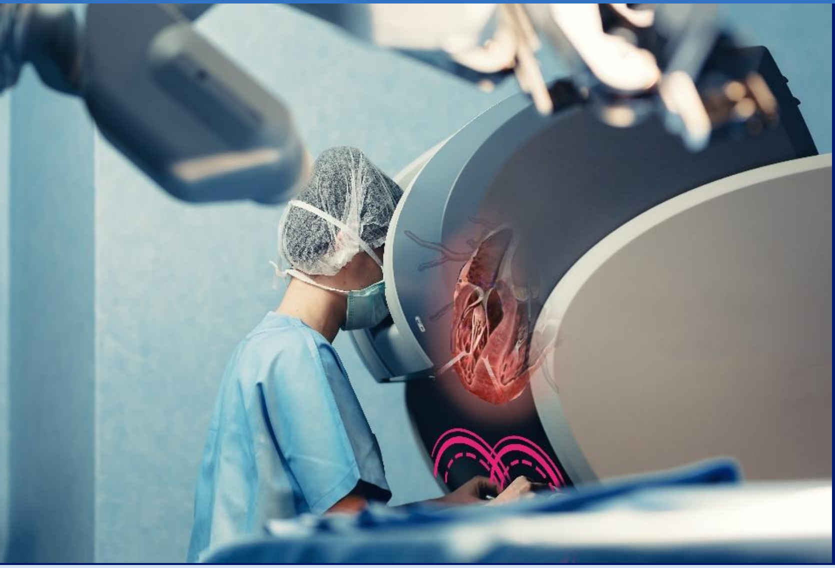
Computer- and robot-assisted Surgery



NCT
NATIONALES CENTRUM
FÜR TUMORERKRANKUNGEN
PARTNERSTANDORT DRESDEN
UNIVERSITÄTS KREBSCENTRUM UCC

getragen von:
Deutsches Krebsforschungszentrum
Universitätsklinikum Carl Gustav Carus Dresden
Medizinische Fakultät Carl Gustav Carus, TU Dresden
Helmholtz-Zentrum Dresden-Rossendorf

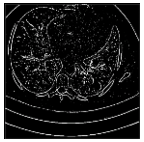
Lecture

Imaging II

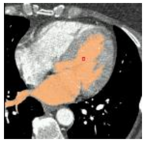
Workflow Computer-assisted Surgery

Image acquisition

Pre-processing

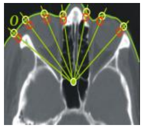


Segmentation

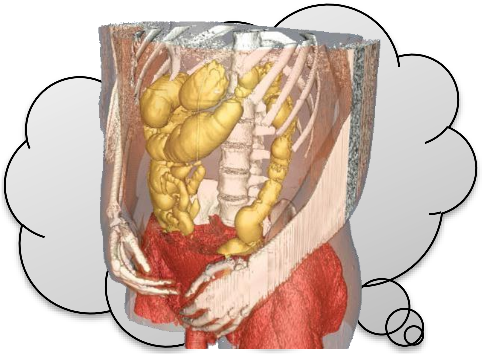


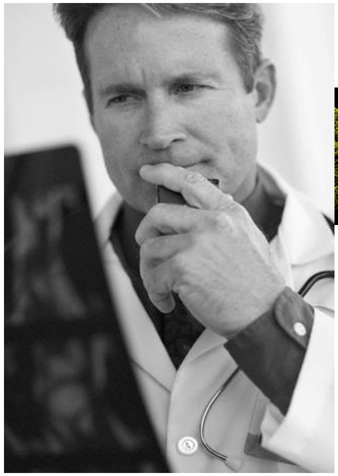
Modelling

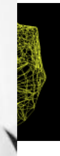
Registration



Visualisation

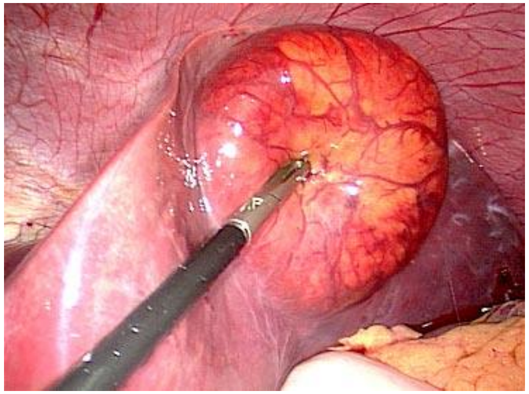






Content

- Magnetic resonance imaging
  - Physical principles: nuclear spin
  - Signal generation: longitudinal and transverse magnetisation
  - Signal measurement: relaxation processes
  - Signal coding: gradient fields
  - signal reconstruction
- Endoscopy imaging
  - Systems
  - Applications
  - Minimal-invasive surgery



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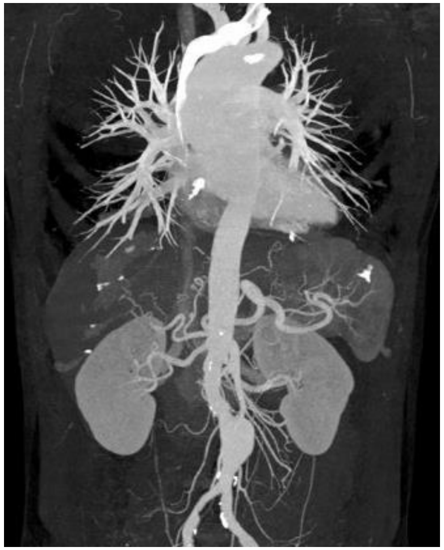
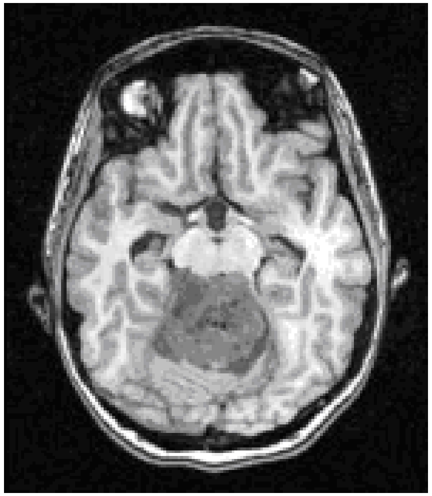
Tomographic Imaging

Computed tomography



Magnetic resonance imaging



Tomographic imaging provides cross-sectional images or slices of the human body

Recall CT

Principle

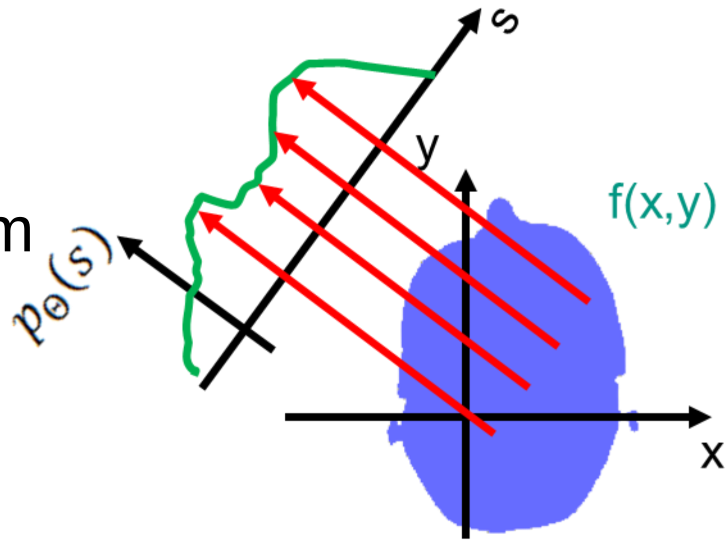
- Based on X-rays
- Many X-ray measurements taken from different angles
- Image reconstruction:
  - Iterative reconstruction
  - Filtered-Backprojection

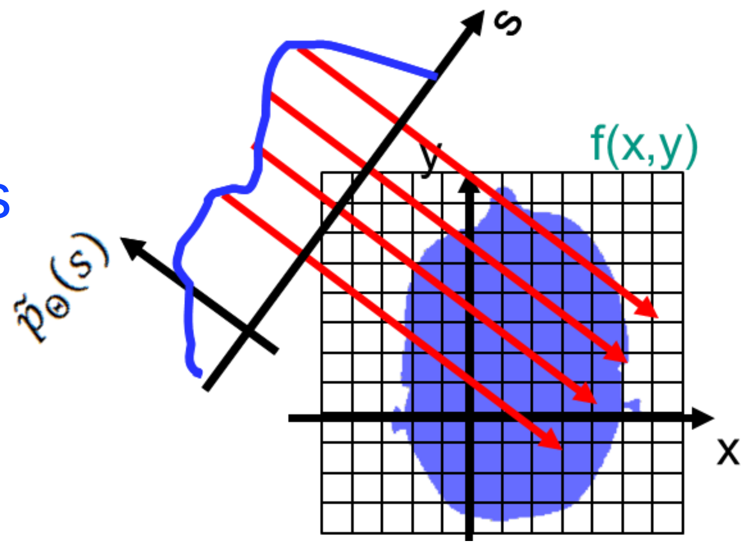
Advantages

- Good visualisation of bone structures
- Very good resolution, very fast acquisition time

Disadvantage

- Radiation exposure





MAGNETIC RESONANCE IMAGING (MRI)

MRI - History

- Nuclear magnetic resonance 1946 (Bloch, Purcell)
- First whole body imaging in 1977 ca. 5 h.
- Noble price in medicine for the development of the MRI

Paul Lauterbur

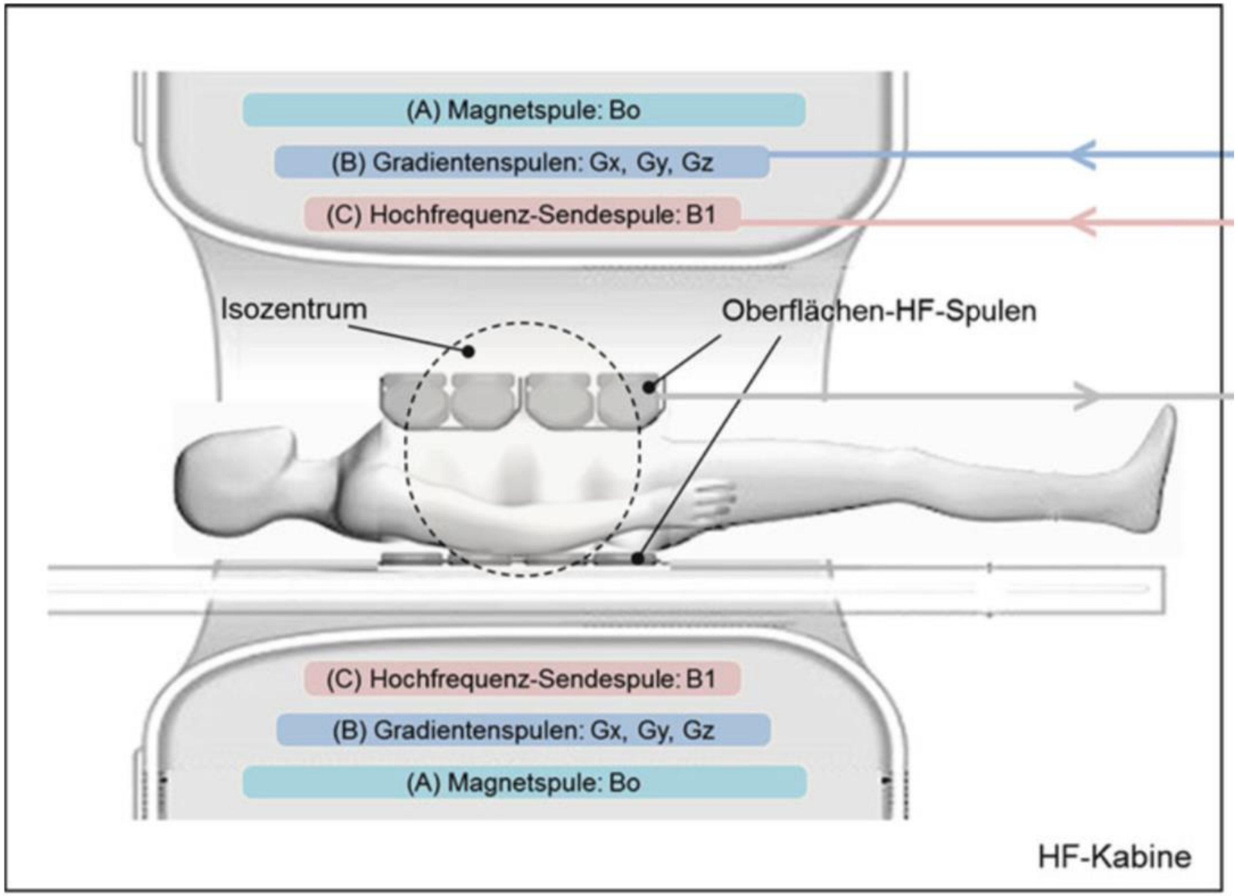
Peter Mansfield

P. Lauterbur, P. Mansfield: MRT-Bildgebung mit Gradienten-Feldern (1976)

MRI - Principle

- Based on quantum properties of nuclear spins
- Excitation properties using radio frequency
- Measurement of tissue relaxation

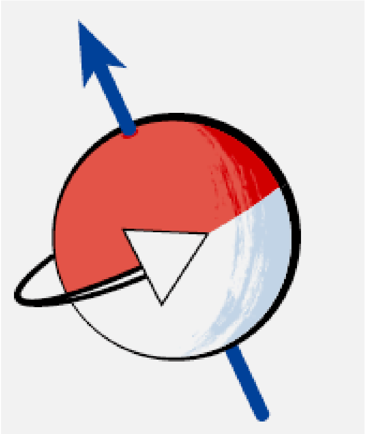
MRI - Scanner



- Usually a tube-shaped system
- Strength of magnetic field: 1.5 Tesla or 3.0 Tesla
- Superconducting magnets → no electrical resistance

Schegel et al, Medizinische Physik, 2018

Physical Principle: Nuclear Spin



Source: Siemens Medical

MRI requirement: nuclear magnetic moment

- Atomic nucleus needs to have 2 properties:
  - Spin
  - Charge

- Atomic nucleus with an odd number of protons or neutrons have a spin

- Atomic nucleus with a spin have a nuclear magnetic moment (otherwise magnetic moment is zero)

$$\vec{\mu} = \gamma \vec{J} = \gamma \hbar \vec{I}$$

gyromagnetic ratio (isotope specific)

Schegel et al, Medizinische Physik, 2018

Physical Principle: Nuclear Spin

MRI requirement: nuclear magnetic moment

- Good MR nuclei are hydrogen (^{1}H), carbon (^{13}C), ^{19}F, ^{23}Na, ^{31}P

Kern	Kernspin I	Gyromagnetisches Verhältnis/2π [MHz/T]	Natürliche Häufigkeit
^{1}H	1/2	42,577	99,9885 %
^{31}P	1/2	17,25	100 %
^{23}Na	3/2	11,27	100 %
^{13}C	1/2	10,71	1,07 %
^{19}F	1/2	40,08	100 %
^{17}O	5/2	5,772	0,037 %
^{129}Xe	1/2	11,78	26,4 %
^{3}He	1/2	32,43	0,000137 %

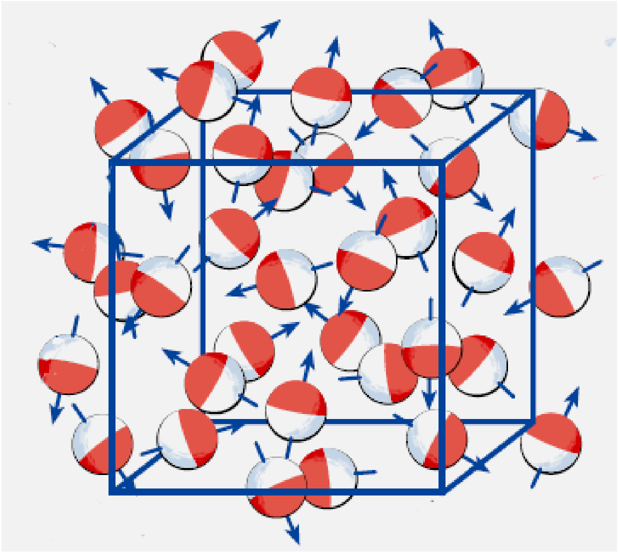
Schegel et al, Medizinische Physik, 2018

Nuclear Spin

Ground state– without external magnetic field (B_0=0)

- nuclear magnetic moments are randomly orientated (due to the thermal movement)

  →non observable magnetisation

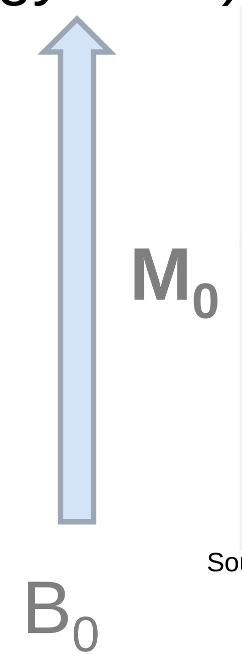


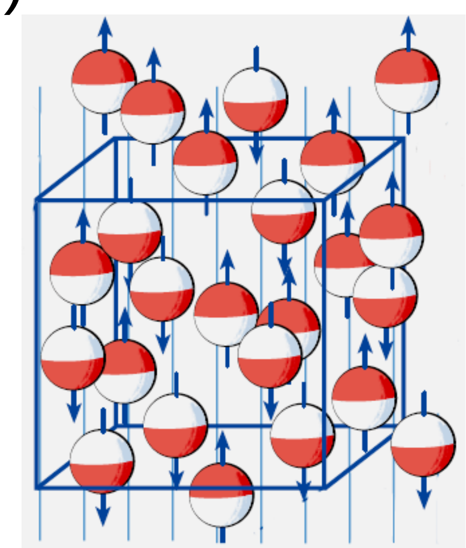
Source: Siemens Medical

Nuclear Spin

Excited state–with magnetic field (B_0>0)

