Lecture 2: MR Physics: Image Origin
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- Magnetic Resonance
- Radio frequency absorption
- Relaxation: Radio frequency emission
- Gradients
- Increases signal/noise: antenna selection, field strength.
Modern neuroscience

• Different tools exist for inferring brain function.
• No single tool dominates, as each has limitations.
• FMRI good for "networks"

<table>
<thead>
<tr>
<th>Temporal resolution</th>
<th>Spatial resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>good (millisecond)</td>
<td>good (neuron)</td>
</tr>
<tr>
<td>poor (months)</td>
<td>poor (whole brain)</td>
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</table>

- lesions
- pet
- tms
- nirs
- eeg
- fmri
- scr

Different tools include:
- fMRI
- PET
- TMS
- NIRS
- EEG
- SCR
How does MRI work?

- We are all made out of water (70%)
- In some elements, Protons spin in a Mag Field
- A radio frequency pulse can perturb the Spin in two independent ways (T1, T2)
- The Proton will emit that frequency and can be “readout
- The frequency can be modulated to select spatial location
- Tissues are differentially perturbed by the RF pulse
- Images can be constructed from manipulated T1 and T2
- A bunch of Lucky coincidents.. but lead to 3 Nobel Prizes.
Anatomy of an atom

- Atoms are the building blocks of our world.
- Composed of 3 components
  - Electrons: tiny negatively charged particles.
  - Protons: heavy positively charged particles.
  - Neutrons: heavy particles without charge.
- Electrons are often thought of like planets: tiny objects distantly orbiting a massive core.
- Neutrons and protons form the dense nucleus of an atom.
Periodic Table of the Elements

- Alkali Metals
- Alkaline Earth Metals
- Transition Metals
- Other Metals
- Nonmetals
- Noble Gases
- Inner Transition Metals

- Gaseous State
- Liquid State
- Solid State
- Synthetically Prepared

- Name Not Officially Assigned

Lanthanide Series
- La
- Ce
- Pr
- Nd
- Pm
- Sm
- Eu
- Gd
- Tb
- Dy
- Ho
- Er
- Tm
- Yb

Actinide Series
- Ac
- Th
- Pa
- U
- Np
- Pu
- Am
- Cm
- Bk
- Cf
- Es
- Fr
- Md
- No
Atomic Nuclei

- Nuclei are composed of protons and neutrons.
- Protons determine the element.
- Neutrons determine the isotope
  - Hydrogen: always one proton
    - Usually no neutrons (‘Proton’ $^1\text{H}$); Rarely one (Deuterium $^2\text{H}$) or two (Tritium $^3\text{H}$: radioactive, spontaneous decay).
  - Helium: always two protons
    - Usually two neutrons ($^4\text{He}$); Rarely only one ($^3\text{He}$).
Nuclear Magnetic Resonance

- Felix Block and Edward Purcell
  - 1946: the nuclei of some elements absorb and re-emit radio frequency energy when in magnetic field
  - 1952: Nobel prize in physics
- Atoms with odd number of protons/neutrons spin in a magnetic field
  - Nuclear: properties of nuclei of atoms
  - Magnetic: magnetic field required
  - Resonance: interaction between magnetic field and radio frequency
- Analogy: atoms precess in a magnetic field like tops spin in gravitational field
Outside magnetic field
• Spins randomly oriented

In magnetic field:
• Spins align parallel or anti-parallel to magnetic field.
• At room temperature, ~4 parts per million more protons per Tesla align with versus against field.
• As field strength increases, there is a bigger energy difference between parallel and anti-parallel alignment (faster rotation = more energy).
  • A larger proportion will align parallel to field.
  • More energy will be released as nuclei align.
  • MR signal increases with square of field strength.
Resonant Frequency of Nuclei

- We will focus on $^1$H
  - Most abundant in body (70% of atoms).
  - Elements with even numbers of neutrons and protons have no spin, so we can not image them ($^4$He, $^{12}$C).
  - $^{23}$Na and $^{31}$P are relatively abundant, so can be imaged.

