MRI Physics I: Spins, Excitation, Relaxation

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Outline

• Introduction to Nuclear Magnetic Resonance Imaging
  – NMR Spins
  – Excitation
  – Relaxation
  – Contrast in images
Magnetic resonance is based on the emission and absorption of energy in the radio frequency range of the electromagnetic spectrum by nuclear spins.
Historical Notes

- In 1946, MR was discovered independently by Felix Bloch and Edward Purcell.
- Initially used in chemistry and physics for studying molecular structure (spectrometry) and diffusion.
- In 1973 Paul Lauterbur obtained the 1st MR image using linear gradients.
- 1970’s MRI mainly in academia.
- 1980’s MRI was commercialized.
- 1990’s fMRI spread rapidly.
- 2000’s era of new fast imaging methods.
Important Events in the History of MRI

- 1946 MR phenomenon - Bloch & Purcell
- 1950 Spin echo signal discovered - Erwin Hahn
- 1952 Nobel Prize - Bloch & Purcell
- 1950 - 1970 NMR developed as analytical tool
- 1963 Doug Noll born
- 1972 Computerized Tomography
- 1973 Backprojection MRI - Lauterbur
- 1975 Fourier Imaging - Ernst (phase and frequency encoding)
- 1977 MRI of the whole body - Raymond Damadian
  - Echo-planar imaging (EPI) technique - Peter Mansfield
- 1980 Spin-warp MRI demonstrated - Edelstein
- 1986 Gradient Echo Imaging NMR Microscope
- 1989 Echo-Planar Imaging (images at video rates = 30 ms / image)
- 1991 Nobel Prize - Ernst
- 1992 BOLD Functional MRI (fMRI)
- 1994 Hyperpolarized $^{129}$Xe Imaging
- 1997 Parallel MRI
- 2003 Nobel Prize – Lauterbur & Mansfield
- 2007 Sparse sampling/compressed sensing
- 2010 Multiband (simultaneous multislice) MRI
- 2017 The machine learning craze
MR Physics

- Based on the quantum mechanical properties of nuclear spins

- Q. What is SPIN?
  - A. Spin is a fundamental property of nature like electron charge or mass. Spin comes in multiples of 1/2 and can be + or -. 
Properties of Nuclear Spin

Nuclei with:

• Odd number of Protons
• Odd number of Neutrons
• Odd number of both

exhibit a net MAGNETIC MOMENT
(e.g. $^1\text{H}$, $^3\text{He}$, $^{31}\text{P}$, $^{23}\text{Na}$, $^{17}\text{O}$, $^{13}\text{C}$, $^{19}\text{F}$)

Pairs of spins take opposing states, cancelling the observable effects.
(e.g. $^{16}\text{O}$, $^{12}\text{C}$)
# Common NMR Active Nuclei

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Spin</th>
<th>% natural abundance of isotope</th>
<th>( \gamma ) MHz/T</th>
<th>elemental abundance in body</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^1\text{H})</td>
<td>(1/2)</td>
<td>99.985%</td>
<td>42.575</td>
<td>63%</td>
</tr>
<tr>
<td>(^2\text{H})</td>
<td>1</td>
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Bar Magnets
“North” and “South” poles
A “Spinning” Proton

A “spinning” proton generates a tiny magnetic field

Like a little magnet + angular momentum
In a magnetic field, spins can either align with or against the direction of the field.
Protons in the Human Body

• The human body is made up of many individual protons.

• Individual protons are found in every hydrogen nucleus.

• The body is mostly water, and each water molecule has 2 hydrogen nuclei.

• 1 gram of your body has $\sim 6 \times 10^{22}$ protons
Spinning Protons in the Body

Spinning protons are randomly oriented.

No magnetic field - no net effect
Protons in a Magnetic Field

Spinning protons become aligned to the magnetic field.

