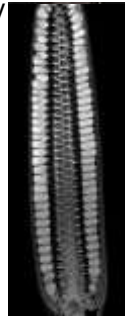

Image contrast
in Magnetic Resonance Tomography

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Master's in Biomedical technologies
WS 2017/2018

What is MRT?

- Magnetic Resonance Tomography
 - Slice selective imaging
 - Magnetic field, no radioactivity
- ‚Nuclear spin‘
 - Medical applications: Water, Lipids
- Image contrast:
 - Magnetic Environment of spins
 - MR Sequence



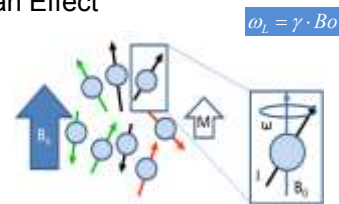
What is MRT?

- Spin excitation and preparation
- Encoding of spatial information in k-space
- Read-out of magnetization multiple times
- Fourier transform (or other) and image generation
- Coding signal by grey-level values

.....each step influences image contrast!!

...some repetition

- Zeeman Effect

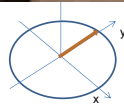
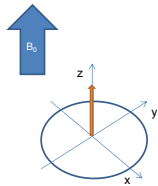


- Bloch- Equations

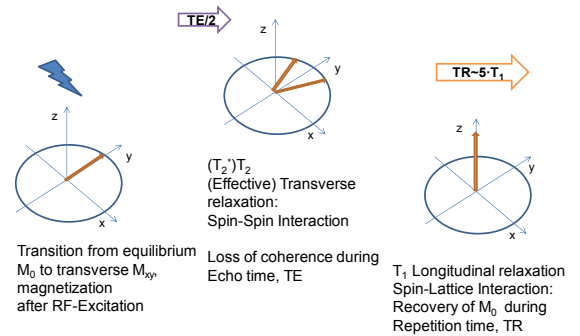
$$\frac{d\vec{M}}{dt} = \gamma \vec{M} \times \vec{B} - \frac{M_x}{T_2} \hat{x} - \frac{M_z - M_0}{T_1} \hat{z}$$

Magnetization states

- Equilibrium
 - M_0 : Magnetization
- Excitation:
 - Transition to anti-parallel spin state



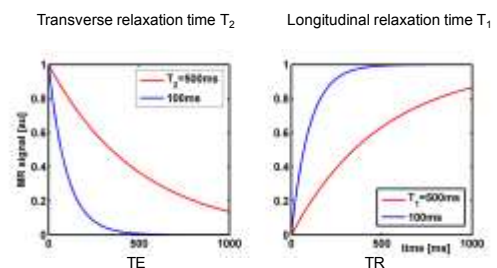
Relaxation and Sequence parameters



... signal intensity depends on:

- MR properties of the tissue
 - influence the magnetization available for signal generation
- MR Method:
 - Determines which magnetization state is observed

Relaxation



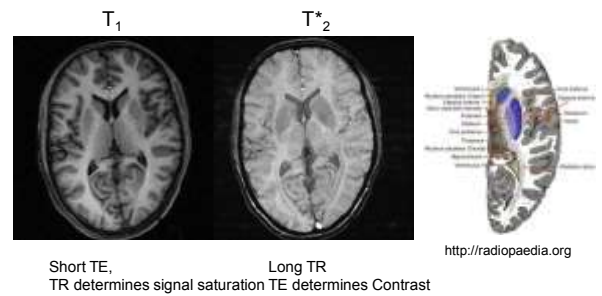
Some MR properties of tissues

.. at 1.5T

Tissue	T_1 (s)	T_2 (ms)	ρ^a
CSF	0.8 - 20	110 - 2000	70-230
White	0.76 - 1.08	61-100	70-90
Grey	1.09 - 2.15	61 - 109	85 - 125
Meninges	0.5 - 2.2	50 - 165	5 - 44
Muscle	0.95 - 1.82	23 - 67	25 - 90
Adipose	0.2 - 0.75	53 - 94	50 - 100

.. and magnetic susceptibility..