- nuclear magnetic moments align with the magnetic field
- measurable net magnetic moment M_0 in direction of B_0
- Alignment: parallel Spin Up (low energy state) or anti-parallel Spin Down (high energy state)
- Ratio between both states is not 50:50
  - weak magnetisation M_0
- T=300 K (room temperature)
  B_0=1.41 T
  $\Rightarrow N_{up}/N_{down} \approx 0,9999904$
  Every 100 000-te proton contributes to the signal





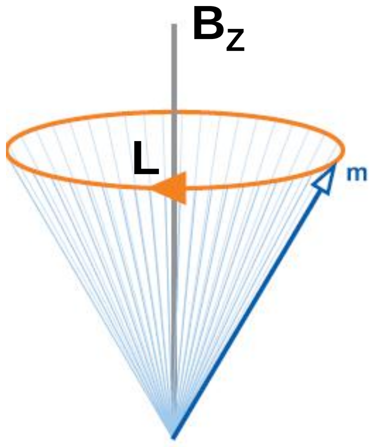
Source: Siemens Medical

Precession

- Protons experience a torque in perpendicular to the direction of the applied magnetic field that causes precession
- Precession occurs with an angular frequency ω_0 (Larmor frequency):

$$\omega_0 = \gamma B_0$$

- Proportional to the magnetic field strength B_0 and gyromagnetic ratio

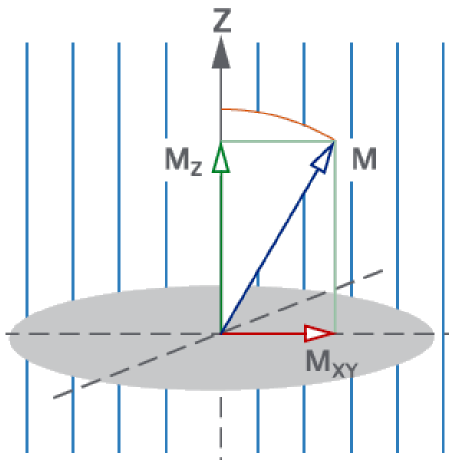


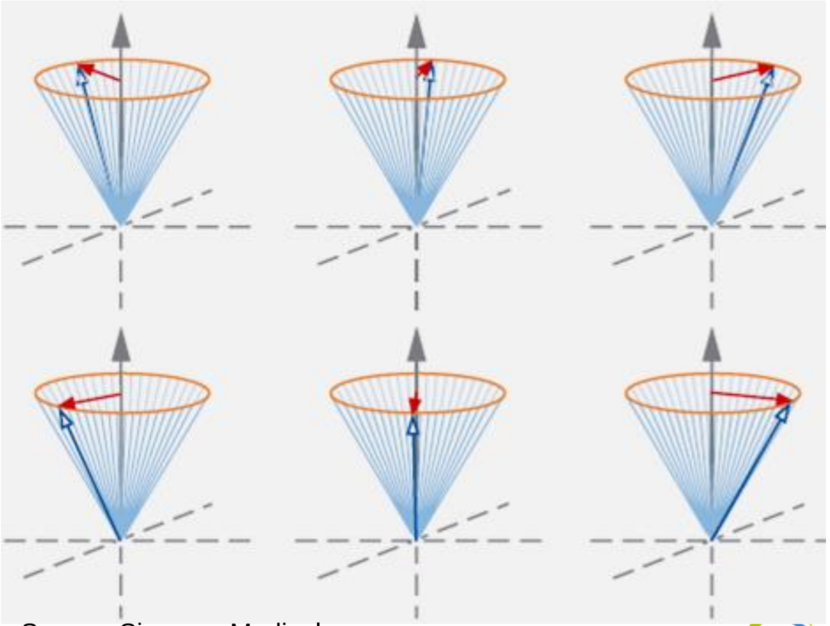
Source: Siemens Medical

Precession

State of identical atomic nucleus in the magnetic field B_0

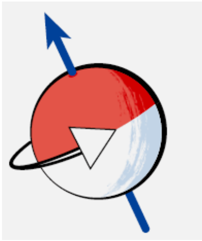
- Spins precess with the same Larmor frequency
- Magnetic moment of each spin has a longitudinal and a transverse component
- But: phase position is arbitrarily
  - → No transverse magnetisation
  - → No measurable signal



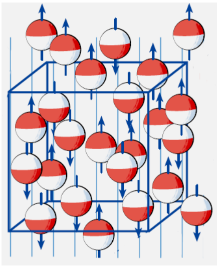


Source: Siemens Medical

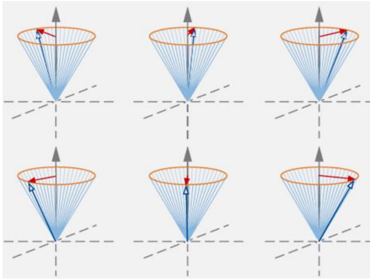
MRI - Summary I



- Some atomic nuclei have a nuclear spin



- Spins align in the magnetic field
  - Two possible (energy) states
- Spins precess with the same Larmor frequency but different phase position



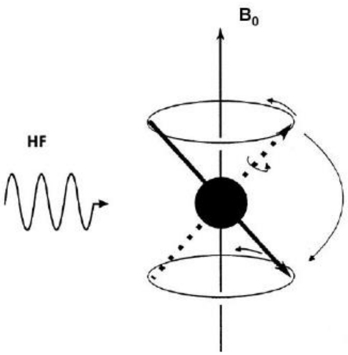
Source: Siemens Medical

- How is a signal generated?

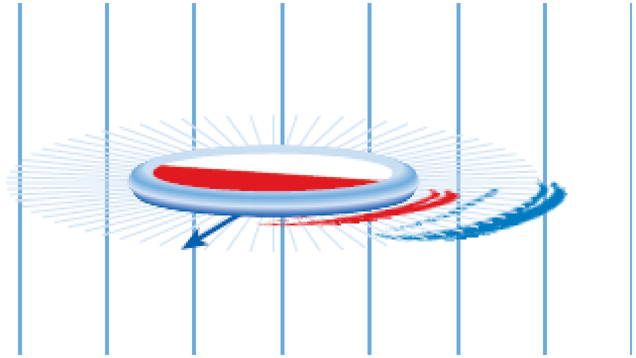
→ Radio frequency (RF) pulse

Radio frequency (RF) pulse

- Aim: Deflection of magnetisation from idle position
- Radio frequency (RF) pulse for given flip angle α
  - Short period of high intensity radio-waves at a frequency close to the Larmor frequency $\omega_{HF} = \varpi_0$
  - Generates a circular magnetic field B_{XY} in the *x,y*-direction



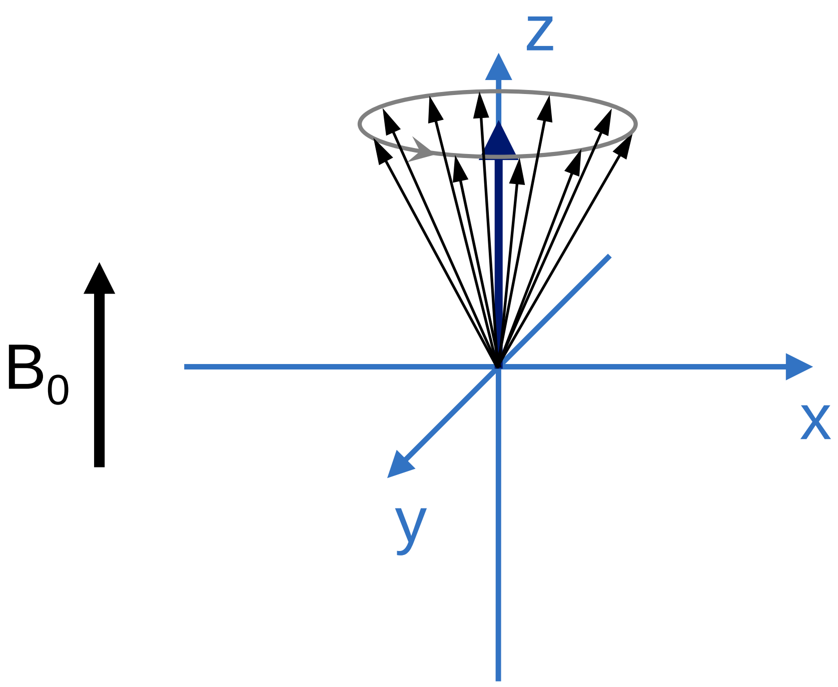
- Two effects:
  - Energy input: Spins are deflected from low to higher energy level (spin up to spin down)
    → Change in the longitudinal magnetisation M_0
  - Spins have same phase position
    → Change in the transverse magnetisation M_{xy}



Source: Siemens Medical

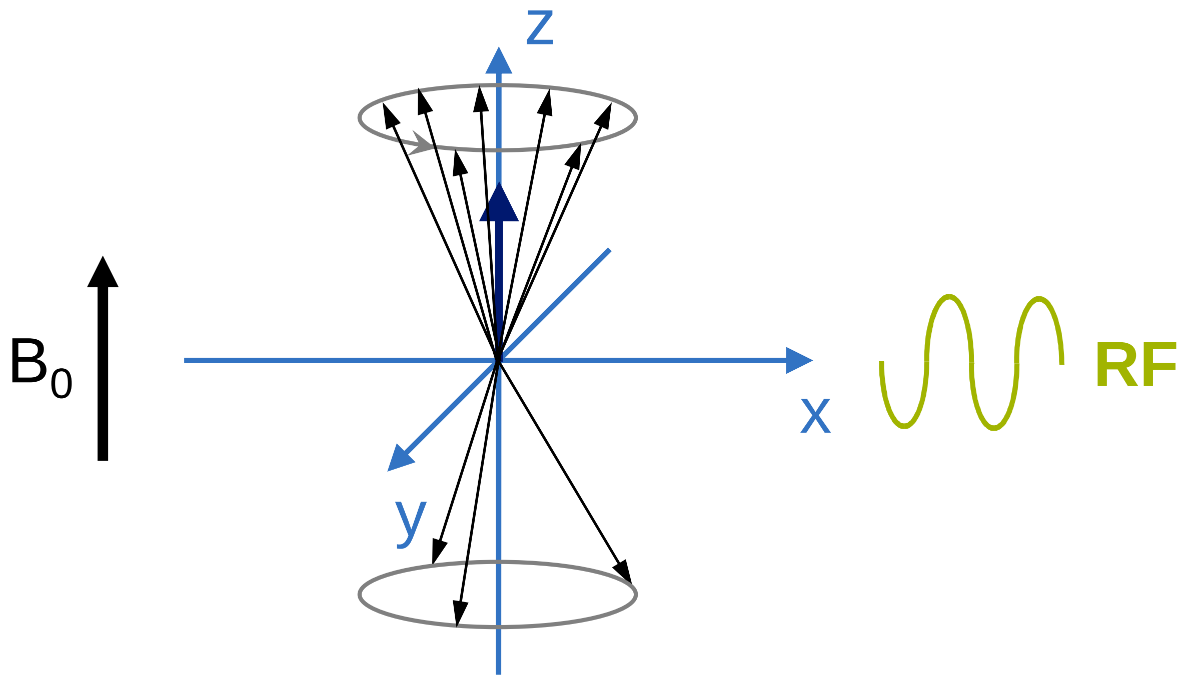
Longitudinal Magnetisation

- Before RF pulse:
  - Longitudinal magnetisation is maximal
  - Spins precess around the magnetic field B_0



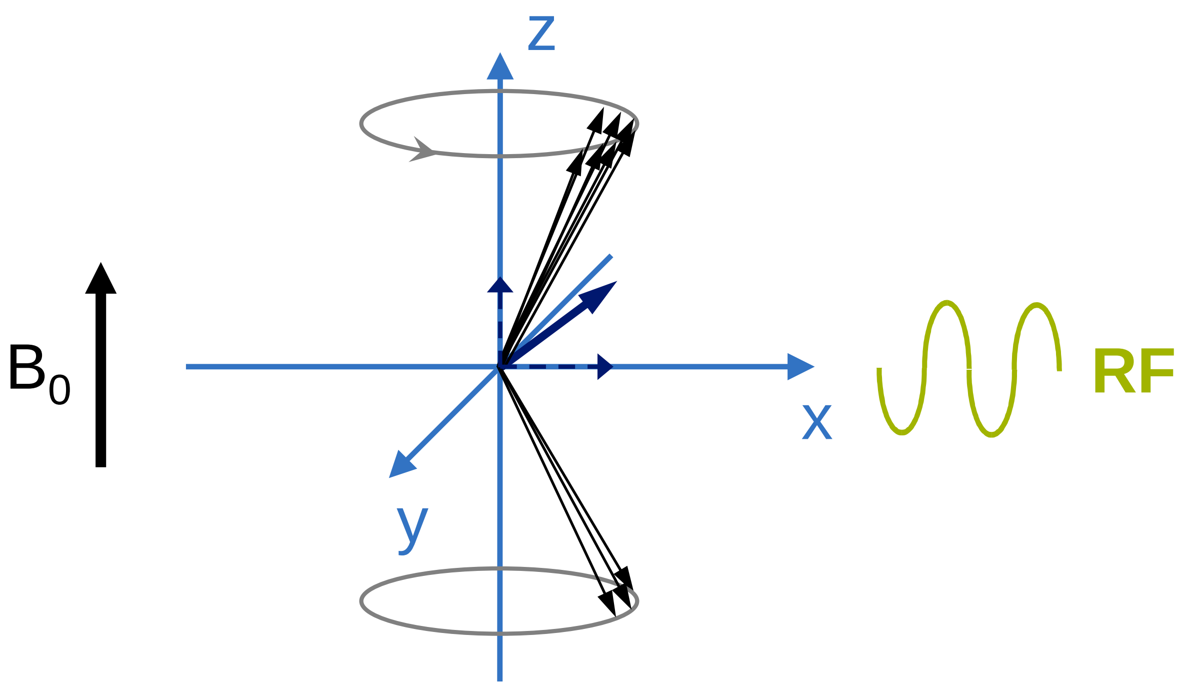
Transverse Magnetisation

- During RF pulse: α=90°
  - Individual spins are flipped down, raised to an energetically higher level
  - Longitudinal magnetisation becomes smaller



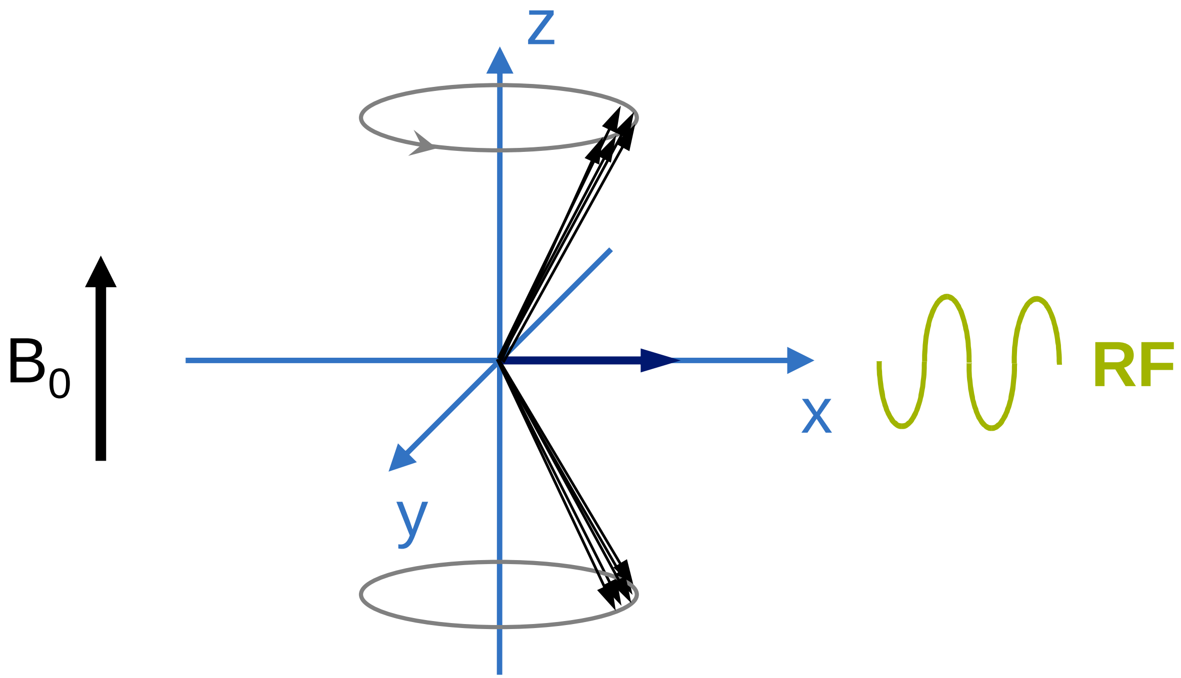
Transverse Magnetisation

- During RF pulse: α=90°
  - Individual spins are flipped down, raised to an energetically higher level
  - Longitudinal magnetisation becomes smaller
  - Transverse magnetisation becomes higher



Transverse Magnetisation

- During RF pulse: α=90°
  - Spins have the same phase position
  - Transverse magnetisation is equal to longitudinal magnetisation
  - Longitudinal magnetisation is zero



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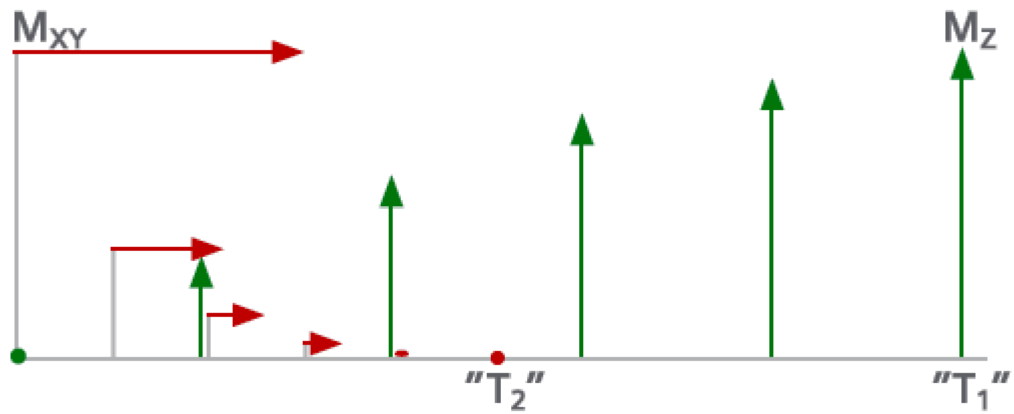
Nuclear Magnetic Relaxation

