Master‘s Program in Medical Physics

Physics of Imaging Systems

Basic Principles of Magnetic Resonance Imaging III

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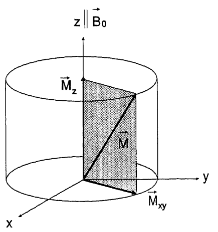
Relaxation

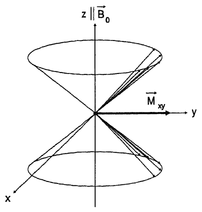
Relaxation

Magnetization: M_z and M_{xy}



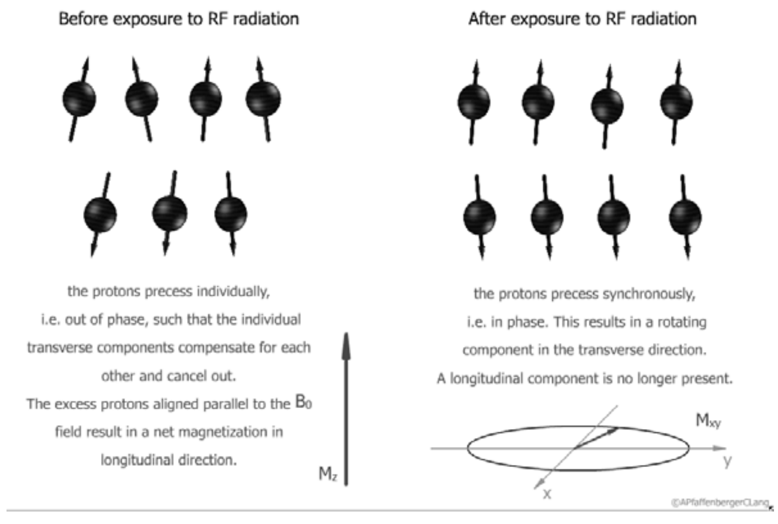
longitudinal magnetization: M_z

transversal magnetization: M_{xy}



transversal magnetization: M_{xy}
- phase synchronization after a 90°-pulse
- the magnetic moments μ of the probe start to precede around B_1 leading to a synchronization of spin packages → M_{xy}
- after 90°-pulse $M_{xy} = M_0$

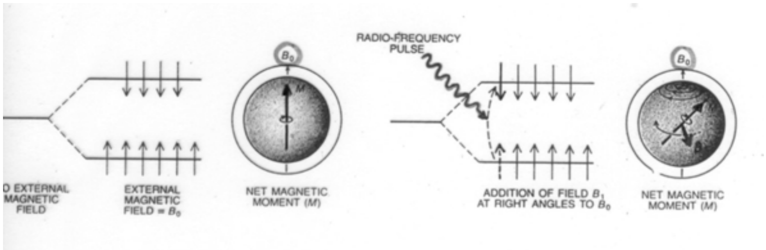
Movie: M_z and M_{xy}



source: Schlegel and Mahr. “3D Conformal Radiation Therapy: A Multimedia Introduction to Methods and Techniques" 2007

Longitudinal Relaxation Time: T1

thermal equilibrium | excited state



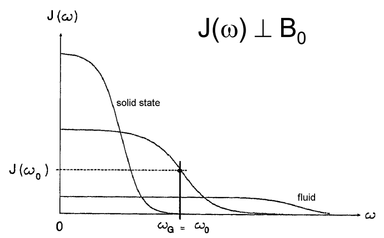
after 90°-pulse:
- $N_{-1/2} = N_{+1/2}$ and $M_z = 0$, $M_{xy} = M_0$

after RF switched off:
- magnetization turns back to thermal equilibrium
- $M_z = M_0$, $M_{xy} = 0$

→ T1 relaxation
longitudinal relaxation time T1
spin-lattice-relaxation time T1

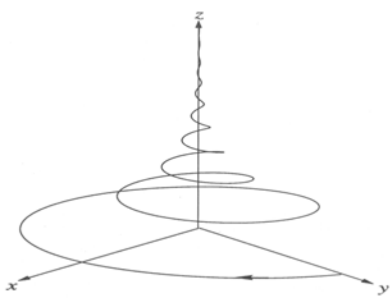
Physical Model of T1 Relaxation

$J(\omega) \perp B_0$



- in a real spin system (tissue) every nuclei is surrounded by intra- and intermolecular magnetic moments
- thermal motion (rotation, translation, oscillation) leads to an additional fluctuating magnetic field $B_{loc}(t)$ with typical spectral distribution $J(\omega)$
- longitudinal components of $J(\omega)$ at ω_0 allow energy transfer $\hbar\omega_0$ from the spin system to the "lattice"

→ T1 relaxation



- trajectory of the tip of magnetization vector in the laboratory system

source: Liang and Lauterbur. "Principles of Magnetic Resonance Imaging" 2000

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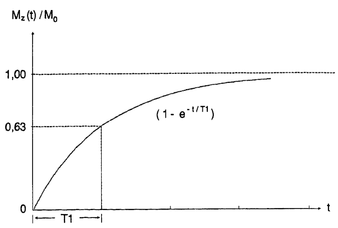
Phenomological Description of T1 || B_0

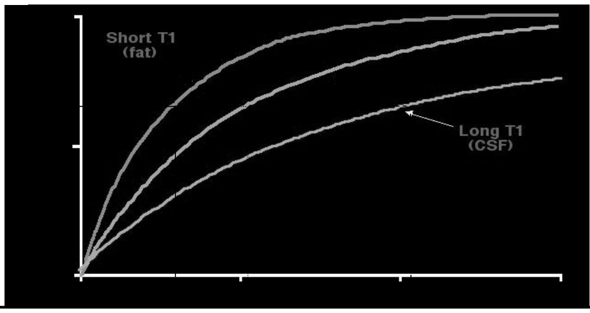


the longitudinal magnetization M_z relaxes exponential to the equilibrium state $M_z = M_0$ with a typical time constant T1