T_1 and T_2/T_2^* – weighting



Definition of Image contrast

... Image CONTRAST :

intensity difference between tissue types

- MR signal variation across image
- Signal difference between selected areas, A and B, with intensity I

$$C(A, B) = \frac{|I(A) - I(B)|}{I_{ref}}$$

I_{ref} : arbitrary intensity reference, e.g. standard deviation of background noise

Contrast in MRT

Local tissue properties	• T1, T2, T2*, PD • Susceptibility, chemical shift • water motility
MR Sequence	• <i>Class</i>: GE, SE, FID • <i>Prep</i>: Inversion Recovery, saturation recovery, T2-prep, Magnetization transfer etc.
Sequence parameters	• TE, TR, FA • TI, delay etc

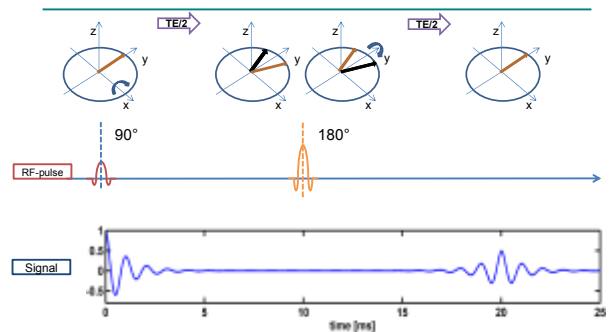
Overview

- Spin Echo, Gradient Echo, Free Induction Decay MRI
- T2/T2* weighting: Comparison SE, GE
- T1 weighting: multiple echo techniques
- Spin preparation: Inversion Recovery (and more)
- Contrast agents in MRI

Overview

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Spin Echo



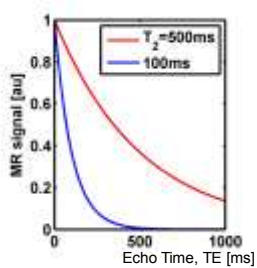
T₂: the tortoise and the hare

.. Aesop's fable made MR compatible..



T₂ relaxation

- Irreversible loss of 'coherence'

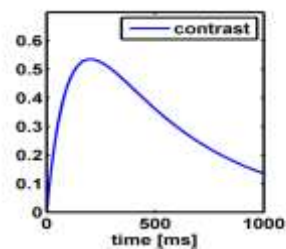


$$SE = k \cdot e^{-TE/T_2}$$

T₂ relaxation

- Contrast: T₂-weighting

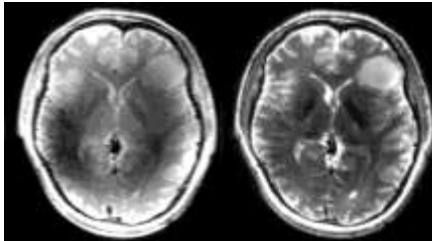
$$contrast = k \cdot e^{-TE/T_2^A} - k \cdot e^{-TE/T_2^B}$$



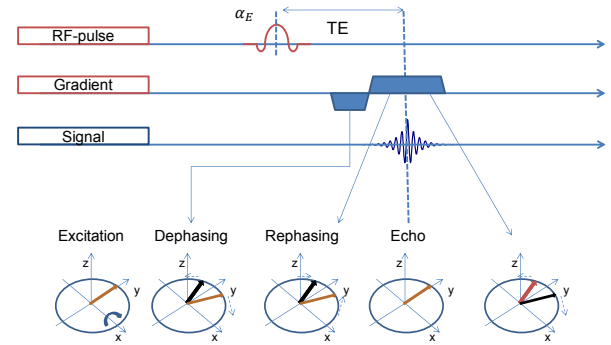
- Maximum at TE given by T₂ relaxation times

Example: SE at 9.4T

- ShortTE vs long TE

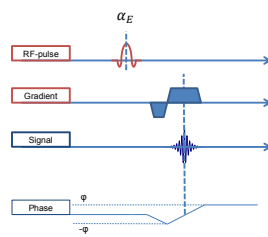


MRI Sequence: Gradient Echo



MRI Sequence: Gradient Echo

- Excitation with flip angle α_E
- Gradient dephasing and rephasing of MR signal
- No change in precession direction