- Relaxation = “recovery”
- Immediately after the α=90° pulse:
  - Spins return to their equilibrium state → Relaxation
- Two effects occur:
  - **Spin-lattice Relaxation**: Individual spins "fold" from the energetically high (antiparallel) to the energetically low (parallel) state

    → Longitudinal magnetisation M_z>0
  - **Spin-Spin Relaxation**: Spins no longer in phase, they diverge

    → Transverse magnetisation M_{xy}=0

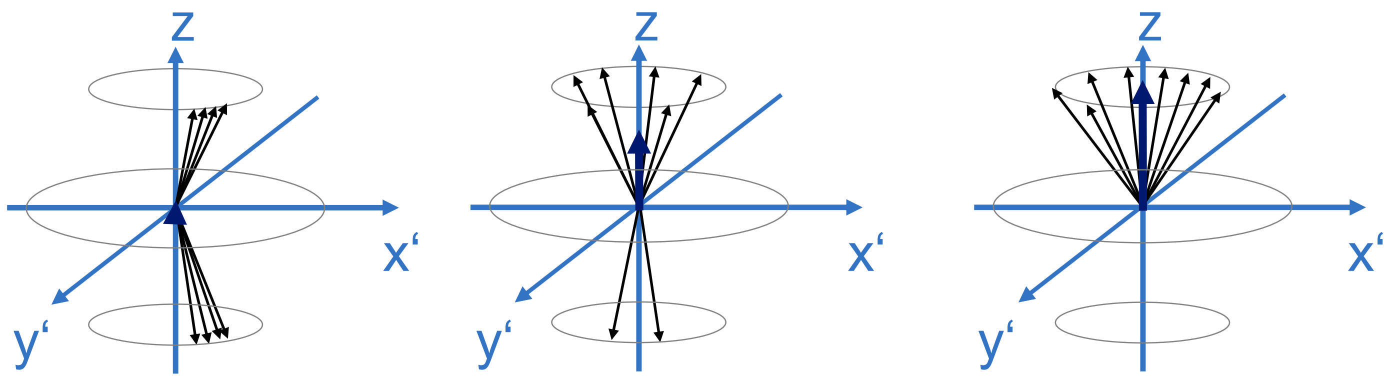


Source: Siemens Medical

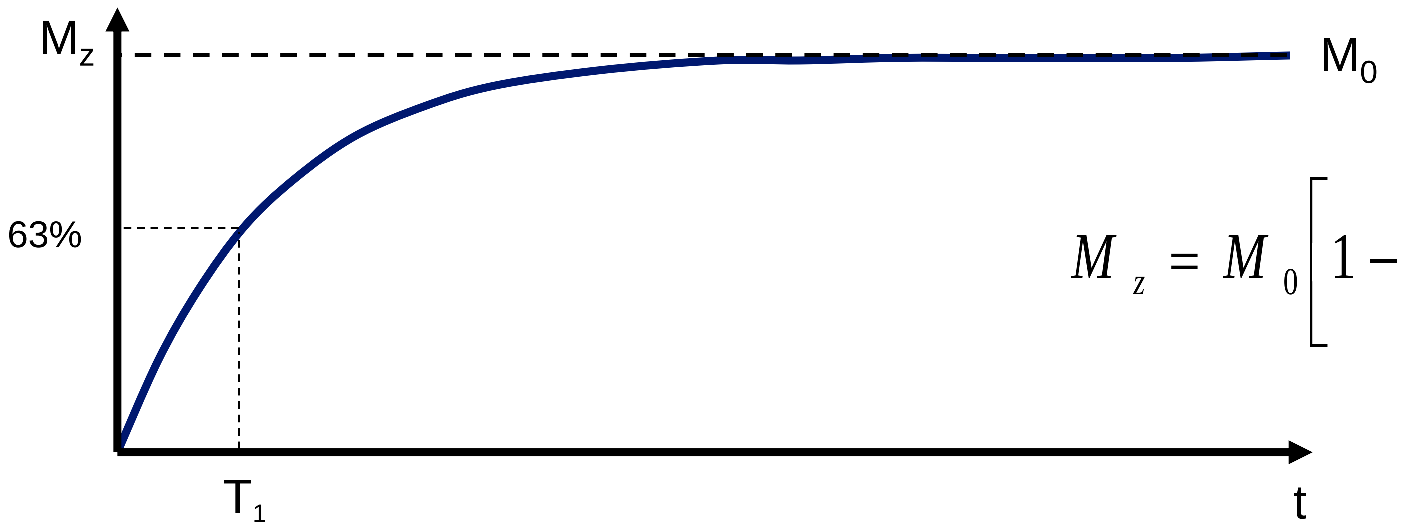
Spin-lattice Relaxation

- After RF pulse:
  - Interaction with surrounding atoms
  - Thermal equilibrium between atoms in the low and high energy levels (i.e., energy dissipation)
  - Longitudinal magnetisation builds up exponentially with the time constant T_1 (longitudinal relaxation time)

Spin-lattice Relaxation



Longitudinal magnetisation

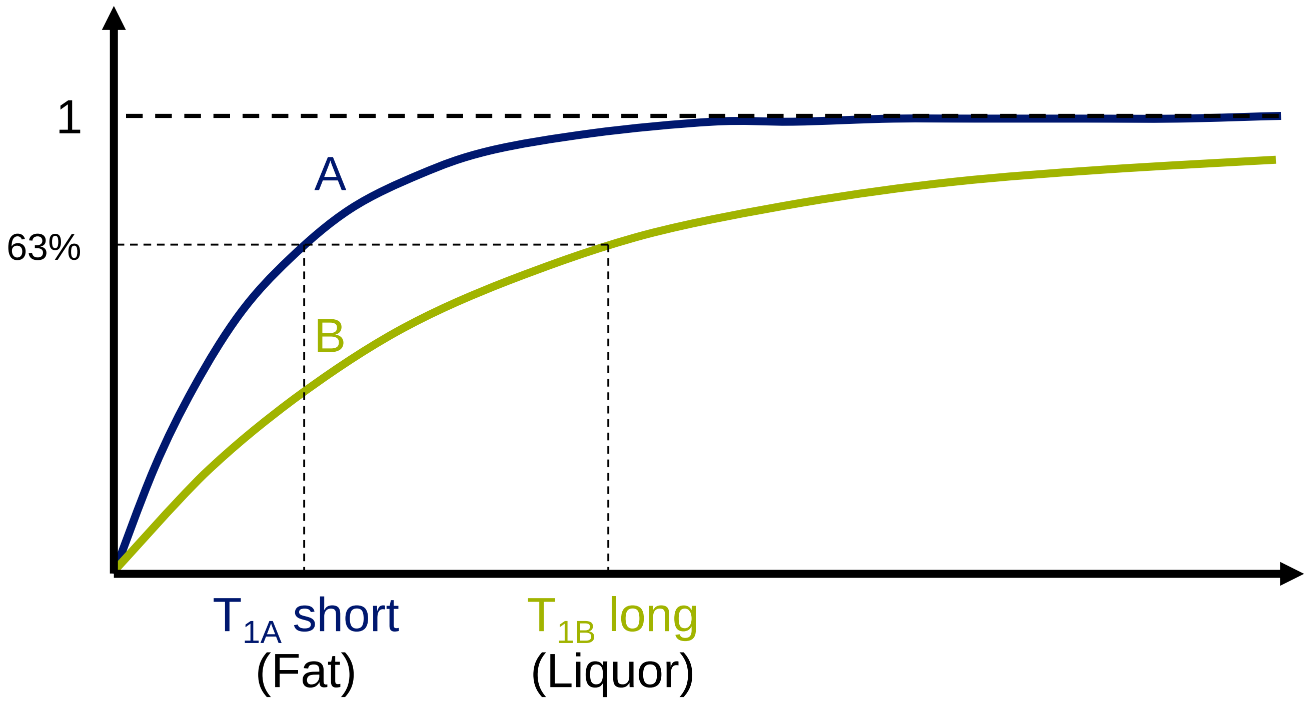


$$M_z = M_0\left[1 - \exp\left(-\frac{t}{T1}\right)\right]$$

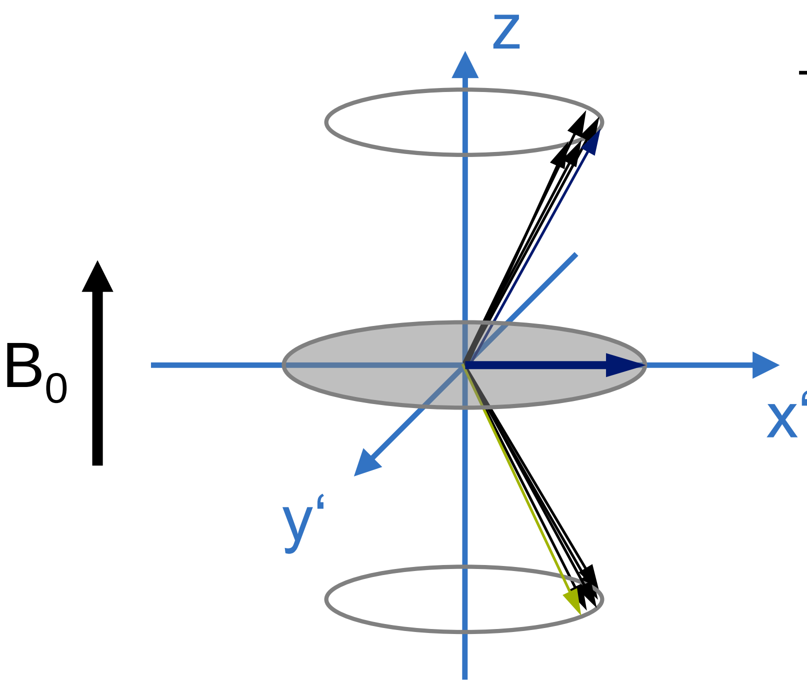
NCT

Spin-lattice Relaxation

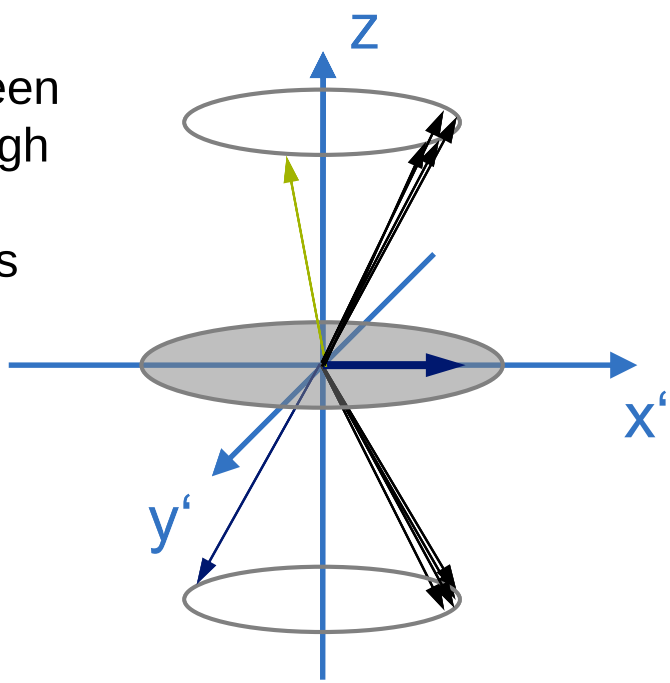
- Each tissue has its own T_1 time
  - Time after which 63% of the original longitudinal magnetisation has been restored



Spin-Spin Relaxation



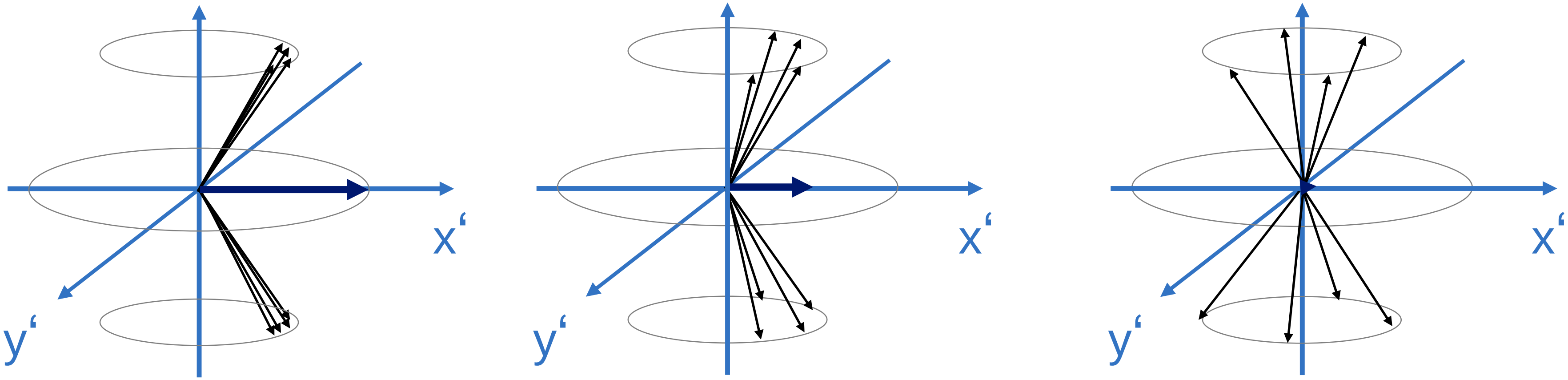
Transitions between spin states through local inhomogeneity's

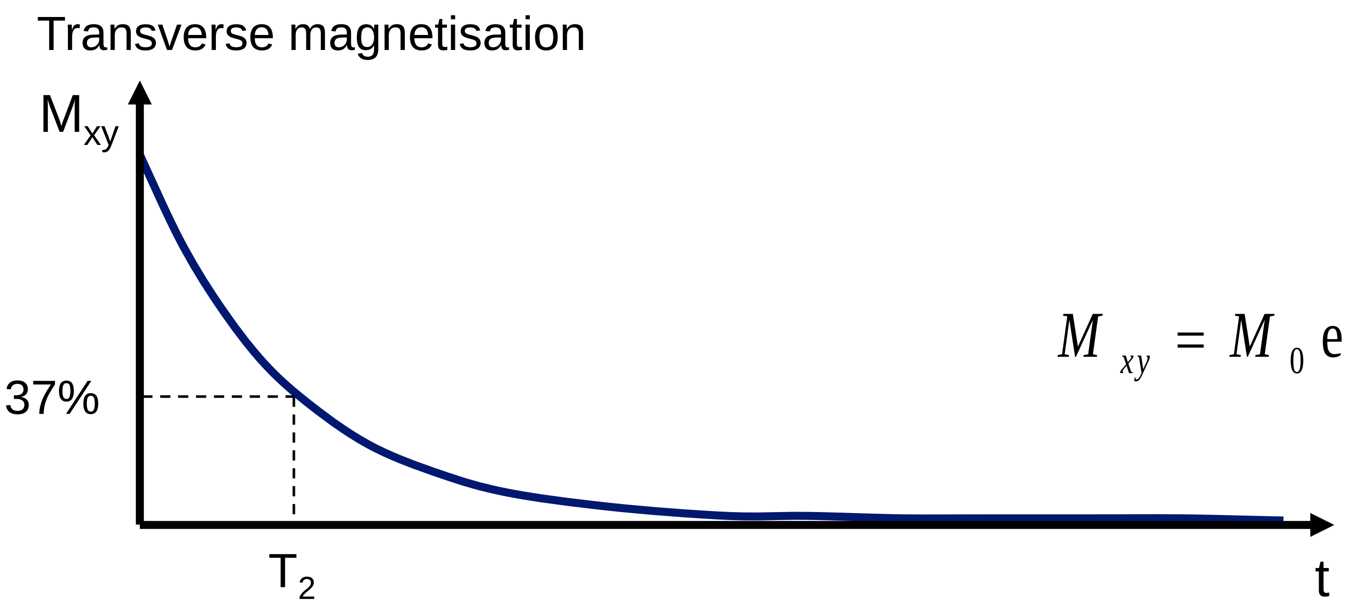


Max. Phase coherence
Max. transverse magnetisation M_{xy} directly after 90° RF pulse

Loss of phase coherence & transverse magnetisation M_{xy} through spin transitions (no changing the energy balance)
→T_2 relaxation

