CONTRAST (CNR) IN MRI

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

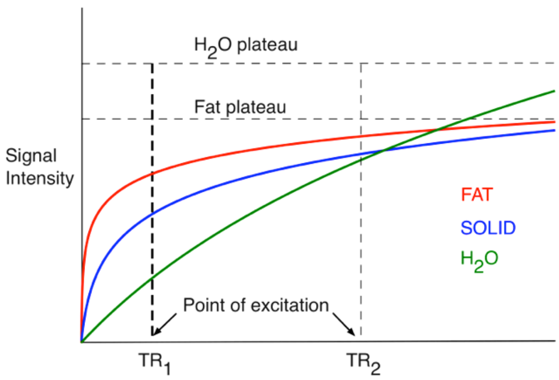
- Physical and instrumental parameters
  - Magnetic field strength (through T_1 field dependence)
  - Contrast agents (through T_1 dependence)
  - Proton density
  - T_1 and T_2 relaxation times of protons in tissue
  - Diffusion coefficient of water in tissue (microstructure environment)
- Imaging sequence 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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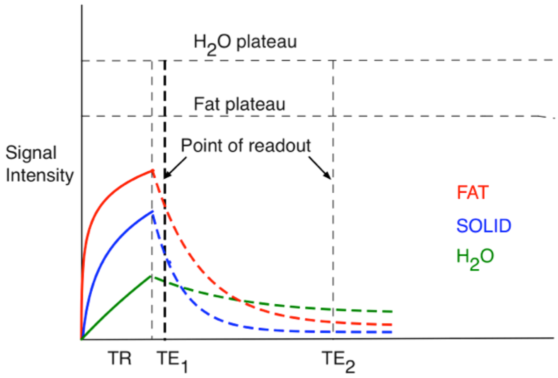


CNR: T_1- Weighted Images

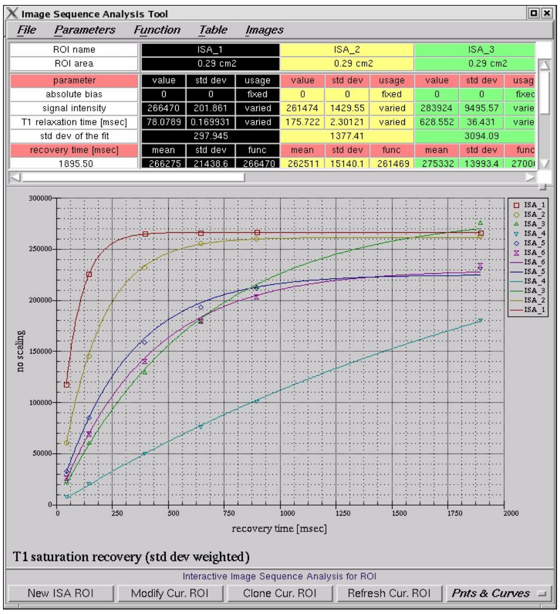
- T_1-weighted images produce contrast based on differences in T_1-relaxation times of tissues

- 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

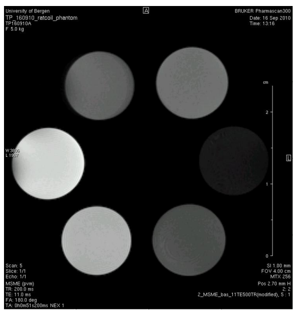
- **Demonstration:**
  - Collect an image of the contrast phantom:
    - Use spin-echo sequence with short TR (200 ms) and short TE (11 ms)
  - Observe contrast between different samples
  - Explain



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	283924	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(

