# Introduction to MR Physics


Andrew Fagan Ph.D.

Centre for Advanced Medical Imaging
& School of Medicine

St. James's Hospital, Dublin
&
University of Dublin Trinity College


## Talk Overview

1. Introduction to MRI
2. NMR Physics
3. System Components
4. Imaging Protocols – some basics

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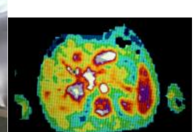
**€ 1.5 - 2 million, one of the most expensive machine in hospital**



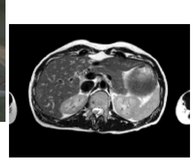
**1979**

**University of Aberdeen**

**0.04 T**

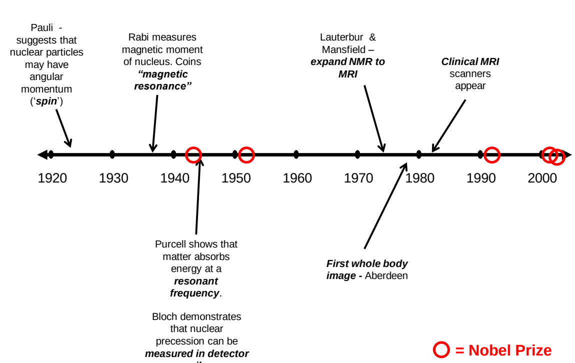


Transverse liver scan





## Timeline of MR Imaging



## MRI

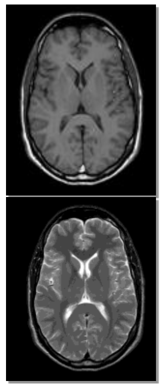
Advantages:

- Excellent / flexible contrast
- Non-invasive
- No ionizing radiation
- Arbitrary scan plane

Challenges:

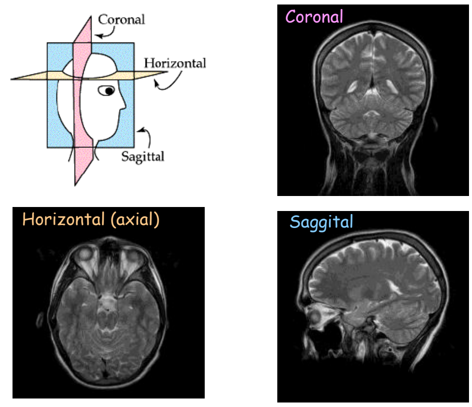
- Faster imaging
- New contrast mechanisms
- New contrast agents

  e.g. paramagnetic nanoparticles for
  molecular imaging applications





## Images can be generated in any plane

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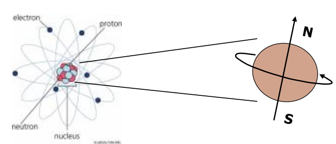
## 2. NMR Physics

MRI – more accurately termed NMRI (nuclear magnetic resonance imaging)

- "Spin" is a property of some elementary particles
  - e.g. electron has spin = ½ → Electron Spin Resonance (ESR)
- Some nuclei also have property of" spin"
  - can have spin = ½, 1, 1½, 2, …..
- Examples: $^{1}H$, $^{13}C$, $^{19}F$, $^{23}Na$, and $^{31}P$, plus many others……



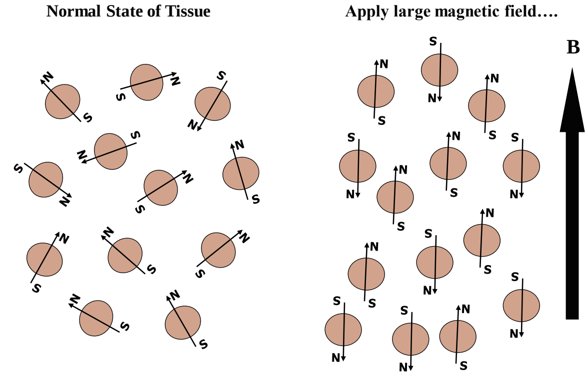

**Electric Charge +**
**Spin**
**=**
**Magnetic Moment**



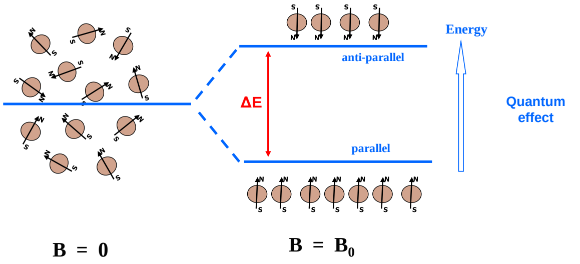
- Most prevalent atom in body is Hydrogen, $^{1}H$ :
  - nucleus = 1 proton
  - positively charged
  - spin = ½
    → hence $^{1}H$ nuclei act like tiny magnets
- MRI – mainly looking at $^{1}H$ in water molecules ($H_2O$)
  → different environments - intra-cellular, extra-cellular, intravascular,…
  → also $^{1}H$ in fat molecules ($…CH_2$), + …
- Bodies are about 70-80% water, therefore lots of hydrogen nuclei
  → we measure a big signal, hence produce nice images



