Introduction to MRI Physics

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Slides available at:
http://users.fmrib.ox.ac.uk/~mchiew/teaching/
MRI Physics

Monday:
★ Basics of magnetic resonance
★ Image formation
★ Signal statistics (SNR)
★ Functional MRI

Wednesday:
★ Image contrast (T₂ and T₂*)
★ Spin vs. gradient echo
★ Fast imaging
★ Diffusion MRI
What are we trying to achieve?

**Informed decision making:** You need to take responsibility for the design, implementation & execution of your study

- Protocols need to be tailored to the problem
- Learning some physics will make this less daunting

**A common language:** You need to be able to talk to experts

- Communicate your needs to physicists/radiographers/techs
- Build an MR vocabulary (terminology/jargon)
- Gain some intuition behind imaging concepts
MRI Physics

- Basics of magnetic resonance
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Almost all sub-atomic particles have “spin”

• All nuclei with odd numbers of protons/neutrons will have non-zero net spin
The abundance of water in the human body makes this very powerful!

All hydrogen protons will act like little magnets.

$^1\text{H}, ^{13}\text{C}, ^{23}\text{Na}, ^{31}\text{P}$
$^1\text{H}, ^{13}\text{C}, ^{23}\text{Na}, ^{31}\text{P}$

Can also do this with phosphorous nuclei
Spins, or magnetization (when referred to in bulk) behave similarly to classic physical systems.

In many ways analogous to simple oscillators, like swings or pendulums.
1. **Excitation**
   Magnetization can be moved or rotated by applying “excitation” magnetic fields (RF)

2. **Resonance**
   Magnetization will “resonate” at a frequency proportional to magnetic field strength

3. **Relaxation**
   The oscillations die out, i.e. magnetisation “relaxes” back to equilibrium – speed of relaxation is tissue-dependent!
The External Magnetic Field ($B_0$)

Normally: protons randomly oriented $\Rightarrow$ no net magnetism

External field: protons align slightly $\Rightarrow$ net magnetization ($M$)

Only a few parts-per-million!
Magnetic resonance

**Magnetic:** external field ($B_0$) magnetizes sample

![Diagram of magnetization](image)

$$\omega_0 = \gamma B_0$$

This “Larmor Equation” defines the resonant frequency

**Resonance:** magnetization has characteristic (resonant) frequency proportional to external field $B_0$
Coordinate system

Direction of main field ($B_0$) defines coordinate system

Longitudinal axis: parallel to $B_0$ (typically z)

Longitudinal magnetisation: Portion of $M$ aligned with $B_0$
Direction of main field \((B_0)\) defines coordinate system

Transverse plane: perpendicular to \(B_0\) (typically x,y)

Transverse magnetisation: Portion of M perpendicular to \(B_0\)
The Basic MRI Experiment:
1. Excitation

Excitation pulse (yellow) tips magnetisation away from $B_0$

Excitation must occur at the resonant frequency $\omega_0$

$\omega_0 = \gamma B_0$

courtesy of William Overall
In a frame that rotates with $B_1$, magnetisation is simply “flipped” or “tipped” out of alignment with $B_0$

Hence the term “flip angle” or “tip angle”
Once excited, magnetisation precesses/oscillates/rotates at resonance frequency

\[ \omega_0 = \gamma B_0 \]

courtesy of William Overall
As it precesses, it also “relaxes” back into alignment with $B_0$.

Speed of relaxation has time constants: $T_1$, $T_2$, $T_2^*$, which relate to the image contrast.
The Basic MRI Experiment:
3. Relaxation

$T_1$: describes speed of recovery along longitudinal (z) axis
$T_2, T_2^*: $ describe speed of signal decay in transverse (x-y) plane

courtesy of William Overall
As the magnetization precesses and relaxes
The precession induces a voltage in the receive coils
Coils only detect rotating, transverse magnetisation
Magnetic fields everywhere…

Main magnetic field ($B_0$): always on, static

Excitation RF field ($B_1$): pulsed on & off, 60-300 MHz

Magnetic field gradients ($G$): pulsed on & off, “static”

MRI scans: carefully timed RF and gradient “pulse sequences”
MRI Physics

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Magnetic Field Gradients

Differentiate between signal from different locations

Add a spatially varying magnetic field gradient $(G)$

- Field varies linearly along one direction
- Gradient field adds to or subtracts from $B_0$
No Gradient
x-Gradient
y-Gradient
Precession

\[ \omega_0 = \gamma(B_0 + G(x,y,z)) \]

Resonance frequency is proportional to total field: Static \( B_0 \) + applied gradients

courtesy of William Overall
Gradients and Resonance

\[ \omega_0 = \gamma (B_0 + G(x,y,z)) \]

Distinguish different spatial locations by assigning different resonant frequencies to different positions
Imagine differentiating between instruments based on their frequency content!
Frequency decomposition

- Violins (playing the loudest)
- Cellos (playing the loudest)
- Bass (playing quietly)
- Other instruments (playing quietly)

Amplitude vs. time (s)

Amplitude vs. frequency (Hz = s⁻¹)

Fourier Transform

Inverse Fourier Transform
Simple “imaging” experiment (1D)

- Increasing field

![Diagram showing increasing field with corresponding y and x axes, and magnetization and signal markers.](image-url)
Simple “imaging” experiment (1D)

Fourier Transform:
Gives us the “frequency content” of our signals.

