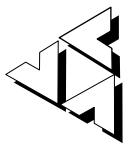


Function of an MRI scanner and principle of MR imaging

Fritz Schick

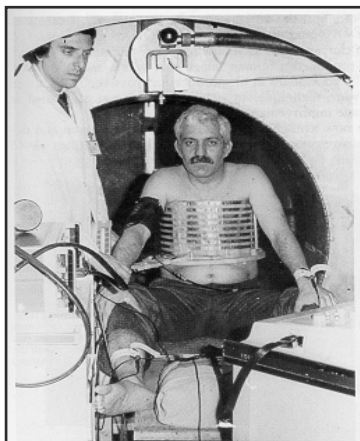


Section on Experimental Radiology
Department on Diagnostic and
Interventional Radiology
University of Tübingen, Germany



Module Bioimaging, Master degree course: „Biomedical Technologies“

History of MR imaging State of technology 1977

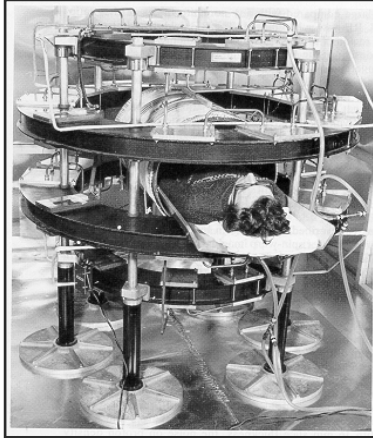


First Volunteer

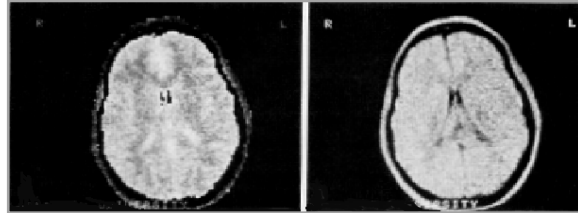


First MR image
recording time > 1 hour

History of MR imaging State of technology 1981

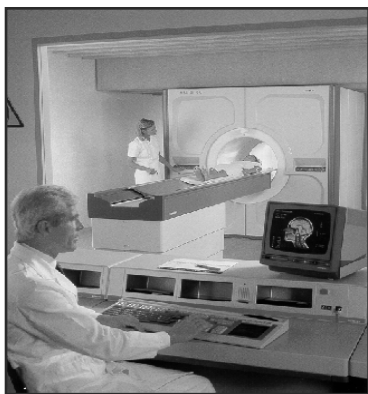


MR-System, Aberdeen 1981

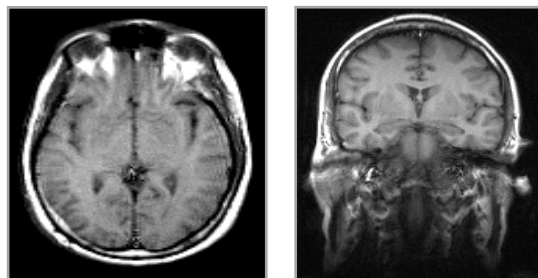


MR images recorded in Aberdeen
recording time 45 minutes

History of MR imaging State of technology 1985



MR-System
Siemens MAGNETOM



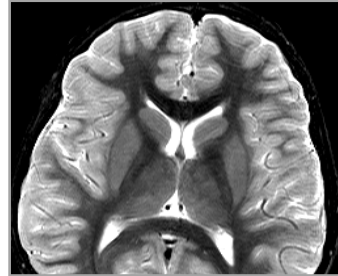
Spinecho-Images
recording time 10 min
field strength: 1,5 Tesla
gradient strength: 3 mT/m
gradient slew rate: 1 T/m s

History of MR imaging

State of technology 2005



MR-System
Siemens SONATA



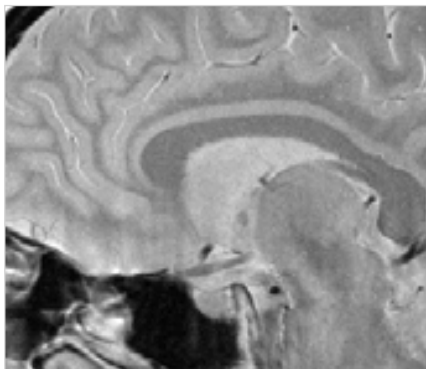
FSE-Image

recording time < 1 min

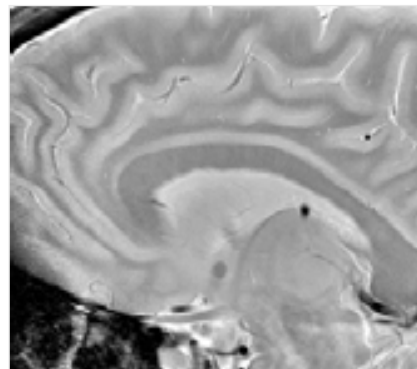
*field strength: 1,5 Tesla
gradient strength: 40 mT/m
gradient slew rate: 200 T/m s*

History of MR imaging

High field imaging 2010



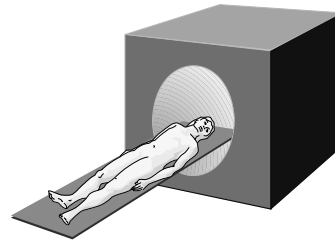
3 Tesla



7 Tesla

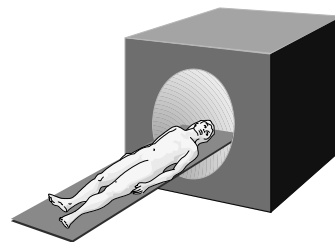
TSE sequence; resolution $0.4 * 0.4 * 3.0 \text{ mm}^3$; recording time 7 min

Outline



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

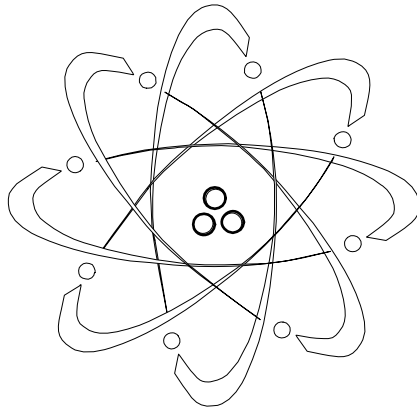
Outline



- Basic principles of magnetic resonance
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Nuclear Spin and Magnetic Moment

Atom



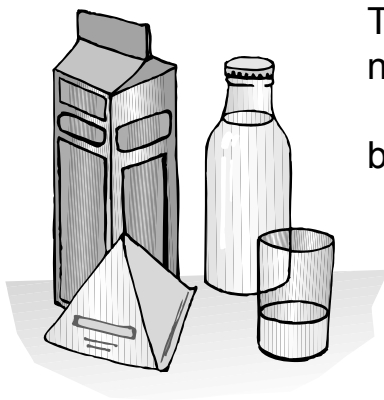
Mechanical
property :

Spin

Magnetic
property :

Magnetic
moment

What is necessary for generating
detectable signals by atomic nuclei?

