MRI Physics I: Spins, Excitation, Relaxation

Douglas C. Noll
Biomedical Engineering
University of Michigan
Michigan Functional MRI Laboratory
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
• 2010’s: technology continues, standardization
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
• 1988 Angiography – O’Donnell & Dumoulin
• 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. $^1$H, $^3$He, $^{31}$P, $^{23}$Na, $^{17}$O, $^{13}$C, $^{19}$F )

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

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Spin $I$</th>
<th>% natural abundance of isotope</th>
<th>$\gamma$ MHz/T</th>
<th>elemental abundance in body</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1$H</td>
<td>1/2</td>
<td>99.985%</td>
<td>42.575</td>
<td>63%</td>
</tr>
<tr>
<td>$^2$H</td>
<td>1</td>
<td>0.015%</td>
<td>6.53</td>
<td>63%</td>
</tr>
<tr>
<td>$^{13}$C</td>
<td>1/2</td>
<td>1.108%</td>
<td>10.71</td>
<td>9.4%</td>
</tr>
<tr>
<td>$^{14}$N</td>
<td>1</td>
<td>99.63%</td>
<td>3.078</td>
<td>1.5%</td>
</tr>
<tr>
<td>$^{15}$N</td>
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<td>0.37%</td>
<td>4.32</td>
<td>1.5%</td>
</tr>
<tr>
<td>$^{17}$O</td>
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<td>1/2</td>
<td>100%</td>
<td>40.08</td>
<td>0%</td>
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<tr>
<td>$^{23}$Na</td>
<td>3/2</td>
<td>100%</td>
<td>11.27</td>
<td>0.041%</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 ~ 6 x 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

[Diagram showing magnetization of tissue]
A spinning top in a gravitational field is similar to a nuclear spin in a magnetic field (classical description)
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 \((M)\) and angular momentum \((L)\):

\[
M = \gamma L
\]

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

\[
T = \frac{dL}{dt} = M \times B_0
\]
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 NMR Signal

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
  • http://www.youtube.com/watch?v=JiM6AtNLXX4

• Air Track
  • 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 $B_0$ → 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 $B_1 = 1-2 \times 10^{-5} \text{ T}$.
- 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
T₂ Relaxation
$T_1$ Relaxation
$T_1$ Relaxation
T₁ 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
T2 Contrast

• 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:

$$\text{Signal} \propto \rho (1 - e^{-\frac{TR}{T1}}) e^{-\frac{TE}{T2}}$$

- 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 chose 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

https://sites.google.com/a/wisc.edu/neuroradiology/image-acquisition/the-basics
Imaging Joints

Normal ACL

Torn ACL

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

Noll

Tagging Cardiac Motion

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

Diffusion and Perfusion Weighted MRI
