

Function of an MRI scanner and principle of MR imaging

Fritz Schick



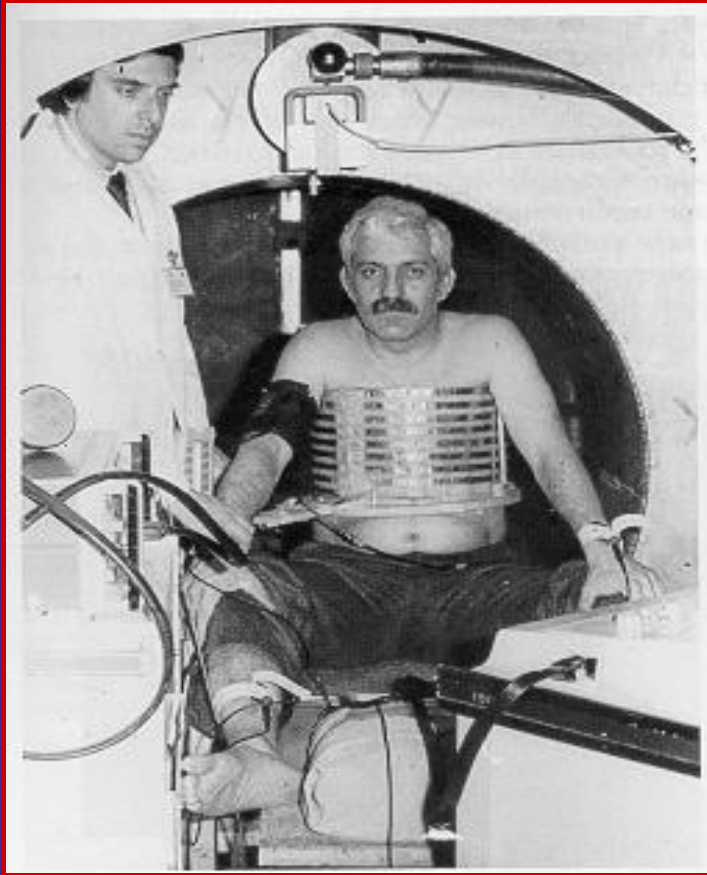
Section on Experimental Radiology
Department on Diagnostic and
Interventional Radiology
University of Tübingen, Germany



Module Bioimaging, Master degree course: „Biomedical Technologies“

History of MR imaging

State of technology 1977



First Volunteer



First MR image

recording time > 1 hour

Nobel Price 2003

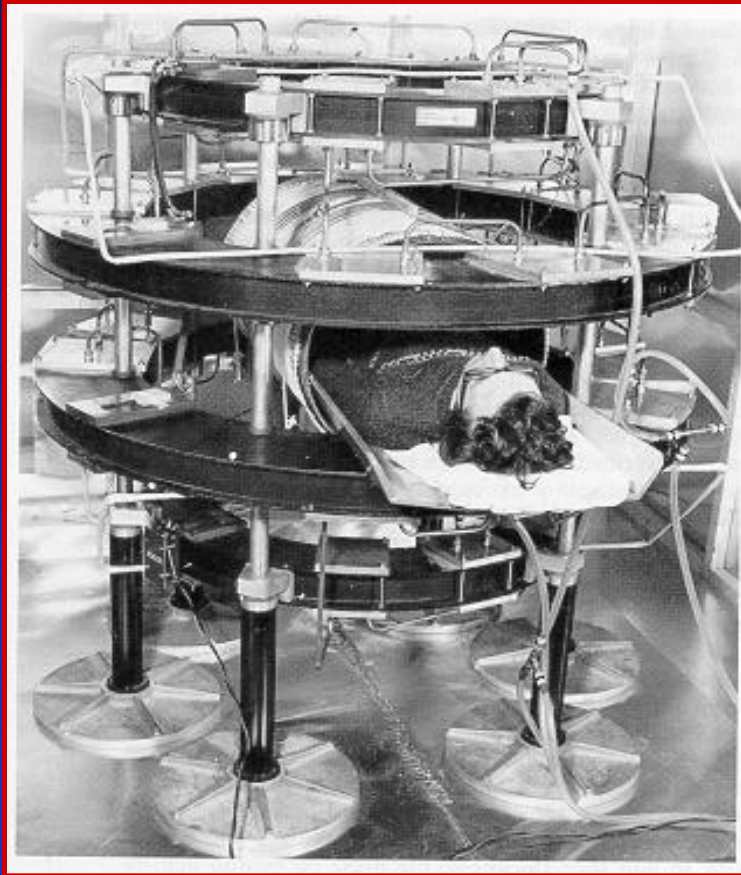
**Nuclear magnetic resonance (NMR) experiments
with spatial encoding (= MR imaging = MRI)**



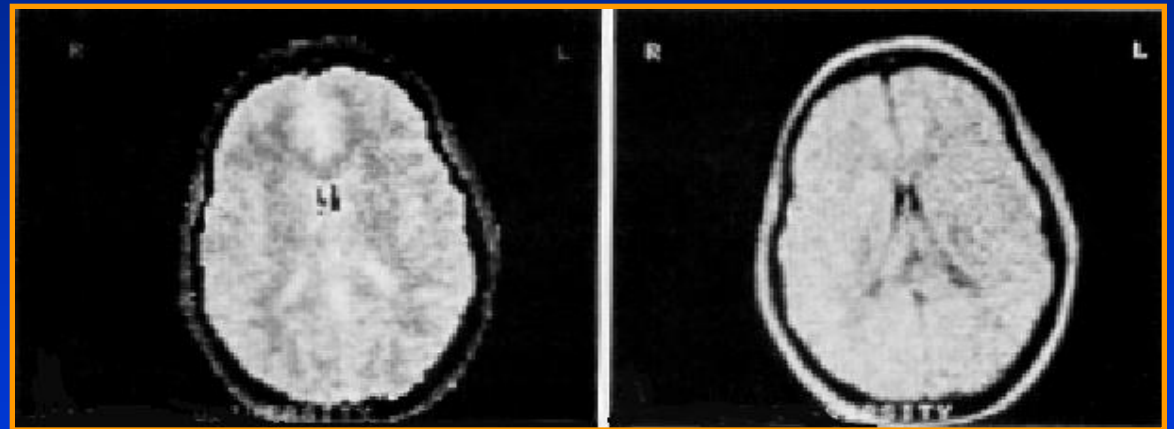
*Peter Mansfield (*1933) Paul C. Lauterbur (1929-2007)*

History of MR imaging

State of technology 1981



MR-System, Aberdeen 1981



MR images recorded in Aberdeen

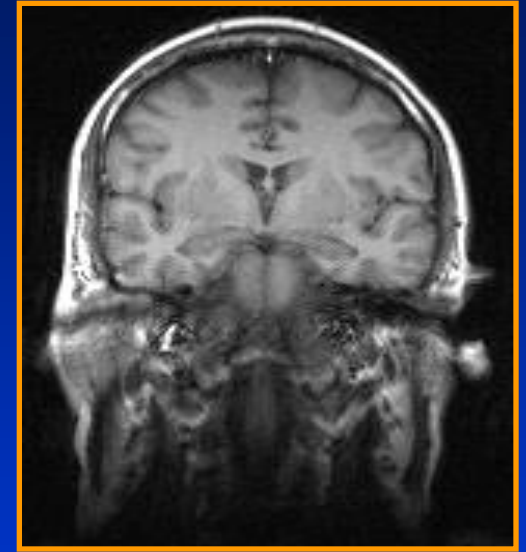
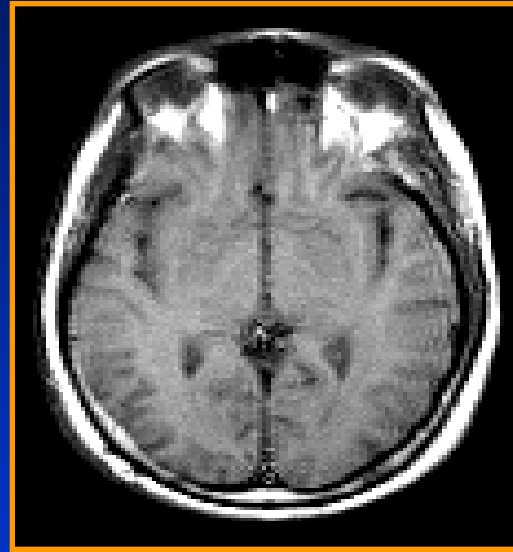
recording time 45 minutes

History of MR imaging

State of technology 1985



MR-System
Siemens MAGNETOM



Spinecho-Images

recording time 10 min

field strength: 1.5 Tesla

gradient strength: 3 mT/m

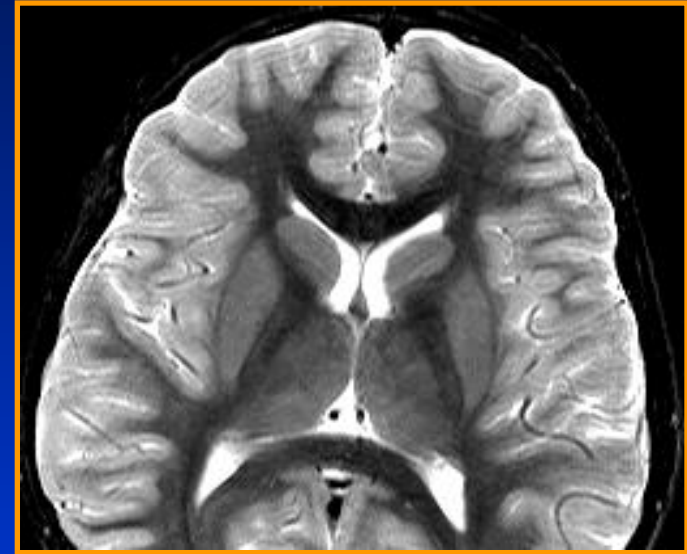
gradient slew rate: 1 T/m s

History of MR imaging

State of technology 2005



MR-System
Siemens SONATA



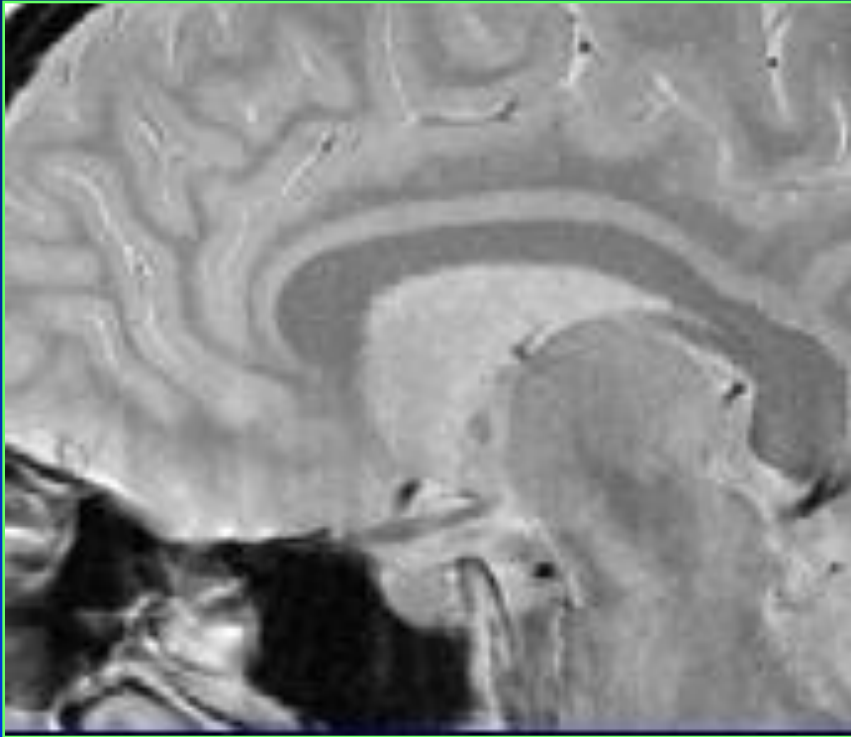
FSE-Image

recording time < 1 min

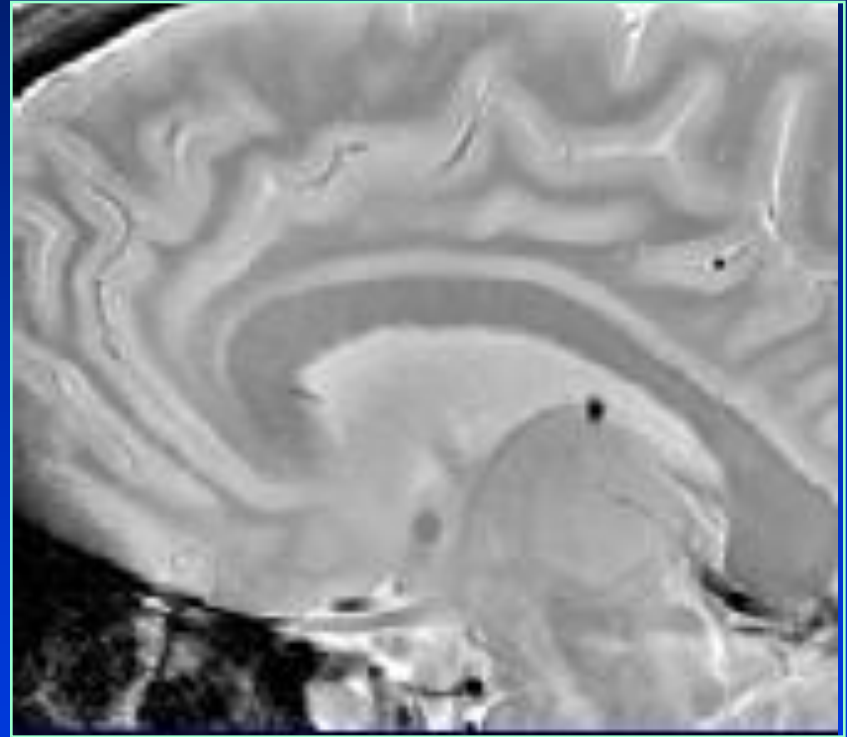
field strength: 1.5 Tesla
gradient strength: 40 mT/m
gradient slew rate: 200 T/m s

History of MR imaging

High field imaging 2010



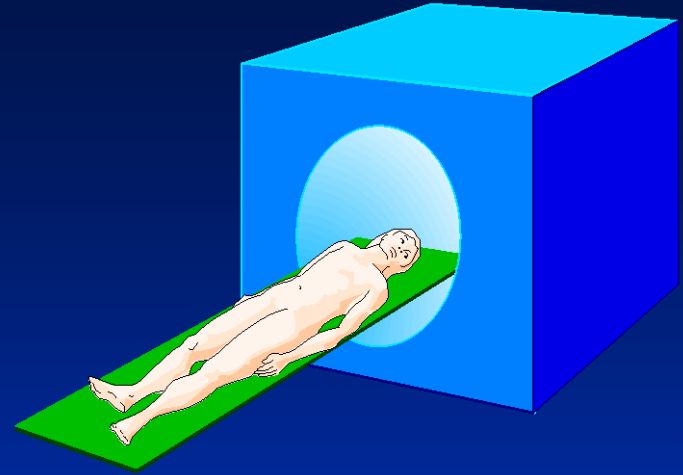
3 Tesla



7 Tesla

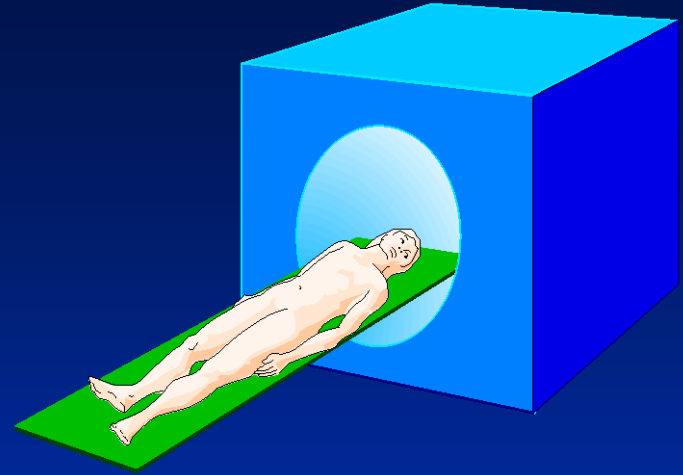
TSE sequence; resolution $0.4 * 0.4 * 3.0 \text{ mm}^3$; recording time 7 min

Outline



- Basic principles of magnetic resonance
- MRI, spatial encoding, contrast mechanisms
- MRS, spatial encoding, chemical shift
- Hardware components
- Recent developments in MRI

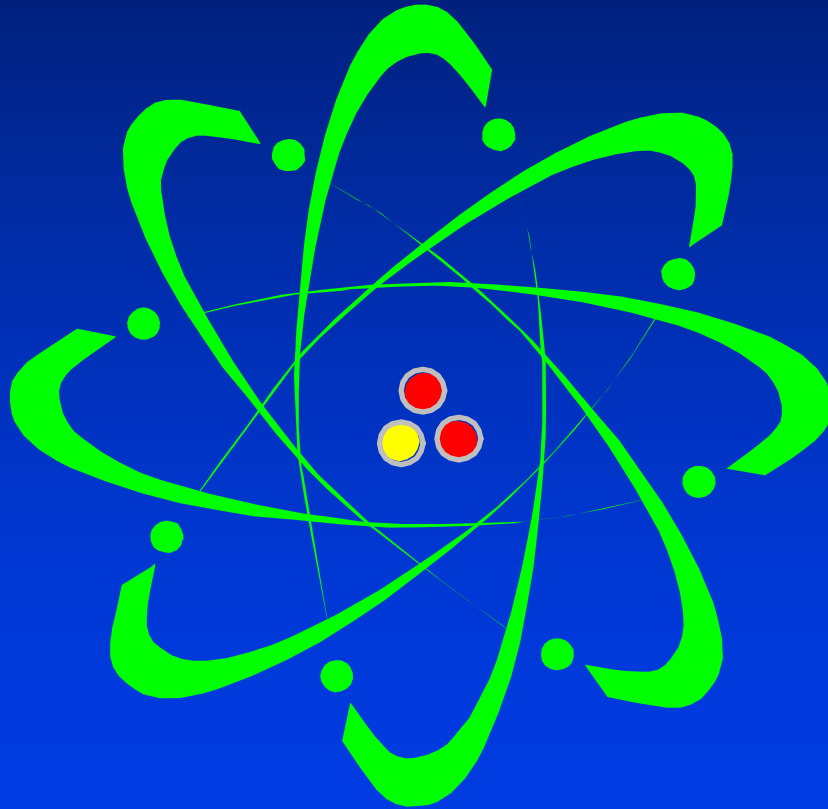
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Nuclear Spin and Magnetic Moment

Atom



Mechanical
property :

Spin

Magnetic
property :

Magnetic
moment

What is necessary for generating detectable signals by atomic nuclei?

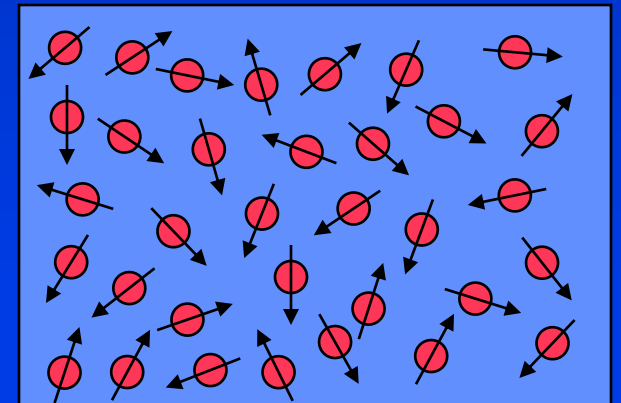


There are more than 10^{25} hydrogen nuclei in a glass of milk -

but no detectable macroscopic effect

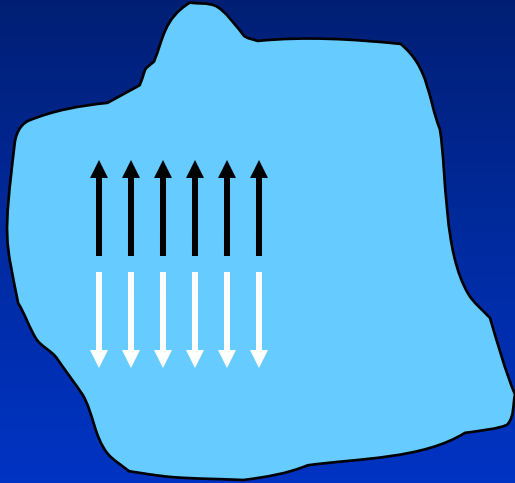
Macroscopic
Magnetization

$$\vec{M} = 0$$



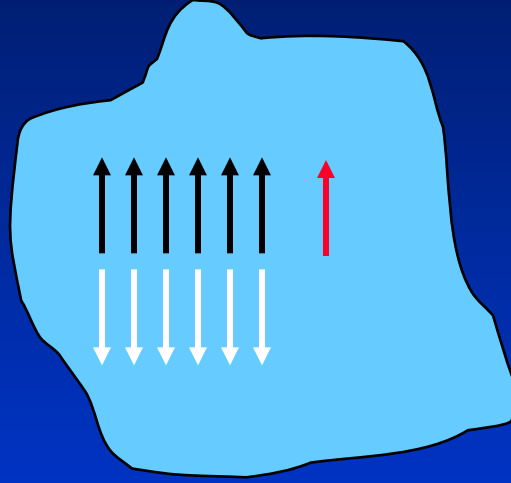
Effect of increasing field strength B_0

0 Tesla



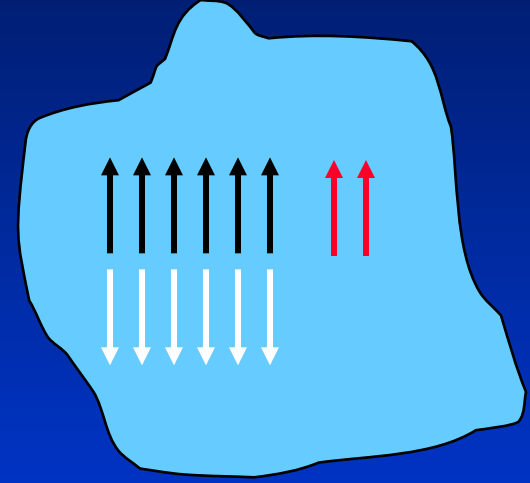
0 : 1.000.000

1.5 Tesla



5 : 1.000.000

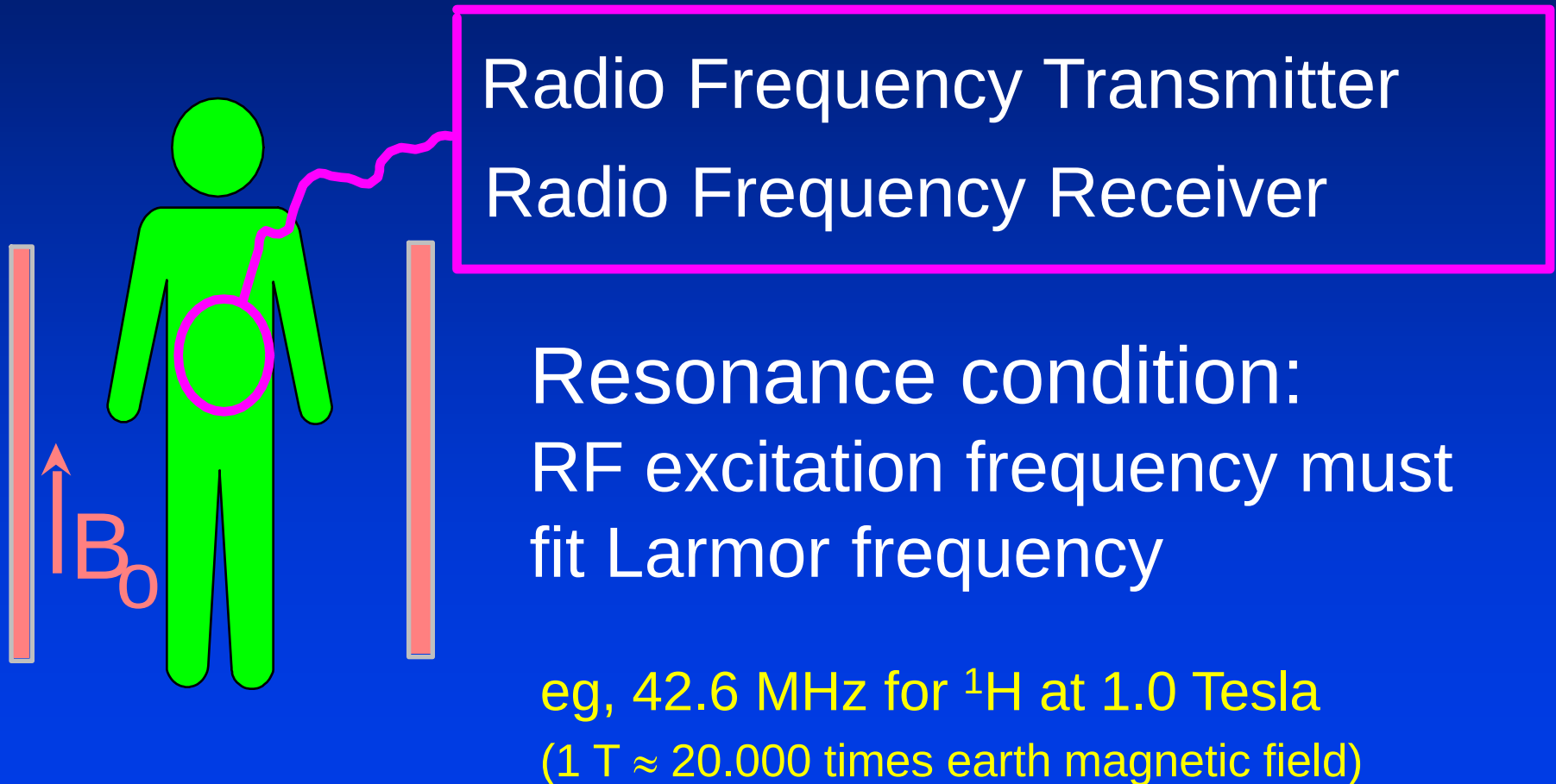
3 Tesla



10 : 1.000.000

Surplus of magnetization along the outer magnetic field B_0 at room temperature

Generation of signals in magnetic resonance



Typical ^1H resonance frequencies as applicable for medical imaging

0.2 Tesla:	8.5 MHz	($\lambda_{\text{air}} = 35.2 \text{ m}$)
1.0 Tesla:	42.6 MHz	($\lambda_{\text{air}} = 7.0 \text{ m}$)
1.5 Tesla:	63.9 MHz	($\lambda_{\text{air}} = 4.7 \text{ m}$)
3.0 Tesla:	127.7 MHz	($\lambda_{\text{air}} = 2.3 \text{ m}$)

Resonance frequencies (Larmor frequencies) of magnetization are strictly proportional to the field strength B present at the atomic nuclei.

