A brief history…

- Isidor Rabi wins Nobel prize in Physics (1944) for his resonance method for recording the magnetic properties of atomic nuclei.
- Felix Bloch and Edward Purcell share Nobel Prize in Physics (1952) for discovery of magnetic resonance phenomenon.
- Richard Ernst wins Nobel Prize in Chemistry (1991) for 2D Fourier Transform NMR.
- His post-doc, Kurt Wuthrich awarded a Nobel Prize in Chemistry (2002) for 3D structure of macromolecules.
- Nobel Prize in Physiology & Medicine awarded to Sir Peter Mansfield and Paul Lauterbur (2003) for MRI.
- Who’s next? Seiji Ogawa for BOLD fMRI?
Outline

- **Hardware:**
  - MRI scanner
  - RF coil
  - Gradients
- **Image contrast**
- **Software:**
  - Pulse sequences
  - Fourier Transform

How does it work?

[video link: http://www.med.harvard.edu/AANLIB/cases/caaes17fma.mpg]
Original Concept*

1. Rotating Gradient
2. Filtered Back-projection


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Fourier Imaging*

1. Three orthogonal gradients:
   - Slice Selection
   - Phase Encoding
   - Frequency Encoding
2. k-space
   - Representation of encoded signal

MRI scanners

19 Tesla
4.7 Tesla
1.5 Tesla

To generate $B_0$ field and create polarization ($M_0$)

MRI coils

Mouse MRI platform
Torso coil
Head coil

To transmit RF field ($B_1$) and receive signal
Gradients

To spatially encode the MRI signal

Image Contrast

Contrast in MRI based on differences in:

- Relaxation times ($T_1$, $T_2$, $T_2^*$, $T_{1p}$)
  - Local environment
- Magnetization = spin density
  - Concentration of water, sodium, phosphorous etc.
- Macromolecular interactions
  - Chemical-exchange, dipole-dipole, quadrupolar interactions
- Contrast agents
  - Gadolium-based, iron-oxide, manganese
Magnetization

"spin"  "spin ensemble"  spin-up or spin-down = Boltzmann distribution

Net Magnetic Moment

Energy levels

Boltzmann distribution

\[ \frac{N_+}{N_-} = \exp \left( -\frac{\Delta E}{k_B T} \right) \]

Energy gap

\[ \Delta E = \hbar \gamma B_0 \]

Larmor Equation

\[ \omega_0 = \gamma B_0 \]
MR experiment

RF pulse applied in x-y “transverse” plane

RF off

M₀ aligned along B₀
M_z = M₀

M “nutates” down to x-y plane
M_z = M₀cosα
and
M_xy = M₀sinα

Detect M_xy signal in the same RF coil

T₁ recovery  T₂⁺ decay  T₂ decay

Equation of motion

\[
\frac{dM(t)}{dt} = M(t) \times γB(t)
\]

Bloch Equation (simple form)
Effect of RF pulse

The 2nd B field

\[ B_{1r}(t) = B_1 \left\{ \cos(\omega_{RF}t + \phi) i + \sin(\omega_{RF}t + \phi) j \right\} \]

Choosing a frame of reference rotating at \( \omega_{RF} \)
makes \( B_1 \) appear static:

\[ B'_{CR} = B_1 \cos \phi i' + B_1 \sin \phi j' + \frac{\Omega}{\gamma} k' \]

where \( \Omega = \omega_0 - \omega_{RF} \) (offset)

Nutation

Lab frame of reference
e.g. \( B_1 \) oscillating in x-y plane

Rotating frame of reference
e.g. \( B_1 \) along y-axis

http://www-mrsrl.stanford.edu/~brian/mri-movies/
After RF pulse-Relaxation

Spin-Lattice relaxation
time=return to thermal equilibrium $M_0$

Spin-spin relaxation
without "reversible" dephasing

Spin-spin relaxation
with reversible dephasing

$T_1 > T_2 > T_2^*$

Signal detection

http://www-mrsrl.stanford.edu/~brian/mri-movies/
How does MRI work?

