

Physics of Medical Imaging and Radiotherapy

Magnetic Resonance Imaging

Lecture 1; Section 4: Free induction decay

K. Long (k.long@imperial.ac.uk)

Department of Physics, Imperial College London/STFC

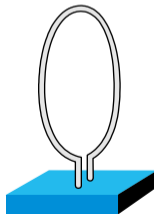
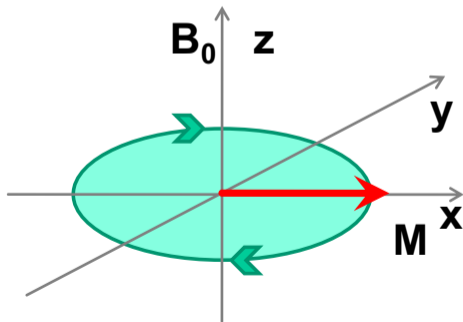
Section 4

Free induction decay

Detection of signal precession of magnetisation vector

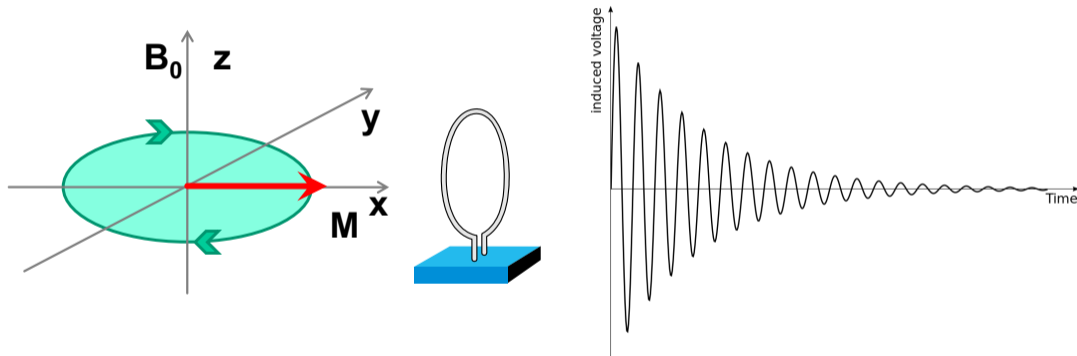
\mathbf{M} rotated using B_1 RF pulse. If flip angle α is not a multiple of 180° , then, result of B_1 pulse is a component of magnetisation in the x, y plane that is precessing

This yields an RF wave that can be detected



Free induction decay (FID)

Occurs when perturbing field (B_1) is turned off



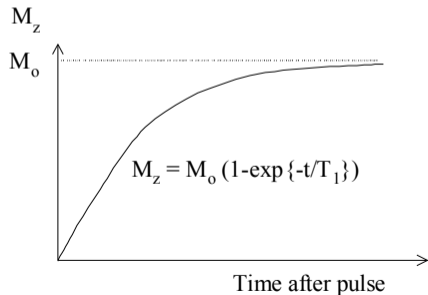
Note; exponential decay of amplitude of transverse magnetisation. Frequency of rotation remains the Larmor frequency corresponding to B_0

Spin-lattice (longitudinal) relaxation

When the B_1 pulse is turned off, the longitudinal magnetisation, M_z , recovers:

$$\frac{dM_z}{dt} = \frac{M_0 - M_z}{T_1} \quad \Rightarrow \quad M_z(t) = M_0 \left[1 - \exp\left(-\frac{t}{T_1}\right) \right]$$

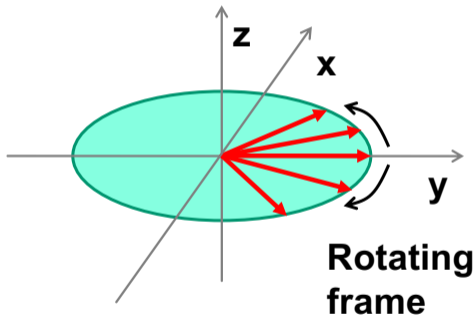
The process is characterised by a time constant T_1



Spin-lattice relaxation:

- ^1H spins relax to the low-energy state. Energy released returns to the "lattice" as heat
- Relatively ineffective thermal coupling to ^1H nuclei results in T_1 being large, typically $T_1 > 200$ ms

