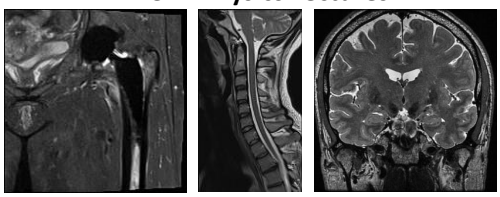
Magnetic Resonance Imaging

F.R.C.R. Physics Lectures



Lawrence Kenning PhD

Remarkable people. Extraordinary place.

History

- 2003 Nobel Prize in Physiology or Medicine was awarded to Paul Lauterbur and Peter Mansfield for their discoveries concerning magnetic resonance imaging (MRI)
- Lauterbur's imaging experiments moved science from the single dimension of NMR spectroscopy to the second dimension of spatial orientation - the foundation of MRI
- Mansfield further developed the utilisation of gradients in the magnetic field. He showed how the signals could be mathematically analysed, which made it possible to develop a useful imaging technique



Paul C. Lauterbur

The Nobel Prize in Physiology or Medicine 2003

1929 - 2007



Sir Peter Mansfield

The Nobel Prize in Physiology or Medicine 2003

1933 - 2017

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Today

MRI:

- Non-ionising radiation. Suited to patients requiring multiple imaging examinations
- Large range of tissue contrasts
- Functional imaging 'flavours' such as diffusion, perfusion and metabolism
- Scanning can be performed in any imaging plane

CT:

- Much faster than MRI (less sensitive to motion)
- Cheaper than MRI
- Accurate detection of calcification and metal foreign bodies
- No risk to the patient with implantable medical devices

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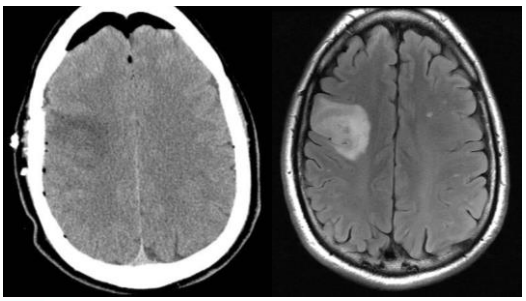
Today

Soft Tissue Contrast



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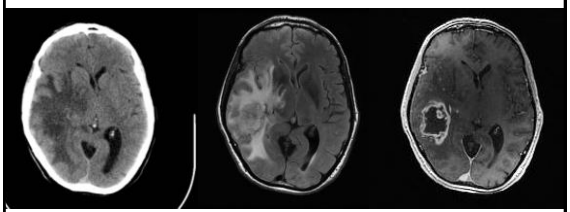
Today

Soft Tissue Contrast



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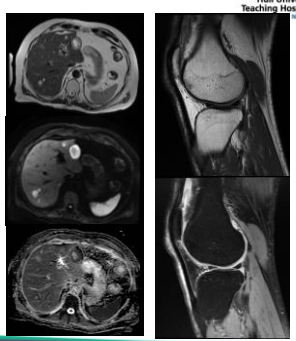
Today

- Neurology
- Musculoskeletal
- Cardiac
- Gastrointestinal
- Oncology



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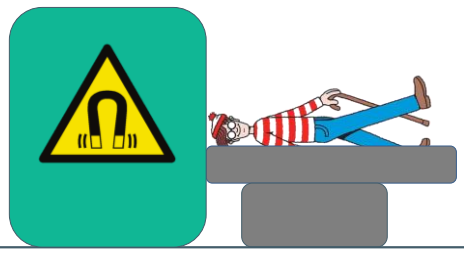
Nuclear Magnetic Resonance

Nuclear Magnetic Resonance Syllabus

- Nuclear spin, angular momentum and nuclear magnetic moment
- Bulk magnetisation and the effect of field strength
- Precession in a magnetic field and the Larmor equation
- Resonance with radiofrequency pulses
- Relaxation mechanisms and relaxation times
- Free induction decay
- Spin echo sequences

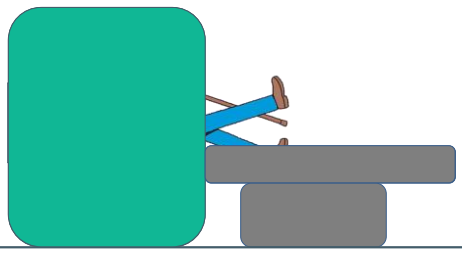
MRI – A Brief Summary

- Magnetic resonance imaging consists of placing the patient inside a large magnetic field



