CONTRAST (CNR) IN MRI

Content

Part 3: Contrast (CNR) in MRI

or How to see/detect what you want to see

- Definition of CNR
- Factors influencing CNR: proton density, T1 and T2-weighted images
- Pulse sequences (gradient echo, spin echo)

Content

- Factors influencing CNR: T1, T2 and proton density weighted images
- Pulse sequences (gradient echo, spin echo)

Demonstrations on the scanner

Computing CNR

- CNR (contrast-to-noise ratio) is a measure of how distinguishable two structures are from each other.
- For magnitude images (most commonly used in MRI), the contrast-to-noise ratio is:

$$CNR = SNR_1 - SNR_2 = \frac{0.655 \cdot (S_1 - S_2)}{\sigma_{air}}$$

- This relationship tells us that:
  - High SNR does not mean high CNR
  - High CNR necessitates regions with high and regions with low SNR (i.e., bright and dark regions)

Factors Influencing CNR in MRI

- Physical and instrumental parameters
  - Magnetic field strength (through T_1 field dependence)
  - Contrast agents (through T_1 dependence)
  - Proton density
  - T_1 and T_2 relaxation times of protons in tissue
  - Diffusion coefficient of water in tissue (microstructure environment)
- Imaging sequence parameters
  - Repetition time, *TR*
  - Echo time, *TE*
  - Flip angle, α
  - Inversion time, *TI*
  - Etc (diffusion time, flow parameters, etc…)

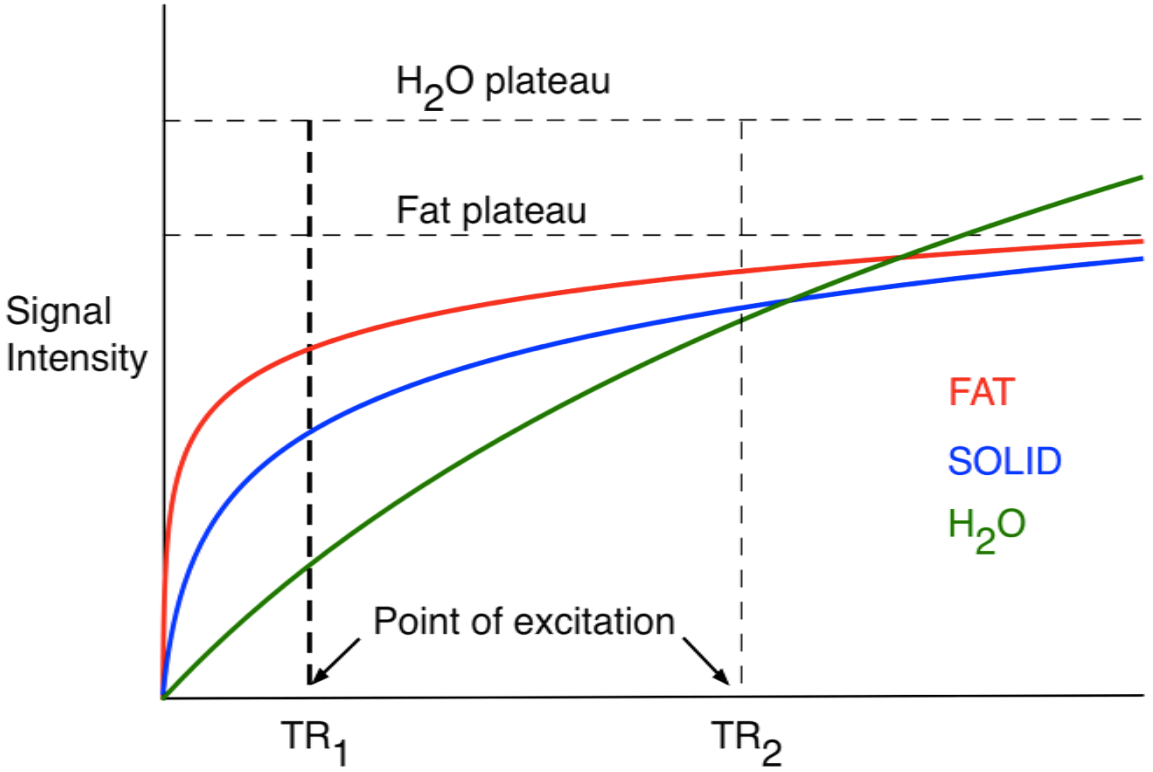
CNR: T_1 and Repetition Time

$$S_{MRI} = \iiint M_0(x,y,z)e^{-i\omega_0 t}e^{-TE/T_2}\left(1-e^{-TR/T_1}\right)f\left(G(t)\right)dxdydz$$

TR (relaxation time) is time between each excitation

T_1 differs among tissue types, depending on the efficiency of energy transfer:

- H_2O, liquids have long T_1
- Fats have short T_1
- Solids have intermediate T_1



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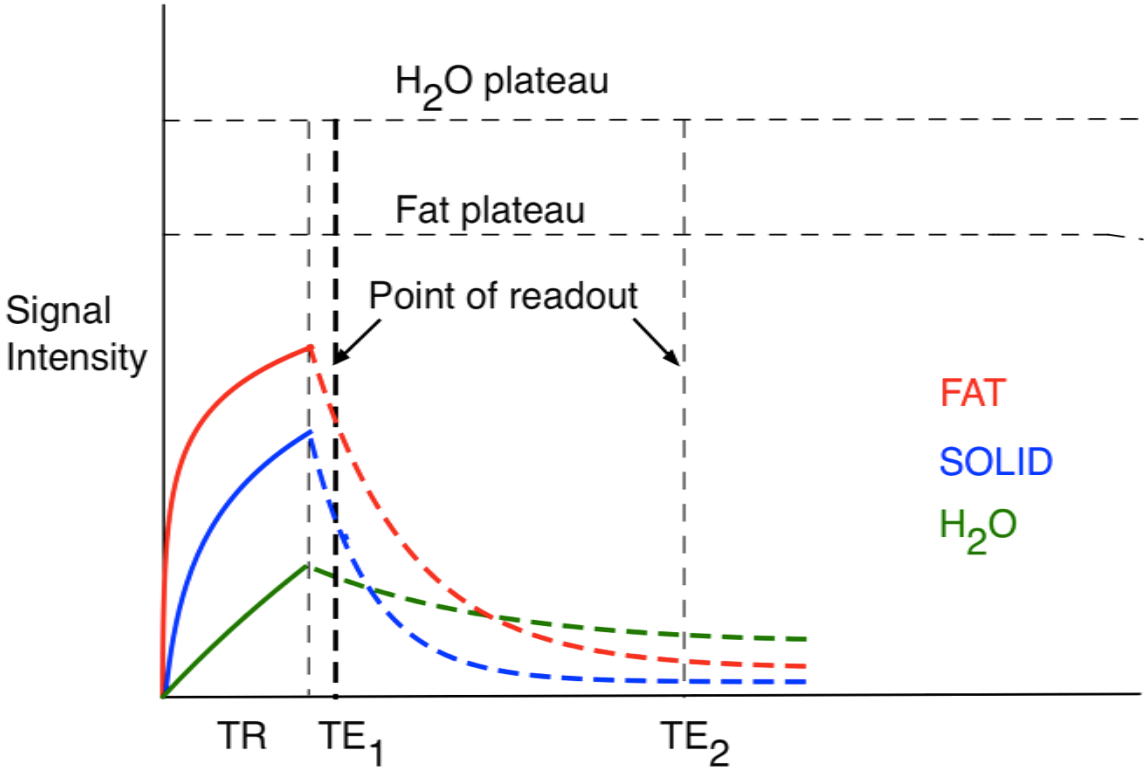


CNR: T_1- Weighted Images

- T_1-weighted images produce contrast based on differences in T_1-relaxation times of tissues

- For T_1 contrast (T_1-weighting), we need:
  - **Short TR** times to enhance T_1 weighting
  - **Short TE** times times to minimize T_2 weighting

$$S_{MRI} \propto \rho_0\left(1 - e^{-TR/T_1}\right)$$

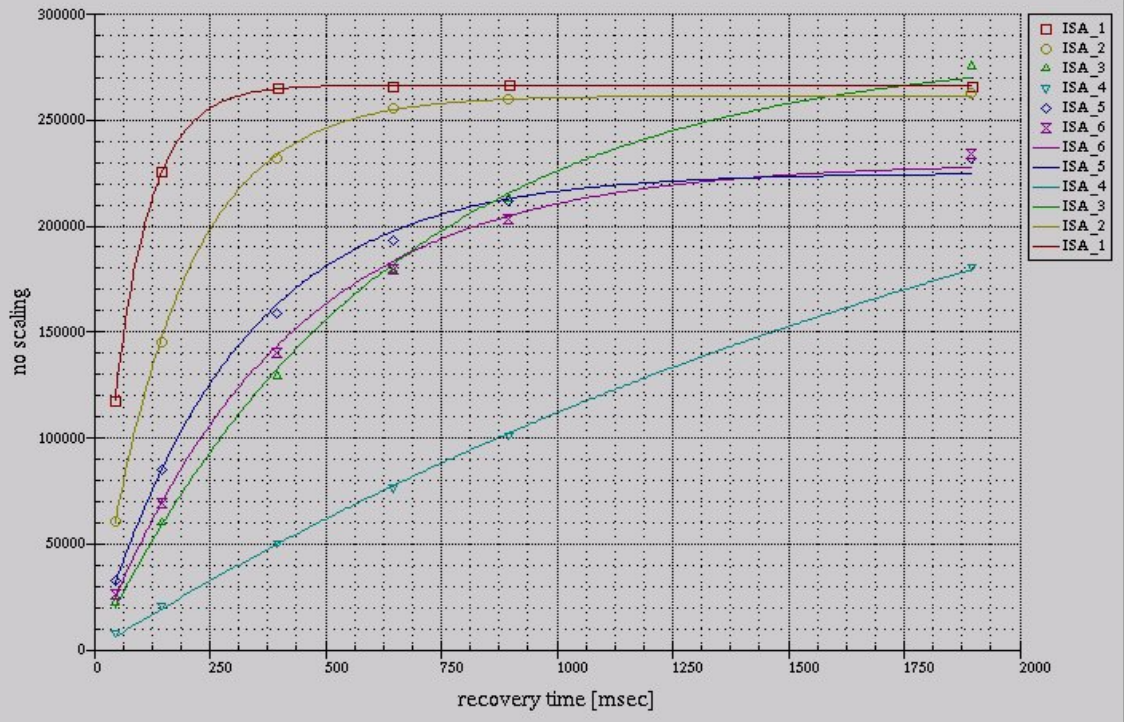
CNR: T_1- Weighted Images

- **<u>Demonstration:</u>**
  - Collect an image of the contrast phantom:
    - Use spin-echo sequence with short TR (200 ms) and short TE (11 ms)
  - Observe contrast between different samples
  - Explain

