



Basics of MRI

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Home

Staff

Research

Research Groups

Publications

Links

Lectures

Contact

Home >

Lectures

Our group is involved in the following study courses:

- Biomedical Engineering
- Translational Medical Research
- Medical Physics
- MaReCum
- HeiCuMed

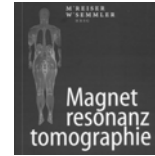
The list of current lectures and their schedule can be found in the LSF.

Accompanying Materials to our Lectures

- **Physikalische Grundlagen der MRT für Jedermann**
 - Elektrostatik, Magnetismus und Elektrodynamik
 - Grundlagen der Magnetresonanz
 - Relaxationszeiten T1 und T2
 - Bilderzeugung
 - Grundlagen der Bildkontraste
 - Risiken, Standard Meßsequenzen: Spinecho, IR
 - Spezielle Meßsequenzen: FLASH, MRA, 3D
- **Medical Physics: Lab Rotation MR-Radiology**
 - Relaxation Times T1 and T2
 - Introduction
 - Exercises
 - Data
 - Program
 - Diffusion
 - Introduction
 - Exercise
 - Data
 - Program



- Reiser, Semmler, Hricak:
“Magnetic Resonance Tomography” Chapter 2, 2008
- Vlaardingerbroek and den Boer:
“Magnetic Resonance Imaging
Theory and Practice”, 2003
- Haacke:” Magnetic Resonance Imaging:
Physical Principles and Sequence Design”

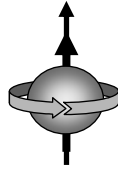


MRI Basics

Notation: MRI & NMR



Nuclear



(Kernspin)

Magnetic



Magnet

Resonance



Resonanz

(Imaging)



Tomographie

Proton

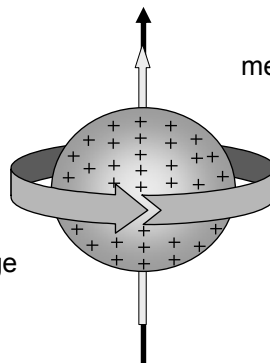


N Nuclear

M Magnetic

R Resonance

nuclear magnetic
moment



mechanic moment
(spin)

rotation

charge

Max Planck (1858–1947)



Nobelpreis 1918

Sir Ernest Rutherford (1871–1937)



Nobelpreis 1908

Louis de Broglie (1892–1987)



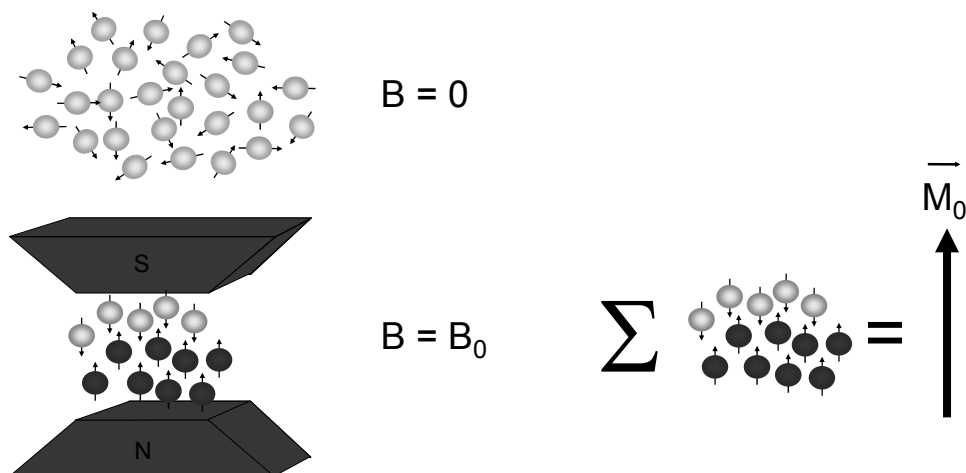
Nobelpreis 1929

NMR Nuclei



nucleus	spin I	gyromagnetic ratio γ [$10^8 \text{ rad s}^{-1} \text{ T}^{-1}$]	natural abundance of isotope in %	sensitivity \bar{S} for $B_0 = \text{const.}$ in % (rel. to ^1H)	
^1H	1/2	2,675	99,98	100,00	MRI: 110 mol
^2H	1	0,410	0,01	$9,60 \times 10^{-1}$	
^{12}C	0	-	98,89	-	
^{13}C	1/2	0,673	1,11	$1,75 \times 10^{-2}$	
^{14}N	1	0,193	99,63	$1,00 \times 10^{-1}$	
^{16}O	0	-	99,76	-	
^{17}O	5/2	-0,363	0,04	$1,11 \times 10^{-3}$	
^{19}F	1/2	2,518	100,00	83,40	MRS: $< 10^{-3}$ mmol
^{23}Na	3/2	0,708	100,00	9,27	MRI: 50 mmol
^{25}Mg	5/2	-0,164	10,00	$2,68 \times 10^{-2}$	
^{31}P	1/2	1,084	100,00	6,65	MRS: 40 mmol
^{33}S	3/2	0,205	0,75	$1,70 \times 10^{-3}$	
^{35}Cl	3/2	0,262	75,77	$3,58 \times 10^{-1}$	MRI: 50 mmol
^{39}K	3/2	0,125	93,26	$4,76 \times 10^{-2}$	MRI: 50 mmol
^{43}Ca	7/2	-0,180	0,14	$8,68 \times 10^{-4}$	