Spin-Spin Relaxation

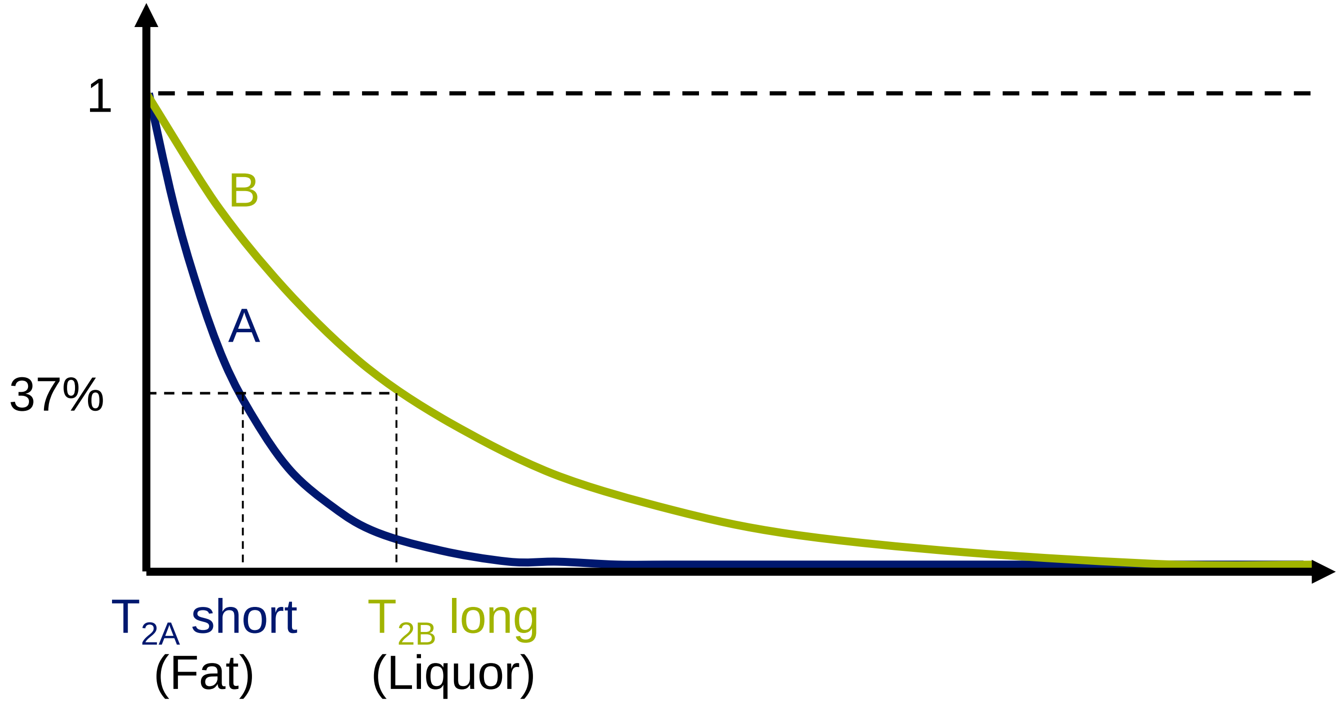




$$M_{xy} = M_0 \exp\left(-\frac{t}{T2}\right)$$

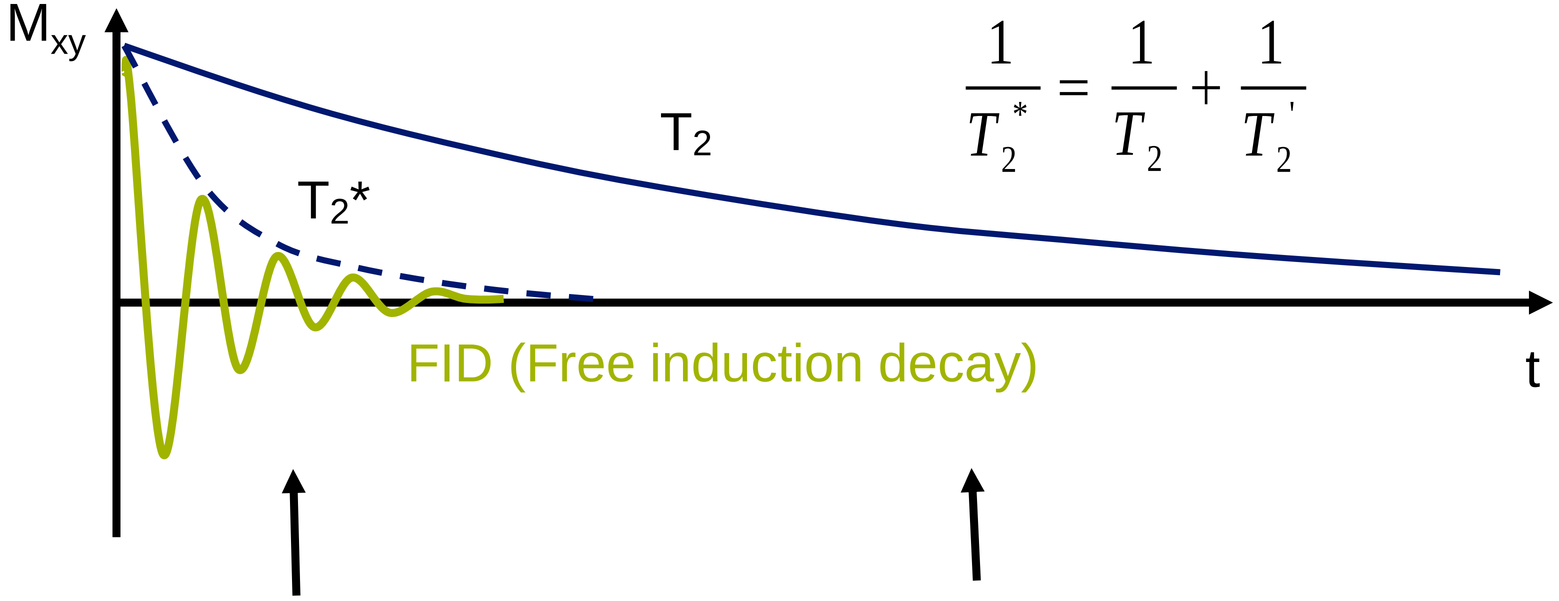
Spin-Spin Relaxation

- Each tissue has its own T_2 time
  - Time after which the original transverse magnetisation has dropped to 37%



Spin-Spin Relaxation

- Spin-spin relaxation is really caused by:
  - Spin-spin interactions (T_2)
  - Macroscopic magnetic field inhomogeneity's (T_2*)



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

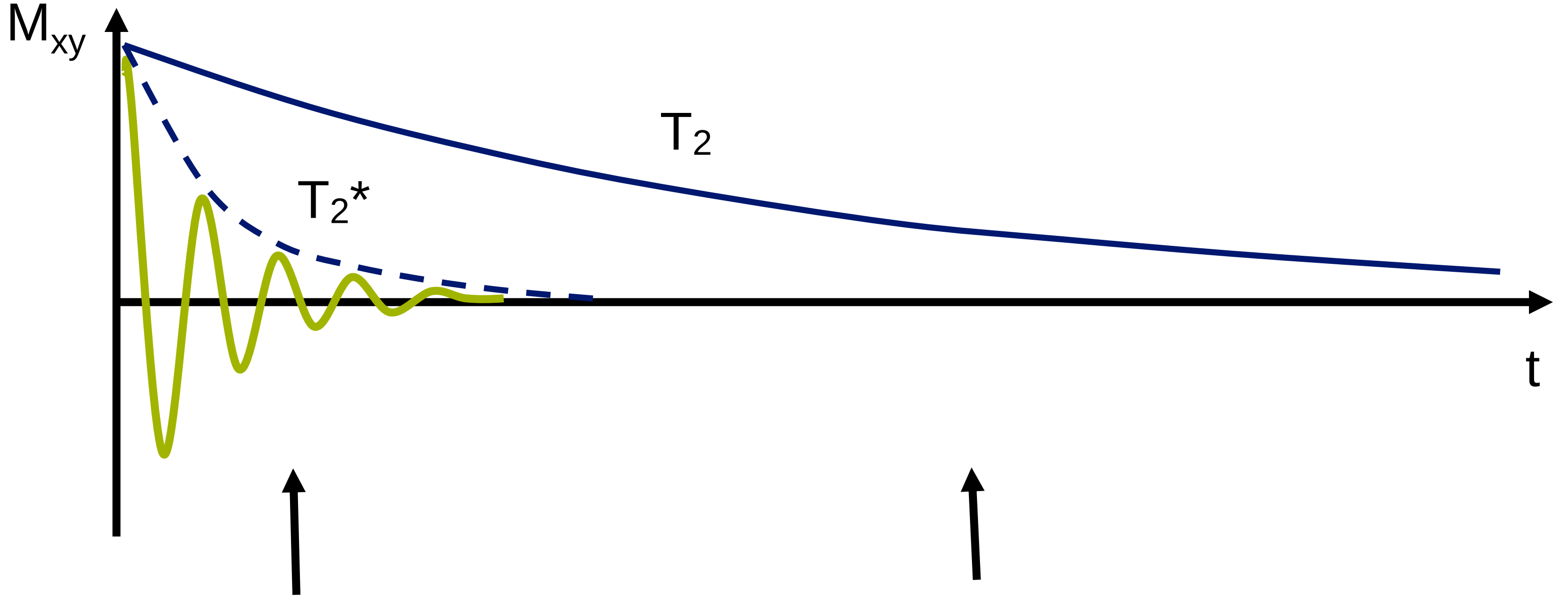
Signal decays very fast with T_2* macroscopic magnetic field inhomogeneity's

How can the signal be restored at this point?

MRI – Summary II

- Behaviour of the nuclear spins during and after the RF pulse
  - First effect: RF pulse disturbs balance of spins
  - Second effect: spins precess in phase
- After RF α=90° :
  - Longitudinal magnetisation $M_Z=0$
  - Transverse magnetisation $M_{XY}=max$
- Two relaxation processes with times T_1 and T_2
  - T_1 significantly greater than T_2
- Duration of relaxation depending on the tissue

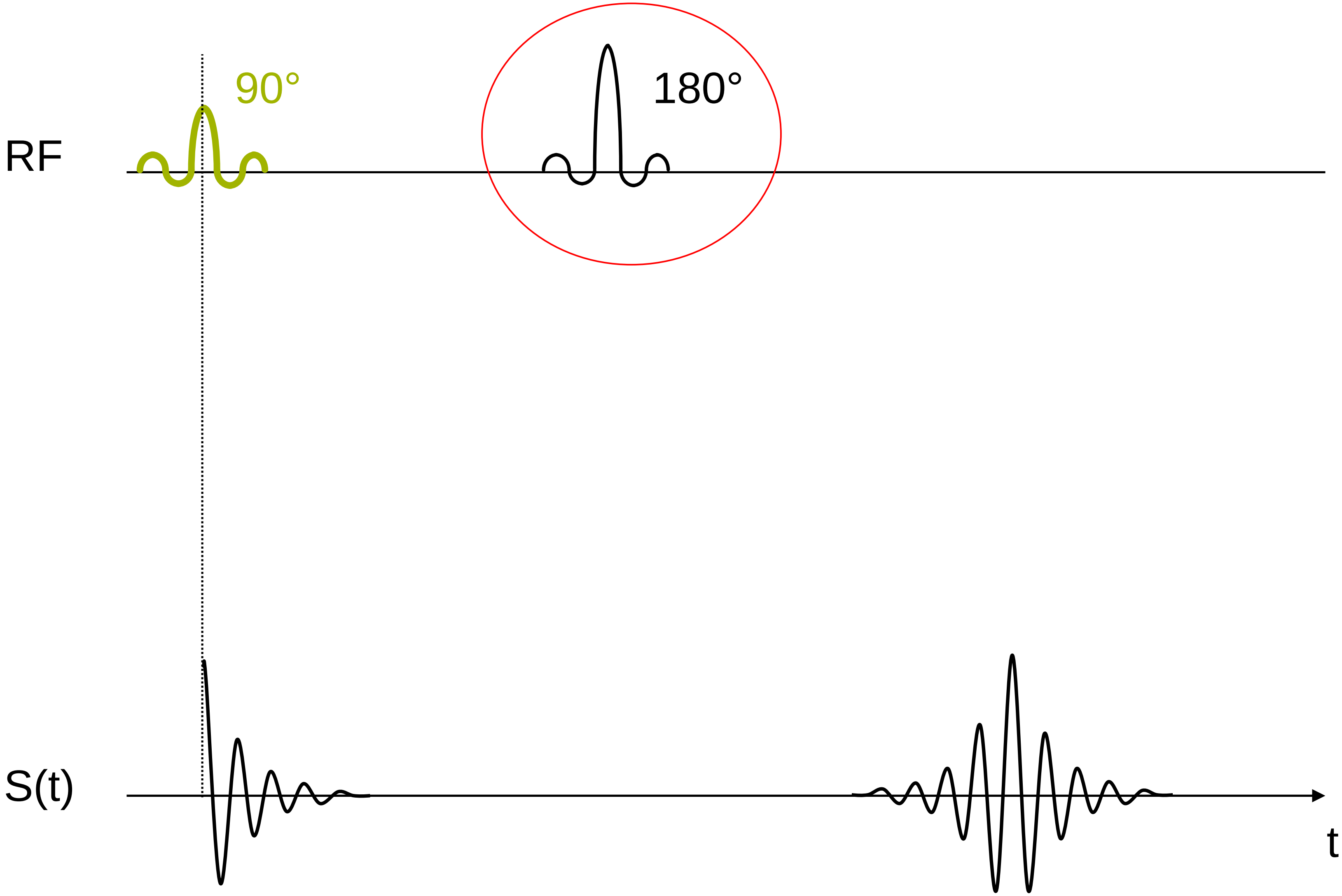
MR Image Sequences – Spin Echo



Signal decays very fast with T_2*
macroscopic magnetic field inhomogeneity's

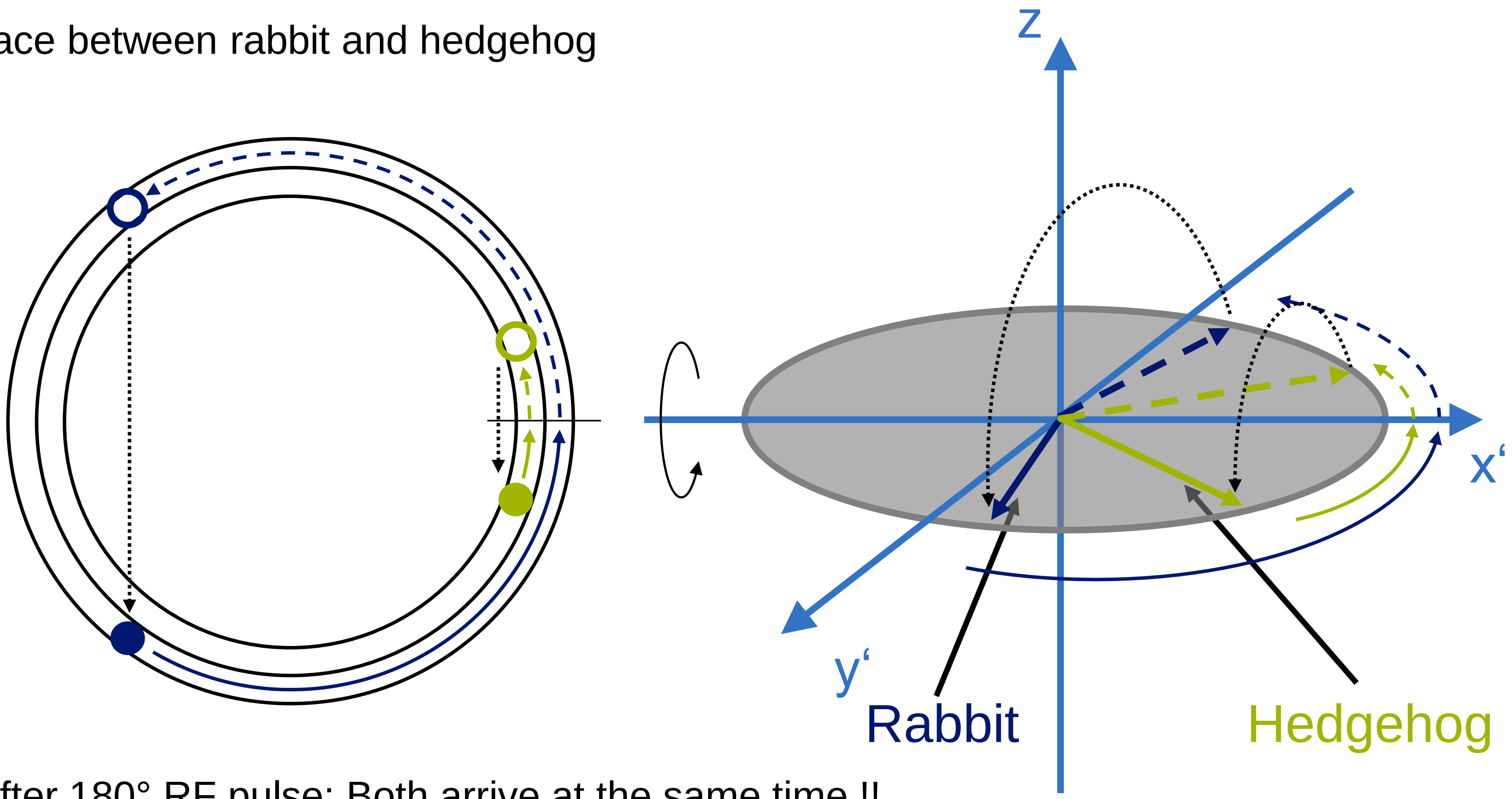
How can the signal be restored at this point?