**Normal State of Tissue** **Apply large magnetic field….**



## Applied Magnetic Field → the Zeeman Effect




The applied $B_0$ field causes splitting of energy levels

→ we have ***"polarised"*** the spin population in the sample

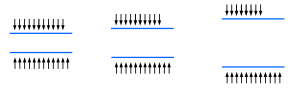


## Population Difference → Boltzmann's equation

$$\frac{N_{anti-//}}{N_{//}} = e^{-\Delta E / kT}$$

Interesting points from this :

1. Depends on T
   - at 0 K, all spins occupy the lower energy state (parallel)
   - at body temperature (~310 K), the population **difference** is VERY small
2. Depends on ΔE → $\Delta E = \gamma \hbar B_0$



$B_0 = 1$ T, excess = 3.3 ppm; $B_0 = 1.5$ T, 5 ppm; $B_0 = 3$ T, 10 ppm; $B_0$ = 7 T, 9.4 T, 11.7 T, ……



The inherent sensitivity of an MRI experiment is quite small (5 ppm at 1.5 T)

→ only the excess population contributes to the measured signal

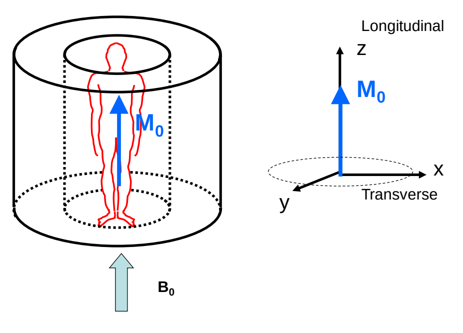
→ for each gram of tissue, of the approx $10^{22}$ protons, we have an excess of approx $10^{17}$ protons, so enough to contribute a signal !

The excess of spins in the lower energy state produce a macroscopic **"Net Magnetisation, $M_0$"** within the sample, parallel to $B_0$

This Net Magnetisation, $M_0$, can be manipulated by applying an oscillating magnetic field at a very specific frequency



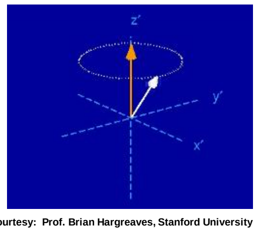
## Co-ordinate system






## Precession

In reality, the spins are not exactly aligned with $B_0$, rather they ***precess*** around the direction of $B_0$ at a certain angle.




Courtesy: Prof. Brian Hargreaves, Stanford University

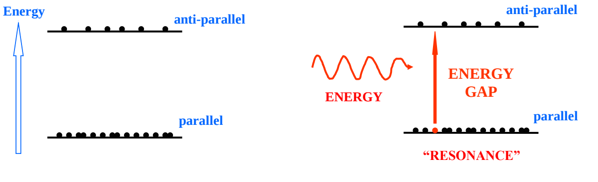
The frequency of precession is proportional to the strength of the applied magnetic field, $B_0$,

→ is given by the Larmor Equation: $\omega = \gamma B_0$



## NMR Experiment → "Excite" the spin system

To excite a "transition" from the lower energy state to the higher energy state, we must supply energy to the system.




Energy Gap $\Delta E = \gamma \hbar B_0$

Energy of a photon $= \hbar \omega$

therefore $\hbar \omega = \gamma \hbar B_0$

or $\omega = \gamma B_0$ i.e. the same frequency that the spins precess at !