On average - body become magnetized.
Magnetization of Tissue
A spinning top in a gravitational field is similar to a nuclear spin in a magnetic field (classical description)
A Top in a Gravitational Field

Gravity exerts a force on top that leads to a Torque (T):

\[ T = \frac{dL}{dt} = L \times \left( \frac{rm}{L} \right) g \]
A Top in a Gravitational Field

This causes the top to *precess* around $g$ at frequency:

$$\Omega = \frac{r \, g \, m}{L}$$
Spins in a Magnetic Field

Spins have both magnetization ($\mathbf{M}$) and angular momentum ($\mathbf{L}$):

$$\mathbf{M} = \gamma \mathbf{L}$$

Applied magnetic field ($\mathbf{B_0}$) exerts a force on the magnetization that leads to a torque:

$$\mathbf{T} = \frac{d\mathbf{L}}{dt} = \mathbf{M} \times \mathbf{B_0}$$
Spins in a Magnetic Field

This can be rewritten to yield the famous Bloch Equation:

\[ \frac{dM}{dt} = M \times \gamma B_0 \]

which says that the magnetization will precess around the applied magnetic field at frequency:

\[ \omega_0 = \gamma B_0 \]

“Larmor Frequency”
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So far …

- At the microscopic (quantum) level: spins have angular momentum and magnetization
  - We use spin, proton, hydrogen nucleus interchangeably

- The magnetization of particles is affected by magnetic fields: torque, precession

- At the macroscopic level: They can be treated as a single magnetization vector (makes life a lot easier)

- Next: NMR uses the precessing magnetization of water protons to obtain a signal
Spins in a Magnetic Field

Three “spins” with different applied magnetic fields.
The precessing magnetization generates the signal in a coil we receive in MRI, $v(t)$.
Frequency of Precession

• For $^1\text{H}$, the frequency of precession is:
  – 63.8 MHz @ 1.5 T ($B_0 = 1.5$ Tesla)
  – 127.6 MHz @ 3 T
  – 300 MHz @ 7 T

\[ \omega_0 = \gamma B_0 \]

“Larmor Frequency”
Excitation

- The magnetization is initially parallel to $B_0$

- But, we need it perpendicular in order to generate a signal
The Solution: Excitation

RF Excitation (Energy into tissue)

Magnetic fields are emitted
Excitation

- Concept 1: Spin system will absorb energy at $\Delta E$ corresponding difference in energy states
  - Apply energy at $\omega_0 = \gamma B_0$ (RF frequencies)

- Concept 2: Spins precess around a magnetic field.
  - Apply magnetic fields in plane perpendicular to $B_0$. 
Resonance Phenomena

- Excitation in MRI works when you apply magnetic fields at the “resonance” frequency.

- Conversely, excitation does not work when you excite at the incorrect frequency.
Resonance Phenomena

- **Wine Glass**
  - [Link](http://www.youtube.com/watch?v=JiM6AtNLXX4)

- **Air Track**
  - [Link](http://www.youtube.com/watch?v=wASkwB8DJpo)
Try this: Apply a magnetic field ($B_1$) rotating at $\omega_0 = \gamma B_0$ in the plane perpendicular to $B_0$.

$\uparrow$

Magnetization will tip into transverse plane.
Off-Resonance Excitation

• Excitation only works when $B_1$ field is applied at $\omega_0 = \gamma B_0$ (wrong $\Delta E$)

• We will see that this allows us to select particular groups of spins to excite (e.g. slices, water or fat)
Flip Angle

- Excitation stops when the magnetization is tipped enough into the transverse plane
- We can only detect the transverse component: \( \sin(\alpha) \)
- 90 degree flip angle will give most signal (ideal case)
- Typical strength is \( B_1 = 1-2 \times 10^{-5} \) T
- 90 degree tip takes about 300-600 \( \mu \)s

Courtesy Luis Hernandez
What next? ✡ Relaxation

Excitation

Spins “relax” back to their equilibrium state
Relaxation

• The system goes back to its equilibrium state

• Two main processes:
  – Decay of traverse (observable) component
  – Recovery of parallel component
$T_1$ - relaxation

- Longitudinal magnetization ($M_z$) returns to steady state ($M_0$) with time constant $T_1$
- Spin gives up energy into the surrounding molecular matrix as heat
- Factors
  - Viscosity
  - Temperature
  - State (solid, liquid, gas)
  - Ionic content
  - Bo
  - Diffusion
  - etc.
T1 Recovery