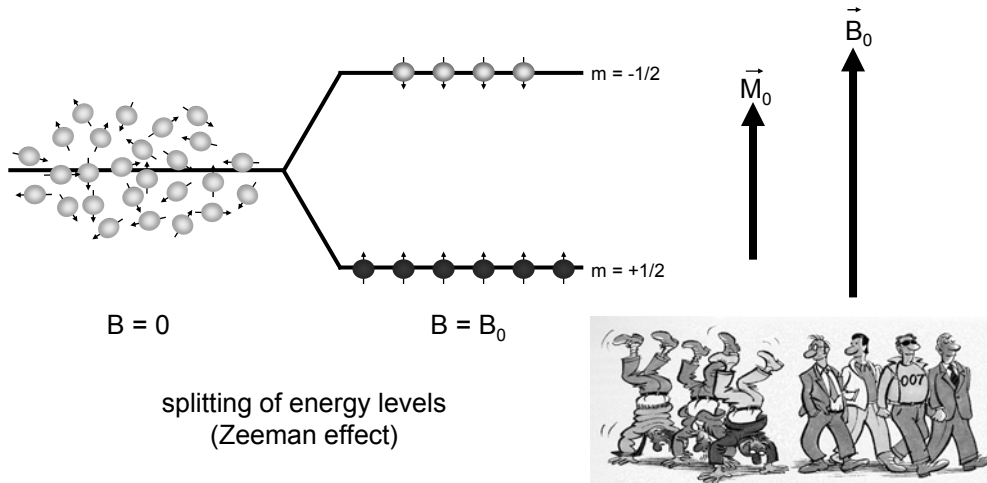
Magnetization M_0 for Spin 1/2





Zeeman Effect

$$\text{Curie's law: } M_0 = \frac{\rho \cdot l(l+1) \cdot \gamma^2 \cdot \hbar^2 \cdot B_0}{3kT}$$

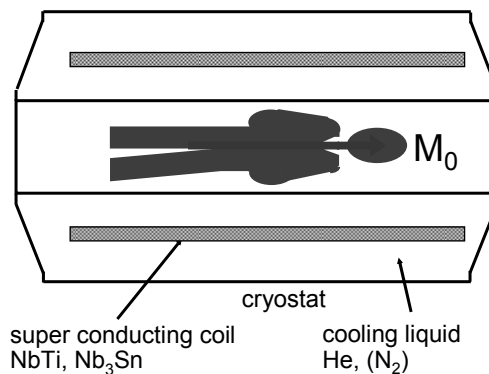
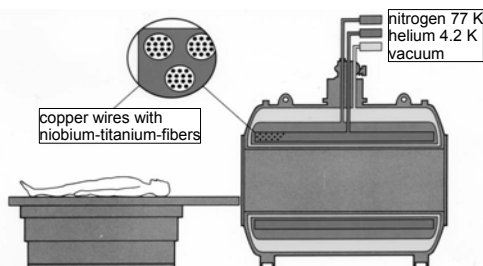


Magnetic Field B₀



static magnetic field B₀

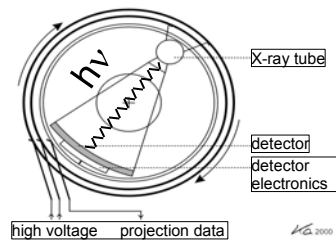
field strength 1.5 – 3.0 Tesla
homogeneity < 1.0 ppm



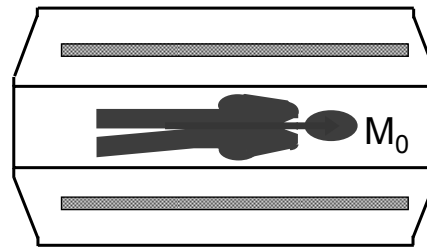
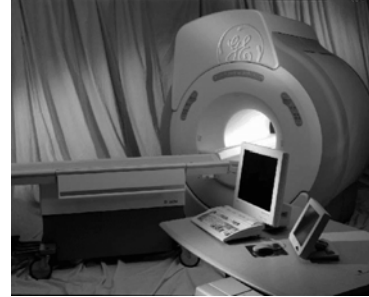


Comparison: CT - MRI

CT = transmission tomography



MRI = "direct" tomography



Correspondence Principle

in 1 mm³ water about 6x10¹⁹ protons / mol (Avogadro number)

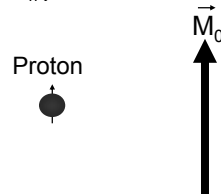
10 ppm (10⁻⁶) energy level ratio at 1.5 T

→ 6x10¹⁴ parallel spins in M₀



Bohr's correspondence principle

lim_{n → ∞} QM → classical physics

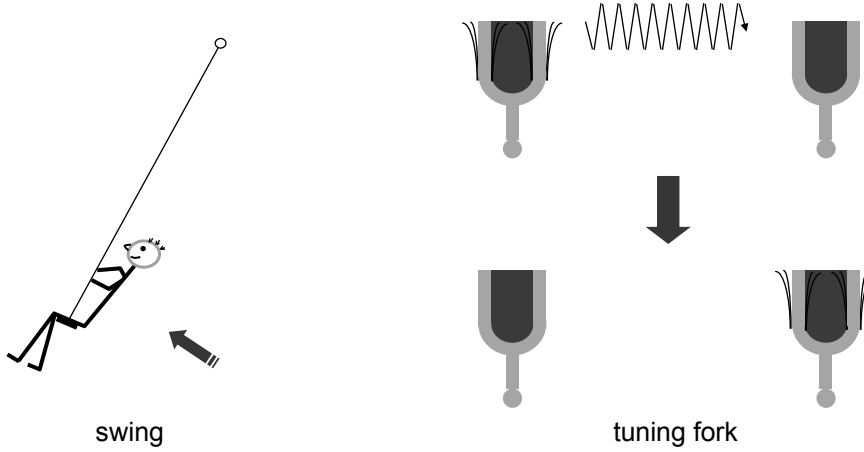


Niels Bohr (1885–1962)



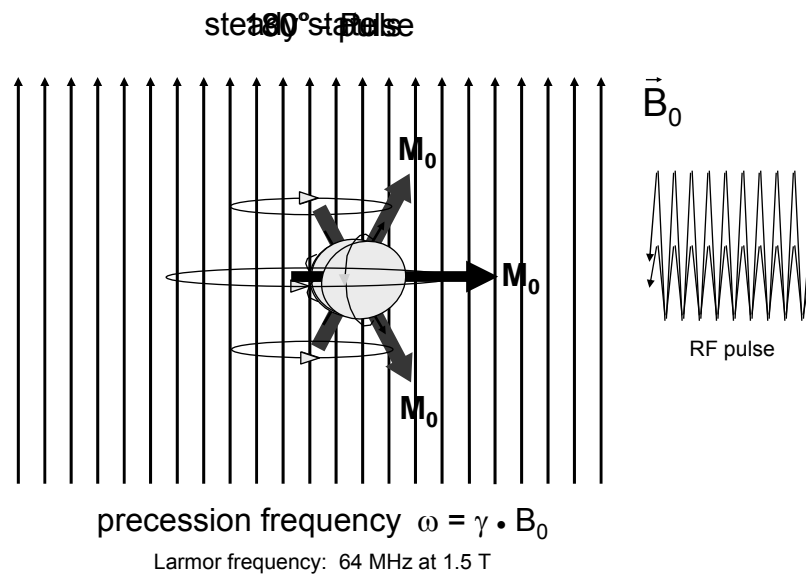
Nobelpreis 1922

Resonance: Basic Principle



- energy transfer between A and B is only possible if both systems are resonant
- RF system has to work at 64 MHz at 1.5 T

