2.5.2 Project: T_1 and T_2 Estimation on a 3T system using an ADNI phantom

Introduction and Aim

Relaxation times (T_1 and T_2) and proton density provide the three most basic contrast mechanisms in MRI. These parameters are of importance for tissue characterization i.e. differentiating between normal and malignant tissue. Quantification of T_1 & T_2 (relaxometry) allows better understanding of contrast mechanisms so imaging protocols can be optimised to produce efficient discrimination of pathological tissue. Relaxometry also enables objective rather than subjective image interpretation and objective multicentre comparison of results. The accuracy of the tissue T_1 & T_2 measurements depends on factors like temperature and field strength and these have to be taken into account.

This experiment was carried out using a phantom specially designed for MR relaxometry studies. The ADNI (Alzheimer's Disease Neuroimaging Initiative) Magphan phantom contains 165 polycarbonate spheres (with varying diameters ranging from 1 to 6 cm) filled with copper sulphate pentahydrate solution of different concentrations (figure 2.5 (a)) [4]. The 3 cm spheres are coloured red, orange, blue and yellow (figure 2.5(b)). The Physics department at NHNN required accurate estimations of T_1 and T_2 for optimisation of sequence parameters for future studies.

Method

The phantom was placed on its flat surface in the 12 channel Total imaging matrix (Tim) head matrix coil in the Siemens Trio system and rotated around so that the R, L (right and left) and I, S (Inferior and Superior) markings on the phantom are in the correct position with respect to the patient table. Foam padding on either side of the phantom was used to prevent it from moving. Images were acquired with TE 10 ms and TE 500ms (figure 2.6) .TR was kept constant at 3000ms so that the longitudinal magnetisation is fully relaxed.

a) b)

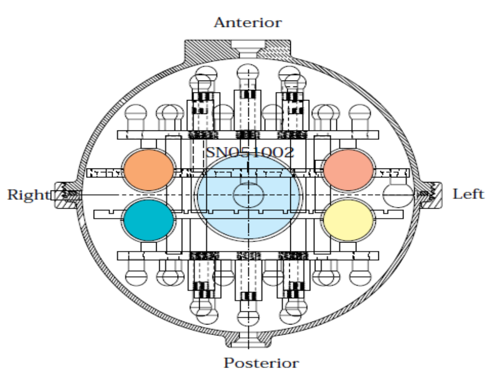


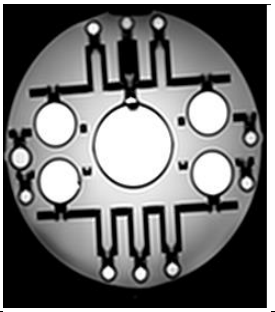
Figure 2.5 a) View of the ADNI Magphan phantom from the inferior side. b) Cross sectional view from the inferior side showing the position of the coloured spheres.

Analysis

<u>T_2 Estimation</u>

a) b)

Figure 2.6 Images acquired with TE 10 ms (a) and TE 500ms (b). TR was kept constant at 3000ms so that the longitudinal magnetisation is fully



Suppose the mean signal intensities ρ_1 and ρ_2 are measured from ROIs in the centre of two slices acquired using different echo times TE_1 and TE_2 respectively (where $TE_2 > TE_1$), then ρ_1 and ρ_2 are related to the proton density ρ_0, transverse relaxation time T_2, longitudinal relaxation time T_1 by the following equations [2,3]

$$\rho_1 = \rho_0 e^{-TE_1/T_2}(1 - e^{-TR/T_1}) \tag{2.10}$$

$$\rho_2 = \rho_0 e^{-TE_2/T_2}(1 - e^{-TR/T_1}) \tag{2.11}$$

Taking the ratio of the two signal measurements above eliminates ρ_0 and the term containing T_1. Rearranging for T_2 gives the following expression which allows direct estimation of T_2.

$$T_2 = \frac{(TE_2 - TE_1)}{\ln\left(\frac{\rho_1}{\rho_2}\right)} \tag{2.12}$$

Alternatively equation 2.10 or 2.11 can be rearranged to give:

$$\ln(p) = \frac{-TE}{T_2} + B \tag{2.13}$$

where the constant B = $\rho_0 \, (e^{-TR/T_1})$, ρ is the mean signal intensity, TE is the echo time and T_2 is the transverse relaxation time. A plot of ln(ρ) vs TE gives a straight line with negative intercept = $-1/T_2$ and allows estimation of T_2 (figure 2.7).