Image Sequence Analysis Tool

File Parameters Function Table Images

ROI name	ISA_1			ISA_2			ISA_3		
ROI area	0.29 cm2			0.29 cm2			0.29 cm2		
parameter	value	std dev	usage	value	std dev	usage	value	std dev	usag
absolute bias	0	0	fixed	0	0	fixed	0	0	fixec
signal intensity	266470	201.861	varied	261474	1429.55	varied	263924	9495.57	varie
T1 relaxation time [msec]	78.0789	0.169931	varied	175.722	2.30121	varied	628.552	36.431	varie
std dev of the fit	297.945			1377.41			3094.09		
recovery time [msec]	mean	std dev	func	mean	std dev	func	mean	std dev	func
1895.50	266275	21438.6	266470	262511	15140.1	261469	275332	13993.4	2700



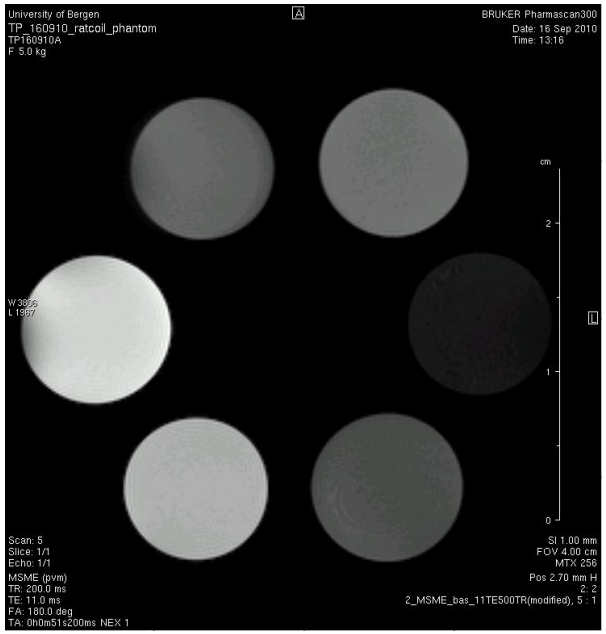
T1 saturation recovery (std dev weighted)

Interactive Image Sequence Analysis for ROI

New ISA ROI | Modify Cur. ROI | Clone Cur. ROI | Refresh Cur. ROI | Pnts & Curves

Phantom = 6 tubes:

1. Doped water, T_1≈100 ms
2. Doped water, T_1≈200 ms
3. Doped water, T_1≈500 ms
4. water, T_1≈3000 ms
5. Cooking oil
6. Motor oil



TR=200 ms, *TE*=11 ms

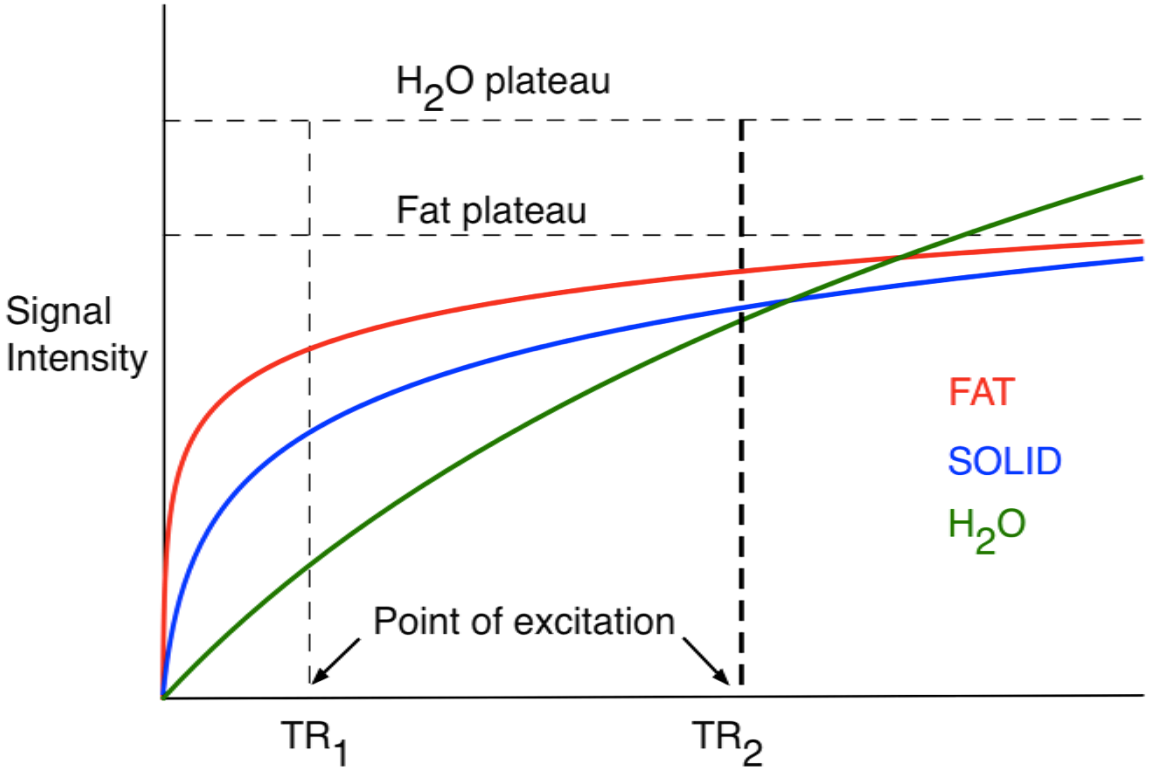
CNR: T_2 and Echo Time

$$S_{MRI} = \iiint M_0(x,y,z)e^{-i\omega_0 t}e^{-TE/T_2}\left(1-e^{-TR/T_1}\right)f\left(G(t)\right)dxdydz$$

***TE* (echo delay time)** is time between between excitation and readout of the signal

T_2 differs among tissue types, depending largely on the mobility of spins:

- H_2O, liquids have long T_2
- Fats have intermediate T_2
- Solids have short T_2



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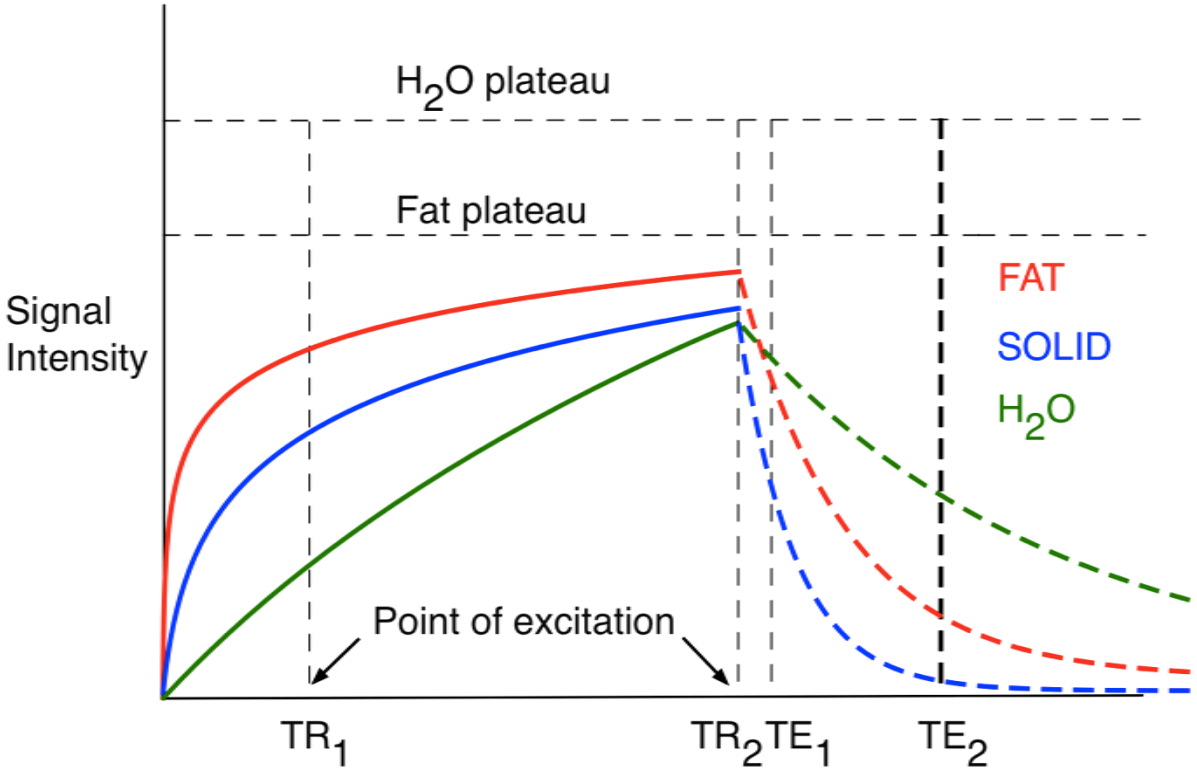