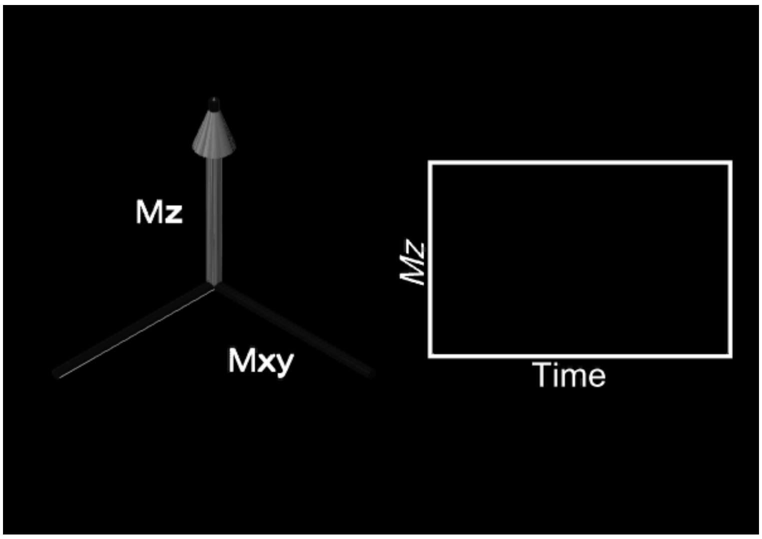
$dM_z/dt = (\gamma \times B)_z + (M_0 – M_z)/T1$: Bloch equation with T1

with $M_z = 0$ at $t = 0$:

$M_z(t) = M_0 (1 – \exp(-t/T1))$ → solution of Bloch equation



Movie: T1 Relaxation



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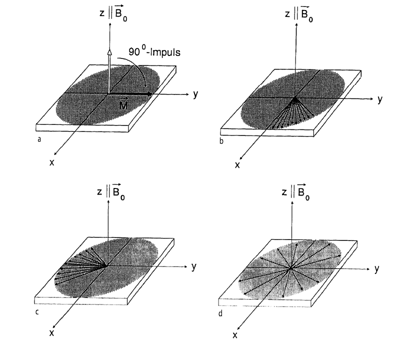
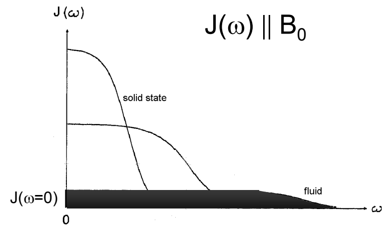
Transversal Relaxation Time: T2





$J(\omega) \parallel B_0$

after 90°-pulse:
- $N_{-1/2} = N_{+1/2}$ and $M_z = 0$, $M_{xy} = M_0$

after RF switched off:
- magnetization M_{xy} starts to rotate in the x,y-plane at Larmor frequency
- all transversal components $J(\omega)$ of the fluctuating magnetic field $B_{loc}(t)$ result in a dephasing of M_{xy} → spin-spin interaction
- mainly static frequency components $J(\omega)$ of the fluctuating magnetic field $B_{loc}(t)$ at $\omega = 0$ are contributing
- no energy transfer in the spin system (entropy ↑)
- no influence of T2 on T1, they are independent !

→ T2 relaxation
transversal relaxation time T2
spin-spin-relaxation time T2

- although technical in homogeneities of B_0 cause dephasing of M_{xy} → T2* (effective relaxation)

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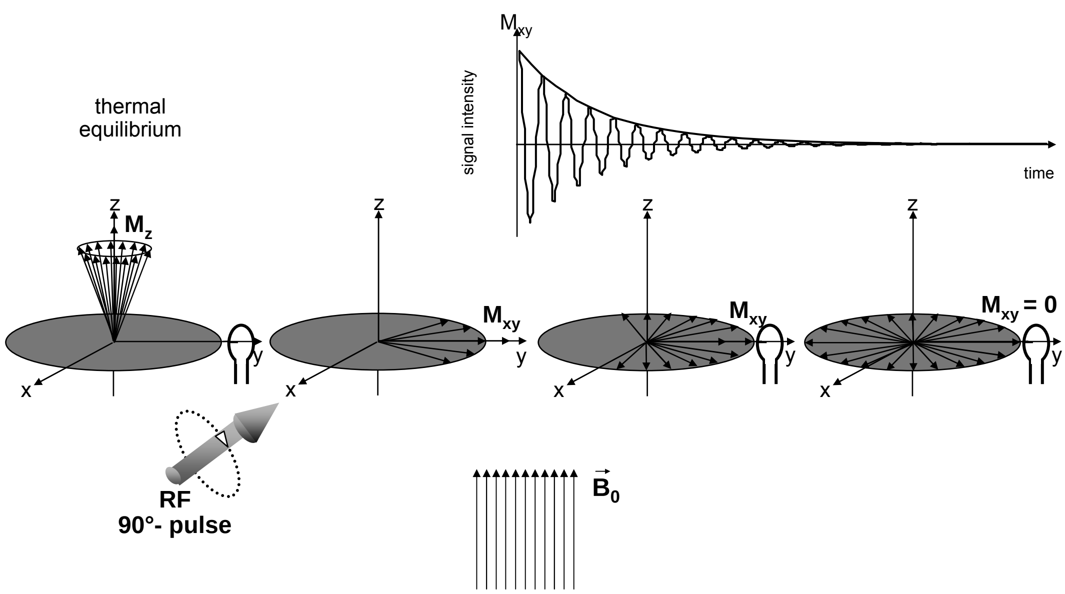
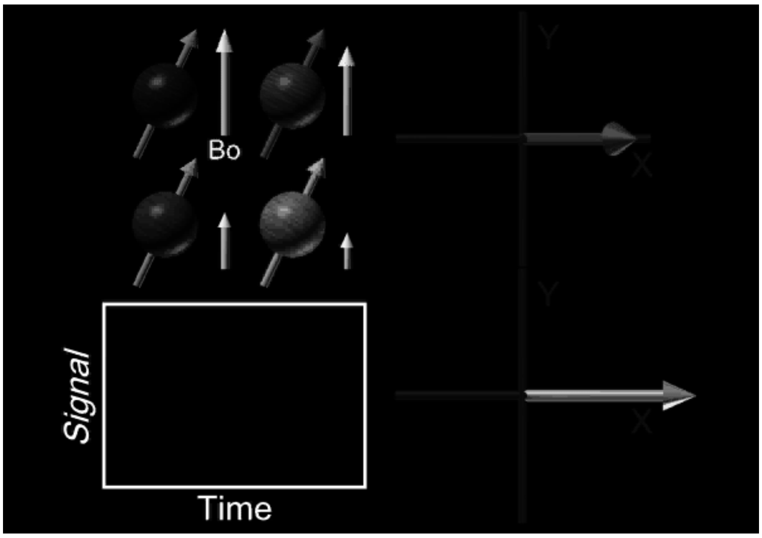
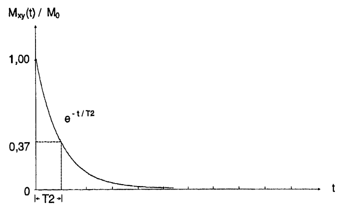
Physical Model of T2 Relaxation



