Lecture 3: MR Physics: Controlling the Image

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- MR Physics
- Constrasts
- Pulse Sequences
- Heuristics
- Artifacts
TMS-- Magnetic pulse on scalp

Magnetic field (2T) near scalp produced electrical fields sometimes pulsed.. to effect neurons within 2-3CM of the coil.

Very different from RF pulse during MRI
Anatomy of an MRI scan

- Place object in strong static magnetic field, then.
  1. Transmit Radio frequency pulse: atoms absorb energy
  2. Wait
  3. Listen to Radio Frequency emission due to relaxation
  4. Wait, Goto 1

- Time between set 1 and 3 is our Echo Time (TE)
- Time between step 1 being repeated is our Repetition Time (TR).
- TR and TE influence image contrast.

<table>
<thead>
<tr>
<th>Time</th>
<th>TR</th>
<th>TE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
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</table>
Variables that are Control T1, T2

There are FOUR variables that affect the Image:

- TR
- TE
- Flip Angle (α)
- Tissue type (CSF, Gray, White, Fat, Blood)

(in that we select them to contrast)

trading off SPEED, CONTRAST, SPATIAL RESOLUTION (noise)
Sequences

T2

Single Shot FSE HASTE

Fast Spin Echo

Inversion Recovery

Spin Echo

STIR

FLAIR

GE EPI

GRASE

Multi-shot EPI

Utrafast GE

Spoiled GE

CE MRA

PC

TOF

Gradient Echo

T1

Balanced Steady State GE

Contrast Enhanced Steady State GE

Gradient Echo

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T1 and T2

T1-Relaxation: Recovery
- Recovery of longitudinal orientation of $\mathbf{M}$ along z-axis.
- ‘T1 time’ refers to time interval for 63% recovery of longitudinal magnetization.
- Spin-Lattice interactions.

T2-Relaxation: Dephasing
- Loss of transverse magnetization $\mathbf{M}_{xy}$.
- ‘T2 time’ refers to time interval for 37% loss of original transverse magnetization.
- Spin-spin interactions, and more.
Developing Contrast Using Weighting

- Contrast = difference in image values between different tissues
  T1 weighted example: gray-white contrast is possible because T1 differs between these two types of tissue
## Properties of Body Tissues

<table>
<thead>
<tr>
<th>Tissue</th>
<th>T1 (ms)</th>
<th>T2 (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grey Matter (GM)</td>
<td>950</td>
<td>100</td>
</tr>
<tr>
<td>White Matter (WM)</td>
<td>600</td>
<td>80</td>
</tr>
<tr>
<td>Muscle</td>
<td>900</td>
<td>50</td>
</tr>
<tr>
<td>Cerebrospinal Fluid (CSF)</td>
<td>4500</td>
<td>2200</td>
</tr>
<tr>
<td>Fat</td>
<td>250</td>
<td>60</td>
</tr>
<tr>
<td>Blood</td>
<td>1200</td>
<td>100-200</td>
</tr>
</tbody>
</table>
Basic Physics of MRI: T1 and T2

T1 is shorter in fat (large molecules) and longer in CSF (small molecules). T1 contrast is higher for lower TRs.

T2 is shorter in fat and longer in CSF. Signal contrast increased with TE.

- **TR determines T1 contrast**
- **TE determines T2 contrast**.
Relaxation

- After RF absorption ends, protons begin to release energy
  - Emission at Larmor frequency.
  - Emissions amplitude decays over time.
  - Different tissues show different rates of decay.
  - ‘Free Induction Decay’ (FID).
  - Analogy: tuning fork – initially loud, quieter over time, always at resonant frequency.

- Strongest signal immediately after transmission.
  - Most signal with short TE.
  - Why not always use short TE?
TE and T2 contrast

- Signals from all tissue decays with time.
- Signal decays faster in some tissues relative to others.
- Optimal contrast between tissue when they emit relatively different signals.
Optimal contrast

- Optimal TE will depend on which tissues you wish to contrast
  - Gray matter vs White matter
  - CSF vs Gray matter
Every scan is influenced by both T1 and T2. However, by adjusting TE and TR we can determine which effect dominates:

- T1-weighted images use short TE and short TR.
  - Fat bright (fast recovery), water dark (slow recovery)
- T2-weighted images use long TE and long TR: they are dominated by the T2
  - Fat dark (rapid dephasing), water bright (slow dephasing).
- Proton density images use short TE and long TR: reflect hydrogen concentration. A mixture of T1 and T2
Effect of Varying TE
Effect of Varying TR