Resonance





NMR History: Theory

Leipzig -
Stanford

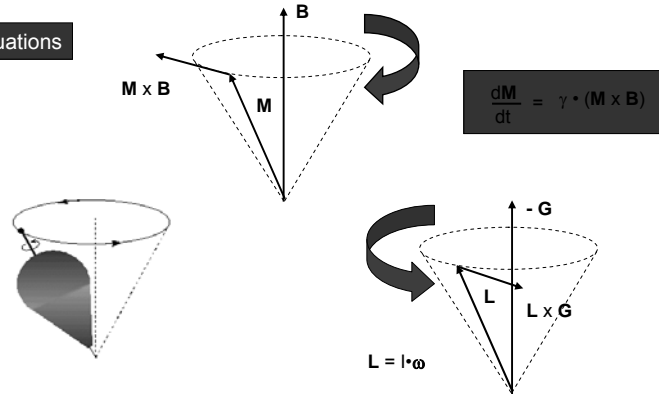
1946



Felix Bloch

- achieved the same in a sample of water
- provided the mathematical characterization of the nuclear magnetic resonance phenomenon
- Nobel Prize for physics (Bloch & Purcell) in 1952

the Bloch equations

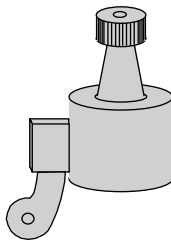


© Yves De Deene. University of Gent, Belgium

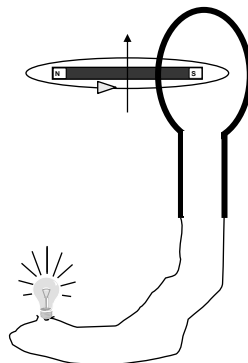


Faraday Induction

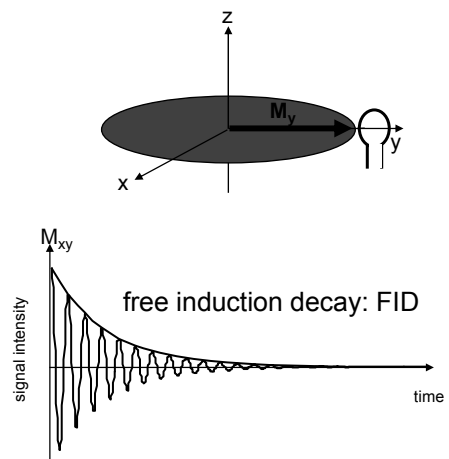
bicycle
dynamo



loop with
rotating magnet



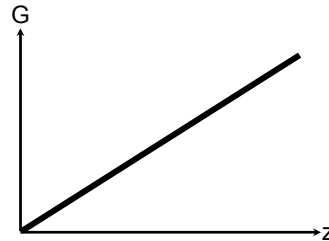
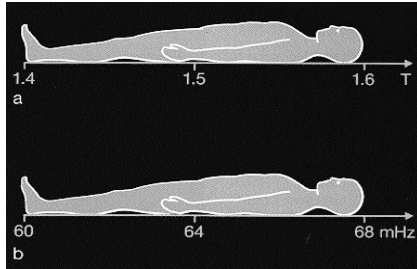
rotating magnetic
moments



Gradient Field: Slice Selection



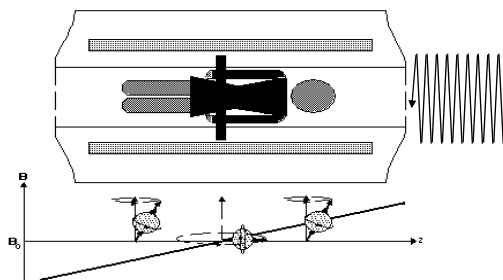
magnetic field gradient, i.e. G_z



Paul Lauterbur (1929-2007)



Nobelprize 2003



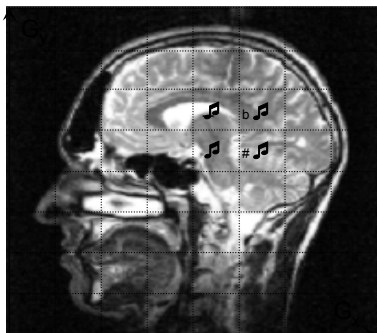
radiofrequency:
 $\omega(z) = \gamma (B_0 + G_z z)$

gradient G_z

Imaging: Gradient Fields

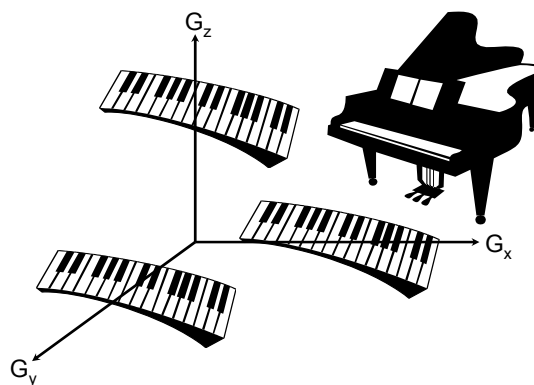


magnetic field gradients G



precession frequency $\omega = \gamma \cdot B$
with $B = B_0 + G_x + G_y + G_z$

“3D piano”



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Imaging: k-space

image
↑
Fourier transformation
↓
k-space

Jean Baptiste Fourier (1768-1830)

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2/1/2011 | Page 20

MRI Components: Physical Parameters

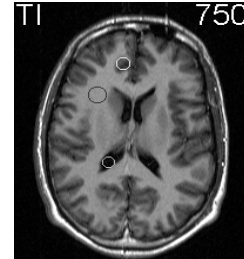
technical component	→	physical parameter
static field B_0	→	M_0
radiofreq. RF	→	signal
gradients G_{xyz}	→	image



Measurement of Brain Relaxation Times T1 and T2

1. Evaluate from an Inversion Recovery measurement the T1-relaxation of White Matter (WM), Grey Matter (GM), and Cerebrospinal Fluid (CF).