Movie: Spin Dephasing



Phenomological Description of T2 $\perp$ B_0

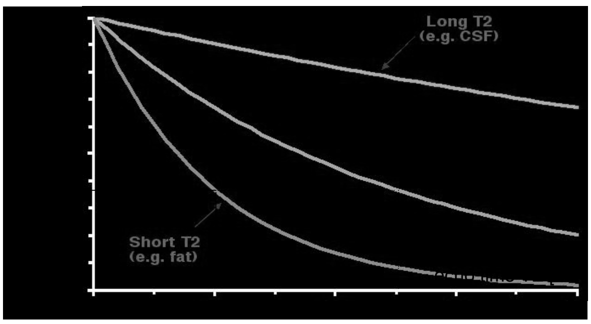


the transversal magnetization M_{xy} relaxes exponential to $M_{xy} = 0$ with a typical time constant T2

$dM_{xy}/dt = (\gamma \times B)_{xy} – M_{xy}/T2$: Bloch equation with T2

with $M_{xy} = M_0$ at t = 0:

$M_{xy}(t) = M_0 \exp(-t/T2))$ → solution of Bloch equation



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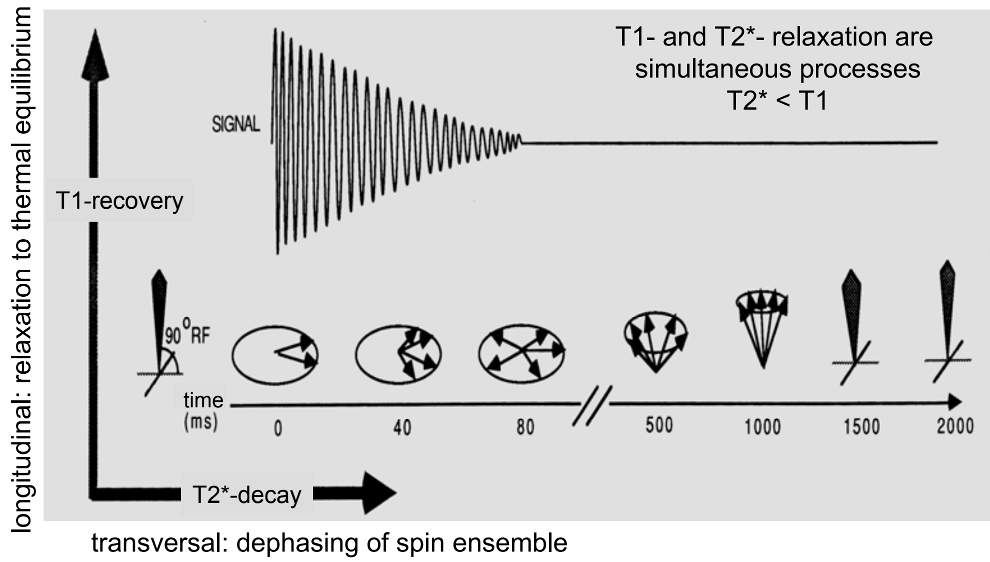
Simultaneous T1 and T2 Relaxation



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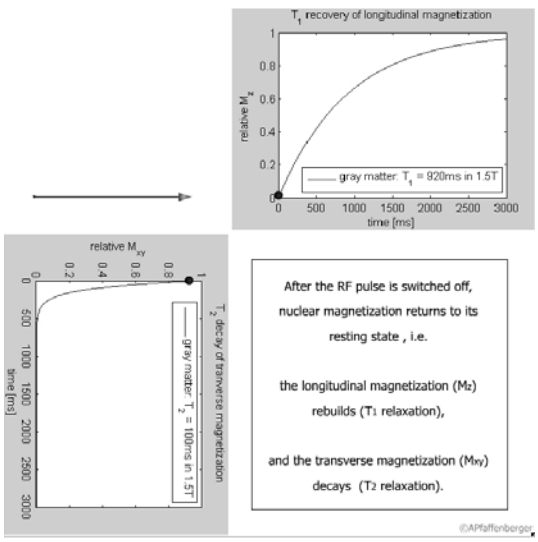
Movie: T1 and T2 Relaxation

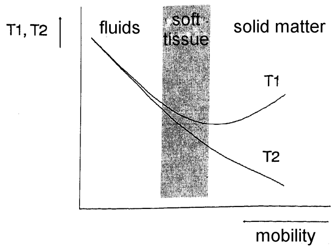


source: Schlegel and Mahr. “3D Conformal Radiation Therapy: A Multimedia Introduction to Methods and Techniques" 2007

T1 and T2 Relaxation Times *in-vivo*

tissue	T2 [ms]	T1 [s] at 0.5 T	T1 [s] at 1.0 T	T1 [s] at 1.5 T
skeletal muscle	47 ± 13	0,55 ± 0,10	0,73 ± 0,13	0,87 ± 0,16
myocardium	57 ± 16	0,58 ± 0,09	0,75 ± 0,12	0,87 ± 0,14
liver	43 ± 14	0,33 ± 0,07	0,43 ± 0,09	0,50 ± 0,11
kidney	58 ± 24	0,50 ± 0,13	0,59 ± 0,16	0,65 ± 0,18
spleen	62 ± 27	0,54 ± 0,10	0,68 ± 0,13	0,78 ± 0,15
fat[a]	84 ± 36	0,21 ± 0,06	0,24 ± 0,07	0,26 ± 0,07
grey matter	101 ± 13	0,66 ± 0,11	0,81 ± 0,14	0,92 ± 0,16
white matter	92 ± 22	0,54 ± 0,09	0,68 ± 0,12	0,79 ± 0,13

[a] more than one exponential component



- T1 increases with B_0
- T2 nearly independent of B_0

Bottomley et al. Med Phys 1984

NMR History: Relaxation Times

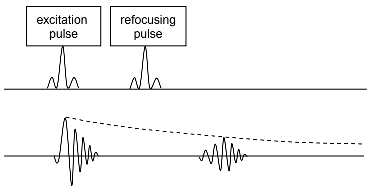
Harvard

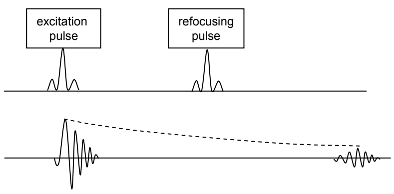
1948

Nicolaas Bloembergen

Robert Pound

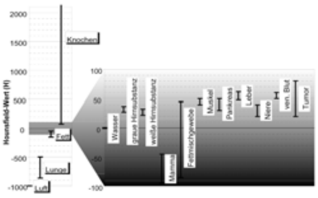
Edward Purcell





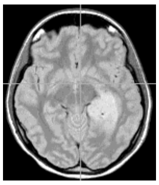
• characterized the <u>relaxation times</u> of the nuclear response signal in detail