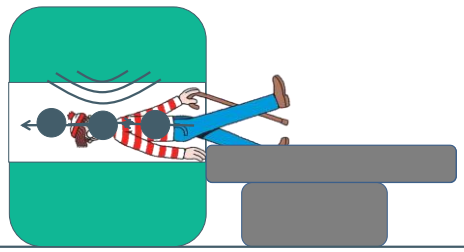
MRI – A Brief Summary

- Magnetic field causes protons in water molecules to align with/against the magnetic field



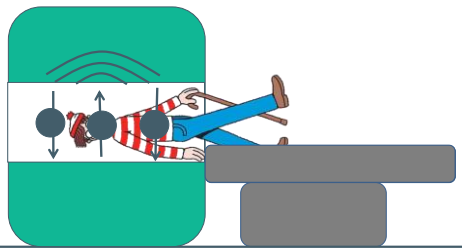
MRI – A Brief Summary

- Radiofrequency (RF) pulses are used to "excite" protons



MRI – A Brief Summary

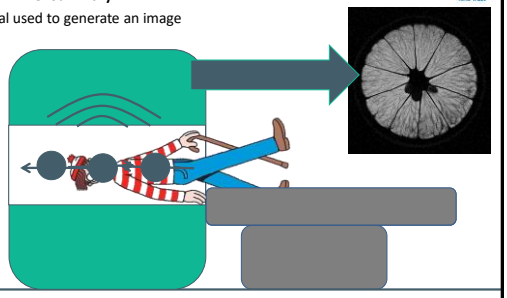
- Energy is subsequently released as RF signal



NMR

MRI – A Brief Summary

- Signal used to generate an image



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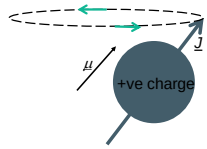
NMR

Nuclear Spin

- The human body predominantly consists of water and fat, with hydrogen as the main constituent
- Each ^{1}H atom consists of a single proton with an orbiting electron, with the nucleus then rotating around its own axis
- The rotating motion of the positively charged proton creates a magnetic field also known as a magnetic moment



$$\underline{\mu} = \gamma \underline{J}$$

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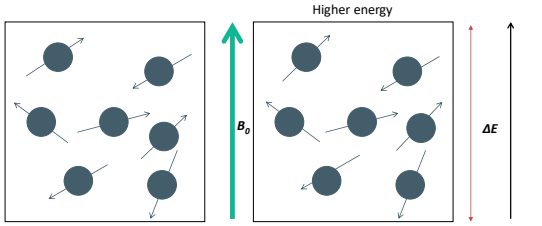
μ = magnetic moment. J = angular momentum. γ is the gyromagnetic ratio (constant for a given nucleus)

NMR

Charge in a field – bulk magnetisation

Antiparallel spins ('spin down')
Higher energy



Parallel spins ('spin up')
Lower energy

Due to thermal energy at equilibrium, a slight majority exists in the low-energy, parallel direction. **B_0 = static magnetic field**

Net magnetic moment

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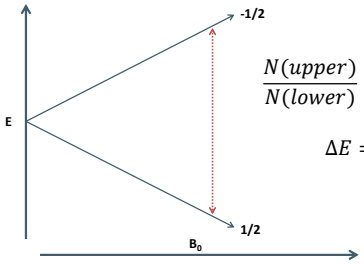
NMR

Boltzmann distribution



$$\frac{N(upper)}{N(lower)} = \exp(-\frac{\Delta E}{kT})$$

$$\Delta E = \frac{\gamma h B_0}{2\pi}$$

An increase in spin population difference can be achieved by increasing B_0 or decreasing temperature (T)

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k is the Boltzmann constant (1.381×10^{-23} joules/°K)
γ is the gyromagnetic ratio, *h* is Planck's constant

NMR

Effect of field strength

- Stronger magnetic fields increase:
  - energy separation of the low- and high-energy levels
  - number of excess protons in the low-energy state
- At 1.0 T, the number of excess protons in the low-energy state is approximately 3 protons per million ($3x10^{-6}$)
- Typical voxel in MRI has 10^{21} protons. This means there are approximately $3x10^{15}$ more protons in the low-energy state!
- This number of excess protons produces an observable "sample" nuclear magnetic moment

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NMR

Magnetic field strength

- The Earth's magnetic field ~ 0.5 Gauss
- 1 Gauss = $1x10^{-4}$ Tesla (T) / 1 Tesla = 10,000 Gauss
- Hull University Teaching Hospitals NHS Trust:

1.5T MR Scanners / 15,000G

3.0T MR Scanner / 30,000G

University of Hull:

11.7T NMR Scanner / 117,000G

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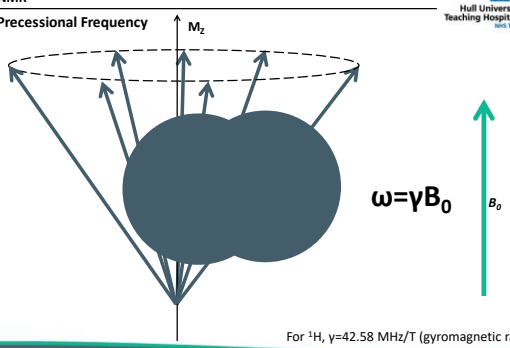
NMR

Precessional Frequency



For ^1H, γ=42.58 MHz/T (gyromagnetic ratio)

ω= angular frequency or Larmor frequency

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NMR

Larmor Equation

$$\omega=\gamma B_0$$

ω = precessional frequency or Larmor frequency
γ = gyromagnetic ratio (constant = 42.58 MHz/T)
B_0 = static magnetic field

- Precessional frequency increases as B_0 increases

$$\omega_{1.5T} = \gamma \times 1.5T = 63.87 \text{ MHz}$$

$$\omega_{3.0T} = \gamma \times 3.0T = 127.74 \text{ MHz}$$

- This is important for excitation! - B_1 RF pulses must be at the correct frequency for resonance to occur!

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NMR

Excitation

- The plane in which in the net magnetisation exists can be manipulated using RF pulses (B_1)
- To stimulate the spins, an RF-coil must produce a time-varying excitation field ($B_1(t)$) with the following characteristics:
  - $B_1(t)$ must have components that rotate near the resonant frequency (ω_0)
  - $B_1(t)$ must have components perpendicular to the static magnetic field (B_0)
- For a simple RF pulse, a generator can be switched on and off, with the flip angle produced expressed as:

$$\alpha=\gamma B_1 t_p$$

- where α is the flip angle, γ is the gyromagnetic ratio, B_1 is the strength of the RF pulse and t_p is the RF pulse duration

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NMR

T_1 Relaxation (spin-lattice relaxation)

- Following a B_1 excitation pulse, longitudinal magnetisation begins to recover immediately
- *Spin-lattice relaxation* is the term describing the release of energy back to the *lattice* (the molecular arrangement and structure of the hydration layer), and the regrowth of M_z
- T_1 is the time needed for the recovery of 63% of M_Z after a 90-degree pulse

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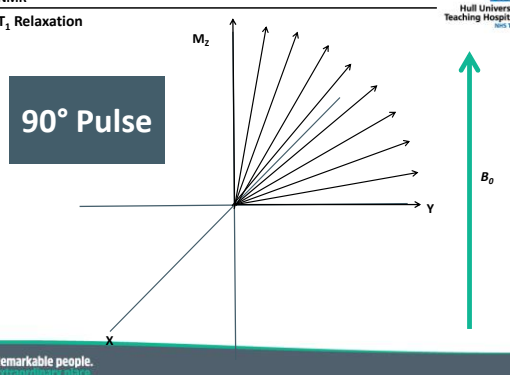
NMR

T_1 Relaxation



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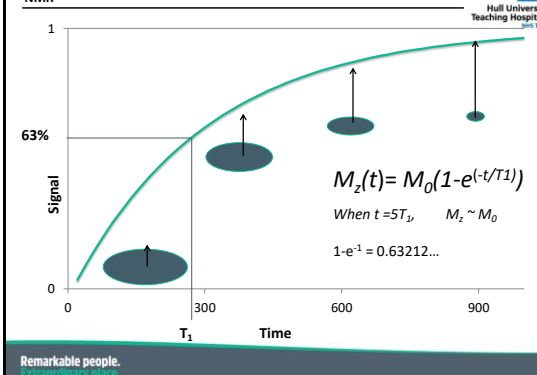
NMR



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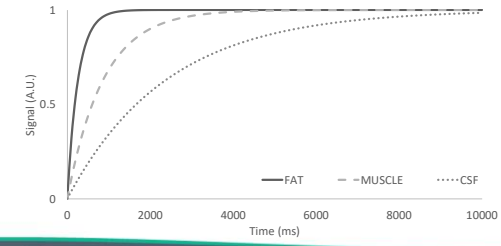
NMR

Tissue	T_1 1.5T
Fat	260
Muscle	870
CSF	2400



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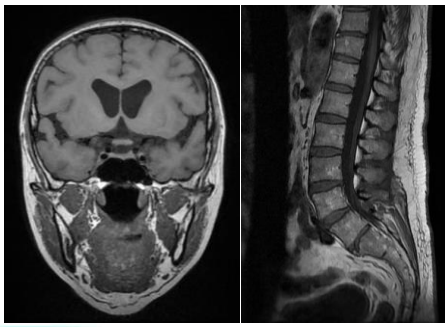
NMR