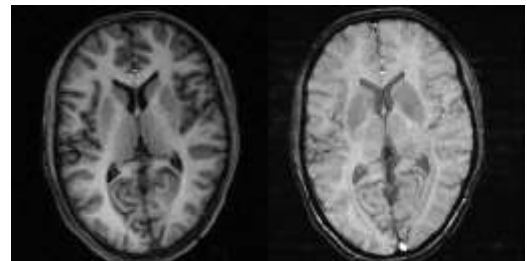


@steady state

$$GE_{ss} = k \cdot \sin(\alpha_E) \cdot \frac{1 - e^{-TR/T_1}}{1 - e^{-TR/T_1} \cdot \cos(\alpha_E)}$$

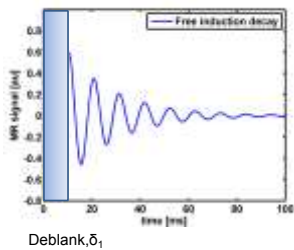
Example: FLASH

- T1w using short TR vs T2*w using long TE

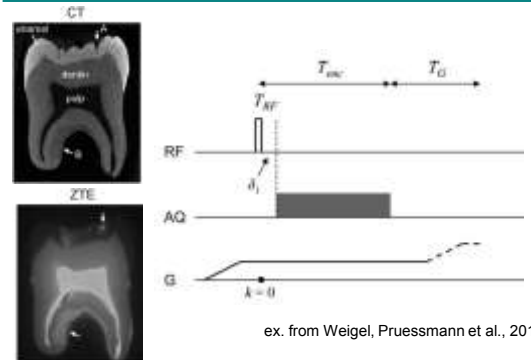


FID MRI?

- Free Induction decay



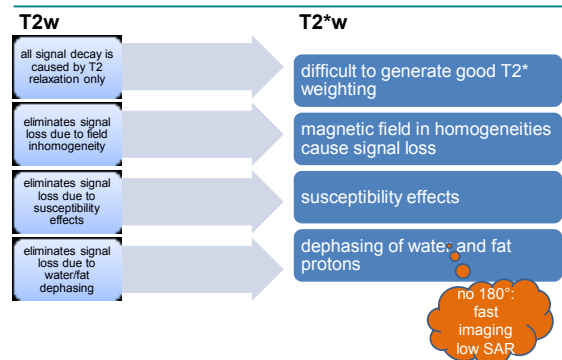
Zero Echo Time



Overview

- Spin Echo, Gradient Echo, Free Induction Decay MRI
- T2/T2* weighting: Comparison SE, GE
- T1 weighting: multiple echo techniques
- Spin preparation: Inversion Recovery (and more)
- Contrast agents in MRI

Spin echo vs Gradient echo



T_2 and T_2^*

Spin Echo

- T_2 : transverse relaxation
- Only due to irreversible losses

$$\frac{1}{T_2} = \frac{1}{T_2^*} - \frac{1}{T_2'}$$

Measurements of T_2 has high accuracy, precision and reproducibility

Gradient Echo

- T_2^* : effective transverse relaxation
- As voxel size $\rightarrow 0$, then $T_2^* \rightarrow T_2$
- Includes reversible dephasing, T_2' due to:
 - magnetic field inhomogeneity 'bad shim'
 - Tissue susceptibility variation
 - water-fat 'incoherence'
- $\frac{1}{T_2^*} = \frac{1}{T_2} + \frac{1}{T_2'}$

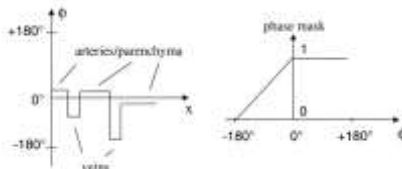
Magnetic field inhomogeneity



- $T_2^* < T_2$, due to inhomogeneity of the magnetic field inside the voxel
- T_2^* enhanced close to air-tissue borders
- T_2^* weighting enhances tissues with intrinsic susceptibility differences, e.g. Venography by SWI

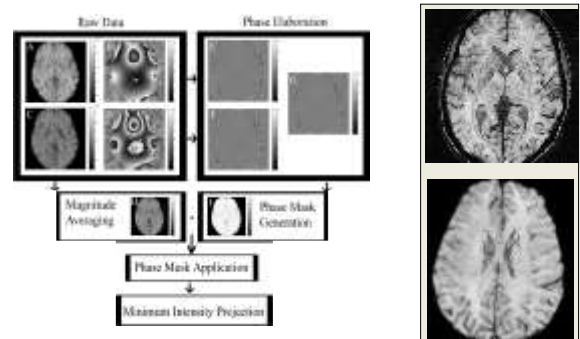
SWI: Idea

- **SWI - Susceptibility Weighted Imaging: Venography**
 - Mask generated from MR phase image is applied on modulus image