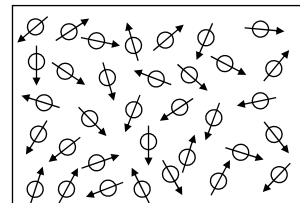


There are more than 10^{25} hydrogen
nuclei in a glass of milk -

but no detectable macroscopic effect

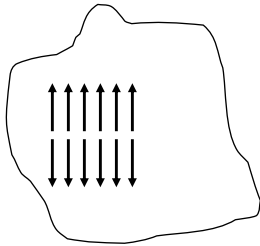
Macroscopic
Magnetization

$$\vec{M} = 0$$



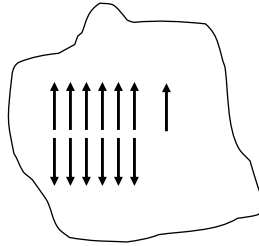
Effect of increasing field strength B_0

0 Tesla



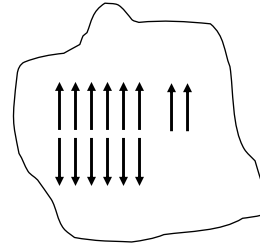
0 : 1.000.000

1.5 Tesla



5 : 1.000.000

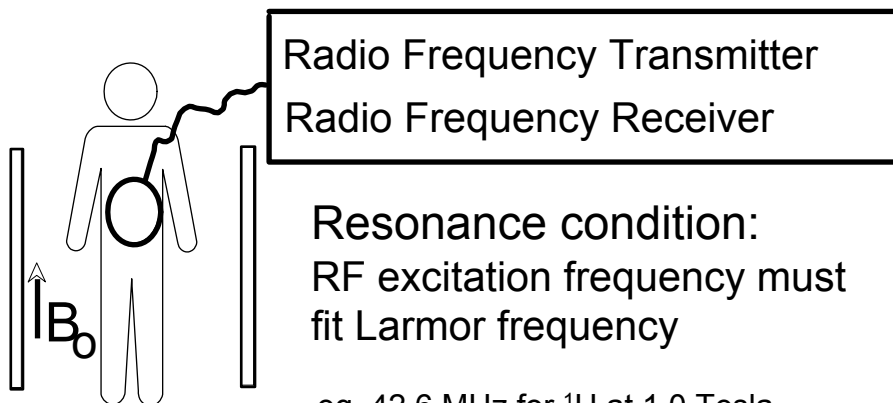
3 Tesla



10 : 1.000.000

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

Generation of signals in magnetic resonance



Resonance condition:
RF excitation frequency must
fit Larmor frequency

eg, 42.6 MHz for ^1H at 1.0 Tesla
(1 T $\approx$ 20.000 times earth magnetic field)

Typical ^1H resonance frequencies as applicable for medical imaging

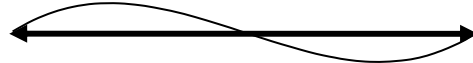
0,2 Tesla:	8,5 MHz	($\lambda_{\text{air}} = 35,2 \text{ m}$)
1,0 Tesla:	42,6 MHz	($\lambda_{\text{air}} = 7,0 \text{ m}$)
1,5 Tesla:	63,9 MHz	($\lambda_{\text{air}} = 4,7 \text{ m}$)
3,0 Tesla:	127,7 MHz	($\lambda_{\text{air}} = 2,3 \text{ m}$)

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

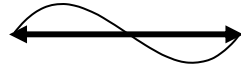
Resonance frequencies immediately change, if field strengths are changing eg, by gradient switching).

^1H wavelength in water for different field strengths

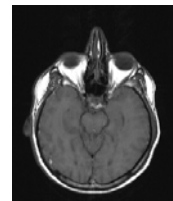
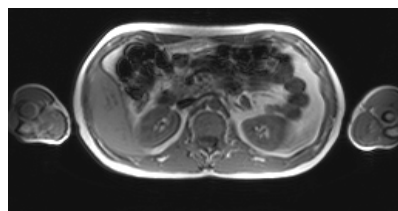
1.5 Tesla: $\lambda_{\text{H}_2\text{O}} = 52 \text{ cm}$



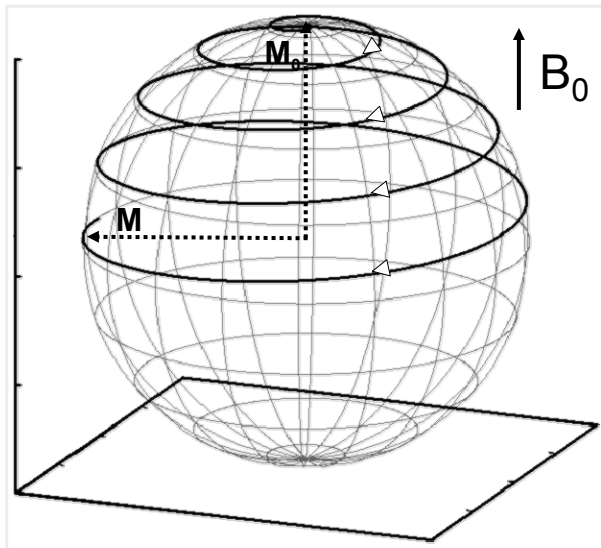
3.0 Tesla: $\lambda_{\text{H}_2\text{O}} = 26 \text{ cm}$



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



RF excitation of magnetization (90°-pulse)

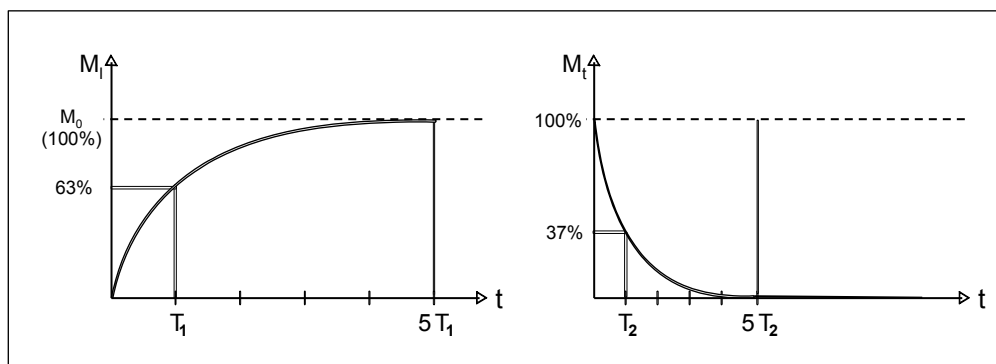


Duration of excitation:
approx. 1 ms

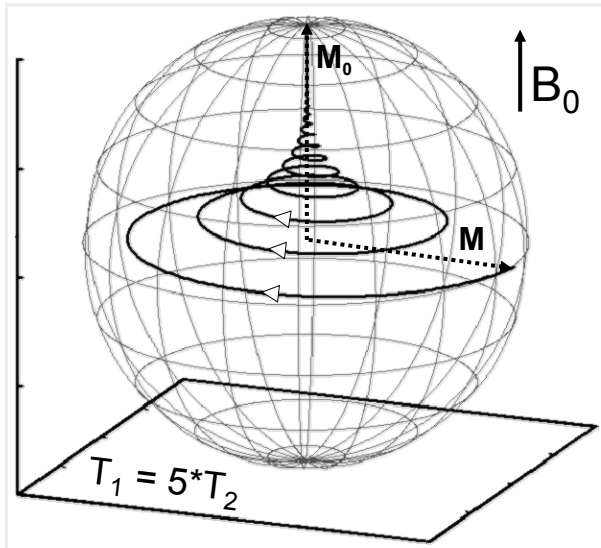
Relaxation of magnetization (following 90°-pulse)

longitudinal
magnetization

transverse
magnetization

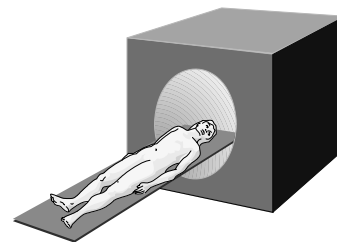


Relaxation of magnetization (following 90°-pulse)



Duration of relaxation
in tissues:
several seconds

Outline



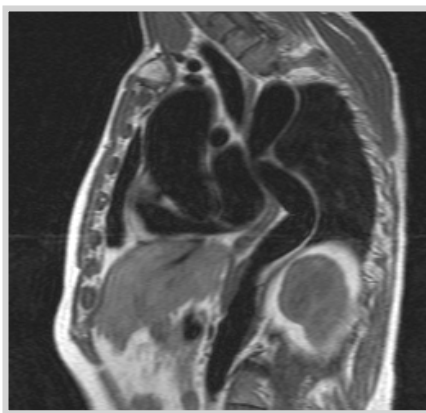
- Basic principles of magnetic resonance
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- Recent developments in MRI

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



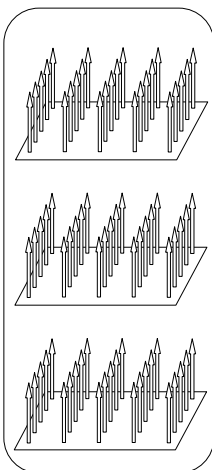
Spatial encoding in MRI

Three spatial dimensions:

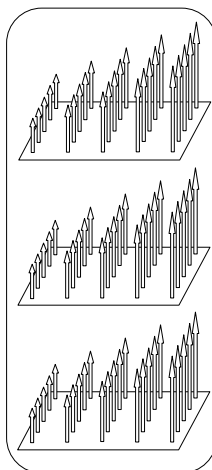
1. Slice selective excitation (z)
2. Frequency encoding of signals (x)
3. Phase encoding of signals (y)

Switchable magnetic field gradients

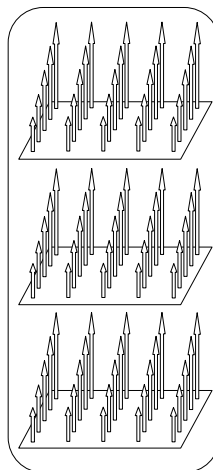
No field gradient



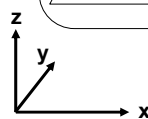
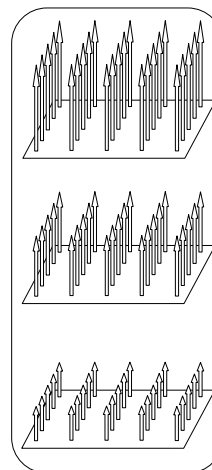
x - gradient



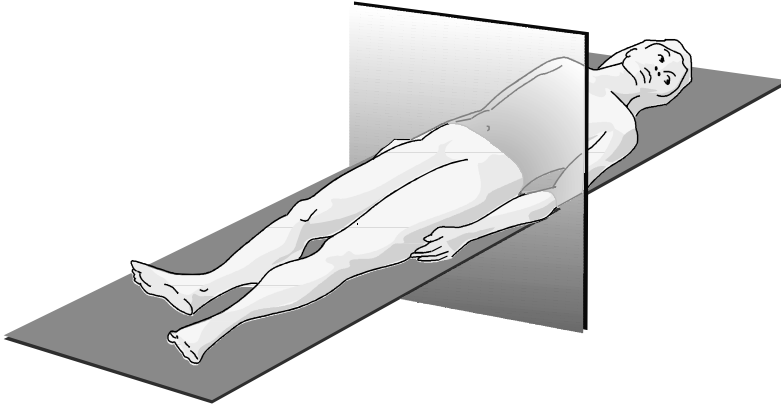
y - gradient



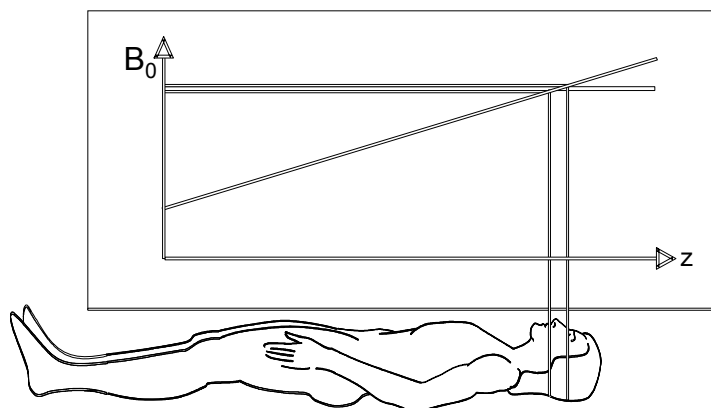
z - gradient



Slice in 3D space

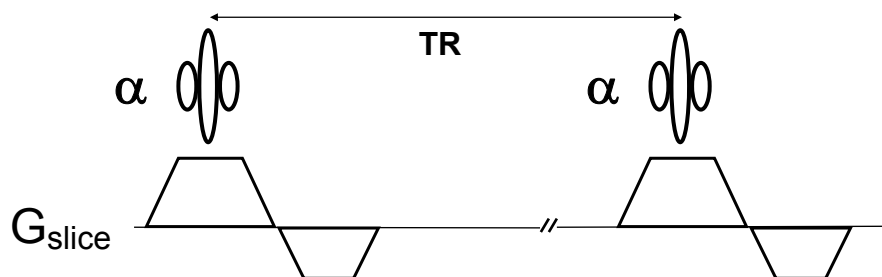


Slice selective excitation

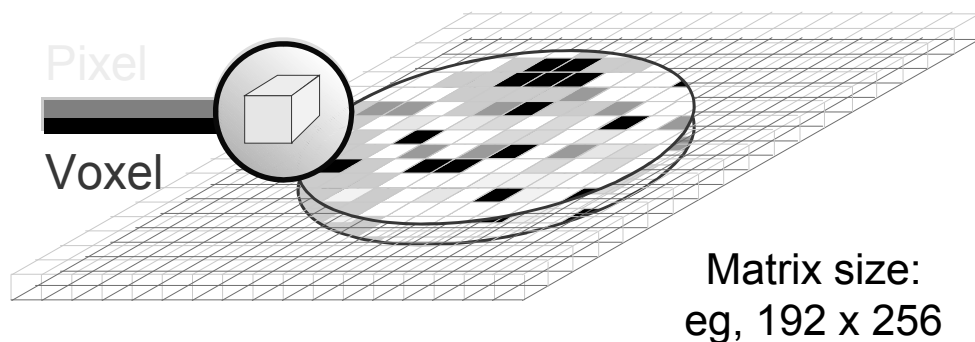


Principle: Frequency selective RF-pulse
+
Magnetic field gradient

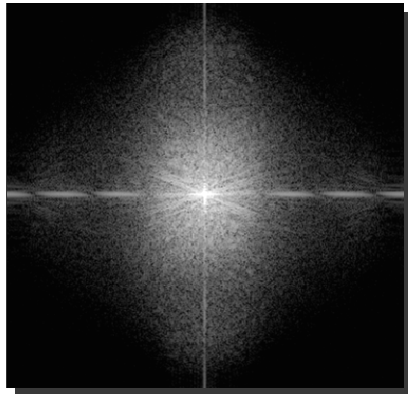
Representation in sequence plot:



Spatial encoding in-plane



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)

2D-FT

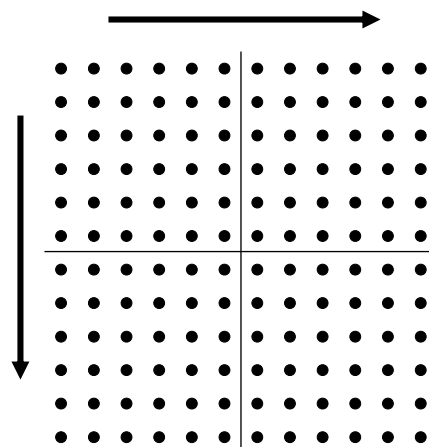


Image data

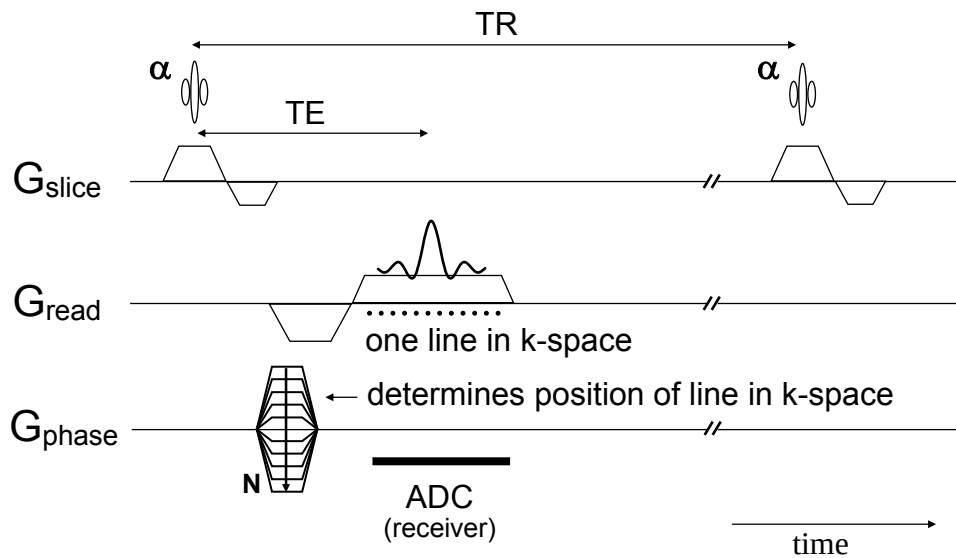
Raw data
acquisition:

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

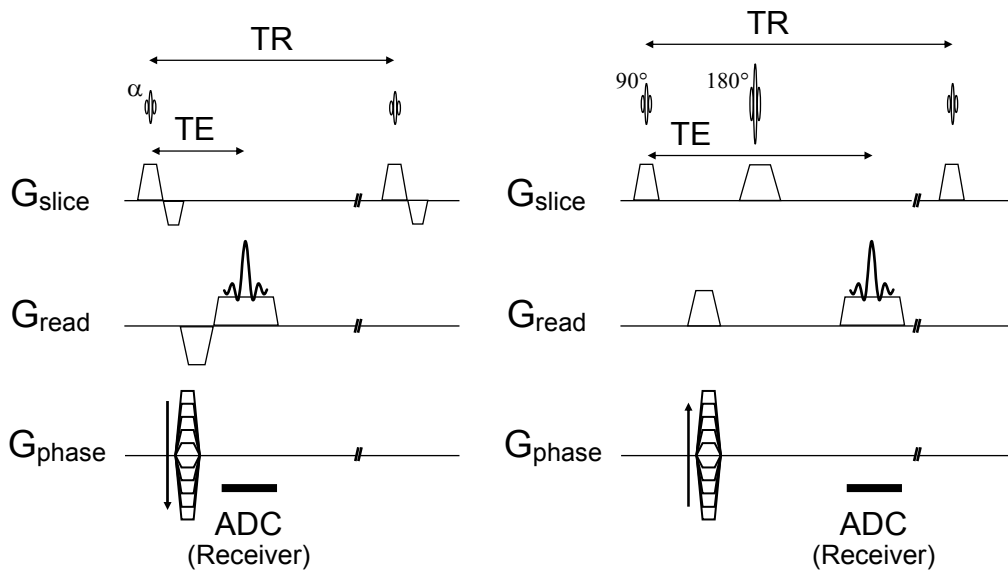
Positioning of
data in k-space



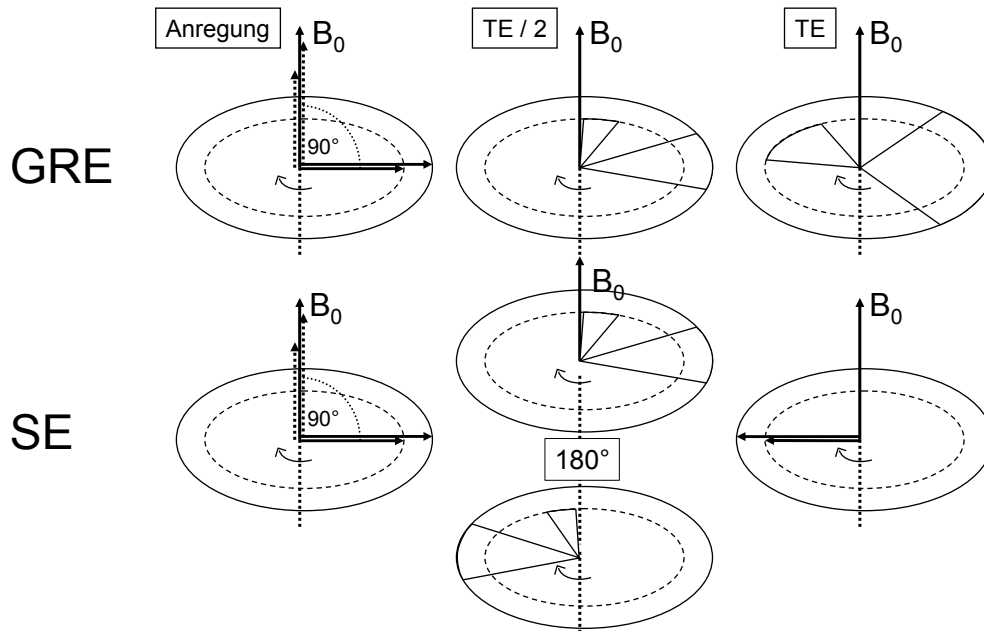
Simple gradientecho sequence



Gradient echo and spinecho sequence

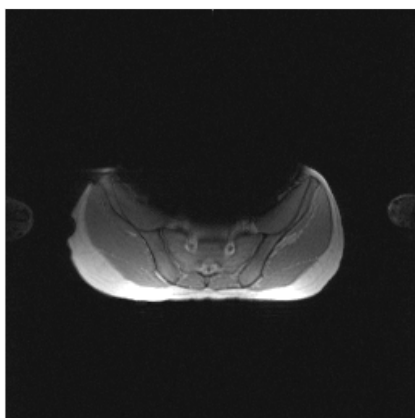


Dephasing within picture elements for GRE- und SE-sequences

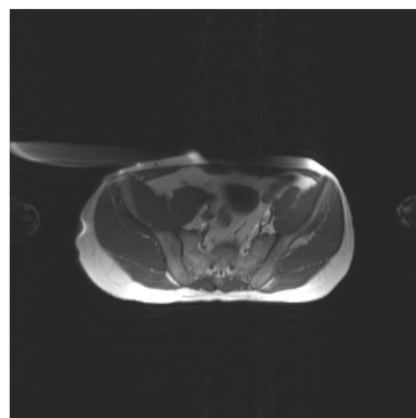


Artifacts arising from a metallic trouser button

gradient echo sequence



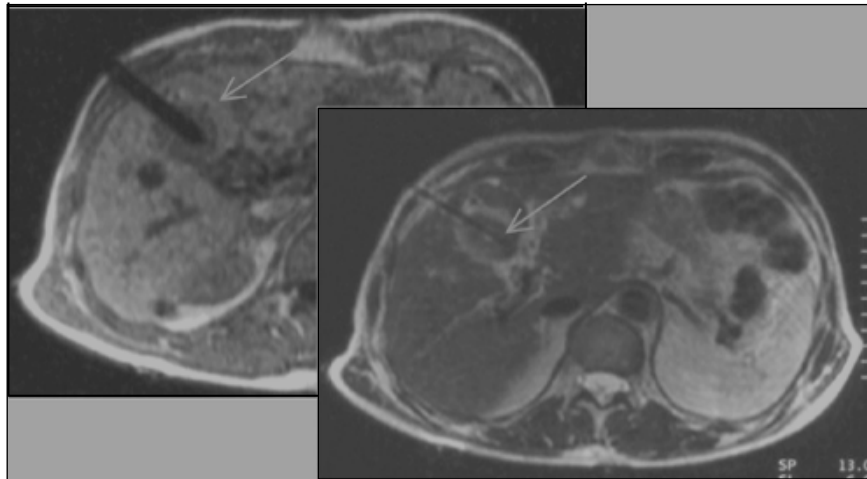
spinecho sequence



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

gradient echo sequence

spinecho sequence



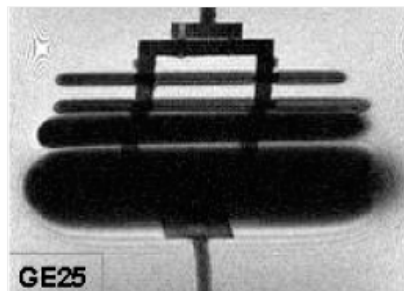
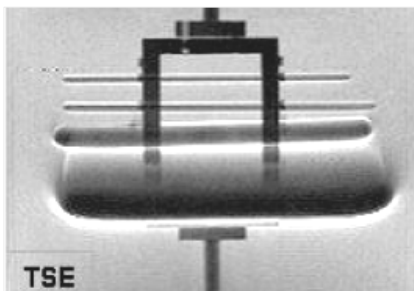
Artifacts of paramagnetic wires ⇒ susceptibility effects