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



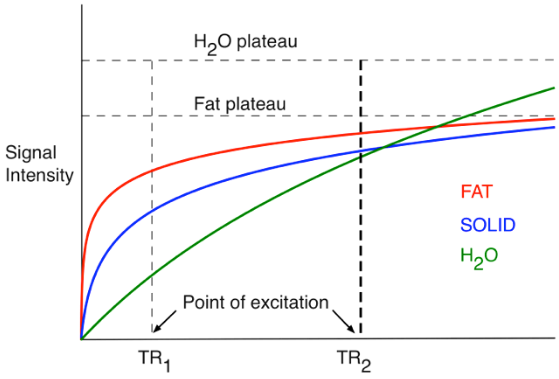
TR=200 ms, *TE*=11 ms

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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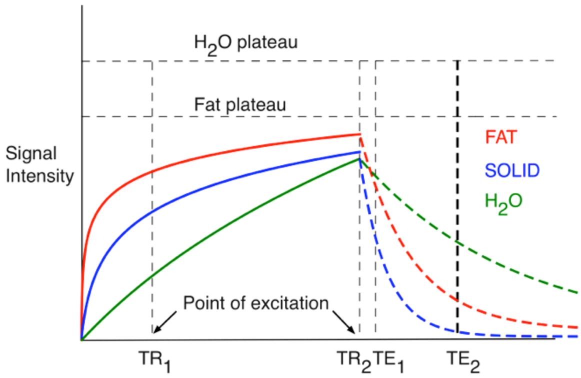


CNR: T_2- Weighted Images

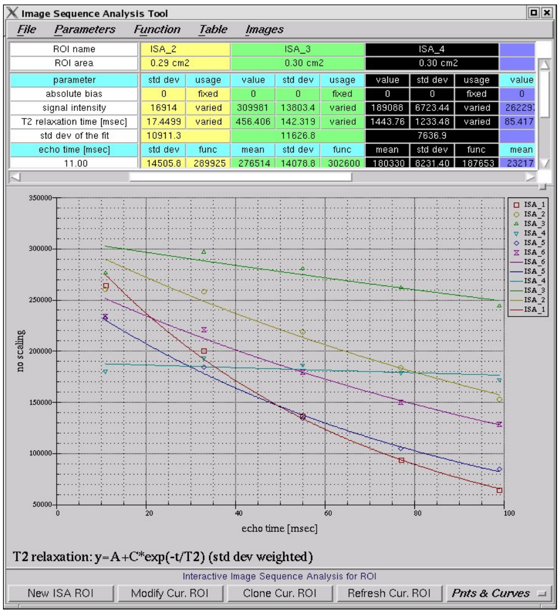
- T_2-weighted images produce contrast based on differences in T_2-relaxation times of tissues

- 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



Phantom = 6 tubes:

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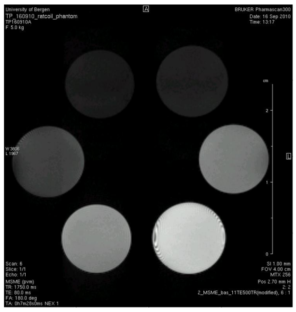
6. Motor oil



TR=1750 ms, TE=80 ms

CNR: Proton Density

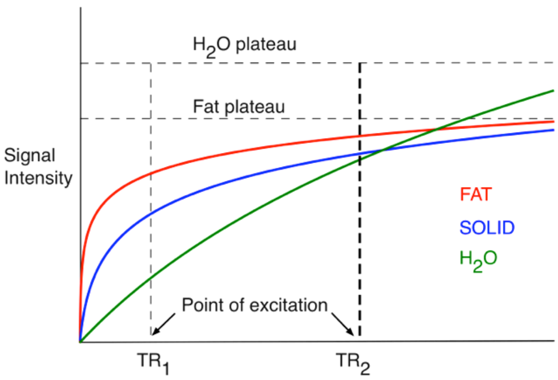
$$S_{MRI} = \iiint \frac{\rho_0 \gamma^2 \hbar^2}{4kT} B_0(x,y,z) e^{-i\omega_0 t} e^{-TE/T_2} \left(1 - e^{-TR/T_1}\right) f\left(G(t)\right) dxdydz$$