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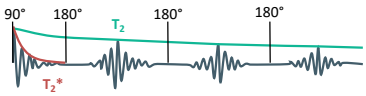
NMR

T_2 Relaxation (spin-spin relaxation)

- T_2 decay is the process whereby spins begin to dephase, occurring **simultaneously with T_1 relaxation**
- Due to individual spins observing local differences in the magnetic field **caused by interactions between spins**
- Spins dephase much quicker than the 'true' T_2 due to inhomogeneities in the static magnetic field (B_0) causing the signal decay to be characterised as T_2^*



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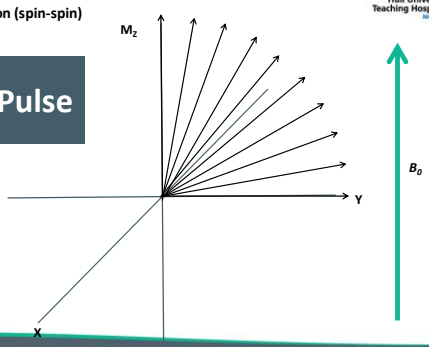
NMR

T_2 Relaxation (spin-spin)

90° Pulse



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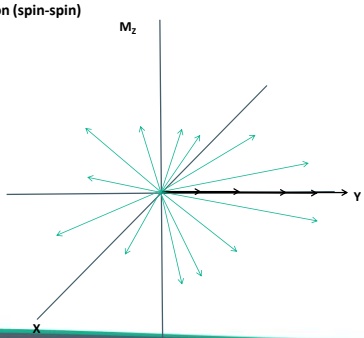
NMR

T_2 Relaxation (spin-spin)



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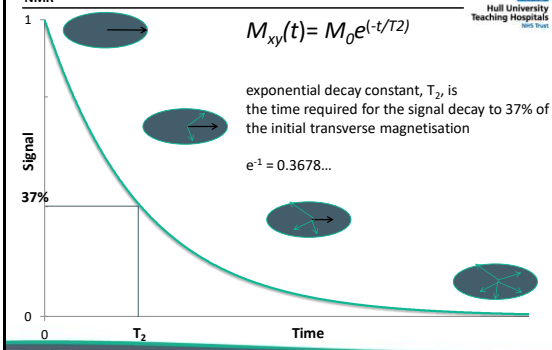
NMR

$$M_{xy}(t) = M_0 e^{(-t/T2)}$$

exponential decay constant, T_2, is the time required for the signal decay to 37% of the initial transverse magnetisation

$e^{-1} = 0.3678...$



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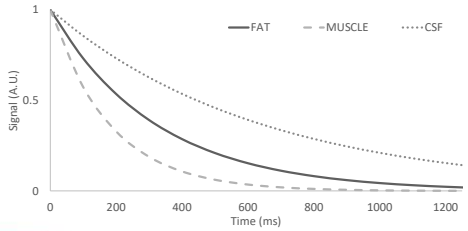
NMR

Tissue	T_2 Relaxation Time (ms) (1.5T)
Fat	80
Muscle	45
CSF	160



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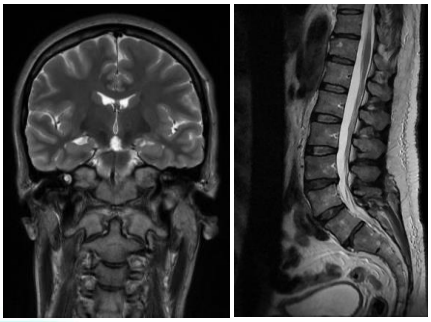
NMR



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NMR

Tissue	T_1 1.5T (ms)	T_2 1.5T (ms)
Fat	260	80
Liver	500	40
Muscle	870	45
White Matter	780	90
Grey Matter	900	100
CSF	2400	160

- Return to equilibrium (T_1) always occurs over a longer time period than T_2 relaxation
- $T_1 >> T_2$

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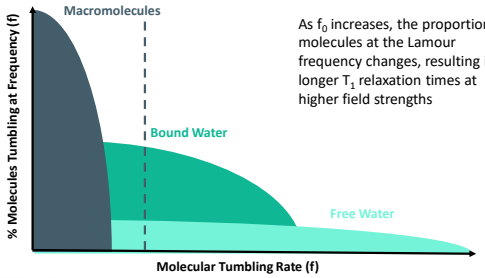
NMR

Field Strength Dependence of T1



As f_0 increases, the proportion of molecules at the Lamour frequency changes, resulting in a longer T_1 relaxation times at higher field strengths