MR Image Sequences – Spin Echo



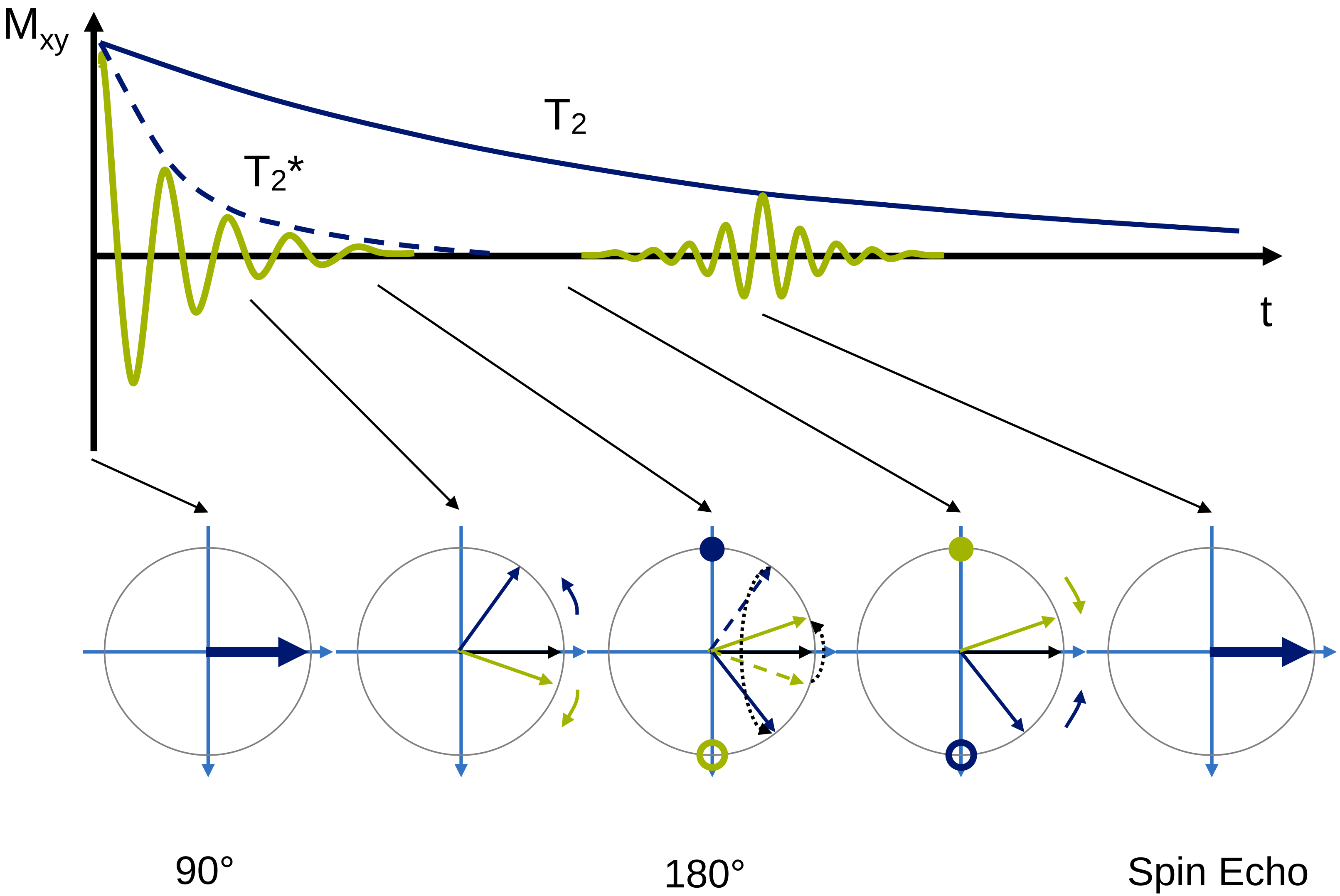
MR Image Sequences – Spin Echo

Race between rabbit and hedgehog

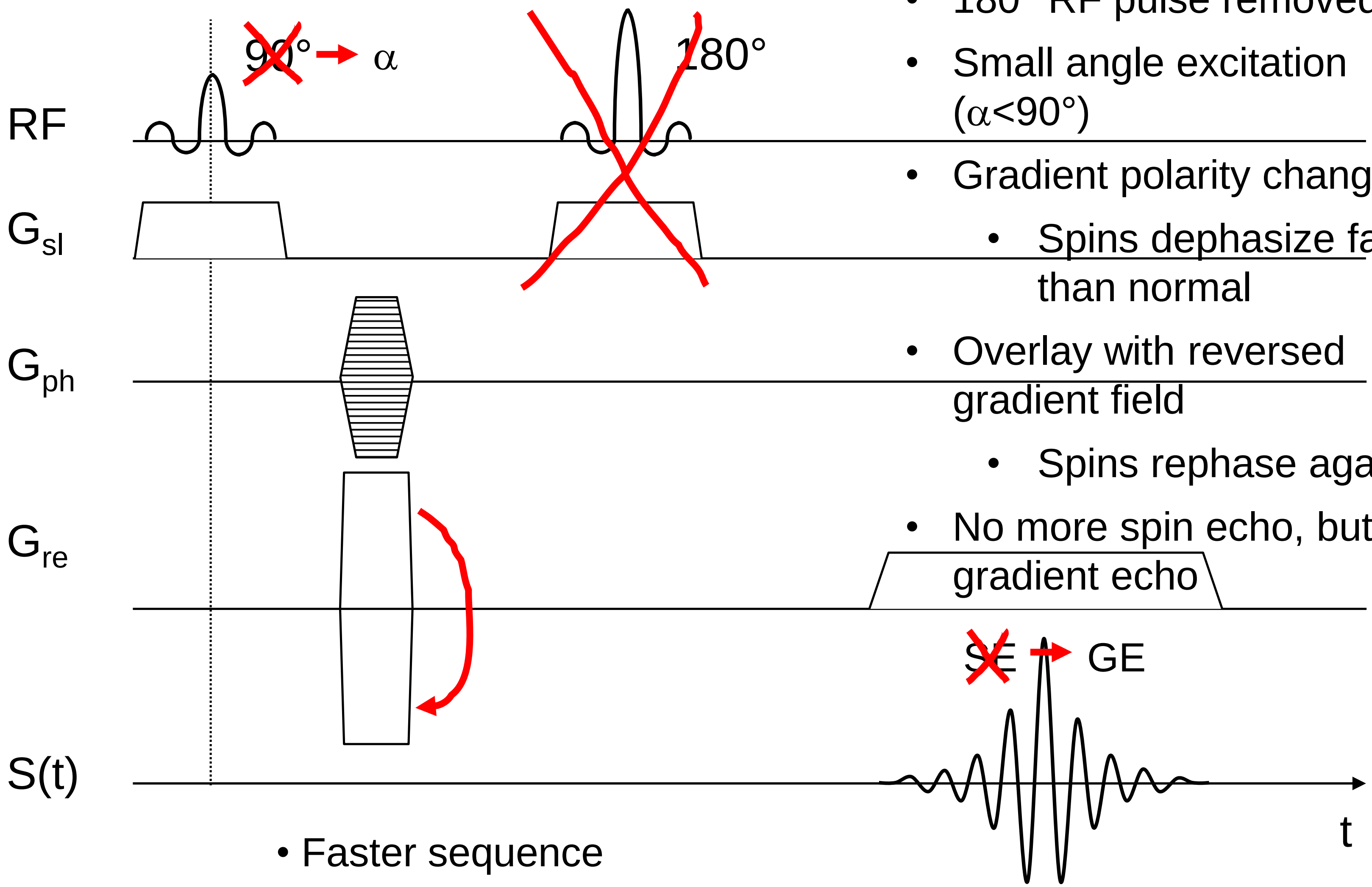


After 180° RF pulse: Both arrive at the same time !!

MR Image Sequences – Spin Echo



MR Image Sequences – Gradient Echo



- 180° RF pulse removed
- Small angle excitation (α<90°)
- Gradient polarity changes
  - Spins dephasize faster than normal
- Overlay with reversed gradient field
  - Spins rephase again
- No more spin echo, but gradient echo

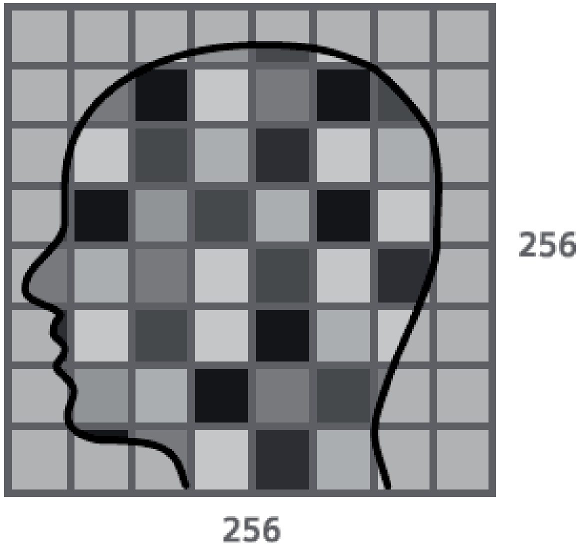
- Faster sequence
- No refocusing of magnetic field inhomogeneity's (T_2* dependence)

From Signal to Images

- The result of such measurement is a signal but no Image

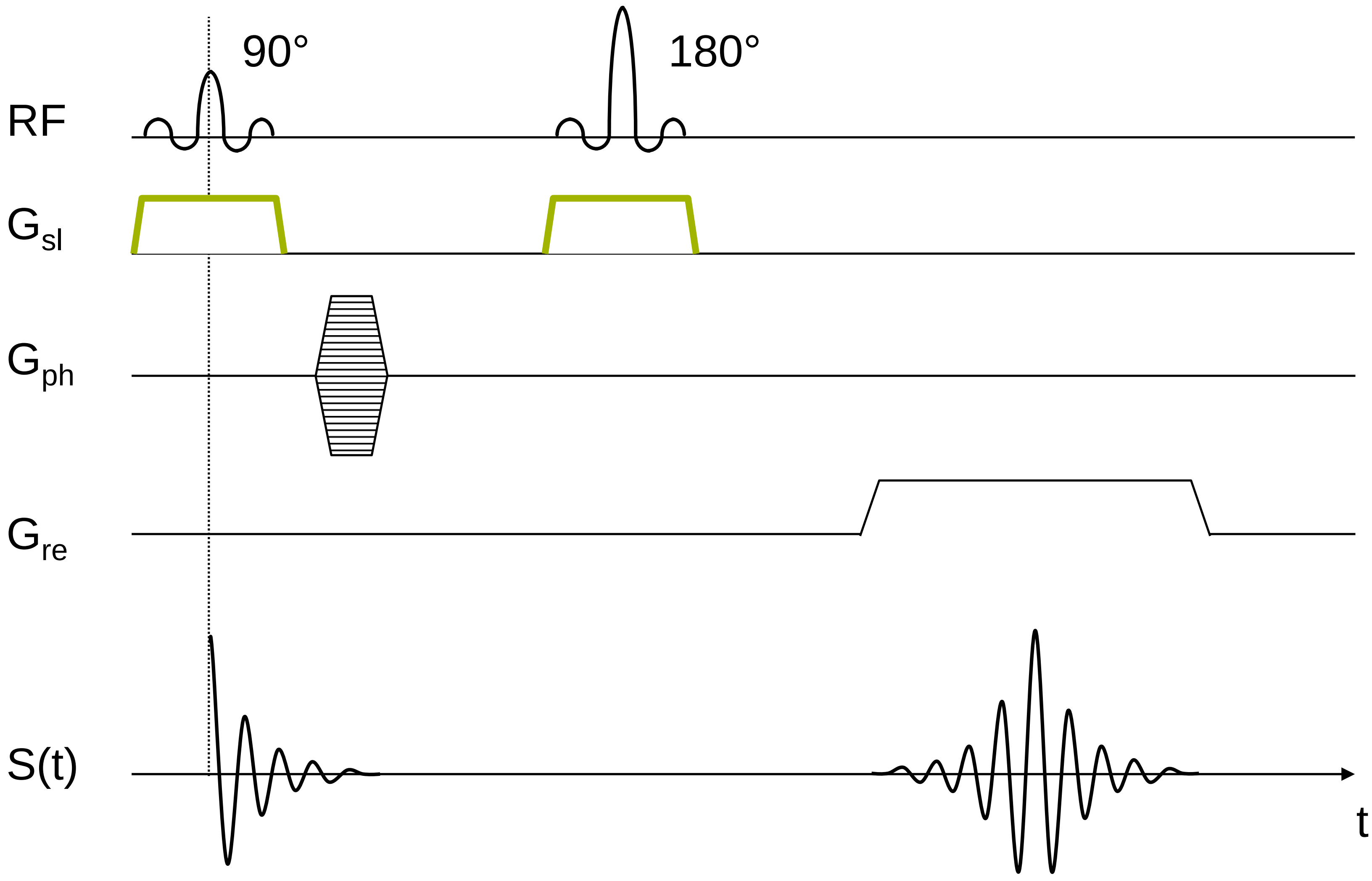
→ Location encoding required

- Spatial encoding:
  - Make Larmor frequency $\omega = \gamma * B_0$ location-dependent
- Make magnetic field location dependent
  - During excitation
  - During signal acquisition
  - Between
- Application of different gradient fields
  - Slice Selection Gradient (z-direction)
  - Phase encoding (y-direction)
  - Frequency coding (x-direction)



Source: Siemens Medical

Slice Selection Gradient (z-direction)

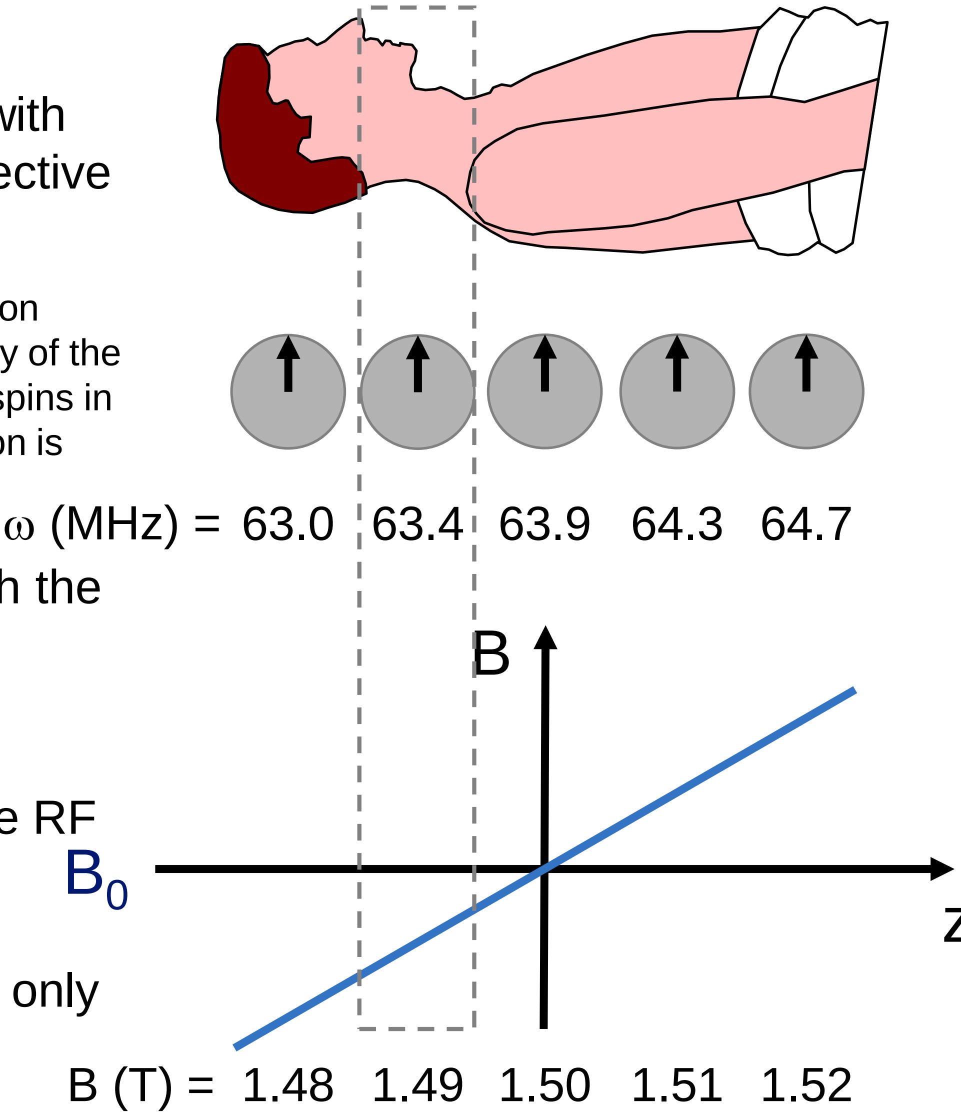


Slice Selection Gradient (z-direction)