CNR: T_2- Weighted Images

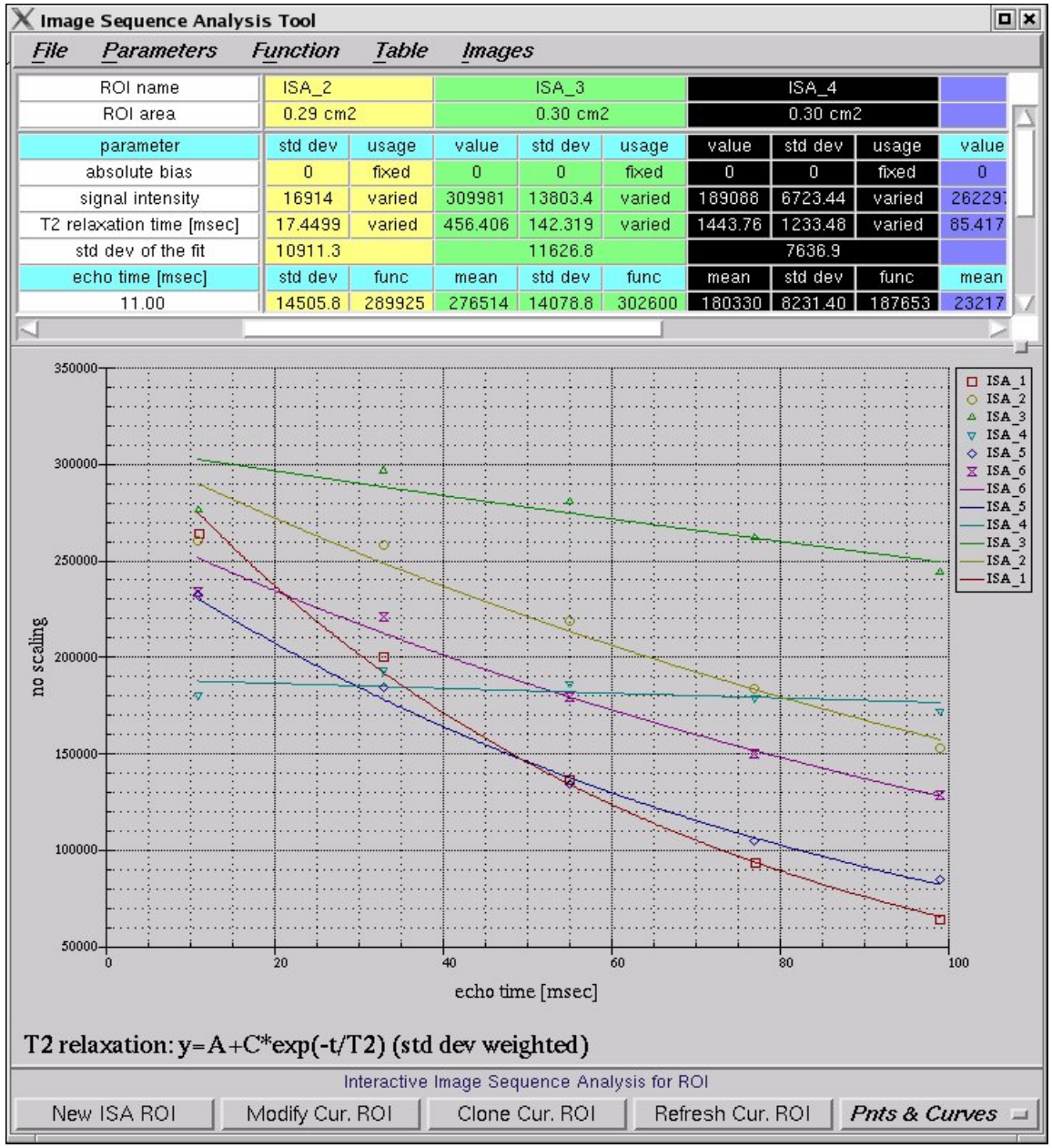
- T_2-weighted images produce contrast based on differences in T_2-relaxation times of tissues

- For T_2 contrast (T_2-weighting), we need:
  - **Long TR** times to minimize T_1 weighting
  - **Long TE** times times to enhance T_2 weighting

$$S_{MRI} \propto \rho_0 e^{-TE/T_2}$$

CNR: T_2- Weighted Images

- **Demonstration:**
  - Collect an image of the contrast phantom:
    - Use spin-echo sequence with long TR (1750 ms) and long TE (80 ms)
  - Observe contrast between different samples
  - Explain



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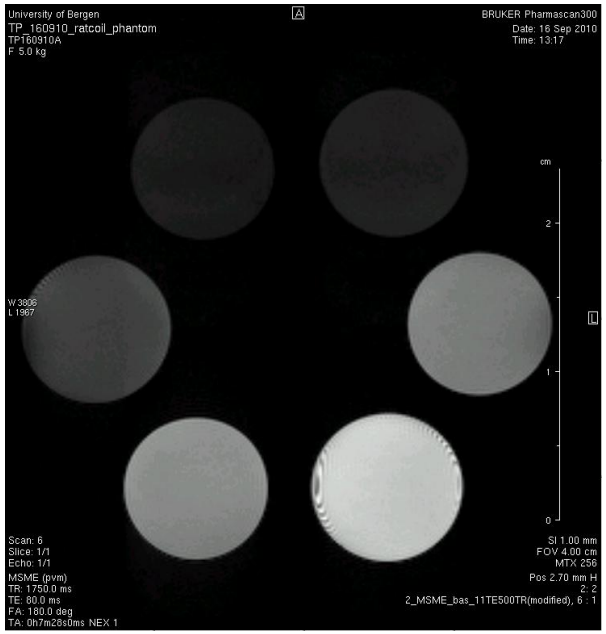


TR=1750 ms, TE=80 ms

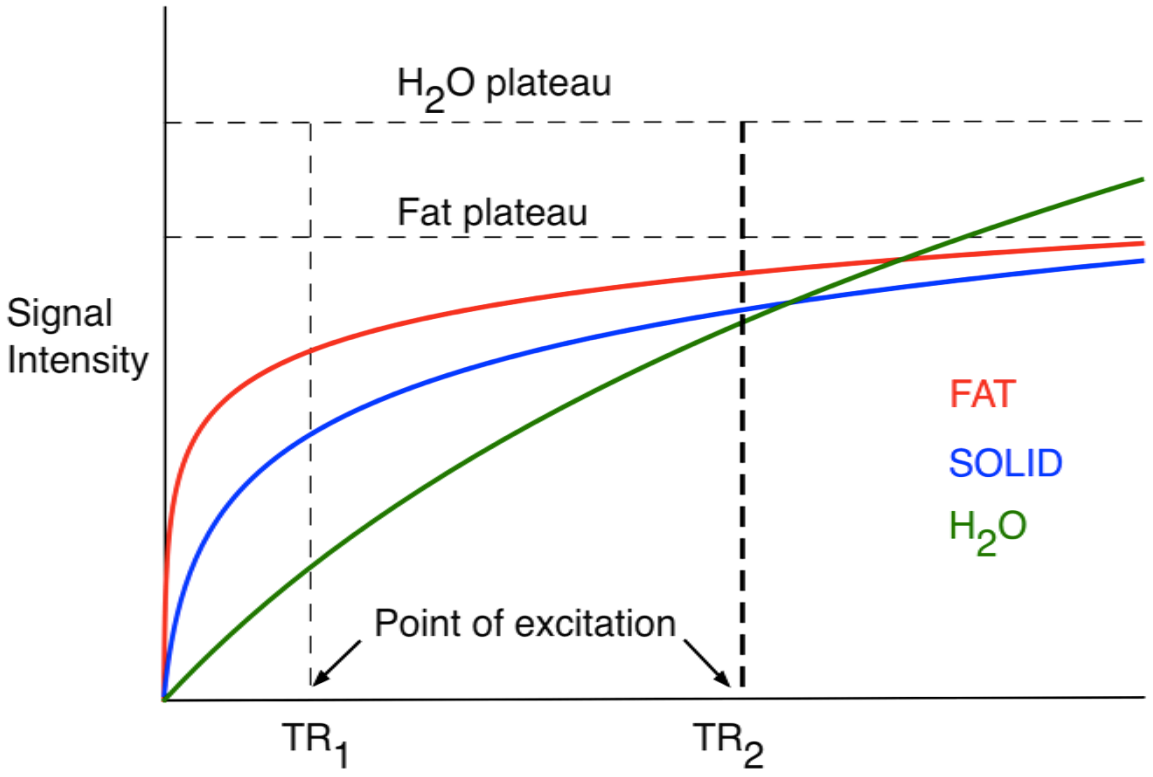
CNR: Proton Density

$$S_{MRI} = \iiint \frac{\rho_0 \gamma^2 \hbar^2}{4kT} B_0(x,y,z) e^{-i\omega_0 t} e^{-TE/T_2} \left(1 - e^{-TR/T_1}\right) f\left(G(t)\right) dxdydz$$

PD depends on the number of hydrogen atoms (or water content) in tissues

PD varies slightly for different tissue types (muscle, fat, cerebral spinal fluid, gray/ white matter, etc):

- Fluids have the highest PD (over 95%)
- Water and fat-based tissues have similar PD (between 60% to 85%)