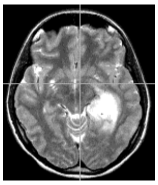
Comparison: CT and MRI

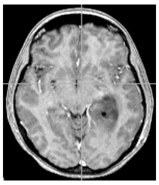


CT

WM:	1025 Hu	
GM:	1035 Hu	} Δ = 1%
CSF:	1000 Hu	







patient: astrocytoma grade II

	T2	T1	MRI
WM:	90 ms	550 ms	
GM:	100 ms	1000 ms	} Δ = 100%
CSF:	>1000 ms	2000 ms	

- no bones
+ best soft tissue contrast
+ no radiation

Bloch Equations with T1 and T2

$dM_z/dt = (\gamma \times B)_z + (M_0 - M_z)/T1$

$dM_{xy}/dt = (\gamma \times B)_{xy} - M_{xy}/T2$

rotating system:

$$\frac{d\vec{M}(t)}{dt} = \gamma \cdot \vec{M} \times \vec{B}(t) - \frac{M_x(t)\ \vec{i} + M_y(t)\ \vec{j}}{T_2} - \frac{(M_z(t) - M_z^0)\ \vec{k}}{T_1}$$

laboratory system:

$$M_x(t) = e^{-\frac{t}{T_2}} \cdot (M_x(0)\cos(\omega_0 \cdot t) + M_y(0) \cdot \sin(\omega_0 \cdot t))$$

$$M_y(t) = e^{-\frac{t}{T_2}} \cdot (M_y(0)\cos(\omega_0 \cdot t) - M_x(0) \cdot \sin(\omega_0 \cdot t))$$

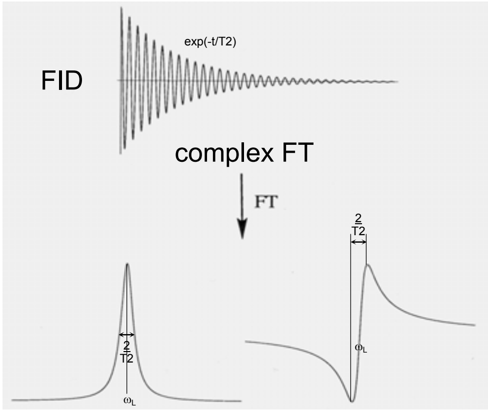
$$M_z(t) = M_0 \cdot (1 - e^{-\frac{t}{T_1}}) + M_z(0) \cdot e^{-\frac{t}{T_1}} \qquad \omega_0 = \gamma \cdot B_0$$

complex signal:

$M_\perp = M_x + iM_y$

$M_\perp = M_0 \exp(-i\omega_L t - t/T2)$

Complex Signal: Simulated FID

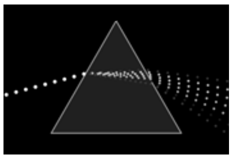


absorption
M_x: real part FT

$$M_x(\omega) = M_0 \frac{T2}{1 + (\omega - \omega_L)^2 T2^2}$$

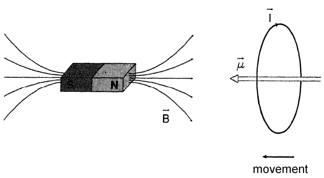
dispersion
M_y: imaginary part FT

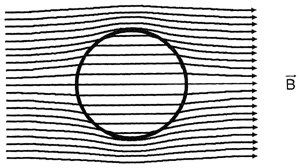
$$M_y(\omega) = M_0 \frac{T2^2 (\omega - \omega_L)}{1 + (\omega - \omega_L)^2 T2^2}$$



source: Liang and Lauterbur. "Principles of Magnetic Resonance Imaging" 2000

Macroscopic Effect: Diamagnetism





- Lenz's law: the induced current produces an own magnetic moment μ in a conductor opposite to B_0

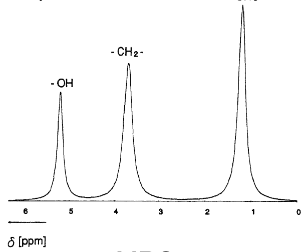
- most of biological tissues have diamagnetic properties since the electron magnetization M_e of the electron sheath is opposite to B_0 due to Lenz's law:
  $B = \mu_0(H + M_e)$
  $M_e = \chi H$
  with $\mu_0 = 1.257\ 10^{-6}$ Vs/A magnetic field constant
  $\chi_{H2O} = -0.72\ 10^{-6}$ magnetic susceptibility

- weaker B-field inside a diamagnetic sphere due to e^--shielding which is very effective since
  $\gamma_{e-} = 658\ \gamma_p$

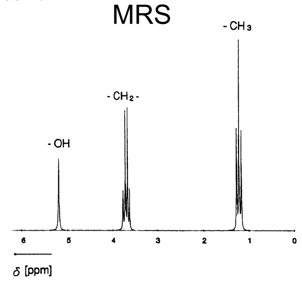
- intersection of different tissues creates additional local field inhomogeneities of B_0
  can be "homogenized" by additional shim coils

Microscopic Effect: Chemical Shift

^{1}H spectrum of ethanol



MRS



- precession frequency of nuclei bound in a specific molecule is determined by the local magnetic field B_{loc}:

  $B_{loc} = B - \delta B$
  $\omega_{loc} = \gamma \, B_{loc} = \gamma(1 - \delta)B$

  with $\delta = 10^6 \, (\omega - \omega_{ref})/\omega_0$
  the relative chemical shift [ppm]

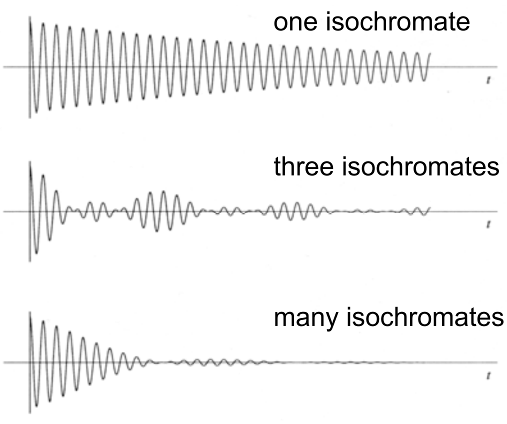
- $\delta \sim 10$ ppm for ^{1}H
  $\delta \sim 100$ ppm for ^{13}C, ^{19}F, and ^{31}P