TR=250

TR=600

TR=1000

TR=1500
### TE and TR lead to weightings of T1 and T2

<table>
<thead>
<tr>
<th>TR</th>
<th>TE</th>
<th>T1 Weighted</th>
<th>T2 Weighted</th>
<th>Source: Mark Cohen’s web slides</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHORT</td>
<td>SHORT</td>
<td>PROTON DENSITY (clinical)</td>
<td>Not USEFUL</td>
<td></td>
</tr>
<tr>
<td>LONG &gt;1600ms</td>
<td>LONG &gt;20ms)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SHORT</td>
<td>300 to 600 ms</td>
<td>T1 WEIGHTED</td>
<td>T2 WEIGHTED</td>
<td></td>
</tr>
</tbody>
</table>

**Short TEs reduce T2 W**

**Long TRs reduce T1 W**
Tissue Contrast Dependence on TR, TE

TR (time in 1000's of ms)

Long

Short

TE (time in 10's of ms)

Short

Long

PDW

T1

T2

poor!
Venous Infarct (occlusion, thrombosis)
Glioblastoma Multiforme (tumour)

T1-Weighted

T2-Weighted
Cerebral Lymphoma (tumor, cancer)

T1-Weighted

T2-Weighted
Anaplastic Astrocytoma (cancer)

T1-Weighted

T2-Weighted
CONSTRUCTING THE IMAGE

Two Spaces

k-space

k_y

k_x

Image space

y

x

FT

FT⁻¹

Acquired Data

MRI task is to acquire k-space image then transform to a spatial-domain image. k_x is sampled (read out) in real time to give N samples. k_y is adjusted before each readout.

Final Image

MR image is the magnitude of the Fourier transform of the k-space image.
K-space Catherine and the Cat.
K-space

For 2-D MR image, k-space stores amplitude and phase information (as a complex number), for each simple component. This can be used to reconstruct a very complicated 2-D waveform (i.e., the image) via Fourier transform → “k” is transformed to “x”.

Harmonics with long wavelengths → stored near the middle of k-space
Harmonics with short wavelengths → stored near the periphery of k-space
k-space and the MR Image

If the image is a 256 x 256 matrix size, then k-space is also 256 x 256 points. The individual points in k-space represent spatial frequencies in the image.

- Contrast is represented by low spatial frequencies; detail is represented by high spatial frequencies.
Spatial Frequencies

low frequency = contrast
high frequency = detail
The most abrupt change occurs at an edge. Images of edges contain the highest spatial frequencies.
Low Spatial Frequency
Higher Spatial Frequency
K-Space

Source: Traveler’s Guide to K-space (C.A. Mistretta)
K-space composition
Two Main Classes of Pulse Sequence (Filling K space)

• Spin Echo (SE) - uses a second RF-pulse to refocus spins
  - TR & TE control T1 and T2 contrast

• Gradient Echo (GE) - uses a gradient to refocus spins
  - Flip Angle & TE control T1 and T2* contrast
  - Used in EPI (fMRI) sequences
Spin Echo Pulse Sequence

Spin Echo

One of two major pulse sequences. Historically the oldest Attempts to recover real T2—but was very slow Minutes..
Basic template MRI Frequency Encoding:

- RF Excitation
- Slice Selection ($G_z$)
- Frequency Encoding ($G_x$)
- Readout

Exercise drawing k-space manipulation

Digitizer on
The k-space Trajectory

Frequency Encoding
Gradient \( (G_x) \)

Move to left side of k-space.

Digitizer records N samples along kx where ky = 0

Digitizer records N samples along kx where ky = 0

(kx, ky)
SPIN ECHO MRI Frequency Encoding

Excitation

Slice Selection

Frequency Encoding \( (G_x) \)

Readout

digitizer on

Exercise drawing k-space representation
Spin Echo Sequence

- Spin echo sequences apply a 180° refocusing pulse halfway between initial 90° pulse and measurement.
- This pulse eliminates phase differences due to artifacts, allowing measurement of recovery of true T2.
- Spin echo dramatically increases signal.
Gradient Echo Imaging

THE NEED FOR SPEED...
Reduce the flip angle $\alpha = < 50 \text{ deg}$
Faster T1 and T2
Find the Optimal alpha for a given Tissue
This made a very fast pulse sequence for T1 collection and T2$^*$... since it could not recover T2
Also more artifacts then SE...
Ernst angle ($\theta_E$) for optimum SNR.

$$\cos(\theta_E) = e^{-\frac{TR}{T1}}$$
EPI Speeding up K-Space!