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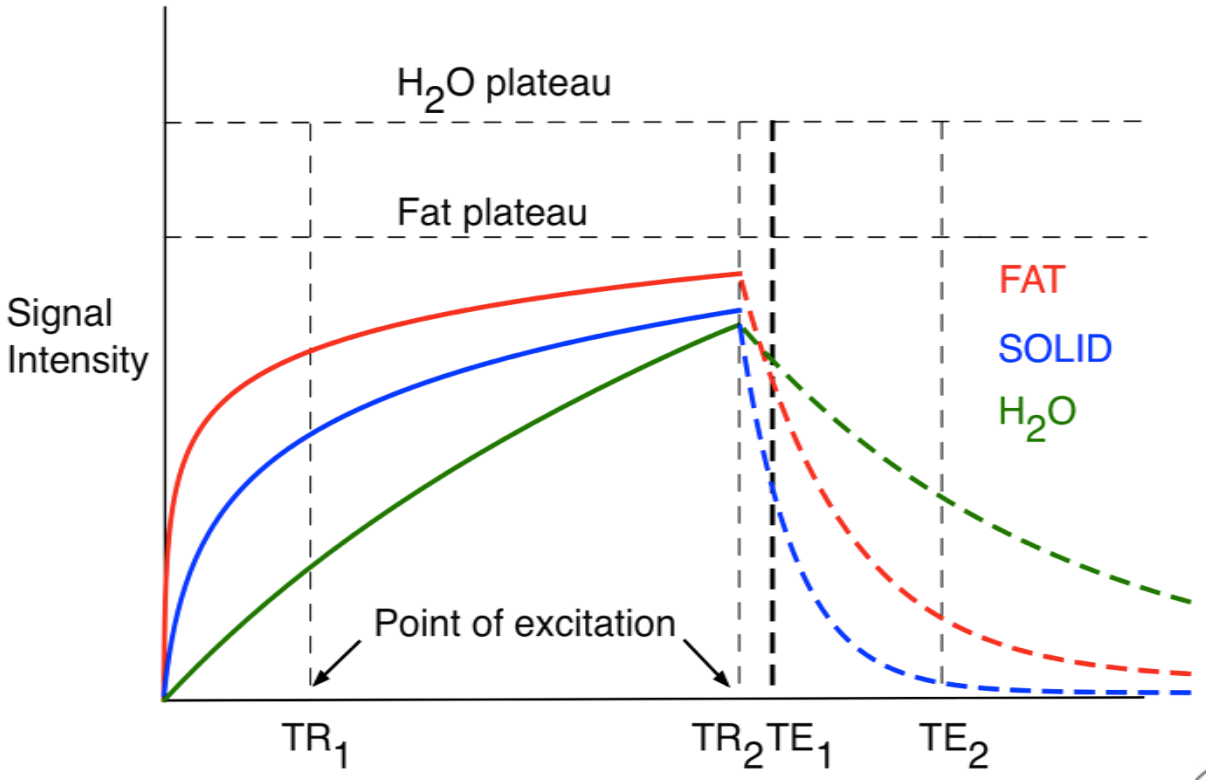


CNR: PD- Weighted Images

- PD-weighted images produce contrast based on differences in PD of tissues

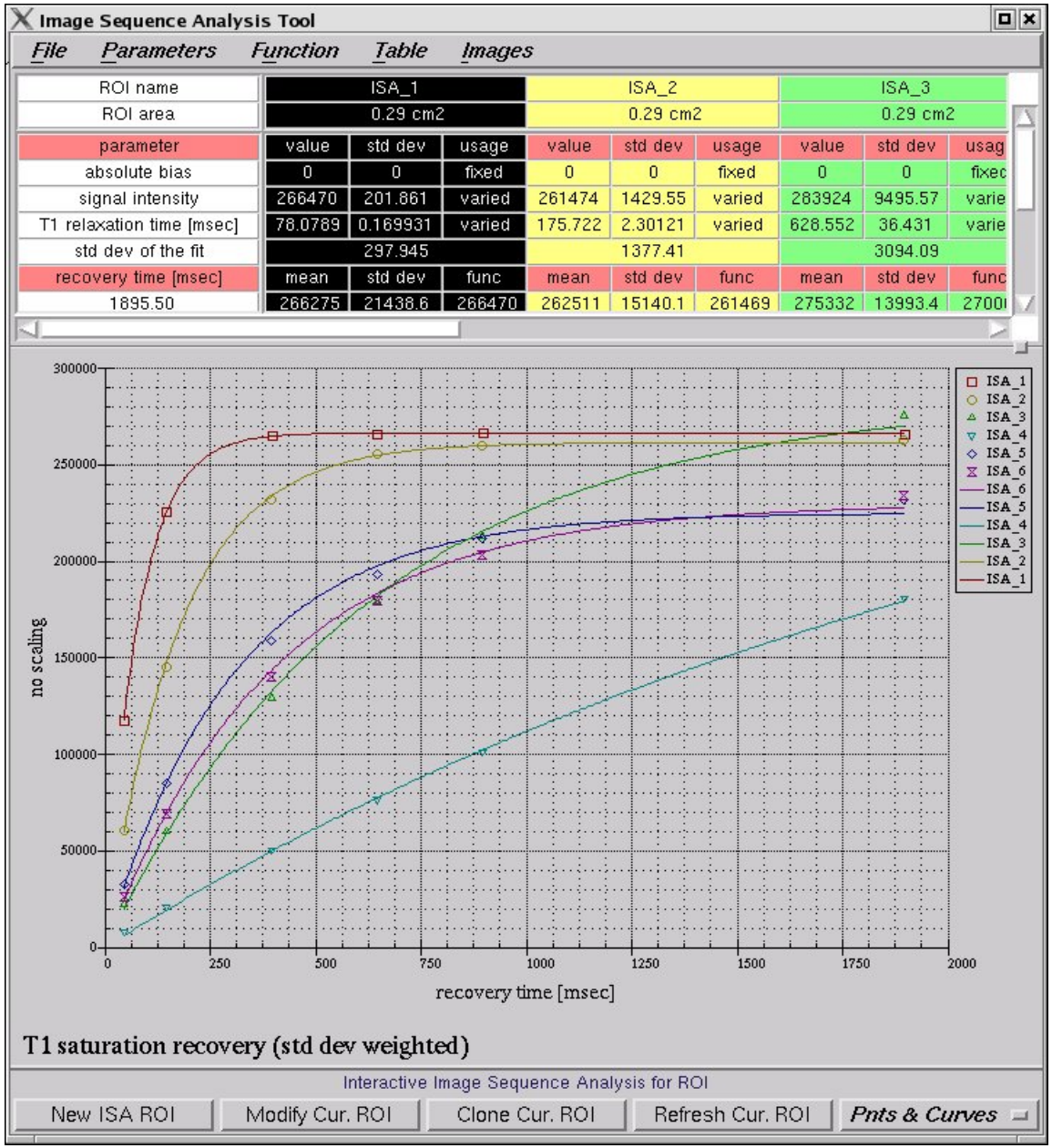
- For PD contrast (PD-weighting), we need:
  - **Long TR** times to allow for complete recovery of magnetization (even for longest T_1 components) and minimize T_1 weighting
  - **Short TE** times times to minimize T_2 weighting

$$S_{MRI} \propto \rho_0$$

- Note, that pure PD contrast is not achievable in practice, since we would need:
  - Infinitely long TR times
  - TE times equal to 0
- Proton density weighting = We put less *weight* on T_1 and T_2 by lengthening TR and shortening TE, thus giving more *weight* to proton density

CNR: PD- Weighted Images

- **Demonstration:**
  - Collect an image of the contrast phantom:
    - Use spin-echo sequence with long TR (1750 ms) and short TE (11 ms)
  - Observe contrast between different samples
  - Explain



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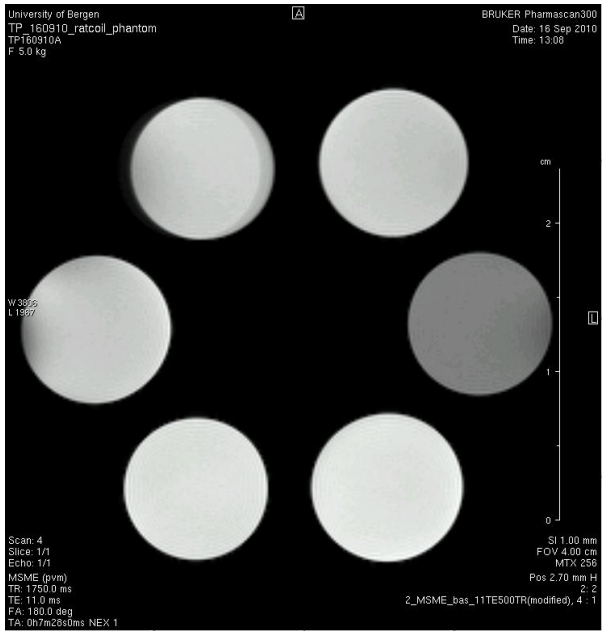
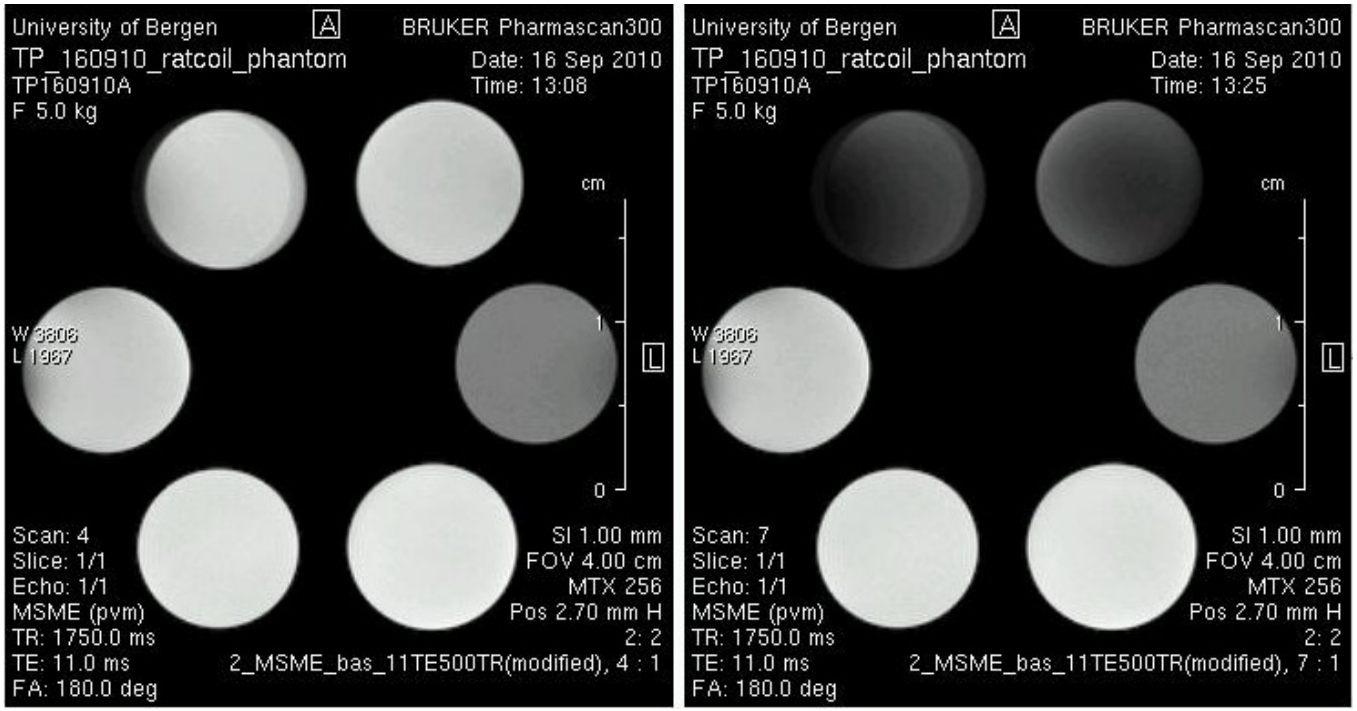