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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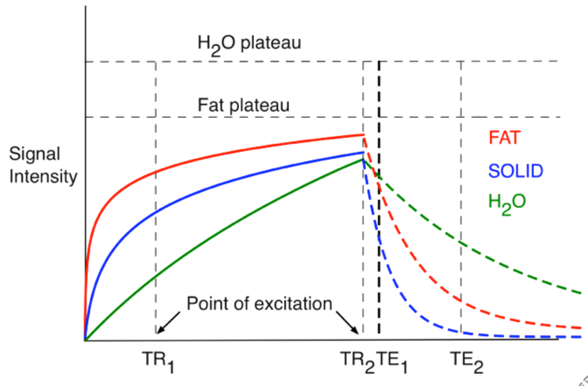

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CNR: PD- Weighted Images

- 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

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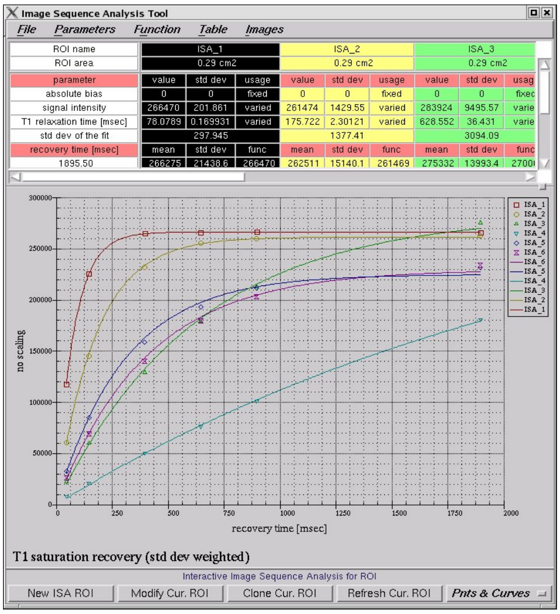
CNR: PD- Weighted Images

- **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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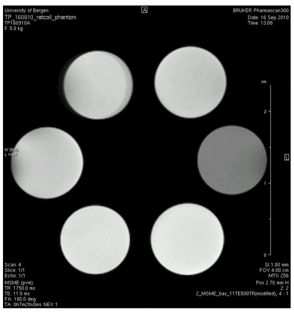
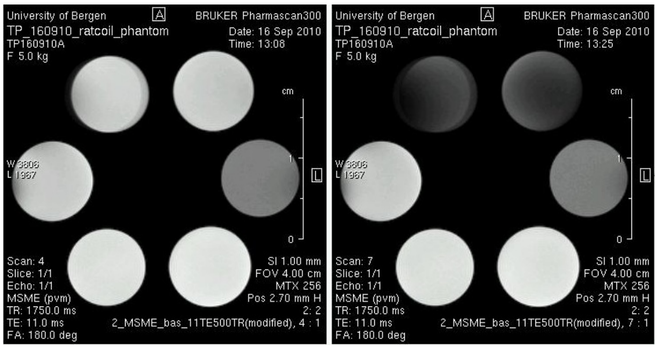


TR=1750 ms, *TE*=11 ms

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



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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

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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**

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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)

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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:

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

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

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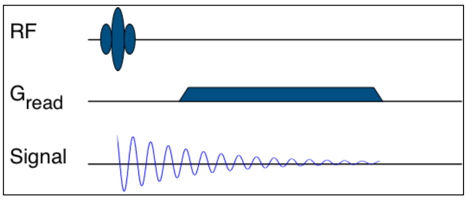
Pulse Sequence Diagrams

- 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



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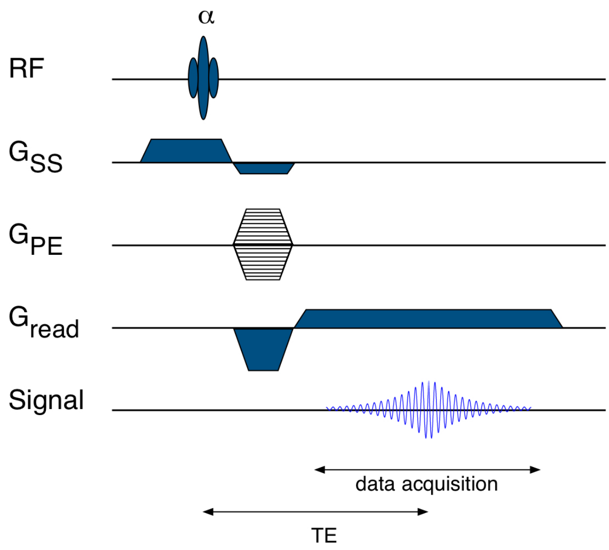
Gradient Echo Sequence or GRE