**Fourier Transform:** Gives us the “frequency content” of our signals.
Simple “imaging” experiment (1D)

Signal

Time

Fourier transform

“Image”

Frequency/Position

This is “frequency encoding”
Magnetic gradients

It’s a bit more complex in more than 1 dimension
Have 3 gradient fields (along x, y, z)
Manipulate the strength & timing independently

$G_x, G_y$
Gradients in multiple dimensions
Magnetic field gradients

\( B_0 \)
Gradients in multiple dimensions
Combined field gradients
Spatial frequencies or patterns

At any instant in time, signal is across space is defined by a specific “pattern” of the magnetisation phase (orientation), i.e., its spatial frequency that depends on the applied gradients.

Spatial frequencies:

• sinusoidal pattern over space instead of time
• extend to multiple dimensions
Gradients and Spatial Frequency

Strong, positive gradient

Strong, negative gradient

Zero gradient
Gradients and Spatial Frequency

- Higher resonance frequency
- Faster precession
- Lower resonance frequency
- Slower precession

- Stronger gradient magnetic field
- Zero gradient
This is one spatial frequency...

0 cycles along x: $k_x=0$

2 cycles along y: $k_y=2$
This is another one...

Along y:
\[ k_y = 0 \]

Along x:
\[ k_x = 2 \]
This is another one...

2 cycles along y: $k_y=2$

2 cycles along x: $k_x=2$
Each of these represents one 2D pattern or frequency: denote \((k_x, k_y)\).

“\(k\)” values are the number of cycles in each direction.
2D “k-space” describes contribution of each spatial frequency

Patterns determine the “where” in k-space
2D “k-space” describes contribution of each spatial frequency.

Sum total signal after application of these patterns determines the “value” of each k-space location.
Signal from RF coil

Filling k-space

"k-space"

Fourier transform

Image
Think of each pattern (k-space location) as a filter on a camera.
Imagine our “camera” can only see one colour at a time
Imagine our “camera” can only see one colour at a time (blue filter)
Imagine our “camera” can only see one colour at a time (red filter)
Imagine our “camera” can only see one colour at a time (green filter)
Combine the filtered images to form the final image
Scanner takes a series of measurements with each k-space “spatial filter” (as many filters as voxels)

The “spatial filters” are applied using gradients

Measurements are then combined using the Fourier Transform to form image
Scanner takes a series of measurements with each k-space “spatial filter” (as many filters as voxels)

Higher resolution means “finer” features, which require “finer” filters

More spatial resolution → more voxels and filters needed → longer acquisition time
If gradient is on, spatial frequencies change over time

Visualize as gradients “move us” through k-space!
If gradient is on, spatial frequencies change over time

Visualize as gradients “move us” through k-space!
The trajectory is the ordering of k-space data acquisition. The signal from the RF coil is transformed into a k-space trajectory. This trajectory represents the path through k-space or the sequence of spatial filters. The Fourier transform is applied to convert the k-space data into an image.
Linescan (2DFT) Acquisition

Acquire one line after each excitation
Linescan (2DFT) Acquisition

Acquire one line after each excitation

Useful for structural images (minimal artifacts)
Echo-planar Imaging (EPI) Acquisition

Acquire all of k-space in a “single shot”
Used for FMRI, diffusion imaging
Slice Selection

Transmit all frequencies corresponding to desired slice

\[ \omega_0 \]

frequency

gradient

excited slice
2D Multi-slice Imaging

Slices excited and acquired sequentially (separately)
Most scans acquired this way (including FMRI, DTI)
Simultaneous Multi-slice Imaging

“Multi-Band” Factor 2
MRI Physics

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Signal-to-noise ratio (SNR)

\[ \text{SNR} = \frac{\text{Signal}}{\sigma_{\text{noise}}} \]

All else being equal, we want to maximize SNR!!
Signal-to-noise ratio (SNR)
Protocol choices affecting SNR...

- RF receive coil & field strength
- Timing: bandwidth, TE & TR
- Voxel volume
- Scan duration (imaging time)
- Anything affecting signal!!!
SNR and acquisition time or averages

Longer acquisition ⇒ less noise ⇒ higher SNR

SNR improves with the *square root* of scan time

i.e., to *double* SNR you need to scan *4x* longer
Larger voxels have signal from more tissue!
- Signal proportional to voxel volume
- 2x2x2mm has 8x higher SNR than 1x1x1mm!
Averaging to achieve high resolution

Can we recover lost SNR by averaging?
Yes! But requires a 64-fold increase in scan time (because you only get square root benefit)
Contrast-to-noise ratio (CNR)
MRI Physics

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A source of signal loss: dephasing

When spins are “in-phase”, they are all oriented the same way.
Over time, the spins within a voxel lose alignment ("dephase").
Apparent increase in $T_2 = T_2^*$

Dephasing causes magnetization vectors to partially "cancel" each other out.