TR=1750 ms, *TE*=11 ms

CNR: PD- Weighted Images with Fat-Suppression

- **Demonstration:**
  - Collect an image of the contrast phantom using fat suppression:
    - Use spin-echo sequence with long TR and short TE
  - Observe contrast between different samples
  - Explain



CNR: Flip Angle

- Flip angle determines contrast in gradient-echo sequence when TR is much shorter than T_1 (FLASH).
- See slide on FLASH for more details

CNR: Contrast Agents

- Contrast agents alter relaxation times of water/tissue => **enhance contrast** in the MR images
- Three main types of exogenous contrast agents:
  - Gadolinium, Gd (Omniscan, Magnevist, Dotarem, etc…): paramagnetic
  - Iron oxide (Feridex): superparamagnetic
  - Manganese (Mn-DPDP): paramagnetic
- Paramagnetic contrast agents are primarily used as T_1-shortenig agents => **signal enhancement on T_1-weighted images**
- Superparamagnetic contrast agents are primarily used as T_2/ T_2* -shortening agents => **signal drop/void on T_2-weighted images**

CNR: Contrast Agents Theory

- Effect of contrast agent on tissue relaxation times is best described using relaxation rates: $R_1=1/T_1$, $R_2=1/T_2$
- Relaxation rates are additive
- In the presence of contrast agent, the new relaxation rate is:

$$R' = R + rC = 1/T' + rC$$

R' is the relaxation rate is the presence of contrast agent

R is the original relaxation rate (e.g., of tissue, water, etc…)

C is the concentration of contrast in tissue, in mM (mMolar = mmol/L)

r is **specific relaxivity** of the contrast agent, in mM/s (4mM/s for Gd)

CNR: Contrast Agents Theory Cont.

- Example:
  - We would like to create a 50 ml phantom with T_1=200ms
  - We have 5 ml of Dotarem, with concentration of 500mM
  - The relaxivity of Dotarem is 4/mMs.
  - The T_1 of pure water at 7T is around 3sec.
- We, first compute the concentration of solution:

$$C = \frac{R'_1 - R_1}{r_1} = \frac{(1/0.2 - 1/3)/\mathrm{s}}{4/\mathrm{mMs}} = 1.167\mathrm{mM}$$

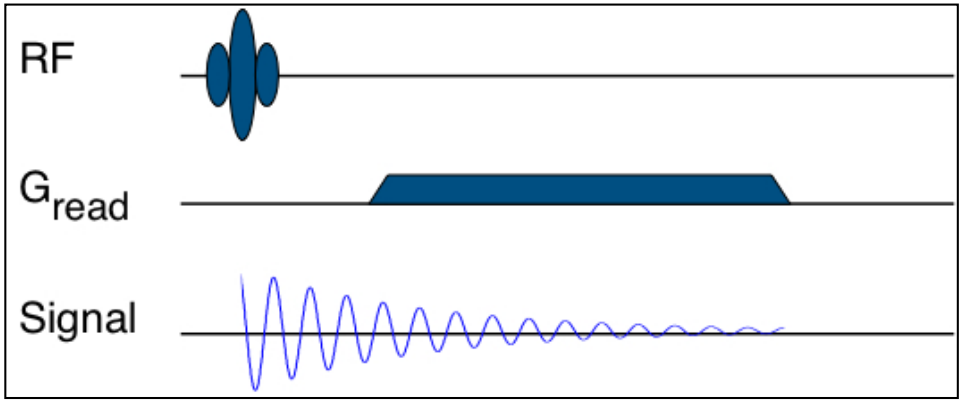
- Then, we compute the volume of contrast agent we need:

$$C_{sol}V_{sol} = C_{Gd}V_{Gd} \Rightarrow V_{Gd} = \frac{C_{sol}V_{sol}}{C_{Gd}}$$

$$V_{Gd} = \frac{1.167 * 50}{500}\mathrm{mM} = 0.117\mathrm{ml} = 117\mu\mathrm{l}$$

Pulse Sequence Diagrams

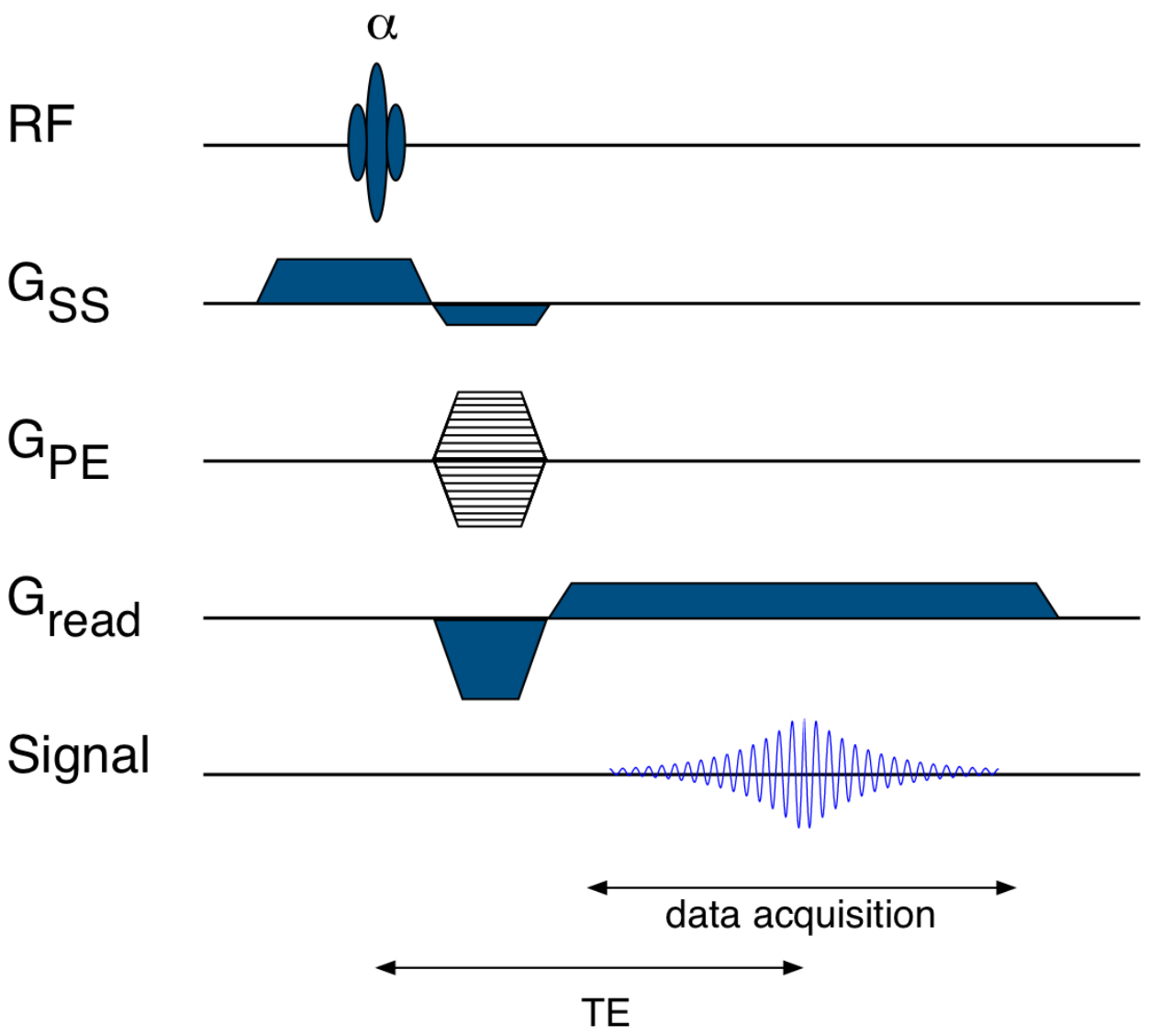
- Is a simple means of showing how the RF (excitation) and gradient pulses (spatial encoding) are applied
- Horizontal axis = time, vertical axis = amplitude
- From the sequence diagram we can get the following info:
  - Timing parameters: TE, TR, diffusion time, etc
  - RF parameters: shape, flip angle α.
  - Gradient parameters: strength and duration
  - Knowledge of how we transverse the *k*-space



Gradient Echo Sequence or GRE

- Echo is formed by de-phasing and re-phasing of an MR signal by an imaging gradient => **gradient echo**
- Effect of magnet inhomogeneities and local susceptibility changes are NOT compensated (T_2* decay)
- Can give *PD*, T_1, T_2* contrast (in special cases also T_2)
- RF pulse (α) can be any value between 0^0 and 90^0
- Speed is achieved by using a small flip angle and short *TR*
- Three main groups of gradient echo sequences:
  - **Spoiled or incoherent** GE (e.g., FLASH)
  - **Rewound or coherent** GE (e.g., FISP)
  - **Steady state/contrast enhanced** (e.g., SSFP)
- Ideally suited for studies in which speed is important: dynamic contrast MRI, angiography, breath-hold studies and 3D imaging (3D FT).

