What is MRI?

• Also known as NMR (nuclear magnetic resonance)
• “Nuclear” was dropped because of fear of something radioactive in MRI (there is no ionizing radiation in MRI)
• MRI in a nutshell
  • Strong magnet aligns protons in the body
  • Coils send radio waves that wack these protons out of alignment
  • Energy is released when these protons “relax” and return to their aligned orientation
  • Released energy is detected and used to create an image.
• OK, it gets a bit more complicated, but that’s the upshot.
MRI Hardware
MRI Safety
MRI Hardware
4 Requirements for MRI

- Static magnetic field B0
  - Generated by a giant superconducting electromagnet
- Radiofrequency coils
  - Turn on and off during scan
  - Induce perturbations at the resonant frequency (excitation).
  - When turned off, protons return to equilibrium and release energy (relaxation and decay)
- Gradient coils
  - Encode spatial details by varying the magnetic field strength in a spatially controlled manner.
- Shimming coils
  - Correct for field and gradient inhomogeneities.
• Thermal energy causes protons to spin about themselves.
• Protons are charged species -> generate an electrical current.
• Moment (µ) is the torque exerted on this moving charge in a magnetic field.
• Angular momentum (J) is the product of the spin’s mass and its angular velocity.
• Net magnetization (M) is the sum of all moments.
MR Signal Generation

- Protons assume either a parallel or anti-parallel state to the direction of $B_0$
- This happens through a gyroscopic motion called precession (like a spinning top)
Precession
MR Signal Generation

- Protons assume one of two states in $B_0$:
  - Parallel to magnetic field (low energy state, stable)
  - Anti-parallel to magnetic field (high energy state, unstable)
- Proportion depends on temperature and magnetic field strength
- The ratio of protons in each state determines $M$
Excitation and Reception

More spins in the low-energy state

Excitation by absorbing energy

Releasing absorbed energy -> Relaxation
Relaxation

Longitudinal relaxation

Transverse relaxation

T1 relaxation

T2 relaxation
$T_1$ and $T_2$

(A) Longitudinal magnetization (arbitrary units) vs. Time since excitation (s)

(B) Transverse magnetization (arbitrary units) vs. Time since excitation (ms)

- $T_1$ recovery
- $T_2$ decay
T1 recovery

- Excitation pulse at 90°
- Longitudinal magnetization (arbitrary units)
- Time (s)
- T1 recovery curve
- Points A, B, C
T2 Decay

X-projection (real axis)
\[ M_x = (-M_0 \cos \omega t)e^{-t/T_2} \]

Y-projection (imaginary axis)
\[ M_y = (M_0 \sin \omega t)e^{-t/T_2} \]
How do we get to an image?

- Longitudinal magnetization
- Slice excitation
- Free precession
- Filling K-space
- 2D/3D FT
- MR image
What is K-space?

- It’s where we store the MR signal
- It has a mathematical relationship to the image (Fourier Transform)
- We can create an MR image from data stored in K-space (i.e. raw data)
- We need to fill lots of K-space (line by line) before we can generate a good MR image.
The Fourier transform allows us to determine the constituent sine waves of any signal.
What do sine waves look like?

(A)

(B)
Storing data in k-space

many radiofrequency signals

“raw data space”
K-space is an array of numbers whose Fourier transform is the MR image.
RF spikes
K-space High vs. Low Frequencies
K-space High vs. Low Frequencies
Fourier Transforms

final image
Fourier Transforms

final image
There are many ways to fill K-space

Fig. 4. Multi-shot projection imaging paths
Fig. 5. Example of multi-shot FT imaging
Fig. 6. Single-shot, spiral FT imaging
Fig. 7. Spiral imaging path
Summary of image formation

- Longitudinal magnetization
- Slice excitation
- Free precession
- Filling K-space
- 2D/3D FT
- MR image
Parallel Imaging Techniques

- Undersample K-space and collect data from multiple imaging coils.

Each coil will produce a picture that is 1/4 the size and made up of the overlap of the 4 sections.
What is BOLD?

- **Blood-oxygenation-level-dependent** signal
- Local neuronal activity has metabolic demands
- BOLD captures changes in the vascular system that (in theory) occur in response to changes in neural activity.
- Complicated relationship

![Diagram illustrating the relationship between stimulus, neural activity, CMRO₂, CBF, CBV, and BOLD signal](image)

Buxton (2001)
Discovery of the BOLD signal

- Oxygenated and deoxygenated hemoglobin have different magnetic susceptibility.
- Deoxyhemoglobin (dHB) is paramagnetic and oxygenated hemoglobin (Hb) is diamagnetic (Pauling, 1936).
Discovery of the BOLD signal

- Blood oxygen affects the visibility of blood vessels on T2* weighted images (Ogawa, 1990).
- Controlled the amount of oxygen breathed by anesthetized rats.

- MR pulse sequences sensitive to T2* should show this signal contrast.
BOLD fMRI at a glance

- Basal CBF
- Basal CBV
- Basal dHB levels
- Normal signal

- Increased CBF
- Increased CBV
- Decreased dHB
- Increased signal
The hemodynamic response

- BOLD signal:
  - $[dHB]$ increase
  - CBV decrease

- $[HbO2]$ influx
- CBV increase

- $[HbO2]$ normalize
- CBV normalize (slow)

Inset: T2* contrast vs. time with graphs for $HbO2$ and $dHB$ signal strength.
Spatial resolution in BOLD fMRI

Affected by several factors:

- Hardware (field and gradient strength)
- Ability of subject to remain still
- Hemodynamic effects (size of capillary bed)
- Spatial sensitivity of contrast mechanism
- Draining vein effects
Temporal resolution in BOLD fMRI

Affected by several factors:

- Speed of hemodynamic response
- $T_1$ recovery time (ideally $TR > T_1$ [1-1.5s])
- Gradient duty cycle
- Peripheral nerve stimulation by fast switching gradients
BOLD signal considerations

The magnitude of the BOLD signal is very small compared to the overall MR signal

- Subject motion
- Thermal noise
- Cardiac and respiratory effects
- Scanner drift
- Susceptibility artifacts
- Draining veins
Variability in the BOLD response

- Aguirre and D’Esposito showed that the general shape of the HRF is stable within individuals.
- Precise shape differed from individual to individual and from one cortical area to another.
- Solution: subject-specific HRF based on a different dataset.

Aguirre, Zarahn and D’Esposito et al., 1997
Variability in the BOLD response

- Hemodynamic coupling also changes with age
- Increased variability in HRF in older adults, not due to head motion
- Weaker BOLD response in older adults possibly due to differences in CBF?

D’Esposito et al. 1999
Ances et al. 2009
Link to neural activity - fMRI/EEG

Logothetis 2002
Reflects a change in neural activity directly and monotonically.

Most directly related to local field potentials (LFP), i.e., sum of input and local processing within the region. (marginally better than MUA)