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http://mriquestions.com/bo-effect-on-t1--t2.html

NMR

PHYSICAL REVIEW VOLUME 70, NUMBERS 7 AND 8 OCTOBER 1 AND 15, 1946

Nuclear Induction

F. Bloch
Stanford University, California
(Received July 19, 1946)

$M_x(t) = M_o e^{-t/T2} \sin \omega t$
$M_y(t) = M_o e^{-t/T2} \cos \omega t$
$M_z(t) = M_o (1 - e^{-t/T1})$

The magnetic moments of nuclei in normal matter will result in a nuclear paramagnetic polarization upon establishment of equilibrium in a constant magnetic field. It is shown that a radiofrequency field at right angles to the constant field causes a forced precession of the total polarization around the constant field with decreasing latitude as the Larmor frequency approaches adiabatically the frequency of the r-f field. Thus there results a component of the nuclear polarization at right angles to both the constant and the r-f field and it is shown that under normal laboratory conditions this component can induce observable voltages. In Section 3 we discuss this nuclear induction, considering the effect of external fields only, while in Section 4 those modifications are described which originate from internal fields and finite relaxation times.

- Bloch equations describe behaviour of the magnetic moment of a sample of weakly interacting spins

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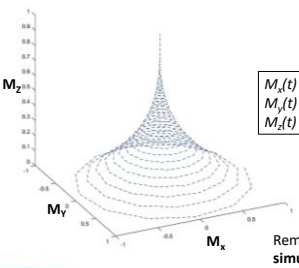
NMR

Free Induction Decay (FID)

- Bloch equations describe behaviour of the magnetic moment of a sample of weakly interacting spins



$M_x(t) = M_o e^{-t/T2} \sin \omega t$
$M_y(t) = M_o e^{-t/T2} \cos \omega t$
$M_z(t) = M_o (1 - e^{-t/T1})$

Remember! - T_2 decay occurs **simultaneously with T_1 relaxation**

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NMR

Free Induction Decay (FID)

- In MR, free induction decay is the observable NMR signal generated by non-equilibrium nuclear spin magnetization precessing about the magnetic field (typically along z)
- Receiver coil sees oscillating magnetic field which induces a varying voltage
- Coils only measures signal in transverse (M_{xy}) plane
- Relaxation occurs due to interactions between spin-lattice (T_1) and spin-spin (T_2)
- FID is attenuated by characteristic relaxation time T_2*

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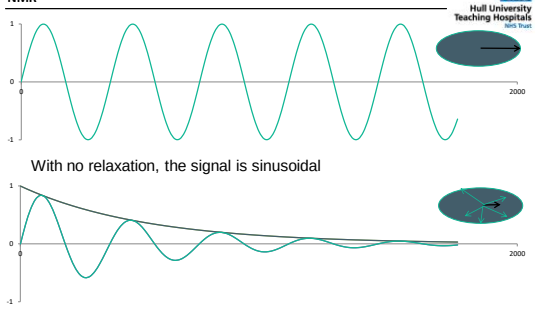
NMR



With no relaxation, the signal is sinusoidal

However, signal is attenuated (sinc function) due to relaxation (FID)

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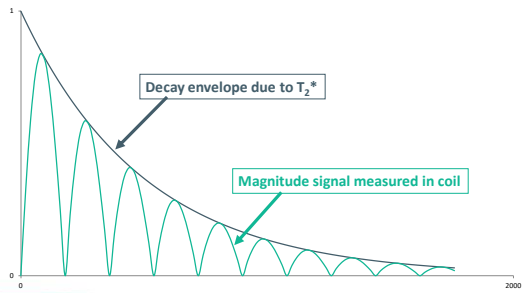
NMR

Free Induction Decay (FID)



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Spin Echo

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Spin Echo (SE) Pulse Sequences

- Spin echo describes the excitation of the magnetised protons in a sample with a **90° RF pulse** and production of a FID, followed by a refocusing **180° RF pulse** to produce an echo
- The 90° pulse converts M_z into M_{xy} and creates coherent transverse magnetisation that immediately begins to decay at a rate described by T_2* relaxation
- The 180° RF pulse applied at TE/2 inverts the spins and induces phase coherence at TE
- Inversion of the spins causes the protons to experience external magnetic field variations opposite of that prior to TE/2, resulting in the cancellation of the extrinsic inhomogeneities and associated dephasing effects

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Spin Echo (SE) Pulse Sequences