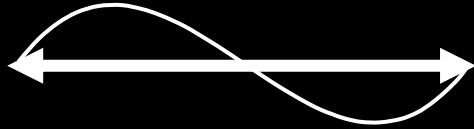
Resonance frequencies immediately change, if field strengths are changing eg, by gradient switching).

^1H wavelength in water for different field strengths

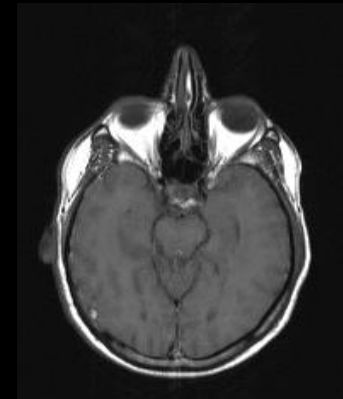
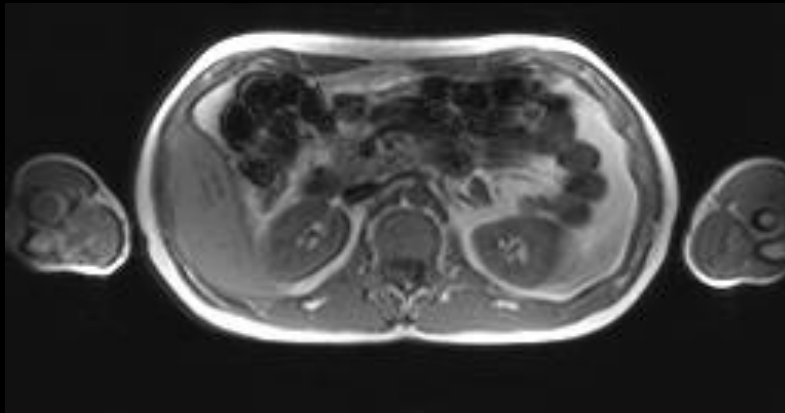
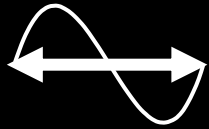
1.5 Tesla: $\lambda_{\text{H}_2\text{O}} = 52 \text{ cm}$



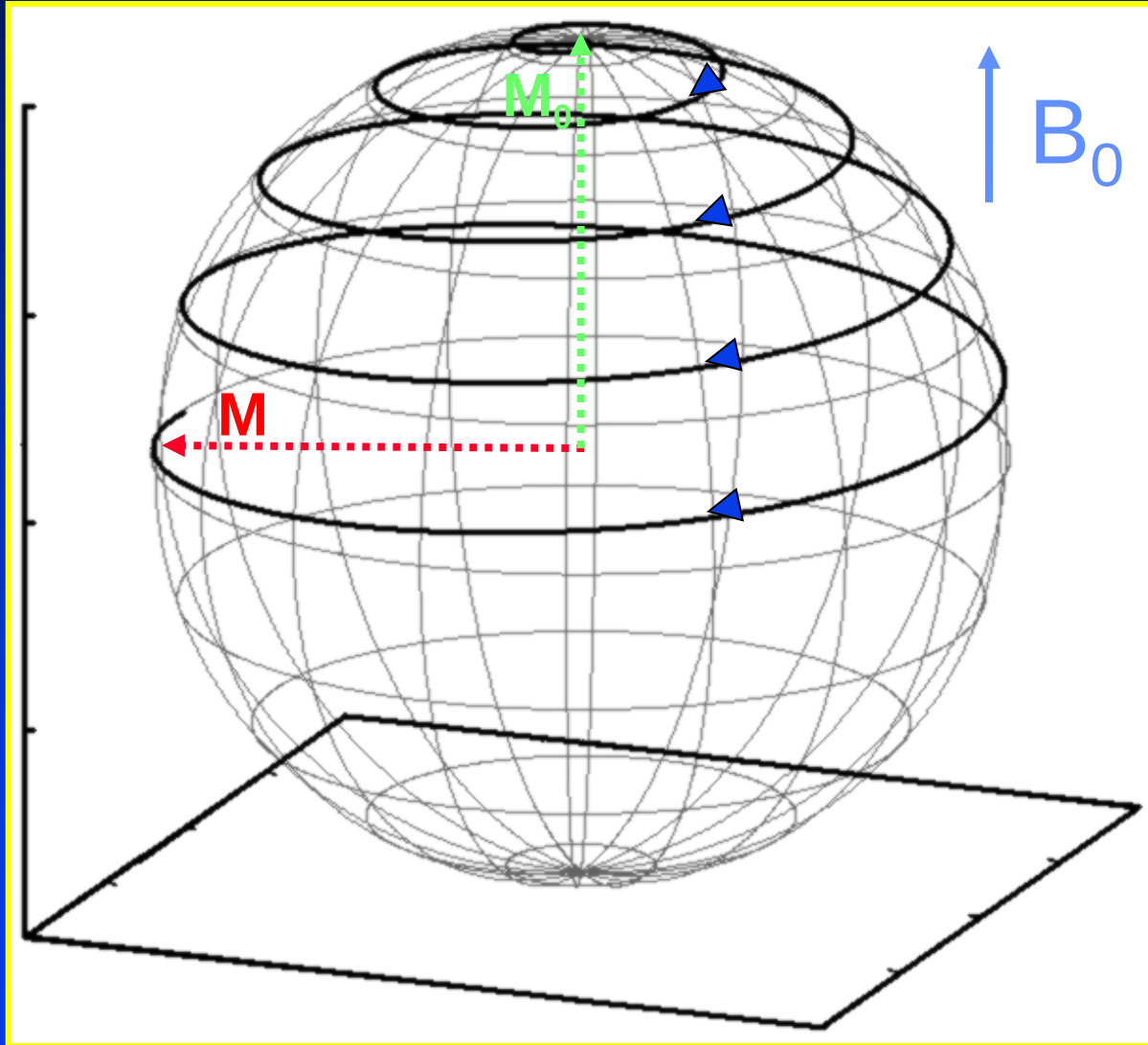
3.0 Tesla: $\lambda_{\text{H}_2\text{O}} = 26 \text{ cm}$



7.0 Tesla: $\lambda_{\text{H}_2\text{O}} = 11 \text{ cm}$

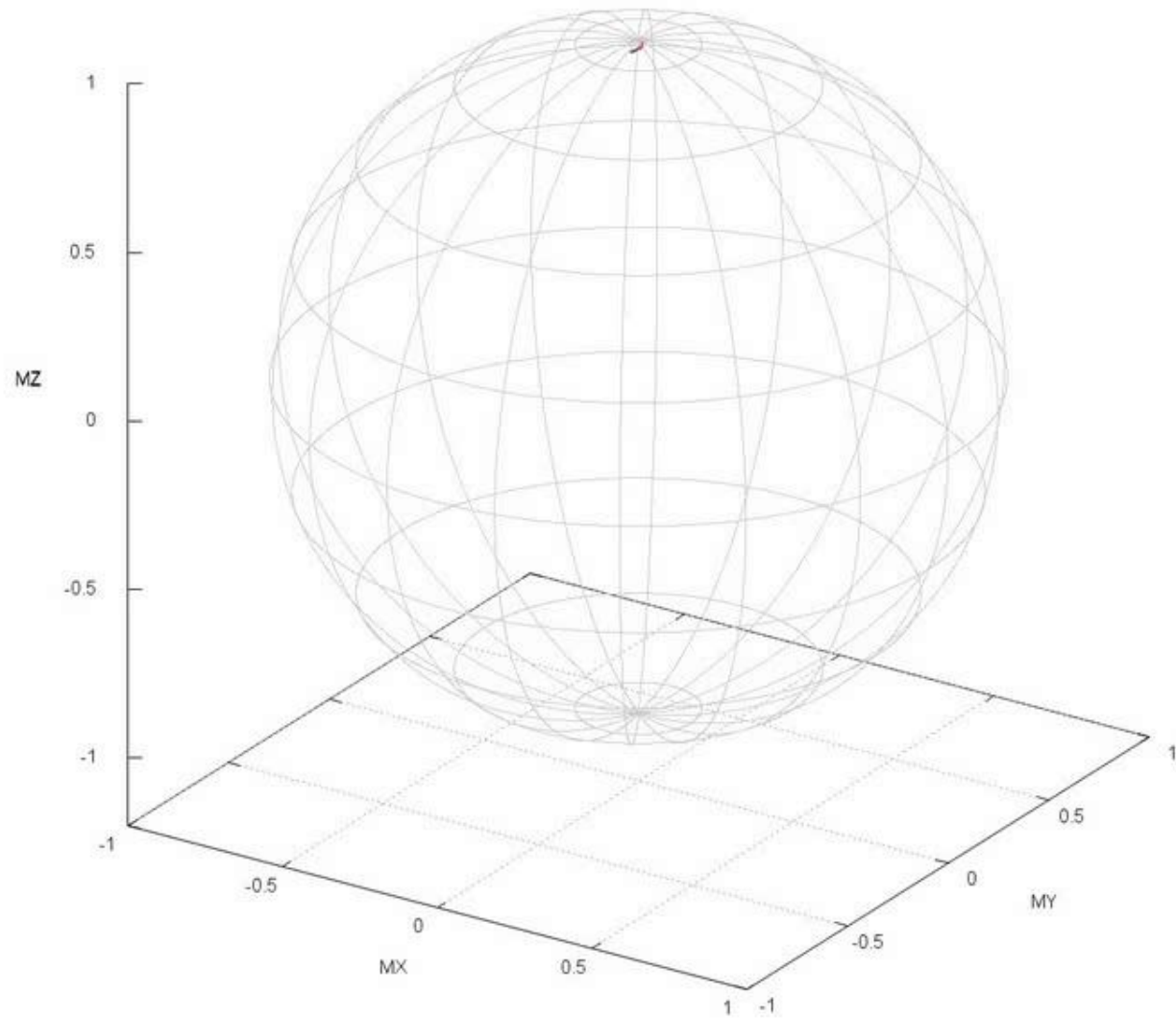


RF excitation of magnetization (90°-pulse)



Duration of excitation:
approx. 1 ms

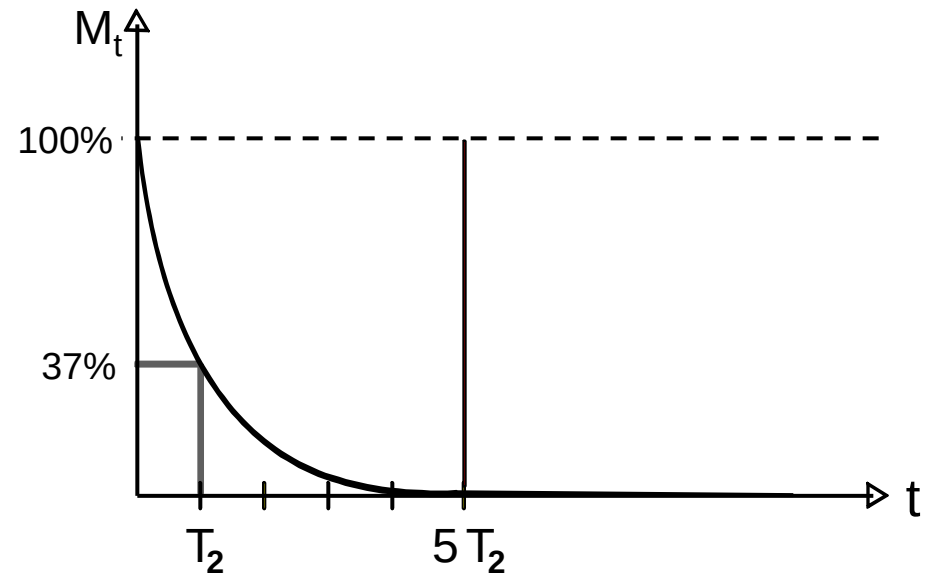
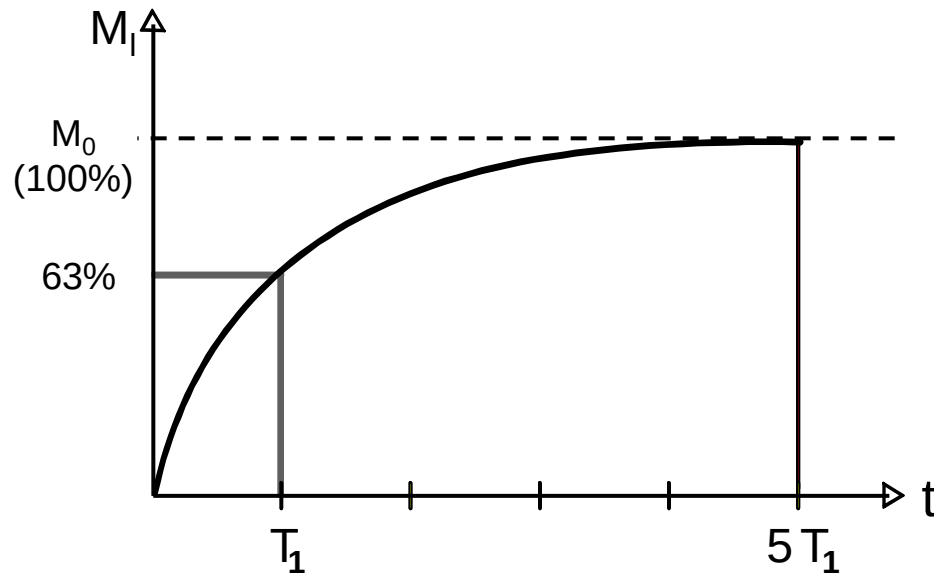
Excitation



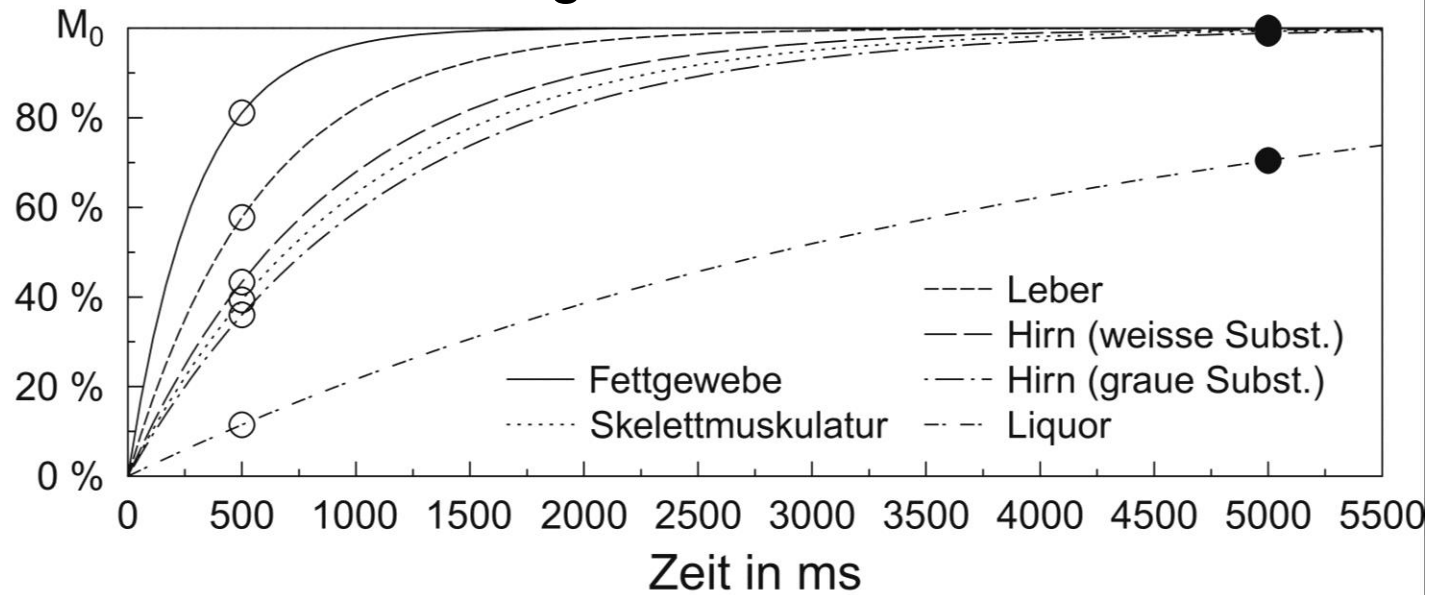
Relaxation of magnetization (following 90°-pulse)

