Physics of MR Image Acquisition

HST-583, Fall 2002

- Review:
  - MRI: Overview
  - MRI: Spatial Encoding

- MRI Contrast: Basic sequences
  - Gradient Echo
  - Spin Echo
  - Inversion Recovery
Overview of an MRI procedure

Tissue protons align with magnetic field (equilibrium state)

RF pulses

Protons absorb RF energy (excited state)

Relaxation processes

Protons emit RF energy (return to equilibrium state)

NMR signal detection

Repeat

Spatial encoding using magnetic field gradients

Larmor Equation

\[ \omega_0 = \gamma B_0 \]

RAW DATA MATRIX

Fourier transform

IMAGE

\( S_{(x_1,x_2)} \)

\( S_{(t_1,t_2)} \)
Dynamics of the Magnetization

\[
\frac{d\vec{M}(t)}{dt} = \vec{M}(t) \times \gamma \vec{B}_{\text{ext}}(t) - \frac{(M_x \hat{i} + M_y \hat{j})}{T_2^*} - \frac{(M_z - M_0)}{T_1} \hat{k}
\]

- Geometrical description: damped precession
- Mathematical Description: precession + relaxation (Bloch equations)

\[\alpha_0 = \gamma B_0\]
Spatial Encoding in MRI

Key concept: \[ \omega(r) = \gamma (B_0 + G \cdot r) \]

- **Slice Selection**
  - Location
  - Thickness
  - Rephasing/Refocussing

- **Frequency Encoding**
  - Fourier Transform
  - FOV
  - Gradient Echo Formation

- **Phase Encoding**
  - Phase / Frequency Equivalency
  - FOV
Slice Selection

- RF excitation (selective bandwidth) + magnetic field gradient
- RF pulse properties
  - shape & duration
  - bandwidth ($bw$)
  - frequency ($w_o$)

Magnetic field gradient ($G_z$)

$$\omega_{(r)} = \gamma (B_0 + G_z r)$$

Slice parameters

- Slice thickness ($\Delta z$): $bw = \gamma G_z \Delta z$
- Slice center ($z_o$): $w_o = \gamma G_z z_o$
‘Pulse sequence’ so far

RF

“slice select”

G_z

MR signal from whole
Selected slice

S(t)

Sample points

T_2^*

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Courtesy of L. Wald
Frequency Encoding

• After slice selection all spins in the selected plane have the same frequency and phase (a)

• Signal is acquired while a magnetic field gradient $G_x$ is on (b)

\[ w(x) = \gamma G_x x \]
‘Pulse sequence’ so far

- RF
- "slice select"
- "freq. encode" (read-out)
- \( S(t) \)
- Sample points

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Courtesy of L. Wald
More signal can be obtained:

RF

“slice select”

“freq. encode” (read-out)

$G_z$

$G_x$

$S(t)$

Sample points

Dephase

Rephase

Acquisition window

We can save some time …
‘Pulse sequence’ so far

- RF
- "slice select"
- \( G_z \)
- "freq. encode" (read-out)
- \( G_x \)
- \( S(t) \)
- Sample points
- Acquisition window
- Gradient Echo
Frequency Encoding

Measured signal: time domain

\[ S(t) \]

Sampling time \( \delta t = 1 / bw_{\text{rec}} \)

\( N_x \): number of samples

Frequency spectrum: 1D x-projection

\[ S(\omega) \]

Relevant parameters

- Acquisition time (\( t_{\text{acq}} \)):
  \[ t_{\text{acq}} = N_x \delta t = N_x / bw_{\text{rec}} \]

- Resolution (\( \delta x \)):
  \[ \delta x = FOV_x / N_x \]

- Field of view (\( FOV_x \)):
  \[ bw_{\text{rec}} = \gamma G_x FOV_x \]

\[ \omega(r) = \gamma (B_0 + G \cdot r) \]
We could have measured ‘exactly’ the same information differently:

So far we’ve used ONE RF excitation and we’ve acquired \( N_x \) sampling points while the read-out gradient was ON.

“slice select”

“freq. encode” (read-out)

RF

G\(_z\)

G\(_x\)

S\((t)\)

Sample points

Acquisition window

Each

t
Let’s look at one arbitrary sampled point in the MR signal

\[
S(t) = HST.583 + \frac{1}{2} (G_x + G_z) - \frac{1}{2} G_x \int S(t) dt
\]

\(S(t)\) depends on net dephasing during \(t\)

Same net dephasing
We can do the same for all Nx sampled points:

- RF
  - Gz
  - Gx

Measure **one point after** dephasing gradient

- RF
  - Gz
  - Gx

Net negative dephasing

Repeat experiment Nx times to sample all points

- RF
  - Gz
  - Gx

Net zero dephasing

- RF
  - Gz
  - Gx

Net positive dephasing
We could have measured ‘exactly’ the same information differently:

Measured signal: time domain

Frequency spectrum: 1D x-projection

Repeat Nx times
Basic Gradient Echo Sequence

RF $\alpha$ $TE$ $TR$ $\alpha$

Gz Slice

Gy Phase

Gx Read

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Conventional spin-warp MRI sequence

The signal we measure is in spatial frequency space ($k$-space)

$$k_{(t)} = \frac{\gamma}{2\pi} \int_{0}^{t'} G_{(t')} dt'$$

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Contents:

• Definition of Contrast
• Contrast parameters
• Concept of MRI contrast weighting
• Properties of pulse sequences & sequence parameters
• **Goal:** maximise the contrast (USEFUL IMAGES!)