- Larmor frequency varies for elements:
  - $^1$H = 42.58 Mhz/T
  - $^{13}$C = 10.7 Mhz/T
  - $^{19}$F = 40.1 Mhz/T
  - $^{31}$P = 17.7 Mhz/T

- Therefore, by sending in a RF pulse at a specific frequency we can selectively energize $^1$H.
MRI signals are in the same range as FM radio and TV (30-300MHz).
Unlike X-rays, MRI is non-ionizing radiation.
Specific absorption rate (SAR):
- Absorbed RF warms tissue
- Increases ~ with square of field strength.
- FDA limits SAR, and is a limiting factor for some protocols
- For head, limit is 3 W/kg averaged over 10 minutes.
  - Problem for light individuals (children)
  - Tune sequence, or alternate between high and low energy sequences
Radiofrequency Pulses

- **Align**
  - Nuclei align to static magnetic field.
  - Nuclei precesses at Larmor frequency

- **Flip**
  - A radiofrequency (RF) pulse at the Larmor frequency will be absorbed.
  - Degree of spin tilted (flipped).

- **Relax**
  - Nuclei re-aligns to static field
  - Emits RF at the Larmor frequency
  - We can measure this signal
Anatomy of an MRI scan

- Place object in strong static magnetic field, then.
  1. Transmit Radio frequency pulse: atoms absorb energy
  2. Wait
  3. Listen to Radio Frequency emission due to relaxation
  4. Wait, Goto 1

- Time between set 1 and 3 is our Echo Time (TE)
- Time between step 1 being repeated is our Repetition Time (TR).
- TR and TE influence image contrast.
Precession
1. in B0

2. RF PULSE

3. Return to B0
T1 and T2 definitions

- After RF is absorbed, emitted RF signal decays with time.
- Two simultaneous but independent reasons for signal loss: recovery and dephasing.
- **T1-Relaxation: Recovery**
  - Recovery of longitudinal orientation.
  - ‘T1 time’ refers to interval where 63% of longitudinal magnetization is recovered.
- **T2-Relaxation: Dephasing**
  - Loss of transverse magnetization.
  - ‘T2 time’ refers to interval where only 37% of original transverse magnetization is present.
Contrast: T1 and T2 Effects

- T1 effects measure recovery of longitudinal magnetization.
- T2 refers to decay of transverse magnetization.
- T1 and T2 vary for different tissues. For example, fat has very different T1/T2 than CSF. This difference causes these tissue to have different image contrast.
- T1 is primarily influenced by TR, T2 by TE.

![Graph showing T1 and T2 effects](image_url)
MR Contrast – a definition

- Contrasts influence the brightness of a voxel.
  - E.G. water (CSF) dark in a T1-weighted scan, bright in a T2 scan.
- Types of MR contrasts:
  1. Static Contrast: Sensitive to relaxation properties of the spins (T1, T2)
  2. Endogenous Contrast: Contrast that depends on intrinsic property of tissue (e.g. fMRI BOLD)
  3. Exogenous contrast: Contrast that requires a foreign substance (e.g. Gadolinium)
  4. Motion contrast: Sensitive to movement of spins through space (e.g. perfusion).
How does all this Flipping etc make a spatial image?

- To create spatial images, we need a way to cause different locations in the scanner to generate different signals.
- To do this, we apply gradients.
- Gradients make the magnetic field slightly stronger at one location compared to another.
MRI scanner anatomy

- A helium-cooled superconducting magnet generates the static field.
  - Always on: only quench field in emergency.
  - niobium titanium wire.
- Coils allow us to
  - Make static field homogenous (shims: solenoid coils)
  - Briefly adjust magnetic field (gradients: solenoid coils)
  - Transmit, receive RF signal (RF coils: antennas)
Reconstruction

- Raw MRI data is 2D fourier image
- Modern scanners automatically convert k-space to image space (reconstruction).
- Use Tokarczuk’s free Intel Reconstruction Tool to manually reconstruct: www.mricro.com/mricro/import/index.html
- Images with even number of rows/columns faster to reconstruct
  - This is why most image matrices are a power of 2 (64, 128, 256)
  - Modern scanners allow other values (e.g. 96) but not primes (97)
Recipe to

- 1. SELECT Slice
- 2. ACTIVATE Slice
- 3. READOUT Slice

- Do it again.
Slice Selection Gradient

- Gradients: field stronger at one location compared to another.
- Larmor frequency different along this dimension.
- RF pulse only energizes slice where field strength matches Larmor frequency.
Slice Selection Gradient

1. Gradual gradients select thick slices, steep gradients select thinner slices.
   - Rapid changes in field strength (dB/dt) induce electrical currents.
   - For MRI, FDA limits dB/dt - some protocols elicit peripheral nerve stimulation (mild tingling, muscle twitches).
   - Transcranial Magnetic Stimulation (TMS) intentionally employs extreme dB/dt to stimulate brain activity.