- Tissue property (typically 1-3 seconds)
- Spins give up energy into molecular matrix
- Differential Equation:

\[
\frac{dM_z}{dt} = - \frac{(M_z - M_0)}{T1}
\]
$T_2$ - relaxation

- Transverse magnetization ($M_{xy}$) decay towards 0 with time constant $T_2$
- Factors
  - $T_1$ ($T_2 \leq T_1$)
  - Phase incoherence
    » Random field fluctuations
    » Magnetic susceptibility
    » Magnetic field inhomogeneities (RF, $B_0$, Gradients)
    » Chemical shift
    » Etc.
T2 Decay

- Tissue property (typically 10’s of ms)
- Spins dephase relative to other spins
- Differential Equation:

\[
\frac{dM_{xy}}{dt} = -\frac{M_{xy}}{T2}
\]
Steps in an MRI Experiment

0. Object goes into $B_0$
1. Excitation
2a. $T_2$ Relaxation (faster)
2b. $T_1$ Relaxation (slower)
Excitation
Relaxation
Resting State
Excitation
Excitation
$T_2$ Relaxation
$T_2$ Relaxation
$T_2$ Relaxation
$T_2$ Relaxation
$T_1$ Relaxation
T$_1$ Relaxation
$T_1$ Relaxation
$T_1$ Relaxation
## Typical $T_1$’s, $T_2$’s, and Relative “Spin Density” for Brain Tissue at 3.0 T

<table>
<thead>
<tr>
<th>Tissue Type</th>
<th>$T_1$ (ms)</th>
<th>$T_2$ (ms)</th>
<th>$\rho_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>4000</td>
<td>2000</td>
<td>1</td>
</tr>
<tr>
<td>CSF</td>
<td>4000</td>
<td>500</td>
<td>1</td>
</tr>
<tr>
<td>Gray matter</td>
<td>1330</td>
<td>110</td>
<td>0.95</td>
</tr>
<tr>
<td>White matter</td>
<td>830</td>
<td>80</td>
<td>0.8</td>
</tr>
<tr>
<td>Fat</td>
<td>380</td>
<td>45</td>
<td>1</td>
</tr>
</tbody>
</table>

Several refs: Wansapura et al., JMRI, 1999; Bojoquez et al. MRI, 2017, and others.

Note: Large variability based on technique, individual, area of brain, etc.
The Pulsed MR Experiment

- MRI uses a repeated excitation pulse experimental strategy
Contrast

• TR mainly controls T1 contrast
  – Excitation or flip angle also contributes

• TE mainly controls T2 contrast
T1 Contrast and TR
T1 Contrast and TR
T1 Contrast and TR
T1 Contrast and TR
T1 Contrast and TR
T1 Contrast and TR
T1 Contrast

- For short TR imaging, tissues with short T1’s (rapidly recovering) are brightest
  - Fat > brain tissue
  - White Matter > Grey Matter
  - Gray Matter > CSF
T2 Contrast and TE
T2 Contrast and TE
T2 Contrast and TE
T2 Contrast and TE
T2 Contrast and TE
For long TE imaging, tissues with short T2’s (rapidly recovering) are darkest
- Fat < brain tissue
- White Matter < Grey Matter
- Gray Matter < CSF
Contrast Equation

- For a 90 degree flip angle, the contrast equation is:

\[
\text{Signal} \propto \rho \left(1 - e^{-\frac{TR}{T1}}\right) e^{-\frac{TE}{T2}}
\]

- Spin Density
- T1-weighting
- T2-weighting
Can the flip angle be less than 90?

- Of course, but the contrast equation is more complicated.
- Flip angle can be chosen to maximize signal strength: Ernst Angle
Next Step

Making an image!!

First – some examples of MR Images and Contrast
Supratentorial Brain Neoplasm

T1-weighted image with contrast

T2-weighted image
Cerebral Infarction

MR Angiogram

T2-weighted image
Imaging Breast Cancer

http://tristans.com/services/breast-mri/
Imaging any Orientation

Axial (transverse)  Sagittal  Coronal
Imaging Joints

Normal ACL

Torn ACL

http://wolverhamptonhipandkneeclinic.co.uk/services-view/anterior-cruciate-ligament-acl-surgery/
Imaging Air Passages
Tagging Cardiac Motion

https://www.nature.com/articles/nrcardio.2009.189
Calculated Images

Diffusion and Perfusion Weighted MRI