Combination with frequency-selective RF pulse

Precession frequency of the nuclear spins in z-direction is different

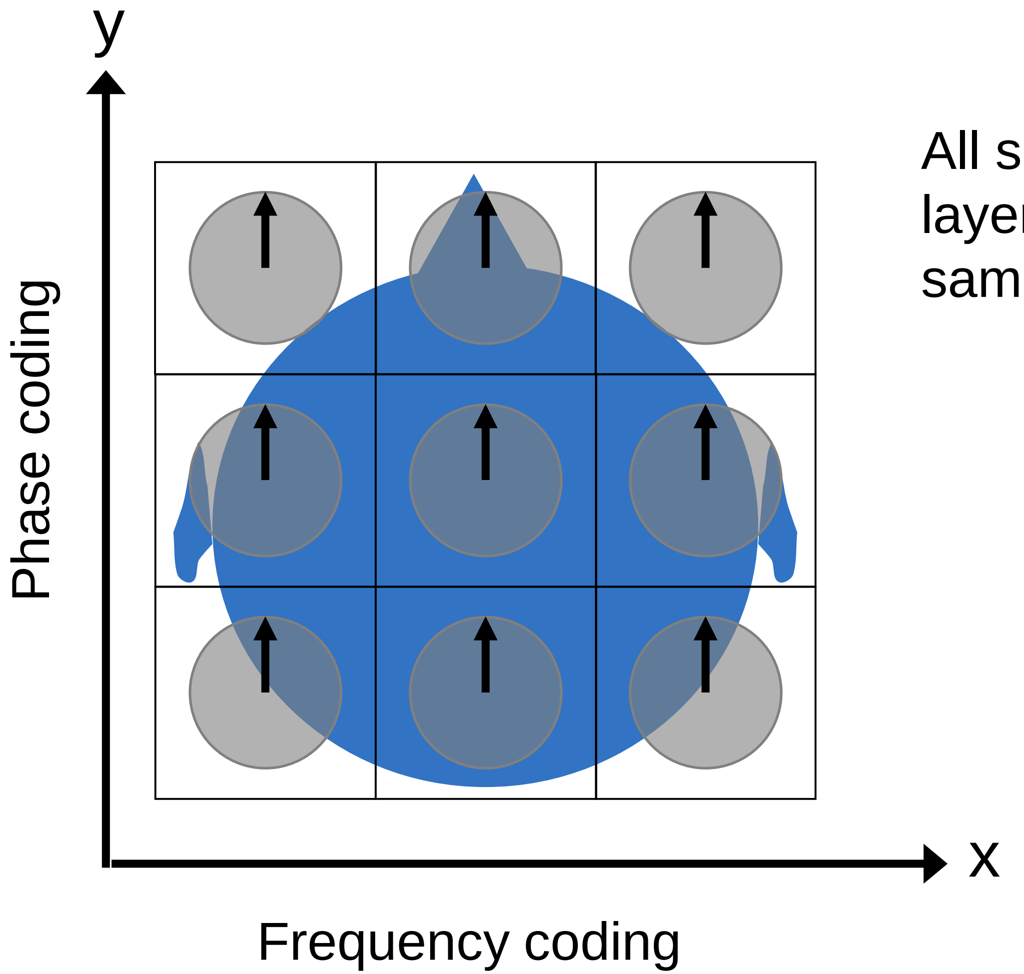
Only spins with the appropriate precession frequency are flipped with the RF pulse
→ Transverse magnetisation only in this layer



$$\omega = \omega_0 + \gamma G_z z$$

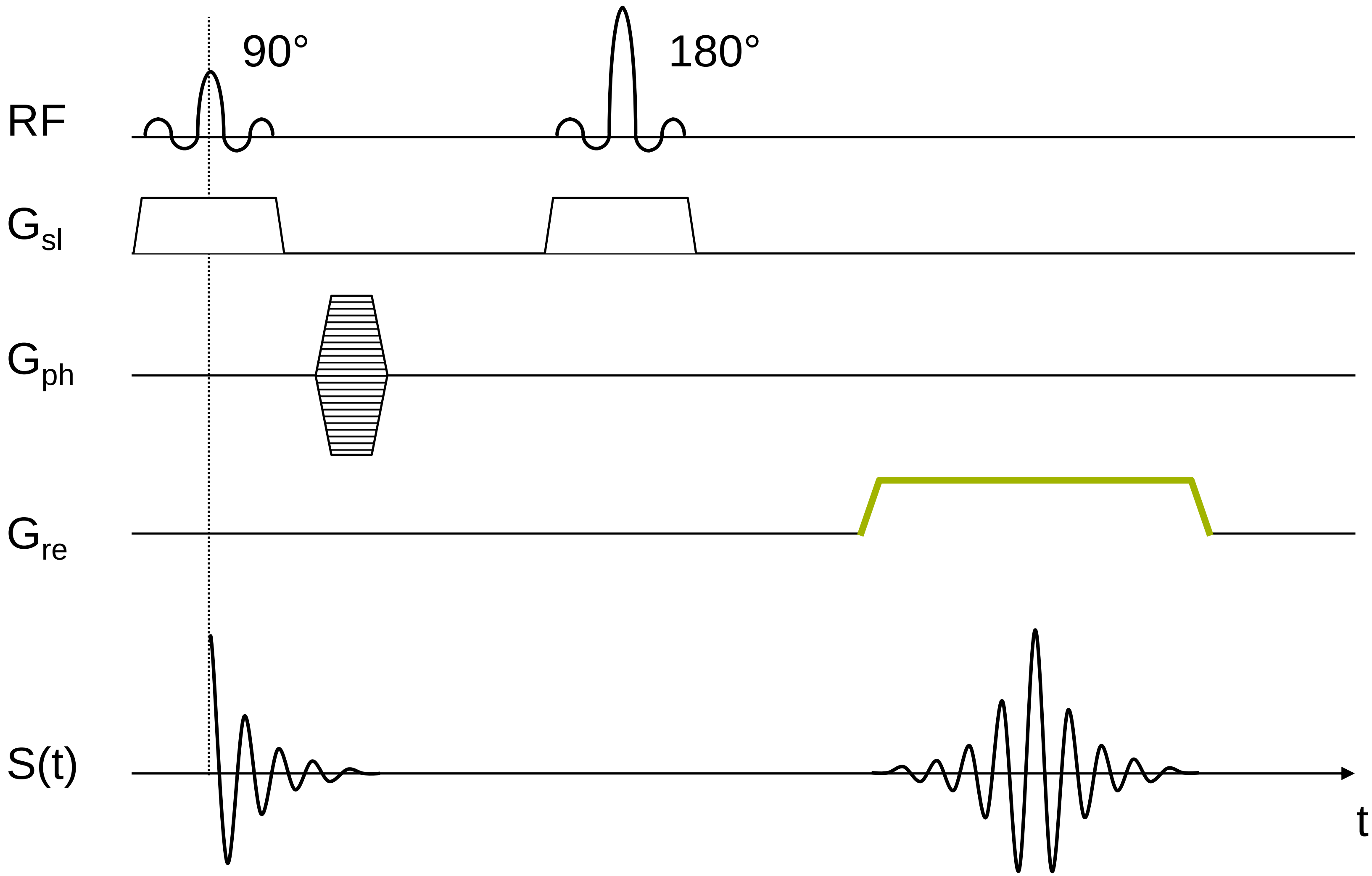
$$B = B_0 + G_z z$$

Slice Selection Gradient (z-direction)



All spins of an excited layer precess at the same frequency.

Frequency Coding Gradient (x-direction)

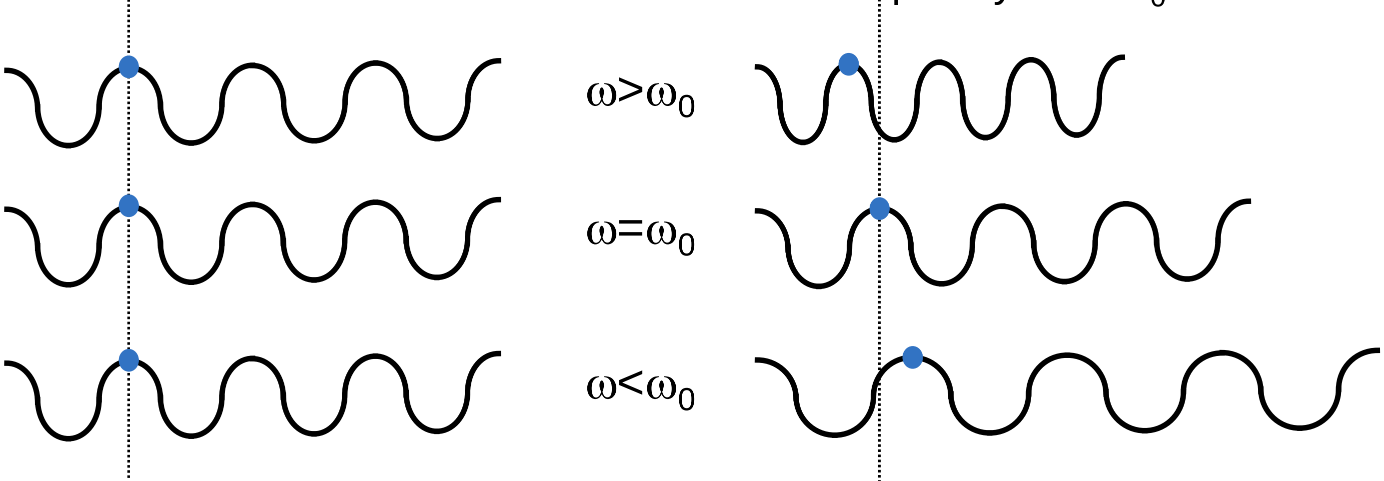


Frequency Coding Gradient (x-direction)

Before

During

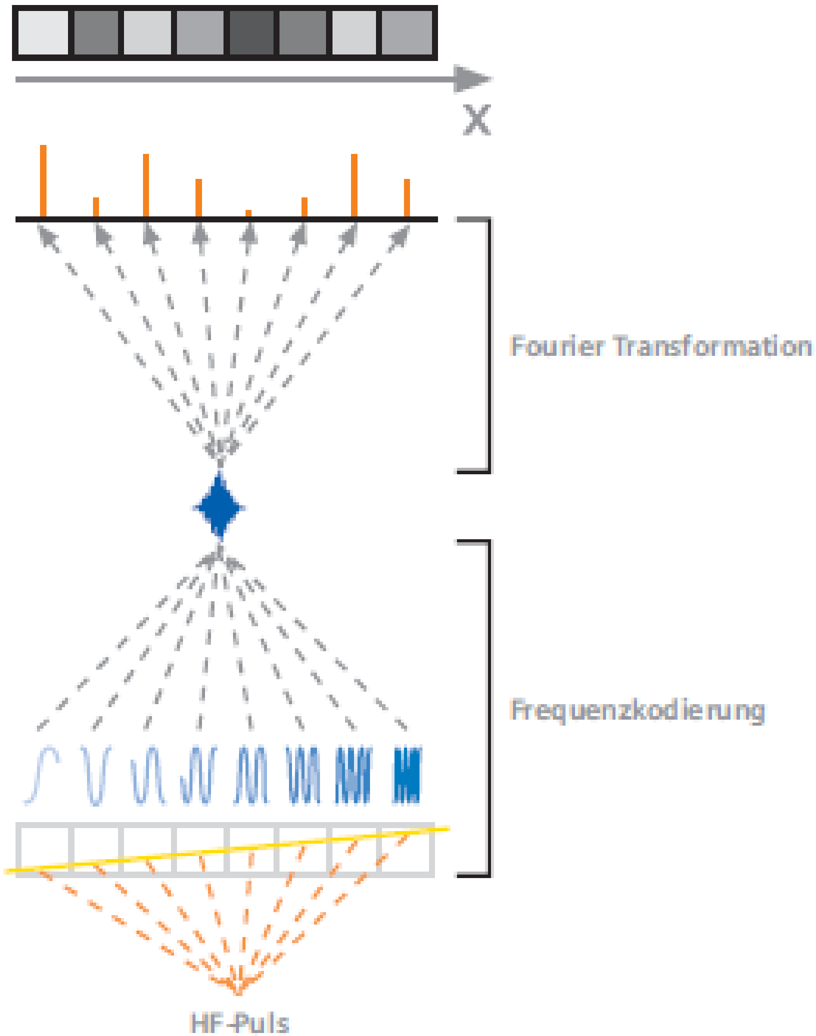
Magnetic field is stronger.
Spins precess higher frequency than ω_0.



Spins feel the same magnetic field and precess with ω_0.

Magnetic field is weaker.
Spins precess at a lower frequency than ω_0.

Frequency Coding Gradient (x-direction)

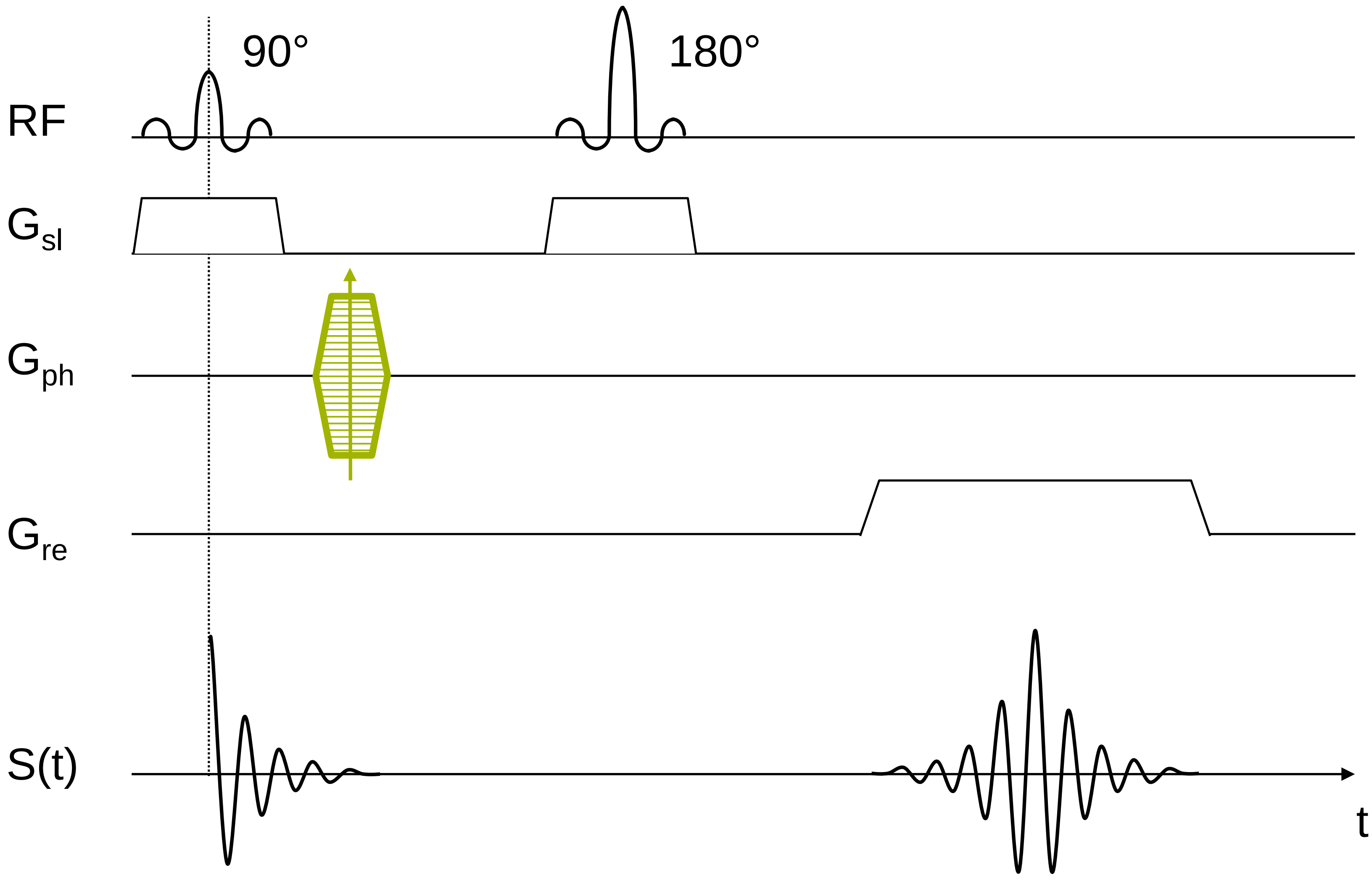


Source: Siemens Medical

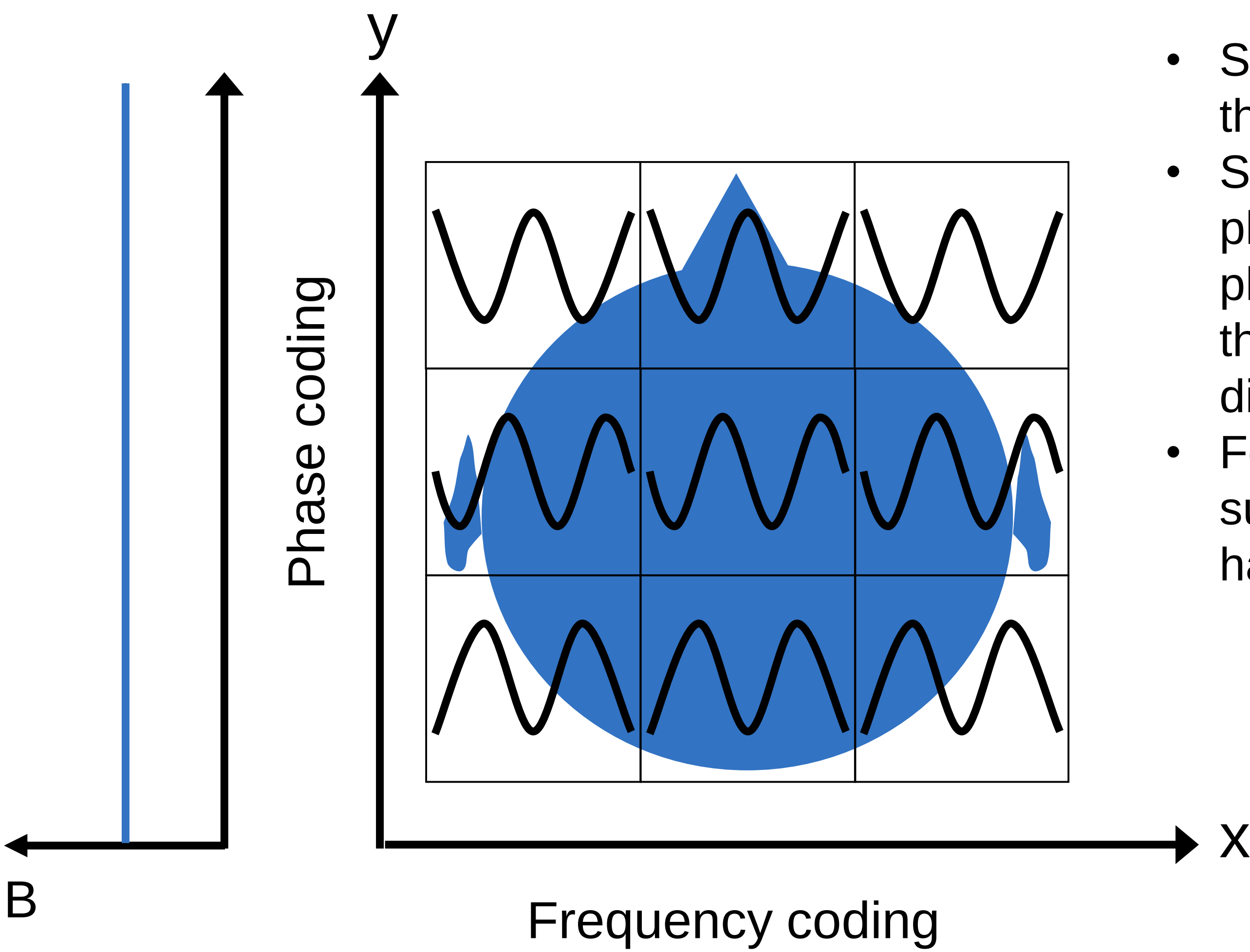
- Measured FID signal is the sum of all individual contributions.

- Spins precess at different frequencies according to their position in the magnetic field gradient.
- Each spin has an individual, frequency-coded location-dependent frequency.

