Optimizing MR Imaging Procedures: The Physicist as a Consultant

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Substantial number of slides courtesy of Geoff Clarke, UTHSCSA

Overview

- Image contrast in standard clinical sequences (pulse timing parameters)
- Interactions between spatial resolution, imaging speed and signal-to-noise ratio
- Adapting MR protocols to physiology and system configuration

Morphology & Physiology

- Tissue parameters (T1, T2, PD, mag transfer)
- Chemical shift (water vs. fat)
- Blood motion (macroscopic & microscopic)
- Gross motion (peristalsis, respiration)
- Tissue susceptibility
- Diffusion of water
- Patient (clinical status, body habitus, prep)

adapted, G. Clarke
Optimizing MRI Protocols

- **SNR**
- **SPEED**
- **SAFETY**
- **COVERAGE**
- **COMFORT/COMPLIANCE**
- **PRICE**
- **RESOLUTION**

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### MR Brain Imaging

- **AX T1W**
- **AX T2W**
- **FLAIR**
- **Diffusion**
- **Gadolinium**
- **MRA**

Brain MR Imaging requires:
- Good gray-white matter contrast
- High spatial resolution
- Excellent timing and gradient control
- See inside bony structures
- Depict white matter lesions
- Evaluate cerebral blood flow (angiogram or perfusion)

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### MR Knee Imaging

- **Axial T1W**
- **Axial T2W FS**
- **Coronal T2W FS**
- **T2W GRE**
- **Sagittal PD**
- **PD fat sat**

Skeletal MR Imaging requires:
- Small FOV, high spatial resolution
- Off-center imaging
- Avoidance of wrap-around
- Elimination of fat signals
- Soft tissue contrast
- See tendons, ligaments, bone marrow, cartilage
- Arthroscopy or kinematic evaluation

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### MR Liver Imaging

- **Axial T2W**
- **Axial EPI**
- **Axial T1W Ferumoxide**

Body MR Imaging requires:
- Control of respiratory and other motion artifacts
- Identification and/or elimination of fat signals
- Avoidance of wrap-around (aliasing) artifact
- Advantages:
  - Soft tissue contrast
  - High degree of contrast manipulation
  - Lesion characterization
  - High sensitivity to iron

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G.D. Clarke, UT HSC San Antonio
User Selectable Parameters

- Magnetic Field Strength ($B_0$)
- Coil selection

Image Contrast

- Basic image contrast is effected by the amplitude and timing of the RF pulses used to excite the spin system.
- Also manipulated by use of gradient pulses (to modulate motion) and exogenous contrast agents (alter tissue properties)

User Selectable Parameters

- Magnetic Field Strength ($B_0$)
- Coil selection
- RF pulse timing (TR, TE, TI)
- RF pulse amplitude - flip angles ($\alpha$)
- Receiver bandwidth (BW)
- Gradient amplitude & timing (b-value)
- RF pulse excitation frequency & bandwidth

T1W Images

Spin Echo Sequence
- 22 axial slices
- 20 sagittal slices

CSF has weak/no signal
fat emits a strong signal
T2W Images

Spin Echo Sequence

CSF emits a strong signal. fat emits a weak signal.

SE – Effect of TR

Spin Echo Pulse Sequence

Fat emits a weak signal.

Multi-Echo Acquisitions
Spin Echo - Rules of Thumb

\[ I = M_0 [1 - e^{-TR/T1}] e^{-TE/T2} \]

- TR controls T1 dependence
  - \( \uparrow \uparrow \) Scan time
  - \( \downarrow \downarrow \) SNR
  - \( \uparrow \downarrow \) #slices possible in multi-echo

- TE controls T2 dependence
  - \( \uparrow \downarrow \) SNR
  - \( \uparrow \downarrow \) #slices possible in given TR

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T1, T2 and for Various Tissues

