### Magnetic Resonance Imaging: Basics and Techniques

31540 Introduction to medical imaging  

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DTU Elektro  
[http://www.elektro.dtu.dk/](http://www.elektro.dtu.dk/)

MR afdelingen, Hvidovre Hosp.  
[http://www.drcmr.dk/](http://www.drcmr.dk/)

### MR imaging

- Extreme flexibility with respect to...
  - body part, coverage and orientation
  - contrast mechanisms: structure, flow, diffusion, thinking...

### Overview, 1st lecture

#### Basic NMR
- Equipment
- Nuclear spin and magnetization
- Precession
- Resonance and excitation
- Pulse sequences

#### Contrast
- Quick overview
- Relaxation
- Dephasing
- Spin-echoes

### Supplementary material

- **Lecture notes:**
  - [http://www.drcmr.dk/ MR notes](http://www.drcmr.dk/ MR notes)
  - 47 pages in English and Danish

- **Animations and software:**
  - [http://www.drcmr.dk/ MR](http://www.drcmr.dk/ MR)
  - [http://www.drcmr.dk/bloch](http://www.drcmr.dk/bloch)

### Equipment

**You need...**

- Magnet, radio wave transmitter and receiver, patient

### Nuclear spin

- Certain nuclei possess “spin”
  - H-1, P-31, C-13, F-19, Na-23, He-3, ...

- **Protons (Hydrogen nuclei):**

  Proton spin gives rise to magnetic property:  
  Hydrogen nuclei behave like bar magnets with angular momentum
Influence of the magnetic field

Partial alignment of the magnetic moments:

A macroscopic magnetization is formed.
The equilibrium magnetization is along the magnetic field.

Repetition: Java compass
http://www.drcmr.dk/MR

Precession

When a compass needle is kicked...
...it oscillates in a plane through north.

When a proton is kicked...
...the magnetization "precess" in a cone around north:

The difference is due to the rotation of the protons.

Precession and the RF field

The magnetization precesses at the Larmor frequency:
\[ f = \gamma B_0 = 42 \text{ MHz/T} \times B_0 \]

- The "gyromagnetic ratio" is 42 MHz/T for hydrogen.

Typically the RF field is also rotating around \( B_0 \).
- Magnetic field vector follows precession.
- This is most efficient.

The spin distribution

Equilibrium spin distribution in absence of field is isotropic:

Field effects: Polarization and precession

Reasons that nuclei don't align perfectly:
- Nuclear interactions and motion.
- Think compasses in tumble dryer.
The equilibrium magnetization

The net magnetization:
- Nearly nothing (Boltzmann: a few ppm compared to full alignment).
- It is proportional to the applied magnetic field.
- It is impossible to detect in the equilibrium state.

The spin distribution

Radio waves can rotate the spin distribution as a whole.
- The magnetic component of the EM field is responsible.
Relative orientations are preserved:
- Sufficient to keep track of net magnetization!

The MR signal

The basic MR experiment:
- Place patient in the strong magnetic field.
- Apply radio waves perturbing the equilibrium magnetization.
  - E.g. a 30 degree rotation.
- Switch off RF and measure the precession of the magnetic dipole:
- Analyze the weak emitted radio signal.

Excitation

Resonance:
The perturbation is induced by radio waves (excitation).
Large effect if the system is perturbed at the right frequency.

Pushing the swing at the eigen-frequency changes the amplitude.
Radio waves at the Larmor frequency changes the angle $\nu$.
Transfer of energy!

Precession

Reestablishing the equilibrium after excitation:

![Diagram showing precession](image)

The system returns to thermal equilibrium.
Radio waves are emitted and detected.

Upcoming....

*Animated Bloch Dynamics*
Animated Bloch Dynamics

\[
\frac{dM}{dt} = gM \times (B_0 + B_1(t)) + \text{relaxation terms}
\]

- **Precession**
- Resonant excitation (soft pulses)
- Non-selective excitation (hard pulses)
- Transverse and longitudinal relaxation
  - The spin ensemble
  - The rotating frame of reference

**starring**

- \(B_0\): The main magnetic field along \(z\)
- \(\omega_0\) = \(\gamma B_0\): The Larmor precession frequency
- \(\omega\): The RF field frequency
- \(B_1\): The amplitude of the transversal RF field (i.e. in the xy-plane)
- \(T_1\): The transverse relaxation time (i.e. orthogonal to \(B_0\))
- \(T_2\): The longitudinal relaxation time (i.e. along \(B_0\))

*Start Block*

The MR signal

The oscillating transversal magnetization:

- The transversal relaxation time \(T_2\) is a time constant for loss of magnetization.