**……the resonance phenomenon**

At 3 T, the frequency needed to excite the transition is 128 MHz ( $= \gamma B_0$ )

→ we call this the **"Radio Frequency"** range

At 7 T, frequency = 300 MHz

Light photons
~ 600,000 MHz

X-ray photons
~ 3,000,000,000 MHz

- cause damage when passing through tissue



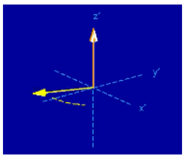
The spin population "absorbs" energy from this applied EM field

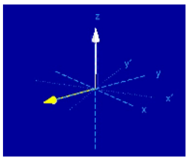
→ only consider the magnetic component → the **$B_1$ field**

→ we send in a short **"pulse"** of RF energy

→ immediately after absorbing the energy, we say that the sample is **"excited"**

The Net Magnetisation vector $M_0$ is tipped away from alignment with $B_0$, and begins to spiral at the Larmor frequency, eventually reaching the transverse (x-y) plane if enough RF energy is supplied (a **"90° flip" → $M_y$**)





Courtesy: Prof. Brian Hargreaves, Stanford University



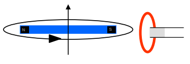
The rotating $M_y$ will induce a voltage in a neighbouring "receiver" coil (at the same frequency)

→ this is how we measure the signal in MRI

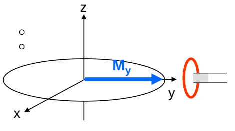
**Faraday Induction**

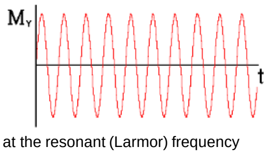
bicycle dynamo

rotating magnet beside loop of wire



rotating magnetic moments

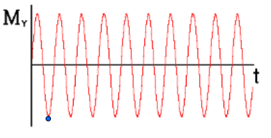


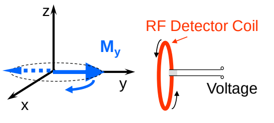



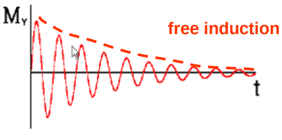

sine wave at the resonant (Larmor) frequency



## Signal Detection



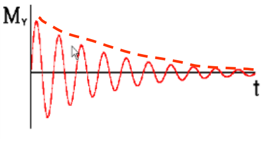

**free induction decay: FID**

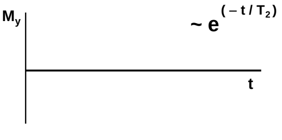
The signal decays due to 'relaxation' processes

- basically, the coherence of the many spins (adding to give $M_y$) decreases

→ $M_y$ drops






$T_2$ is a **"time constant"** describing the rate of decrease of $M_y$, and hence the rate of decrease of our Signal

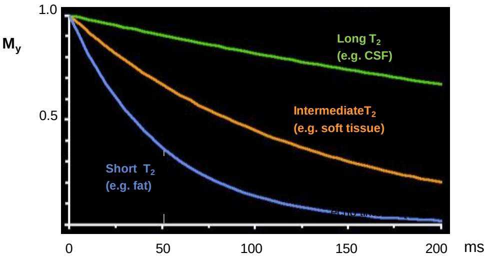
- occurs due to interactions between neighbouring spins in the sample, hence called the **"spin-spin relaxation"**



$T_2$ is very sensitive to interactions occurring on a molecular level, and hence to the molecular environment of the $^1$H nuclei

→ $T_2$ varies widely between different tissue types and indeed among different pathologies

→ can be used to introduce contrast into images (**"$T_2$-weighted"** images)



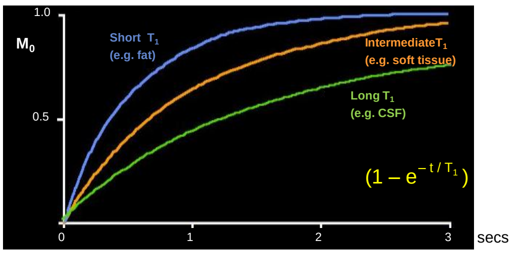
After exciting the spin system, it returns to its equilibrium state

→ this process is called **"spin – lattice relaxation"**

→ $M_0$ recovers, also following an exponential curve

→ time constant called "$T_1$" → hence **"$T_1$ relaxation"**

→ $T_1$ also very sensitive to molecular environment → **"$T_1$ weighed"** images

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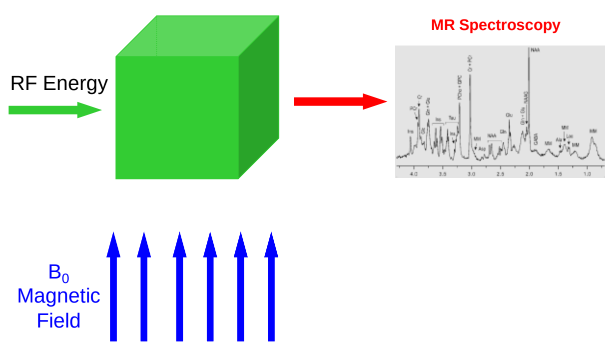
Clinical - 1.5T, 3T, …