<table>
<thead>
<tr>
<th>Tissue</th>
<th>T1 (ms)</th>
<th>T2 (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liver</td>
<td>675±142</td>
<td>54±8</td>
</tr>
<tr>
<td>Kidney</td>
<td>559±10</td>
<td>84±8</td>
</tr>
<tr>
<td>Muscle</td>
<td>1123±119</td>
<td>43±4</td>
</tr>
<tr>
<td>Gray Matter</td>
<td>1136±91</td>
<td>87±15</td>
</tr>
<tr>
<td>White Matter</td>
<td>889±30</td>
<td>86±1.5</td>
</tr>
</tbody>
</table>

\( G. \) Clarke, Akber, 1996 (at 63 MHz)

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\( \sim T_1 \) for Various \( B_o \)

<table>
<thead>
<tr>
<th>Tissue</th>
<th>0.5T</th>
<th>1.5T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fat</td>
<td>215</td>
<td>250</td>
</tr>
<tr>
<td>Liver</td>
<td>323</td>
<td>675</td>
</tr>
<tr>
<td>Kidney</td>
<td>559</td>
<td></td>
</tr>
<tr>
<td>Muscle</td>
<td>600</td>
<td>1123</td>
</tr>
<tr>
<td>Gray Matter</td>
<td>656</td>
<td>1136</td>
</tr>
<tr>
<td>White Matter</td>
<td>539</td>
<td>889</td>
</tr>
</tbody>
</table>

(example values from multiple sources)
Manipulating Contrast

- The “weighting” of image contrast is related to delay times, TR (repetition time) & TE (echo time)
- Spin Echo – manipulates image contrast with 180° refocusing pulses (insensitive to B₀ inhomogeneities)
- Gradient Echo – manipulates image contrast by varying the excitation flip angle (fast scans)
- Inversion Recovery – manipulates image contrast with 180° inversion pulses

Pulse Sequence Classifications

<table>
<thead>
<tr>
<th>Name</th>
<th>RF Pulses</th>
<th>Contrast Weighting</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin Echo</td>
<td>Two or more</td>
<td>T1, PD or T2</td>
<td>Conventional</td>
</tr>
<tr>
<td>Gradient Echo</td>
<td>One</td>
<td>T1 or T2*</td>
<td>Fast imaging (3DFT)</td>
</tr>
<tr>
<td>Inversion Recovery</td>
<td>Three</td>
<td>T1 and T2</td>
<td>Exclude certain tissues</td>
</tr>
</tbody>
</table>

MR Sequences

- RF refocusing
- Single echo
- RARE
- multishot
- FSE
- TSE
- Gradient refocusing
- RF & Gradient refocusing
- GRASE
- Single shot
- ssFSE
- ssTSE

Steady state
- TrueFISP
- B-FFE
- FIESTA
- Mag prep
- SPGR
- TurboFLASH

T1W Images

- Brain or Spine: Spin Echo or FSE
- Liver: Gradient echo or EPI

Fig 4.23 Leyendecker

Images from G. Clarke
Fast Spin Echo

Scan time depends on # TR

Conventional SE: one k-space line per echo per TR

FSE: multiple k-space lines per TR
  multiple echoes per TR - echo train length (ETL)
  one k-space line per echo

K-Space Region vs. Contrast & Resolution

FSE Pulse Sequence

ETL = Echo Train Length

G. Clarke
Contrast is a mixture

- effective TE (ETE): echo placed in center of k-space
- echo train spacing (ETS): T2 contribution, #slices

Example: bright fat on T2-weight FSE
Consider time of first and last echoes as well as echo spacing

Spin Echo vs. Fast Spin Echo

<table>
<thead>
<tr>
<th>FSE</th>
<th>T1-weighted (TR = 500)</th>
<th>T2-weighted (TR = 2000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE = 30 ms</td>
<td></td>
<td>TE = 120 ms</td>
</tr>
</tbody>
</table>

Effect of Echo Spacing

- Signal-to-noise decreases for short T2 tissues (gray & white matter) leading to a decrease in spatial resolution

Liver Imaging

- Very fast (EPI or Gradient Echo) T1-weighted images allow effective management of respiratory motion

