Magnetic Resonance Imaging
Week 4; Lecture 8; Section 3: Free induction decay

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Section 3

Free induction decay

Detection of signal precession of magnetisation vector

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
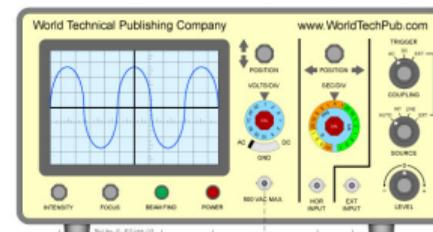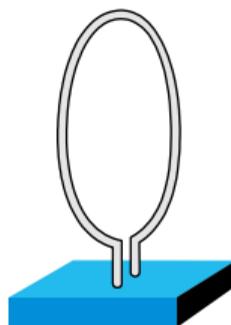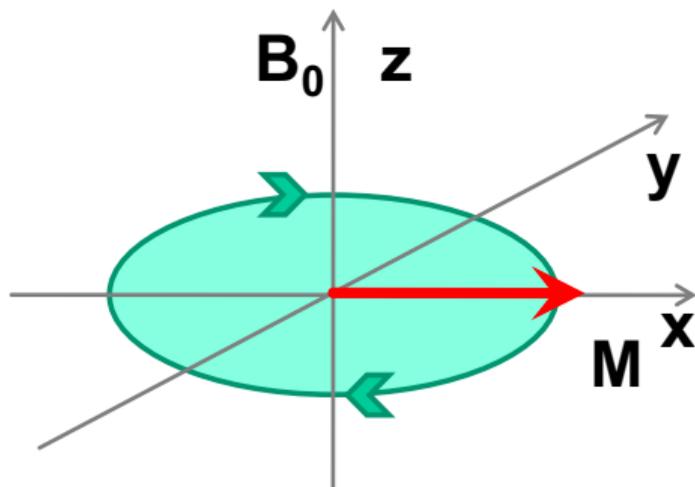
Free induction decay (FID)

Occurs when perturbing field (B_1) is turned off
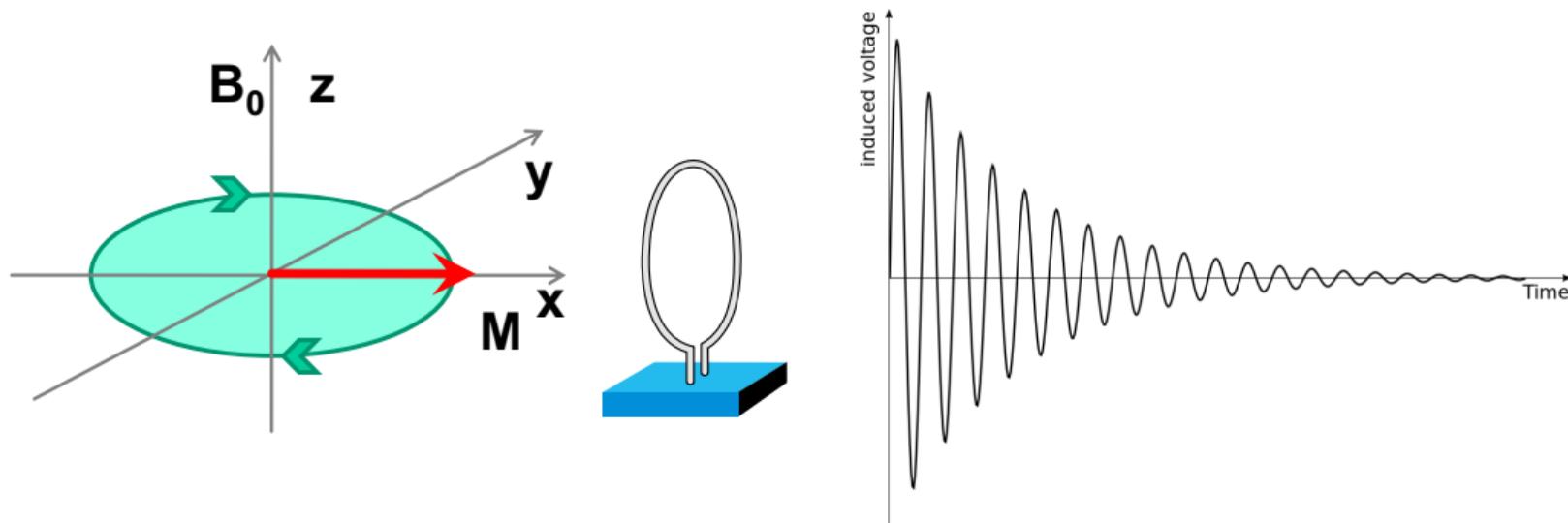
Note; exponential decay of amplitude of transverse magnetisation. Frequency of rotation remains the Larmor frequency corresponding to B_0