- high resolution spectrum at $B_0 > 1.5$ T with $\Delta B/B_0 < 0.1 - 0.5$ ppm show multiplet splitting due to spin-spin coupling
  → domain of MRS

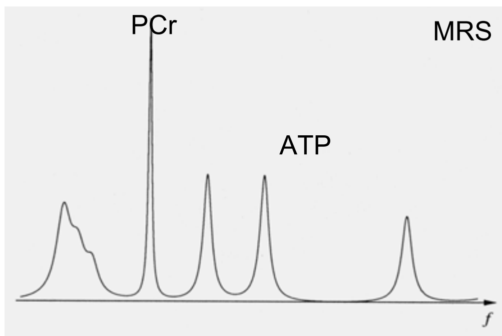
- in MRI only protons of water are imaged, chemical shift is not relevant !
  exception: $\delta_{fat} = 3.5$ ppm (220 Hz) at 1.5 T

Summary: FID and MRS

simulated isochromates



simulated ^{31}P absorption spectrum



source: Liang and Lauterbur. “Principles of Magnetic Resonance Imaging” 2000

Summary: FID and MRI

FID signal is the transient response of a spin system after RF excitation;
FID is a complex signal with amplitude and phase

FID amplitude is dependent on many parameters like: flip angle, number of spins, and magnetic field strength

FID timing is dependent on the grade of local magnetic field inhomogeneities characterized by T2*:

$1/T2^* = 1/T2 + \gamma\Delta B_z$ with $T2^* < T2$

T2*: the effective (local) T2 relaxation time
T2 : the true T2 relaxation time

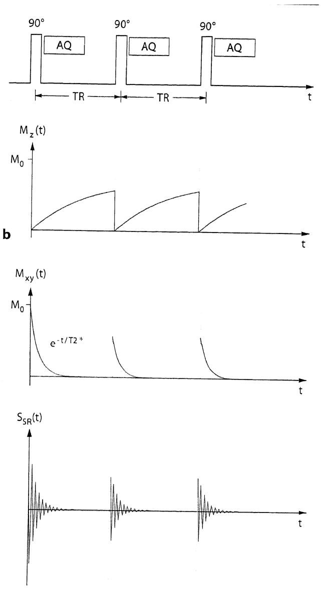
Standard Techniques for T1 and T2

Saturation-Recovery Sequence

Inversion-Recovery Sequence

Spin-Echo Sequence

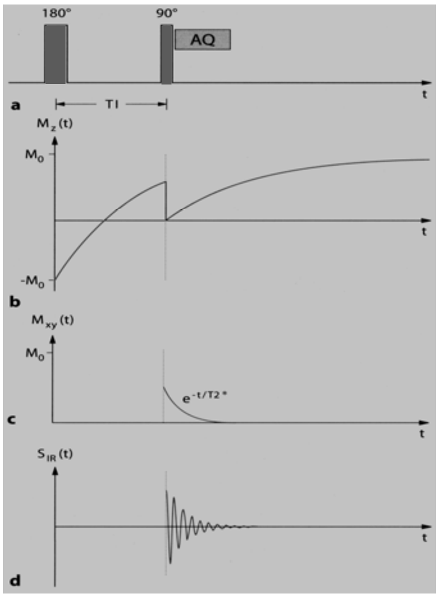
Saturation-Recovery Sequence



- saturation-recovery sequence
- 90°-pulse moves the longitudinal magnetization M_0 to the x-, y – plane → FID
- transversal magnetization M_{xy} decays with T2*
- longitudinal magnetization starts to recover to thermal equilibrium → M_z↑ with T1
- after TR actual (reduced) magnetization M_z is moved to the x-, y – plane → FID
- repeat measurement with different TR → T1 determination by

S ~ ρ [1 - exp(-TR / T1)] with TR >> T2*

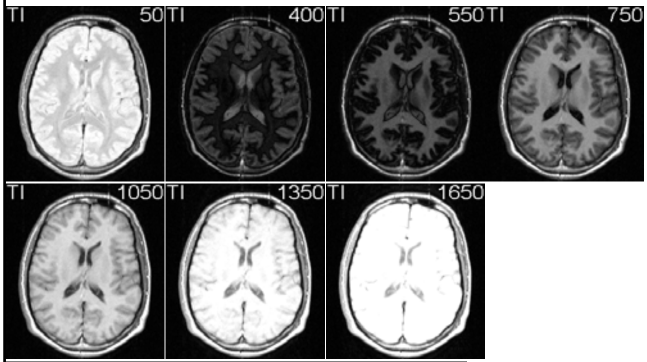
Inversion-Recovery Sequence

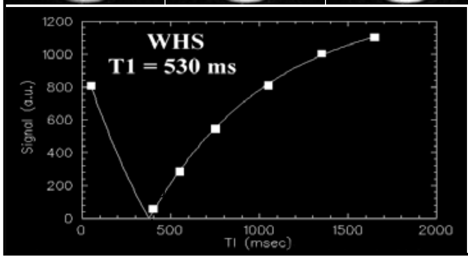


- inversion-recovery sequence
- 180°-pulse invert the longitudinal magnetization M_0 to $-M_0$ at the z-axes
- longitudinal magnetization starts to recover to thermal equilibrium → M_z↑ with T1
- inversion time TI
- after TI 90°-pulse moves the actual (reduced) longitudinal magnetization M_z to the x-, y – plane → FID
- transversal magnetization M_{xy} decays with T2*
- repeat measurement with different TI → T1 determination by

S ~ ρ [1 – 2 exp(-TI / T1)] with TR > 5 T1

T1 Measurement: Inversion Recovery



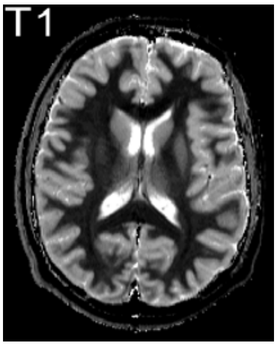


inversion recovery ($M_z(0) = -M_0$):