G. Clarke
Liver Imaging

- **AX FSE**
- **AX EPI**
- **AX T1W**
- Ferumoxide

- T2-Weighted FAST SPIN ECHO is often used to reduce motion artifact & scan time

**Fast Spin Echo - Rules of Thumb**

- ETL controls scan time
  - ↓↑ Scan time --- fit with TR
  - ↓↑ Image blurring
  - ↓↑ SAR
- ETE controls contrast

**What is SAR?**

- The patient is in an RF magnetic field that causes spin excitation (the B1 field)
- The RF field can induce small currents in the electrically conductive patient which result in energy being absorbed.
- The RF power absorbed by the body is called the **specific absorption rate** (SAR)
- SAR has units of watts absorbed per kg of patient
- If the SAR exceeds the thermal regulation capacity the patient’s body temperature will rise.

**Scan Parameters Effecting SAR**

- **Patient size**: SAR increases as the patient size increases – directly related to patient radius
- **Resonant frequency**: SAR increases with the square of the Larmor frequency (ω₀) – therefore ↑ with B₀²
- **RF pulse flip angle**: SAR increases as the square of the flip angle (α²)
- **Number of RF pulses**: SAR increases with the number of RF pulses in a given time

adapted, G. Clarke

Liver Imaging with Fat sat

what is sar?

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fast spin echo - rules of thumb

- etl controls scan time
  - ↓↑ scan time --- fit with tr
  - ↓↑ image blurring
  - ↓↑ sar
- ete controls contrast

adapted, g. clarke

Liver Imaging with Fat sat
**SNR and Imaging Parameters**

\[
\text{SNR} \propto \frac{\text{FOV}_{\text{ro}} \cdot \text{FOV}_{\text{ph}} \cdot \Delta z}{\sqrt{\text{M}_{\text{ro}}} \cdot \sqrt{\text{M}_{\text{ph}}} \cdot \sqrt{\text{NSA}}} \cdot \sqrt{\text{BW}_{\text{rx}}}
\]

- FOV = field of view
- \( \text{M} \) = matrix size
- NSA = number of signals averaged
- \( \text{BW}_{\text{rx}} \) = receiver bandwidth
- \( \text{ro} \) = read out (frequency encoding) direction
- \( \Delta z \) = slice thickness
- \( \text{ph} \) = phase encoding direction

**Bandwidth Conversions**

*Values are field dependent*

- Version A: quoted in kHz, is ± kHz
- Version B: quoted in Hz/pixel

- Conversion at 1.5T:
  - 12.8 kHz for a 256 matrix = 25.6 kHz for 512 matrix
  - = 100 Hz/pixel

  220 Hz chemical shift of fat
  => 2.2 pixel fat-water shift

**FLAIR Images**

- Spin Echo Sequence, with Inversion Recovery

**Inversion Recovery**

\[
M = M_0 (1 - 2 \exp(-T_1/T_2))
\]

G. Clarke
Fluid Attenuated Inversion Recovery (FLAIR)

- Uses magnitude display.
- Initial 180° pulse applied.
- $M_z = 0$ is the “bounce point.”
- At TI, 90° pulse applied: longer TI 1800 - 2500ms.
- If $M_z = 0$ at TI, maximum possible echo = 0.
- Allows selective suppression of contrast limiting signals, e.g., CSF in ventricles.

**CSF SUPPRESSION: NEUROLOGICAL**

**FLAIR**
(FLuid Attenuated Inversion Recovery)

**Multiple Sclerosis**

<table>
<thead>
<tr>
<th>Proton Density</th>
<th>T2-Weighted</th>
<th>FLAIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>TR = 2350</td>
<td>TR = 2350</td>
<td>TR = 2600</td>
</tr>
<tr>
<td>TE = 30</td>
<td>TE = 80</td>
<td>TE = 145</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TI = 1000</td>
</tr>
</tbody>
</table>