longitudinal
magnetization

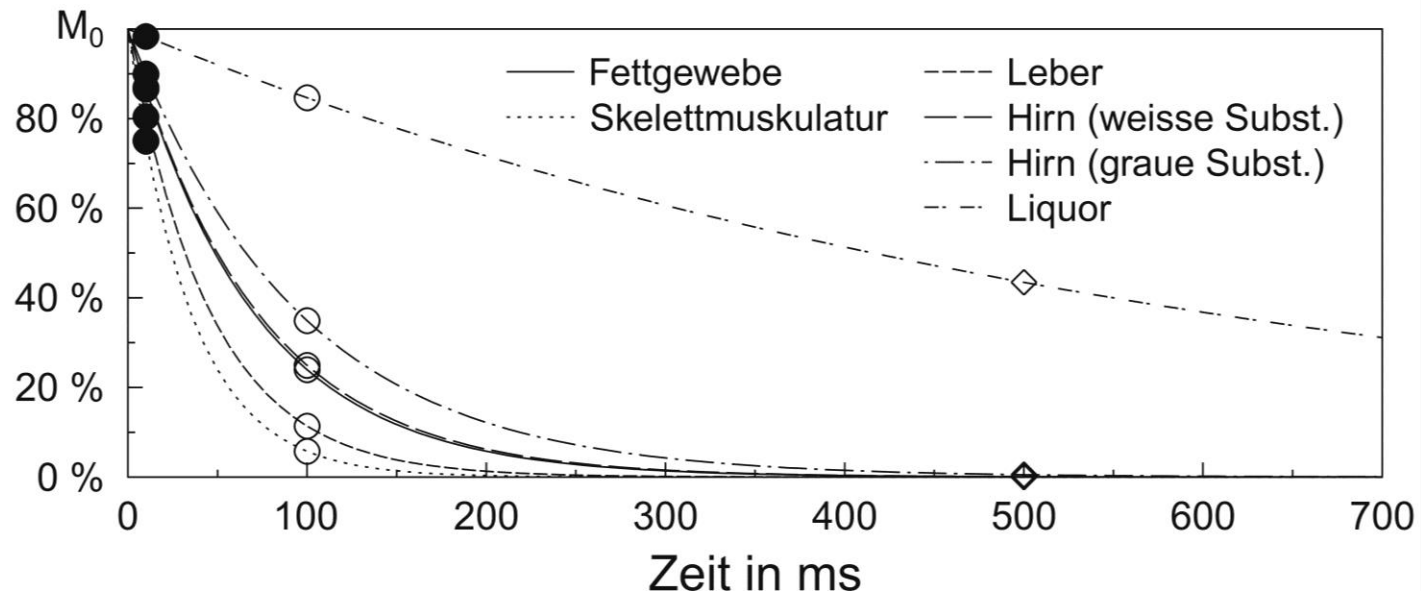
transverse
magnetization



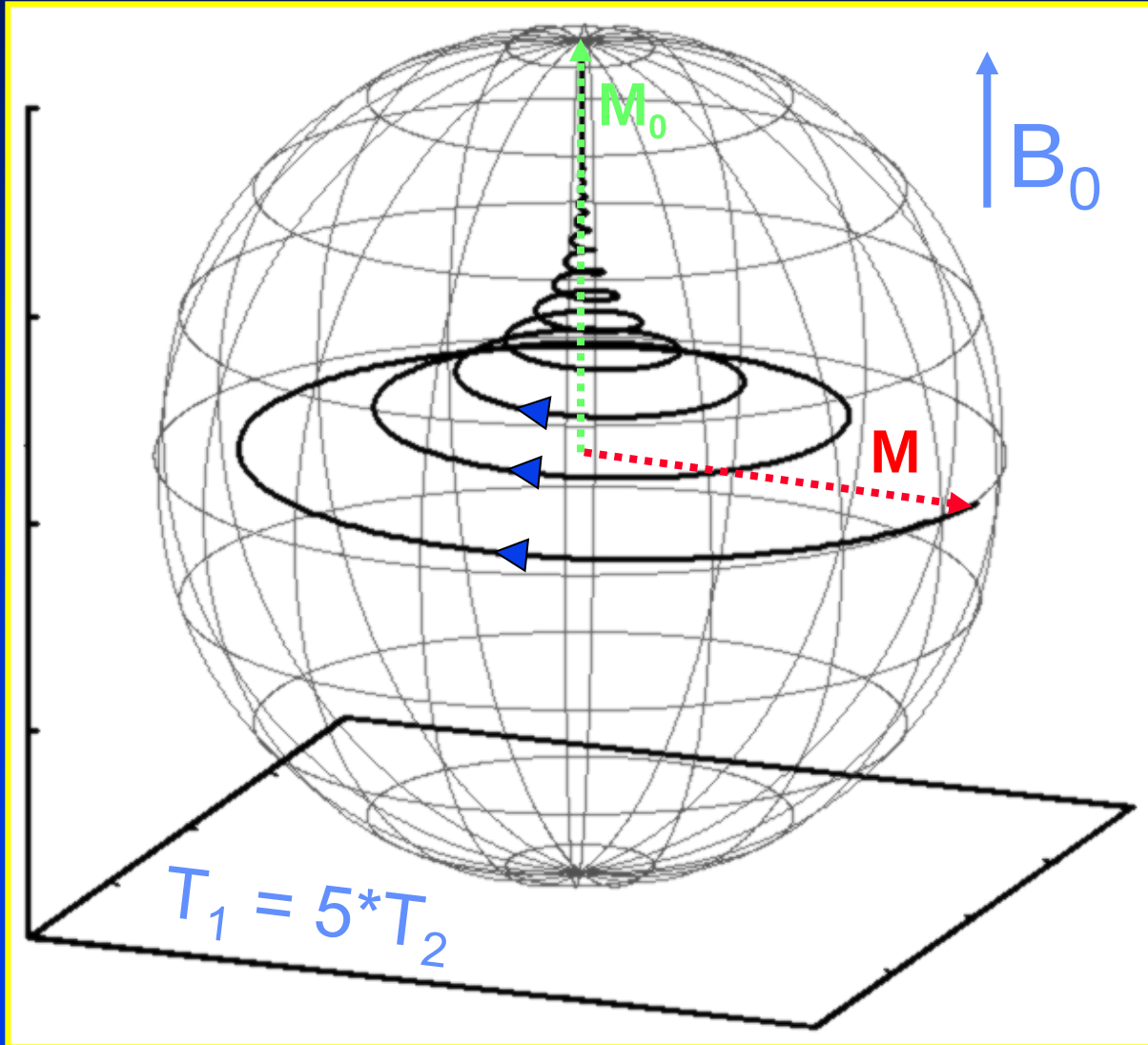
Longitudinal relaxation



Transverse relaxation

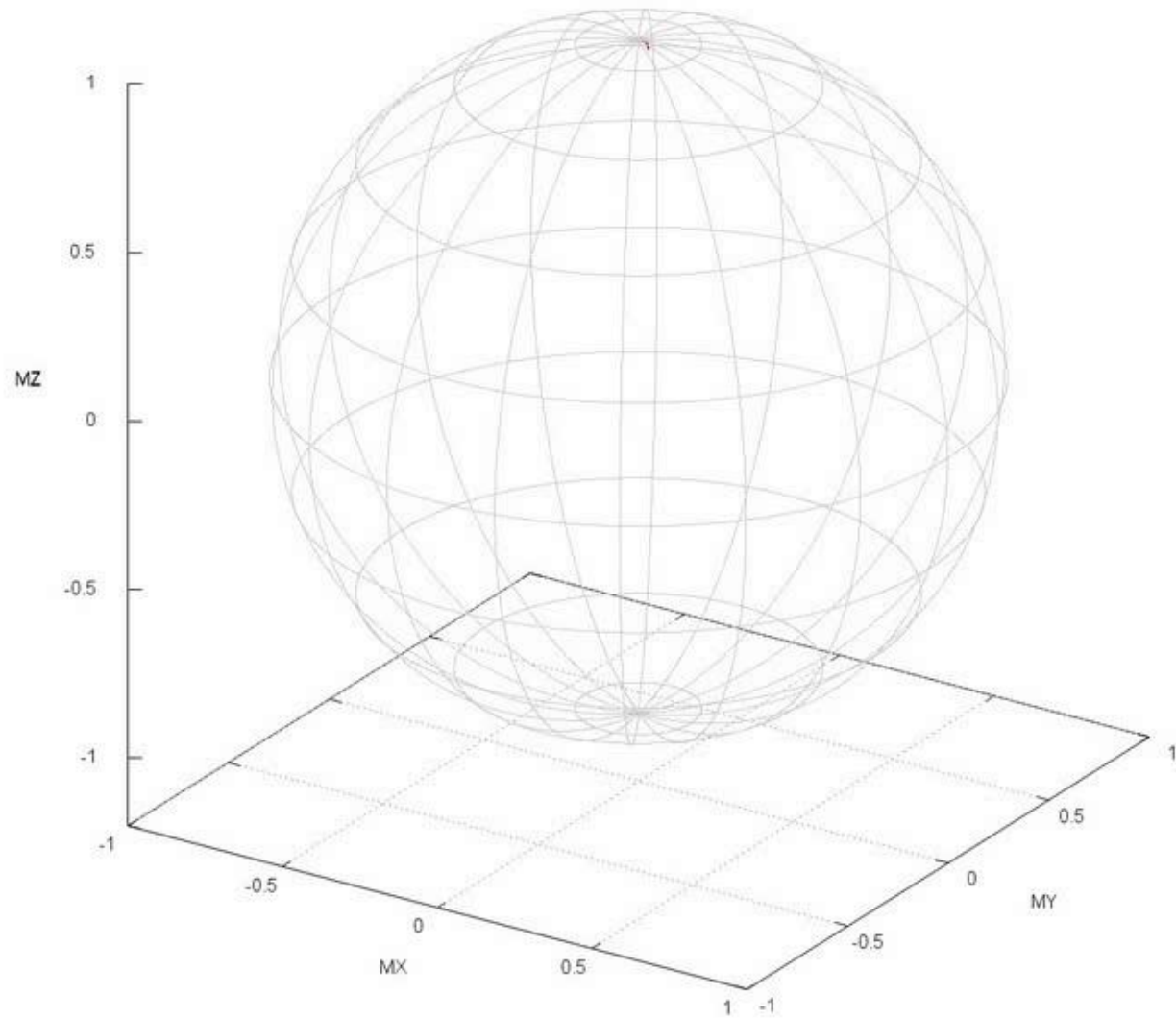


Relaxation of magnetization (following 90°-pulse)

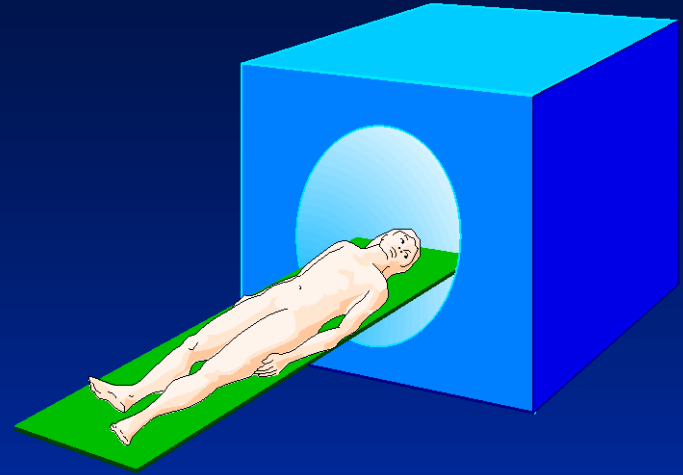


Duration of relaxation
in tissues:
several seconds

Excitation



Outline



- Basic principles of magnetic resonance
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- Recent developments in MRI

Imaging

- Total signal intensities from a large number of volume elements recorded simultaneously are presented as grey values in a matrix of picture elements
- Signals are recorded in the presence of a field gradient allowing spatial encoding in one direction
- The contrast in the images depends on the composition of the tissue and on the parameters applied by the imaging sequence

Magnetic resonance imaging

Morphology



Function



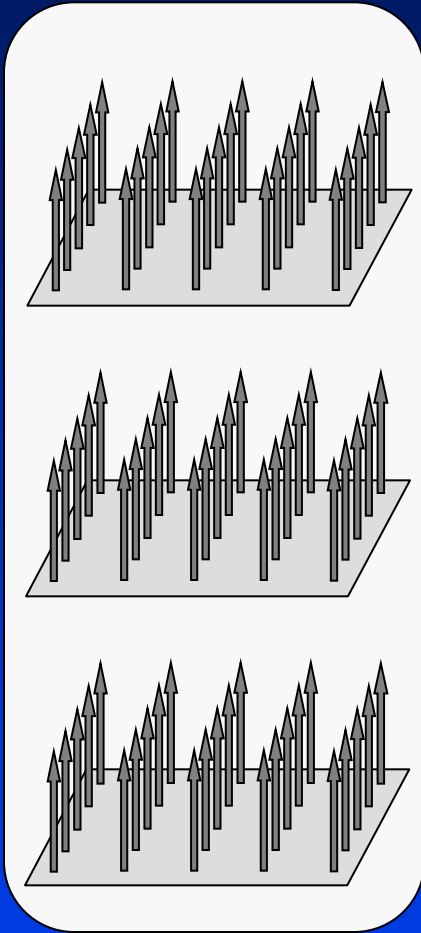
Spatial encoding in MRI

Three spatial dimensions:

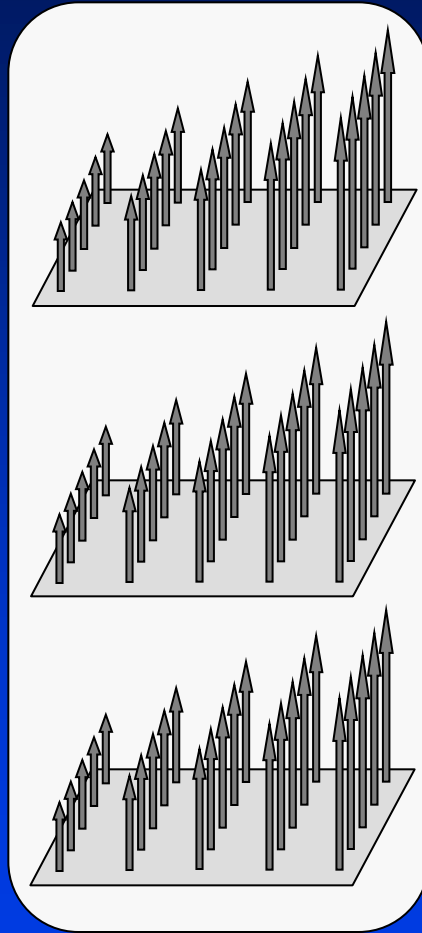
1. Slice selective excitation (z)
2. Frequency encoding of signals (x)
3. Phase encoding of signals (y)

Switchable magnetic field gradients

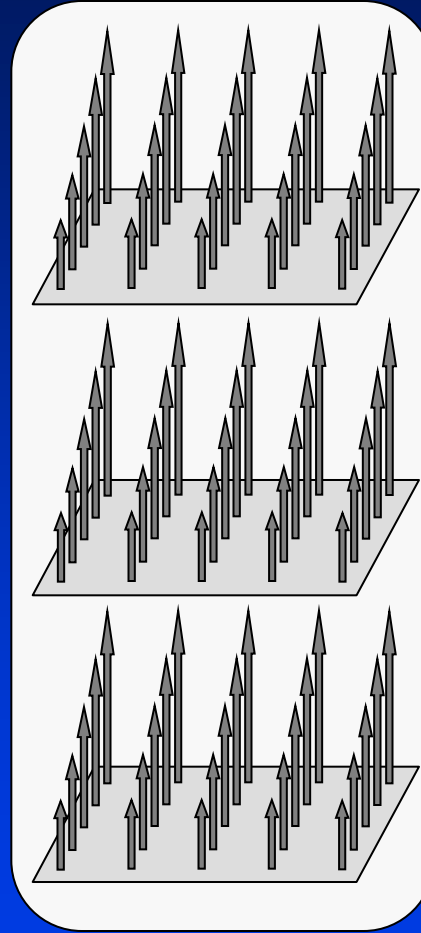
No field gradient



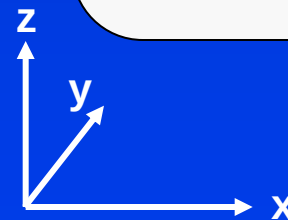
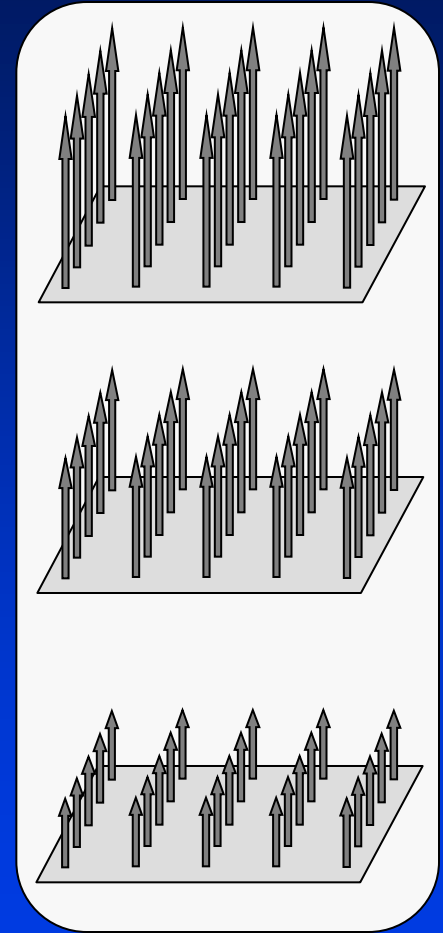
x - gradient



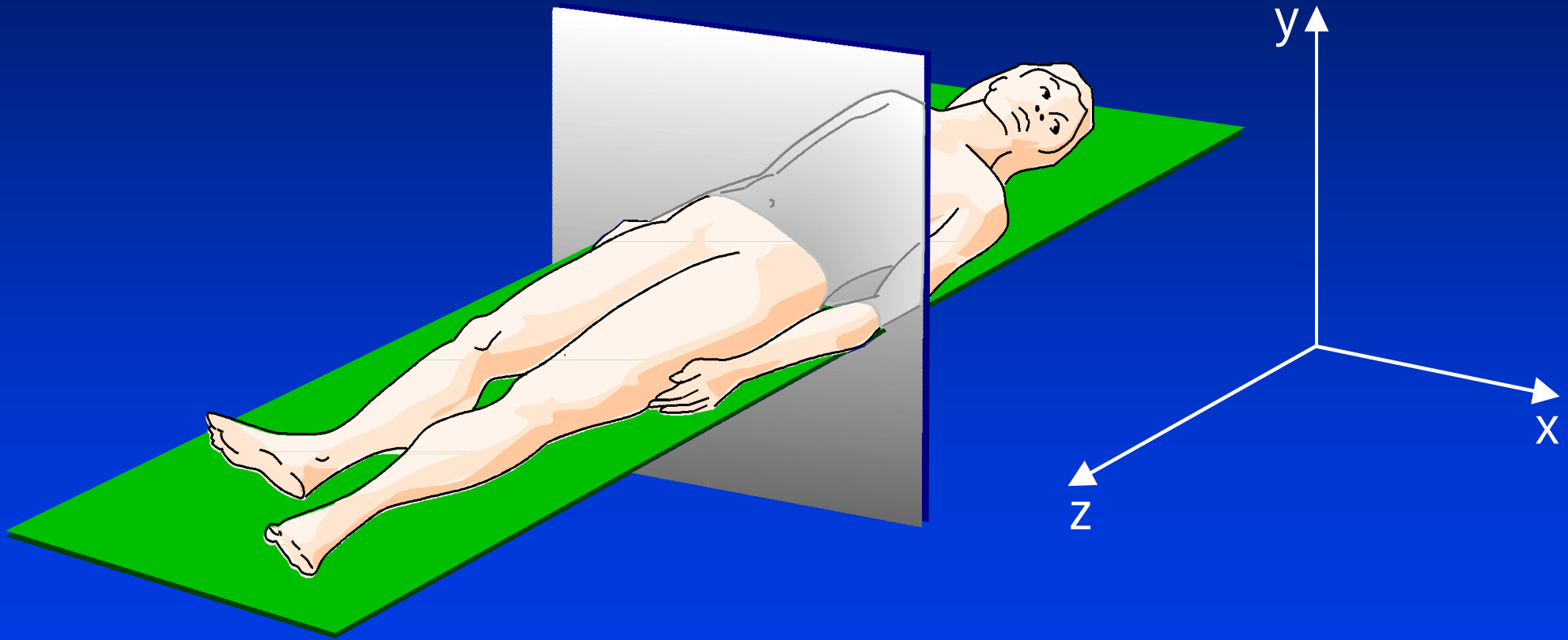
y - gradient



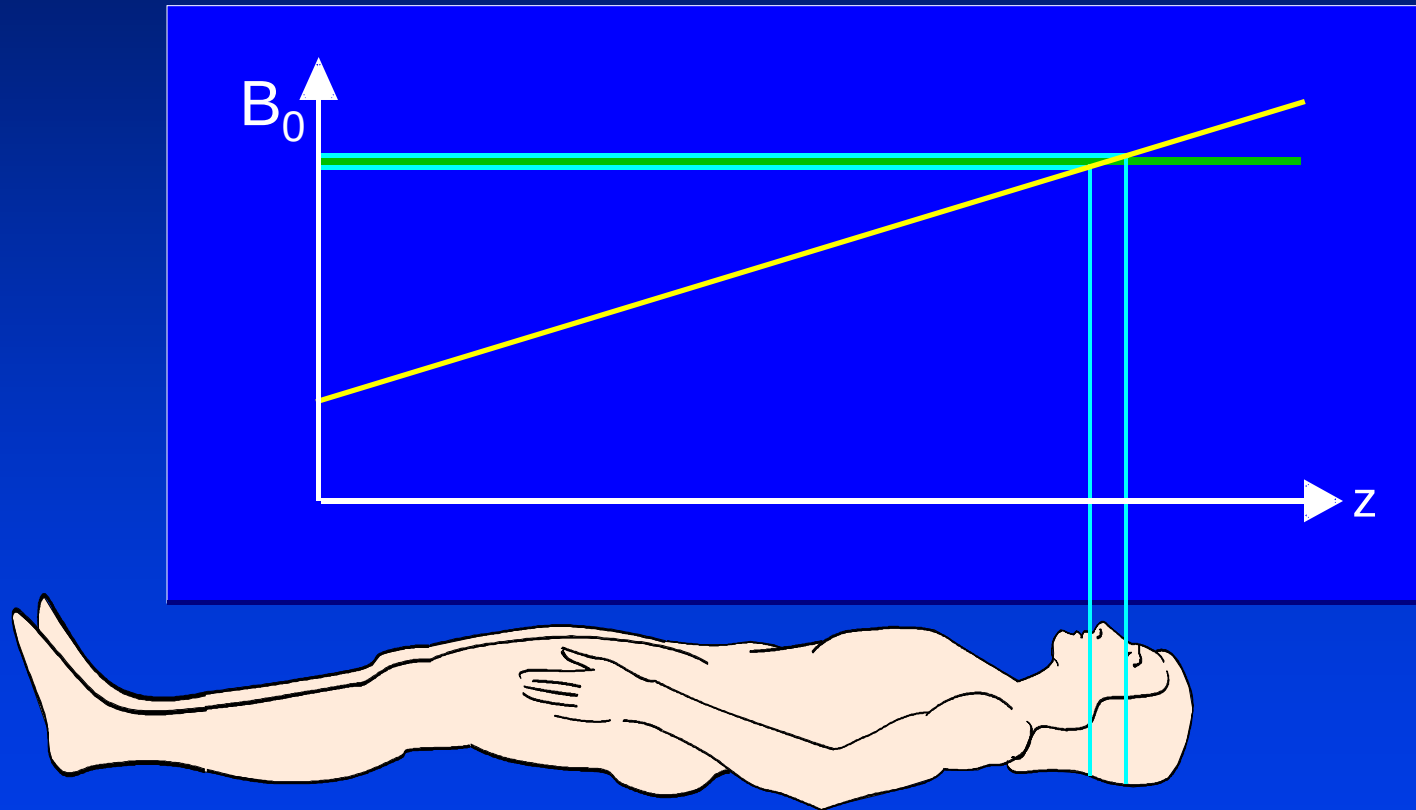
z - gradient



Slice in 3D space

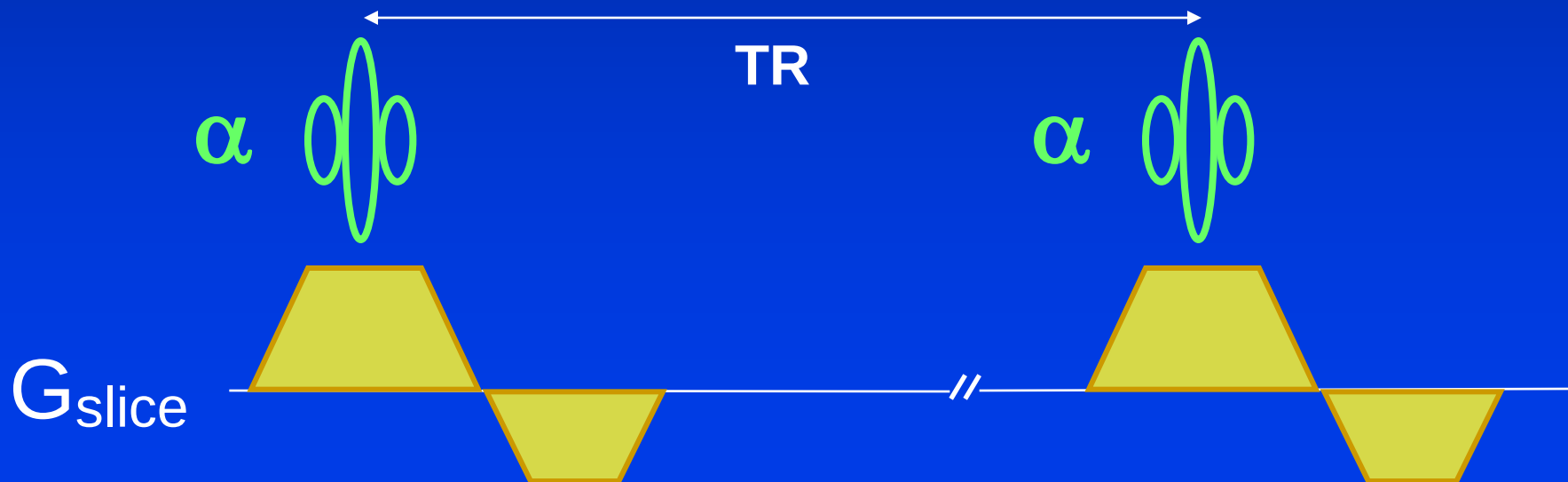


Slice selective excitation

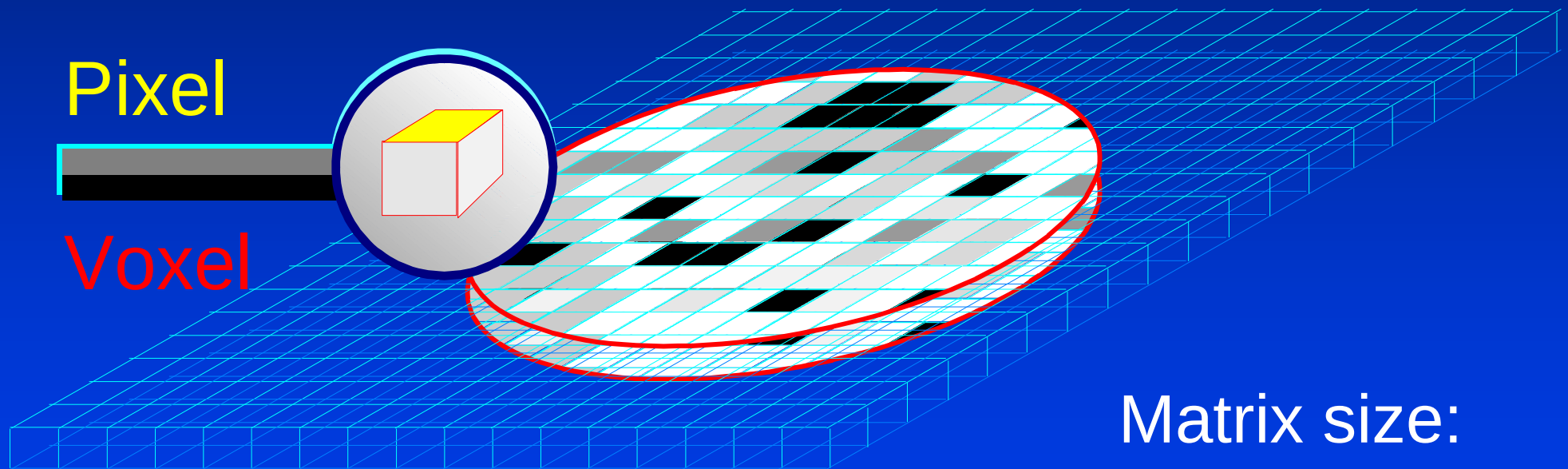


Principle: Frequency selective RF-pulse
+
Magnetic field gradient

Representation in sequence plot:



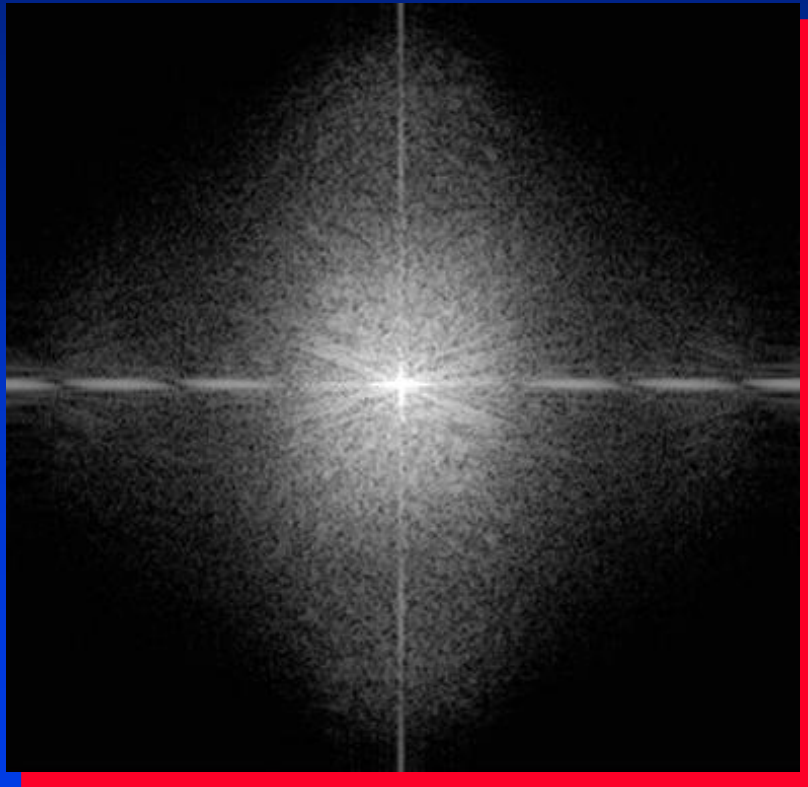
Spatial encoding in-plane



Matrix size:
eg, 192 x 256

A matrix of raw data must be recorded
(each point is the induced voltage in the
receiver coil for a specific time point)

Final image is calculated using 2D-Fourier transform



Raw data (k-space)

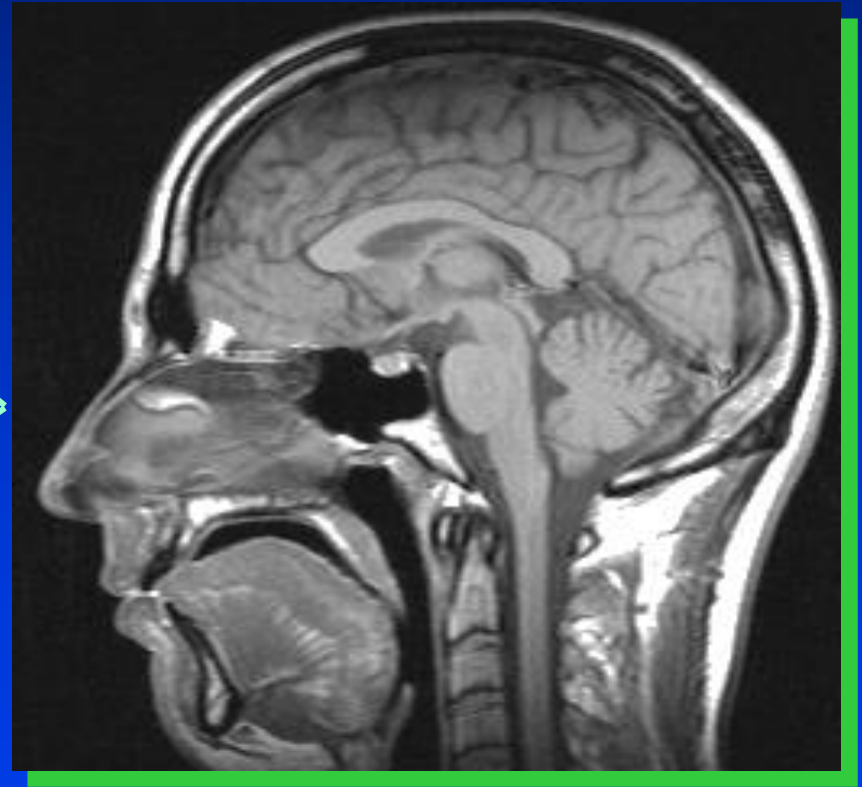
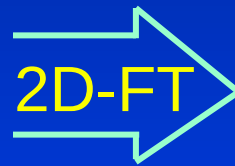
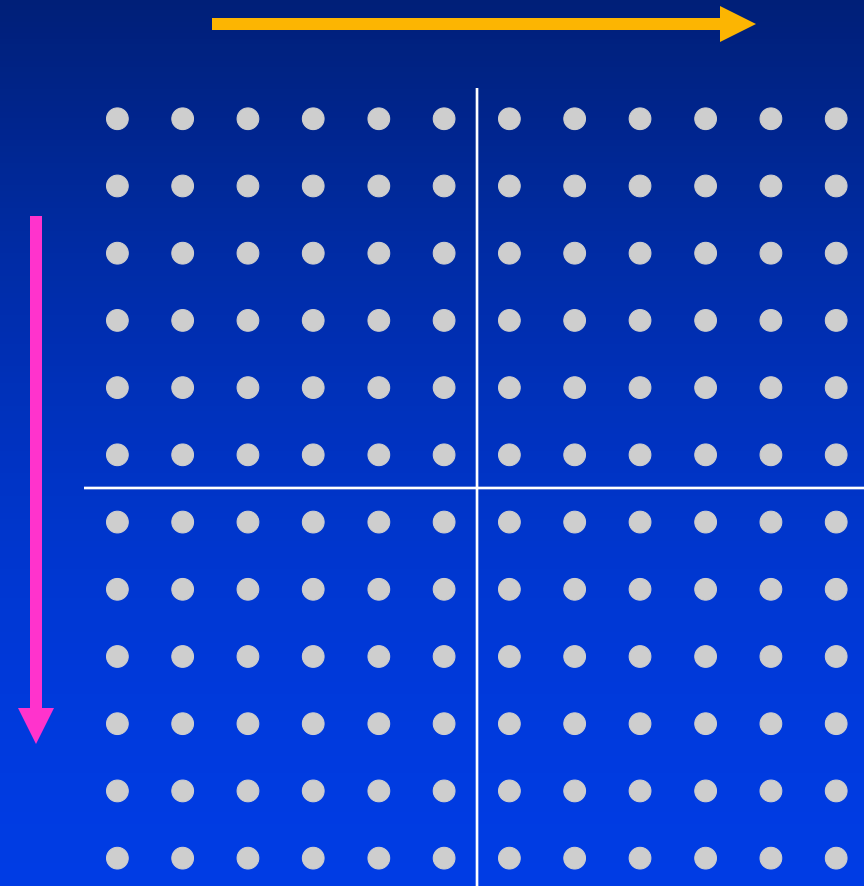


Image data

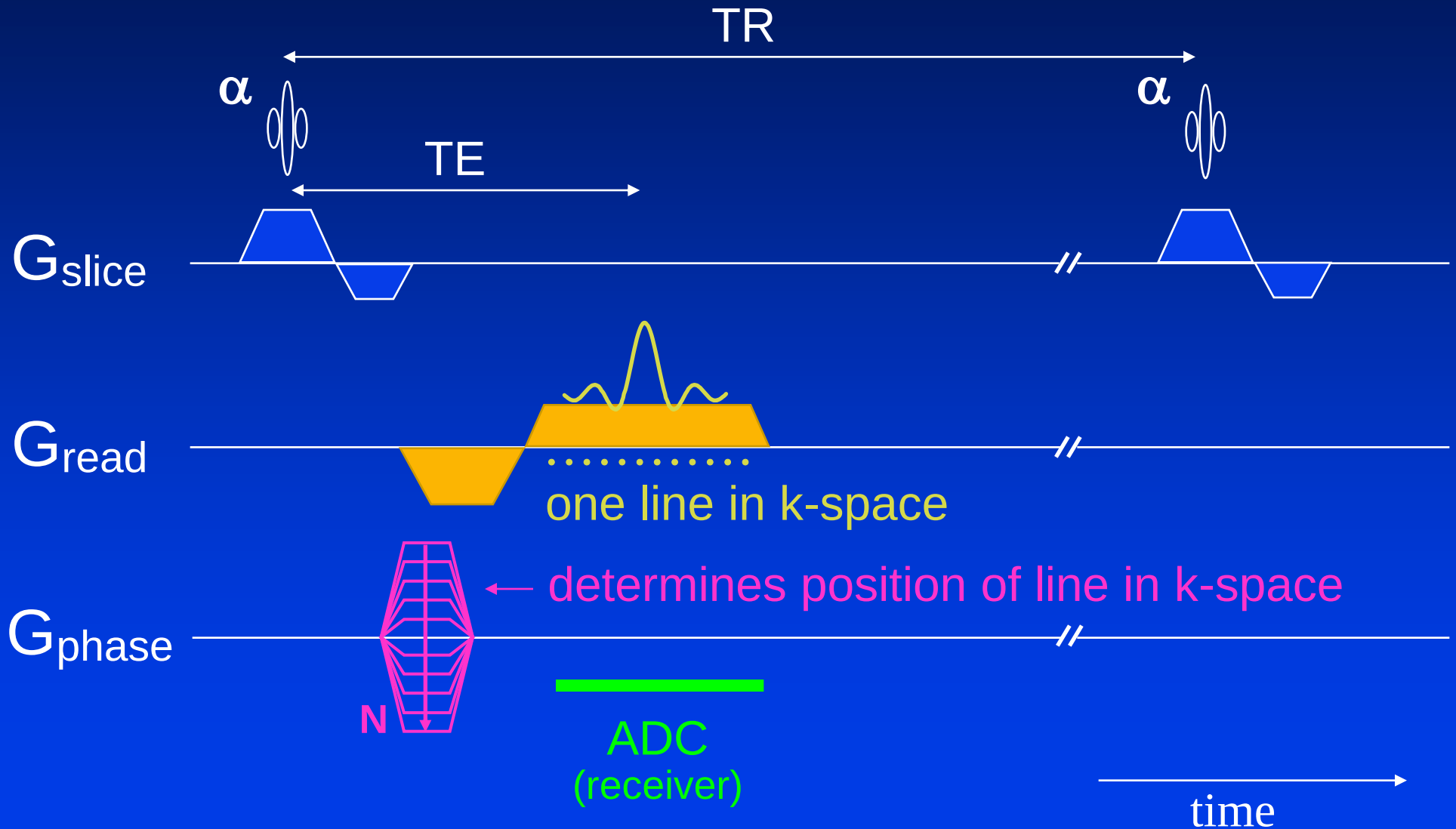
Raw data
acquisition:

1. Frequency
encoding (read)
2. Phase
encoding (phase)

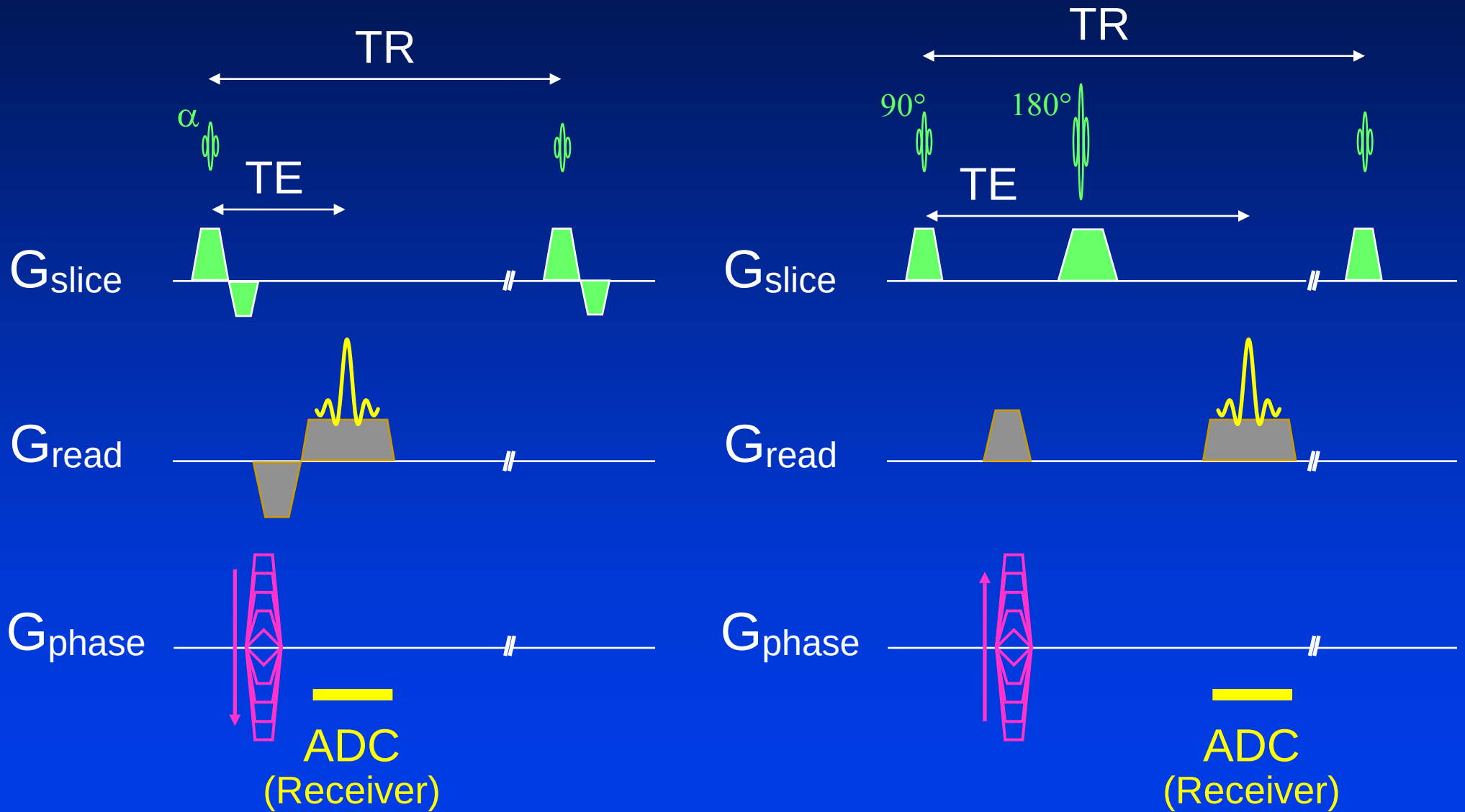
Positioning of
data in k-space



Simple gradientecho sequence

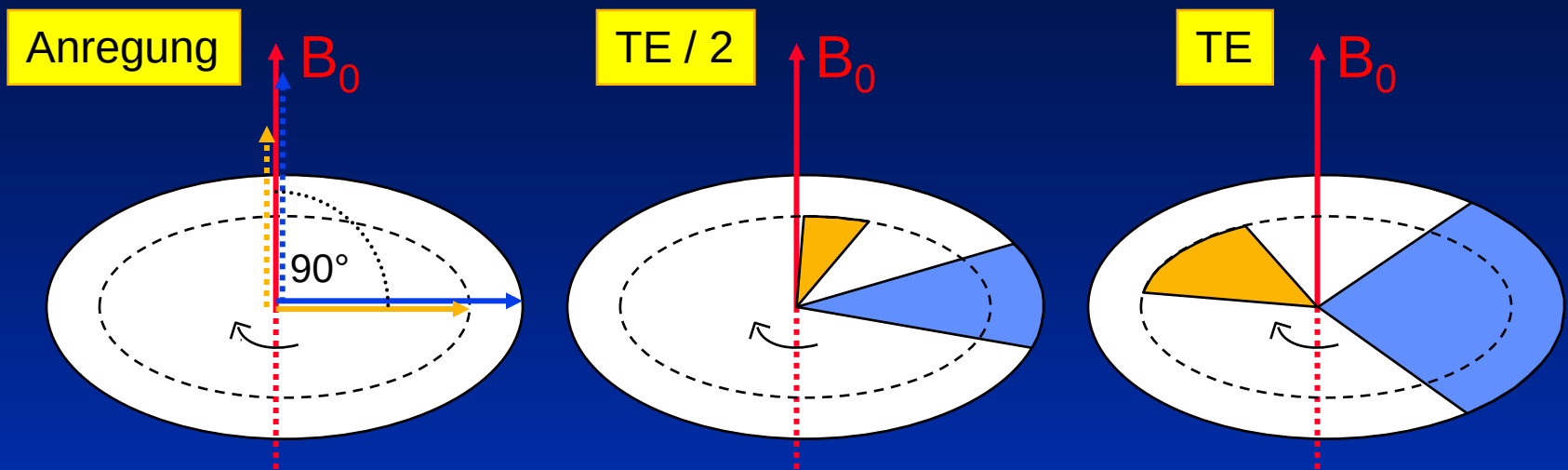


Gradient echo and spinecho sequence

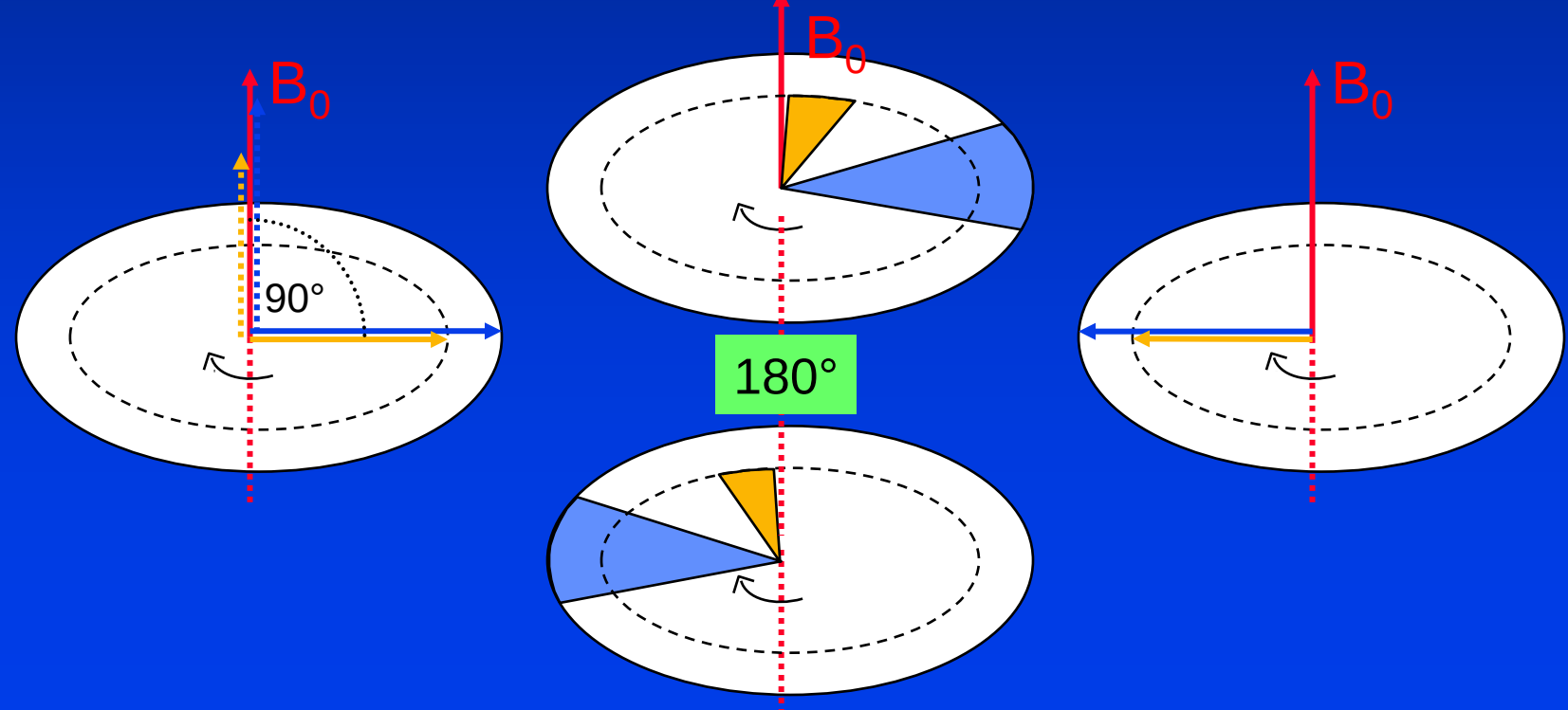


Dephasing within picture elements for GRE- und SE-sequences

GRE

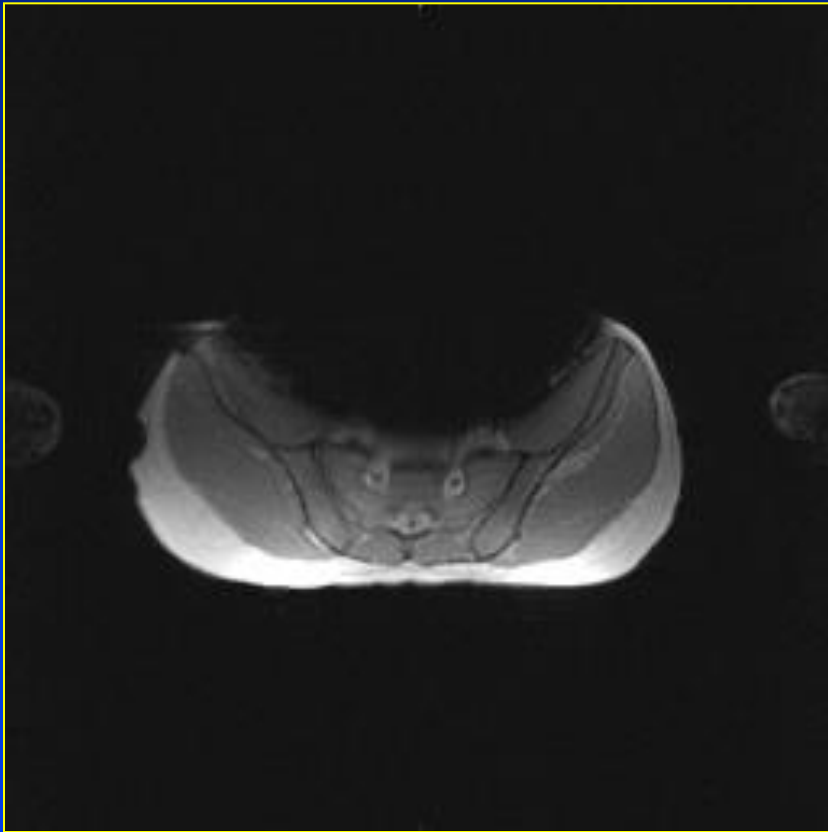


SE

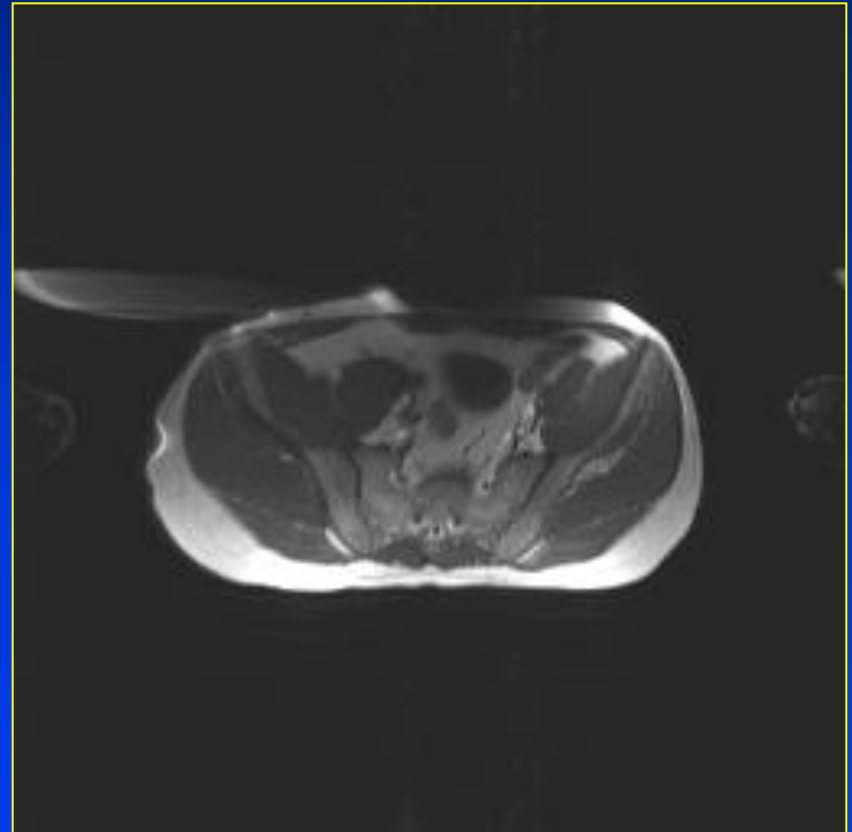


Artifacts arising from a metallic trouser button

gradient echo sequence



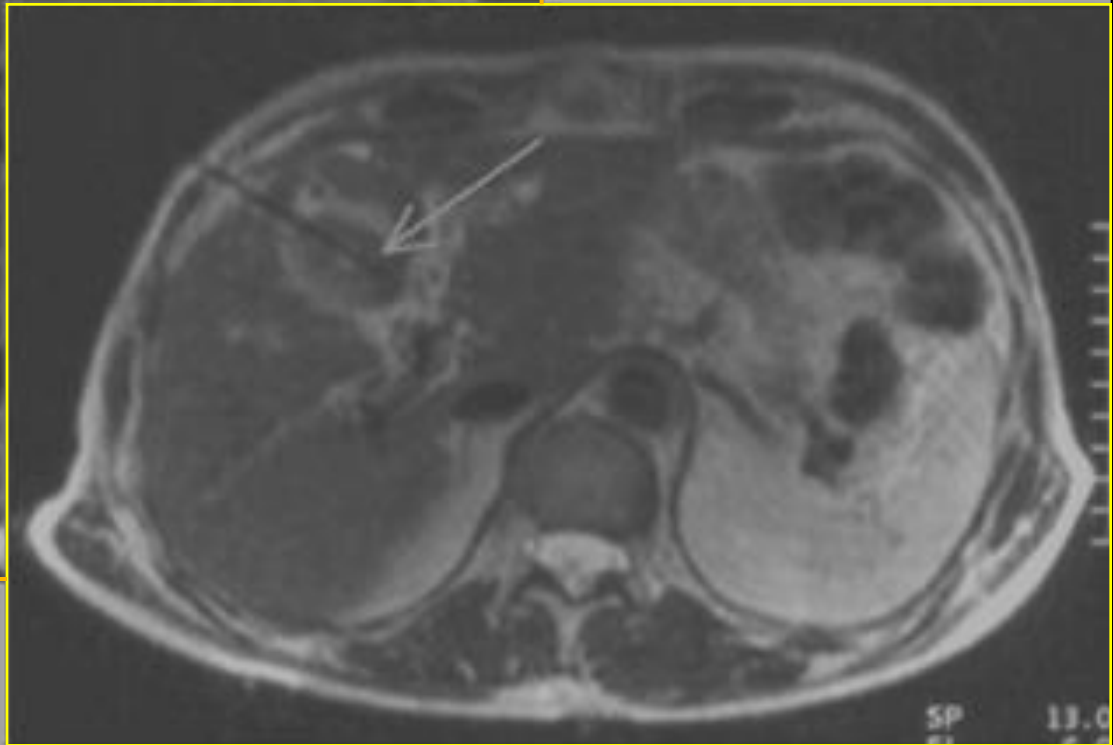
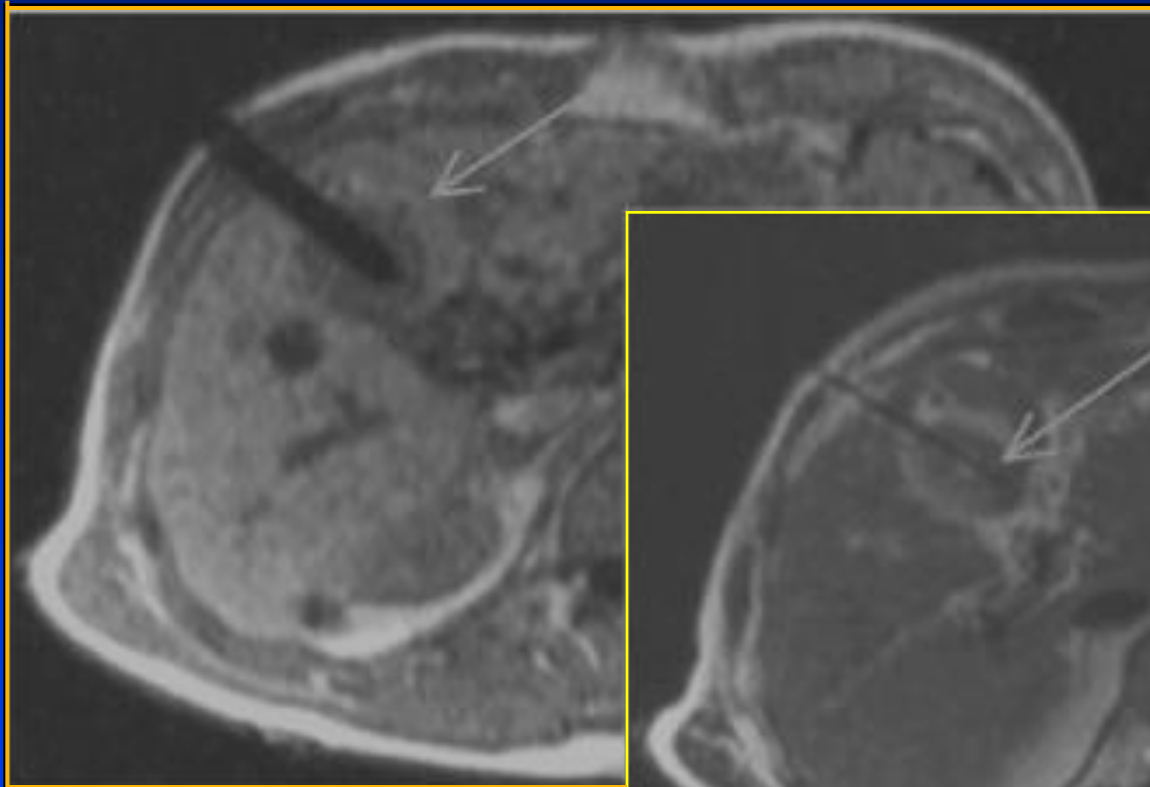
spinecho sequence



Artifacts caused by an MR-compatible RF applicator for local thermotherapy

gradient echo sequence

spinecho sequence

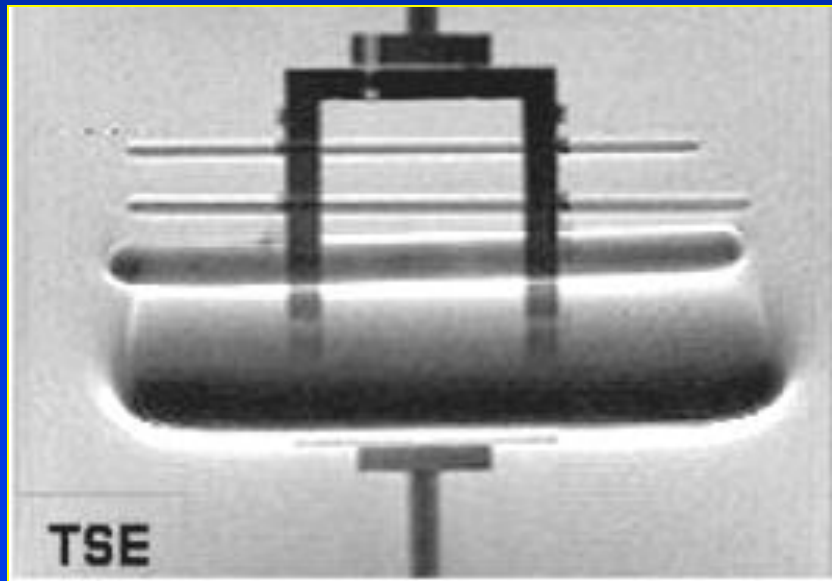


Artifacts of paramagnetic wires ⇒ susceptibility effects

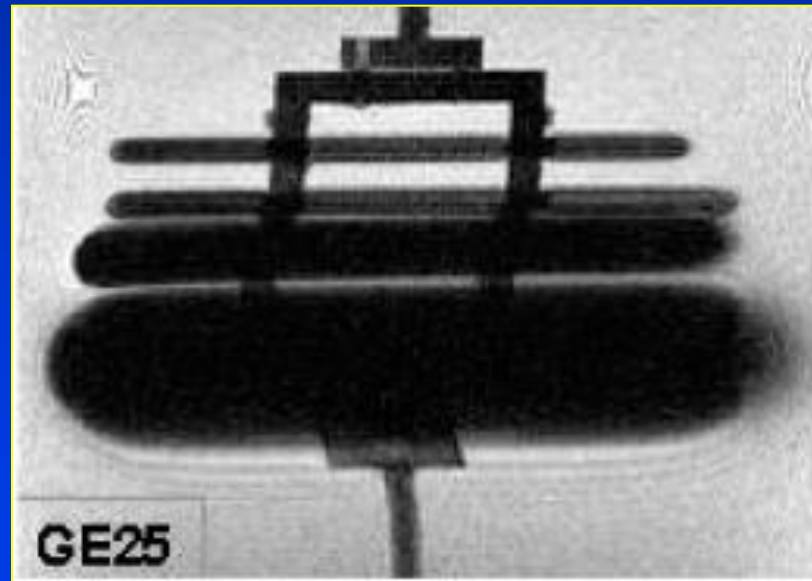
(caused by magnetic field inhomogeneities in the vicinity of metals)

all metallic wires had 1 mm diameter

Fast spinecho sequence



Gradient echo sequence



Material

- nitinol
- titanium
- phynox
- stainless steel

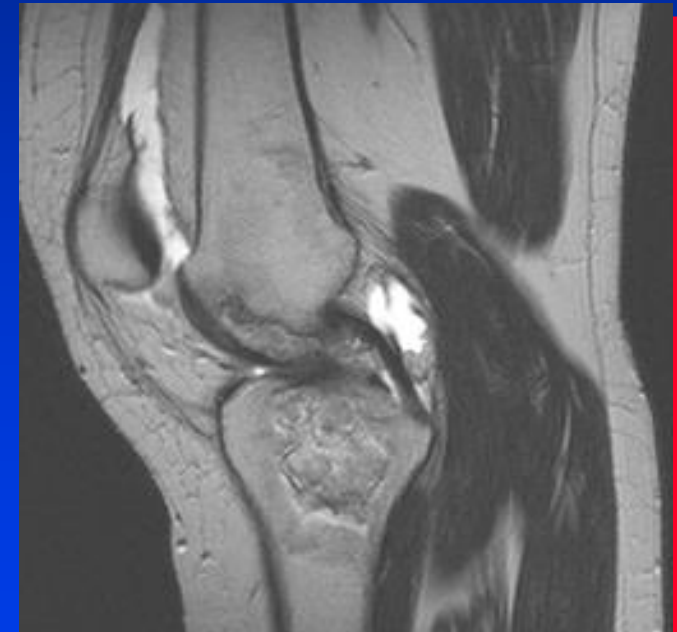
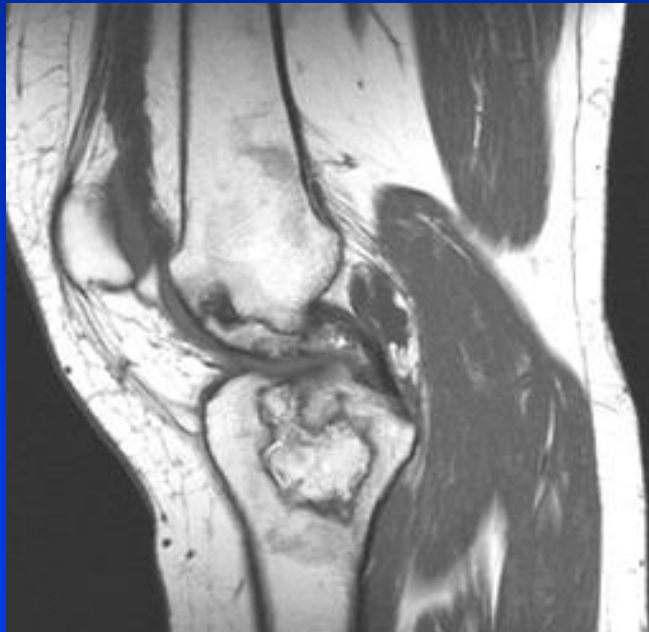
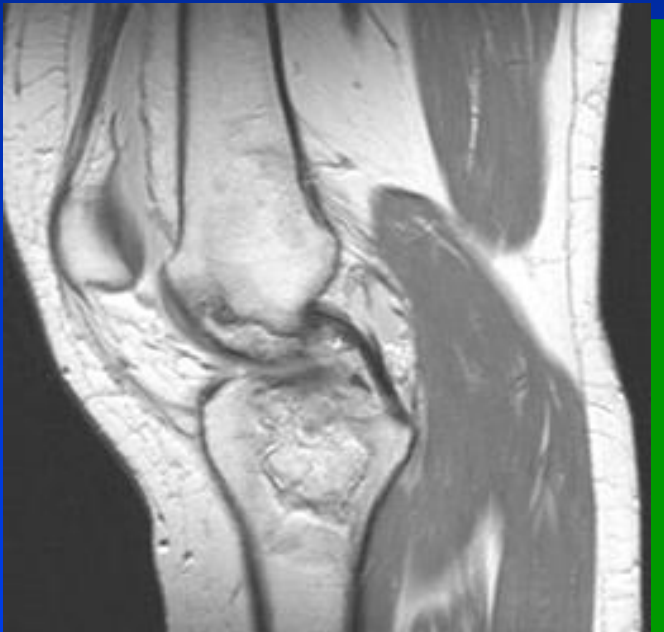
Contrasts in standard clinical MRI

Proton density
weighting

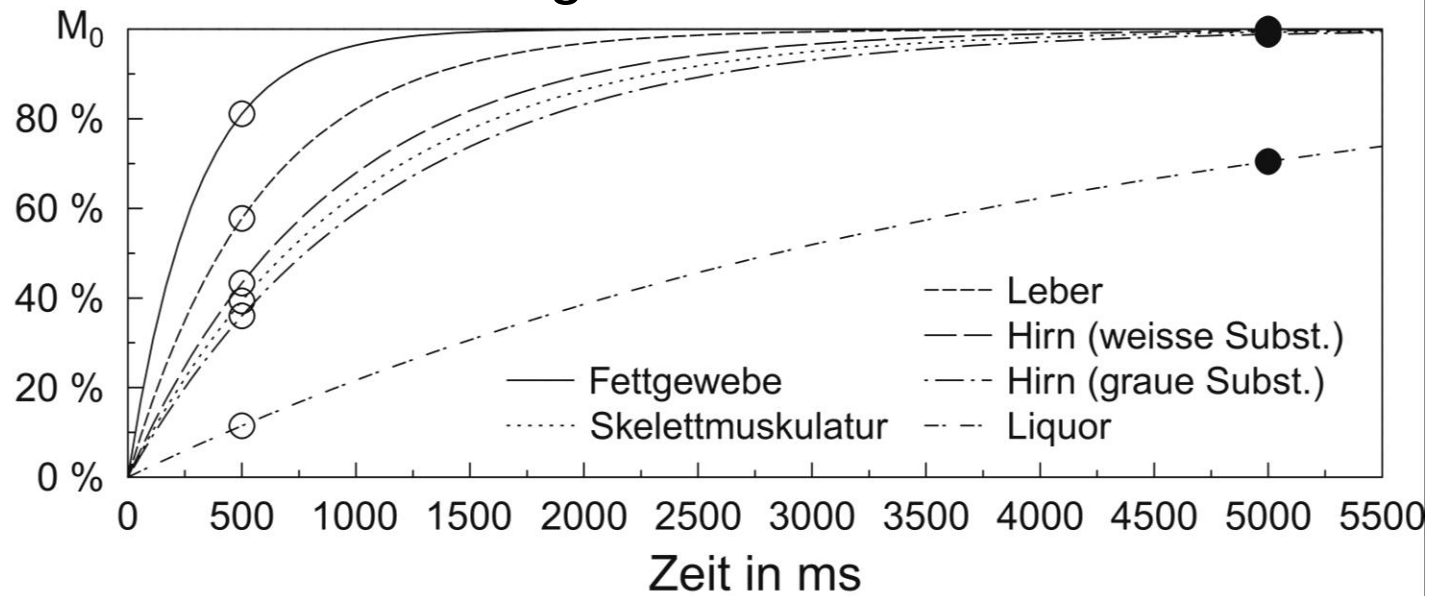
Relaxation weighting

T1-weighting

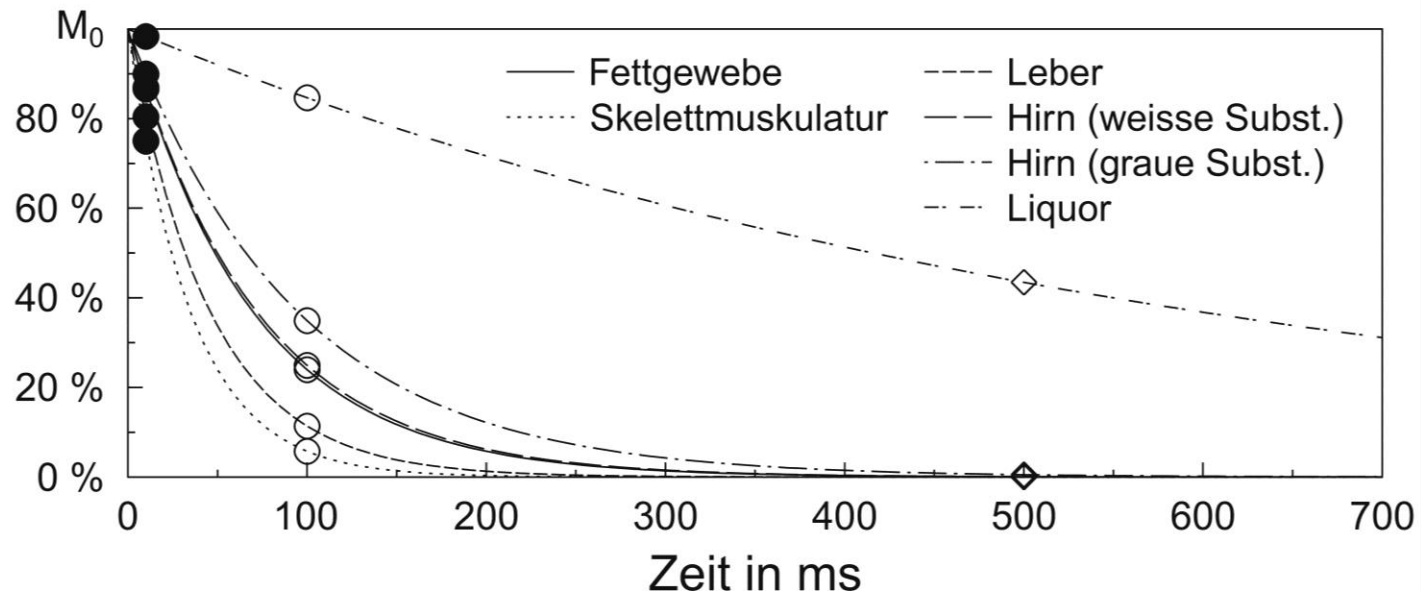
T2-weighting



Longitudinal relaxation

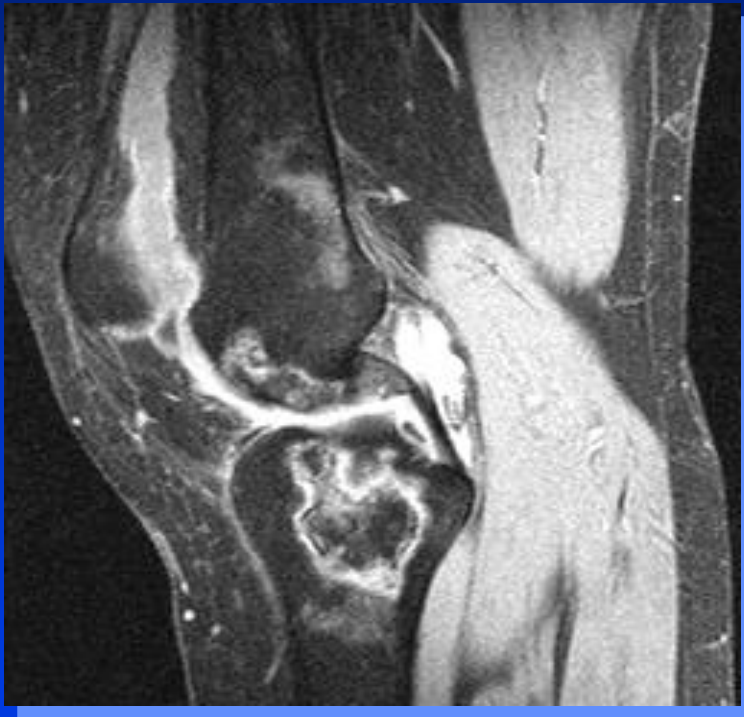


Transverse relaxation

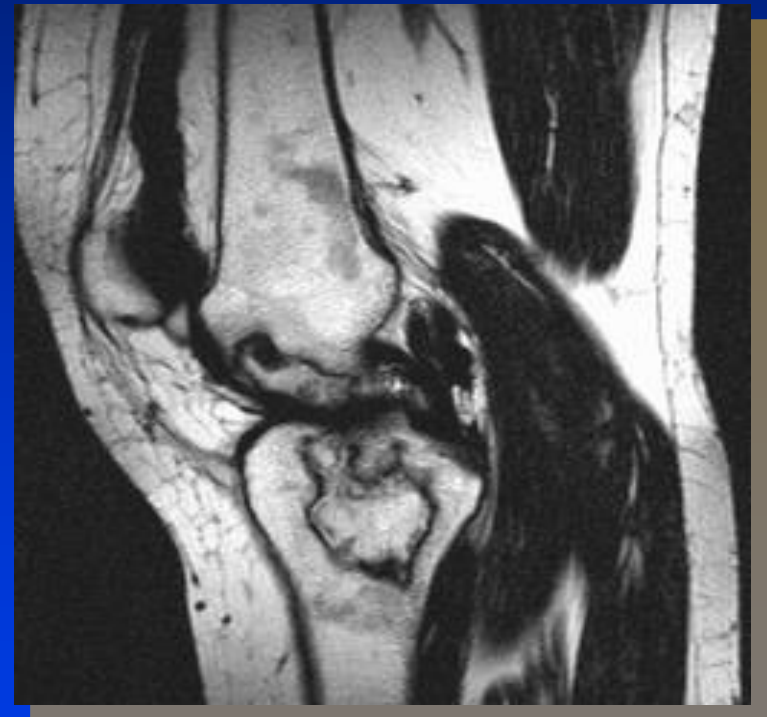


Chemical Shift MRI

water selective

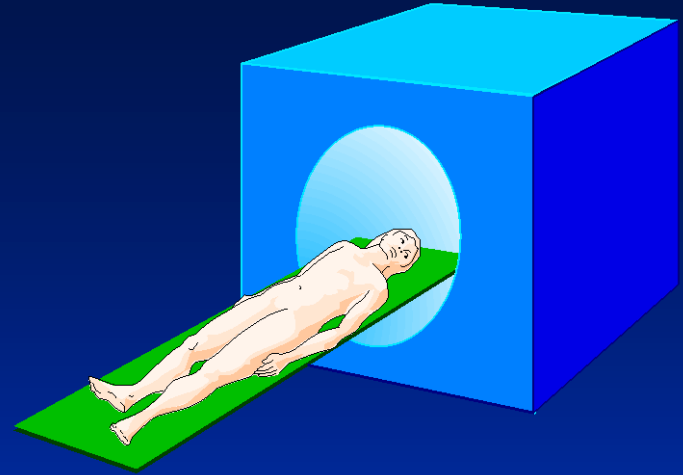


fat selective



Shimming is required!