- 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:

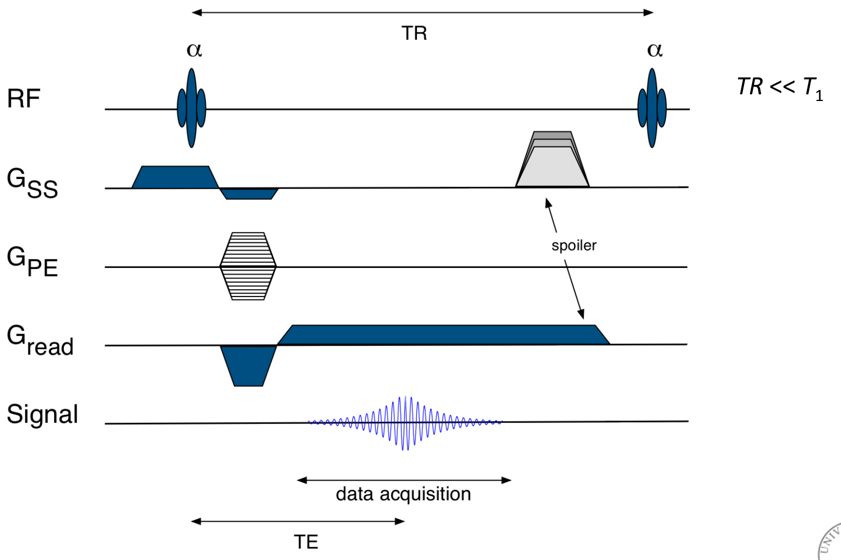
$$S_{MRI} = \rho \frac{\sin\alpha \cdot \left(1 - e^{-\frac{TR}{T_1}}\right) \cdot e^{-\frac{TE}{T_2^*}}}{1 - \cos\alpha \cdot e^{-\frac{TR}{T_1}}}$$