- Subsequent 180° RF pulses during the TR interval produce corresponding echoes with peak amplitudes that are reduced by intrinsic T_2 decay of the tissues, and are immune from extrinsic inhomogeneities
- Digital sampling and acquisition of the signal occurs in a time window symmetric about TE, during the evolution and decay of each echo
- **Spin Echo sequences can produce T_1, T_2 and P.D. weightings**

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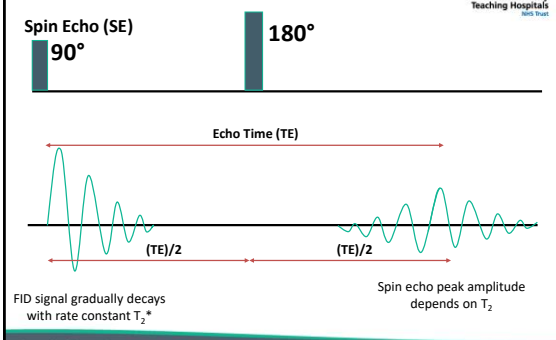
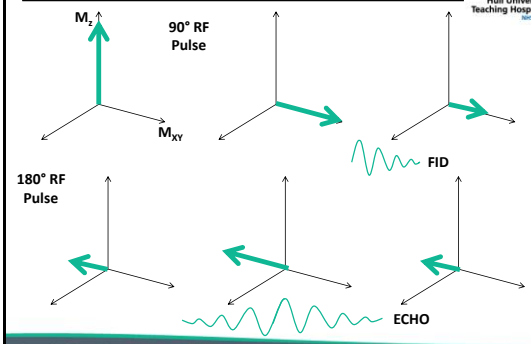
Spin Echo (SE) Pulse Sequences



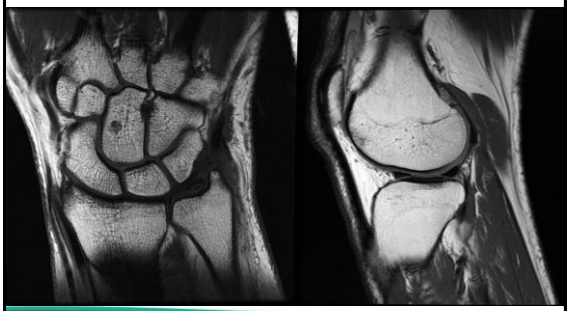
Spin Echo (SE) Pulse Sequences



Spin Echo (SE) Pulse Sequences

- SE sequences are generally:
  - High SNR
  - Resolute
  - Lengthy
  - Less susceptible to metallic artefacts

Spin Echo (SE) Pulse Sequences



Spin Echo (SE) Pulse Sequences



Tissue Contrast

Tissue Contrast

Time of Repetition (TR)

- Acquiring an MR image requires the repetition of a sequence in order to sample the volume of interest and periodically build the complete dataset
- The time of repetition (TR) is the period between B_1 excitation pulses.
- During the TR interval, T_2 decay and T_1 recovery occur in the tissues
- TR values range from extremely short (milliseconds) to extremely long (10,000 ms) time periods, determined by the type of sequence employed

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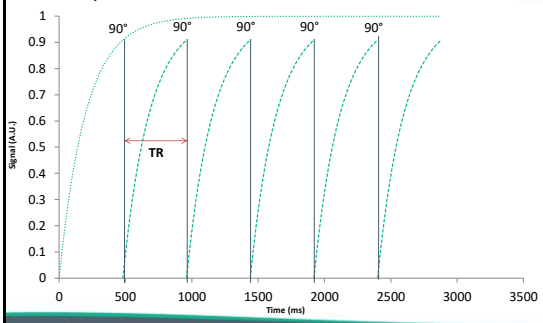
Tissue Contrast

Time of Repetition



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Tissue Contrast

Time of Echo (TE)

- Excitation of spins with the B_1 RF pulse creates the M_{xy} FID signal
- To separate the RF energy deposition and returning signal, an "echo" is induced to appear at a later time, with the application of a 180-degree RF inversion pulse.
- This can also be achieved with a gradient field and subsequent polarity reversal
- The TE is the time between the excitation pulse and the appearance of the peak amplitude of an induced echo, which is determined by applying a 180-degree RF inversion pulse or gradient polarity reversal at a time equal to TE/2

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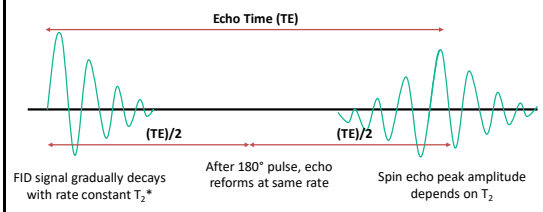
Tissue Contrast