Experiment #1: 6 images were measured (IR_01.ima ... IR_06.ima, data at: <http://www.ma.uni-heidelberg.de/inst/cbmr/ckm/lehre/> "Medical Physics: Lab Rotation MR-Radiology") with TI = 50, 400, 550, 750, 1200, 2000 ms. Plot signal intensity (= pixel mean value of ROI) as a function of TI and calculate T1 of WM, GM and CF.



2. Evaluate from a spin-echo measurement the T2-relaxation of WM, GM and CF.

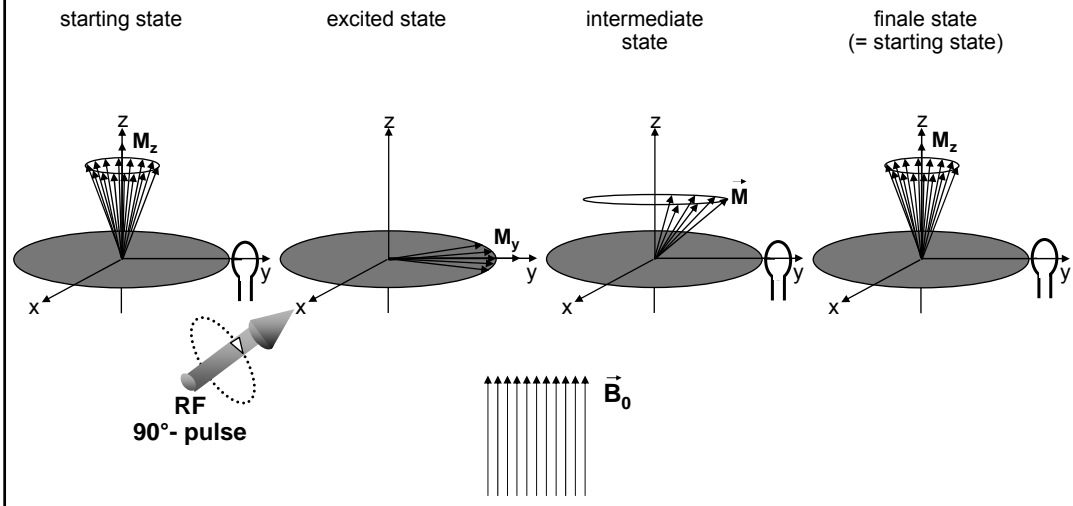
Experiment #2: 11 images were measured (SE_01.ima ... SE_11.ima) with TE = 25, 50 ... 275.0 ms. Plot signal intensity (= pixel mean value of ROI) semi-logarithm as a function of TE and calculate T2 of WM, GM and CF.