The MR signal

A voltage is induced in the receiving coil (antenna).

**MR signal with a single frequency component:**

Orthogonal coils detect changes in \(M_x\), \(M_y\), respectively.

Signals are modulated down from the Larmor frequency to near zero.

The Bloch equation demonstration

The demonstration showed:
- **Precession:**
  - The magnetization oscillate in the xy-plane
  - Radio waves are emitted
- **Resonant excitation (selective, soft pulse)**
  - A weak resonant RF field will rotate the magnetization.
  - Only circularly component following precession contributes.
- **Non-selective excitation**
  - A short strong RF pulse excite non-selectively
- **\(T_2\)- and \(T_1\)-relaxation**
- **Rotating frames of reference**
  - Often chosen to match the RF frequency
- **MR measurements are described in this frame**
- **Measurement data are demodulated by this frequency**

Software and animations with soundtracks:
- [http://www.drcmr.dk/bloch](http://www.drcmr.dk/bloch)

MR sequences

**MR sequence definition:**
- A succession of RF pulses, gradient pulses, waiting and sample periods.

MR sequences can be fairly complicated and have long acronyms:
- Example: MPRAGE (Magnetization Prepared Rapid Gradient Echo)
- Long coherence time leaves enormous room for creativity.

- Sequence and sequence parameters determine contrast.

- **Contrast**
Image contrast

Many influences on the signal:
- Water content (proton density, PD).
- Relaxation (local nuclear environment).
- Flow, perfusion and diffusion.
- Neural activation.
- Metabolic properties.
- ...

Unwanted contrast:
- Coil sensitivity variation.
- Field inhomogeneity.
- Motion artifacts.

Relaxation time contrast

Typical radiologist statement after MRI exam:
"PD- and T1-weighted imaging were normal.
T2-weighted imaging revealed a subcortical lesion."

T1, T2 and PD are parameters characterizing tissue:
- just like "temperature" or "water content".
- The PD is, in fact, the water content.

T1 and T2 time-constants are somewhat special:
- Can only be determined by MRI (they are "MRI contrast parameters")
- Reflect aspects of consistency (molecular mobility)

So what is "weighting"??
- The parameters above are seldom measured quantitatively...
- but their relative values may be apparent in the images.
- i.e.: The contrast in a "T1-weighted" image comes mostly from T1-differences.

So why all this talk about T1 and T2?

Relaxation time dependence on nuclear mobility:

- The correlation time is typical time between changes in nuclear environment.
- Solids: Short T2, Long T1
- Liquids: Long T2xT1 (seconds)
- Intermediate: Intermediate

The Larmor frequency depends on the field strength
- High field shifts properties toward solid regime.

Relaxation - quantitative

Relaxation changes the transversal and longitudinal magnetization
$M_x$ and $M_z$ as follows (subt. T2 with T2* if inhomogeneity matters):

$M_x(t) = M_x(0) e^{-t/T2}$
$M_z(t) = M_z(0) e^{-t/T1} + M_z(1 - e^{-t/T2})$

Example: Starting from equilibrium $M_z = M_0$ and after a 90° excitation at time $t = 0$, converting all longitudinal mag, to transversal:

$M_x(t) = M_0 e^{-t/T2}$
$M_z(t) = M_0 (1 - e^{-t/T1})$

More generally, a short resonant RF pulse at time $t = 0$ with tip angle $\alpha$ rotates longitudinal magnetization as follows:

$M_x(t = 0) = M_x(t = 0) \sin(\alpha)$
$M_z(t = 0) = M_z(t = 0) \cos(\alpha)$

The equations are combined to find effect of a series of pulses (for each: Redefine $t = 0$ and make sure that $M_x(0) = 0$ before the pulse).

Animated Bloch Dynamics - Reloaded

T1 and T2 contrast
Field inhomogeneity
Reversible dephasing: T2*
Recovering lost signal: The spin echo

* Start Bloch...
Overview, 2nd lecture
Basics continued...
- Relaxation time contrast revisited
More contrast mechanisms
- Contrast agents and perfusion
- Flow and diffusion
- Spectroscopy
- Functional imaging
- Imaging methodology

Relaxation time contrast revisited

T2* contrast
Signal decay time $T2^* < T2$.
Field inhomogeneity result from...
- limited hardware capabilities.
- variations in magnetic properties of tissue/air/bone.
- variations in magnetic properties on a microscopic scale.