- 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**

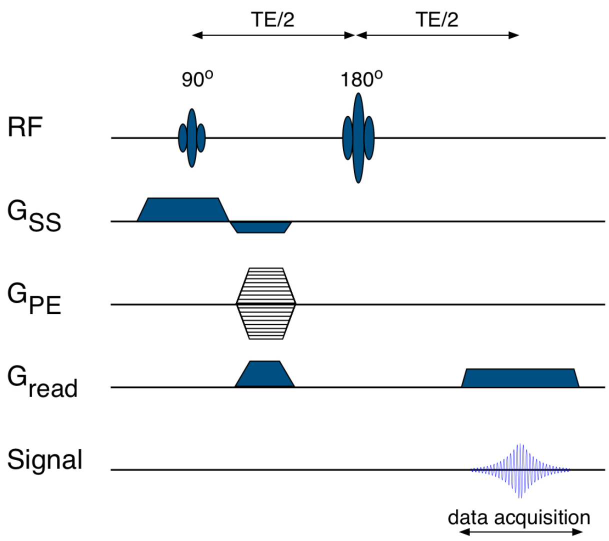
FLASH: Sequence Diagram



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…

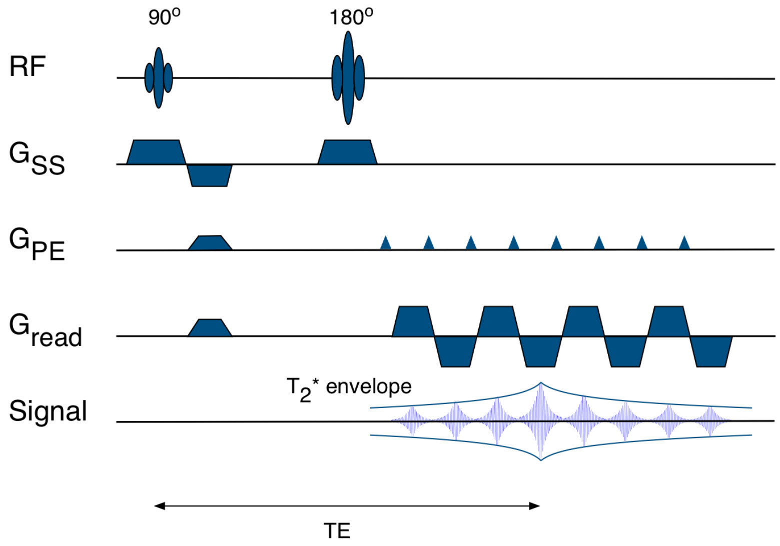
SPE: Sequence Diagram



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



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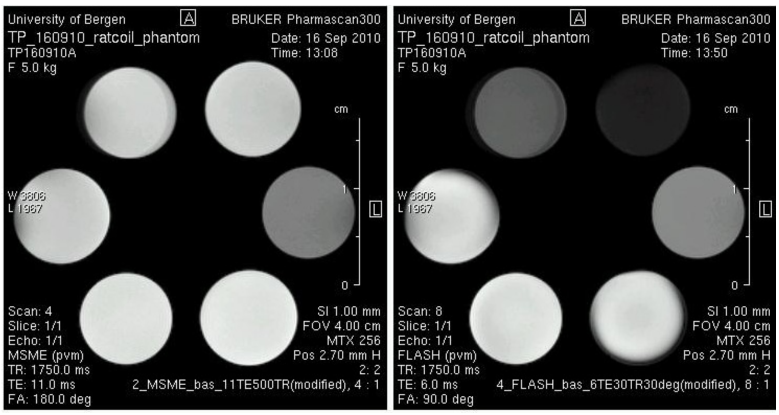
Some Examples

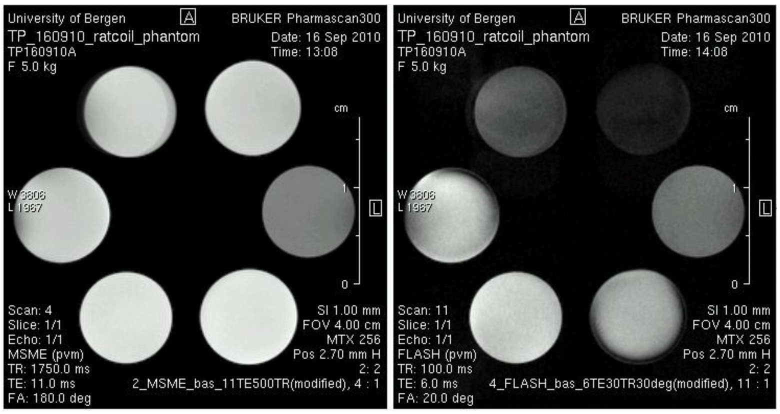
PD-Weighting: MSME vs. FLASH at long TR



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.

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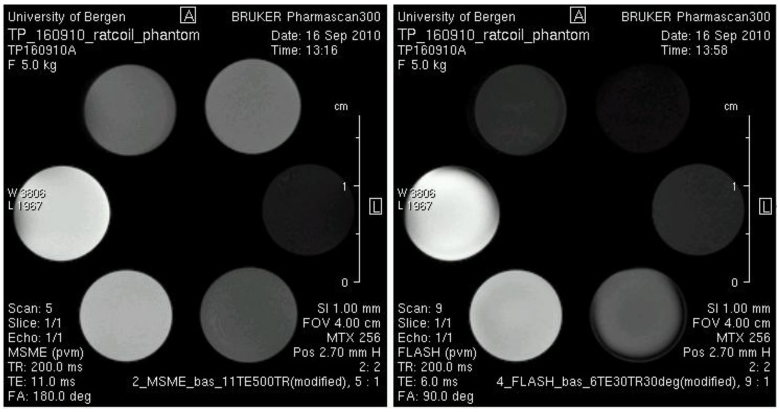
T_1-Weighting: MSME vs. FLASH at short TR, large α