Phase Coding Gradient (y-direction)



Phase Coding Gradient (y-direction)

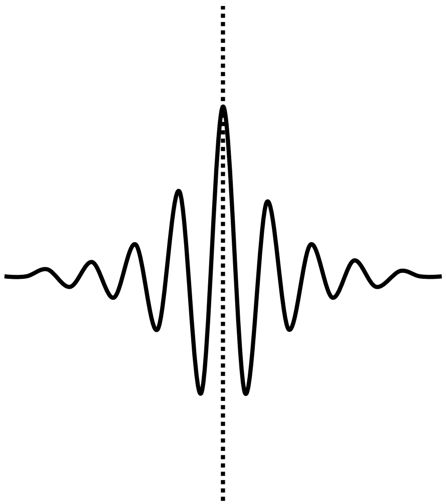


- Spins precess with the same frequency.
- Spins possess a phase-dependent and phase difference in the phase coding direction.
- For every y-entry such a Spin echo have to be generated!

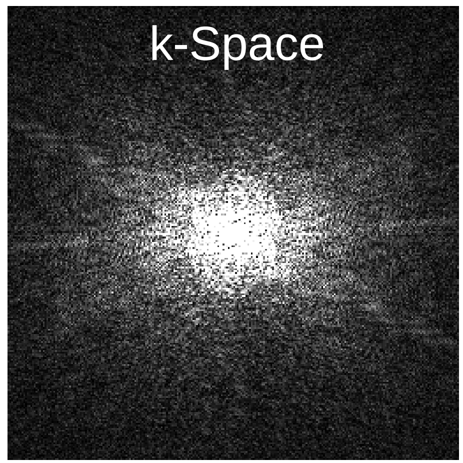
Image Reconstruction

Time domain
(no location information)

Frequency domain
(linked to location)



Gradient



Fourier
transform

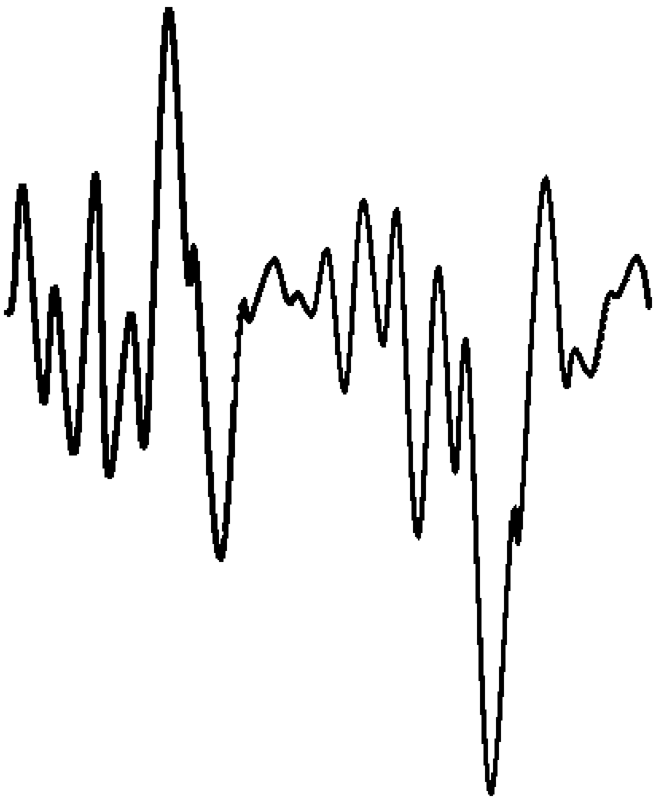
Signal at
certain time
point

Signal at different
time points and
phase coding
differences

Gray value
corresponds to the
strength of the
transverse
magnetisation at the
time of measurement

Image Reconstruction – Fourier transform

Measured signal in
the time domain



FT →

Decomposition into
individual frequency
components

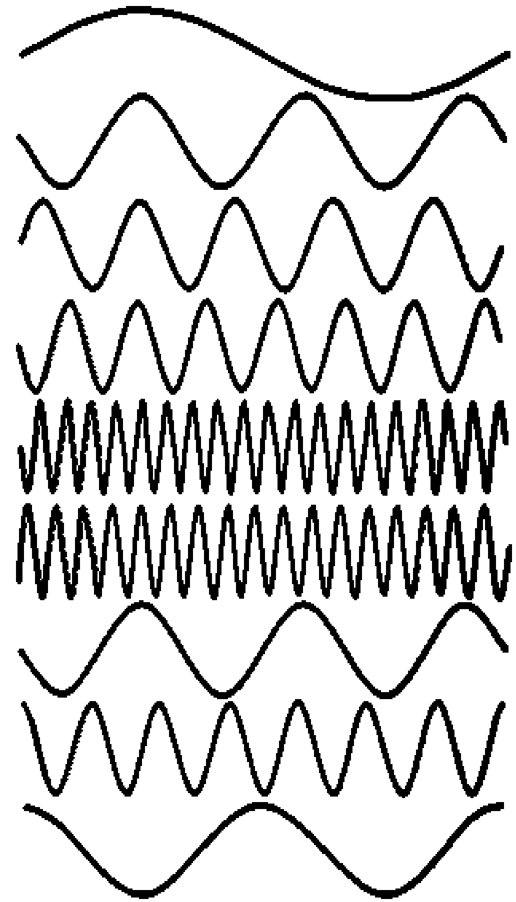
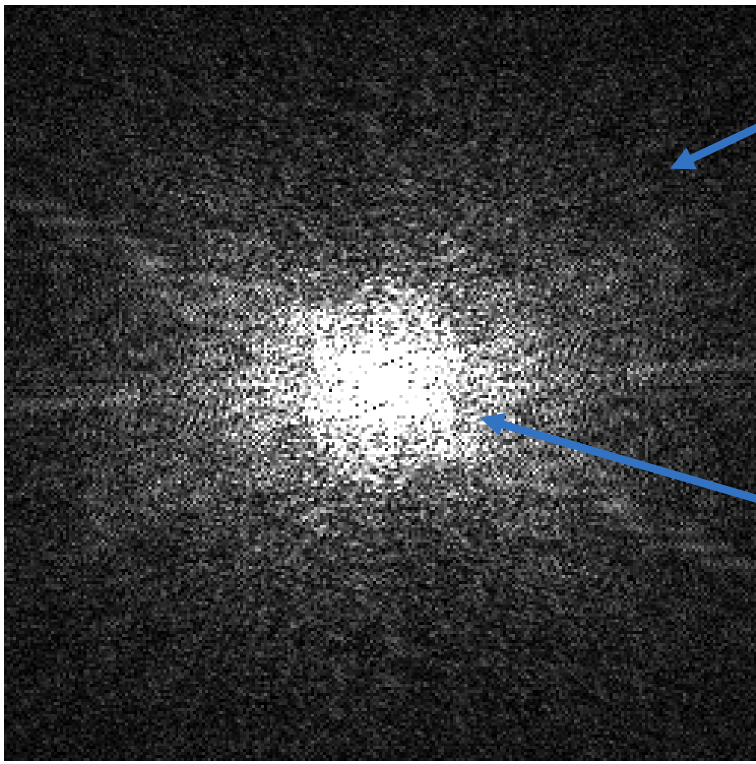


Image Reconstruction – k-Space property

Resolution information
in the periphery



Contrast information
in the centre

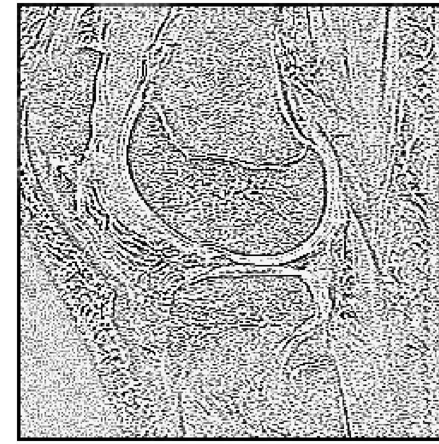
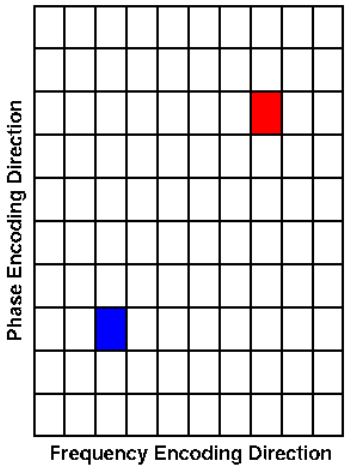
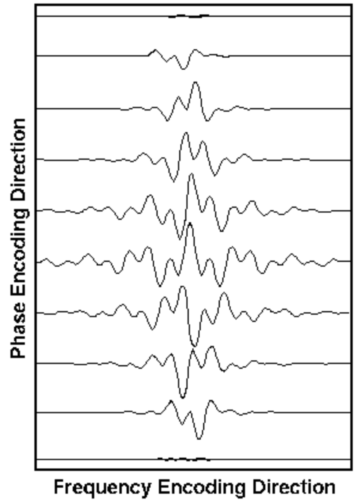


Image Reconstruction – Example

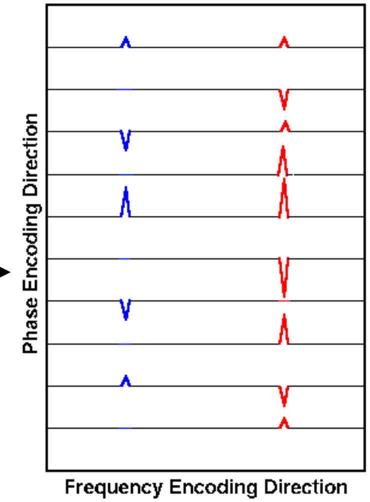
Voxel



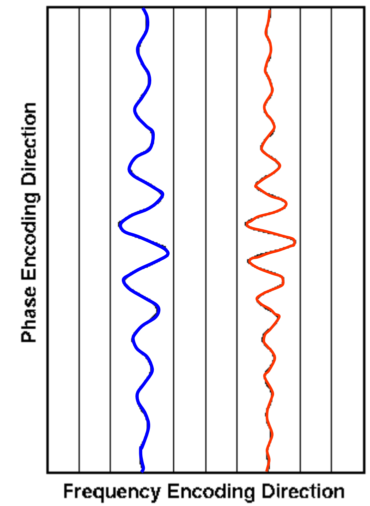
Raw data matrix = k-Space



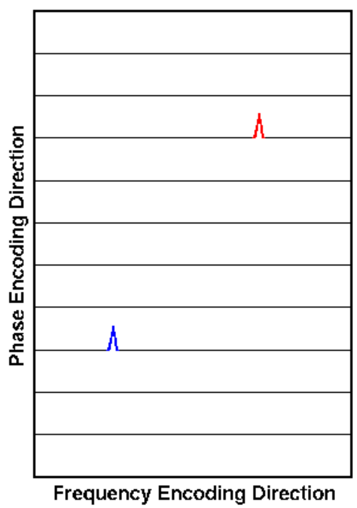
FT

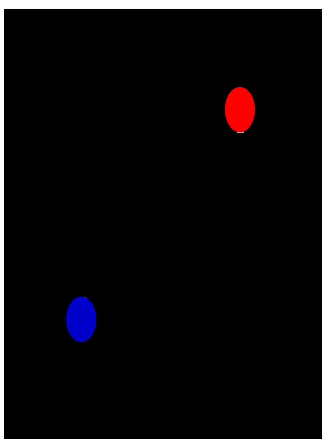


=



FT





MR-Image

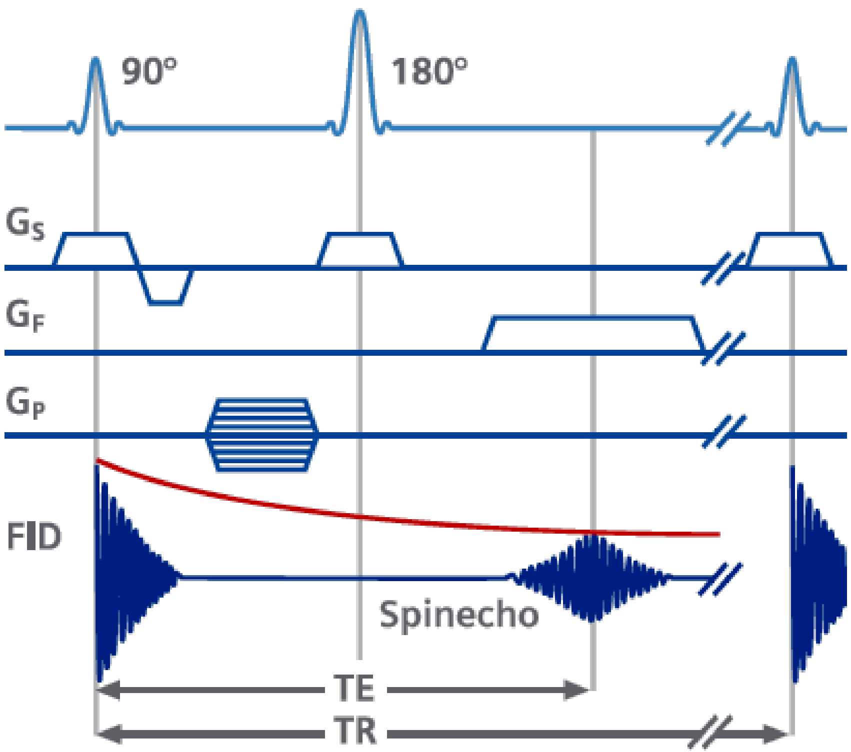
MR – Image Contrast

- Image contrast is determined by several physical quantities:
  - □ proton density
  - T_1 spin-lattice relaxation time
  - T_2 spin-spin relaxation time

- Spin-Echo-Signal:

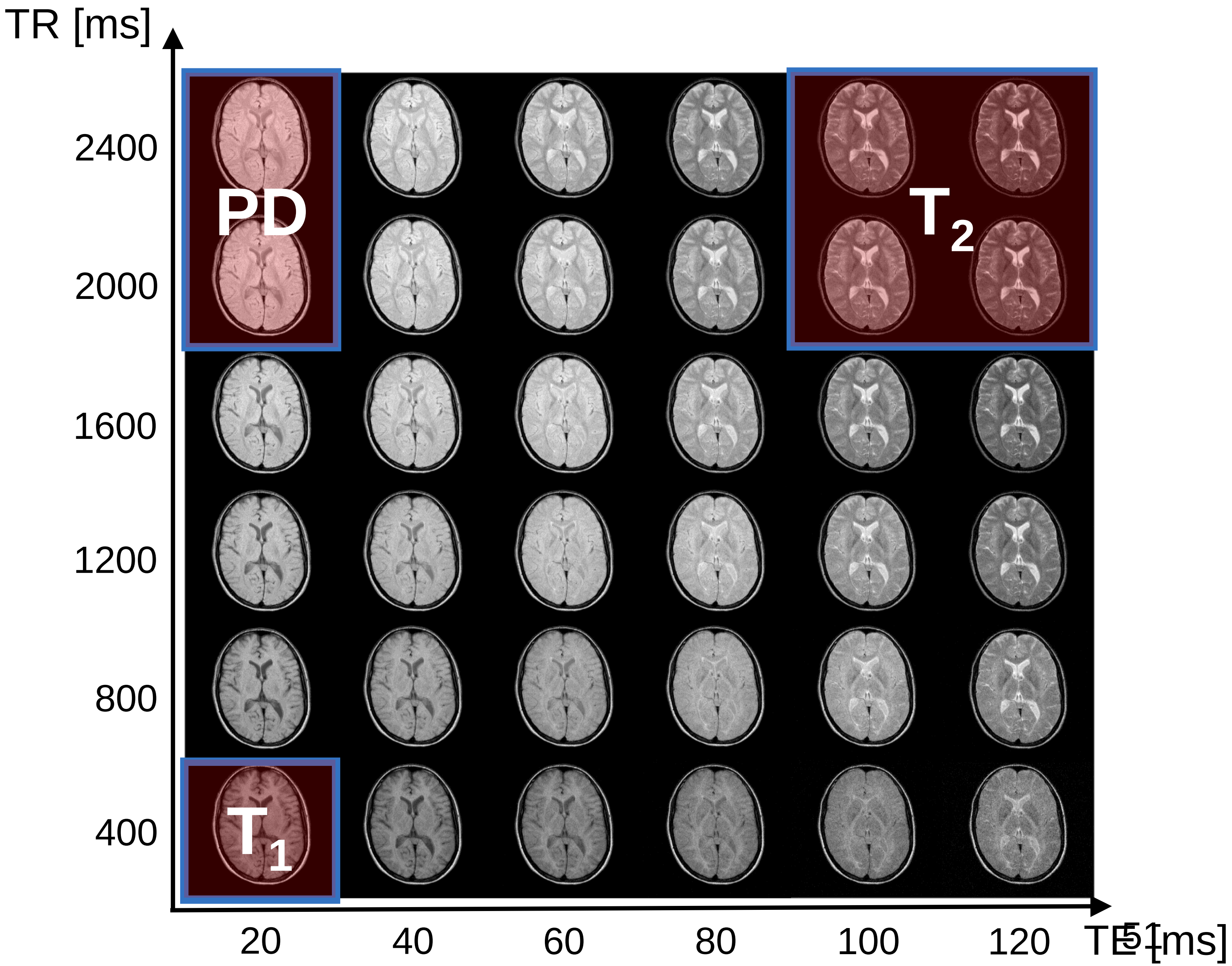
$$S_{SE} = \rho \cdot \left[1 - \exp\left(-\frac{TR}{T1}\right)\right] \cdot \exp\left(-\frac{TE}{T2}\right)$$

