Nuclear diagnostics and Magnetic Resonance Imaging

Lecture 9: Magnetic Resonance Imaging: measurement of T_1 and T_2

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Outline

1. **Calculation from lecture 8**
   - Result of calculation from lecture 8
2. **Measurement of spin-lattice and spin-spin time constants**
   - Introduction
   - Spin-lattice relaxation time, T_1
   - Spin-spin relaxation time, T_2
   - T_1: inversion recovery pulse sequence
   - Example
3. Lecture summary

Section 1

Calculation from lecture 8

Example: calculating the duration of a 90° pulse

The magnitude of B_1 is $10\,\mu$T (i.e. 10^{-5} T)

At what rate with the **M** rotate away from the $\mathbf{B}_0$ axis?

It will rotate at the Larmor frequency, ω_1 arising from the field B_1, i.e. $\omega_1 = \gamma B_1$

- For ^{1}H, $\gamma = 267.513\,\mathrm{rad\,MHz\,T^{-1}}$
- So, $\omega_1 = 267.513 \times 10^6 \times 10 \times 10^{-6} = 2.675\,\mathrm{rad\,kHz}$

How long will it take for the flip angle to reach 90°?

The angle can be obtained by solving the equation: $\frac{\pi}{2} = \gamma B_1 t_P^{90^\circ}$ for $t_P^{90^\circ}$

- Solving for $t_P^{90^\circ}$: $t_P^{90^\circ} = \frac{\pi}{2}\frac{1}{\gamma B_1}$
- So $t_P^{90^\circ} = \frac{\pi}{2} \times \frac{10^{-3}}{2.675} = 587\,\mu$s

Section 2

Measurement of spin-lattice and spin-spin time constants

What does it take to make an MRI image

NMR can be used to generate signals that depend on the concentration of ^{1}H in tissue; the basis of an imaging technique

The spin-lattice and spin-spin relaxation times, T_1 and T_2 respectively, depend on tissue type—so can be used to distinguish neighbouring tissues

To generate an image need to:

- Extract T_1 and T_2; and
- Spatially localise the signal

This lecture: extraction of T_1 and T_2 using RF pulse sequences
Next lecture: spatial localisation

Relaxation times revisited

Tissue Type	T1 (ms)	T2 (ms)
Adipose tissues	240-250	60-80
Whole blood (deoxygenated)	1350	50
Whole blood (oxygenated)	1350	200
Cerebrospinal fluid (similar to pure water)	4200 - 4500	2100-2300
Gray matter of cerebrum	920	100
White matter of cerebrum	780	90
Liver	490	40
Kidneys	650	60-75
Muscles	860-900	50

Relaxation times characteristic of tissue type

For materials important for human imaging $T_1 > T_2$

T_1 characteristic of recovery of longitudinal magnetisation

T_2 must be extracted from the decay of the transverse magnetisation which is characterised by T_2^* which is related to T_2 by:

$$\frac{1}{T_2^*} = \frac{1}{T_2} + \frac{1}{T_2'}$$

The spin-lattice relaxation time constant, T_1

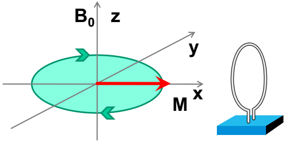
System set up in equilibrium; net magnetisation, $\mathbf{M}_{\rm eqm}$, parallel to $\mathbf{B}_0$ and of magnitude $M_{\rm eqm}$

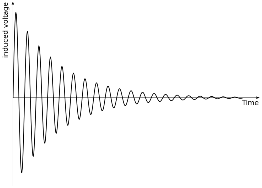
90° RF magnetic field pulse applied to rotate net magnetisation, $\mathbf{M}_{\rm eqm}$, into x, y plane

Take $t = 0$ to be time at which 90° degree pulse ends. Magnitude of transverse magnetisation, M_{xy}, at $t = 0$:

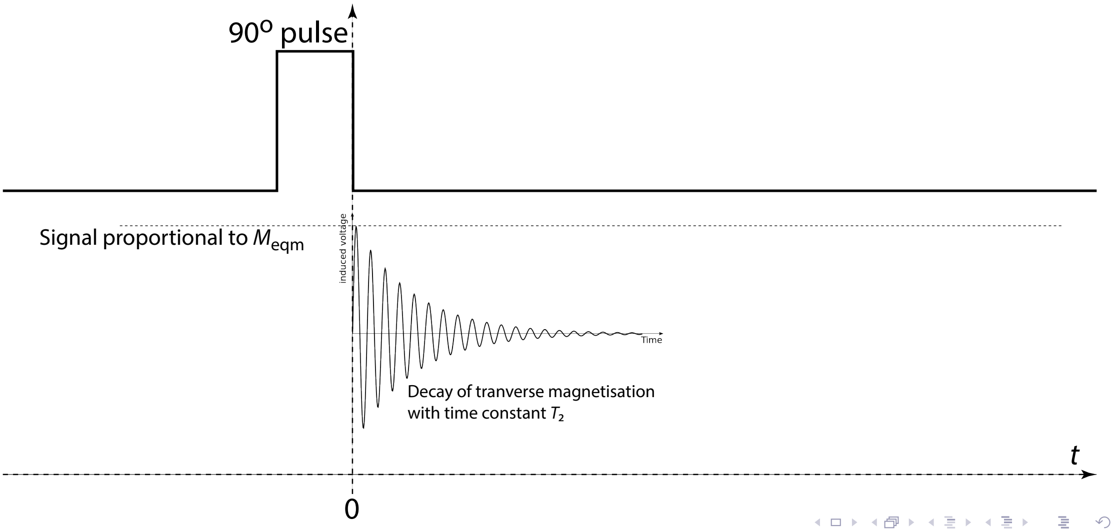
$$M_{xy}(t = 0) = M_{xy}(0) = M_{\rm eqm}$$

M_{xy} decays exponentially, as described in lecture 8





The spin-lattice relaxation time constant, T_1



The spin-lattice relaxation time constant, T_1

Longitudinal magnetisation recovers according to:

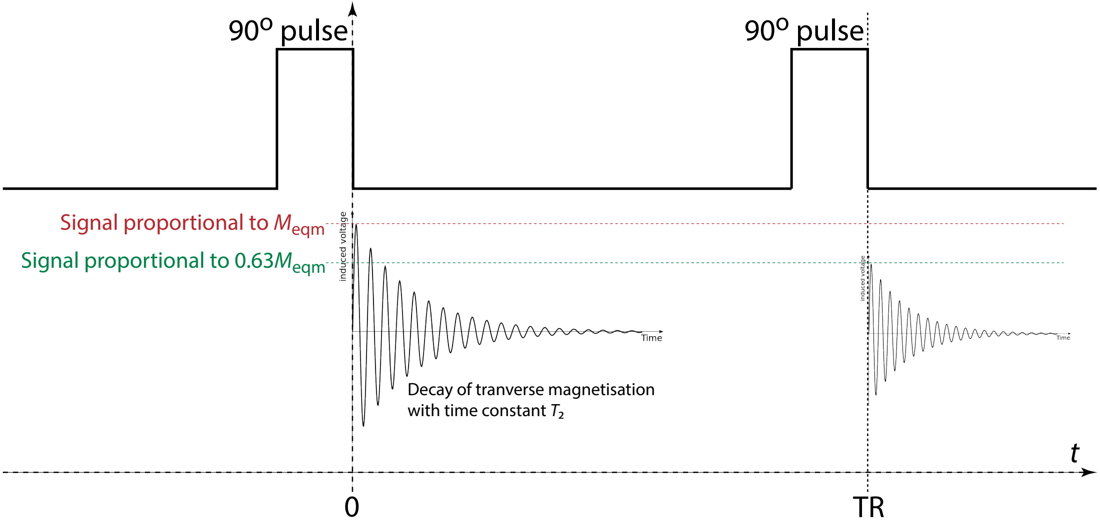
$$M_z(t) = M_{\rm eqm}\left[1 - \exp\left(-\frac{t}{T_1}\right)\right]$$

So, for $t \gtrsim 5\,T_1$, $M_z - M_{\rm eqm} \lesssim 0.5\%$, i.e. longitudinal magnetisation has recovered

If a second 90° pulse is applied for $t < 5\,T_1$ then the resulting M_{xy} will be less than $M_{\rm eqm}$

For example, if the second 90° pulse is applied at $t = T_1$, then $M_{xy}(t = T_1) = 0.63 M_{\rm eqm}$