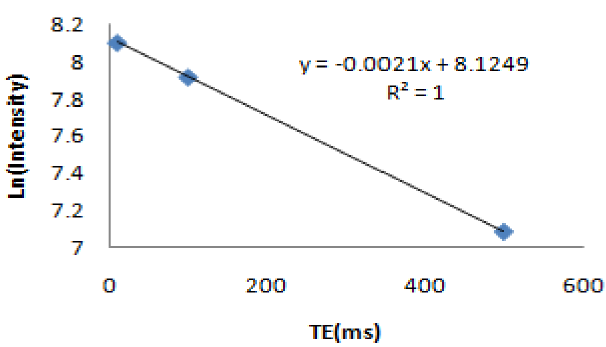


Figure 2.7 Plot of ln (ρ) vs TE for the red sphere giving a gradient ($-1/T_2$) =-0.0021. The T_2 was estimated to be 476 ms

T_1 Estimation: Method 1

a) b) c)

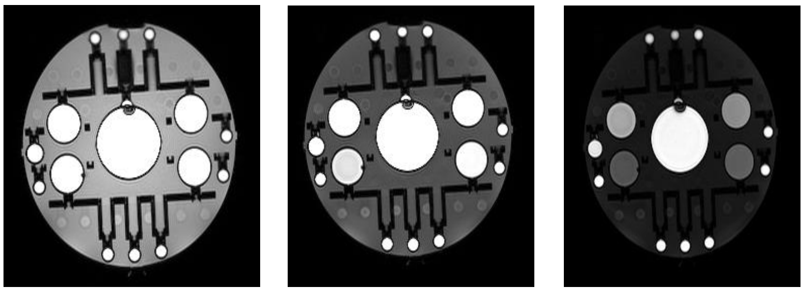


Figure 2.8 Images acquired with a spoiled gradient echo sequence using flip angles a) 10° b) 20° and c) 60° and a very short TR of 20 ms. T_1weighting increases for larger flip angles (normally above 50°).

Images were acquired using a spoiled gradient echo pulse sequence with a short TR and varied flip angles: 10°, 20°, 60° (figure 2.8). The mean signal intensities ρ_{GE} are measured from ROIs placed in the sphere of interest. ρ_{GE} is also given by the following equation [2,3]:

$$\rho_{GE} = \rho_0 \frac{\sin\alpha.\left(1 - e^{-TR/T_1}\right).e^{TE/T_2^*}}{\left(1 - \cos\alpha.e^{-TR/T_1}\right)} \qquad (2.14)$$

This can be rearranged to give:

$$\frac{\rho_{GE}}{sina} = \frac{\rho_{GE}}{tana}.e^{-TR/T_1} + \rho_0\left(1 - e^{-TR/T_1}\right).e^{TE/T_2^*} \qquad (2.15)$$

Plotting (ρ_{GE}/sin α) vs. (ρ_{GE}/tan α) gives a straight line with gradient e^{-TR/T_1} and intercept $\rho_0\left(1 - e^{-TR/T_1}\right).e^{TE/T_2^*}$ (figure 2.9)

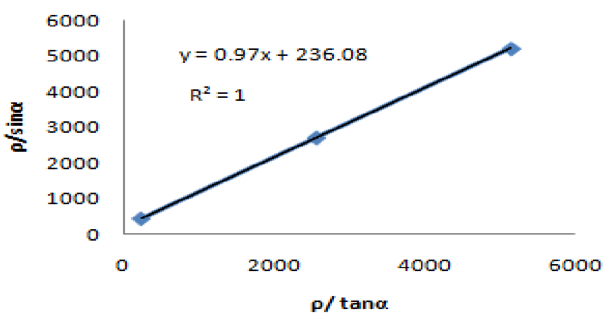


Figure 2.9 Plot of ρ/sinα vs ρ/tanα for the orange sphere. T_1 is estimated from the gradient of the line (0.97) as described in the analysis section