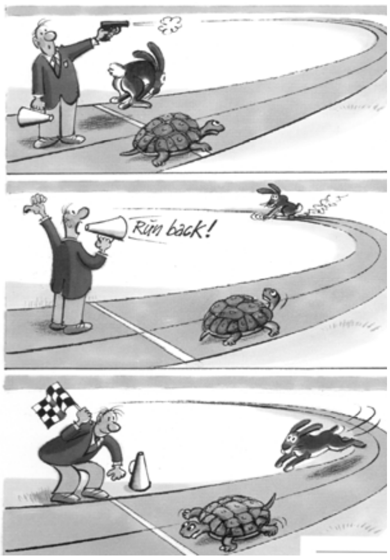
$M_z(t) = M_0 \, (1 – 2 \exp(-TI/T1))$

with $M_z = 0$ at $TI = TI_0$:
$0.5 = \exp(-TI_0/T1)$

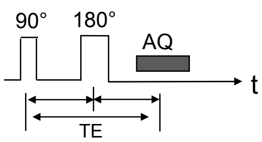
$\rightarrow T1 = -TI_0 / \ln(0.5) = TI_0 / 0.7$

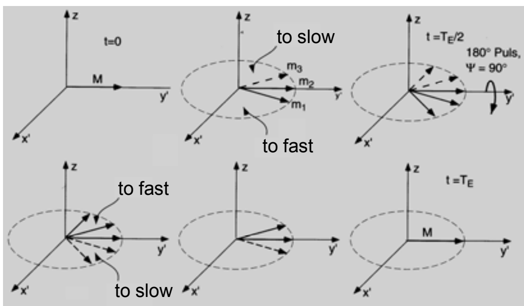


How to get rid of “Scanner’s” Dephasing ?

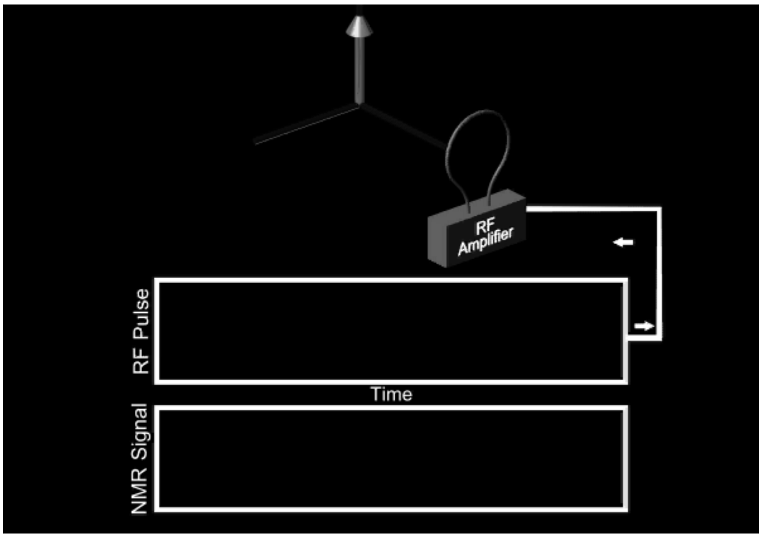


180° refocusing pulse

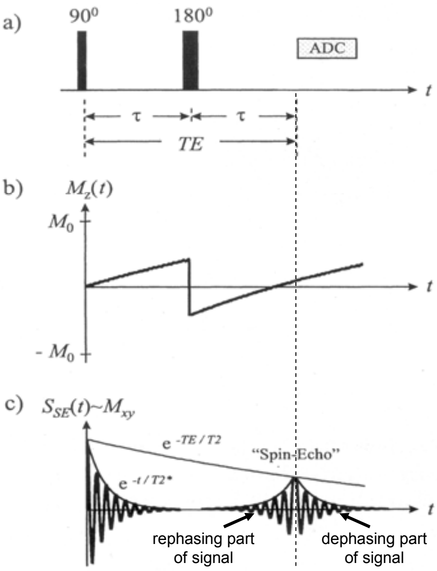




Movie: Spin-Echo I



Spin-Echo Schema



a) RF impulse schema

b) timing of longitudinal magnetization M_z

c) induced measured signal: spin-echo SE

source: Schlegel and Bille. "Medizinische Physik Bd. 2" 2002

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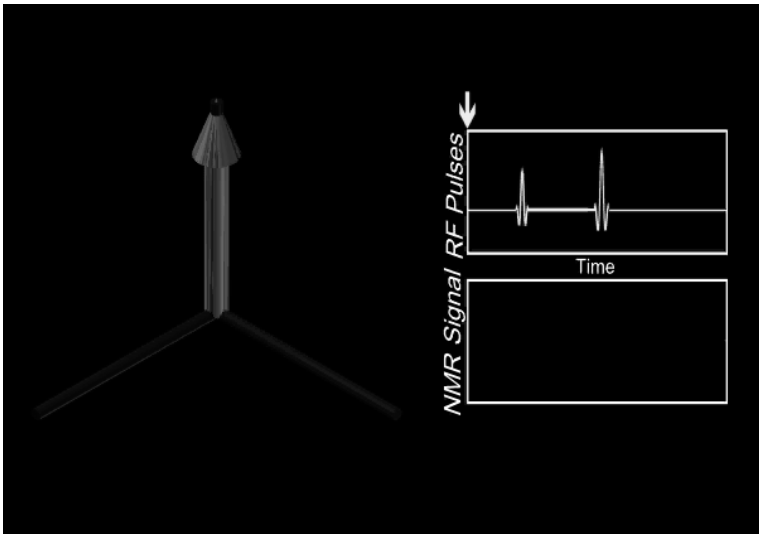
Movie: Spin-Echo II



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Prof. Dr. Lothar Schad

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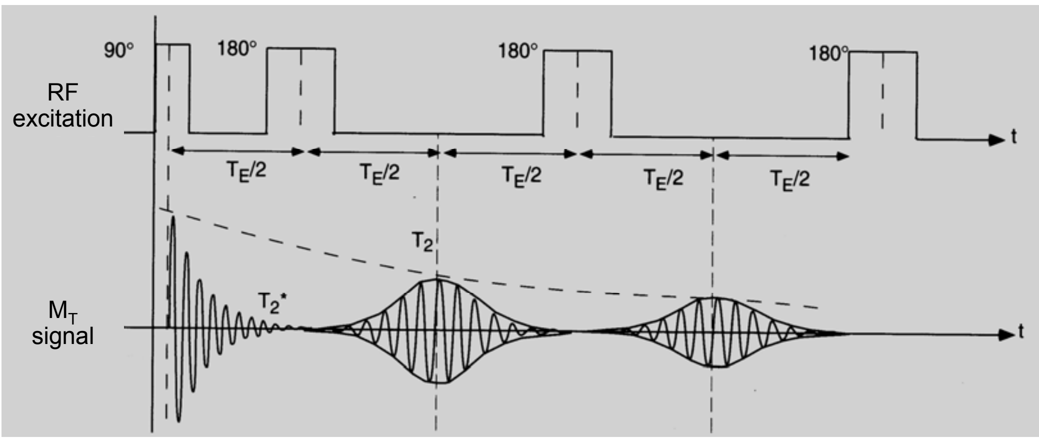
Multi Spin-Echoes