Dephasing results in a lower net signal magnitude.

Apparent decrease in $T_2$: called $T_2^*$ (more on Wednesday).
Deoxyhaemoglobin is the source of FMRI signal
Deoxyhaemoglobin is the source of FMRI signal

When oxygen is bound to the haemoglobin, it shields the magnetic effects of iron atoms in the heme groups.
Deoxyhaemoglobin is the source of FMRI signal

Without oxygen, the iron (Fe) is exposed, causing magnetic field inhomogeneities due to its strong magnetic properties

Field inhomogeneity leads to T2* change (FMRI signals)
The BOLD Effect

Blood Oxygenation Level Dependent (BOLD) effect

Vessels, depending on orientation and blood oxygen content will alter their local magnetic fields
BOLD Effect – vessel orientation

Water

Vessel

0°
Vessel parallel

Water

Vessel

45°

Water

Vessel

90°
Vessel perpendicular
BOLD Effect – vessel size

- B₀ direction
- Strength of Magnetic Field Inhomogeneity

Water

- Vessel

radius = 50 μm
radius = 100 μm
radius = 150 μm
BOLD Effect – blood oxygenation level

Water

Vessel

Oxygenation = 60%

Water

Vessel

Oxygenation = 30%

Water

Vessel

Oxygenation = 0%

B₀ direction

Strength of Magnetic Field Inhomogeneity

Oxygenation

Water
Oxygenation: $Y=60\%$
- More Oxygenated Hb
- Low inhomogeneity
- Longer T2*
- Higher signal

Oxygenation: $Y=0\%$
- More de-oxygenated Hb
- High inhomogeneity
- Shorter T2*
- Lower signal

**BOLD Contrast**
Vascular Response to Activation

- **O₂ metabolism**
- **blood flow**
- **blood volume**

\[ \text{dHb} = \text{deoxyhemoglobin} \]
\[ \text{HbO}_2 = \text{oxyhemoglobin} \]
\[ [\text{dHb}] \]
BOLD Contrast

Signal increases during activation (less decay)
Signal change for longer delay ($T_E$)
Typically, 1–5% signal change
BOLD signal and field strength ($B_0$)

SNR and BOLD effects can increase with field strength.

But image artefacts get worse at higher field strength.

3T is currently a good tradeoff of signal vs artefacts.
Sources of BOLD Signal

Indirect measure of activity (via metabolism!)

Subject’s physiological state & pathology can change neurovascular coupling, muddying interpretation
Hemodynamic response function (HRF)

Vascular response to activity is delayed & blurred
Described by “hemodynamic response function”
Limits achievable temporal resolution
Must be included in signal model
What is required of the scanner?

Typical stimulus lasts 1–30 s
Rapid imaging: an image every few seconds
Anatomical images take minutes to acquire!
Acquire “single-shot” images (e.g., EPI)
## Typical* FMRI Parameters

* Typical, *not* fixed!!

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<tr>
<th>Parameter</th>
<th>Value</th>
<th>Relevant points</th>
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| $T_E$ (echo time)         | 1.5T: 60 ms  
3.0T: 30-40 ms  
7.0T: 15-25 ms | Determines functional contrast, set $\approx T2^*$ |
| $T_R$ (repeat time)       | 1–4 s                                      | HRF blurring $< 1s$; Poor resolution $> 4s$         |
| Matrix size / Resolution  | 64x64 – 96x96  
2–3 mm                               | Limited by distortion, SNR, FOV                     |
| Scan duration             | 2-15 mins                                  | Lower limit: sensitivity  
Upper limit: compliance           |
Confounds: Noise

Purely random noise (example: “thermal”)

Structured noise (example: “physiological”)

Noise: signal fluctuations leading to less robust detection with respect to statistical measures
Confounds: Artefacts

Artefacts: systematic errors that interfere with interpretability of data/images

Dropout

Distortion

“Ghosting”
Source of signal dropout

BOLD contrast is based on signal dephasing
BOLD imaging requires longish delay ($T_E$) for contrast
Dropout is just extreme dephasinging

Dephasing also occurs near air-tissue boundaries
Sensitivity to BOLD means signal loss near air-tissue boundaries
BOLD Signal Dropout

Dephasing near air-tissue boundaries (e.g., sinuses)
BOLD contrast coupled to signal loss ("black holes")
Air-tissue effect is often larger than BOLD effect
Dropout is not correctable post-acquisition!
We think frequency maps to spatial location...
So errors in frequency cause spatial mis-localization!

*More on Wednesday...*
Final thoughts

Understand how different experimental parameters affect SNR and image artefacts

Tradeoffs: you can’t get something for nothing, but you do have options

Get to know an engineer/physicist/radiographer: get help setting up study protocols, show them your artefacts

Quality assurance: always look at your data, even if you are running a well-tested protocol
Questions:

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