Pre-clinical - 7T, 9.4T, 11.7T,…

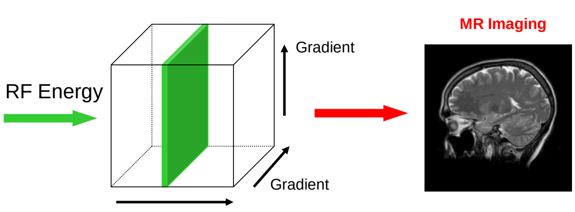


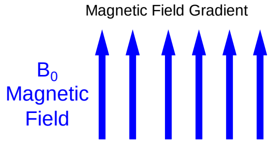
## Magnetic Resonance






## Magnetic Resonance Imaging




The signal from each voxel in the image is comprised of the summation of all spectral signals in that voxel

→ we're sacrificing spectroscopic information in favour of imaging with high spatial resolution

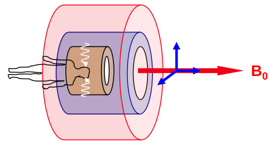


## Main Elements

MRI { MRS { 1. Large magnetic field, $B_0$
2. Transmitter – RF energy into sample
3. Detector – Signal coming from sample }
4. Gradients – to allow for spatial localisation i.e. imaging }

2 + 3 sometimes combined → "Transceiver" RF Coil

## Basic Equipment




**Magnet** **Gradient Coils** **RF Coil**



## RF Coils : Surface Detector Coils

- Also called "Receiver coils"
- Ultimate image quality – determined by the Signal to Noise ratio ("SNR")
- They are designed to maximise the measured signal while minimising noise
- Noise comes from electrical sources (copper wires) but also Brownian motion in the patients themselves
- Max SNR (or "Sensitivity") → when coil is "filled"

  i.e. must match the coil to the anatomy of interest

Courtesy: Philips Medical Systems, Netherlands

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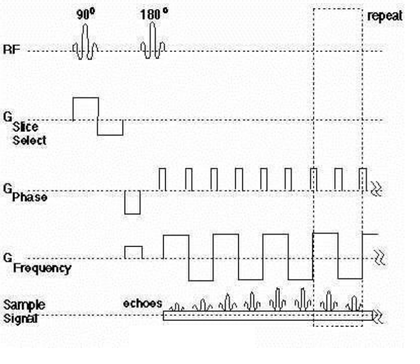
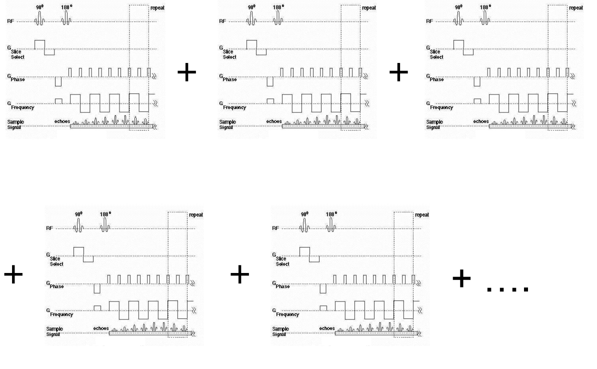
## Imaging "Pulse Sequences"

These are **timing diagrams** describing when the RF pulses & magnetic field gradients are applied and when the MR signal is measured

…. can be fairly complicated beasts !