GRE: Sequence Diagram



Fast Low Angle SHot or FLASH (T_1>>TR)

- The stead-state MR signal in FLASH is:

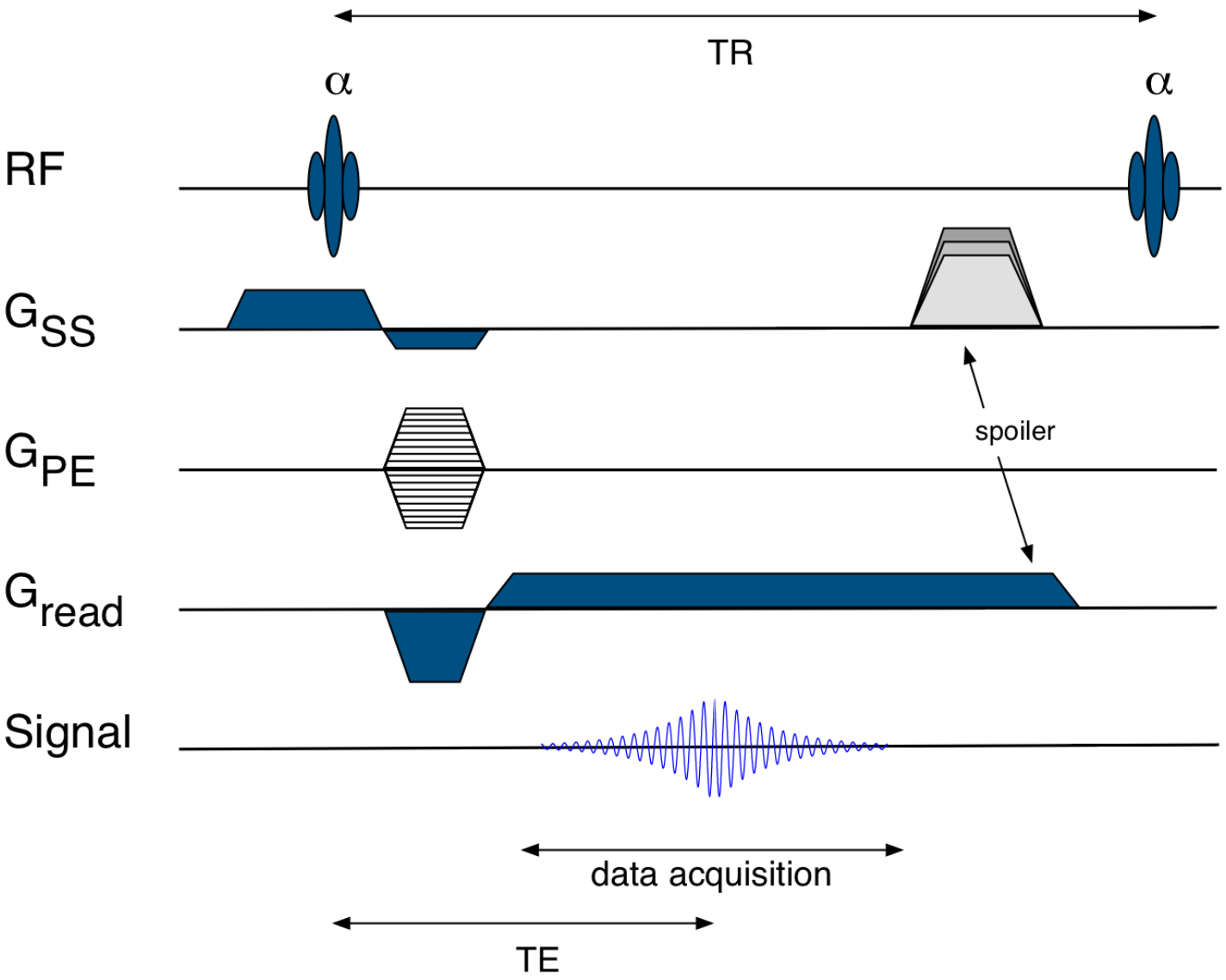
$$S_{MRI} = \rho \frac{\sin\alpha \cdot \left(1 - e^{-\frac{TR}{T_1}}\right) \cdot e^{-\frac{TE}{T_2^*}}}{1 - \cos\alpha \cdot e^{-\frac{TR}{T_1}}}$$

- Flip angle α also determines image contrast
- For each value of T_1 there is an optimum flip angle at which MR signal will be at its maximum => **Ernst angle**

$$\alpha_{Ernst} = \cos^{-1}\left(e^{-\frac{TR}{T_1}}\right)$$

- **For α < Ernst angle => *PD* weighting**
- **For α > Ernst angle => T_1 weighting**

FLASH: Sequence Diagram

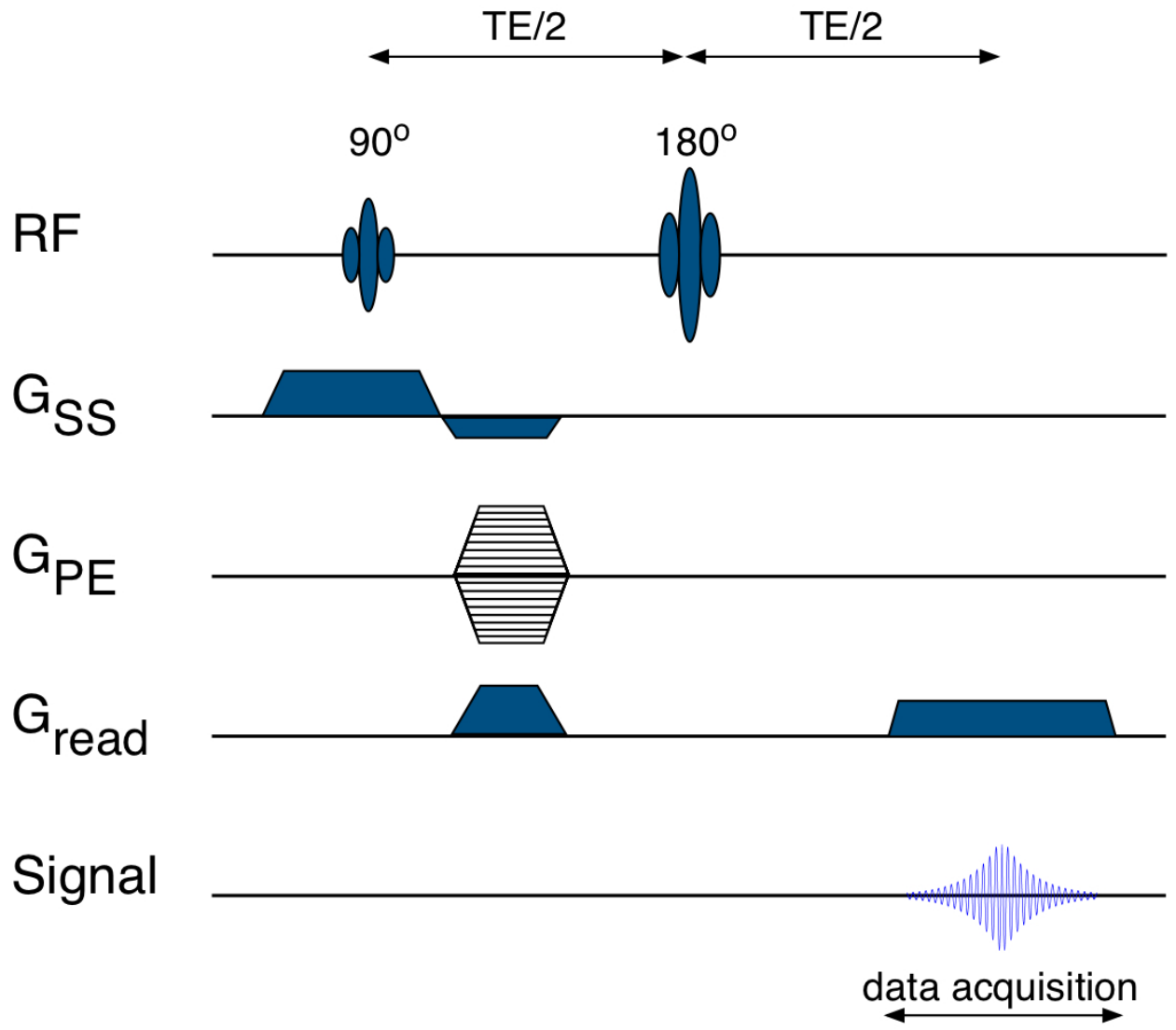


$TR << T_1$

Spin Echo Sequence or SPE

- Echo is formed by a 180^0 pulse => **spin echo**
- Effect of magnet inhomogeneities and local susceptibility changes are compensated (T_2 decay)
- Can give *PD*, T_1, T_2 contrast
- RF pulse (α) is a 90^0 pulse
- Speed is achieved by using multiple echoes to collect several lines of k-space in a single shot (within *TR* period) => segmentation (fast or turbo SE)
- Two main groups of spin echo sequences:
  - **Inversion recovery** SE (e.g., FLAIR)
  - **Fast or Turbo** SE (e.g., RARE, MSME)
- Ideally suited for studies in which susceptibility effects are big: near air/ tissue interfaces in lungs, near bone/tissue interfaces to study joints…