- group 1: WM
- group 2: GM
- group 3: CF

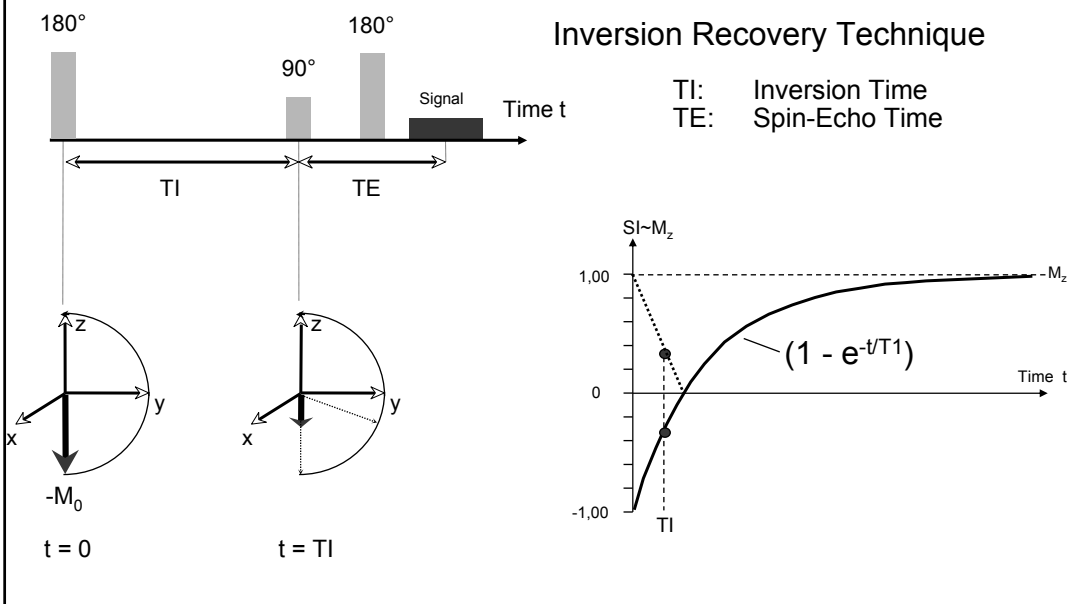


T1 Relaxation

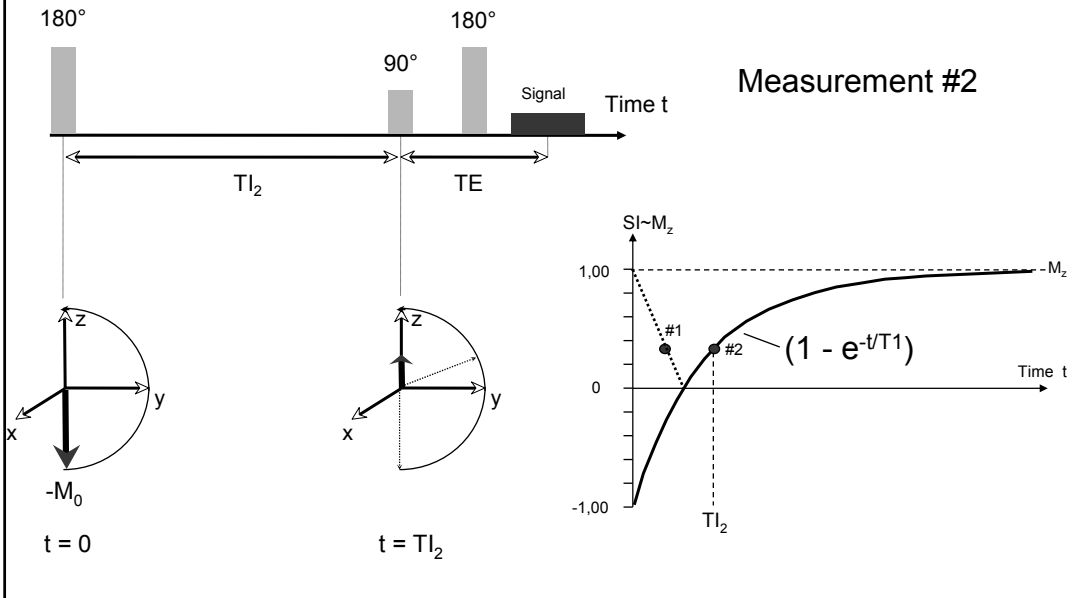
Spin-Lattice-Relaxation T1



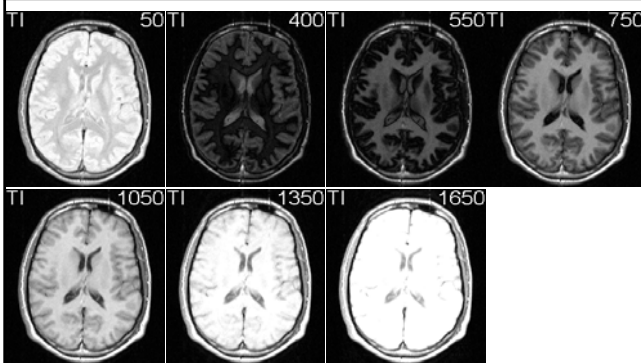
Experiment: T1-Measurement #1



Experiment: T1-Measurement #2



T1 Measurement: Inversion Recovery



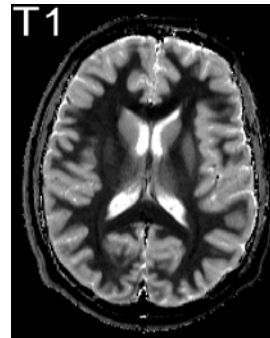
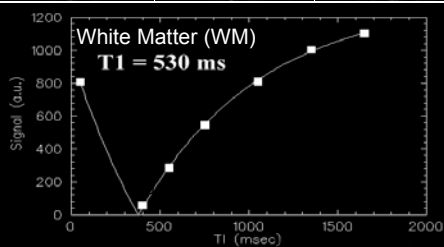
inversion recovery ($M_z(0) = -M_0$):