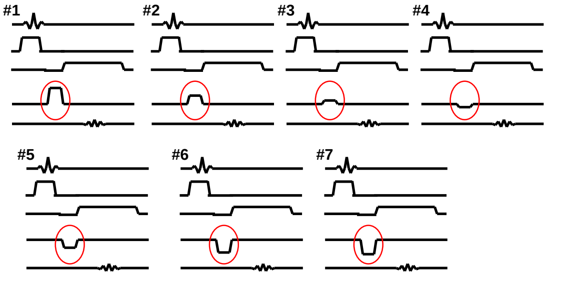




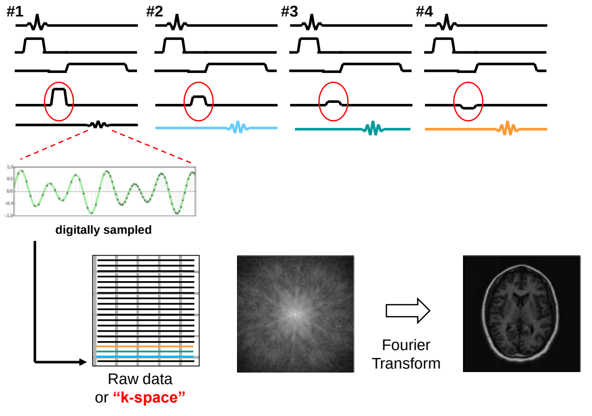




Better spatial resolution → need more repetitions, hence longer acquisition time



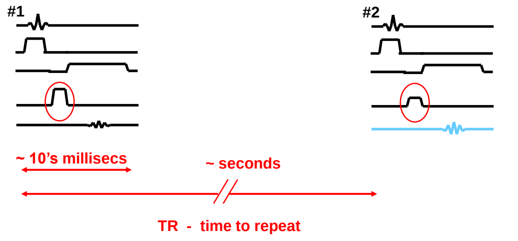



The magnitude of the "phase-encoding" magnetic field gradient is incrementally stepped from repetition to repetition






## Image acquisition times



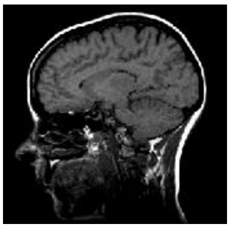

The long TR times are due to the long $T_1$ relaxation times of tissue

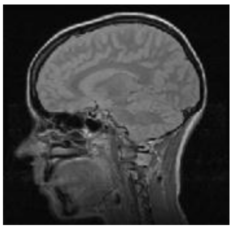
- → we need to wait for $M_0$ to recover before "exciting" the spin system again with another 90º RF pulse
- → acquisition times of ~ minutes are common
- → possible to image in < 1 second, but trade-off image quality for speed



## $T_1$-weighted images

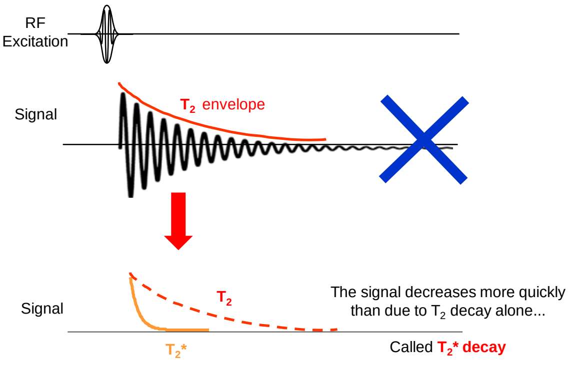
By varying TR, we can introduce varying amounts of $T_1$-weighting into images


Short TR


Long TR



## $T_2$ versus $T_2$* relaxation



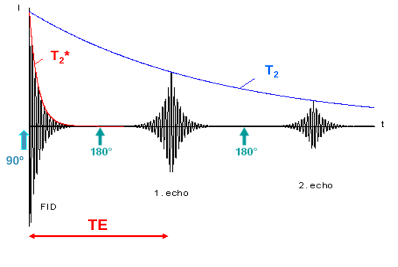



Two contributions to $T_2$* signal decay:

1. true $T_2$ molecular processes
2. non-uniformities in $B_0$

Hence, we form an echo of the signal some time (~ ms) after the excitation

- → this time is called the **"time-to-echo", TE**
- → varying TE allows us to vary the amount of $T_2$-weighting in the images



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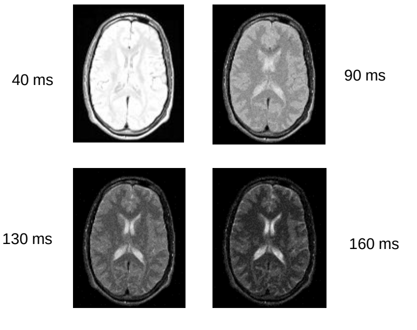
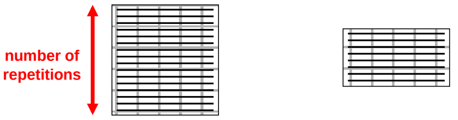


## k-space lines and spatial resolution




High resolution image

4 mins

Low resolution image

2 mins



## Summary

- MRI – based on magnetic properties of certain nuclei
  → mainly focus on $^{1}H$
- 3 magnetic fields used in MRI
  i. $B_0$ – very large, static, caused polarisation of spins in sample
  ii. $B_1$ – RF energy used to resonantly excite the spin system
  iii. Gradients – allow for spatial localisation of signal, i.e. imaging
- Hardware components for each function
- Imaging protocols
  – determine how / when things are turned ON and OFF
  – many variations, producing many different image contrasts