T_1 Estimation: Alternative Method 2

T_1 estimates can also be made using a simple spin echo sequence with different TRs (keeping TE constant). The mean signal intensities ρ_1 and $\rho_2$are measured from ROIs in the two slices acquired using different repetition times TR_1 and TR_2 respectively (where $TR_1 > TR_2$ and TR_1 is at least $5T_1$), then ρ_1 and ρ_2 are related to the proton density ρ_0, transverse relaxation time T_2, longitudinal relaxation time T_1 by the following equations [3]:

$$\rho_1 = \rho_0(1 - e^{-TR_1/T_1})e^{-TE/T_2} \quad (2.16)$$

$$\rho_2 = \rho_0(1 - e^{-TR_2/T_1})e^{-TE/T_2} \quad (2.17)$$

Taking the ratio R, of ρ_1 and ρ_2 eliminates ρ_0 and the exponential term containing T_2

$$R = \frac{1 - exp\left(-TR_1/T_1\right)}{1 - exp\left(-TR_2/T_1\right)} \quad (2.18)$$

Equation 2.18 needs to be solved analytically to obtain a solution for T_1. Alternatively, the data points can be plotted on a graph of intensity vs. TR and equation 2.19 can be used to fit the data points using a least squares curve fitting optimisation technique in MATLAB and extract the T_1 values.

$$\rho = \rho_0(1 - e^{-TR/T_1})e^{-TE/T_2} \quad (2.19)$$

where ρ is a vector of intensities , TR is a vector of repetition times and the other symbols have their usual meanings as in equations 2.10 and 2.11. I have used this method for estimating T_1 of a MagNET oil phantom in section 2.5.3

Results and Conclusion

Table 2.1 Estimated T_1 and T_2 values at 3T and the target T_1 value at 1.5 T (as specified in the instruction manual for the phantom) for the four coloured spheres. The % increase in T_1 with doubling field strength from 1.5 T to 3T is also displayed.

Sphere	Diameter (cm)	Grams/litre of copper sulphate mixture	Estimated T_2 at 3T (ms)	Estimated T_1 at 3T (ms)	Target T_1 at 1.5T (ms)	Increase in T_1 from 1.5 to 3T (%)
Bluish Green	3	0.220	769	1685	900	87.2
Yellow	3	0.295	667	1389	750	85.2
Red	3	0.430	476	806	600	34.3
Orange	3	0.590	385	656	450	45.8

Table 2.1 shows the estimated T_1 and T_2 values for the coloured spheres at 3 T. The T_1 is typically several times longer than T_2. There is an increase in the estimated T_1 at 3 T compared to the target T_1 value at 1.5 T specified in the specification manual. The first obvious reason for this is the doubling of field strength from 1.5 T to 3 T. At the 'Siemens

3 T Clinical Study Day' held in Kidderminster in 2011, there were talks about an increase in T_1 of 25% to 50% in tissue when field strength is increased from 1.5 to 3 T [5]. However in phantoms, this variation will be much larger as seen in the table 2.1. The second reason for this difference in estimated and target T_1 is the possibility of the concentration of the copper sulphate and water solution being slightly different (or changed) from the time the values in the specification manual were formulated in early 2010 (this is approximately a year before I had carried out the experiment). The third reason may be the difference in room temperature at which my measurements and the measurements in the factory were carried out. The temperature was cooler than normal room temperature (17.4 $\pm$ 2 ° C) and did not change markedly during the experiment.

2.5.3 T_1 and T_2 estimation for 1.5T and 3T systems using a MagNET oil phantom

The MagNET oil phantom is used for measuring signal to noise ratio as part of the quality assurance tests on MRI systems at UCLH (described in more detail in section 7.1). To aid my understanding of relaxometry and the effect of field strength on T_1 and T_2, I carried out T_1 and T_2 estimation using this phantom for three MRI systems at UCLH: Siemens Avanto 1.5 T, Siemens Espree 1.5 T and Siemens Trio 3 T systems.