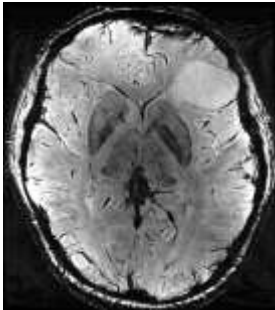


Haacke et al., 2004

SWI: analysis



Ex. SWI at 9.4T



Water-fat ,incoherence'



in-phase



opposed-phase

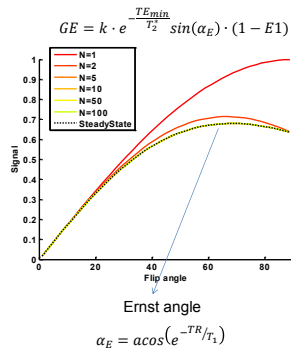
Overview

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- **T1 weighting: multiple echo techniques**
- Spin preparation: Inversion Recovery (and more)
- Contrast agents in MRI

T₁ weighting

- 'til now: assume full recovery of magnetization before next excitation pulse
- Requires long TR, long measurement time!
- Contrast with short TR, 3 regimes:
 1. $T_1 > TR > T_2$
 2. $TR \approx T_2$
 3. $TR \ll T_2$

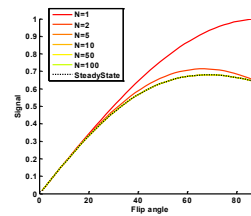
T_1 -weighted Gradient Echoes



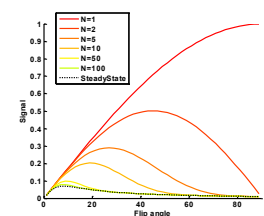
- Maximum signal if full T_1 relaxation is achieved between pulses
- Signal loss increases with number of pulses, N
- Maximum signal at Ernst angle

Multiple excitations: from 1st to 2nd regime

- $T_1/TR=1$

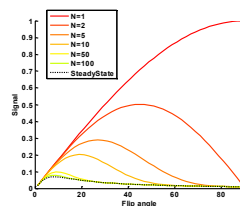


- $T_1/TR=100$



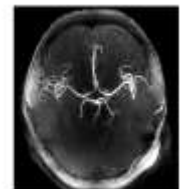
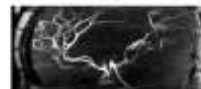
Multiple excitations: Flip angle

- In general for GE: minimize T_1 weighting by reducing flip angle



Example: Time-of-flight MRI

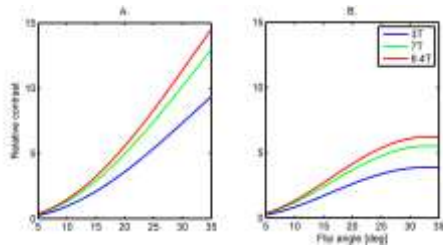
- MR signal from static spins in tissue undergoes many excitations and are suppressed
- Spins in flowing blood senses a single (or few) RF excitations and are enhanced



Expected vessel contrast

- $\text{Relative contrast} = \frac{\text{Vessel-Background}}{\text{Background}}$

- A: N=1: 10-15
- B: N=5: 1-5



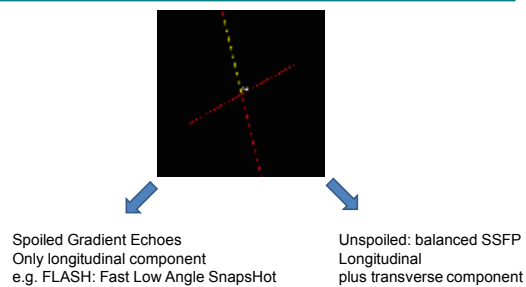
Other Regimes?

$TR \approx T_2$

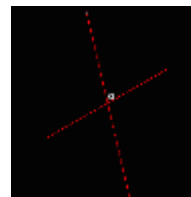
- $TR \ll T_2$

Steady state free precession...

