Basics of Magnetic Resonance Imaging (MRI)

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OUTLINE

• Medical imaging modalities
• History of MRI
• Working principles of MRI
Create images of human body non-invasively

- X-ray radiography
- X-ray computed tomography (CT)
- Medical ultrasonography
- MRI
**Medical Imaging Modalities**

### X-ray radiography

To use X-rays to view the internal structure of a non-uniformly composed and opaque object:

- **2D images**
- **Radiation**: X-ray is absorbed by the subject
X-ray Computed Tomography (CT)

To generate a 3D image of the internal structure of an object from a large series of 2D radiographic images taken around a single axis of rotation.

- 3D images
- X-ray absorbed by the subject is 100 times of that by using x-ray radiography
Medical ultrasonography

Ultrasound-based imaging technique used for visualizing subcutaneous body structures

- **It displays**
  - 2D cross-section of the tissue
  - Blood flow
  - Motion of the tissue over time
  - The location of blood
  - The presence of specific molecules
  - The stiffness of tissues
  - Anatomy of 3D region

- **Advantages**
  - Provide real-time images
  - Portable
  - Low cost
  - No harmful radiation

- **Limitations on field of view**
  - Difficult imaging structure behind bone
  - The skill of operators matters
Medical Imaging Modalities

Magnetic Resonance Imaging (MRI)

- 3D images
- Low RF radiation
- Cost: 2 - 4 millions USD
Different names of MRI

- Magnetic resonance imaging (MRI)
- Nuclear magnetic resonance imaging (NMRI)
- Magnetic resonance tomography (MRT)

Advantages:
- Good contrast
- Noninvasive
- No ionizing radiation
- Arbitrary scan planes

http://mrsrl.stanford.edu/~brian/intromr/
<table>
<thead>
<tr>
<th>Year</th>
<th>Name &amp; Institution</th>
<th>Achievement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1952</td>
<td>Herman Carr (Harvard University)</td>
<td>Produced 1D MRI image</td>
</tr>
<tr>
<td>1960</td>
<td>Vladislav Ivanov (Soviet Union)</td>
<td>Filed a document for a magnetic resonance imaging device (USSR State Committee for Inventions and Discovery at Leningrad)</td>
</tr>
<tr>
<td>1970</td>
<td>Peter Mansfield (University of Nottingham)</td>
<td>Developed a mathematical technique that would allow scans to take seconds rather than hours and produce clearer images than Lauterbur had.</td>
</tr>
<tr>
<td>1971</td>
<td>Raymond Damadian (State University of New York)</td>
<td>Reported tumors and normal tissue can be distinguished in vivo by NMR [Science]. This method is not effective and not practical.</td>
</tr>
<tr>
<td>1972</td>
<td>Raymond Damadian</td>
<td>Created the world’s first MRI machine &amp; filed a patent</td>
</tr>
<tr>
<td>1973</td>
<td>Paul Lauterbur (State University of New York)</td>
<td>Expended Carr’s technique &amp; generated and published the first nuclear magnetic resonance 2D and 3D images (using gradients)</td>
</tr>
</tbody>
</table>


Raymond Damadian's apparatus and method for detecting cancer in tissue [1]

The National Science Foundation notes "The patent included the idea of using NMR to 'scan' the human body to locate cancerous tissue." However, it did not describe a method for generating pictures from such a scan or precisely how such a scan might be done.[2][3]

### History of MRI

<table>
<thead>
<tr>
<th>Year</th>
<th>Name(s)</th>
<th>Achievement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1974</td>
<td>Paul Lauterbur</td>
<td>Generated the <strong>first cross-sectional image of a living mouse</strong></td>
</tr>
<tr>
<td>1977</td>
<td>Raymond Damadian, Larry Minkoff, Michael Goldsmith</td>
<td>Performed and published <strong>the first MRI body scan of a human</strong></td>
</tr>
<tr>
<td>1979</td>
<td>Richard S. Likes (GE)</td>
<td>Filed a patent on k-space</td>
</tr>
<tr>
<td>1970s</td>
<td>John Mallard (University of Aberdeen)</td>
<td>Built <strong>the first full body MRI scanner</strong> at the University of Aberdeen</td>
</tr>
<tr>
<td>1980</td>
<td>John Mallard</td>
<td>Obtained <strong>the first clinically useful image</strong> of a patient’s internal tissues using MRI using the machine he built during the 1970s</td>
</tr>
<tr>
<td>1980</td>
<td>Paul Bottomley (GE)</td>
<td>Built <strong>the first 1.5T whole-body MRI/MRS scanner</strong> (the highest strength at that time)</td>
</tr>
<tr>
<td>1982</td>
<td>Paul Bottomley (Johns Hopkins University)</td>
<td>Performed <strong>the first localized MR Spectroscopy (MRS)</strong> in the human heart and brain</td>
</tr>
<tr>
<td>2003</td>
<td>Paul Lauterbur, Peter Mansfield</td>
<td><strong>Nobel Prize</strong> in Physiology or Medicine for their &quot;discoveries concerning magnetic resonance imaging&quot;</td>
</tr>
</tbody>
</table>
• A group of atoms (with odd number of protons and/or odd number of neutrons)
  • Possess a **nuclear spin angular momentum**
  • Exhibit **nuclear MR phenomena**
  • e.g. hydrogen (\(^1\)H )

