MRI signal in biological tissues
Proton, Spin, T1, T2, T2*  

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Outline  
- Nuclear magnetism  
  - nuclear magnetic moment  
  - protons - spin ½ system  
  - Larmor Equation  
  - Resonance  
- Magnetic Resonance in tissues  
  - Longitudinal magnetization; spin-lattice relaxation time, T1  
  - RF pulses  
  - Transverse magnetization; T2*, T2 relaxation  
  - Spin Echo  
  - T1, T2 contrast

MRI scanner  
- Very strong (1.5T, 3.0T, 7T), uniform magnetic field – to magnetically polarize the patient  
- Radio-frequency coils – to generate and detect MRI signal in tissues (at resonance)  
- Gradient coils – to spatially encode signal for reconstruction (loud noise)
What is the source of MRI signal?

Signal in conventional MRI comes from Hydrogen nuclei ("protons")

- 67% of atoms in human body is hydrogen
- 10^28 hydrogen nuclei
- H_2O (65%)
- Proteins (28%)
- Lipids (12%)

Hydrogen atom
- Negative electron, nucleus = positive proton
- Nuclei are "spinning" (have angular momentum, J)

What is the source of MRI signal?

Signal in conventional MRI comes from Hydrogen nuclei (a.k.a. "protons")

- Hydrogen atom
  - Magnetic nuclei: proton
- Nuclei are "spinning"
  - Spin angular momentum
- Spinning charges have magnetic moment
  - Proportional to angular momentum

\[ \mu = \gamma J \]

<table>
<thead>
<tr>
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<tr>
<td>(^1\text{H})</td>
<td>42.6</td>
</tr>
<tr>
<td>(^7\text{Li})</td>
<td>16.5</td>
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<tr>
<td>(^23\text{Na})</td>
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<td>17.2</td>
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<td>(^129\text{Xe})</td>
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Hydrogen nuclei ("protons")

- Inside the magnetic field (Quantum Mechanics)
  - Moments precess in "parallel" (spin up)

Hydrogen nuclei ("protons")

- Inside the magnetic field (Quantum Mechanics)
  - Moments precess in "parallel" (spin up) or "anti-parallel" (spin down) orientation

"spin-up" state

"spin-down" state
Inside the magnetic field (Quantum Mechanics)

- Moments precess in "parallel" (spin up) or "anti-parallel" (spin down) orientation

\[ \Delta E = h(\gamma B_0) = \hbar \nu_0 \]

Both states have equal energies. The "parallel" state has lower energy than the "antiparallel" state.

\[ \nu_0 = \frac{\hbar c}{2\mu_0 m_0} \]

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Nucleus \( \nu_0 \) \[\text{MHz}(1.5\text{T})\]

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Spontaneous transitions between "parallel" and "antiparallel" states are associated with exchange of Larmor photons between protons and the "lattice".
Spin-lattice relaxation

• When $B_0 = 0$ proton moments are oriented randomly. Tissue magnetization = 0.

• When $B_0 > 0$ proton moments **rearrange** exchanging energy with the lattice.
  • Preferential orientation is parallel with the field (lower energy)

• Tissue magnetization builds up
• When \( B_0 = 0 \) proton moments are oriented randomly. Tissue magnetization = 0.
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  - Preferential orientation is parallel with the field (lower energy)
  - Tissue magnetization builds up
  - In thermal equilibrium ratio moment populations are given by the Boltzmann distribution

\[
\frac{N_{\text{parallel}}}{N_{\text{anti-parallel}}} = \exp \left( \frac{\hbar B_0}{k_B T} \right)
\]

\[
\frac{\Delta N}{N} \propto B_0
\]

• \( T_1 \) – time scale for reaching equilibrium distribution of proton moments: spin-lattice relaxation time
Spin-lattice relaxation

- T1 — time scale for reaching equilibrium distribution of proton moments: *spin-lattice relaxation time*
- T1 varies between different tissues and is one of the sources of MRI contrast

![Graph showing longitudinal magnetization (%) over time](image)

**Magnetic Resonance**

- Transitions between "spin up" and "spin down" states can be driven by RF field applied at resonance (at Larmor frequency)
- Larmor Equation: \( \nu_0 = \gamma \cdot B_0 \) (can select which nuclei we "tune in" to)

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- \( B_0 = 1.5T, \nu_0 = 42.6MHz/T \cdot 1.5T = 64MHz \)
- \( B_0 = 3.0T, \nu_0 = 42.6MHz/T \cdot 3.0T = 128MHz \)

- The RF pulse applied at resonance **tips** equilibrium magnetization away from \( B_0 \)

![Diagram showing MR principles](image)
• The RF pulse applied at resonance tips equilibrium magnetization away from $B_0$

• "90° pulse" rotates magnetization by 90°

• "180° pulse" rotates magnetization by 180° (populations of proton moments inverted)

• Immediately after the 90° pulse
  • There is zero longitudinal magnetization. Entire magnetization is flipped to the transverse plane and becomes transverse magnetization
  • The transverse magnetization precesses around $B_0$ with Larmor frequency

Precessing transverse magnetization is MRI signal
How do we generate and detect MRI signal?

- **Step 1:** Place the patient inside a uniform static magnetic field
  - Tissue magnetization builds up (time-scale T1)

How do we generate and detect MRI signal?

- **Step 2:** RF body coil applies 90° RF pulse
  - Magnetization gets tipped into transverse plane
How do we generate and detect MRI signal?

- Step 2: RF body coil detects the signal
  - Transverse magnetization rotates about $B_0$ and induces voltage in the body coil which is digitized.

Transverse magnetization, $T_2^*$, $T_2$

- Following 90° pulse the signal induced by rotating transverse magnetization eventually disappears.
- This relaxation has exponential envelope with a characteristic time-scale, $T_2^*$.

Transverse magnetization, $T_2^*$, $T_2$

- There are two major contributions to $T_2^*$ relaxation (besides $T_1$ process):
  1. Inhomogeneities of the static magnetic field
  2. $T_2$ process
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Larmor equation:
$$\nu_0 = \frac{\gamma \cdot B_0}{\mu_0}$$
Individual contributions precess at slightly different frequencies and dephase.

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  1. Inhomogeneities of the static magnetic field
  2. $T_2$ process
• Magnetization is the sum of individual contributions built from proton magnetic moments
  – Immediately after 90° pulse moments precess 

b.  
\[ \ldots \]

c.  
\[ \ldots \]
d.  
\[ \ldots \]

Dephasing due to field inhomogeneities can be eliminated using Spin Echo sequence.

Larmor equation:
$$\nu_0(x) = \frac{\gamma \cdot B_0(x)}{\mu_0}$$
Individual contributions precess at slightly different frequencies and dephase.
**Transverse magnetization, T2*, T2**

- There are two major contributions to T2* relaxation (besides T1 process):
  1. Inhomogeneities of the static magnetic field
  2. T2 process

- Dephasing due to field inhomogeneities can be eliminated using Spin Echo sequence.

- T2 process is irreversible

**Spin Echo**

\[ \text{Spin Echo} \propto \exp\left(-\frac{\text{TE}}{T_2}\right) \]

- TE (echo time) = time from excitation to echo
- TR (repition time) = time between 90º pulses (excitations)

**T1 and T2 contrast**

- T1 and T2 are properties of tissue
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- TR and TE manipulated to enhance one over the other in image
  - T1 weighting: visualization of anatomy
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- T1 relaxation
- T2 relaxation

Larmor equation
T1 and T2 contrast

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- T1 relaxation
- T2 recovery

- T1 contrast maximized for short TR
- T2 contrast maximized for moderate TE

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Thank you!