GE when $TR \approx T_2$ or $TR \leq T_2$



Balanced SSFP



- All gradients are refocussed
- Using same sequence parameters, always better signal than spoiled GE (FLASH)
- Different dependence on sequence parameters

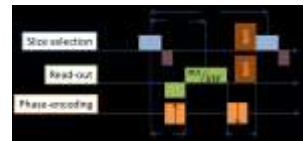
Sequence diagrams

- Slice selection gradient: combined with the RF pulse it selects the MR signal in a slice
- Read-out (or frequency encoding): generation of the gradient echo
- Phase encoding: a different gradient value for each excitation is played out



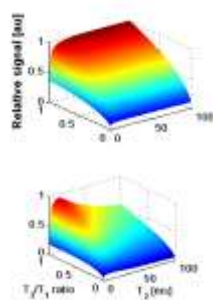
Sequence diagrams

- spGE
 - Spoiled gradient echo
 - FLASH, SPGR, T1-FFE
- balSSFP
 - balanced steady state free precession
 - trueFISP, FIESTA, b-FFE

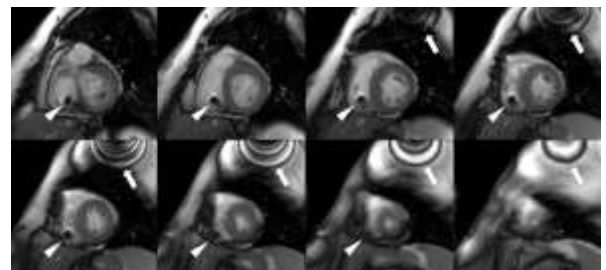


balSSFP vs spGE

- balSSFP mitigates T_2 related signal loss
- Max is independent of T_2 above threshold (40ms)
- Strongly dependent on T_2/T_1 ratio

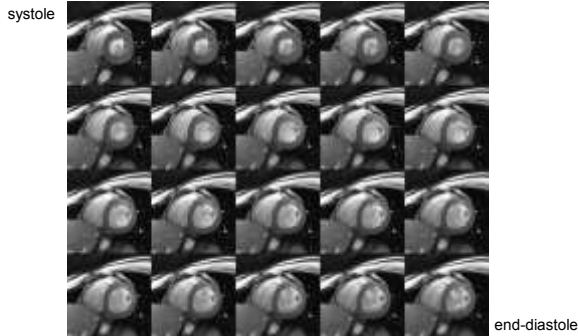


Ex. balSSFP CINE of Heart



left ventricle viewed from base to apex at end-diastole
pacemaker generator (arrows) and lead (arrowheads) cause
artefacts due to magnetic field inhomogeneity.

Ex. spGE cine of heart



Equations

- Spoiled GE

$$GE = k \cdot \sin(\alpha_E) \cdot \frac{1 - E1}{1 - E1 \cdot \cos(\alpha_E)}$$

- balSSFP

$$bSSFP = k \cdot \sin(\alpha_S) \cdot \frac{(1 - E1)}{1 - (E1 - E2) \cdot \cos(\alpha_S) - E1 \cdot E2}$$

- Ernst angle

$$\alpha_E = \arccos(e^{-TR/T_1})$$

- Flip angle:

$$\alpha_S = \arccos\left(\frac{T1/T2 - 1}{T1/T2 + 1}\right)$$

Common factor:

$$k = e^{-\frac{TE_{min}}{T_2}} \cdot \sqrt{\frac{FOV^2 \cdot NEX}{mx \cdot BW}}$$

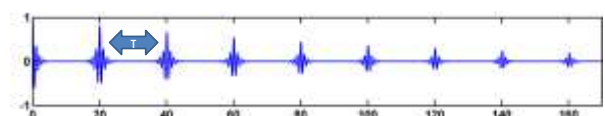
More about Multiple GE

- Steady-state free precession techniques
www.kyb.tuebingen.de/research/dep/ks/spinzo
<http://mrsrl.stanford.edu/~brian/bloch/>
- Echo-planar imaging, EPI
– used for BOLD fMRI studies

What about
multiple spin
echoes?