Time of Echo



FID signal gradually decays with rate constant T_2*

After 180° pulse, echo reforms at same rate

Spin echo peak amplitude depends on T_2

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Tissue Contrast

T_1 Weighting

- "T_1-weighted" sequences are designed to produce contrast primarily based on the T_1 characteristics of tissues (differences), with reduced emphasis of T_2 and proton density contributions to the signal
- Use a relatively short TR (350-700ms) to maximise the differences in longitudinal magnetisation recovery during the return to equilibrium, and a short TE (<30ms) to minimize T_2 decay during signal acquisition

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Tissue Contrast

T_1 Weighting

- To minimise T_2 decay and to maintain the differences in signal amplitude due to T_1 recovery, the TE time is kept short
- White and grey matter have intermediate T_1 values with intermediate signal amplitude, and CSF, with a long T_1, has the lowest signal amplitude
- Short echo times preserve the T_1 signal differences by minimising transverse (T_2) decay
- **T_1-weighted SE contrast therefore requires a short TR and a short T*E***

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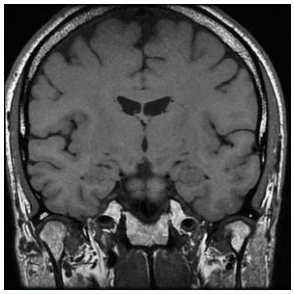
Tissue Contrast

T_1



T_1 Weighted Imaging

CSF – Dark

Grey Matter – Intermediate

White Matter – Intermediate- Bright

Fat – Bright

Bone - Dark

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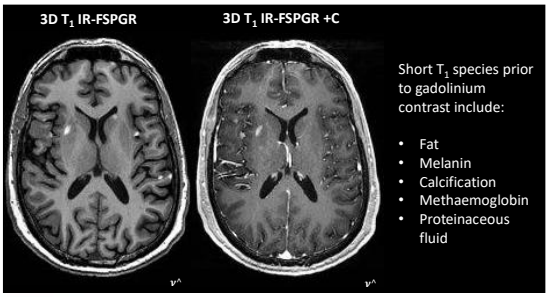
Tissue Contrast

T_1



Short T_1 species prior to gadolinium contrast include:

- Fat
- Melanin
- Calcification
- Methaemoglobin
- Proteinaceous fluid

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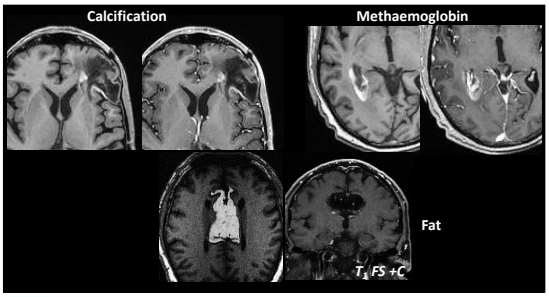
Tissue Contrast

T_1



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Tissue Contrast

T_2 Weighting

- Use a long TR (>2500ms) to minimise the differences in longitudinal magnetisation (T_1) recovery during the return to equilibrium, and a long TE (~100ms) to maximise differences in T_2 decay during signal acquisition
- As TE is increases, more T_2-weighted contrast is achieved, but at the expense of less M_{xy} signal and greater image noise
- **T_2-weighted SE contrast requires a long TR and a long *TE***

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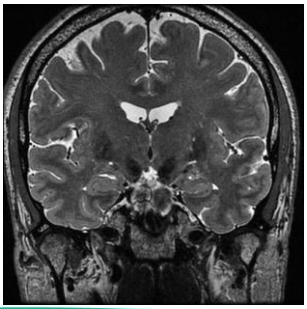
Tissue Contrast

T_2



T_2 Weighted Imaging

CSF – Bright

Grey Matter – Intermediate-Bright

White Matter – Intermediate

Fat - Bright

Bone - Dark

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Tissue Contrast

Proton Density Weighting

- Proton density contrast weighting relies mainly on differences in the number of magnetised protons per unit volume of tissue
- At equilibrium, tissues with a large proton density, such as lipids, fats and CSF, have a corresponding large M_z compared to other soft tissues
- Contrast based on proton density differences is achieved by reducing the contributions of T_1 recovery and T_2 decay
- T_1 differences are reduced by selecting a long TR value to allow substantial recovery of M_z
- T_2 differences of the tissues are reduced by selecting a short TE value
- **PD-weighted SE contrast therefore requires a long TR and a short *TE***

