Talk Overview

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

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

Timeline of MR Imaging

1979
University of Aberdeen

0.04 T

Transverse liver scan


- Paul suggests that nuclear particles may have angular momentum ("spin")
- Rabi measures magnetic moment of nucleus. Caine "magnetic resonance"
- Bloch demonstrates that nuclear precession can be measured in detector coils
- Purcell shows that matter absorbs energy at a resonant frequency
- Lauterbur & Mansfield - expand NMR to MRI
- First whole body image - Aberdeen

= Nobel Prize
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

Talk Overview

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

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 $= \frac{1}{2}$ → Electron Spin Resonance (ESR)
- Some nuclei also have property of "spin" can have spin $= \frac{1}{2}, 1, 1\frac{1}{2}, 2, \ldots$
- Examples: $^1$H, $^13$C, $^14$F, $^{23}$Na, and $^{31}$P, plus many others......

• Most prevalent atom in body is Hydrogen, $^1$H :
  - nucleus = 1 proton
  - positively charged
  - spin $= \frac{1}{2}$ → hence $^1$H nuclei act like tiny magnets

• MRI – mainly looking at $^1$H in water molecules (H$_2$O)
  - different environments - intra-cellular, extra-cellular, intravascular,
  - also $^1$H in fat molecules (…CH$_2$)ₙ + …

• Bodies are about 70-80% water, therefore lots of hydrogen nuclei
  → we measure a big signal, hence produce nice images
The applied $B_0$ field causes splitting of energy levels
$\Rightarrow$ we have "polarised" the spin population in the sample

The inherent sensitivity of an MRI experiment is quite small (5 ppm at 1.5 T)
$\Rightarrow$ only the excess population contributes to the measured signal
$\Rightarrow$ 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

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

The frequency of precession is proportional to the strength of the applied magnetic field, $B_0$
$\Rightarrow$ is given by the Larmor Equation: $\omega = \gamma B_0$

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

therefore $\omega = \gamma B_0$

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

......the resonance phenomenon
Light photons
\~ \(600,000\ \text{MHz}\)

X-ray photons
\~ \(3,000,000,000\ \text{MHz}\)
- cause damage when passing through tissue

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

The spin population “absorbs” energy from this applied EM field
- only consider the magnetic component \(\rightarrow\) 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 \(M_y\) 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 “90º flip” \(\rightarrow M_y\))

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

The spin population “absorbs” energy from this applied EM field
- only consider the magnetic component \(\rightarrow\) 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 \(M_y\) 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 “90º flip” \(\rightarrow M_y\))

Signal Detection

The signal decays due to relaxation processes
- basically, the coherence of the many spins (adding to give \(M_y\)) decreases
- \(M_y\) drops

\[M_y(t) = e^{-t/T_2}\]

\(T_2\) 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

Talk Overview

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

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

4. Imaging Protocols

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
4. Imaging Protocols

#1

#2

#3

#4

Raw data or "k-space"

Digital sampled

Fourier Transform

Image acquisition times

#1

#2

~ 10's millisecc

~ seconds

TR - time to repeat

The long TR times are due to the long \( T_1 \) relaxation times of tissue

\[ \rightarrow \]

we need to wait for \( M_0 \) to recover before "exciting" the spin system again with another 90º RF pulse

\[ \rightarrow \]

acquisition times of ~ minutes are common

\[ \rightarrow \]

possible to image in < 1 second, but trade-off image quality for speed

4. Imaging Protocols

\[ T_1 \]-weighted images

By varying TR, we can introduce varying amounts of \( T_1 \)-weighting into images

Short TR

Long TR

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

\[ \rightarrow \]

this time is called the "time-to-echo", TE

\[ \rightarrow \]

varying TE allows us to vary the amount of \( T_2 \) weighting in the images

4. Imaging Protocols

\[ T_2 \] versus \( T_2^* \) relaxation

RF

Exitation

Signal

\( T_2 \) envelope

\[ \times \]

The signal decreases more quickly than due to \( T_2 \) decay alone...

\[ \rightarrow \]

Called \( T_2^* \) decay

4. Imaging Protocols

\[ T_2 \]-weighted images

By varying TE, we can introduce varying amounts of \( T_2 \) weighting into images

160 ms

90 ms

130 ms

160 ms
4. Imaging Protocols

- **k-space lines and spatial resolution**
  - High resolution image
    - 4 mins
  - Low resolution image
    - 2 mins

5. Summary

- **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