Spin-lattice (longitudinal) relaxation

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

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

The process is characterised by a time constant T_1

$M_z = M_0 (1 - \exp\{-t/T_1\})$
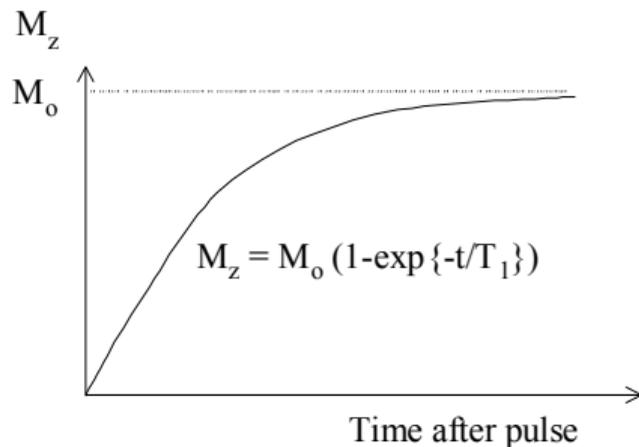
Spin-lattice relaxation:

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

Spin-spin (transverse) relaxation

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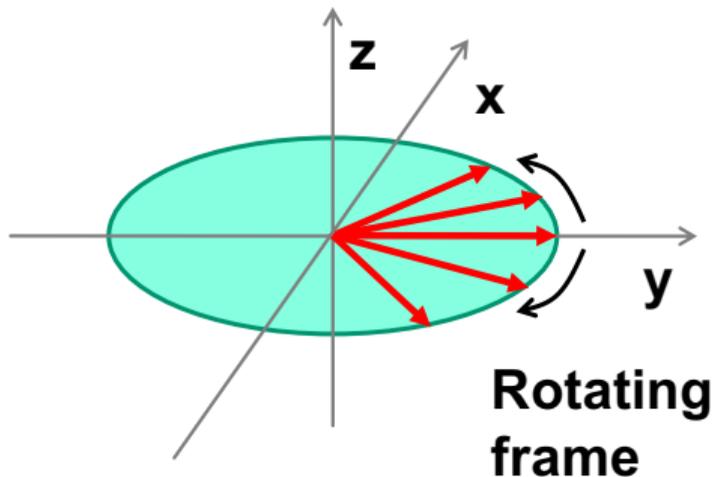
Contributions to M_{xy} smear out (decohere) rapidly

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 o, paramagnetic ions or molecules, outside interference

Spin-spin (transverse) relaxation

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

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

The process is characterised by a time constant T_2

$$\mathbf{M_{xy}} = \mathbf{M_0} \ \mathbf{exp\{-t/T_2\}}$$
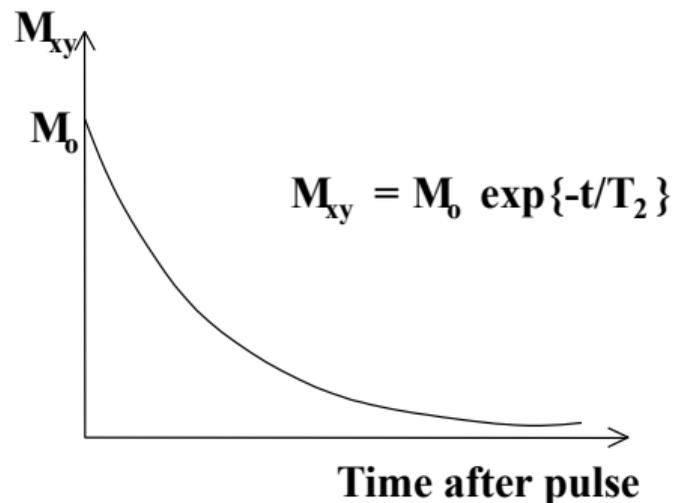
Spin-spin relaxation:

- ^{1}H 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

Block equation may now be updated to include FID:

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

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 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 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 3

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')