(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

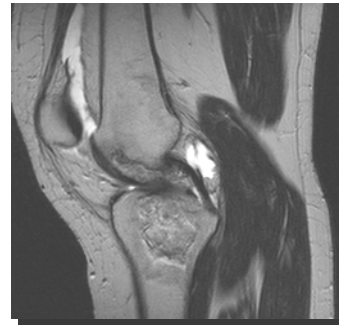
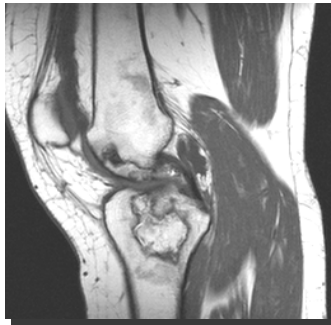
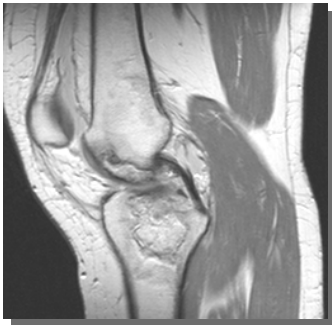
Contrasts in standard clinical MRI

Proton density
weighting

Relaxation weighting

T1-weighting

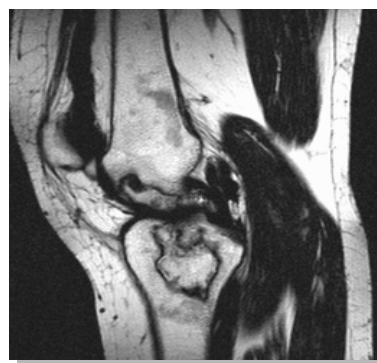
T2-weighting



Chemical Shift MRI

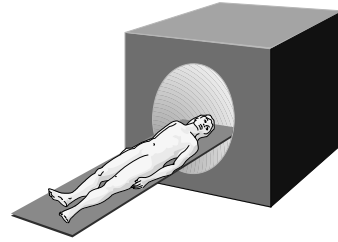
water selective

fat selective



Shimming is required!

Outline



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

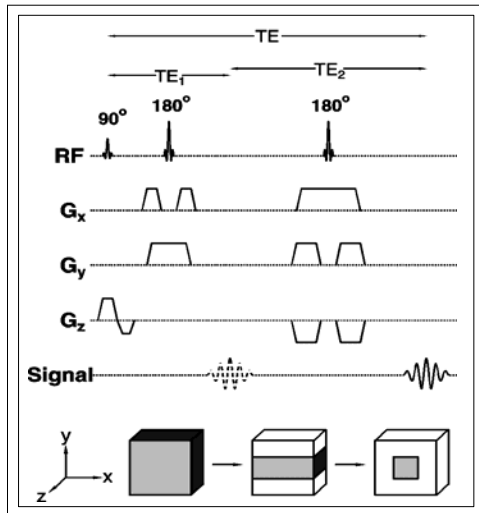
Spectroscopy

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

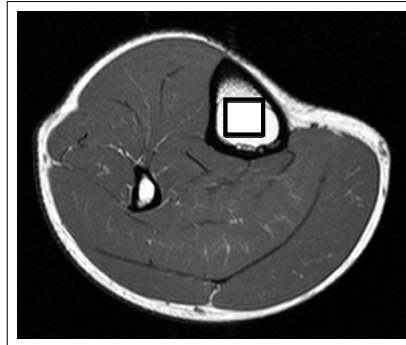
In vivo applications usually require volume selective recording of signals. Most techniques work with slice selective excitation and echo formation.

Shimming is required!

Volume selective ^1H MR-Spectroscopy



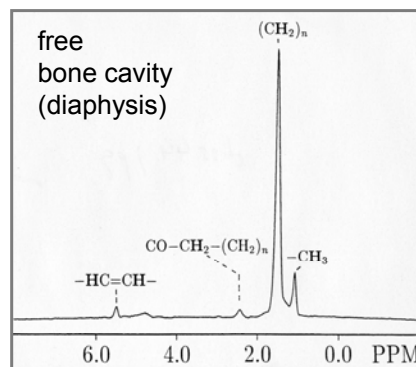
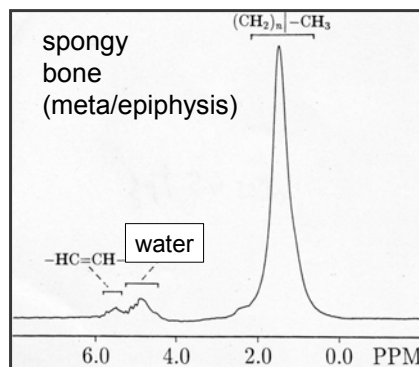
Selection of a cubic volume using three slice selective RF excitation/refocusing pulses



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

narrow lines
⇒ homogeneous B-field

broad lines
⇒ inhomogeneous B-field



Chemical shift effects in molecules

The diagram illustrates the chemical shift effects in a triglyceride molecule. On the left, the chemical structure of a triglyceride is shown, consisting of three fatty acid chains esterified to a glycerol backbone. The protons are labeled with their corresponding chemical shifts in PPM: the glycerol backbone protons are at approximately 4.1-4.3 ppm, the methylene protons adjacent to the ester group are at approximately 2.3 ppm, and the long-chain methylene protons are at approximately 1.3 ppm. On the right, the ^1H NMR spectrum from human bone marrow is shown, with peaks corresponding to the labeled protons in the triglyceride structure. The spectrum shows a broad peak for the glycerol backbone protons (labeled H_2O in capillaries), a sharp peak for the methylene protons adjacent to the ester group (labeled $\text{CO}-\text{CH}_2-(\text{CH}_2)_n$), and a sharp peak for the long-chain methylene protons (labeled $-(\text{CH}_2)_n$). The x-axis is labeled PPM and ranges from 0.0 to 6.0.

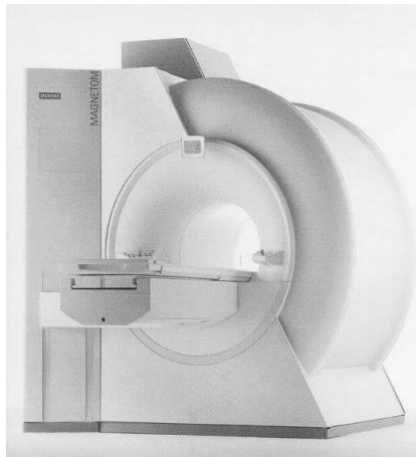
Triglyceride

A diagram showing a person lying on a table inside a large, dark, rectangular box. The box has a circular opening on its side, and the person is positioned so that their head and upper body are inside the box, while their lower body and legs are outside. This illustrates the concept of a closed system where the system boundary is the box, and the person is the system.

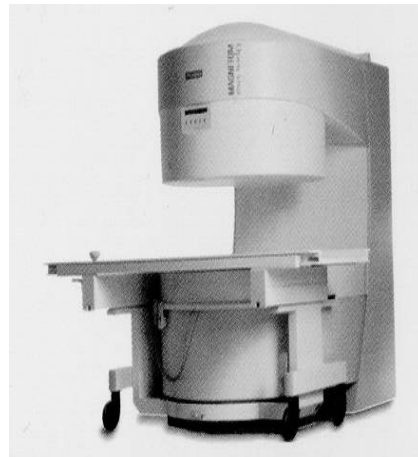
- Basic principles of magnetic resonance
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- MRS, spatial encoding, chemical shift
- Hardware components
- Recent developments in MRI

Hardware components

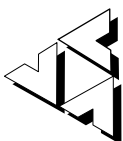
- **Magnet**
 - generates the static homogeneous magnetic field B_0
 - field strength 0.2 to 3.0 (7.0) Tesla for clinical systems
- **Gradient system (+ Shim coils)**
 - rapidly switchable additional magnetic fields for slice selection and spatial encoding of signals superimposed on static field
 - max. 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