$$1/T_2^* = 1/T_2 + 1/T_2'$$

T2* : „effective“ relaxation with T2* < T2
T2 : „true“ relaxation due to irreversible dephasing
T2‘ : „scanner“ relaxation due to static and constant field inhomogeneities

source: Dössel. “Bildgebende Verfahren in der Medizin” 2000

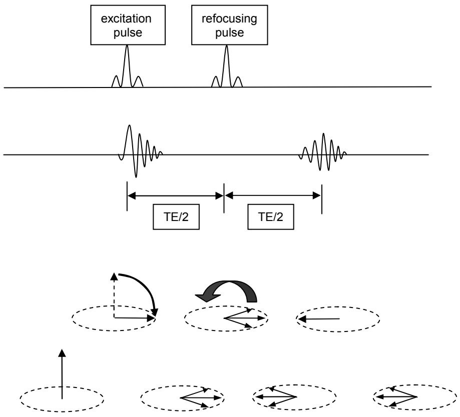
NMR History: Spin-Echo

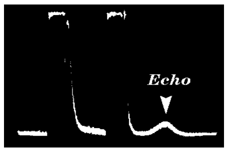
Illinois

1949

Erwin Hahn

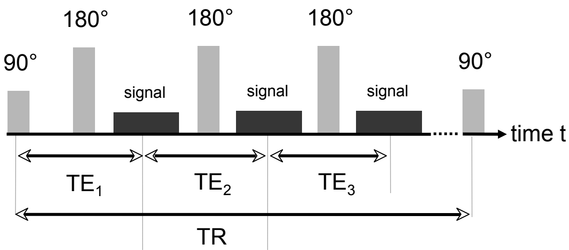
- discovered a “second” nuclear resonance signal, the spin echo
- achieved T1 and T2 weighting

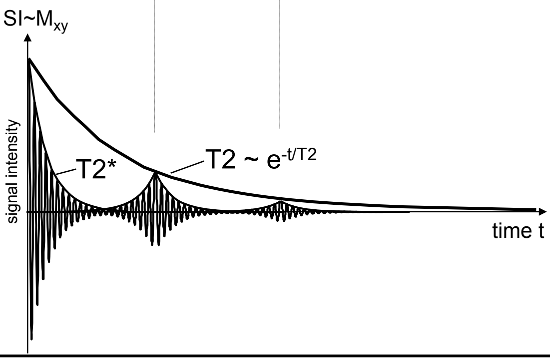




The first observed spin echo by E. Hahn (1950)

T2 Measurement by Multi Spin-Echo





multi spin-echo technique

TR: repetition time
TE: spin-echo time

SE-signal:

$SI \sim M_{xy} = M_{xy}\, e^{-t/T2}$

WM: T2 ≅ 90 ms
GM: T2 ≅ 100 ms
CSF: T2 > 500 ms

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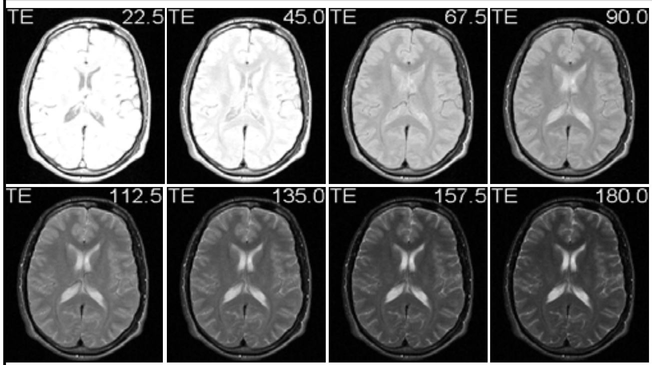
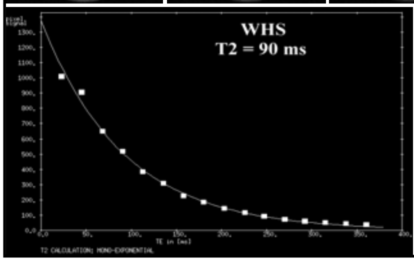
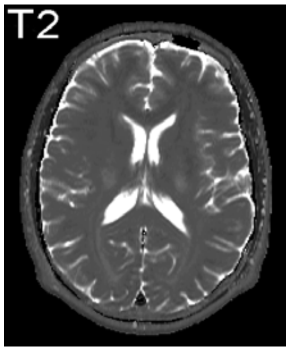
T2 Measurement: Spin-Echo





spin-echo ($M_{xy}(0) = M_0$):

$M_{xy}(t) = M_0 \exp(-t/T2)$



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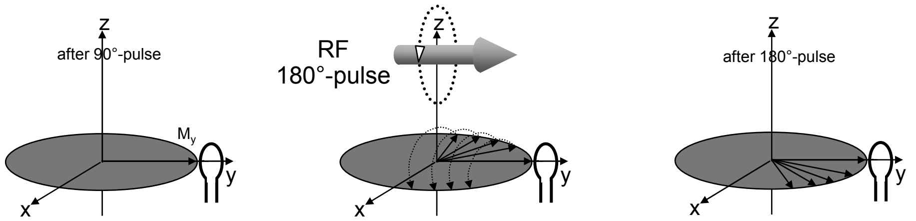
Summary: Spin-Echo



- spin-echo signal is the consequence of refocusing of a large amount of dephased isochromates

- spin-echo signal has maximum amplitude where isochromates reach new phase coherence

- spin-echo signal is a “two-sided” signal with two mirror-inverted FID’s, both components of the spin-echo increase/decay with T2*, but the amplitude of the spin-echo is T2-weighted