• Visualization
  Nucleons
  → Spinning charged spheres
  → Small magnetic moments

• **MR relevant nuclei → spins**
Examples of MR-relevant nuclei (spins)

Hydrogen ($^1$H), single proton
- Most abundant (large amount)
- Most sensitive (gives large signals)
- Most studied

Phosphorus ($^{31}$P)
Important indicator of metabolism
• Spins are aligned to the applied field
→ equilibrium state
• Results: net magnetization
Polarization

MRI Scanner Cutaway

- Radio Frequency Coil
- Gradient Coils
- Magnet
- Patient
- Patient Table
- X, Y, Z axes
- Bo

MRI  MR  Polarization  Precession  Relaxation  Signal Reception  Imaging  FT
• Spins precess about $B_0$
• Angular frequency & frequency of the precession

$$\omega = \gamma B_0 \quad \text{or} \quad 2\pi f = \gamma B_0$$

$$f = \frac{\gamma}{2\pi} B_0$$

$$\frac{\gamma}{2\pi} \approx 42 \text{ MHz/Tesla}$$
• Spins precess about $B_0$

• **Angular frequency & frequency** of the precession

$$\omega = \gamma B_0 \quad \text{or} \quad 2\pi f = \gamma B_0$$

$$f = \frac{\gamma}{2\pi} B_0 \quad \quad \frac{\gamma}{2\pi} \approx 42 \text{ MHz/Tesla}$$

• To obtain MR signal: $B_1$ is tuned to $\omega$ to excite spins **OUT OF** equilibrium

Source: http://mrsrl.stanford.edu/~brian/intromr/
Polarization

MRI Scanner Cutaway

- Radio Frequency Coil
- Gradient Coils
- Magnet
- Patient Table
- Patient
- X, Y, Z axes
- \( B_0 \) and \( B_1 \)
Magnetization returns exponentially to equilibrium

- Longitudinal recovery time constant, $T_1$
- Transverse decay time constant, $T_2$
- Different tissues have different $T_1$ and $T_2$

- Longitudinal recovery time constant, $T_1$
  - 100 – 1500 ms

- Transverse decay time constant, $T_2$
  - 20 – 300 ms
Magnetization returns exponentially to equilibrium

- Longitudinal recovery time constant, $T_1$
- Transverse decay time constant, $T_2$
- Different tissues have different $T_1$ and $T_2$

Source: http://mrsrl.stanford.edu/~brian/intromr/
\( T_1 \) is determined by thermal interactions between the resonating protons and other protons and other magnetic nuclei in the magnetic environment or "lattice".

- \( T_2 \) decay is due to magnetic interactions that occur between spinning protons.
- \( T_2 \) interactions do not involve a transfer of energy but only a change in phase, which leads to a loss of coherence.
• The spin precession causes magnetic flux ($\Phi_B$) change in a RF coil
• The change in flux induces currents/voltage
• The induced currents/voltage generates signal
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Source: http://mrsrl.stanford.edu/~brian/intromr/
• The spin precession causes magnetic flux ($\phi_B$) change in a RF coil
• The change in flux induces currents/voltage
• The induced currents/voltage generates signal
Step 1: Selective excitation:

\[ B_1 \] is applied to the presence of \( B_0 \) & \( G_z \)

Step 2: Spatial signal encoding & signal readout

**Method 1** Projection-reconstruction method (x-ray CT)

**Method 2** 2D Fourier transform method (popular)
B₁ is applied to the presence of B₀ only $\rightarrow$ 3D imaging

Comment:
3D imaging is usually time consuming
$\mathbf{B}_1$ is applied to the presence of $\mathbf{B}_0$ & a linear gradient field $(\mathbf{G}_x, \mathbf{G}_y, \text{or } \mathbf{G}_z)$