The spin-lattice relaxation time constant, T_1



The spin-lattice relaxation time constant, T_1

Longitudinal magnetisation recovers according to:

$$M_z(t) = M_{\mathrm{eqm}} \left[1 - \exp\left(-\frac{t}{T_1} \right) \right]$$

So, for $t \gtrsim 5T_1$, $M_z - M_{\mathrm{eqm}} \lesssim 0.3\%$, i.e. longitudinal magnetisation has recovered

If a second 90° pulse is applied for $t < 5T_1$ then the resulting M_{xy} will be less than M_{eqm}

In general:

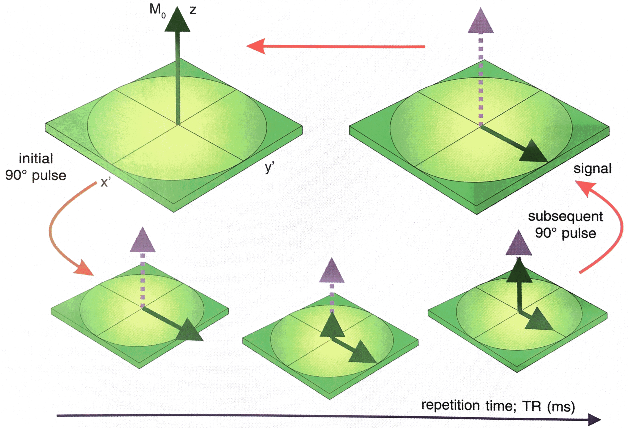
$$M_z(\mathrm{TR}) = M_{\mathrm{eqm}} \left[1 - \exp\left(-\frac{\mathrm{TR}}{T_1} \right) \right]$$

So, repetition of 90° pulse at $t = \mathrm{TR}$ gives $M_{xy}(\mathrm{TR}) = M_z(\mathrm{TR})$

Can extract T_1 by measuring $M_{xy}(\mathrm{TR})$ as a function of TR

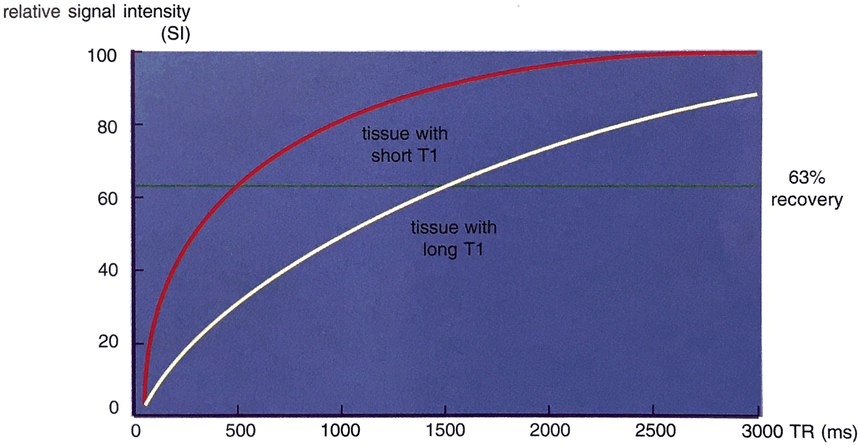
The spin-lattice relaxation time constant, T_1

"**Partial saturation pulse sequence**", graphical representation of evolution of magnetisation

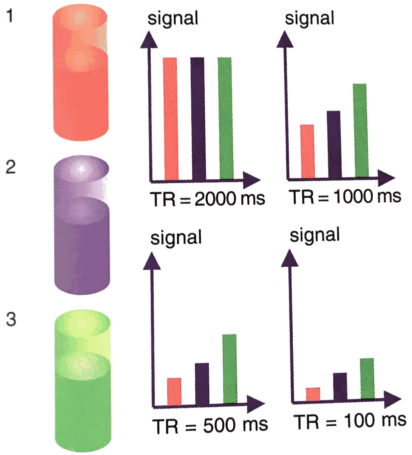


The spin-lattice relaxation time constant, T_1

Comparison of relative signal intensity in partial saturation sequence for two different tissues