• **Contrast:** difference in MR signals between different tissues

Water protons’
 mobility/environment:

MR signal:

Contrast to Noise ratio:

\[
CNR = \frac{S_1 - S_2}{\sigma_{noise}}
\]

Some examples?
Image Contrast: What can we manipulate?

**Tissue Properties: fixed**

<table>
<thead>
<tr>
<th>Tissue</th>
<th>T₁ (ms)</th>
<th>T₂ (ms)</th>
<th>ρ*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fat</td>
<td>260</td>
<td>84</td>
<td>0.90</td>
</tr>
<tr>
<td>White Matter</td>
<td>780</td>
<td>90</td>
<td>0.72</td>
</tr>
<tr>
<td>Gray Matter</td>
<td>920</td>
<td>100</td>
<td>0.84</td>
</tr>
<tr>
<td>CSF</td>
<td>3000</td>
<td>300</td>
<td>1.00</td>
</tr>
</tbody>
</table>

ρ*: % H₂O relative to CSF

**Experimental Variables**

- Pulse sequence
- Pulse sequence parameters
  - Repetition time: TR
  - Echo time: TE
  - Inversion time: TI
  - RF flip angle: α
- Contrast agent

What’s the effect of these variables?
Image Contrast: Weighting the MR Signal

• **General MRI pulse sequence**: combination of contrasts

  Signal Intensity:
  \[ S(x,y) = k \times \rho \times T_1 \times T_2 \times \ldots \]

• **Contrast Weighting**: maximize one term, minimize the others

  Example: \( T_1 \)-weighting
  \[ S(x,y) = k \times \rho \times T_1 \times T_2 \times \ldots \]

  by choosing adequate sequence & sequence parameters

Some examples?
Typical MRI sequences

**Gradient Echo:**
- Proton Density weighting
- T1 weighting
- T2* weighting

**Spin Echo:**
- Proton Density weighting
- T1 weighting
- T2 weighting
- Double echo: PD & T2 weighting

**Inversion Recovery:**
- MP-RAGE: for high T1 contrast
- FLAIR: for PD or T2 weighting without CSF signal
Typical MRI sequences

**Gradient Echo:**
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Basic Gradient Echo Sequence

MR Signal:

\[ S_{GRE} = M_0 \sin \alpha \left[ 1 - \exp \left( -\frac{TR}{T_1} \right) \right] \exp \left( -\frac{TE}{T_2^*} \right) \]
Repetition Time (TR): T1 contrast

GM: gray matter (long T1)
WM: white matter (short T1)

Courtesy of L. Wald
Gradient Echo Sequence

\[ S_{\text{GRE}} = M_0 \sin \alpha \left[ 1 - \exp \left( -\frac{TR}{T_1} \right) \right] \exp \left( -\frac{TE}{T_2^*} \right) \]

**Proton Density weighting**
( TR >> T1, short TE, sin \( \alpha \sim 1 \) )

- Water density

**T1 weighting**
( TR ~ T1, short TE, sin \( \alpha \sim 1 \) )

- Gray / White matter / CSF

**T2* weighting**
( TR >> T1, TE ~ T2* )

- Hemorrhage

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Gradient Echo Sequence

Proton Density Weighting  \[\text{FLASH}\]  T\textsubscript{1} Weighting

- FA = 3°
- FA = 5°
- FA = 30°

Manipulating contrast with flip angle

Courtesy of A. Dale and B. Fischl
Typical MRI sequences

**Gradient Echo:**
- Proton Density weighting
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Basic Spin-Echo Sequence

- **Excitation Pulse**
- **Refocusing Pulse**
- τ
- 90°
- 180°
- TE

**RF**

**Slice**

**Phase**

**Read**

**Spin Echo**
Spin-Echo Sequence:
The MR Signal

\[
S_{SE} = M_0 \left[ 1 - \exp\left( -\frac{TR}{T_1} \right) \right] \exp\left( -\frac{TE}{T_2} \right)
\]
Spin Echo Sequence

$$S_{GRE} = M_0 \sin \alpha \left[ 1 - \exp \left( -\frac{TR}{T_1} \right) \right] \exp \left( -\frac{TE}{T_2} \right)$$

Proton Density weighting
( TR >> T1, short TE, sin \( \alpha \sim 1 \) )
- Water density

T1 weighting
( TR ~ T1, short TE, sin \( \alpha \sim 1 \) )
- Gray / White matter / CSF

T2 weighting
( TR >> T1, TE ~ T2 )
- Hemorrhage

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Double Spin Echo Sequence

- RF
- Slice
- Phase
- Read

RF:
- $90^\circ$

Slice:
- $180^\circ$

Phase:
- $TE_1$
- $TE_2$

Read:
- Echo 1
- Echo 2

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Typical MRI sequences

**Gradient Echo:**
- Proton Density weighting
- T1 weighting
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**Spin Echo:**
- Proton Density weighting
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**Inversion Recovery:**
- MP-RAGE: for high T1 contrast
- FLAIR: for PD or T2 weighting without CSF signal
Inversion Recovery

- **Inversion Pulse**
  - 180° pulse
  - $TI$

- **Refocusing Pulse**
  - 90° pulse
  - 180° pulse

- **RF**
- **Slice**
- **Phase**
- **Read**

- **Magnetization Preparation**
- **Spin Echo**

$TE$
Enhanced $T_1$-weighting: Inversion Recovery

$180^\circ$ Inversion: prepare magnetization prior to Spin Echo detection

$\text{Signal} \propto \rho (1 - 2e^{-\frac{TI}{T_1}} + e^{-\frac{TR}{T_1}}) e^{-\frac{TE}{T_2}}$
Fluid Attenuation Inversion Recovery (FLAIR)

Signal null at: $TI = \ln(2) \times T1$
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