→ Excite a plane ⊥ the z-axis

→ 2D imaging

\[ \mathbf{G}_z = G_z \hat{z} \]

e.g. $G_z = 1 \text{ Gauss} / \text{m}$
B₁ is applied to the presence of $B₀$ & a linear gradient field ($Gₓ$, $Gᵧ$, or $Gₗ$)
→ Excite a plane ⊥ the z-axis
→ 2D imaging

$\omega = \gamma B₀$
B₁ is applied to the presence of B₀ & a linear gradient field (Gₓ, Gᵧ, or Gż)
→ Excite a plane ⊥ the z-axis
→ 2D imaging
Selective Excitation & 2D Imaging

\( B_1 \) is applied to the presence of \( B_0 \) & a linear gradient field \((G_x, G_y, \text{ or } G_z)\)

\[ \rightarrow \] Excite a plane \( \perp \) the z-axis

\[ \rightarrow \] 2D imaging

- The frequency content of \( B_1(t) \) must be a rectangular function
- Ideally, \( B_1(t) \) must be a sinc function
- Practically, \( B_1(t) \) is a “sinc-like” function
Step 1: Selective excitation: \( B_1 \) is applied to the presence of \( B_0 \) & \( G_z \)

Preferred situation: in phase

\[ \Delta z \]

\[ B_0 + G_zz \]

\[ B_1 \]

\[ \text{RF coil (excitation)} \]

\[ \text{RF} \]

\[ t \]

\[ G_z \]
Step 2: Spatial signal encoding & signal readout

Example:

\( G_x = 1 \text{ Gauss/m} \)

so \( B_z = B_0 + G_z z + G_x x \)

\[
\begin{align*}
\vec{G}_z &= G_z \hat{z} \\
\vec{G}_y &= G_y \hat{z} \\
\vec{G}_x &= G_x \hat{z}
\end{align*}
\]
2D Imaging Sequence

Step 2: Spatial signal encoding & signal readout

RF sources

At \( t_1 \), after excitation

\[
\begin{align*}
  t < t_1 & \quad \omega = \gamma (B_0 + G_z z) \\
  t > t_1 & \quad \omega = \gamma (B_0 + G_x x t)
\end{align*}
\]

Method 1 Projection-reconstruction method
Step 2: Spatial signal encoding & signal readout

Method 1: Projection-reconstruction method

At $t_1$, after excitation

$\begin{align*}
  t < t_1 & \quad \omega = \gamma (B_0 + G_z z) \\
  t > t_1 & \quad \omega = \gamma (B_0 + G_x x t) \\

  s(t) &= \int \int m(x, y) e^{-iG_x x t} dx dy \\
     &= \int \left[ \int m(x, y) dy \right] e^{-iG_x x t} dx
\end{align*}$
Step 2: Spatial signal encoding & signal readout

**Method 1** Projection-reconstruction method

At \( t_1 \), after excitation

\[
\begin{align*}
\text{RF} & : \quad t \\
G_z & : \\
G_y & \\
G_x & \\
\text{MRI} &
\end{align*}
\]

\[
\begin{align*}
t < t_1 & \quad \omega = \gamma (B_0 + G_z z) \\
t > t_1 & \quad \omega = \gamma (B_0 + G_x x t)
\end{align*}
\]

\[
s(t) = \int \int m(x, y) e^{-i \gamma G_x x t} \, dx \, dy
\]

\[
= \int \left[ \int m(x, y) \, dy \right] e^{-i \gamma G_x x t} \, dx
\]

\[
= \int g(x) e^{-i \gamma G_x x t} \, dx
\]

\[
g(x) = \int m(x, y) \, dy
\]

\( g(x) \) is the projection of \( m(x,y) \) along the \( y \)-direction
2D Imaging Sequence

Step 2: Spatial signal encoding & signal readout

Method 1 Projection-reconstruction method (with an angle)

\[ \omega = \gamma (B_0 + G_z z) \]

\[ \omega = \gamma (B_0 + G_x x_t + G_y y_t) \]

\[ G_x = G \cos \theta \]

\[ G_y = G \sin \theta \]
Step 2: Spatial signal encoding & signal readout

**Method 1** Projection-reconstruction method (with an angle)

In X-ray CT imaging

Each point in the projection

The sum of the object distribution along the appropriate ray path

- A single project angle **DOES NOT** provide spatial information of the object distribution along the ray path
- Multiple angles are needed.
Step 2: Spatial signal encoding & signal readout