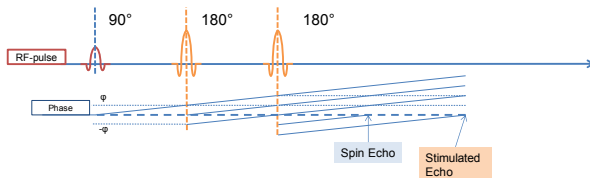
Multiple Spin Echoes: CPMG

- Carr-Purcell-Meibom-Gill
- Train of 180° pulses after single excitation



- Diffusion of spins during during τ
- RF pulse imperfections -> 'stimulated echoes'

CPMG: Phase diagram



CPMG: Exmples

- **RARE** (rapid acquisition with relaxation enhancement, Hennig et al., 3:823, 1986); Turbo Spin Echoes; Fast Spin echo

$$rare = k \cdot e^{-TE/T_2} \cdot \left(1 - e^{-\frac{TR-2TE}{T_1}}\right)$$

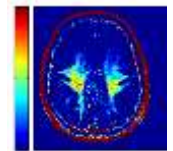


- **Hyperechoes** (Hennig, Scheffler; Magn Reson Med. 46:6, 2001)

$$90^\circ - \alpha_1 - \alpha_2 - \dots - \alpha_N - 180^\circ - \alpha_N - \dots - \alpha_2 - \alpha_1$$

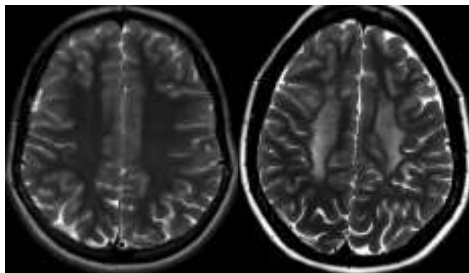
- **Multiecho relaxometry**

- Laplace transform of decay, short T2 component is the myelin water fraction



Ex. RARE of Leukodystrophy

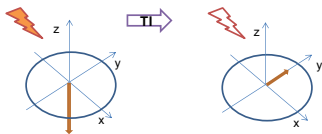
- Normal vs. Lesions



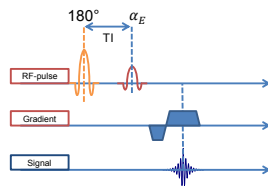
Overview

- Spin Echo, Gradient Echo, Free Induction Decay MRI
- T2/T2* weighting: Comparison SE, GE
- T1 weighting: multiple echo techniques
- **Spin preparation: Inversion Recovery (and more)**
- Contrast agents in MRI

Inversion recovery

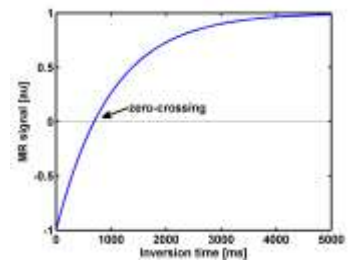


- Inversion pulse (180°)
- Gradient Echo



Inversion Recovery

- $IR = k \cdot (1 - 2e^{-TI/T_1})$
- Find T1 from zero-crossing, $IR = 0$

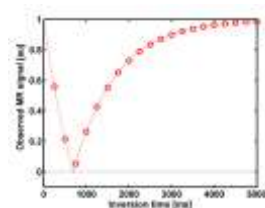


Experimental data..

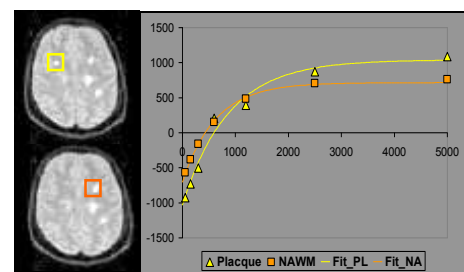
- How find T1?
 - Find negative points and multiply by -1
 - Use MR phase to determine correct sign
 - find minimum, invert preceding points with/without minimum
 - Exclude minimum from fit

- fit absolute value:

$$IR = |k \cdot (1 - 2e^{-TI/T_1})|$$



T₁ relaxometry in multiple sclerosis



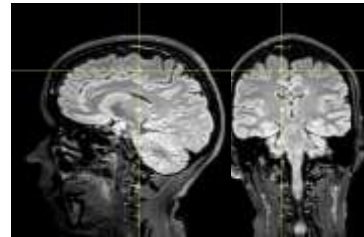
Recovery of M_0

Other types of spin preparation

- Saturation recovery: 90°-dephasing-GE
- T2-prep: 90°-180°-90°-GE
- T1ρ pre-pulse, Spin-Lock: dephasing during RF irradiation at frequency relevant for exchange between tissue compartments
- Suppression of specific signals: fat, fluid suppression
- Magnetization Transfer