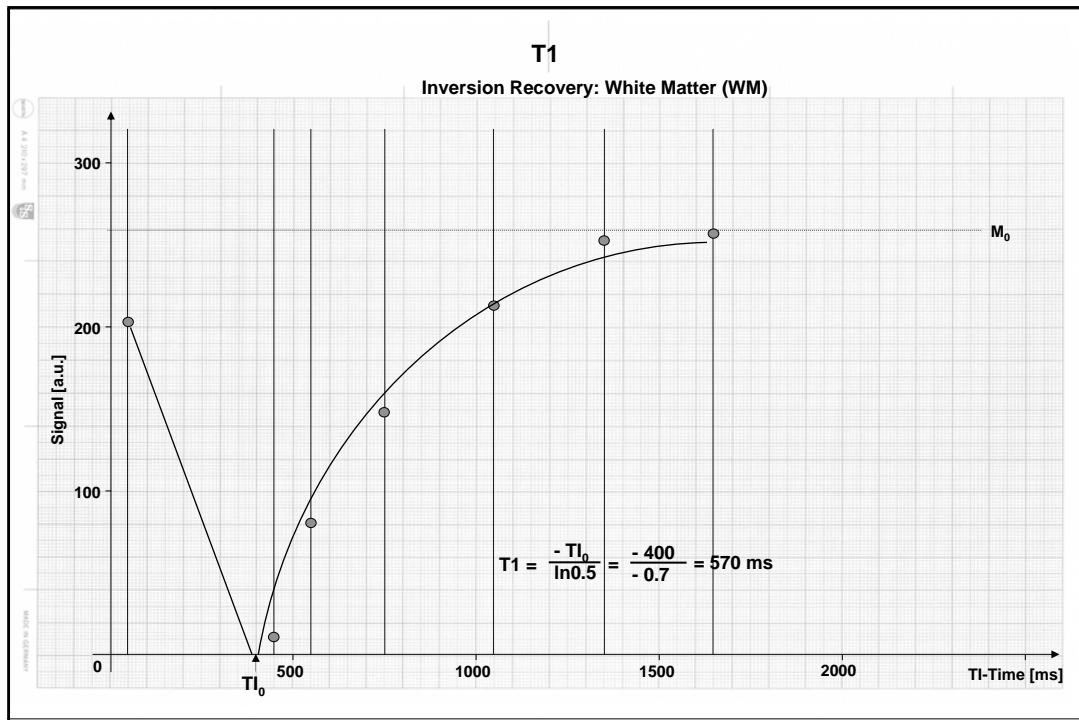
$$M_z(t) = M_0 (1 - 2 \exp(-t/T1))$$

with $M_z = 0$ at $T1 = T1_0$:
 $0.5 = \exp(-T1_0/T1)$

$$\rightarrow T1 = -T1_0 / \ln(0.5) = T1_0 / 0.7$$

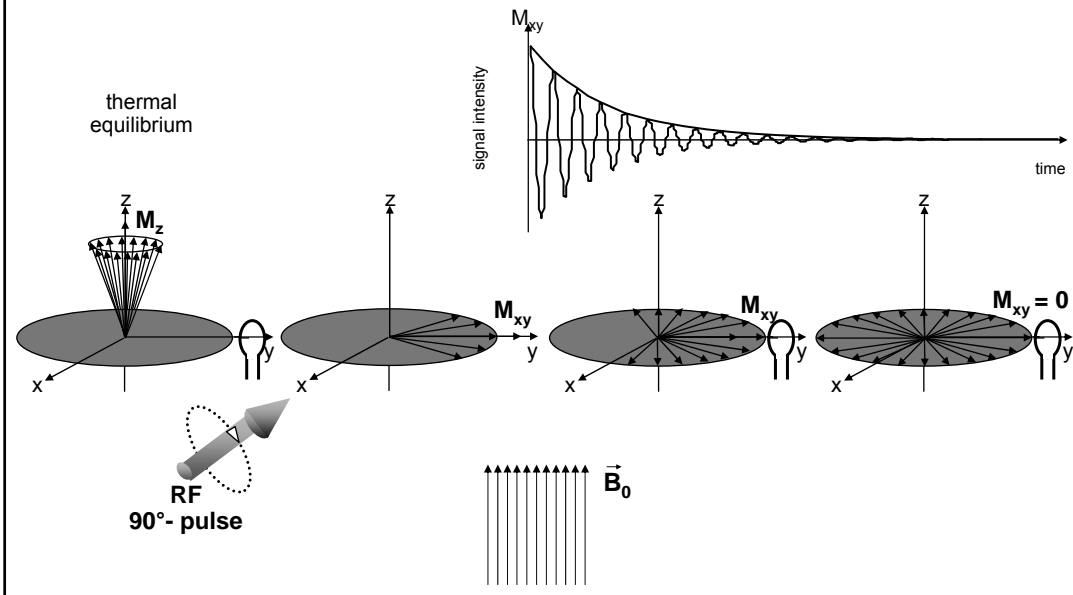
$$T1_{WM} = -400 \text{ ms} / -0.7 = 570 \text{ ms}$$



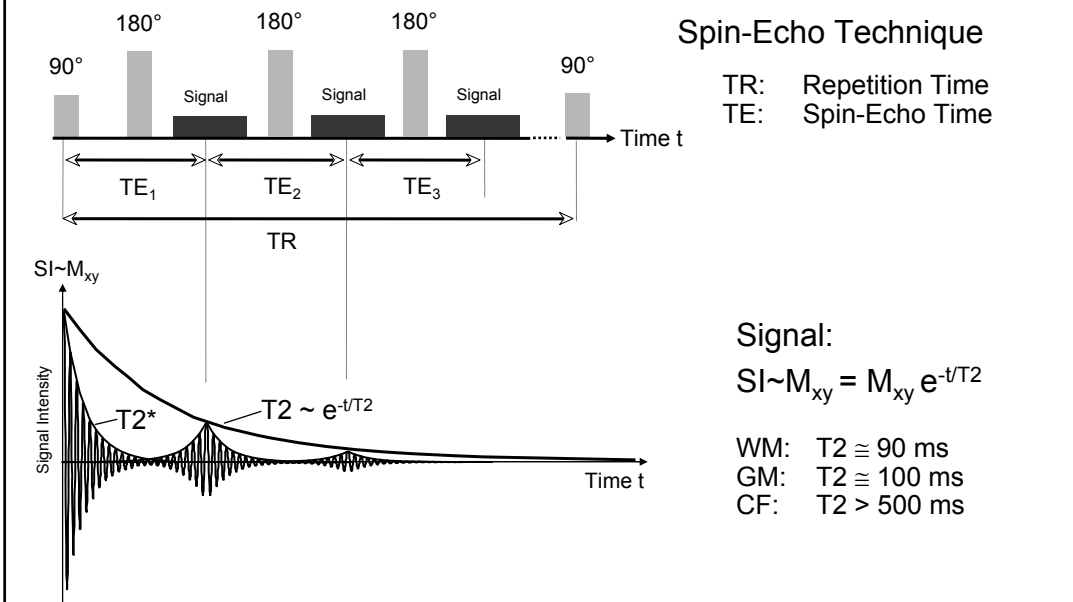


RUPRECHT-KARLS- UNIVERSITY HEIDELBERG Computer Assisted Clinical Medicine Prof. Dr. Lothar Schad 2/1/2011 Page 28	<h2 style="margin: 0;">T2 Relaxation</h2>	
<h1 style="font-size: 2em; margin: 0;">T2 Relaxation</h1>		

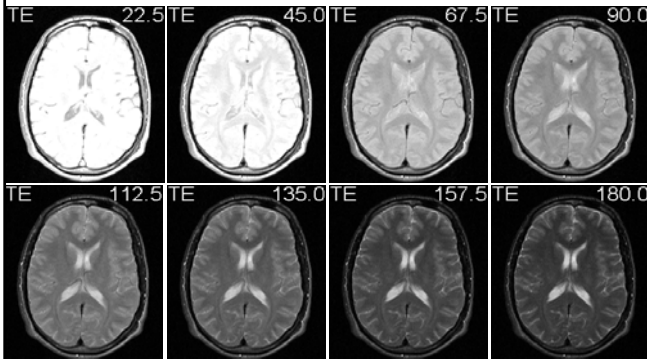
Spin-Spin-Relaxation T2



Experiment: T2-Measurement



T2 Measurement: Spin-Echo

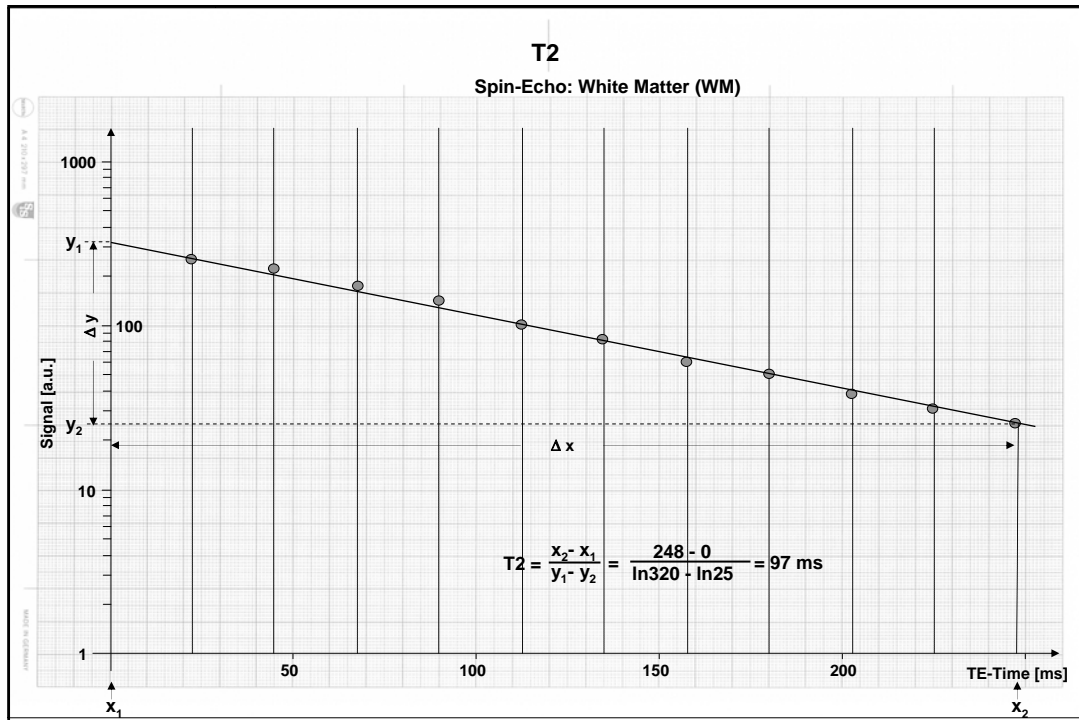
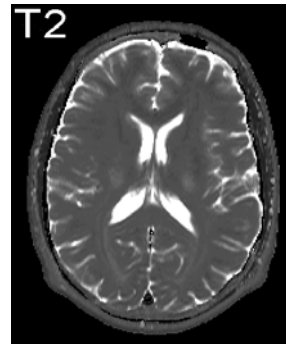
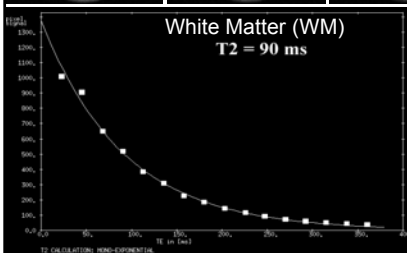