The spin-lattice relaxation time constant, T_1

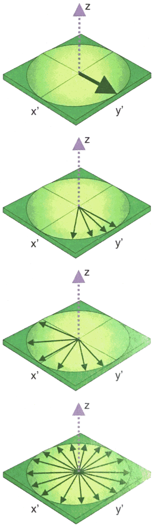


Example three types of tissue:

1. Blood: $T_1 = 1350\,\text{ms}$
2. Muscle: $T_1 = 875\,\text{ms}$
3. Fat: $T_1 = 230\,\text{ms}$

Note how tissues can be distinguished by comparing signal behaviour as a function of TR

Spin-spin relaxation time, T_2



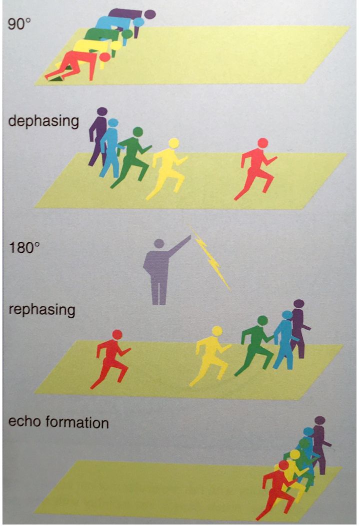
System set up in equilibrium; net magnetisation, $\mathbf{M}_{\rm eqm}$, parallel to $\mathbf{B}_0$ and of magnitude $M_{\rm eqm}$

90° RF magnetic field pulse applied to rotate net magnetisation, $\mathbf{M}_{\rm eqm}$, into x, y plane

Take $t = 0$ to be time at which 90° degree pulse ends. At this instant net magnetisation begins to precess around $\mathbf{B}_0$

Rate of precession of individual ^{1}H nuclei depends on local magnetic environment: some precess faster, some slower. Results in decoherence, time constant T_2^* (see lecture 8)

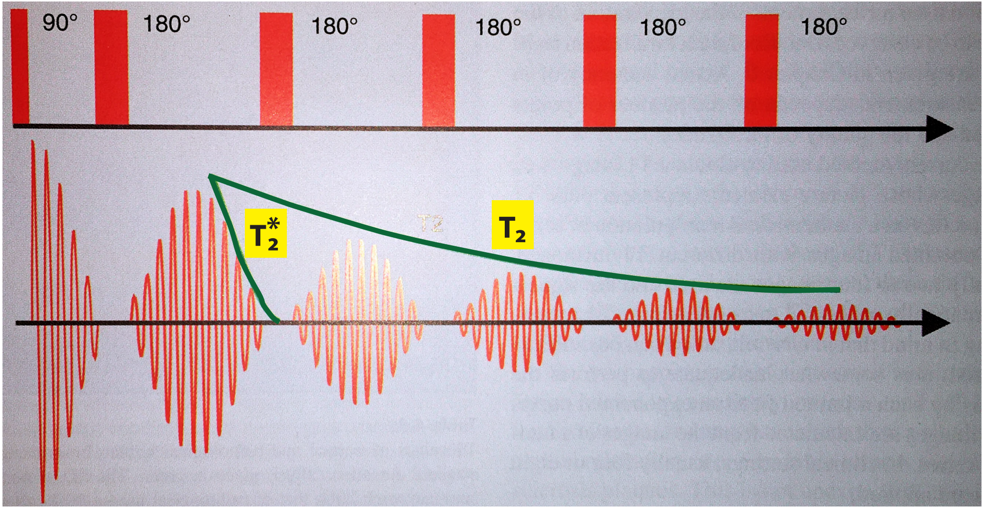
Spin-spin relaxation time, T_2



Before "doing the spins", an analogy:

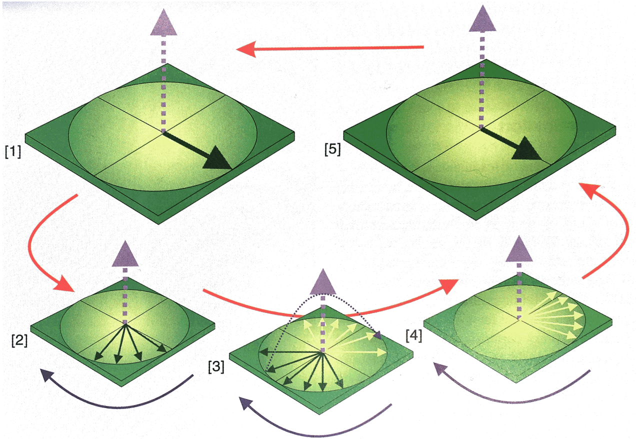
- A set of sprinters have been prepared at the starting line
- The "starting gun" is the end of the 90° pulse
- The sprinters run for a period of time, t_{run}
- At t_{run} the sprinters' phase is rotated by 180°:
  The first becomes the last, etc.
- After a further t_{run} all sprinters are back in line
- The line of sprinters at $t = 2t_{\mathrm{run}}$ is an "echo" of the situation at $t = 0$

