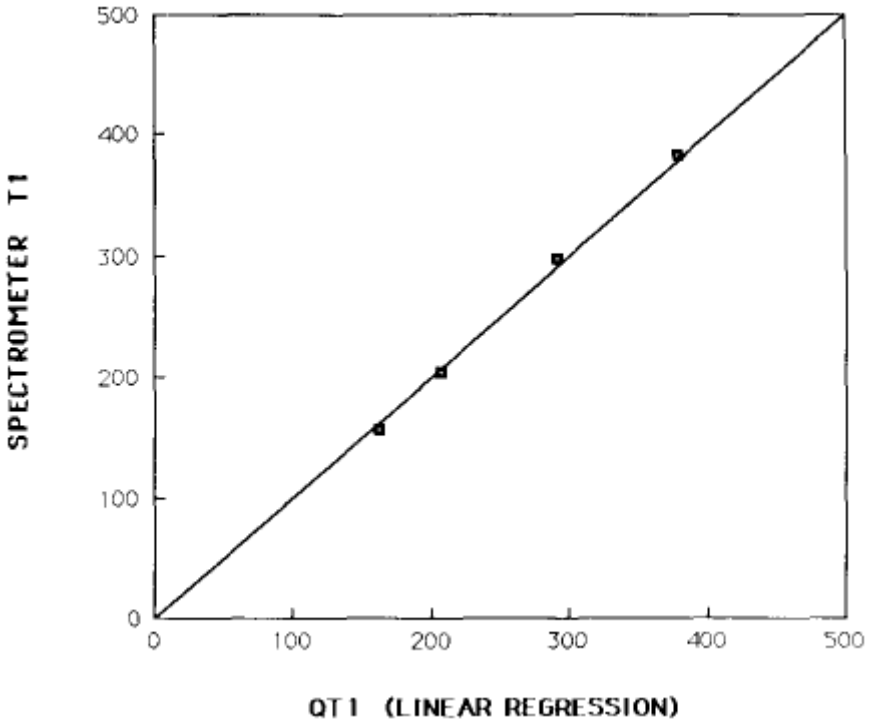

Fig 6.
The "spectrometer" T1 values plotted against the QT1 values calculated from a linear regression with the baseline estimate from the non-pre-inverted part of the sample. The solid line has a slope of 1.0.

Table I

Estimates of T1 for each method. Error estimates in parentheses are from the sigma-squared statistic of a least-square routine (Ref. 8).

($CuSO_4$]	"Spectrometer" T1	QT1 data fit by linear regression
3mM	383 (1)	378 (4)
4mM	297 (1)	291 (3)
6mM	204 (1)	207 (2)
8mM	157 (1)	162 (3)