spin-echo ($M_{xy}(0) = M_0$):

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

→ slope of straight-line in semi-logarithm scale

$$T2_{WM} = 90 \text{ ms}$$

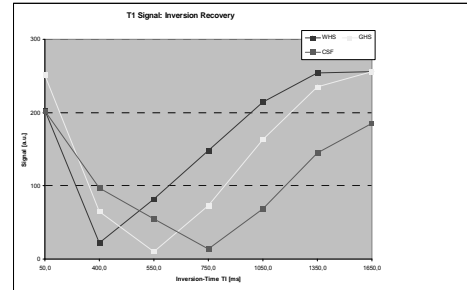


Exercise: T1, T2



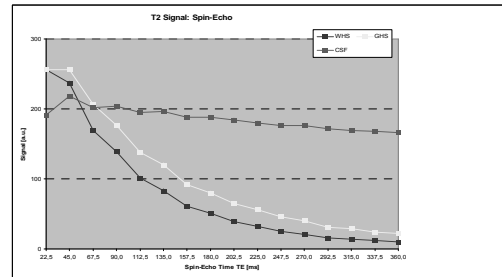
TI [ms]	WM Signal [a.u.]	GM Signal [a.u.]	CF Signal [a.u.]
50,0	203	251	202
400,0	22	65	97
550,0	82	10	55
750,0	148	73	14
1050,0	214	163	69
1350,0	254	235	145
1650,0	256	256	185

T1



TE [ms]	WM Signal [a.u.]	GM Signal [a.u.]	CF Signal [a.u.]
22,5	256	256	191
45,0	237	256	218
67,5	169	206	202
90,0	139	177	204
112,5	101	138	195
135,0	83	120	196
157,5	61	92	188
180,0	51	80	188
202,5	39	65	184
225,0	32	56	180
247,5	25	46	176
270,0	21	40	176
292,5	16	31	172
315,0	14	29	169
337,5	12	24	168
360,0	10	22	166

T2



BOLD Contrast



BOLD Contrast



Magnetization M

An external magnetic field creates an additional magnetic polarization in a probe called magnetization. The magnetization is caused by atomic magnetic moments either created by the external field or by alignment of already existing moments.

Magnetic Susceptibility χ

Quantity for the magnetization of a probe.

χ describes the „answer“ of the magnetization with respect to the external magnetic field:

$$M = \chi H$$



Diamagnetism

- molecules without permanent magnetic dipole moments
- induced magnetic dipole moments are opposed to the external magnetic field

=> magnetic field inside the probe is smaller than the external magnetic field

=> χ is negative ($\chi < 0$)

Paramagnetism

- molecules of paramagnetic substances have permanent magnetic dipoles
- without an external magnetic field there is a randomized distribution of magnetic dipoles in space
- with external magnetic field there is a partial alignment of magnetic dipoles

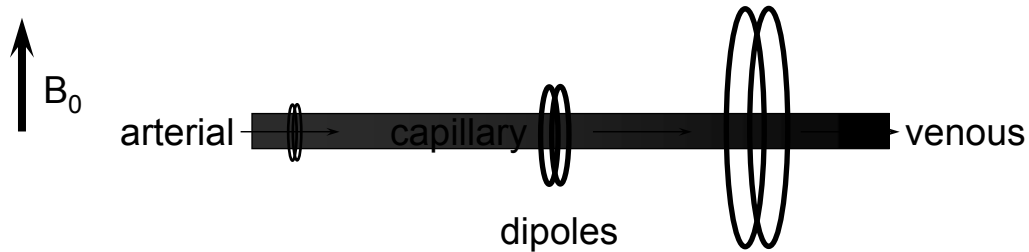
=> magnetic field inside the probe is larger than the external magnetic field

=> χ is positive ($0 < \chi < 1$)

BOLD Contrast



- BOLD: blood oxygen level dependent contrast



magnetic properties of hemoglobin:

oxygenated - diamagnetic
deoxygenated - paramagnetic



$$\left. \begin{array}{l} \text{diamagnetic} \\ \text{paramagnetic} \end{array} \right\} \frac{1}{T_2^*} \sim \Delta B_{loc}$$

Ogawa et al. Proc Natl Acad Sci 1987

Hemoglobin

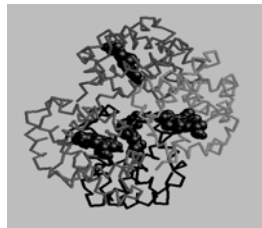


The paramagnetic property of deoxyhemoglobin has been known for 70 years, however, the realization of its usefulness in understanding brain function has only been made possible during the last 15 years.