- In conventional MRI, we collect one line of our matrix with each RF pulse.
- So a 64x64 matrix with a TR of 2s will be generated in 128s.
- Problem: this is unacceptable if the object changes rapidly:
  - Heart motion.
  - Brain activity.
- Echo Planar Imaging (EPI): By rapidly applying the frequency gradient, we can collect a 2D slice with a single RF pulse.
  - Benefit: Collect entire 2D slice with each TR
  - Disadvantage: spatial warping and signal dropout due to slow spatial encoding.
Spiral Sequence in K-Space--Glover

SPIRAL is faster than single shot

Slower than EPI

Fewer artifacts as points in K space relevant to final image are nearest neighbor
Susceptibility artifacts

- Magnet fields **interact** with material.
- Ferromagnetic (iron, nickel, cobalt)
  - Strongly attracted: dramatically increases magnetic field.
  - all steel has Iron (FE), but not all steel is ferromagnetic (try putting a magnet on a austenitic stainless steel fridge).
- Paramagnetic (Gd)
  - Weakly attracted: slightly increases field.
- Diamagnetic (H$_2$O)
  - Weakly repelled: slightly decreases field.

Field strength increases near some tissues, decreases around others.
Tissue Susceptibility

• Due to spin-spin interactions, hydrogen’s resonance frequency differs between materials.
  − E.G. hydrogen in water and fat resonate at slightly different frequencies (~220 Hz; 1.5T).

• Macroscopically: These effects can lead spatial distortion (e.g. ‘fat shift’ relative to water) and signal dropout.

• Microscopically: field gradients at boundaries of different tissues causes dephasing and signal loss.
Field Inhomogeneity Artifacts

- When we put an object (like someone’s head) inside a magnet, the field becomes non-uniform.
- When the field is inhomogeneous, we will get artifacts: resonance frequency will vary across image.
- Prior to our first scans, the scanner is ‘shimmed’ to make the field as uniform as possible.
- Shimming is difficult near air-tissue boundaries (e.g., sinuses).
- Shimming artifacts more intense at higher fields.
Consider very short TR:
- Fat: rapid recovery, each RF pulse will generate strong signal.
- Water: slow recovery, little net magnetization to tip. Later pulses generate little signal.

Before first pulse:
1H in all tissue strongly magnetized.

After several rapid pulses: CSF has little net magnetization, so these tissue will not generate much signal.

T1 effects explain why we discard the first few fMRI scans: the signal has not saturated, so these scans show more T1 than subsequent images.
Phased Array (Parallel Imaging) Coils

SNR of surface coils with the coverage of head coils

OR... faster parallel imaging

modern scanners come standard with 8- or 12-channel head coils and capability for up to 32 channels

12-channel coil

32-channel coil

32-channel head coil

90-channel prototype
Mass. General Hospital
Wiggins & Wald

Photo Source: Technology Review
T2 vs T2*

T2 only one reason for dephasing:
- Pure T2 dephasing is intrinsic to sample (e.g. different T2 of CSF and fat).
- T2* dephasing includes true T2 as well as field inhomogeneity (T2m) and tissue susceptibility (T2ms).
  - Due to these artifacts, Larmor frequency varies between locations.

T2* leads to rapid loss of signal: images with long TE will have little coherent signal.

\[
\frac{1}{T^2} = \frac{1}{T_2} + \frac{1}{T_{2M}} + \frac{1}{T_{2MS}}
\]
Figure 3.11 (a) Comparison of $T_2^*$ with $T_2$ for the same tissue in different magnet homogeneities. (b) $T_2^*$ image of the head produced in a modern well shimmed magnet. (c) The same image with deliberately reduced homogeneity. Notice the overall loss of signal and the loss of grey-white matter contrast. TE was 40 ms in (b) and (c).
T2*-Weighting (GE)

- Refer to T2-weighting in a gradient echo sequence as T2*-weighting
- Because of inhomogeneities in the $B_0$ magnetic field T2 relaxation occurs faster using a gradient echo sequence than ‘true T2 relaxation’ as measured with a spin-echo sequence
- The greater the inhomogeneity the faster T2 decay occurs
T2* Effect--- The origin of Blood Oxygen Level Dependency (BOLD)

Well shimmed

Poorly shimmed
Next week Structural (T1) and BOLD (T2*)