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Tissue Contrast



P.D. Weighted Imaging

Fat - Bright

Fluid – Bright

Muscle – Intermediate

Cortical Bone - Dark

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Tissue Contrast

Spin Echo sequences can produce: T_1, T_2 and P.D. weightings

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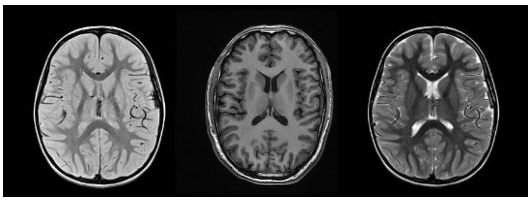
Tissue Contrast

Image Weighting



Proton Density	T_1 Weighted	T_2 Weighted
Short TE Long TR	Short TE Short TR	Long TE Long TR

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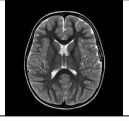
Tissue Contrast

Tissue contrast can be manipulated by changing repetition time (TR) and echo time (TE)

Repetition Time (TR) = time between 90° pulses

Echo Time (TE) = 2 x time between 90° and 180° pulses

	Short TR	Long TR
Short TE		
Long TE		

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Summary

Magnetic Resonance Signal Overview

- Application of RF energy synchronised to the precessional frequency of the protons causes absorption of energy and displacement of the sample magnetic moment from equilibrium conditions
- Return to equilibrium results in the emission of energy proportional to the number of excited protons in the volume
- Occurs at a rate that depends on the structural and magnetic characteristics of the sample (T_1, T_2 and P.D.)
- Contrast between tissue groups is determined using pulse sequence parameters (TE & TR)

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Questions

Question

- What weighting would a sequence with a long TR (3000ms) and a long TE (100ms) have?

  A) T_1
  B) T_2
  C) P.D.

- Which combination of parameters is required to produce an image with proton density weighting?

  A) long TR and long TE
  B) short TR and short TE
  C) long TR and short TE

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Questions

Question

- On a T_2 weighted image, what signal intensity would free fluid produce?

A) Bright
B) Intermediate
C) Dark

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Questions

Question

In magnetic resonance imaging the following are true:

A. A spin echo sequence with a short repetition time TR and a short echo time TE is T_1 weighted.

B. A spin echo sequence with a long repetition TR and a long echo time TE is proton density weighted.

C. A spin echo sequence with a long repetition TR and a short echo time TE is T_2 weighted.

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Questions

Question

In magnetic resonance imaging the following are true:

A. Prior to any radiofrequency (RF) pulse the total magnetic vector in the xy plane (m_{xy}) is equal to 1.

B. The signal measured in a 1.5T magnet will be proportionately more than a 3.0T magnet.

C. The net magnetic vector in the z-axis provides a recordable MR signal.

D. A standard 1.0T MRI scanner produces a magnetic field 100 time's that of the earth.

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Questions

Question

In magnetic resonance imaging the following are true:

A. Signal strength depends only on the proton density of the material.

B. A short TE and a long TR will give a T_1-weighted image.

C. A T_1-weighted image will show water as high signal.

D. Most soft tissues show as high signal on proton density (PD) weighted images.

E. If TE is longer than TR, the image is weighted towards PD.

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Questions

Question

Concerning T_1, which of the following are true:

A. It is the time taken for transverse recovery to reach 37% of the maximum value.

B. T_1 is increased with greater field strength.

C. Fat and melanin both produce a high signal on a T_1-weighted image.

D. A short time to echo (TE) and short time to repeat (TR) will give a T_1-weighted image.

E. T_1 is always longer than T_2.

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Questions

Question

Concerning T_2, which of the following are true:

A. Occurs due to spin-lattice relaxation.

B. T_2 relaxation time increases with an increase in magnet field strength.

C. Is affected by magnetic field inhomogeneities.

D. When 63% of the transverse signal is lost, this is referred to as time T_2

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Questions

Question

In magnetic resonance imaging the following are true:

A. a spin echo sequence with a short repeat time (TR) and a short echo time TE is T_1 weighted.

B. a spin echo sequence with a long repeat time TR and a long echo time TE is proton density weighted.

C. a spin echo sequence with a long repeat time TR and a short echo time TE is T_2 weighted.

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Questions

Question

In magnetic resonance imaging the following are true:

A. FID is a commonly used basic sequence

B. A spin-echo sequence removes the dephasing effect of field inhomogeneities with a second 90° pulse

C. The longer the TE, the smaller the subsequent signal

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Questions

Question

In magnetic resonance imaging the following are true:

A. The SE sequence allows the T_2 effect of a specific tissue to be measured

B. Following rephasing, the MR signal is equal to that immediately after the 90° pulse

C. Immediately following a single 90° pulse, all the dipoles are in phase

D. The 180° rephasing pulse is applied at TE/2 after the initial RF excitation

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