Spin echo contrast
Contrast from relaxation times and water content:
TI-, PD- and T2-weighted spin echo.
**T1 contrast, saturation**

Partial recovery of the longitudinal magnetization:
- Repetition time $TR \sim T1$

**Conventional contrast**

PD-weighting (proton density, water content):
- Long repetition time: $TR \gg T1$
- Full T2 relaxation.
- Short echo time: $TE \ll T2$
  - No T2 signal decay.

T2-weighting:
- Long repetition time: $TR \gg T1$
- Full T2 relaxation.
- Long echo time: $TE \sim T2$
  - Significant T2 signal decay.

T1-weighting:
- Short repetition time, $TR \sim T1$
- No time for relaxation (saturated measurement).
- Short echo time, $TE \ll T2$
  - No T2 signal decay.

**Gradients**

Field gradients:
Linear variations in main field $B_0$ induced by gradient coils.
Gradients are needed for:
- Localization during preparation
- Imaging
- Flow and diffusion encoding
- Suppression of artifacts

Field in presence of gradient: $B_x = B_0 + G \cdot r$
E.g., gradient along $x$: $B_x(x) = B_0 + G_x \cdot x$
Resonance frequency: $f = \gamma B_z$

Spatial axis are converted into freq. axis by gradients.

**Gradients for recording projections**

Gradient gives linear relation between position and frequency:

If a gradient is applied along $x$ or $y$, for example,...
- A frequency analysis (FFT) of the signal yields a spatial projection.

When done for all directions, projection reconstruction can be used...
- but actually this is seldom done. A smarter variant exists.

*Story continues in 31545...*
### More contrast mechanisms

- **Contrast agents**
  - Normally a paramagnetic substance (e.g., gadolinium complex)
  - Used commonly to change relaxation rates
  - Before and after administration of agent shortening T1:
  - Only acute MS lesions are hyper intense (BBB opened in acute phase)

### Fast brain imaging during contrast injection (bolus):

- One second interval between images.

### Measurement of blood supply:

- Duration before bolus arrives in tissue
- Quantitating the perfusion requires deconvolution or spin labelling.

### Flow and diffusion weighting

- Flow and diffusion weighting.

### Fiber directionality

- Measuring nerve-fiber directionality
  - The diffusion is high along the nerve fibers.
  - Diffusion tensor describes anisotropic diffusion
  - Measured by repeated diffusion weighting
  - Basis for tractography

- Corpus Callosum images:
  - Coronal view
  - Sagittal view
**Spectroscopy**

MR can distinguish chemical substances
Molecular structure influences local magnetic field

<table>
<thead>
<tr>
<th>Molecular Structure</th>
<th>Spectroscopy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cho</td>
<td>NAA</td>
</tr>
<tr>
<td>Cr</td>
<td>Lac</td>
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</tbody>
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**Sclerosis and spectroscopy**

Marked regions:
- Normally appearing white matter (solid curve).
- Lesions (dashed curve).

Increased choline reflects turn-over of cell membranes.
Possibility of characterising normally appearing white matter.

**Functional imaging, fMRI**

Activation of brain:
- Increased oxygen consumption
- Increased blood supply.
- Increased oxygen conc.
- Changed relaxation times.
- Deoxy-haemoglobin is paramagnetic.
- Changed MR signal.
  - Activation: Signal increases.
  - Rest: Signal decreases.

Examples:
- Visual stimulation
- Language lateralisation.

**Language lateralisation, fMRI**

Hope: Localization of language areas ahead of surgery.

Semantic task:
- Patient switch between word generation and rest.
  - Categories “fruit”, “month”, “animal”, “tree”...

Phonetic task:
- Patient switch between word generation and rest.
  - Initial letter “P”, “R”, “E”, “T”...

**Language lateralisation, fMRI(2)**

Take-home messages

MRI is:
- Not one, but many different exams:
  - Structural imaging: T1, T2, PD-weighting...
  - Flow and diffusion imaging...
  - Functional imaging...
  - Metabolic imaging and more.

- Provides excellent soft-tissue contrast
- Now present at basically all larger hospitals
- Completely safe, if conducted right.
  - Not relying on ionizing radiation, for example.

- Not always first choice:
  - Time consuming...
  - Since many parameters are typically measured.
  - Relatively expensive. Running costs are high...
- Not independent of fScans.
- Contraindications exist:
  - Pacemaker, claustrophobia...

Regions activated by semantic and phonetic tasks.
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