G. Clarke
Inversion Recovery FSE

- 
- 
- 

FLAIR Imaging

- T2W-FSE
  - TE/TR = 98/3500ms,
  - Slice 51.5mm, ET:8 (split)
  - 256x224, 1 NEX,
  - 20x20 cm FOV, 3:23

- FLAIR-FSE
  - TI/TE/TR = 220/147/10000ms,
  - Slice 51.5mm,
  - 256x160, 1 NEX,
  - 20x20cm FOV, 3:40

Short Tau Inversion Recovery (STIR)

- Uses magnitude display.
- Initial 180° pulse applied.
- $M_z = 0$ is the “bounce point.”
- At TI, 90° pulse applied (TI-110-150ms).
- If $M_z = 0$ at TI, maximum possible echo = 0.
- Allows selective suppression of contrast limiting signals, e.g., fat around orbitals.

FAT SUPPRESSION: MUSCULOSKELETAL
**Spine Imaging**

Bottom: STIR
- Short
- TI
- Inversion
- Recovery

**Fat saturation in MSK MRI**

Fat is not your friend!
- Chemical shift saturation
  - Precession of fat and water are different
  - Fat peak can be selected for saturation
  - Higher field strength required
- Inversion recovery
  - High and low field strength systems
  - Requires more time

**Chemical Shift**

- Chemical shift (fat-water) ~3.5 ppm
  - At 1.5T:
    \[ \Delta f_{\text{fat-water}} = 3.5 \times 10^{-6} \cdot \frac{42.6 \text{MHz}}{T} \cdot 1.5T \equiv 220 \text{ Hz} \]
  - At 0.5T:
    \[ \Delta f_{\text{fat-water}} = 3.5 \times 10^{-6} \cdot \frac{42.6 \text{MHz}}{T} \cdot 0.5T \equiv 73 \text{ Hz} \]
- ↓ field strength ..... ↓ chemical shift

**Chemical Shift in the Frequency Encoding Direction**

Lipid signal is shifted to a lower frequency. Produces a signal void (dark band) on the high-frequency side of the lipid and an increase in signal (bright band) on the low-frequency side.

G.D. Clarke, UT HSC San Antonio
**Chemical Shift – Clinical Presentation**

Coronal T1W fast multiplanar spoiled gradient-echo image (FMPSPGR)
TR(ms)/TE(ms)/α: 103/5.6/80º
Frequency encode: right-to-left

Chemical shift artifacts at the lipid-water interfaces.

**Chemical Shift Artifact**

- Occurs in
  - Readout direction
    - Conventional SE
  - Phase encode direction
    - Echo-Planar
- Controlled by
  - Fat Pre-Saturation
  - STIR sequence
  - BW choice

**CHESS**

- This is typically accomplished by preceding a SE or FSE sequence with a 90º pulse that is frequency, not spatially, selective.

**Liver Imaging**

**Chemical Shift**

A. In phase spoiled FFE image w/ TE = 4 ms
B. Out of phase spoiled FFE images w/ TE = 2 ms
C. T2 breath-hold FSE with fatsat pulse

http://www.users.on.net/~vision/papers/abdomen/abdominal-mri.htm
Magnetization Transfer

**Magnetization Transfer Contrast**

- Multislice FSE:
  - Magnetization Transfer Contrast
  - Enhances T2* Weighted Appearance

3D Imaging - MTF

- MTF background suppression
  - Saturate restricted protons (macromolecules)
  - Spin-exchange with more mobile water protons
- Good: reduces background
  - doesn’t saturate moving blood, CSF
- Bad:
  - Orbital fat is more obvious as parenchyma is less

Conventional MRA MRA with MTF

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Post-Contrast T1 Images

**Left** – Axial T1W image of S1 (note nerve root)

**Right** – Gd-enhanced image confirms abnormal soft tissue is scar

Images from G. Clarke
Contrast Agents - Gd

- Gadolinium chelate - paramagnetic
- Seven unpaired electrons
- Unpaired electrons react with protons in adjacent water molecules shortening their relaxation time

- Reduces T1 relaxation times
- Enhances T1 signal intensity in low concentrations