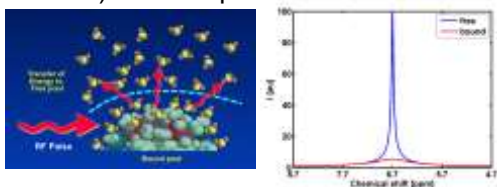
Tissue selective suppression: Ex FLAIR

- Fluid attenuated Inversion Recovery MRI
CSF is suppressed by acquiring the image when CSF is nulled. Improved detection of Multiple Sclerosis Lesions



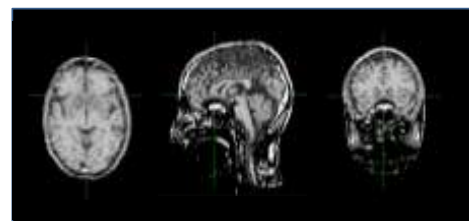
Magnetization Transfer

- Comparison of MR signal from broad band RF excitation of bound pool, narrow band excitation of free water
- Either complex modeling (2, 3 or 4 pool models) or semi quantitative MT - ratio



Ex. MT ratio

$$MTR = \frac{I_{b+f} - I_f}{I_f}$$



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- T1 weighting: multiple echo techniques
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- Contrast agents in MRI

Contrast agents

- Alters the local tissue property (T1 and T2)
- Same MR sequences, but parameters need optimization
- T1 weighting: most common
- T2* weighting: perfusion imaging, negative BOLD; dynamic contrast enhanced MRI

Contrast agents

- Paramagnetic: Gd^{3+} , rare earth metals
- Calcium equivalent- toxic!
- Bound to chelator
- Gd^{3+} concentration dependent alteration of relaxation times with relaxivity r_1 and r_2 expressed in $[mM^{-1}s^{-1}]$:

$$\frac{1}{T_1} = \frac{1}{T_{1,tissue}} + r_1 \cdot [Gd^{3+}]$$

$$\frac{1}{T_2} = \frac{1}{T_{2,tissue}} + r_2 \cdot [Gd^{3+}]$$



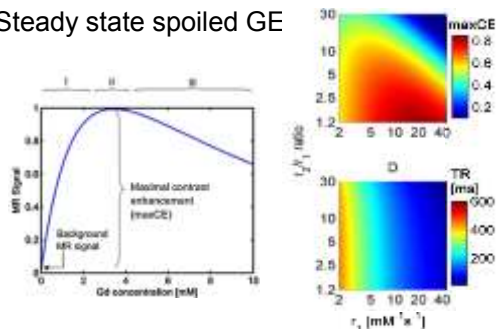
Ex. Contrast enhanced MRI

- Lesion detection
- Musculoskeletal
- Future: Molecular imaging? Ex. Resovist



Contrastagents and sp GE

- Steady state spoiled GE



Optimal flip angle

- Maximize contrast between tissue with and without agent, TR known

- „Pelc“ angle (Pelc, 1994; De Naeyer et al., 2011):

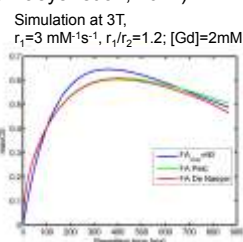
$$T_1^{avg} = \frac{T_1^{tissue} + T_1^{agent}}{2}$$

$$E_1 = e^{-TR/T_1^{avg}}$$

$$\alpha_d = \arccos\left(\frac{2 \cdot E_1 - 1}{2 - E_1}\right)$$

$$d = \frac{T_1^{tissue} - T_1^{agent}}{T_1^{avg}}$$

$$FA_{pelc} = \alpha_d \cdot (1 + 0.1 \cdot d^2 E_1)$$



Contrast in MRT

- Depends on a) tissue; b) MR sequence+parameters
- Two (three) classes: SE, GE, (FID)
- Single – echo vs multi echo techniques
- Methods for Spin preparation
- Contrast weighting: T1, T2 or T2*, T2/T1

Exercise

- Use different methods to determine T1:
 - Vary the flip angle
 - Vary TR
 - Inversion Recovery
- See how image contrast is influenced by T1 time
- See effect of multiple Spin- and Gradient echoes