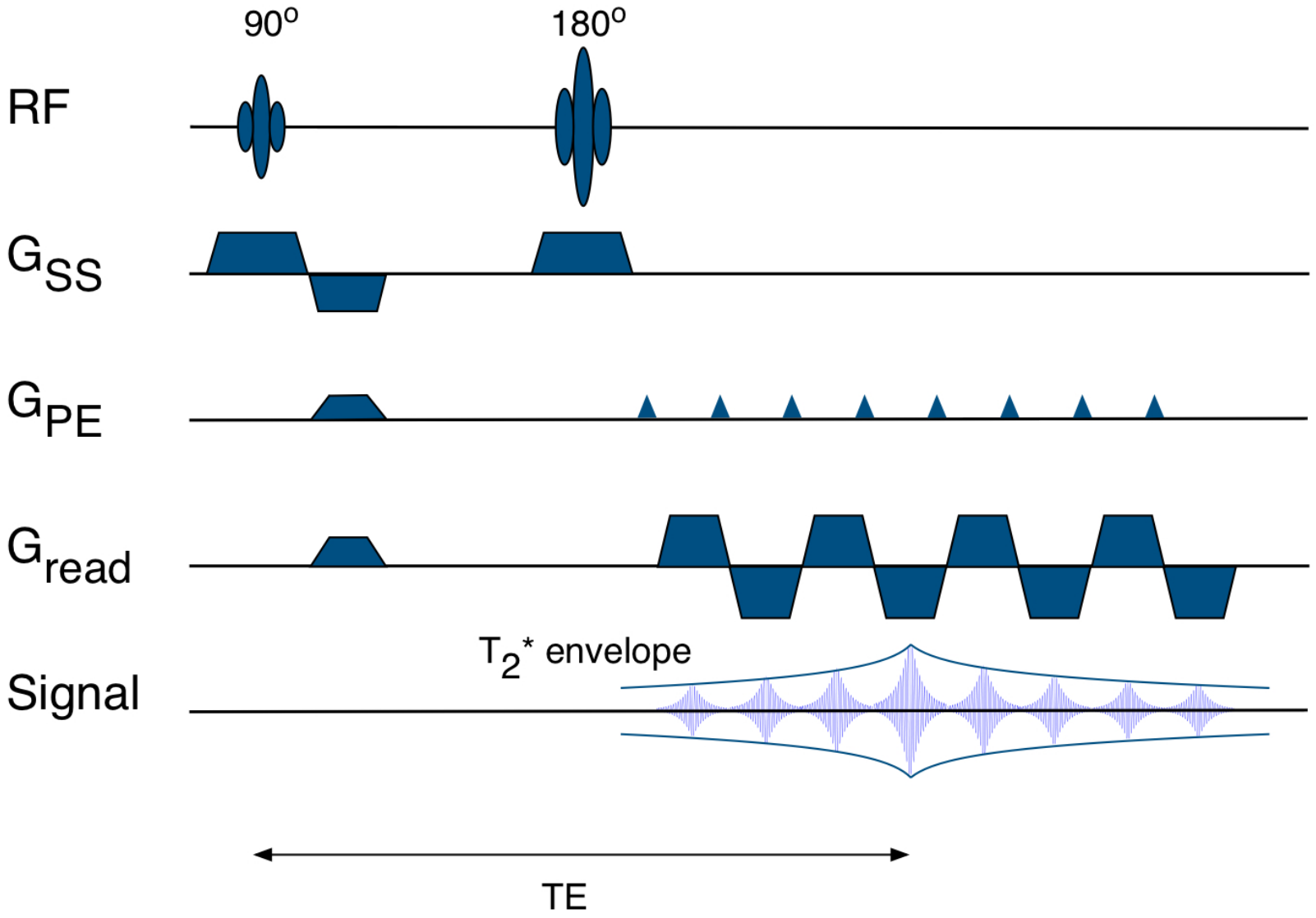
SPE: Sequence Diagram



Echo Planar Imaging EPI (SE-EPI or GE-EPI)

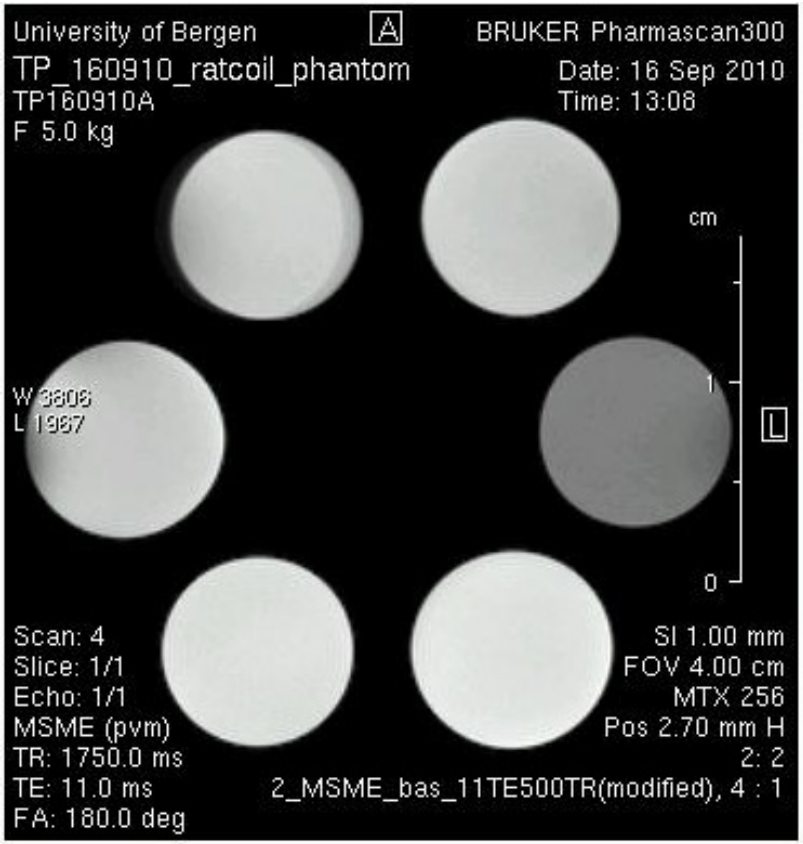
- The fastest pulse sequence available => the entire image can be collected in less than 100 ms
- Two main groups of EPI sequences:
  - **Spin-echo** EPI
  - **Gradient echo** EPI
- Can be **single-shot** or **multi-shot**
- In single-shot case, the whole of *k*-space is sampled with gradient echoes under a single spin echo (in SE-EPI) or under an FID (in GE-EPI)
- Ideally suited for studies in which speed is important: dynamic, diffusion-weighted imaging (EPI-DTI) and fMRI.