The phantom was placed in the centre of a 12 channel (Tim) head matrix coil and scanned at the magnet isocentre on all three systems using a spin echo sequence. For T_1 estimation, axial images were acquired with four different TRs (50,200,750,1500ms) at 1.5T and five TRs (50, 200, 750, 1500, 3000ms) at 3T. For both field strengths the same TE (5.9ms) was used. The maximum TR for both field strengths was chosen so that it was 5 times the predicted T_1. For T_2 estimation, axial images were acquired for two different TEs (6 and 250 ms) with a constant TR (1000ms). Here the two echo times were chosen so that the expected T_2 was in between these two values. T_2 estimation was carried out using the method described in section 2.5.2. T_1 estimation was carried out by plotting a graph of intensity vs. TR and using equation 2.19 to fit the data points using a least squares fit in MATLAB to extract the T_1 component (code in appendix B2).

The T_1 and T_2 values estimated for both 1.5 T systems were in close agreement with each other and were in the range of 175 ± 1 and $66\pm$ 1 ms respectively. T_1 and T_2 at 3T were estimated to be 300 and 76 ms respectively. The graphs in figure 2.10 show the variation of the signal intensity with TR for the 1.5 T Avanto and 3 T Trio system. At a TR of 1000 ms used for T_2 estimation, M_z has reached equilibrium at 1.5T whilst it may not be fully relaxed at 3T. Hence a correction needs to be applied to correct for T_1 effects, when calculating the normalised signal to noise ratio (section 7.1) at 3T. As a rule of thumb, TR must be at least 5 times T_1 for M_z to be fully recovered. Here the correction for T_1 effects was of the order of 3%.

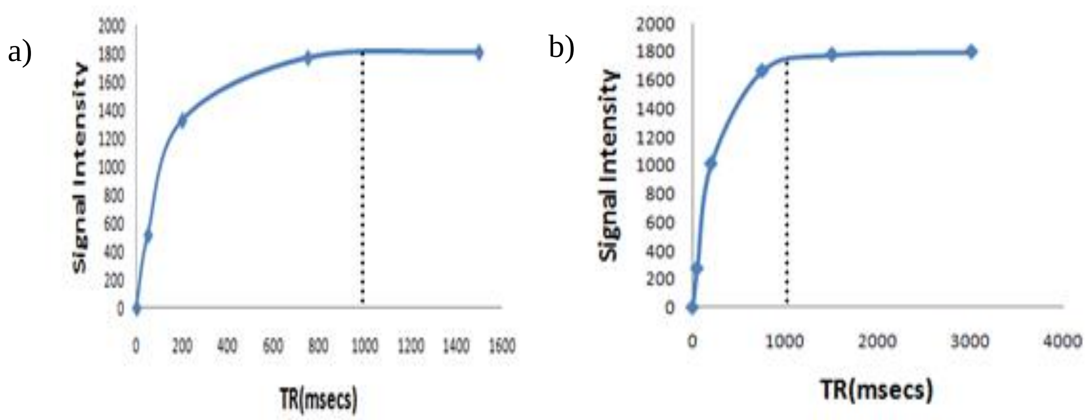


Figure 2.10
Plots of signal intensity vs. TR for the 1.5 T Avanto system (a) and 3T Trio system (b). At a TR of 1000ms (dotted line), Mz has reached equilibrium on the 1.5T system whilst it is just about relaxed at 3T. The T_1 was estimated in MATLAB by using a 'least squares' fit to these data points and extracting the T_1 value.

The obvious increase in T_1 with higher field strength can be explained by the fact that T_1 relaxation is dominated by the presence and number of water molecules tumbling at the Larmor frequency and its integer multiples, and is hence field dependent [1]. T_2 is largely independent of field strength in tissue [6]. Here, a slight increase in T_2 with field strength was noted.