NMR signal

Water 4.7 ppm
Fat 1.2 ppm

MR Image

? =

1) Spatial encoding gradients 2) Fourier transform

Pulse Sequence (timing diagram)

Less MRI time/low image quality

Spin-echo

Fast spin-echo

Gradient-echo

Echo planar imaging
MRI

Slice Selection*

Gradient-echo

RF
slice
phase
freq

α

TR

TE


Slice Selection

\[ \gamma G_z \cdot \Delta z \]

\[ BW_{RF} = \gamma G_z \cdot \Delta z \]

Frequency Encoding*

Frequency Encoding

\[
\gamma G_x \cdot x
\]

\[BW_{\text{read}} = \gamma G_x \cdot FOV_x\]

Phase Encoding*

Phase Encoding

Each PE step imparts a different phase twist on the magnetization along $y$.

Traversing k-space

Spin-warp imaging*

Fourier Transform

k-space \hspace{1cm} image

FT

Traversing k-space

Spiral \hspace{1cm} Radial \hspace{1cm} Echo-planar

freq \hspace{1cm} freq \hspace{1cm} phase

freq \hspace{1cm} freq \hspace{1cm} freq

freq \hspace{1cm} freq

freq \hspace{1cm} freq

freq \hspace{1cm} freq
Fourier Transform

FORWARD TRANSFORM (time $\rightarrow$ frequency)

$$\overline{S}(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dt \ S(t)e^{i\omega t}$$

REVERSE TRANSFORM (frequency $\rightarrow$ time)

$$S(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega \ \overline{S}(\omega)e^{-i\omega t}$$

Typical FT pairs

- Impulse, or "delta" function
- Gaussian
- Sin wave
- Comb
K-space

The signal a coil receives is from the whole object:

\[ S(t_x, t_y) = \iiint \rho(x,y) e^{i(\gamma G_{x,x} t_x + \gamma G_{y,y} t_y)} \, dx \, dy \]

replace: \[ k_{x,y} = \gamma G_{x,y} t \]

K-space signal:

\[ \mathcal{S}(k_x, k_y) = \iiint \rho(x,y) e^{i(\gamma k_x x + \gamma k_y y)} \, dx \, dy \]

The image is a 2D FT of the k-space signal*:

\[ \rho(x,y) = \iiint \mathcal{S}(k_x, k_y) e^{-i(\gamma k_x x + \gamma k_y y)} \, dk_x \, dk_y \]


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K-space weighting

High-frequency data=edges
Low-frequency data=contrast/signal
What is wrong?

Original

Freq. de-phaser too large!

Original

$k_y$ step was too large or $\text{FOV}_y$ was too small!

What is wrong?

Original

Freq. gradient amplitude was too low!

MRI Examples
3D Neuro MRI

Susceptibility-Weighted Imaging (SWI)
BOLD fMRI

Phase Contrast MR Angiography
Knee Imaging

TSE
TE = 25 ms

TSE
Fat Saturated

Resolution: 200x200 µm²

Sodium MRI of IVD
Rationale for Sodium MRI

[PG] decreases with Degeneration

- **Urban et al. Spine 1998**

Sodium is a natural biomarker for PG

How is [Na] related to [PG]?

- **Fixed Charge Density (FCD)**
  - Side chains of PG
  - [Na] correlated with [PG] through [FCD]

\[
\text{[Na]} \rightarrow \text{[FCD]} \rightarrow \text{[PG]} \rightarrow \text{detect early DDD}
\]

Maroudas et al., in Adult Articular Cartilage (1979)

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Sodium MRI

What do you need?

1. RF coil
2. Transmit/receive switch
3. Broadband capable scanner (all vendors)
4. A short echo-time MRI pulse sequence
Sodium MRI Ex Vivo

- Sodium maps in bovine discs

Wang et al., Spine (in press)

Sodium content vs. PG content

Wang et al., Spine (in press)
Sodium MRI *In Vivo*

- Sodium mapping vs. $T_2$ MRI

Wang et al., *Spine* (in press)

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**New 7T MRI!**

- ultra-short echo pulse sequence
- $TE/TR = 200\mu s/25\text{ms}$
- 2mm isotropic
- 15 minute acquisition
Sodium MRI Movies

- Axial
- Coronal
- Sagittal

Sodium MRI Montage

- SNR ~26:1 in cartilage
Take home…

- Magnet
  - Create $B_0$
  - Produce $M_0$

- RF coil
  - Transmit $B_1$ field
  - Detect Signal

- Image contrast
  - Relaxation, concentration, interactions etc.

- Gradients
  - Spatial encoding
  - Signal in k-space

- Fourier Transform
  - From k-space to image space

- Pulse sequences
  - Traverse k-space
  - Image Artifacts