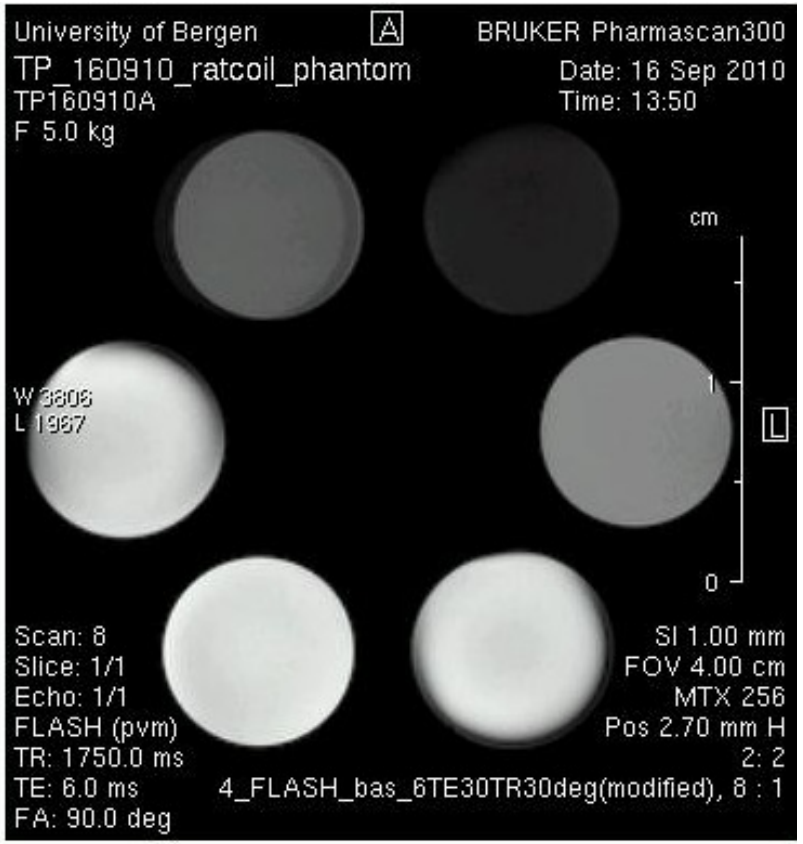
EPI: sequence diagram for SE-EPI



Some Examples

PD-Weighting: MSME vs. FLASH at long TR

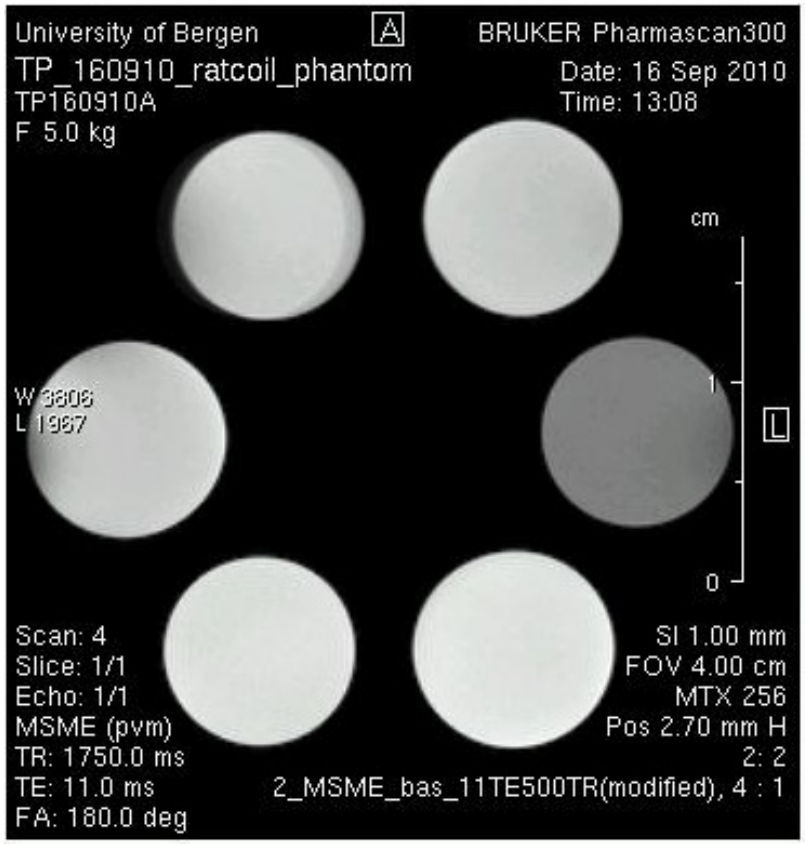


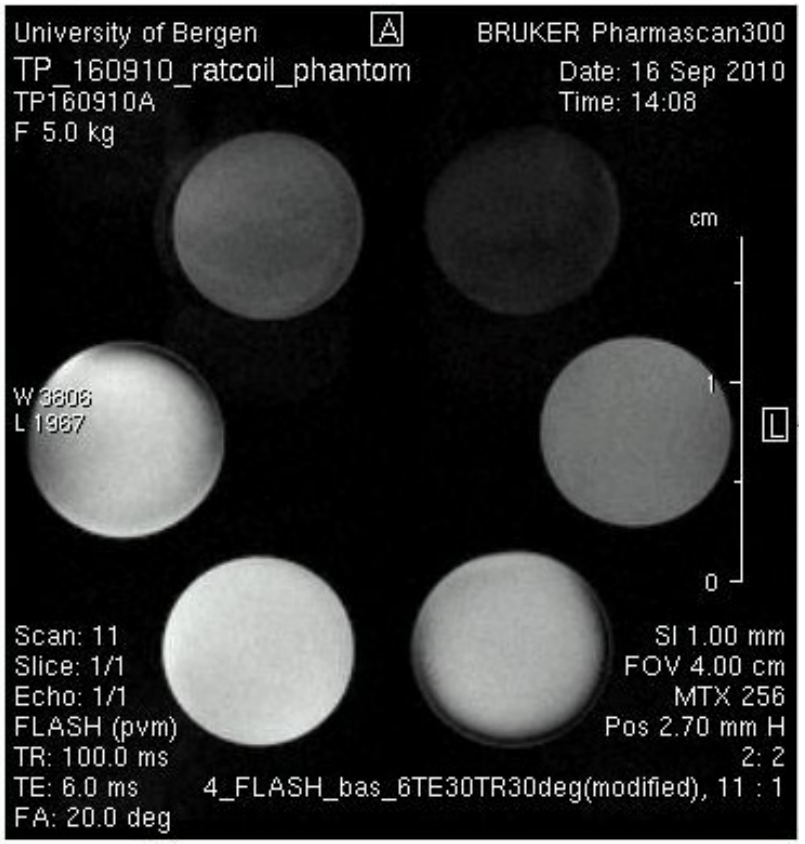


MSME; PD + T_2* weighting** ***FLASH, PD + T_2* weighting

Observe the contrast in the two images. Where do you see the main difference? Why? Hint: think of T_2* and chemical shift.

PD-Weighting: MSME vs. FLASH at short TR, small α

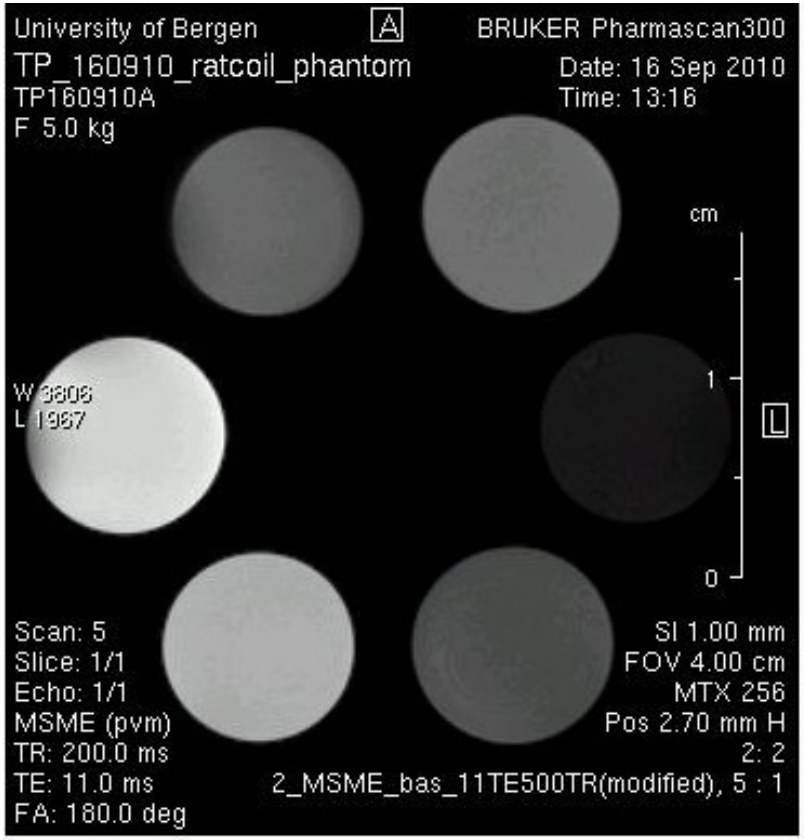


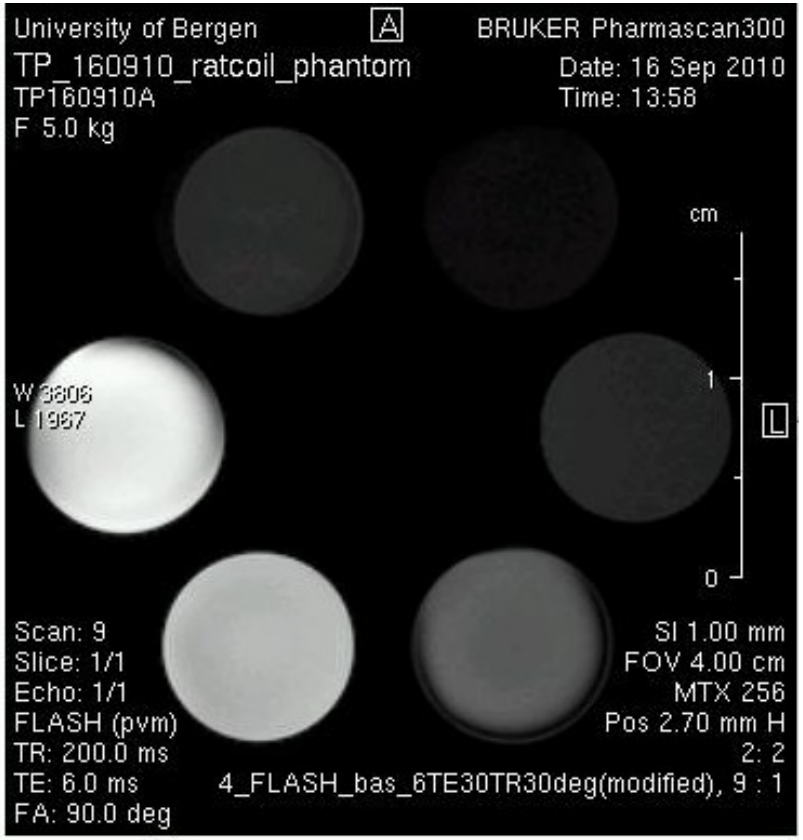


MSME; PD + T_2* weighting** ***FLASH, PD + T_2* weighting

Observe the contrast in the these images as compared to the previous two. Why is the SNR of the right image so much worse now? Hint: think about *TR* and the total scanning time.

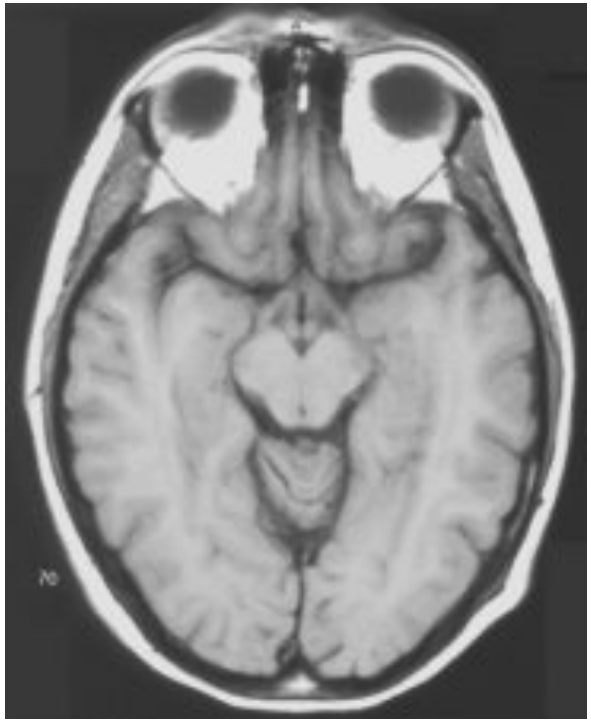
T_1-Weighting: MSME vs. FLASH at short TR, large α

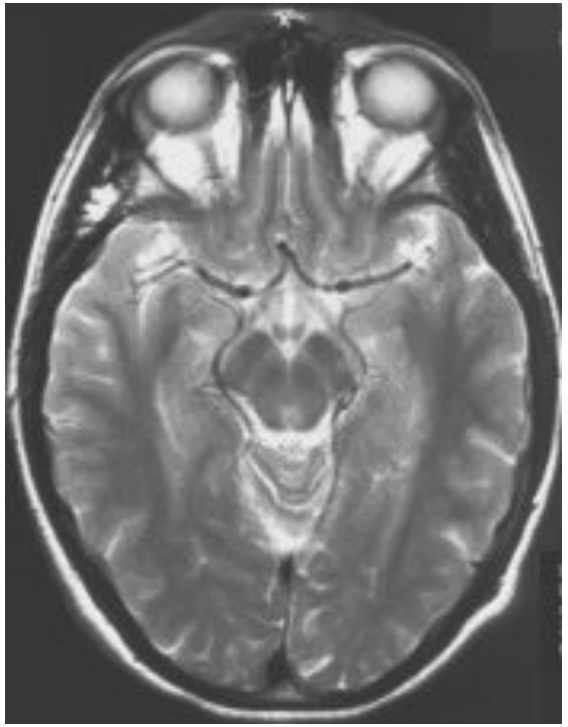




Observe the contrast in the these two images. Again, where do you see the main difference? Why?

T_1 and T_2 Weighted Images, Comparison





<u>*T*1 weighted image</u>
short TR, short TE
”Free water is black”

<u>*T*2 weighted image</u>
long TR, long TE
”Free water is white”

Section Summary:
Choice of TR and TE for SE Sequences

TR	TE	TE
	Short	**Long**
Short	T_1-wt	--
Long	PD-wt	T_2-wt

Section Summary:
Choice of TE and α for GE Sequences with short TR

α (flip angle)	TE	TE
	Short	**Long**
Small	PD-wt	T_2*-wt
Large	T_1-wt	--

Which Sequence is Right for My Application?

- T_1-weighted sequences:
  - Anatomy
  - When using a T_1 contrast (DCE-MRI)
  - Fat imaging
- T_2-weighted sequences:
  - Pathology (tumors, edema, etc)

Optimizing Pulse Sequence Parameters