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Spectroscopy

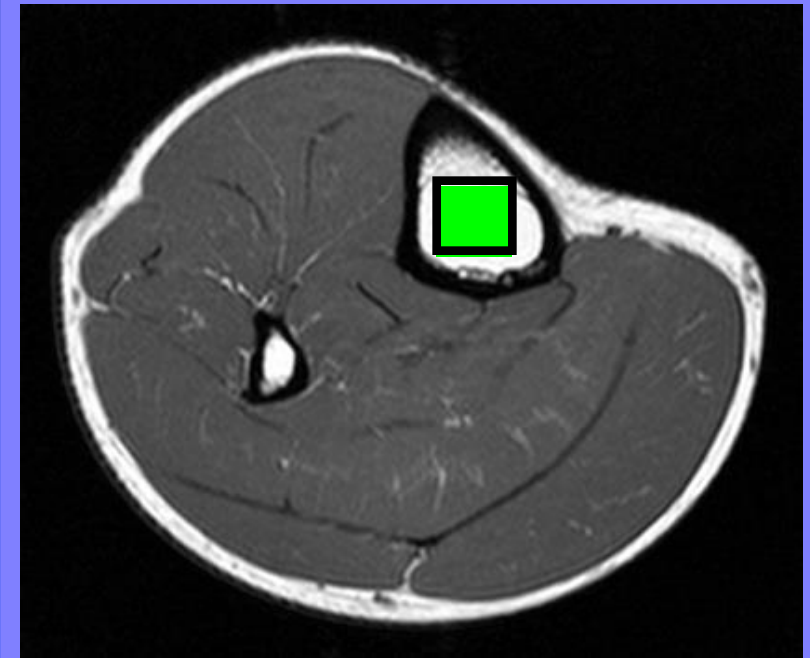
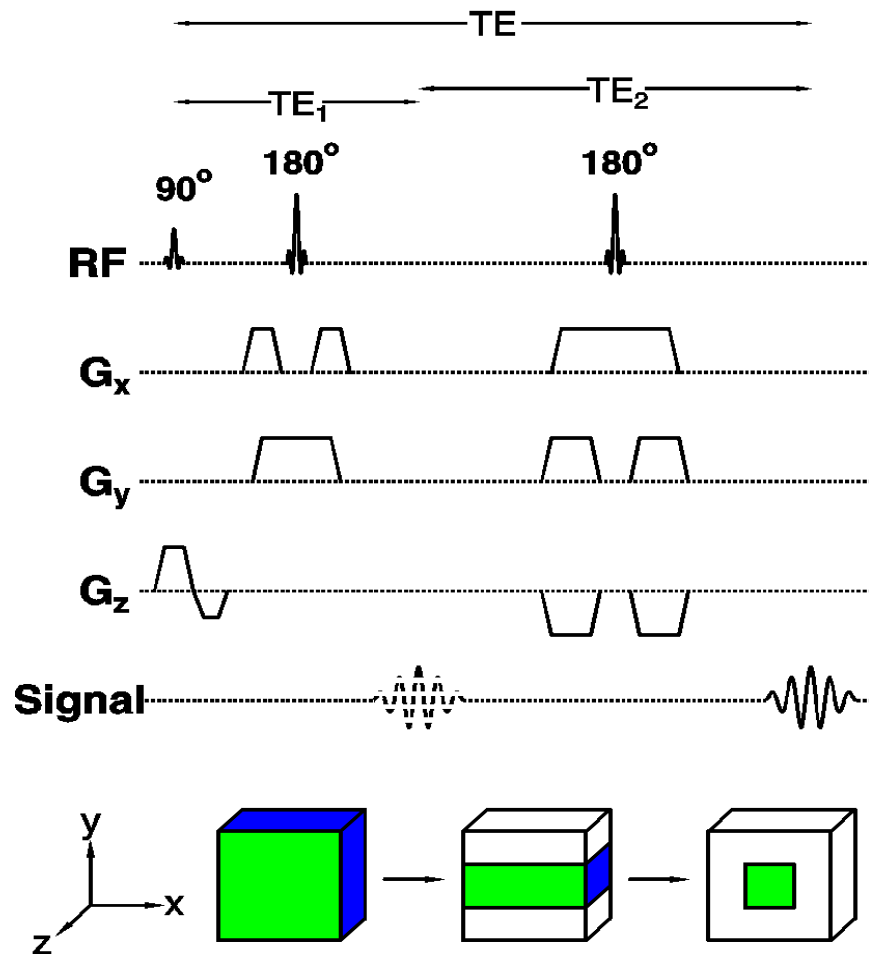
- Signal intensity is drawn as function of signal frequency
- The signal is recorded in the presence of a (hopefully) homogeneous magnetic field

In vivo applications usually require volume selective recording of signals. Most techniques work with slice selective excitation and echo formation.

Shimming is required!

Volume selective ^1H MR-Spectroscopy

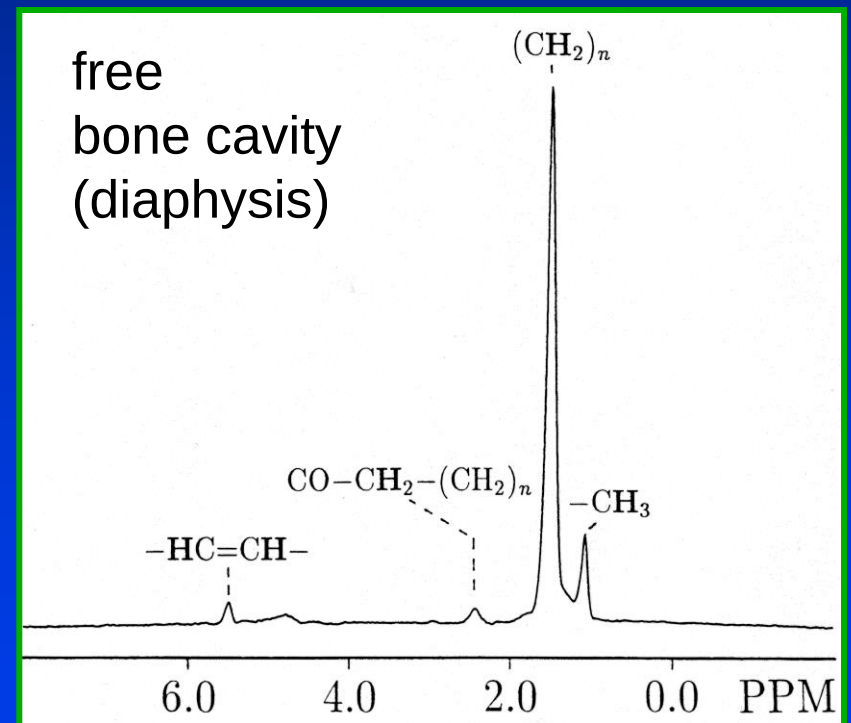
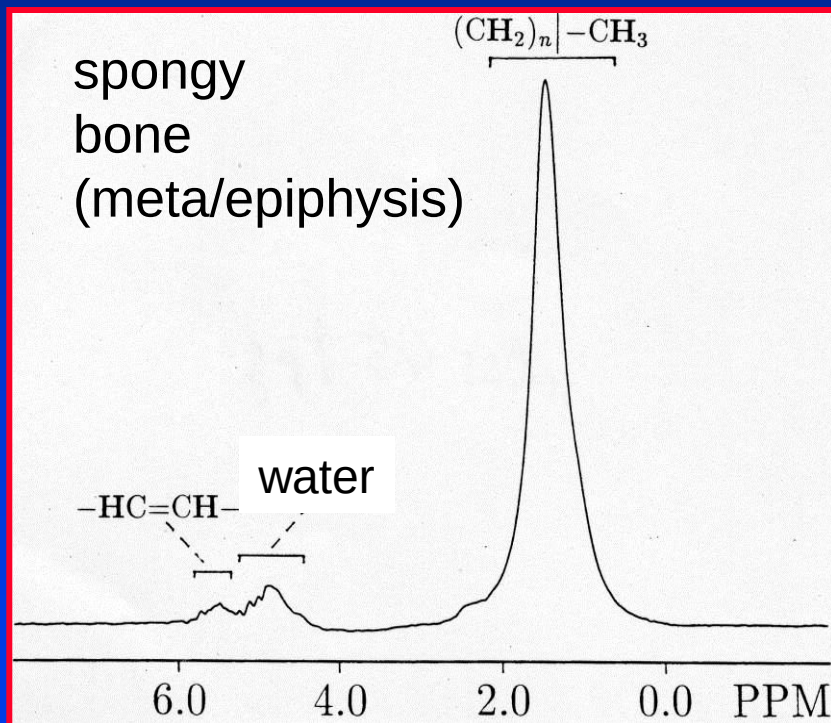
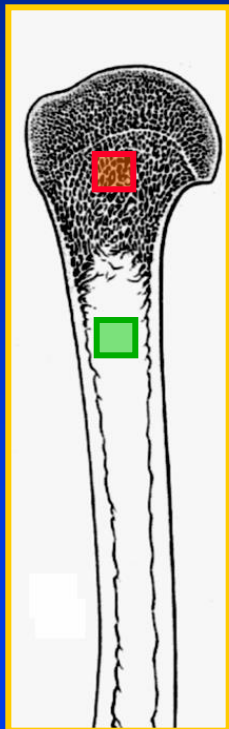
Selection of a cubic volume using three slice selective RF excitation/refocusing pulses



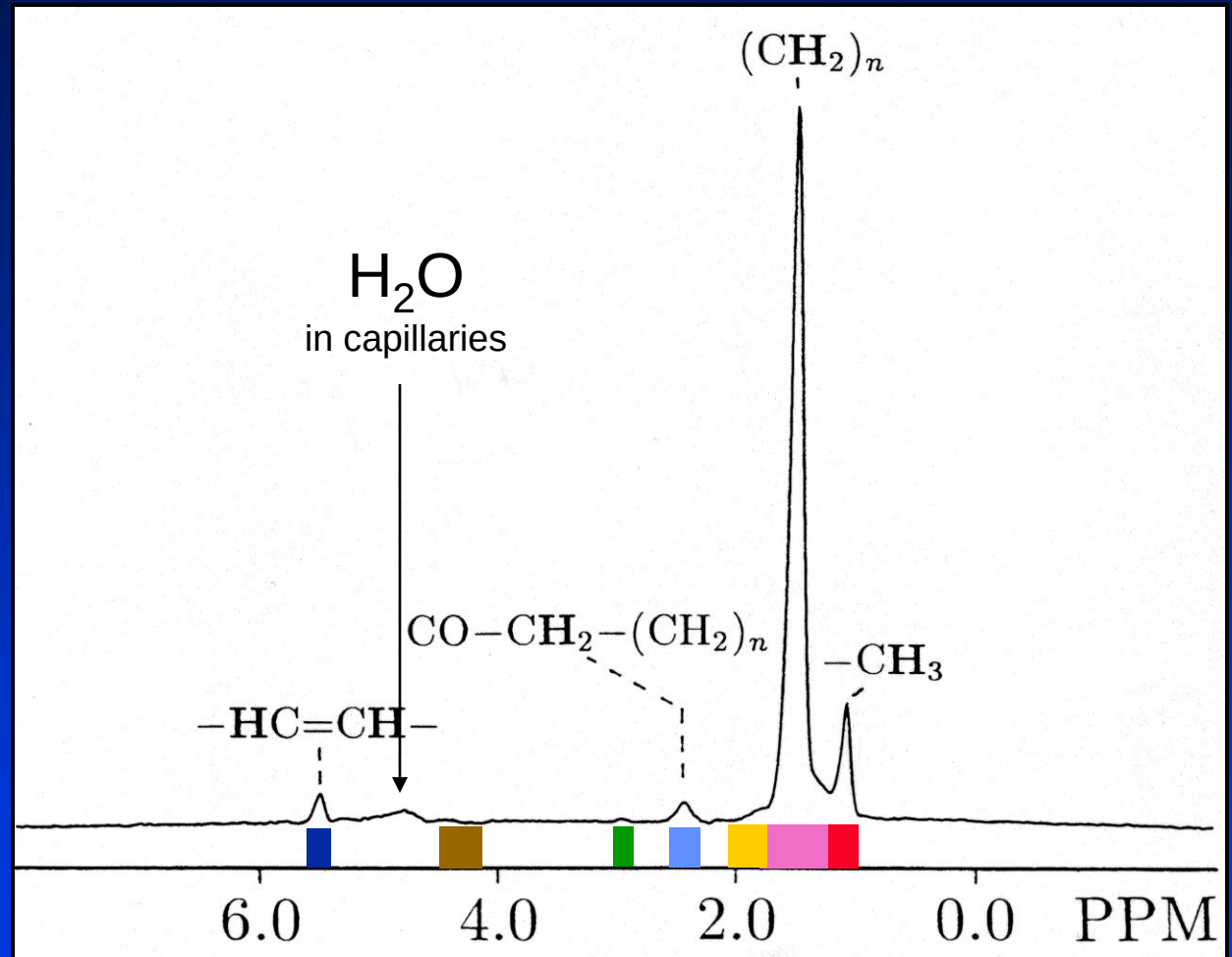
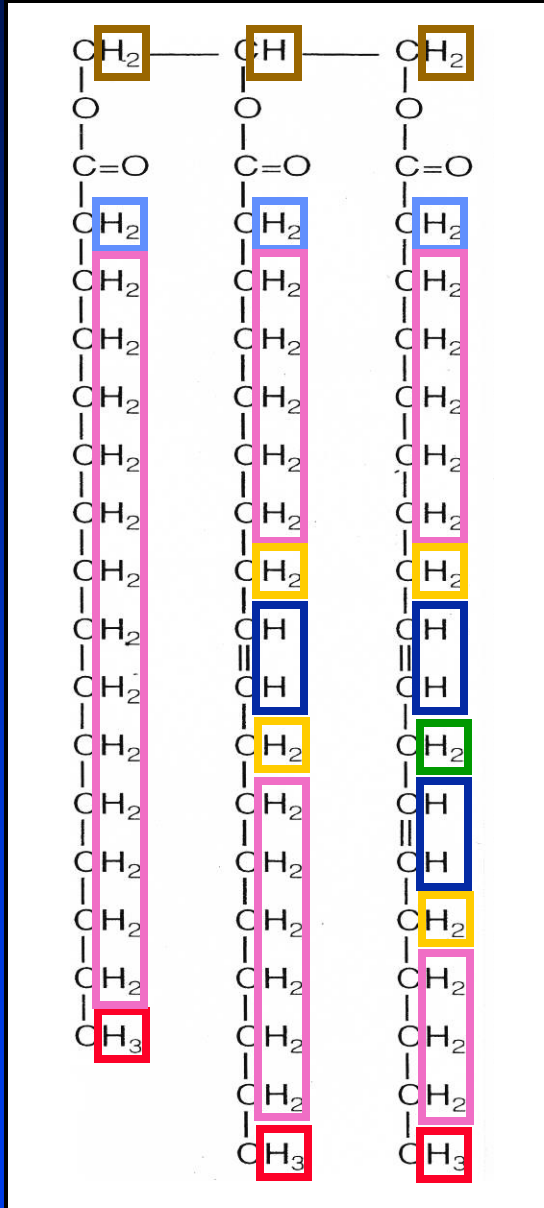
Examples of ^1H spectra from yellow bone marrow in the femur

broad lines
 $\Rightarrow$ inhomogeneous B-field

narrow lines
 $\Rightarrow$ homogeneous B-field



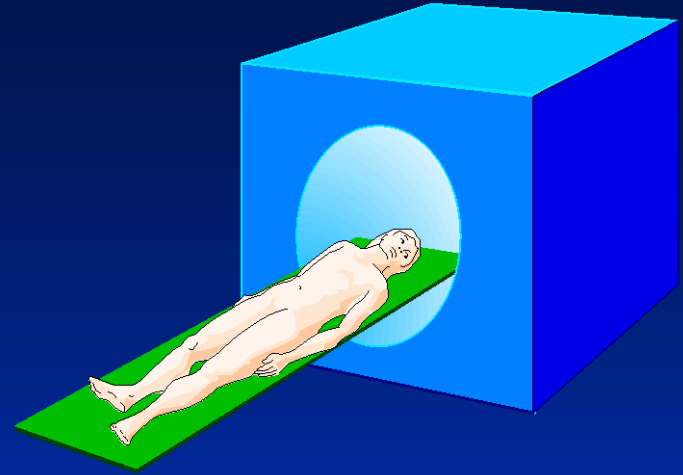
Chemical shift effects in molecules



^1H Spectrum from human bone marrow

Triglyceride

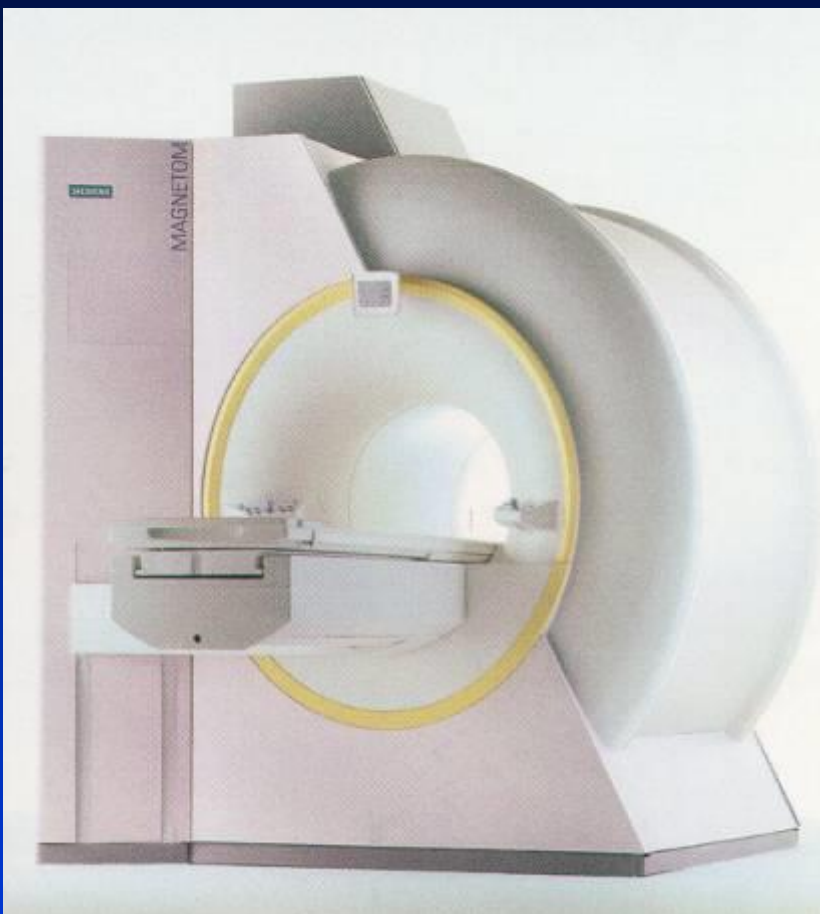
Outline



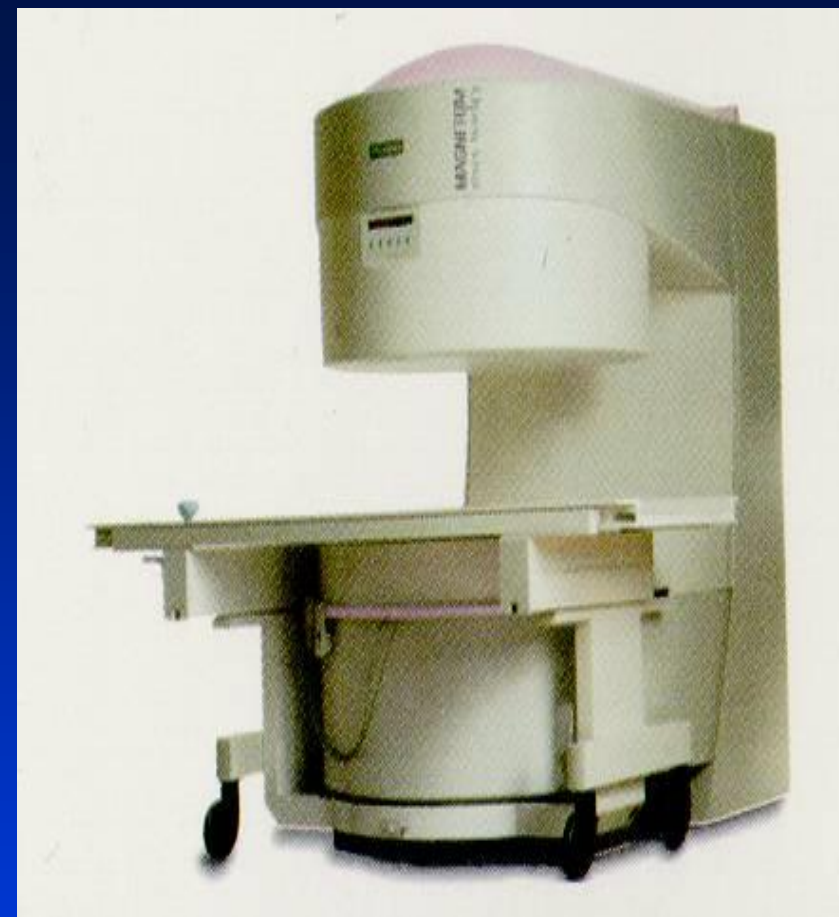
- Basic principles of magnetic resonance
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Hardware components

- Magnet
 - generates the static homogeneous magnetic field B_0
 - field strength 0.2 to 3.0 (7.0) Tesla for clinical systems
- Gradient system (+ Shim coils)
 - rapidly switchable additional magnetic fields for slice selection and spatial encoding of signals superimposed on static field
 - max. amplitude: approx 50 mT/m with 0.2 ms rise time
- RF transmitter
 - RF-transmitter for generation of a spatially homogeneous RF field of spin excitation operating at the Larmor frequency of ^1H nuclei
 - 8.5 MHz (0.2 T) to 128 MHz (3.0 T) with power up to 30 kW !!
- RF receiver (so-called „coils“)
 - highly sensitive resonance circuit with a geometric configuration adapted to the body part of interest