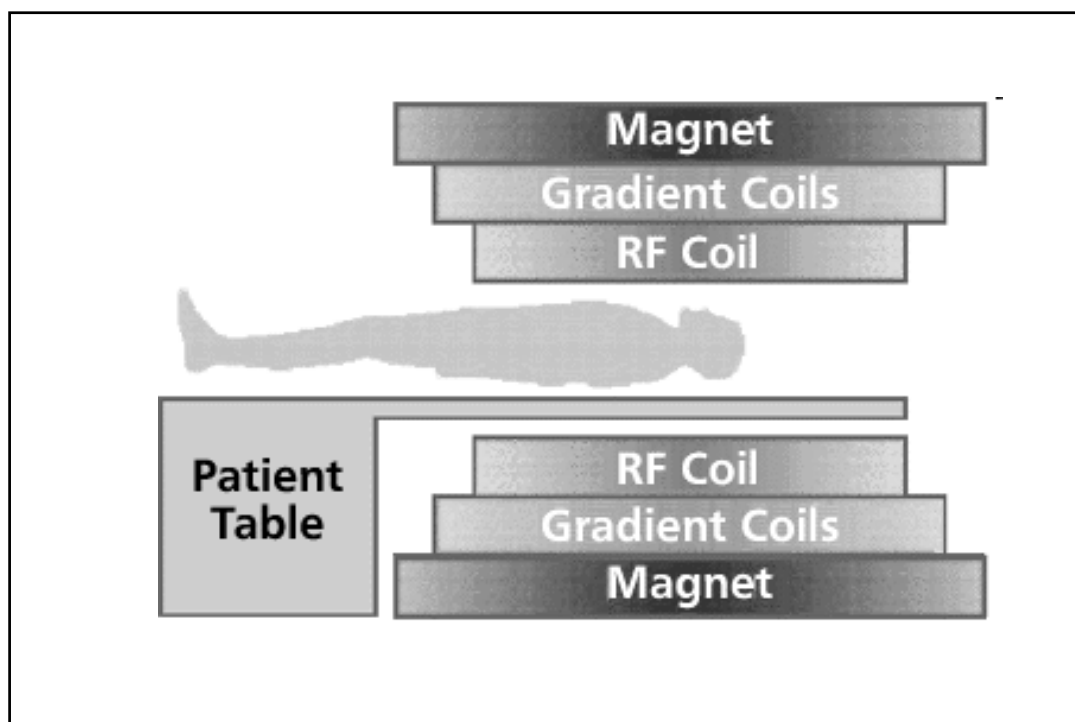
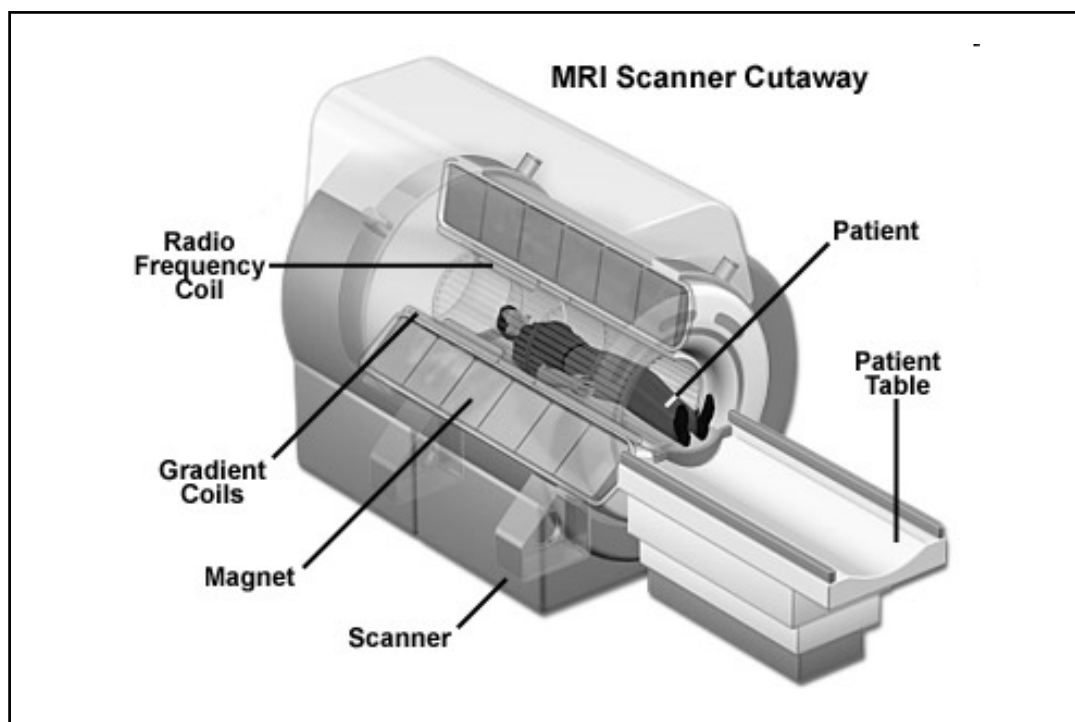
1.5 Tesla,
closed-bore,
superconducting
magnet



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



UKT



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

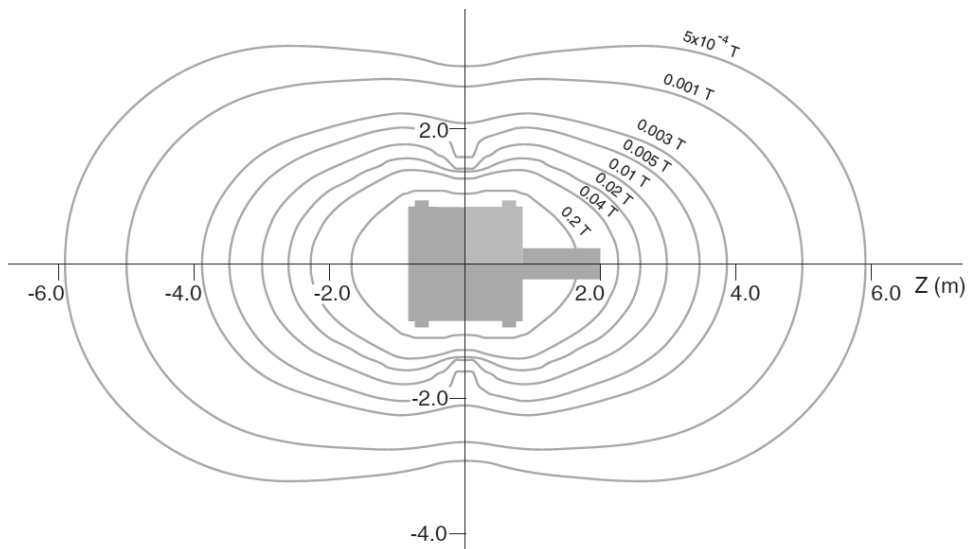
Superconductive magnet

- 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

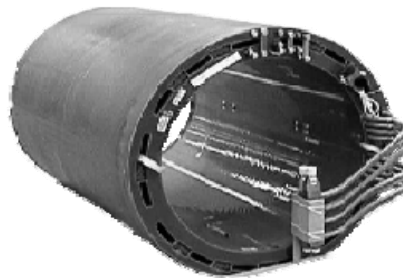


Fringe field of a 3T whole body system



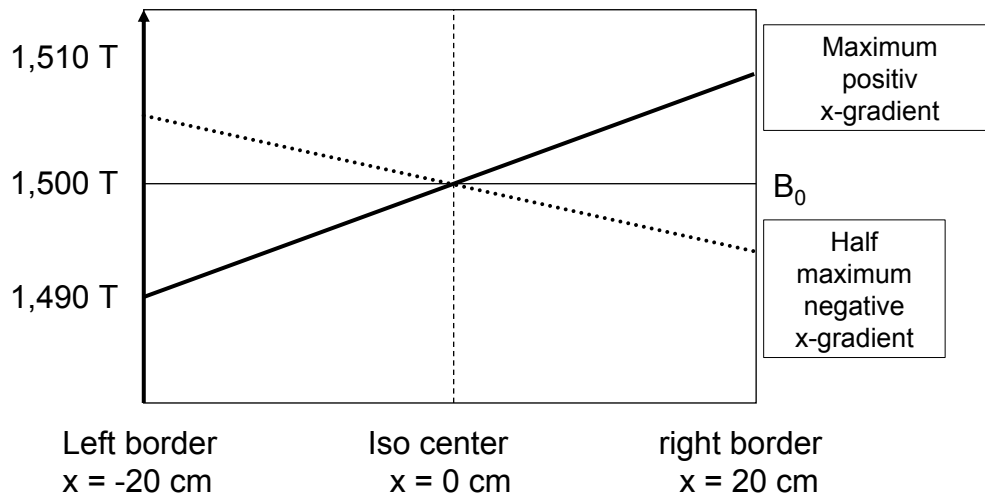
Gradient system

- 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



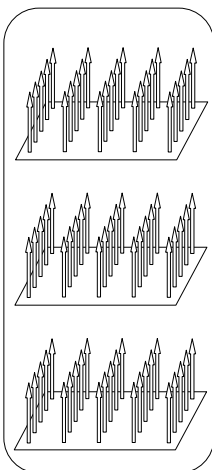
Effect of gradient switching along x-axis