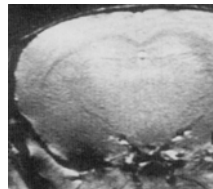
Linus Pauling (1901–1994)



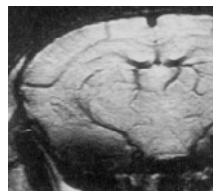
Nobelprize 1954



100% O₂
breathing
280 beats/min



air
breathing
235 beats/min



S. Ogawa

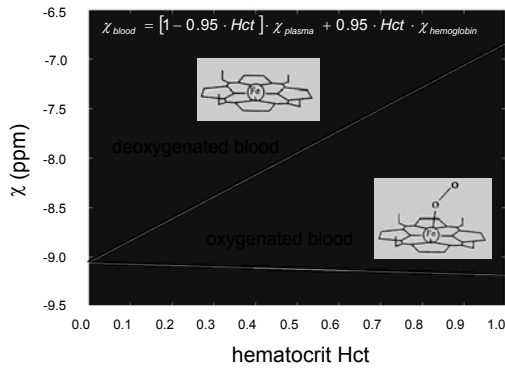
Oxyhemoglobin: no unpaired electrons
Deoxyhemoglobin: four unpaired electrons / heme
 $\mu = 5.46 \mu_B / \text{heme}$

oxygenation contrast in rat images at 7 T

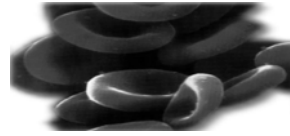
Pauling and Coryell. PNAS 1936

Ogawa et al. MRM 1990

Magnetic Susceptibility of Whole Blood



$$\Delta\chi_{\text{do}} = 2.49 \text{ ppm}$$



measured susceptibilities of erythrocytes

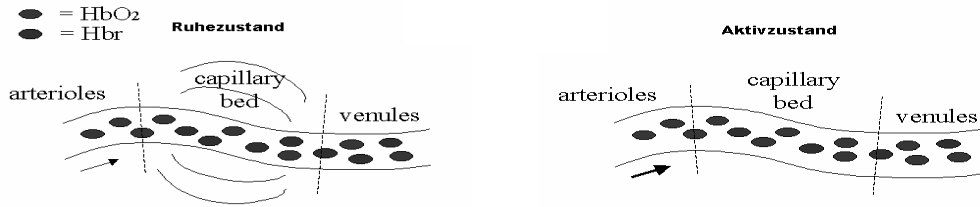
Form of hemoglobin in erythrocyte	Susceptibility $\chi \times 10^6$	Standard deviation $s \times 10^6$
Oxyhemoglobin	- 9.19	0.05
Carboxy-hemoglobin	-9.22	0.05
Deoxyhemoglobin	- 6.7	0.38
Methemoglobin	-7.2	0.38

Functional MRI



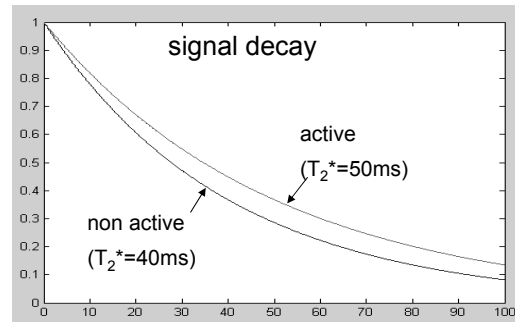
Functional MRI

fMRI: BOLD-Effect

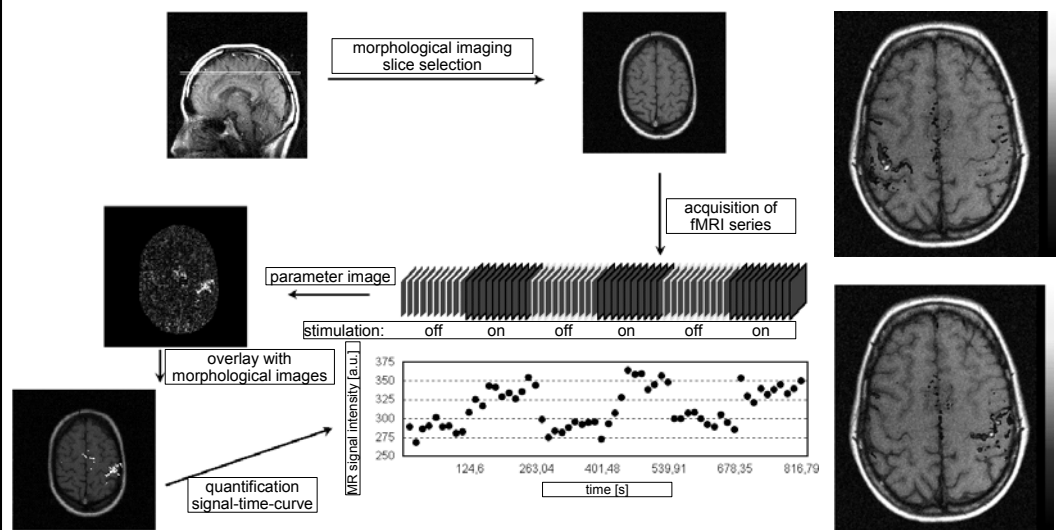


Neuronal activation → increase in perfusion overproportional to the increase of oxygen-consumption → increase of the oxyhemoglobin-concentration

- Deoxyhemoglobin is paramagnetic
→ induces strong magnetic field-inhomogeneities
- Oxyhemoglobin is diamagnetic
→ induces weak magnetic field-inhomogeneities
→ T_2^* changes (**T_2^* -effect**)
→ signal is sensitive to T_2^* with a gradient-echo sequence (EPI)



Functional MRI: Principal



source: Schad, Functional MRI, in "Magnetic Resonance Tomography", Reiser et al., eds. 2008

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2/1/2011 | Page 43

Echo Planar Imaging (EPI)

Sir Peter Mansfield (1933–)
Nobelprize 2003

k-space

EPI-readout

G_{slice}

G_{phase}

G_{read}

time

EPI-image

TR/TE = 960/66 ms

- + high temporal resolution: ~ 100 ms,
- + very good T2* contrast (BOLD-Contrast)
- susceptibility artifacts → image distortions and signal cancellation/drop-out

Mansfield. J Phys Chem 1977, 10:L55-L58

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2/1/2011 | Page 44

Functional MRI: Radiotherapy Planning

- definition of functional structures at risk

patient: glioblastoma, fMRI: finger tapping

Schad et al. Eur Radiol 1996