1.5 Tesla,
closed-bore,
superconducting
magnet

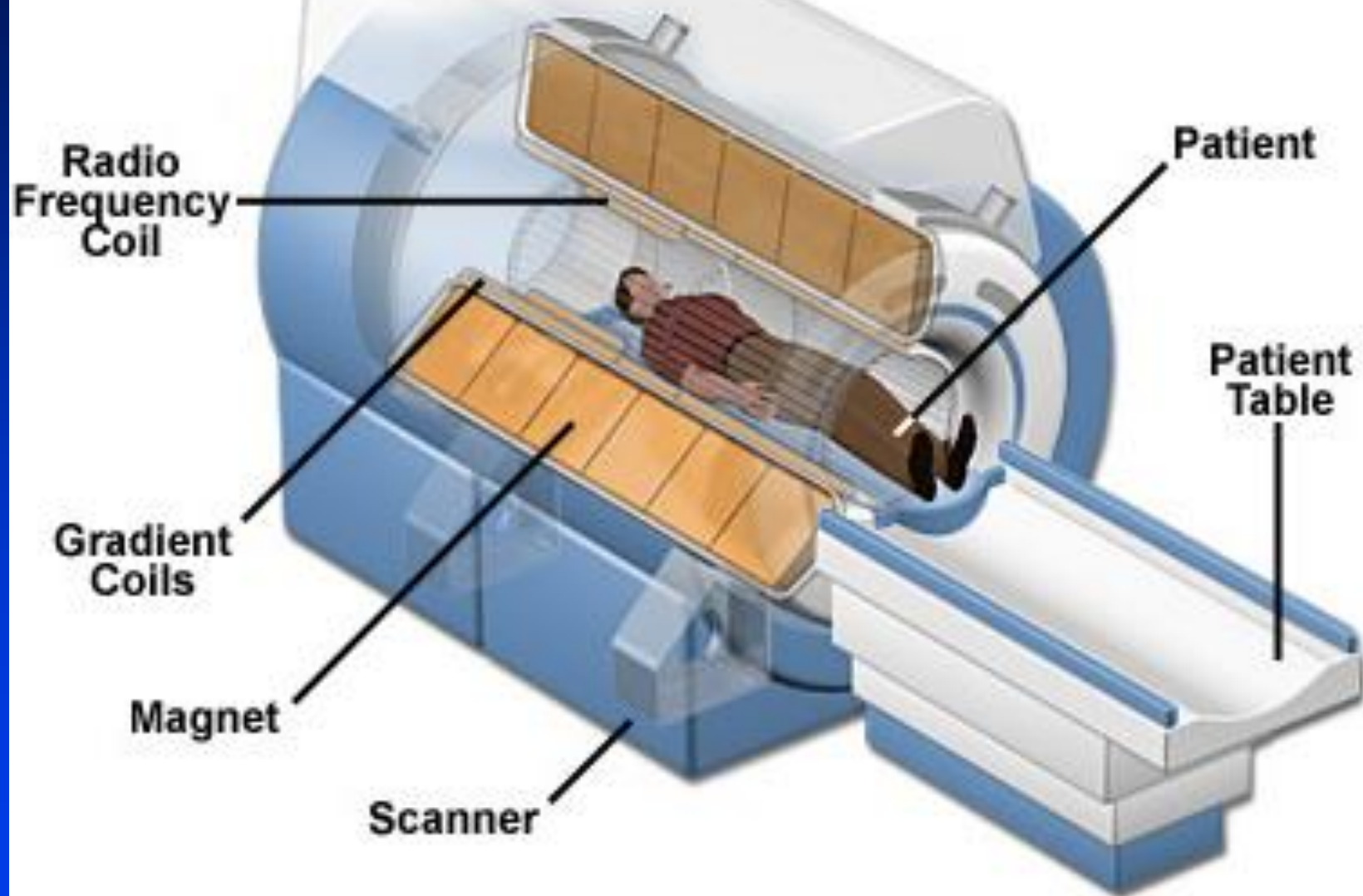


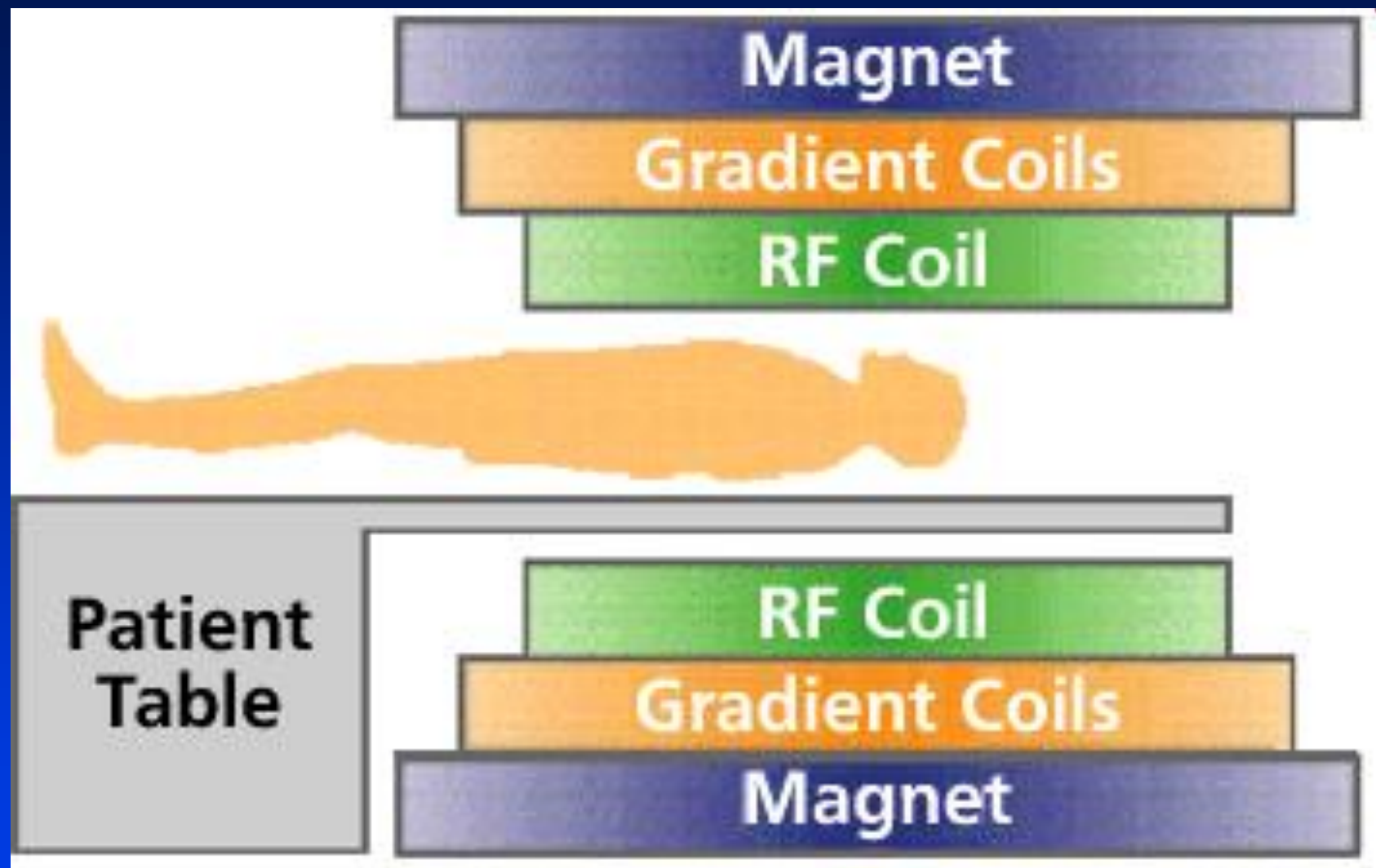
0,2 Tesla, open,
resistive magnet (6 tons)
or
permanent magnet (11 tons)



UKT

MRI Scanner Cutaway





Magnet Types

Resistive electromagnet

- mostly water-cooled
- field strength up to 0.3 Tesla

Permanent magnet

- ferrite, samarium-cobalt or neodymium magnets
- of very heavy weight
- field strength up to 0,35 Tesla

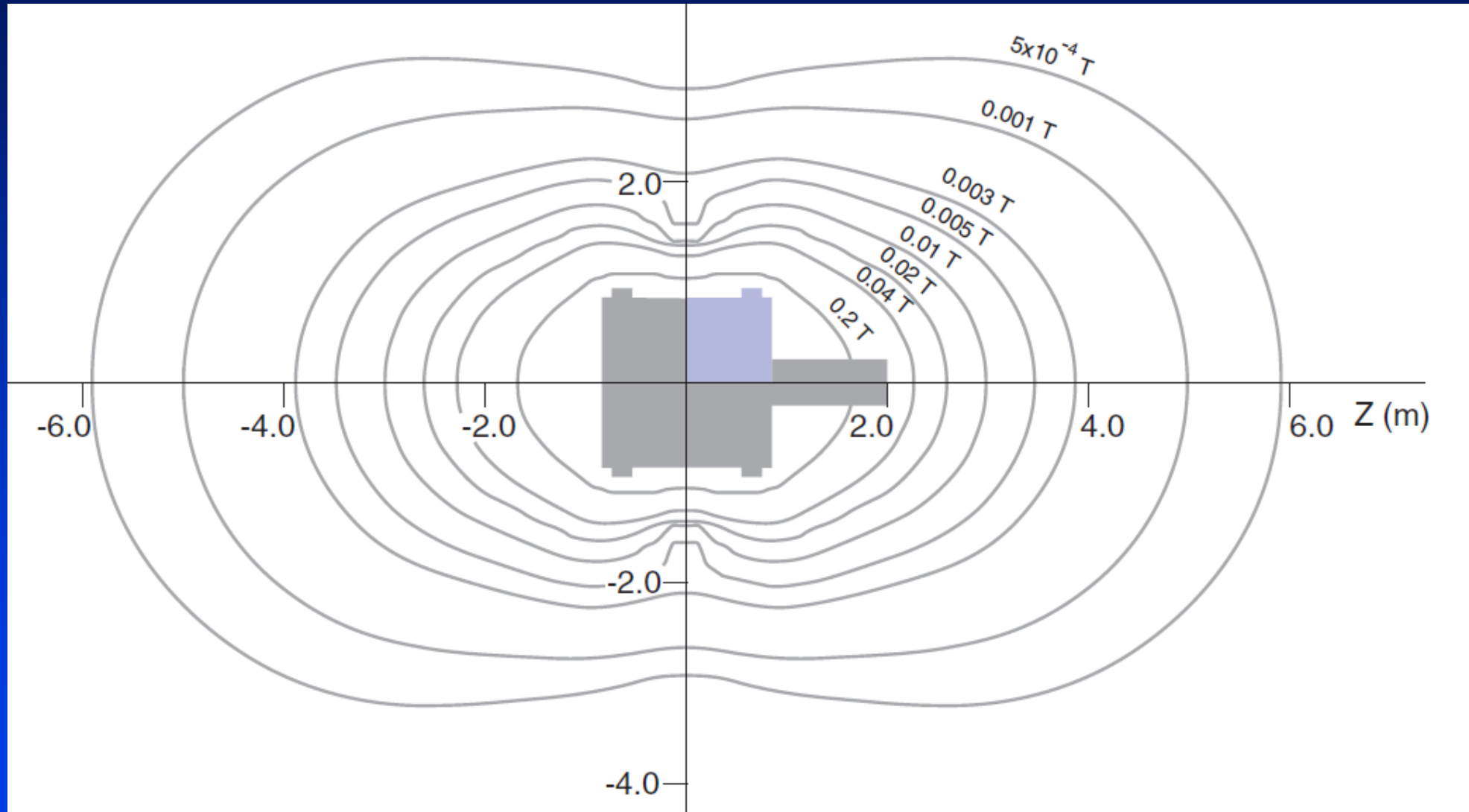
Superconductive magnet

- coil windings of niobium-titanium filaments (critical temp. 10 K)
- liquid helium cooling (boiling temp. 4,2 K)
- field strength currently up to 9.4 T for whole-body systems
- used for most clinical MR units, fieldstrength often 1.5 T

Magnet for a 3T whole-body system

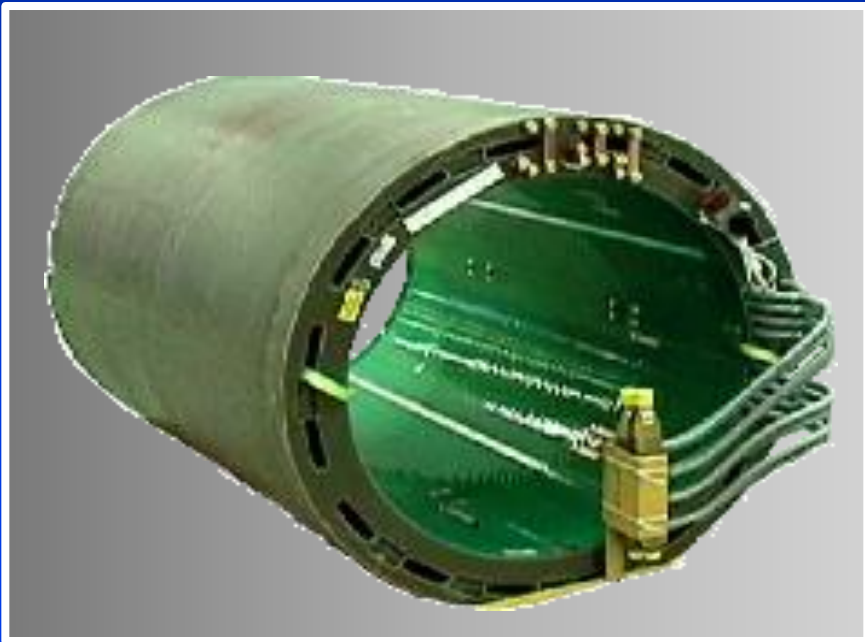


Fringe field of a 3T whole body system



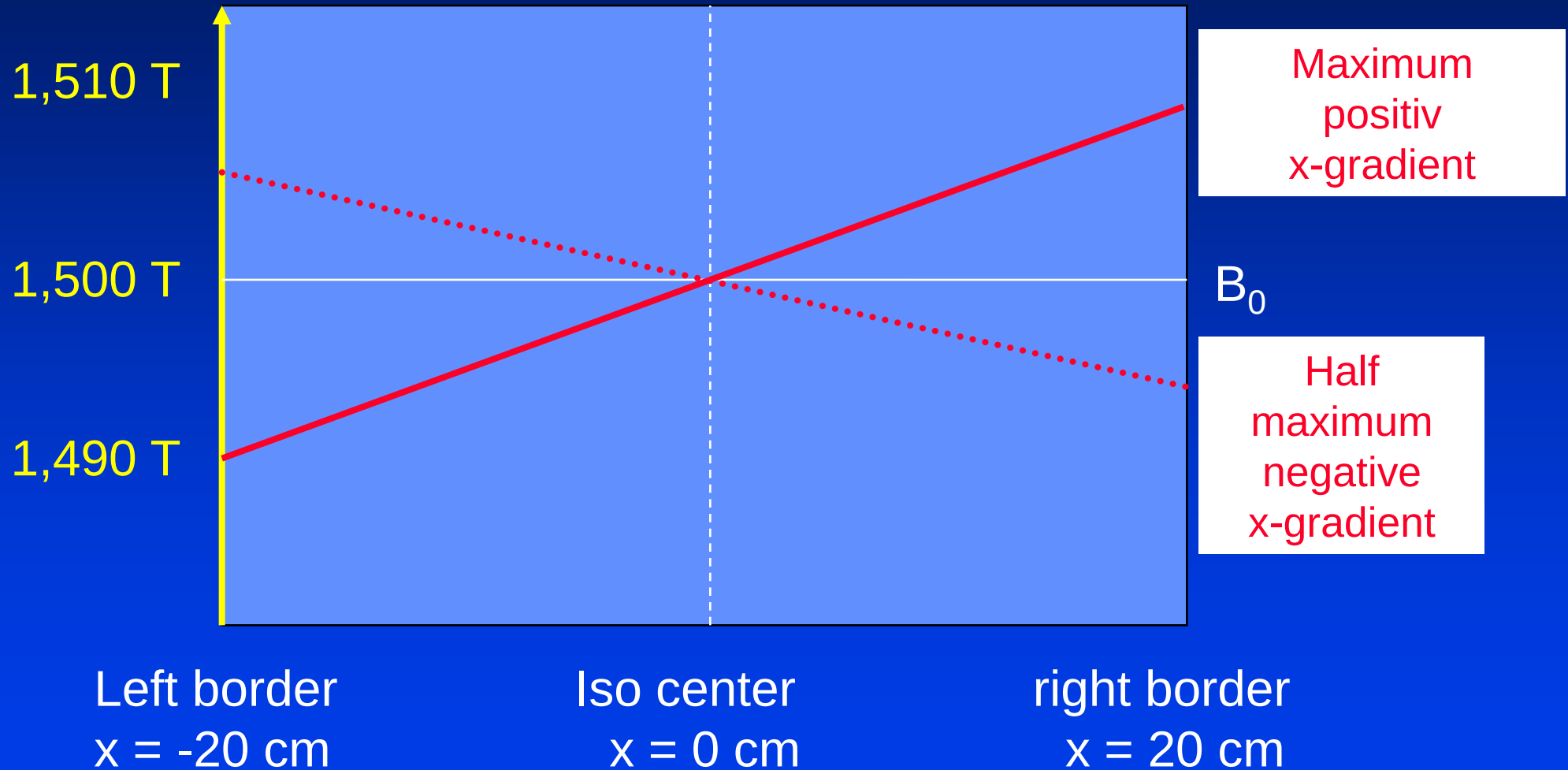
Gradient system

- The gradient system provides constant field gradients in x-, y- or z-direction, respectively (z-direction is along $\vec{B}_0$)
- An MR imaging system has three independent gradient coil systems



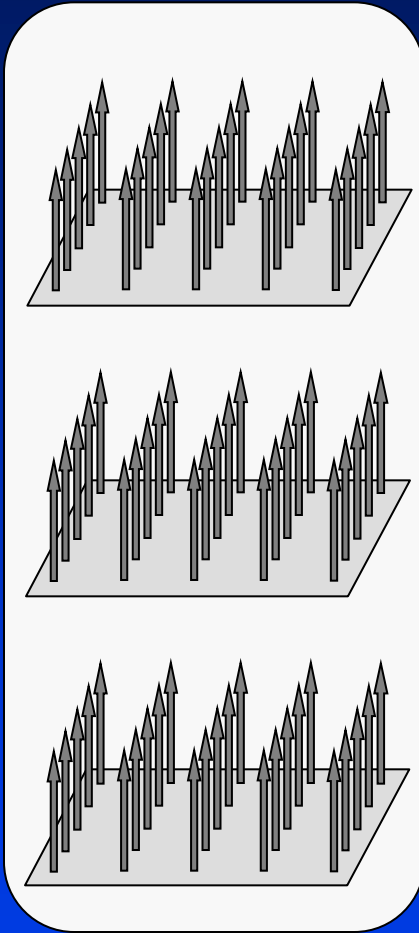
Effect of gradient switching along x-axis

Magnetic field strength

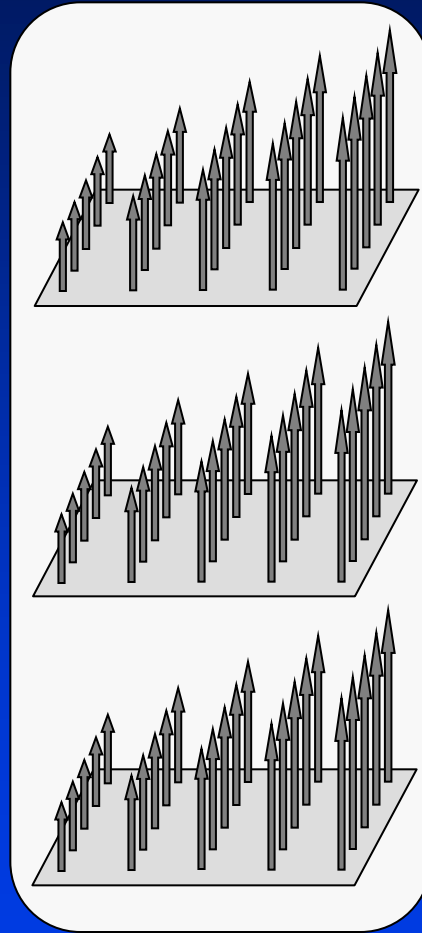


Magnetic field gradients

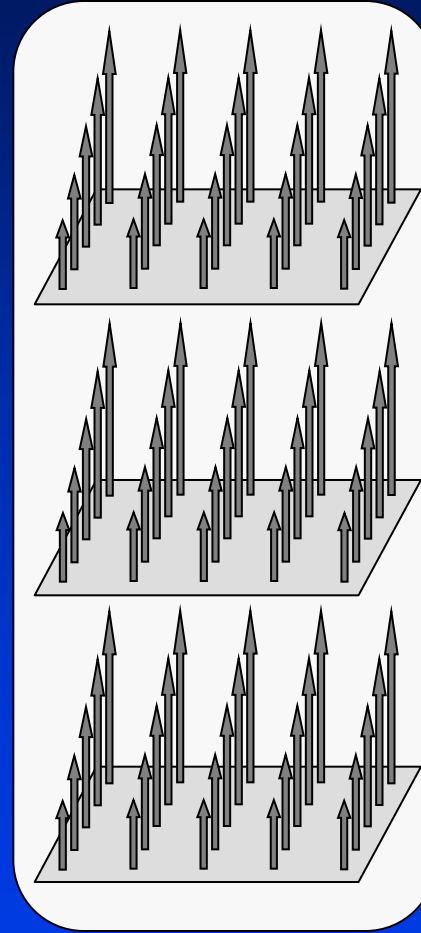
No field gradient



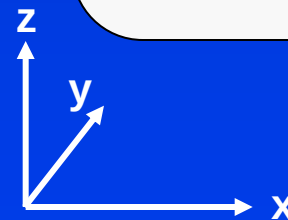
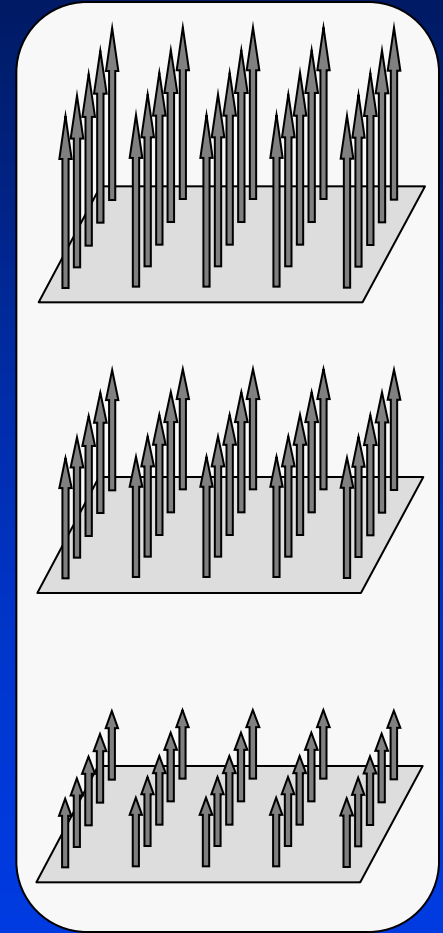
x - gradient



y - gradient



z - gradient



RF transmission

Aims

- homogeneous RF excitation over a large volume
- restriction of RF energy absorbed by the body or body parts (especially for higher field strength)

Types of RF transmitter coils

- by the **large transmitter coil** inside the casing of the MR unit,
or
- by **mobile volume coils**, serving as transmitter and receiver as well



wrist/hand 1-ch



knee 1-ch



spine 12-ch*

RF receiver coils

Aims

- high sensitivity to low intensity MR signals
 - low noise level and low sensitivity to electromagnetic sources in the surroundings and in the coil itself (thermal noise)
 - homogeneous level of sensitivity over (large) body regions under investigation
- Suitable compromises are strongly dependent on the body part under investigation
- Many different receiver coil systems are available for different examinations

Receiver coils

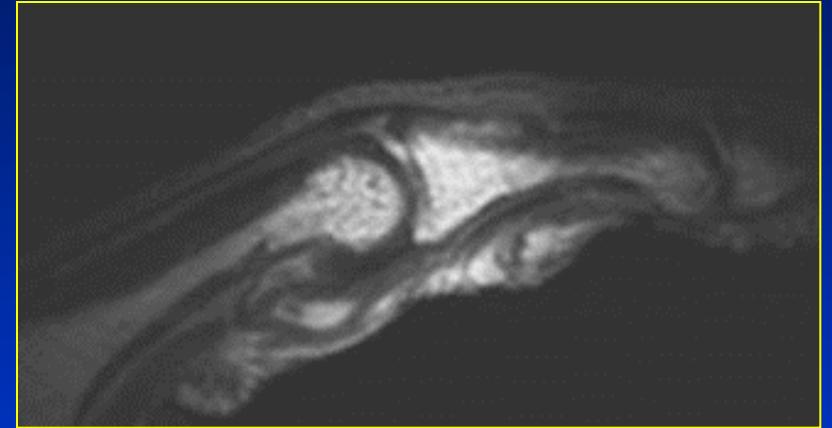
Comparison of large and small single coils



body coil

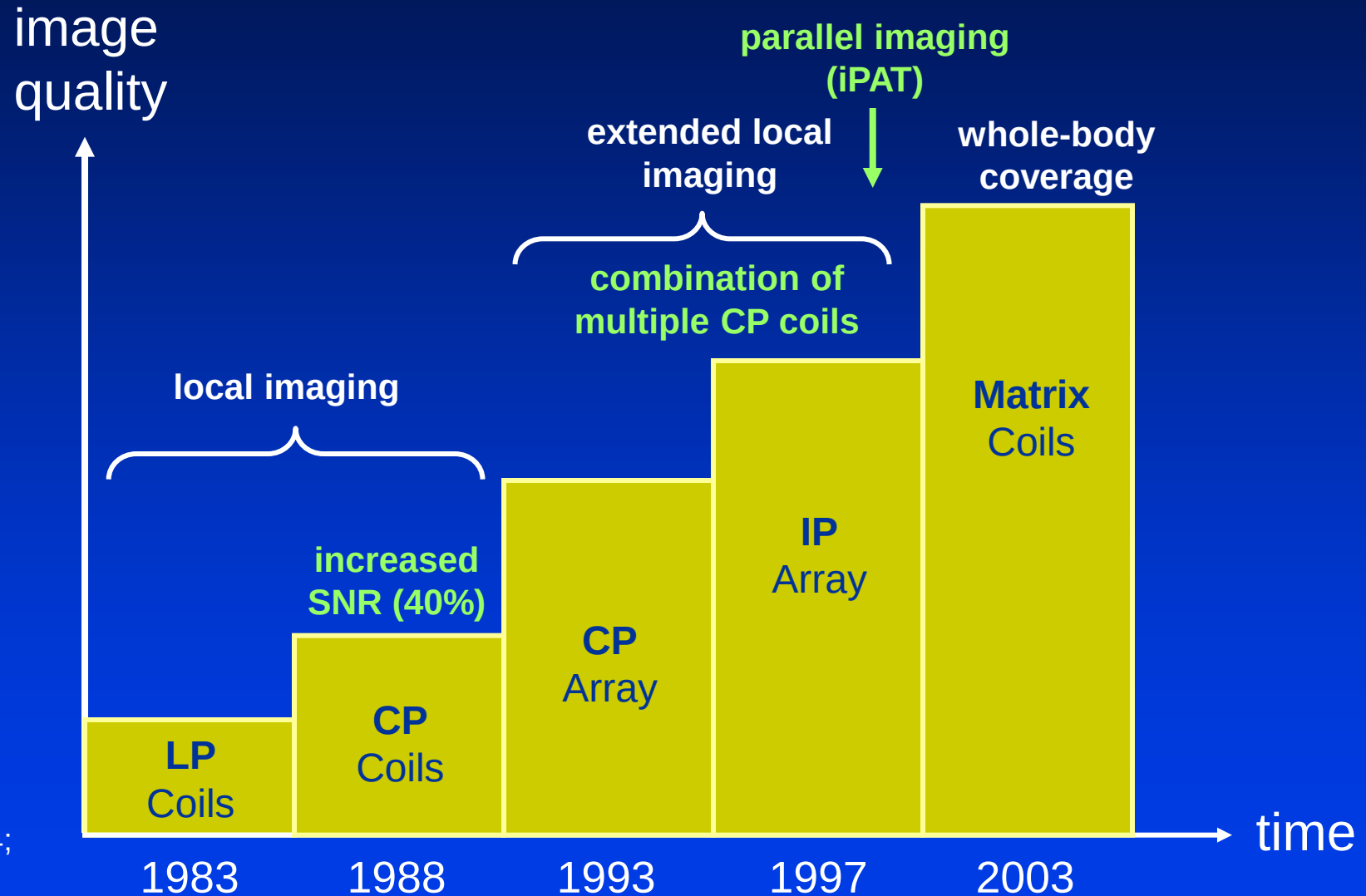


finger coil



finger coil provides higher spatial resolution, but only local sensitivity

Development of receiver coils



Some clinically used receiver coils



wrist/hand 1-ch



knee 1-ch



knee 8-ch



spine 12-ch



torso/cardiac 8-ch



head 1-ch (Bruker)