Magnetic field strength

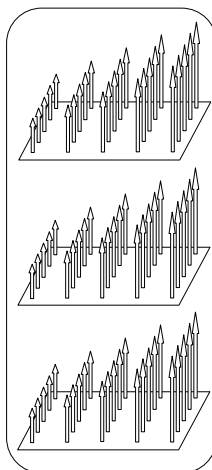


Magnetic field gradients

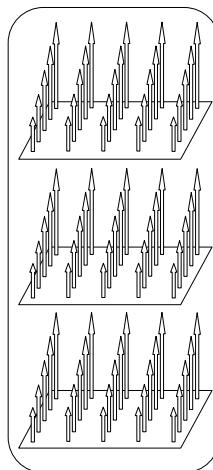
No field gradient



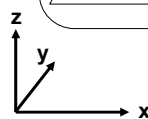
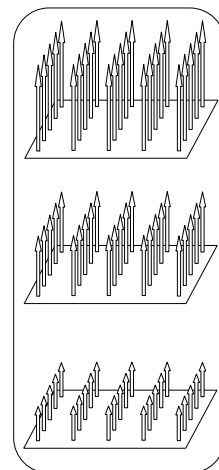
x - gradient



y - gradient



z - gradient



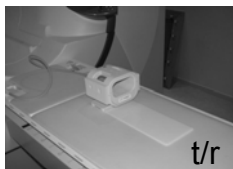
RF transmission

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

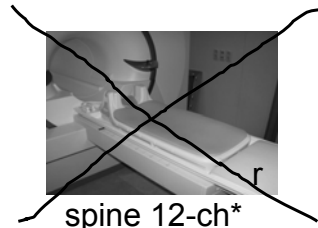
- by the **large transmitter coil inside the casing of the MR unit**,
or
- by **mobile volume coils**, serving as transmitter and receiver as well



wrist/hand 1-ch



knee 1-ch



spine 12-ch*

RF receiver coils

Aims

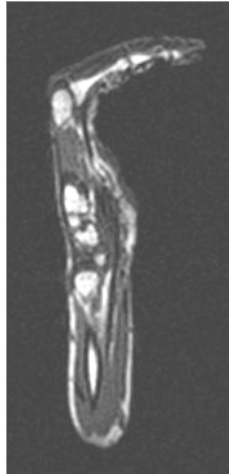
- high sensitivity to low intensity MR signals
- low noise level and low sensitivity to electromagnetic sources in the surroundings and in the coil itself (thermal noise)
- homogeneous level of sensitivity over (large) body regions under investigation

→ Suitable compromises are strongly dependent on the body part under investigation

→ Many different receiver coil systems are available for different examinations

Receiver coils

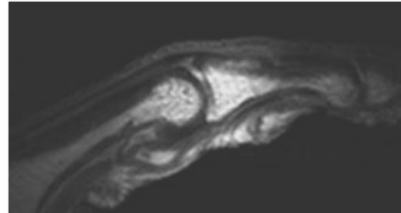
Comparison of large and small single coils



body coil

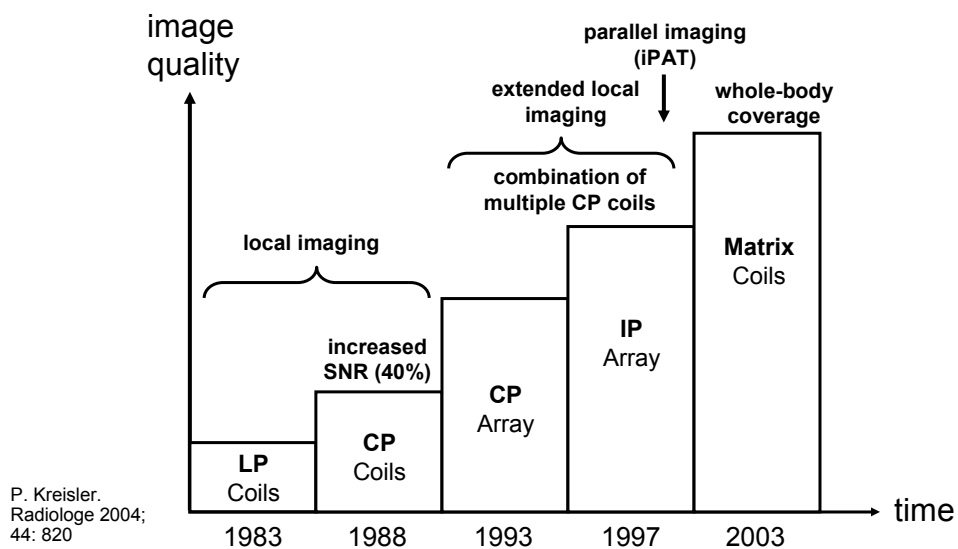


finger coil



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



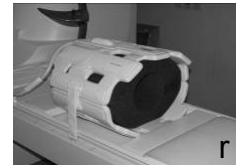
knee 8-ch



spine 12-ch



torso/cardiac 8-ch



head 1-ch (Bruker)

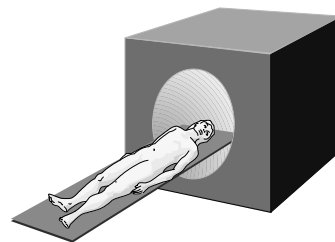


head 1-ch (Siemens)



head 8-ch

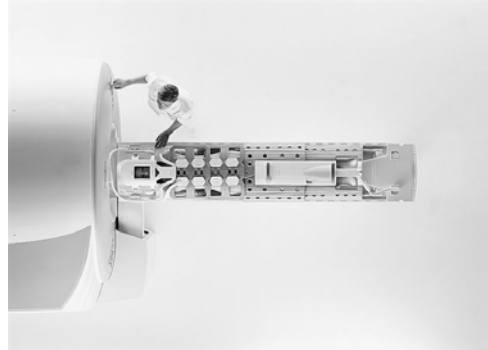
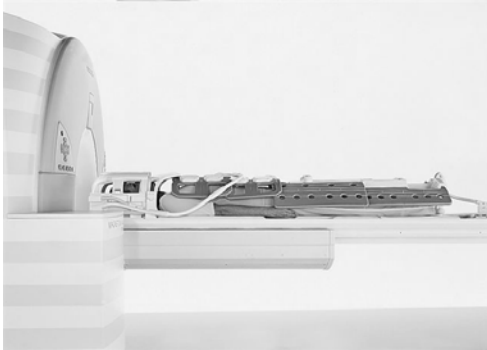
Outline



- 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

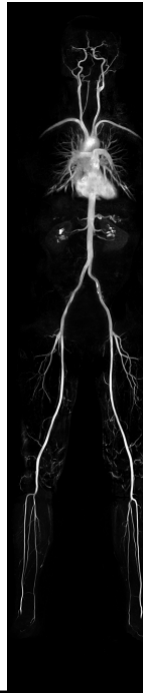


Anatomy

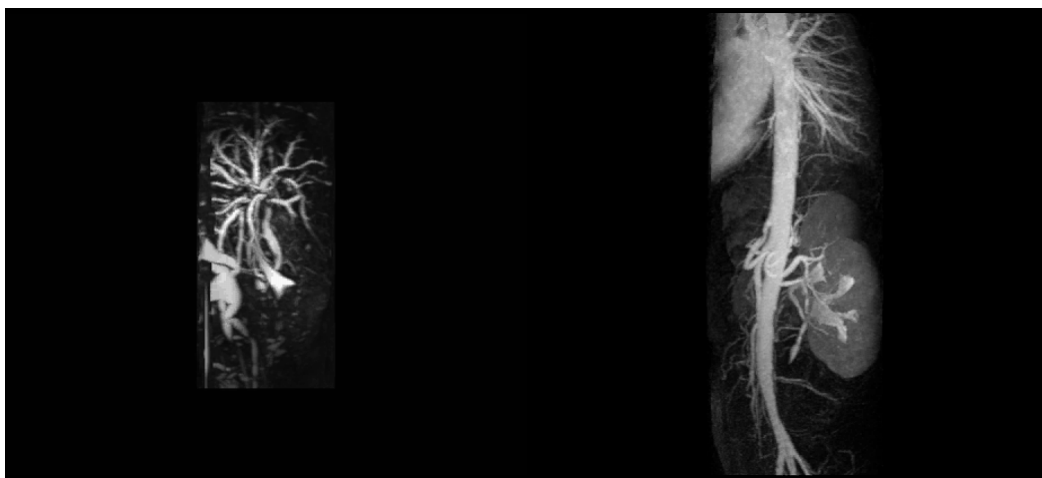




+ Cardiovascular
System



MIP reconstruction of vessels



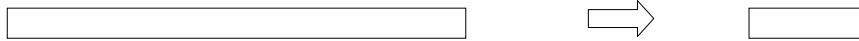
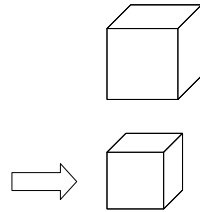
MRCP (T2-w)