Spin-spin relaxation time, T_2



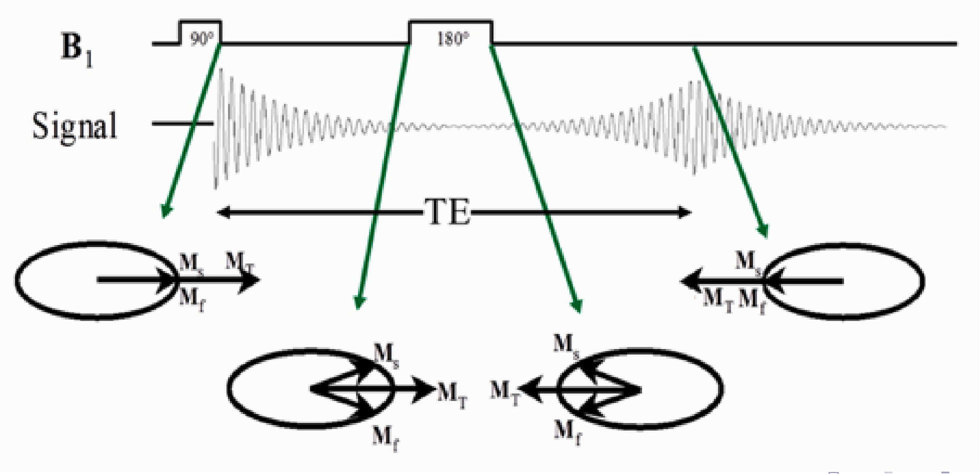
The spin-spin relaxation time constant, T_2