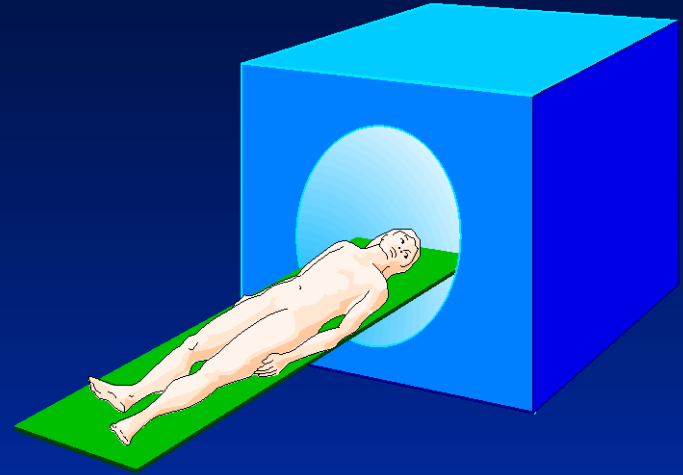


head 1-ch (Siemens)

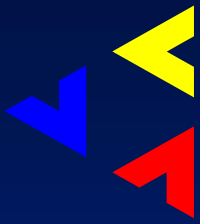


head 8-ch

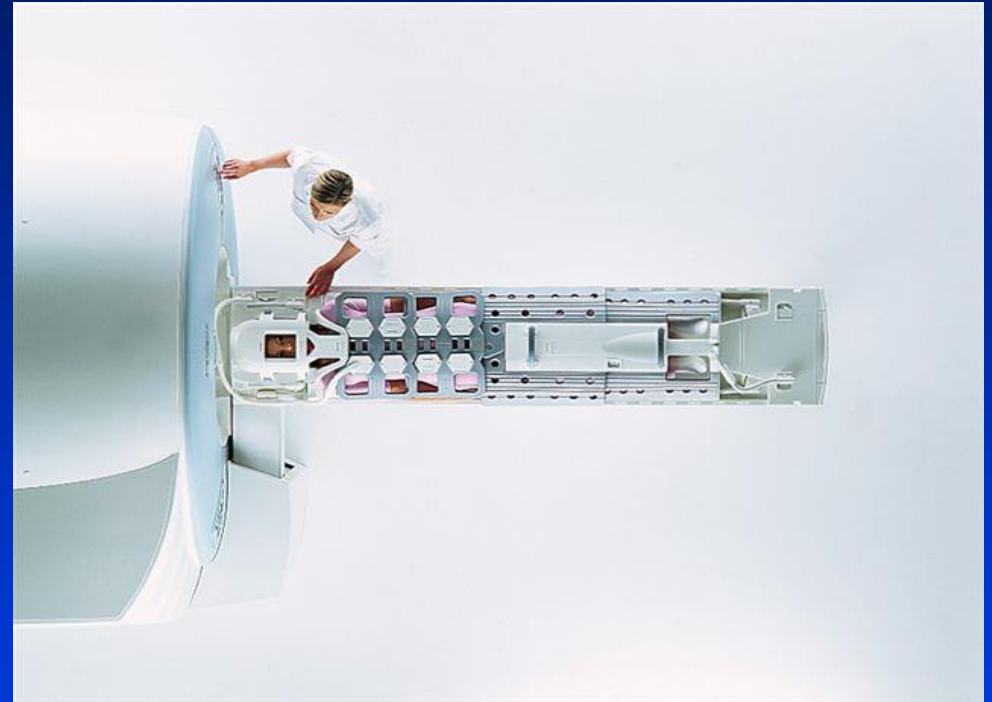
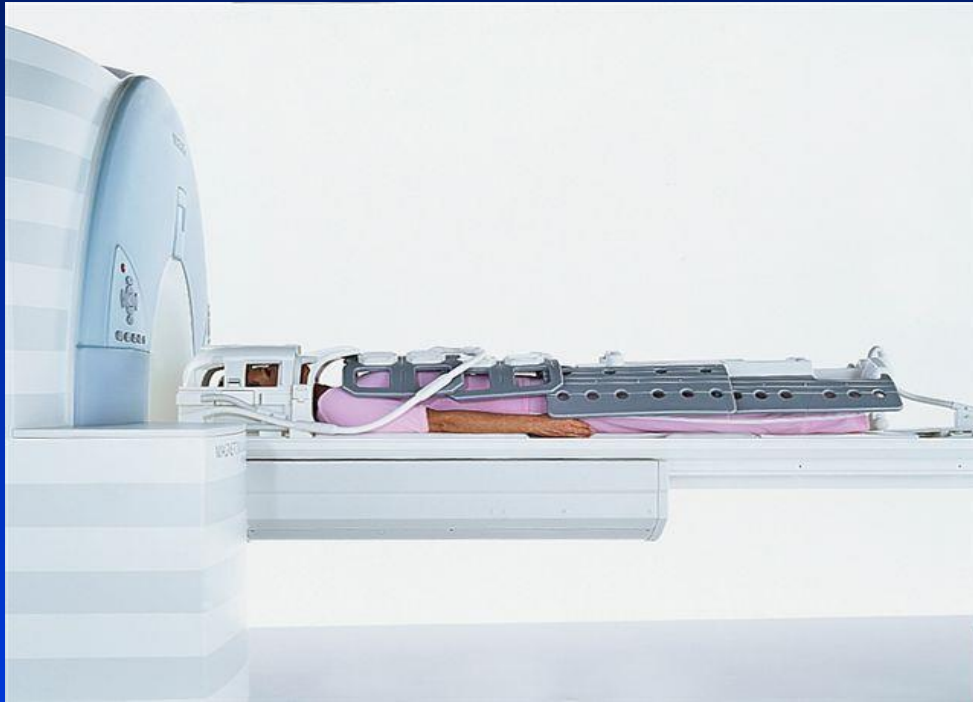
Outline



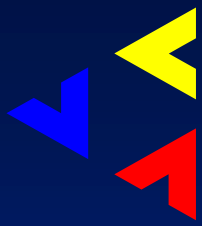
- Basic principles of magnetic resonance
- MRI, spatial encoding, contrast mechanisms
- MRS, spatial encoding, chemical shift
- Hardware components
- Recent developments in MRI



Whole-body MRI

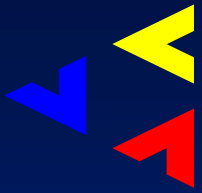


Coverage of the entire body by approx. 70-120 receiver coils allowing whole-body examinations without repositioning of the patient by a technician

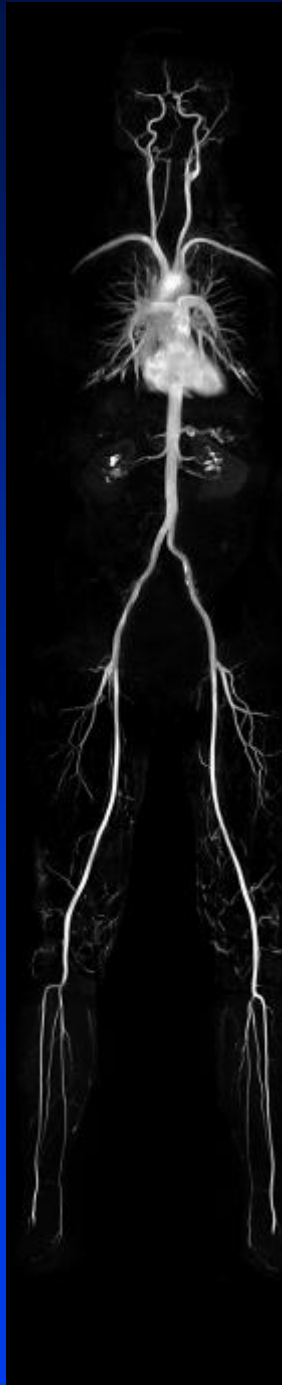


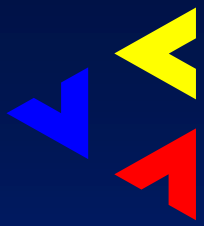
Anatomy





+ Cardiovascular
System





MIP reconstruction of vessels



MRCP (T2-w)

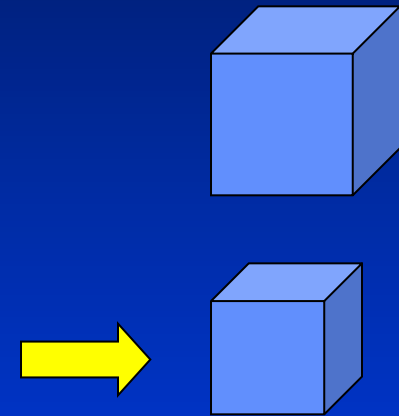


MRA (T1-w with contrast medium)

High field systems with 3 T (or even 7 T)

Doubled SNR can be invested

1. ...in a higher spatial resolution:
one can choose a smaller pixel size
(with a reduction of 20 % along each
axis for an isotropic 3D data set)



2. ...in a shorter measure time:
instead of 4 averaged scans only one single scan is
necessary for the same SNR (i.e. $\frac{1}{4}$ measuring time)



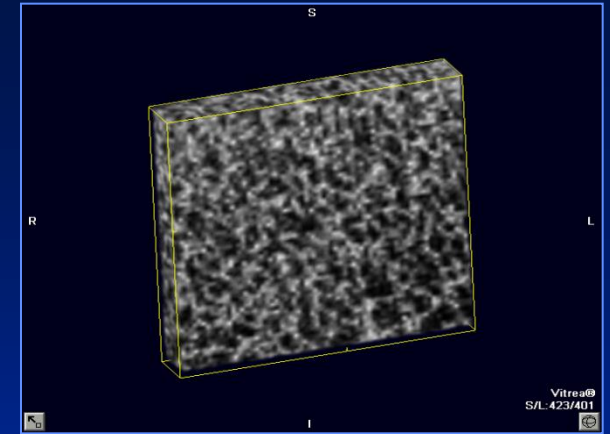
High resolution MRI of wrist bones



High resolution MRI of hand and wrist bones with a special transmit/receive coil at 3T...

..needs less time with same SNR compared to 1.5 Tesla.

3D FISP sequence with 0,3 mm isotropic resolution (8 min measuring time)

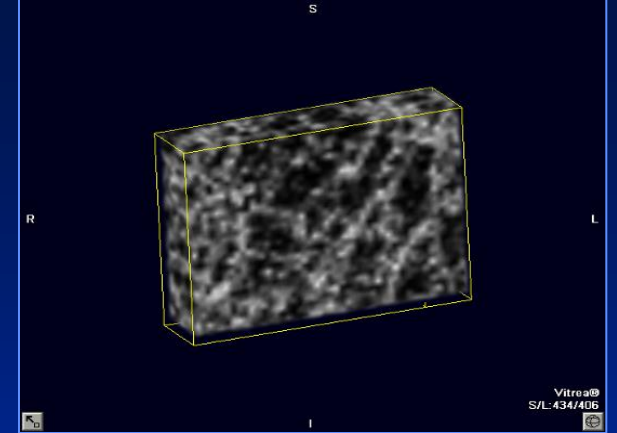
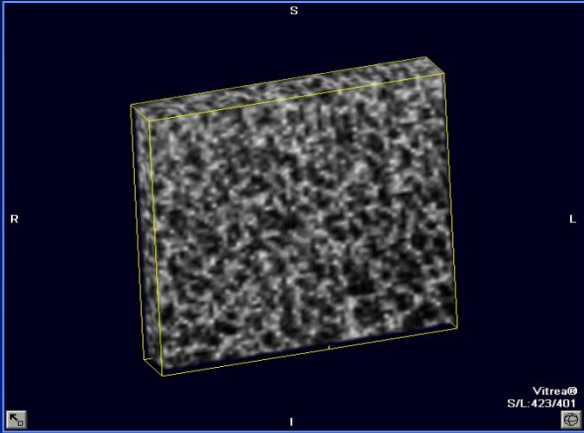


normal

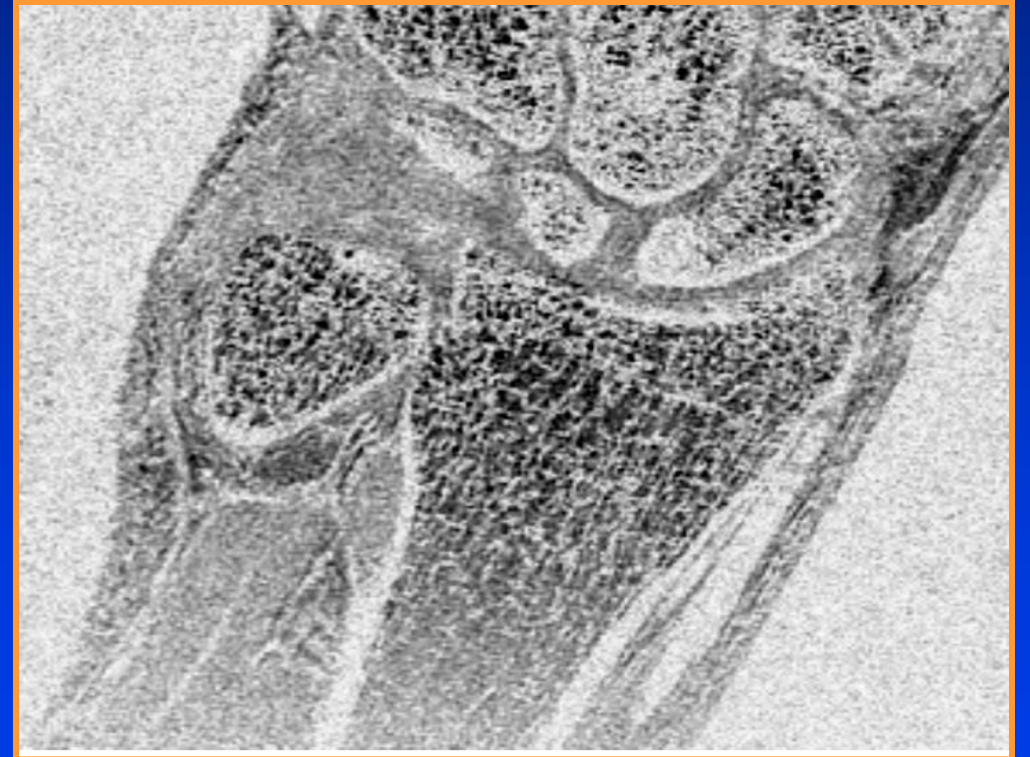


inverted

3D-FISP 0,3 mm isotropic resolution



healthy, 35 years, male



osteoporotic, 81 years, male

Visualization of the inner ear and the vestibular apparatus

„Maximum Intensity Projections” (MIPs)



Cardiovascular MRI

Sequence: cine TrueFISP

TR = 44,7 ms, TE = 1.7 ms

SL = 6 mm

FoV = 350×280 mm²

Matrix = 192×156

Flip angle = 50°

Torso 8-channel phased array coil

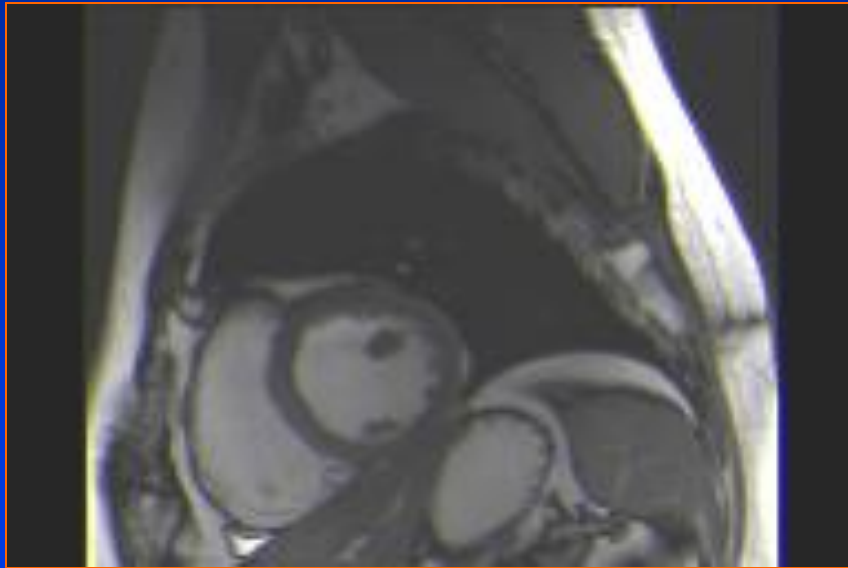
20 cardiac phases

Examination time 12 sec

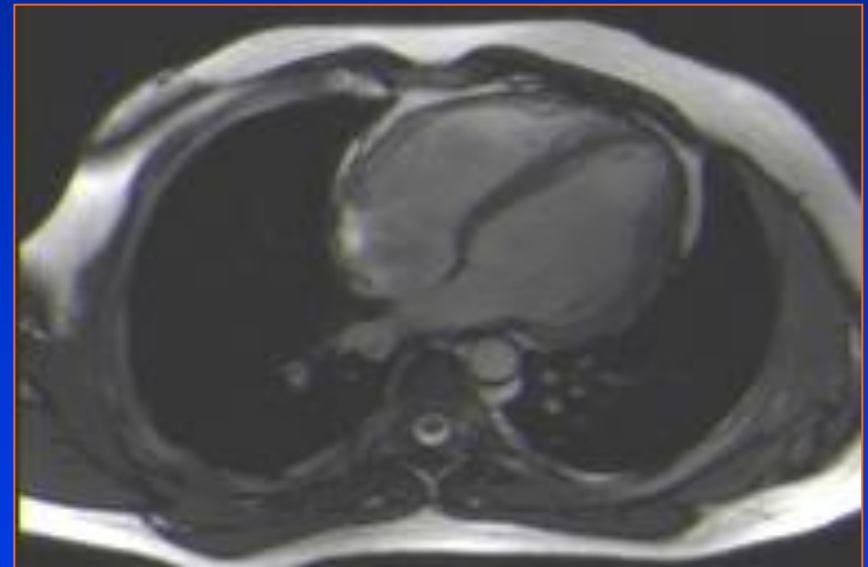
EcG-retro-gated

Breathhold

Courtesy S. Miller, Tübingen



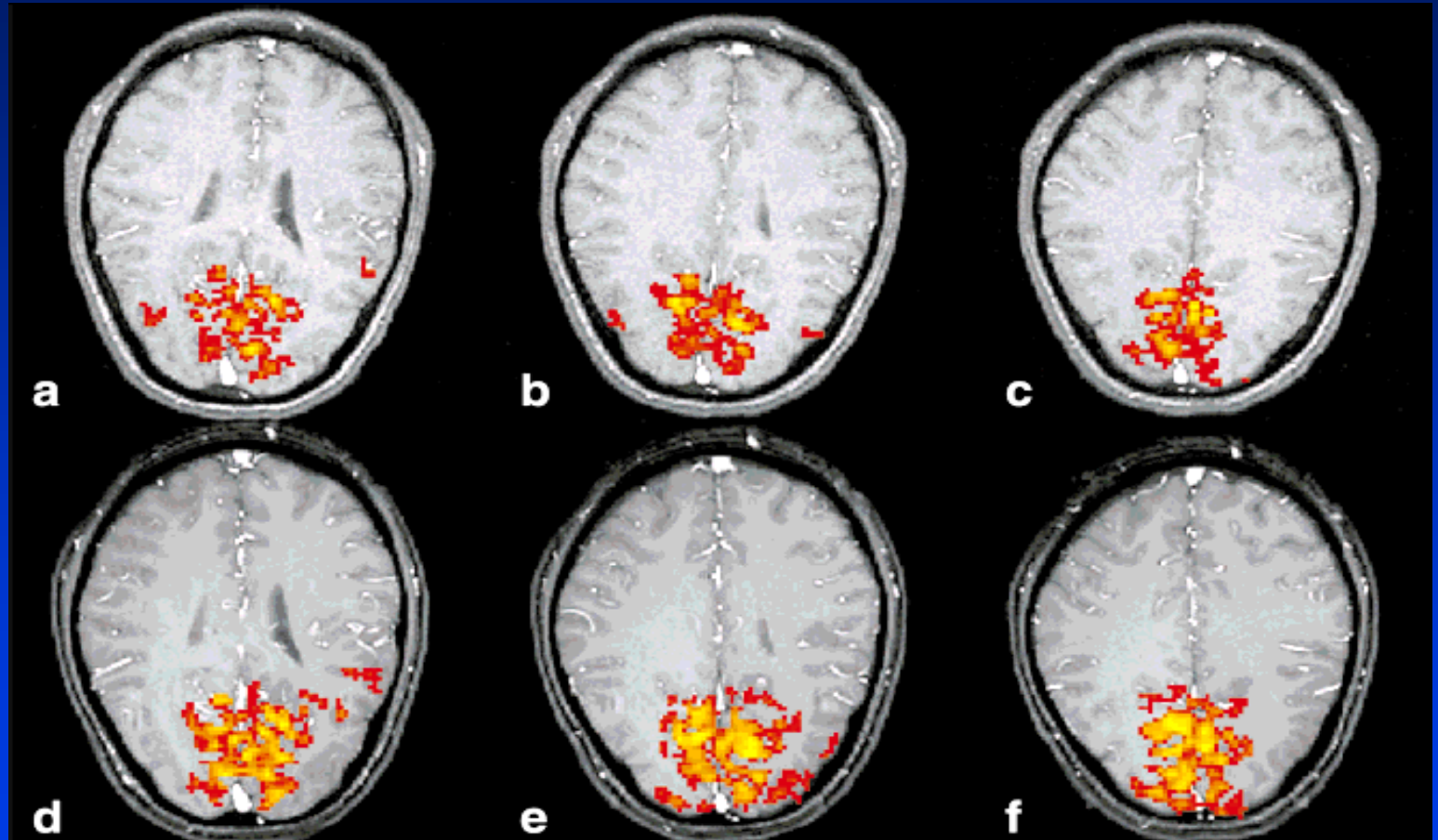
Short axis plane



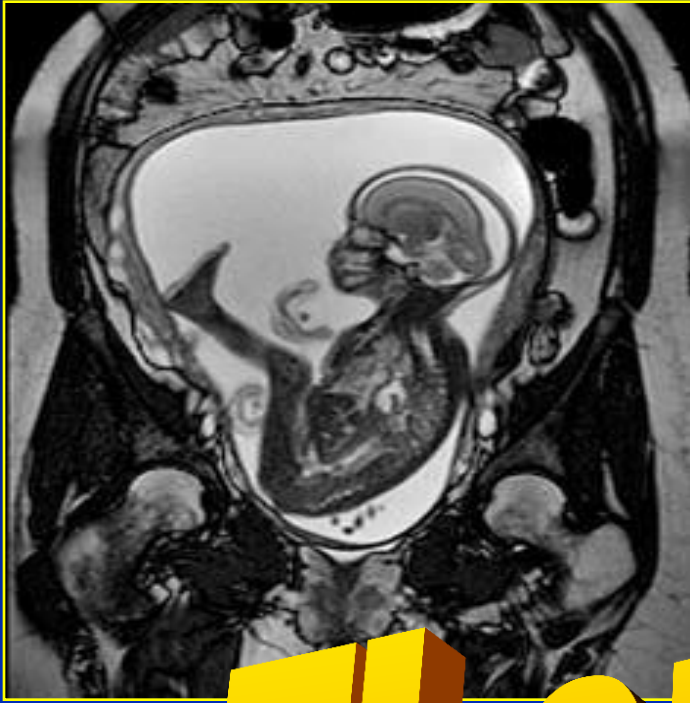
Long axis plane

Functional MRI of brain: effects of optical stimulation

1,5 T



3,0 T



Thank You!