Method 2 2D Fourier transform method (spatial encoding in a smart way)

\[ s(t; y_y) = \int \int m(x, y)e^{-i\gamma G_y y t_y} e^{-i\gamma G_x x t} \, dx \, dy \]
2D Fourier Transform Method

\[ s(t; y_y) = \int \int m(x, y)e^{-i\gamma G_y y t_y} e^{-i\gamma G_x x t} \, dx \, dy \]
2D Fourier Transform Method

\[ s(t; y_y) = \int \int m(x, y)e^{-i\gamma G_{y} y t_y} e^{-i\gamma G_{x} x t} \, dx \, dy \]

Let
\[ k_x(t) = \frac{\gamma}{2\pi} \int_0^t G_x(\tau) d\tau \]
\[ k_y(t) = \frac{\gamma}{2\pi} \int_0^t G_y(\tau) d\tau \]

\[ s(t) = \int \int m(x, y)e^{-i2\pi[k_x(t)x + k_y(t)y]} \, dx \, dy \]

**Signal equation**
\[ s(t) = M[k_x(t), k_y(t)] = \int \int m(x, y)e^{-i2\pi[k_x(t)x + k_y(t)y]} \, dx \, dy \]
2D Fourier Transform Method

\[ s(t; y_y) = \int \int m(x, y) e^{-i \gamma G_y y_t} e^{-i \gamma G_x x t} \, dx \, dy \]

Let
\[ k_x(t) = \frac{\gamma}{2 \pi} \int_0^t G_x(\tau) \, d\tau \]
\[ k_y(t) = \frac{\gamma}{2 \pi} \int_0^t G_y(\tau) \, d\tau \]

\[ s(t) = \int \int m(x, y) e^{-2 \pi [k_x(t)x + k_y(t)y]} \, dx \, dy \]

Signal equation
\[ s(t) = M[k_x(t), k_y(t)] = \int \int m(x, y) e^{-2 \pi [k_x(t)x + k_y(t)y]} \, dx \, dy \]
2D Fourier Transform Method

Signal equation

\[ s(t) = M[k_x(t), k_y(t)] = \int \int m(x, y) e^{-i2\pi[k_x(t)x+k_y(t)y]} \, dx \, dy \]

k-space

Measurable

\[ s(t) \]

Fourier Transform

\[ m(x, y) \]

Object

Source: www.developer.nvidia.com
2D Imaging Sequence

Step 1: Selective excitation: $B_1$ is applied to the presence of $B_0$ & $Gz$

Step 2: Spatial signal encoding & signal readout

Method 1  Projection-reconstruction method (x-ray CT)

Method 2  2D Fourier transform method (popular)
Applications of MRI

- Functional MRI
- Diffusion MRI
- Magnetic resonance spectroscopy
- Real-time MRI
- Interventional MRI
- Magnetic resonance angiography
- Magnetic resonance guided focused ultrasound
Functional MRI (fMRI)

- fMRI measures signal changes in the brain that are due to changing neural activity.
- Compared to anatomical T1-weighted imaging, the brain is scanned at lower spatial resolution but at a higher temporal resolution (typically once every 2–3 seconds)

Diffusion MRI

- Diffusion MRI measures the diffusion of water molecules in biological tissues.
- Clinically, diffusion MRI
  - Is useful for the diagnoses of conditions (e.g., stroke) or neurological disorders (e.g., multiple sclerosis)
  - Helps better understand the connectivity of white matter axons in the central nervous system

Source: http://en.wikipedia.org/wiki/Magnetic_resonance_imaging#Specialized_applications
Magnetic resonance spectroscopy (MRS)

- MRS is used to measure the levels of different metabolites in body tissues.
- The MR signal produces a spectrum of resonances that corresponds to different molecular arrangements of the isotope being "excited".
- This signature is used
  - to diagnose certain metabolic disorders, especially those affecting the brain
  - to provide information on tumor metabolism

Source: http://en.wikipedia.org/wiki/Magnetic_resonance_imaging#Specialized_applications
*Take Home Message*

- The physical process of MRI
  - MR
  - Polarization
  - Precession
  - Relaxation
  - Signal Reception
  - Imaging

- Three main fields:
  - Main field, $B_0$
  - RF field, $B_1$
  - Linear gradient field, $G$

- Imaging sequence
  - Step 1: excitation
  - Step 2: signal encoding & signal readout

- 2D FT method

Signal equation

$$s(t) = M[ k_x(t), k_y(t) ] = \int \int m(x, y) e^{-i2\pi[k_x(t)x + k_y(t)y]} \, dx \, dy$$
Thank you!

for your attention!