"**Spin echo sequence**", graphical representation of evolution of magnetisation

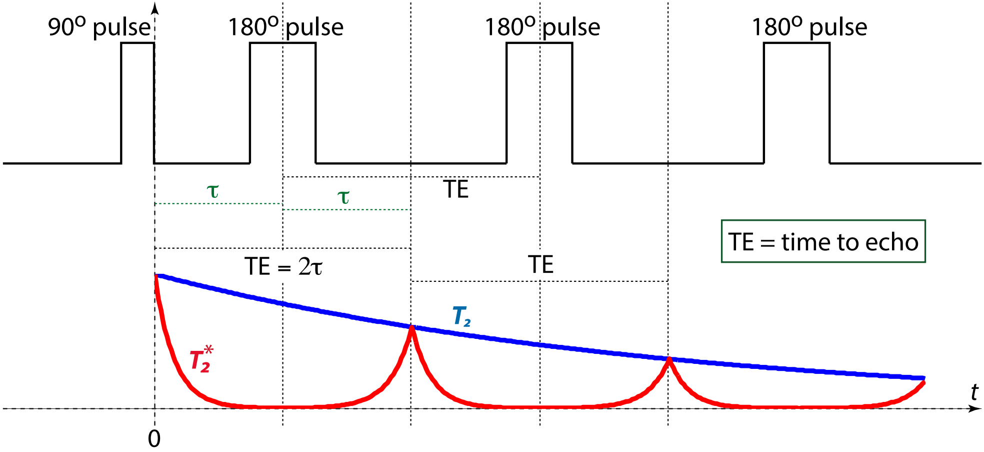


The spin-spin relaxation time constant, T_2

"**Spin echo sequence**", graphical representation of evolution of magnetisation



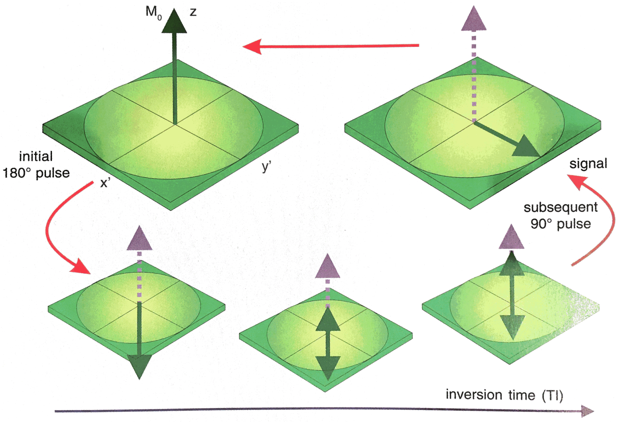
Spin-spin relaxation time, T_2



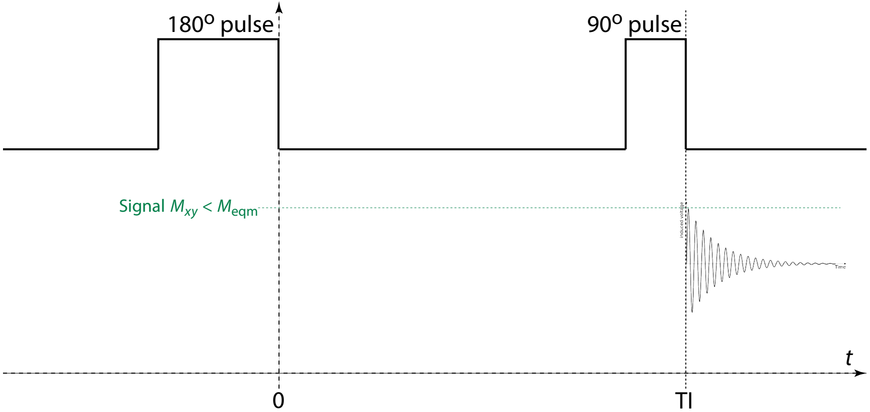
$$M_{xy}(\mathrm{TE}) = M_{\mathrm{eqm}} \exp\left(-\frac{\mathrm{TE}}{T_2}\right)$$

Inversion recovery pulse sequence: T_1

"**Inversion recovery pulse sequence**", graphical representation of evolution of magnetisation



Inversion recovery pulse sequence: T_1



$$M_z(\mathrm{TI}) = M_{\mathrm{eqm}}\left[1 - 2\exp\left(-\frac{\mathrm{TI}}{T_1}\right)\right]$$

Example

You are required to optimise the contrast between CSF and grey matter.

For CSF: $T_1 = 2350\,\text{ms}$ and $T_2 = 180\,\text{ms}$
For grey matter: $T_1 = 900\,\text{ms}$ and $T_2 = 126\,\text{ms}$

Sketch the relaxation curves for the two tissues as a function of TR and TE.

To optimise the contrast find the TR and TE values that maximise the difference between the relaxation curves. This can be done by differentiating and solving for TR or TE when the derivative is 0.

Would you choose "T_1" contrast or "T_2" contrast to maximise the contrast between CSF and grey matter?

Section 3

Lecture summary

Summary

Block equation taking into account effective spin-spin relaxation time, T_2^*:

$$\frac{d\mathbf{M}}{dt} = \gamma\left(\mathbf{M} \times \mathbf{B}_0\right) - \frac{\mathbf{M}_{xy}}{T_2^*} + \frac{M_0 - M_z}{T_1}\hat{\mathbf{k}}$$

Partial saturation pulse sequence: series of 90° pulses separated by TR:

$$M_z(\mathrm{TR}) = M_{\mathrm{eqm}}\left[1 - \exp\left(-\frac{\mathrm{TR}}{T_1}\right)\right]$$

Inversion recovery pulse sequence: 180° pulse followed at $t = \mathrm{TI}$ by a 90° pulse. Sequence repeats after $t > 5\,T_1$:

$$M_z(\mathrm{TI}) = M_{\mathrm{eqm}}\left[1 - 2\exp\left(-\frac{\mathrm{TI}}{T_1}\right)\right]$$

Summary

Spin-echo pulse sequence: 90° pulse followed by series of 180° pulses separated by TE:

$$M_{xy}(\mathrm{TE}) = M_{\mathrm{eqm}} \exp\left(-\frac{\mathrm{TE}}{T_2}\right)$$