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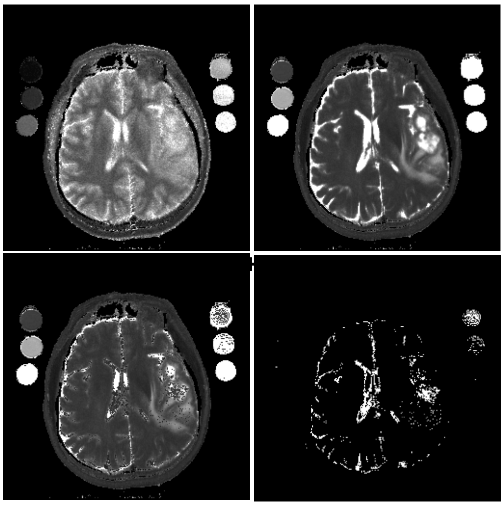
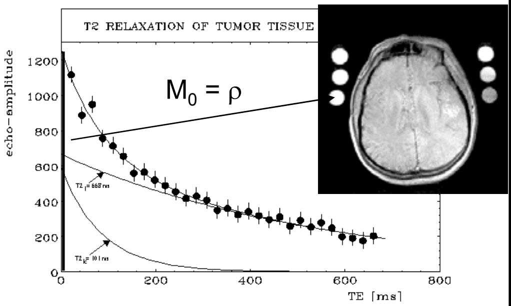
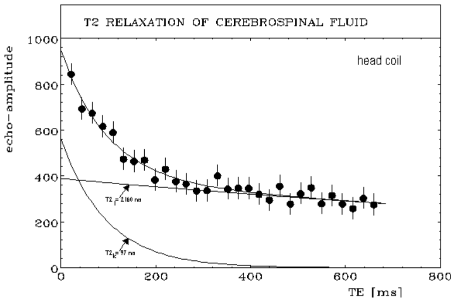
Multi-Exponential T2: Tumor Tissue







most tissues in MRI:
- bi-exponential due to partial volume effect

Schad et al. JCAT 1989

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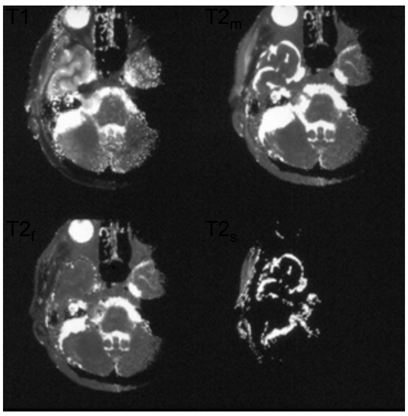
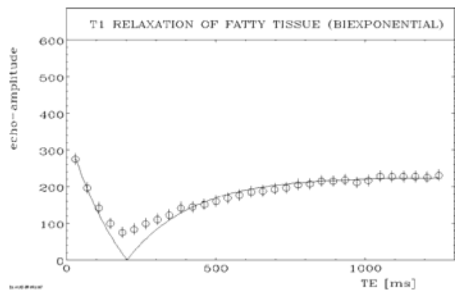
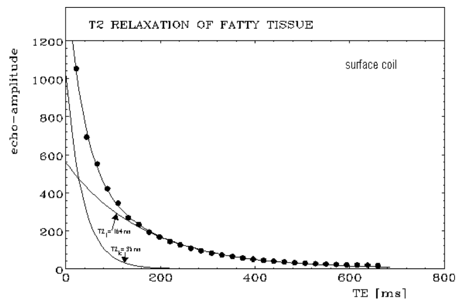
Multi-Exponential T1, T2: Fatty Tissue







fatty tissue : bi-exponential in T1 and T2
tumor tissue : bi-exponential in T2 due to
partial volume effect with CSF

Schad et al. MRI 1989

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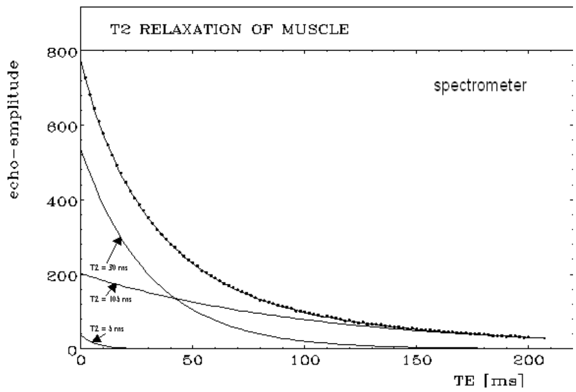
MRI – Based Therapy Planning ?

tissue	p [%]	T2 [msec]	PB [%]
muscle	13,9±1,4	<2	82,4
	3,7 ± 0,5	5,5 ± 1,1	
	59,4 ± 0,7	30,4 ± 0,6	
	23,0 ± 1,0	105,0 ± 2,5	
fat	11,9 ±2,6	< 2	88,1
	38.8 ± 1,5	53,7 ± 1,3	
	49,3 ± 1,7	193,9 ± 4,3	
grey matter	15,6±0,4	<2	84,4
	84,4±0,4	90,1±0,2	
white matter	24,3 ±0,8	< 2	69,9
	4,7±0,3	4,5±0,5	
	69.9 ± 0,7	65,5 ± 0,2	
liver	19,3±0,3	<2	80,7
	80,7 ± 0,3	52,4 ± 0,1	
kidney	16,1 ± 0,4	< 2	83,9
	83,9 ± 0,4	60,0 ± 0,1	



tissues in NMR:
- multi-exponential with very short T2 relaxation components → invisible at conventional MRI
- measurement of proton densities (e.g. for n-dosimetry, HI-therapy) is not possible !

Brix. Dissertation, Heidelberg 1988

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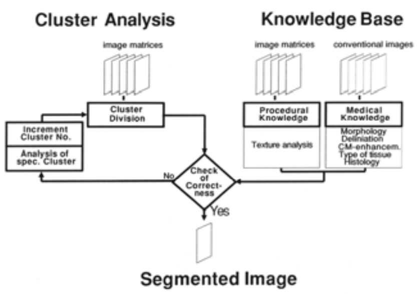
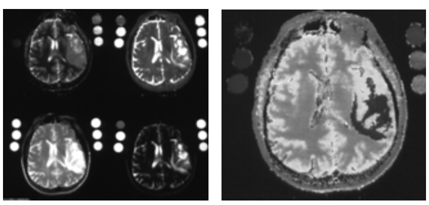
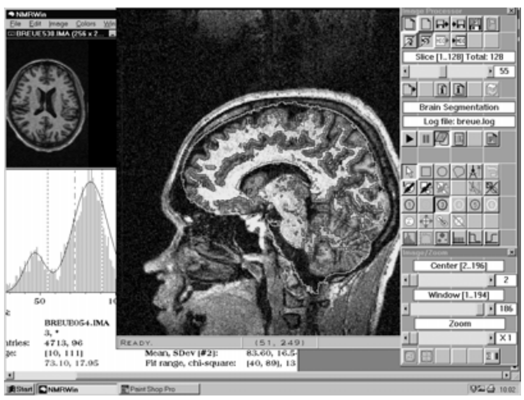
T1-, T2 – Based Tissue Segmentation

tissue characterization





tissue segmentation



Schad et al. ZMP 1992

Friedlinger et al. Comp Med Ima Graph 1995