Contrast Agents & B₀ Strength

- Due to increases in tissue T1’s, Gd-based contrast agents are more effective at 3T compared to 1.5T
- Use less contrast agent to get same tissue contrast
- Achieve much higher tissue contrast for the same dose


Contrast-Enhanced MRA

- T1-weighted sequence for bright blood
- Bolus injection of high dose (40-60ml)
- Acquire central k-space when contrast is in arteries in desired region
- May require test bolus or automatic detection

MoBI-track MR Angiography

- 3D CE MRA: First pass carotid, elliptical-centric (60 sec acquisition) image from SR Thomas

G.D. Clarke, UT HSC San Antonio
**Gadolinium**

- shortens T2 relaxation of water
  - lowers SI on T1 weighted images in high concentrations

- Nonuniform distribution of Gd-DTPA
  *increases magnetic susceptibility differences*
  - Decreases MR signal on T2*-weighted images

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**Liver Imaging**

- **AX T2W** Axial T2 Weighted
- **AX EPI** Axial Echo Planar
- **AX T1W** Axial T1 Weighted
- **Ferumoxide** Super Paramagnetic Iron Oxide is the contrast agent of choice in liver imaging

**Contrast agents**

- T2W Fast Spin Echo
- T2*W Gradient Echo

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**Perfusion**

**Negative Enhancement Integral (NEI)**

“Area below the curve” Related to “rCBV”
Fast Scanning

- Short - TR Sequences
- Segmented k-space
- Echo Planar Imaging (EPI)
- Parallel Imaging

Gradient-Echo Imaging

Reference: Wehrli, Fast-Scan Magnetic Resonance. Principles and Applications

GRE Sequence Advantages

- Fast
  - Short TR values allow for fast scanning (~ 1 sec/image)
- No 180° pulse
  - Decreases by >5X RF power deposition
  - Lower minimum TE --> better T1W
- Low flip angle
  - Partial (<90°) flip angle keeps all longitudinal magnetization from being used up
  - Higher signal intensity for short TR
Spoiled GRE

- Destroying any residual transverse magnetization ($M_{xy}$)
- Used in steady-state imaging, with very short TRs
- Short TR, short TE, large flip angle

SPGR and FLASH

Spoiled Gradient Echo

Also called spoiled GRASS, fast field echo, FLASH, etc.

GRE contrast

Flip Angle
- $<30^\circ$, minimizes T1, thus proton density or T2*
- $>30^\circ$ to 60$, T1

TR
- Long (200ms), allows full $M_{xy}$ decay
- Short (<50ms), steady-state precession condition

TE
- Short TE values preserve SNR
- Long TE => T2* contrast, not T2
- Short TE for T1

Sensitive to susceptibility

Magnetic Susceptibility Effects

<table>
<thead>
<tr>
<th>Material</th>
<th>Signal</th>
<th>$\rho$ (g/cm$^3$)</th>
<th>$\chi$ (ppm/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>No</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>$H_2O$</td>
<td>Yes</td>
<td>1.0</td>
<td>-9.05</td>
</tr>
<tr>
<td>Bone (Cortical)</td>
<td>No</td>
<td>1.7-2.0</td>
<td>-8.86</td>
</tr>
<tr>
<td>CuSO$_4$ + $H_2O$ (0.12 g/ml)</td>
<td>Yes</td>
<td>3.52</td>
<td></td>
</tr>
<tr>
<td>Pyrex</td>
<td>No</td>
<td>2.25</td>
<td>-13.91</td>
</tr>
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</table>
Effect of Echo Delay on Susceptibility Induced Signal Loss.

Signal reduction in the region of the nasal and mastoid sinuses.

Signal loss is less extensive for shorter TE - less T2* effect.

Gradient-Echo Imaging

The susceptibility-induced artifacts in GRE images:

- Increase with TE - limiting the utility of GRE $T_2^*$-weighted images in many cases.
- Are worst for tissue/air interfaces, but noticeable at tissue/bone interfaces.
- Are usually a detriment, but are useful in some circumstances (e.g., blood-sensitive imaging, BOLD contrast functional imaging, etc.).