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

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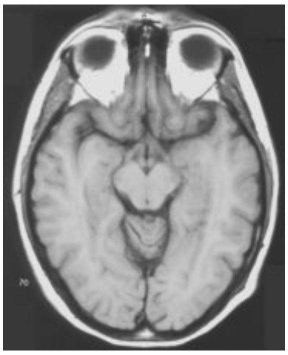
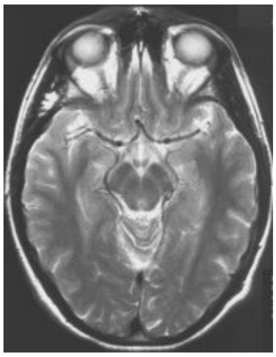
T_1 and T_2 Weighted Images, Comparison



***T1* weighted image**
short TR, short TE
"Free water is black"



***T2* weighted image**
long TR, long TE
"Free water is white"

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Section Summary: Choice of TR and TE for SE Sequences

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

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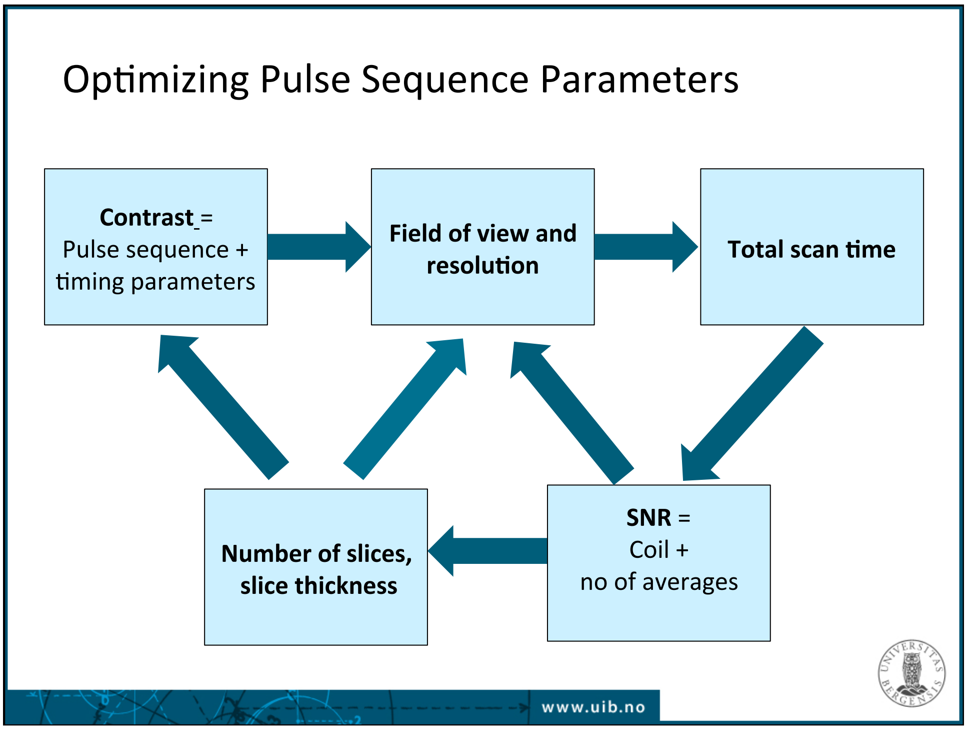
Section Summary: Choice of TE and α for GE Sequences with short TR

α (flip angle)	TE Short	TE 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
Contrast = Pulse sequence + timing parameters
Field of view and resolution
Total scan time
SNR = Coil + no of averages
Number of slices, slice thickness
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