Spin-spin (transverse) relaxation



Contributions to M_{xy} smear out (decohere) rapidly

Causes M_{xy} to decay quickly

Some factors that affect the decoherence rate:

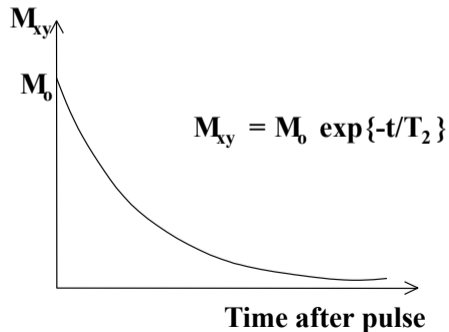
- Resonance frequency changes due to local magnetic fields
- Thermal excitations
- Spin “mobility”
- Presence of large molecules or paramagnetic ions or molecules, outside interference

Spin-spin (transverse) relaxation

When the B_1 pulse is turned off, transverse magnetisation, decays:

$$\frac{dM_{xy}}{dt} = -\frac{M_{xy}}{T_2} \quad \Rightarrow \quad M_{xy}(t) = M_0 \exp\left(-\frac{t}{T_2}\right)$$

The process is characterised by a time constant T_2



Spin-spin relaxation:

- ^1H spins interact magnetically with their neighbours
- Coupling causes a variety of magnetic fields, causing a variety of precessions
- Effective randomisation of precessional modes leads to efficient depolarisation in transverse plane
- Results in T_2 being comparatively small, typically $T_2 \lesssim 100$ ms

Relaxation times for a variety of tissues

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
 $T_1 > T_2$

Bloch equation revisited

Bloch equation may now be updated to include FID:

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

where:

- The first term describes the torque produced by the main (solenoid) field \mathbf{B}_0
- The second term describes the evolution of the transverse magnetisation vector \mathbf{M}_{xy} due to the spin-spin interaction; time constant T_2
- The third term describes the evolution of the longitudinal magnetisation M_z due to the spin-lattice interaction; time constant T_1
- M_0 is the net magnetisation at equilibrium aligned with and proportional to \mathbf{B}_0

Complication: additional factors affecting the decay of the transverse magnetisation

T_2 , the intrinsic spin-spin relaxation time is determined by non-reversible thermodynamic processes at the nuclear level.

The spin-spin relaxation time constant is reduced by a number of factors. A significant contribution comes from inhomogeneities in the main field \mathbf{B}_0

Inhomogeneities give rise to reversible thermodynamic processes. The associated relaxation of the transverse magnetisation is characterised by a time constant T_2'

The effective spin-spin relaxation time constant, T_2^* is given by:

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

$T_2' < T_2$ and so $T_2^* < T_2$. Need to develop techniques to recover T_2 as this carries the clinically-relevant information

Comparison of T_2 and T_2'

T_2

- The individual dipoles that sum up to produce the transverse magnetization are not precessing at precisely the same rate
- As a water molecule tumbles due to thermal motions, each H nucleus feels a small, randomly varying magnetic field in addition to B_0
- When the random field adds to B_0 , the dipole precesses a little faster, and when it subtracts from B_0 , it precesses a little slower
- For each nucleus the pattern of random fields is different, so as time goes on the dipoles get progressively more out of phase with one another, and as a result no longer add coherently

T_2'

- The source of this T_2' effect is magnetic field inhomogeneity
- Because the precession frequency of the local transverse magnetization is proportional to the local magnetic field, any field inhomogeneity will lead to a range of precession rates
- Over time the precessing magnetization vectors will get out of phase with one another so that they no longer add coherently to form the net magnetization
- As a result, the net signal is reduced because of this destructive interference
- Static field offsets rather than fluctuating fields

Summary of section 4

Rotated net-magnetisation vector relaxes back to equilibrium orientation with time constant, T_1 ; spin-lattice relaxation time constant

Projection of net magnetisation vector in x, y plane decays away with time constant, T_2 ; spin-spin relaxation time constant

The effective spin-spin time constant, T_2^* , is a combination of the intrinsic spin-spin relaxation time constant (T_2) and the effect of “instrumental” effects such as inhomogeneities in the applied magnetic field (T_2')