2. Position of gradient determines which 2D slice is selected.

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[Diagram showing field strength and Z position with gradual and steep gradients illustrating slice selection.]
Phase encoding gradient

- Orthogonal gradient between RF pulse and readout
- This adjusts the phase along this dimension.
- Analogy: Phase encoding is like timezones. Clocks in different zones will have different phases.
Frequency encoding gradient

- Apply final orthogonal gradient when we wish to acquire image.
- Slice will emit signal at Lamour frequency, e.g. lines at higher fields will have higher frequency signals.
- Aka ‘Readout gradient’.
MRI terminology

Orientation: typically coronal, sagittal or axial, can be in-between these (oblique)

Matrix Size:
- Voxels in each dimension

Field of view:
- Spatial extent of each dimension.

Resolution:
- FOV/Matrix size.

Axial Orientation
- 64x64 Matrix
- 192x192mm FOV
- 3x3mm Resolution

Sagittal Orientation
- 256x256 Matrix
- 256x256mm FOV
- 1x1mm Resolution
Volumes

- 3D volumes are composed of stacks of 2D slices, like a loaf of bread.
- Each slice has a thickness.
  - Thicker slices have more hydrogen, so more signal
    - Volume of 1x1x1mm voxel is 1mm$^3$
    - Volume of 1x1x2mm voxel is 2mm$^3$
  - Thinner slices provide higher resolution.
- Optional: gap between slices.
  - Reduces RF interference
  - Allows fewer slices to cover whole brain.
Signal and Field Strength

- 1.5-3.0T typical clinical; 3.0T typical research
- NbTi max ~11.7T (~9.4T at atmospheric pressure)
- NbSn max ~22T (brittle, hard to manufacture)
- Increasing field strength yields
  - Faster Larmor frequency
  - Larger ratio of nuclei aligned
  - More signal as nuclei realign
  - T1 increases; T2 decreases (contrast lecture)
  - Signal: square of field strength
  - Noise: ~linear with field strength
  - In theory, 3T twice SNR of 1.5T (Less in practice)
  - Benefits: better SNR
  - Costs: Artifacts, Money, SAR, wavelength effects, auditory noise
Signal to Noise

• Signal To noise is given by the formula
  \[ \text{Signal} = V\sqrt{N} \]
• Where V is the volume and N is the number of samples averaged (referred to as ‘Nex’, as in ‘number of excitations’).
• For example, to get the same SNR as a single 3x3x3mm scan (27mm\(^3\)) we would need to collect 12 2x2x2mm (8mm\(^3\)) scans or 768 1x1x1mm (1mm\(^3\)) scans.
Magnetic attraction

MRI field measured in Tesla.
Force in magnetic field (1.8T, unit dynes)
15,000 Gauss per Tesla
Compass needle moved by Earth's field ~0.5 Gauss
3T MRI ~45,000 Gauss
  Water: -22
  Copper: -2.6
  Copper Chloride: +280
  Iron: +400,000
Diamagnetic material repelled (e.g. H2O).
Paramagnetic material attracted (e.g. CuCl, Gd).
Ferromagnetic material strongly attracted (Fe).

Even without magnetic field, magnetic moments aligned
Dangerous near MRI scanner
A steel shackle meets a 4 Tesla magnet...
There are FOUR variables that affect the Image:

- TR
- TE
- Flip Angle (\(\alpha\))
- Tissue type (CSF, Gray, White, Fat, Blood)

(in that we select them to look at)

trading off SPEED, CONTRAST, SPATIAL RESOLUTION
(noise)
Next time

Making Contrasts: Controlling the IMAGE.
Signal to Noise: Antennas

- The MRI antenna is called a coil.
- We use different coils for different body parts.
- For brains, the most common antenna is the head coil, which is a volume coil: it shows the whole brain.
- We can also use a surface coil: it gives great signal for a small field of view.
Parallel Imaging (SENSE, iPAT)

- Parallel imaging: use multiple surface coils to generate a volume image.
  - Dramatically reduces spatial distortion and increases signal.
  - Optionally, you can acquire images more rapidly by only collecting a portion of k-space.
    - Reduces spatial distortion and increases speed of acquisition. Some loss in signal.
    - E.G. SENSE R=2 collects half of the lines.
    - E.G. SENSE R=3 collects one third

8-channel array
Parallel Imaging (SENSE, iPAT)

- Increasing SENSE reduction factor decreases acquisition time and spatial distortion, but high values lead to reduced signal.