MRA (T1-w with contrast medium)

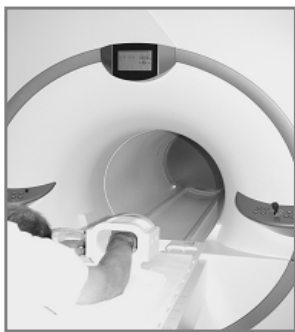
High field systems with 3 T (or even 7 T)

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)



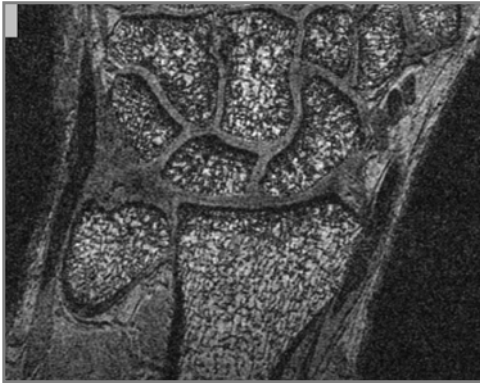
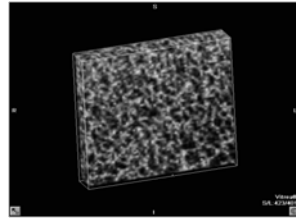
High resolution MRI of wrist bones



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.

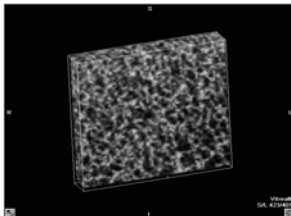
3D FISP sequence with
0,3 mm isotropic resolution
(8 min measuring time)



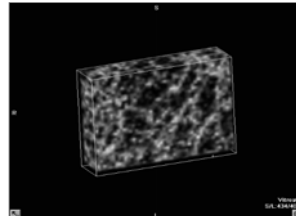
normal



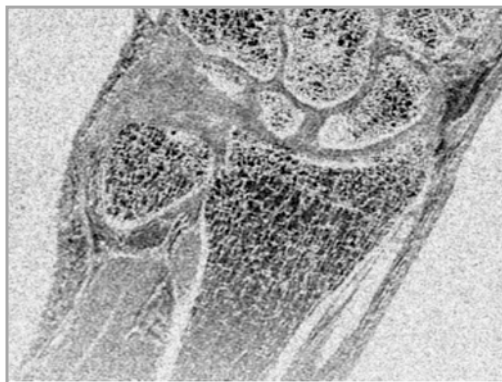
inverted



3D-FISP
0,3 mm isotropic
resolution



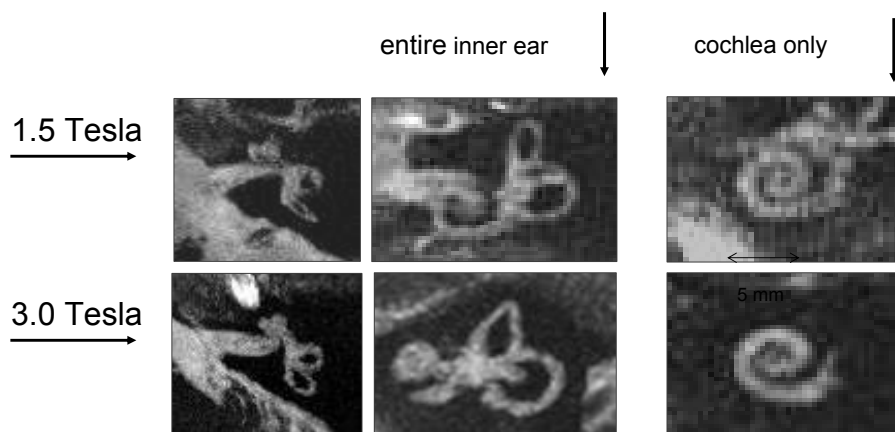
healthy, 35 years, male



osteoporotic, 81 years, male

Visualization of the inner ear and the vestibular apparatus

„Maximum Intensity Projections” (MIPs)



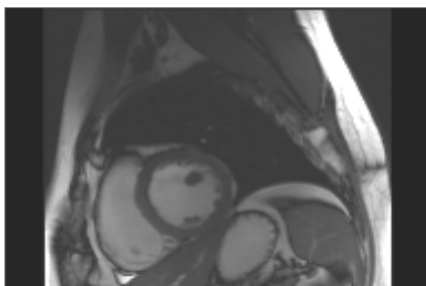
Cardiovascular MRI

Torso 8-channel phased array coil

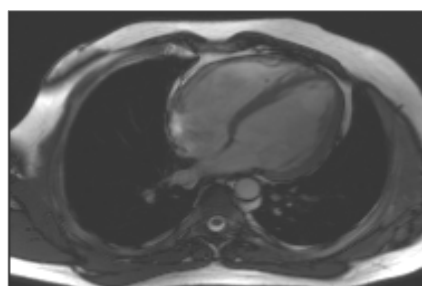
Sequence: cine TrueFISP
 TR = 44,7 ms, TE = 1.7 ms
 SL = 6 mm
 FoV = 350×280 mm²
 Matrix = 192×156
 Flip angle = 50°

20 cardiac phases
 Examination time 12 sec
 EcG-retro-gated
 Breathhold

Courtesy S. Miller, Tübingen



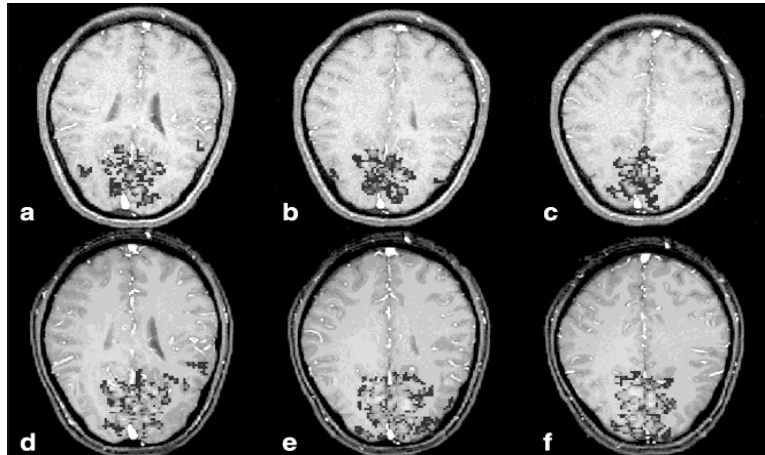
Short axis plane



Long axis plane

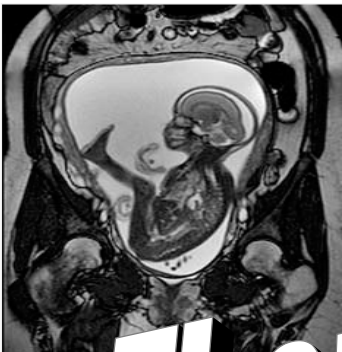
Functional MRI of brain: effects of optical stimulation

1,5 T



3,0 T

Krüger et al., MRM 45:595–604 (2001)



Thank You!