Diffusion Imaging: Principles

- Diffusion gradients sensitize MR Image to motion of extracellular water
- More motion = Darker image

Diffusion Imaging Equations:

$S(b) = S(0)\exp(-bD)$

- Large $D$: mobile water $\rightarrow$ low signal
- Small $D$: restricted motion $\rightarrow$ high signal
- $b$: larger $\rightarrow$ more diffusion weighting

DWI contrast is like an inverse $T_2$ weighting
- Watery tissue - mobile molecules - low signal
- Solid tissue - stronger signal
**DWI Pulse Sequence**

\[ b = \gamma^2 G^2 \delta^2 \left( \Delta - \frac{\delta}{3} \right) \]

Stejskal EO & Tanner JE, 1965. 42: 288-292

adapted, G. Clarke

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**Hyper acute CVA 4Hrs. Evol.**

- MRI Diffusion

- T2 Echo planar

- b-value 1000

- ADC

adapted, R. Rojas

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**Echo Planar Imaging (EPI)**

ultrafast data acquisition

fill k-space by rapid gradient reversals and echoes

after a SINGLE set of RF pulses

Peter Mansfield, 1980s

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**Diffusion Echo-Planar Imaging**

- Signal has to be acquired in time ~T2
- Images in less than 100 ms but poor spatial resolution (~3mm x 3mm pixel)
- Requires very good B\(_0\) homogeneity \(\rightarrow\) big susceptibility artifacts

G. Clarke
EPI limits

Hardware requirements
- gradients - bigger, faster
- rapid A/D
- memory
Artifacts
- chemical shift
- eddy currents
Acoustic noise
Sequence flexibility
Induced currents in patient

Liver Imaging

- Echo planar is the fastest imaging sequence and can be used to minimize motion artifacts
- Long TE Gradient Echoes produce T2* contrast to identify tumors

Parallel Imaging

- Uses spatial information obtained from arrays of RF coils
- Information is used to perform some portion of spatial encoding usually done by gradient fields and RF pulses
- Multiplies imaging speed
  - without needing faster-switching gradients
  - without additional RF power deposited

Image Acceleration

Conventional breath-hold cardiac MRI
Requires 14 heartbeats.

SENSE breath-hold cardiac MRI
Requires 3 heartbeats.
Summary

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Signal-to-Noise</th>
<th>Contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOV &amp; matrix size</td>
<td>FOV &amp; matrix size</td>
<td>Relaxation times</td>
</tr>
<tr>
<td>Slice thickness</td>
<td>RF Pulse flip angles &amp; timing</td>
<td>RF Pulse flip angles &amp; timing</td>
</tr>
<tr>
<td>FSE inter-echo spacing</td>
<td>B₀ field strength</td>
<td>Preparation pulses</td>
</tr>
<tr>
<td>Motion artifact</td>
<td>Receiver bandwidth</td>
<td>Gradient timing (b-value)</td>
</tr>
<tr>
<td>Chemical shift artifact</td>
<td>RF coil sensitivity</td>
<td>Magnetization transfer</td>
</tr>
</tbody>
</table>

Pulse Sequence Factors

- Pulse sequence factors have varying effects
  - $\uparrow$ TR $\uparrow$ SNR by allowing more $M_z$ regrowth
  - $\uparrow$ TE $\downarrow$ SNR by allowing more $M_{xy}$ dephasing
  - 180° refocusing pulses $\uparrow$ SNR
    - SE or FSE
  - $\uparrow$ $T_1$ $\downarrow$ or $\uparrow$ SNR
  - $\uparrow$ $\alpha$ $\downarrow$ or $\uparrow$ SNR depending on Ernst angle

Suggested Reading

- (In order of increasing complexity)

- (practical and specialty references)
  - T1, T2 relaxation and magnetic transfer at 3T. Stanisz et al., MRM 2005 54(3): 507-12.