- Sequence parameters:
  - TR - Repetition time
  - TE - Echo time



Source: Siemens Medical

MR – Image Contrast



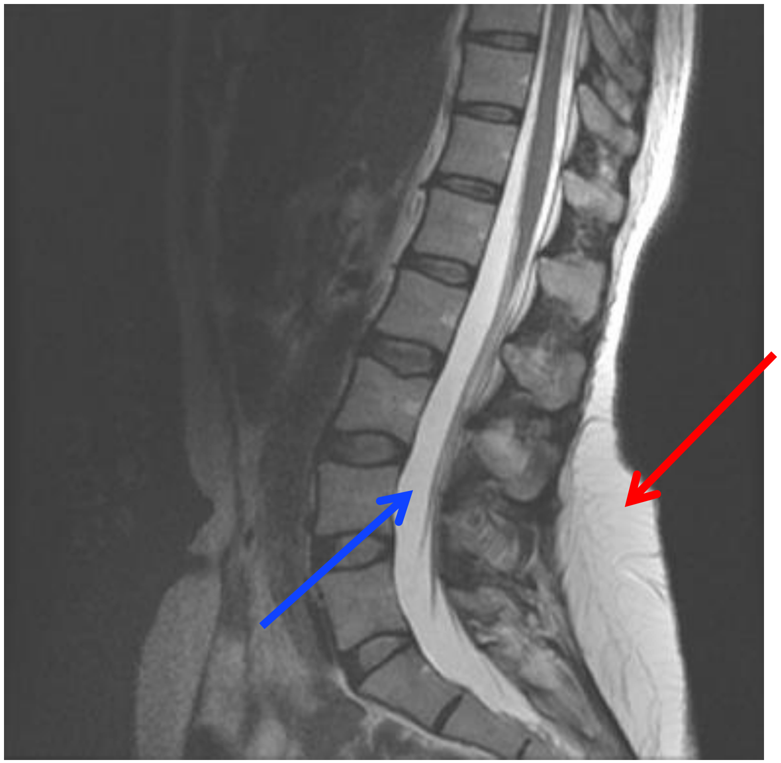
MRI – Summary III

Principle of MR imaging:

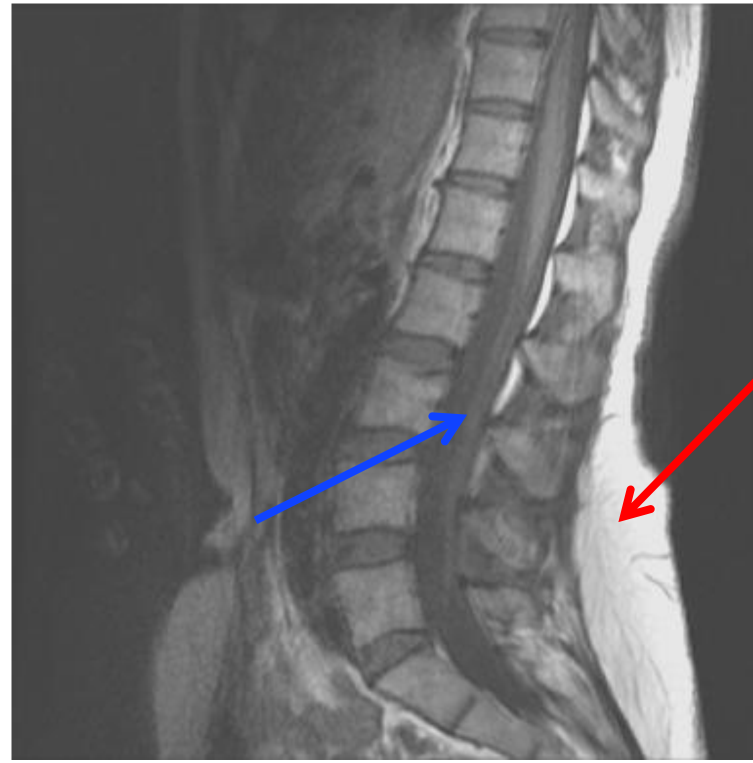
- Measurement of the transverse magnetisation M_{XY}
- Obtaining the measurement signals using gradient fields:
  - Slice selection: excitation of spins within a specific layer
  - 2D measuring matrix by frequency and phase coding in one layer
- Reconstruction with 2D Fourier transformation
- Various contrast are possible during imaging

MRI – Example: Spinal Cord

T2-weighted
(Turbo-Spin-Echo)



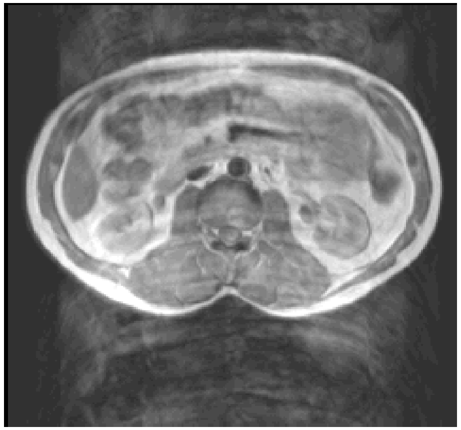
T1-weighted
(Spin-Echo)



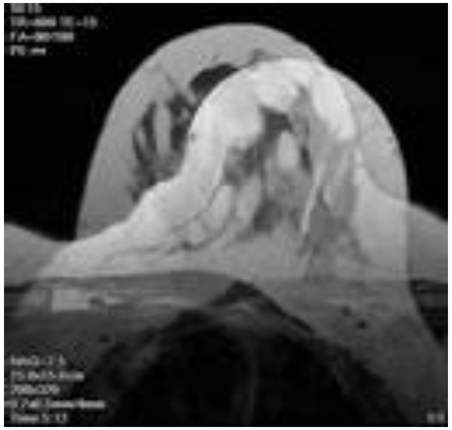
	T2-weighted	T1-weighted
Water:	bright	dark
Fat:	bright	bright

MRI – Artefacts

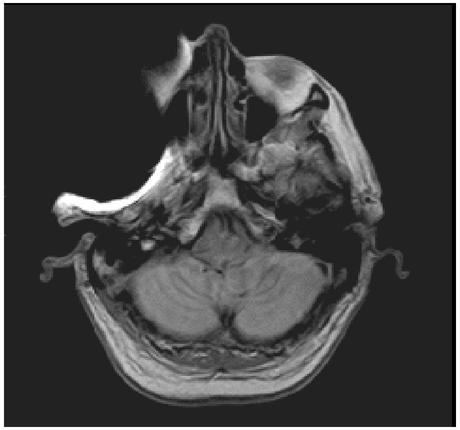
- Motion (Heart, breathing, motion,...)
- Folding artefacts
- Metal artefacts
- Distortion artefacts
- Chemical shift



Breathing



Folding

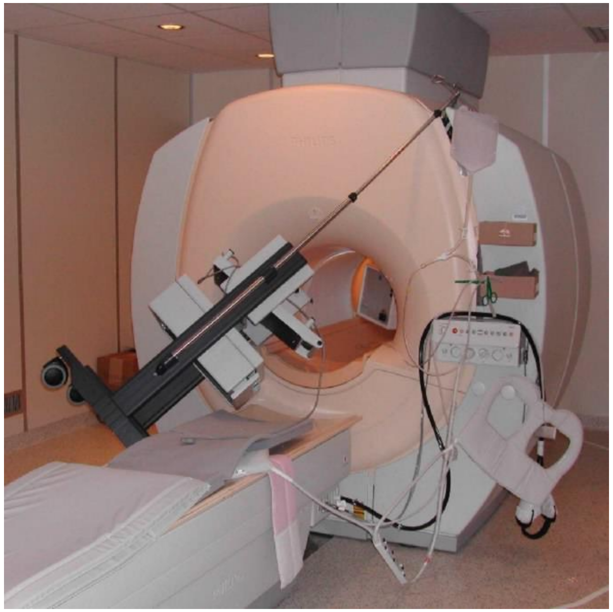


Metal pin

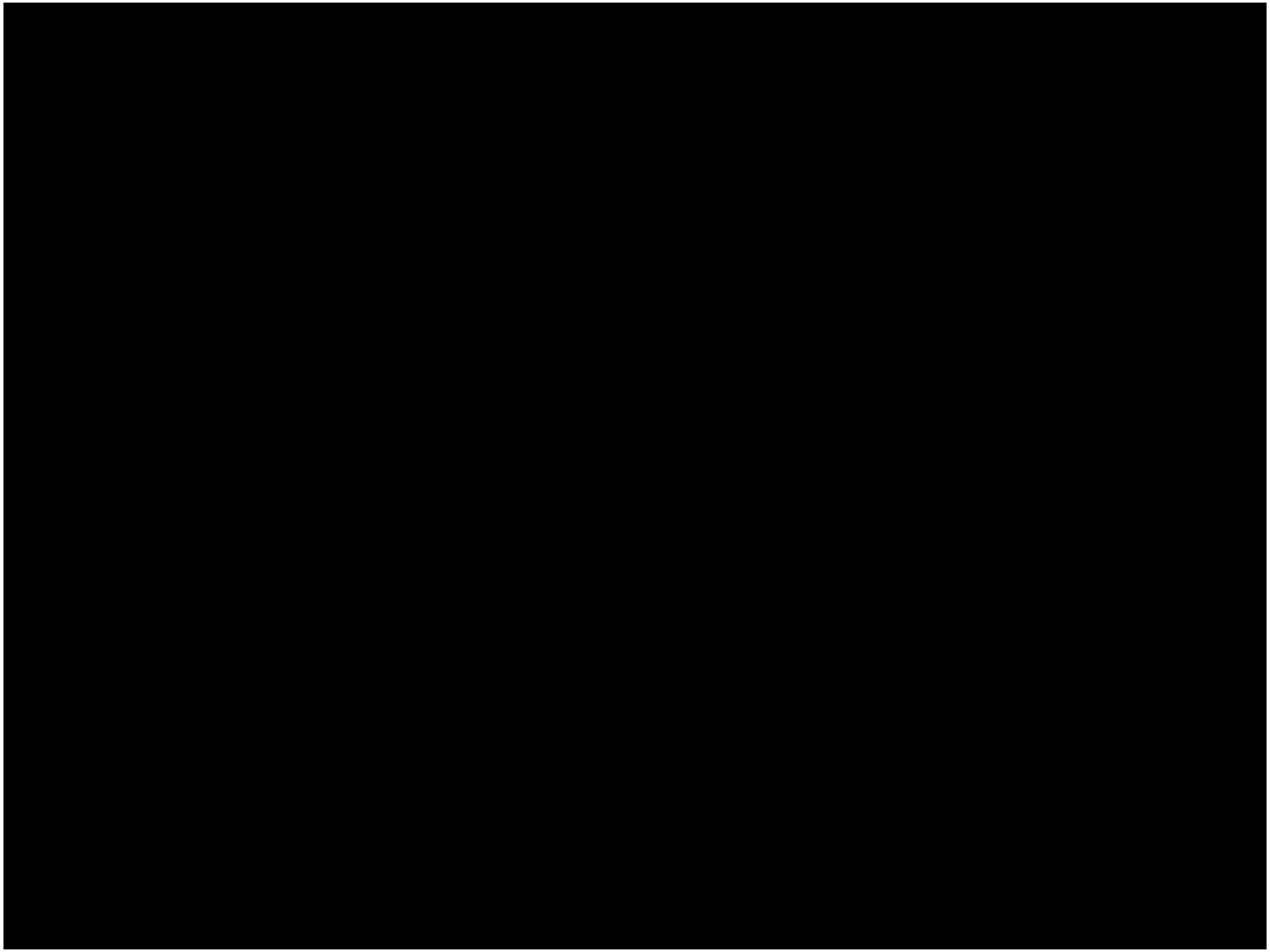
Motion

MRI – Safety Aspects

Superconducting
magnets are
ALWAYS on !!



MRT - Sicherheitsaspekte



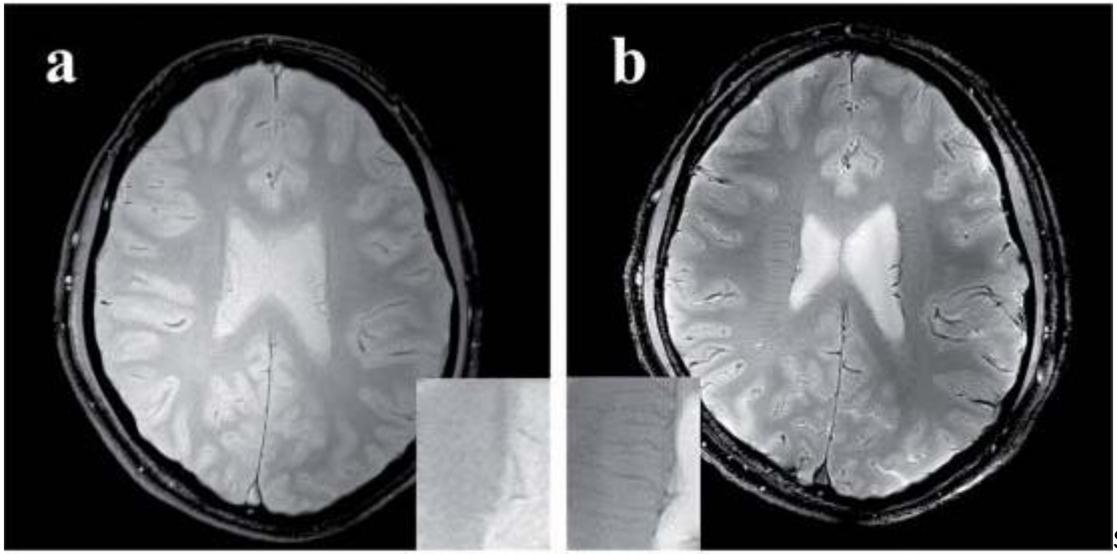
MRI - Resolution

- Maximum resolution depends on the signal-to-noise ratio
- The strength of the MR signal increases quadratically to the magnetic field strength, noise only linearly

  → Stronger magnetic field = higher resolution possible
- Problem: Relaxation time also shortened

  → Faster imaging needed

3 Tesla



7 Tesla

Source: Siemens Medical

MRI - Summary

Principle

- Certain properties of atoms in the magnetic field are used for imaging
- Signal coding by means of gradient fields
- Image contrast depends on several parameters

Advantages and disadvantages

\+ No radiation exposure

\+ High resolution: Good representation of soft tissue and organs

- Relatively long recording time
- Expensive
- Direct comparison between MRI images difficult
- Intraoperative use very difficult
- Loud and tight

NCT

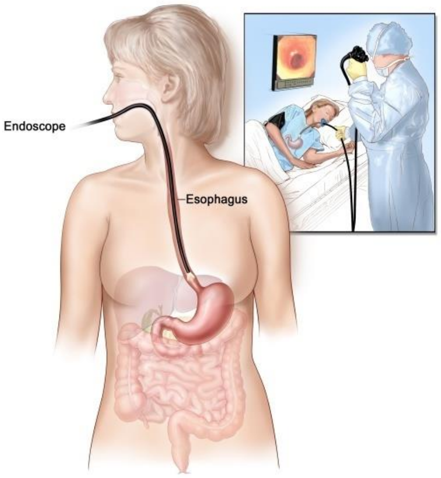
ENDOSCOPY

Endoscopy

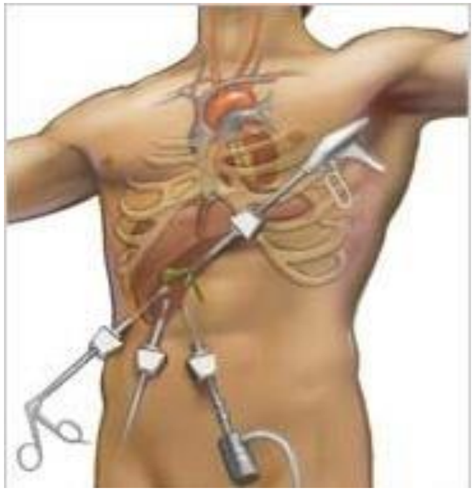
- The word “endoscope” comes from the Greek and means "to look inside" (endo = inside, scope= to look at)
- Endoscope = tube / tubular instrument that visualises images of the inside of the body via an optical system
- Advantages:
  - Real-time observation of reality
  - Interactive,
  - Easy interpretation of images
  - No radiation exposure

Endoscopy

- **Diagnostic endoscopy:**
    - Endoscopic examination using available body cavities for diagnostic purposes
    - Non-invasive

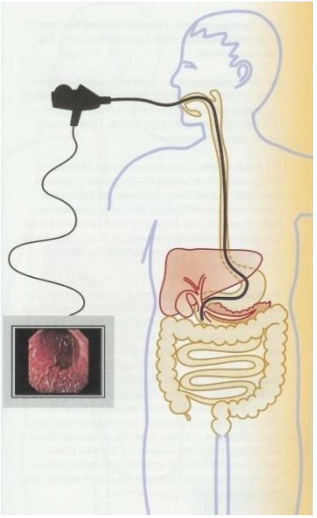


- **Endoscopic (minimally invasive) surgery:**
    - Surgical procedures using an endoscope and special surgical instruments inserted through small incisions



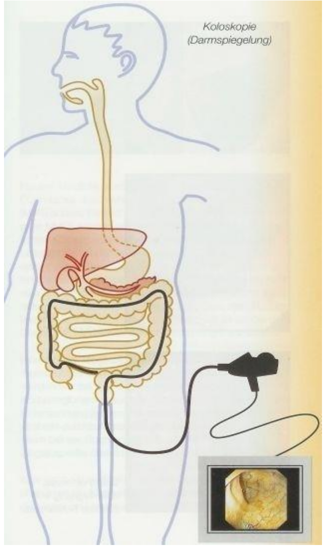
Diagnostic Endoscopy: Applications

- **Gastroscopy (esophagogastroduodenoscopy):**
  - Examination of the esophagus, stomach and duodenum with flexible gastroscope



- **Colonoscopy (colonoscopy, rectoscopy):**
  - Examination of the rectum, the colon and the lower end of the small intestine. Endoscopes are between 20 cm (rigid rectoscope) and 180 cm (flexible coloscope).

- **Tracheotomy (bronchoscopy):**
  - With a flexible bronchoscope, the trachea and the bronchi can be examined.



Source: www.drstrauch.de

Capsule-Endoscopy

- Endoscope capsule for the diagnosis of gastrointestinal diseases
- Presentation of the entire small intestine

- Capsule consists of:
  - Battery
  - Transmitter
  - Light source
  - Microchip camera (over 55,000 images in 6 hours)

Source: Endoline

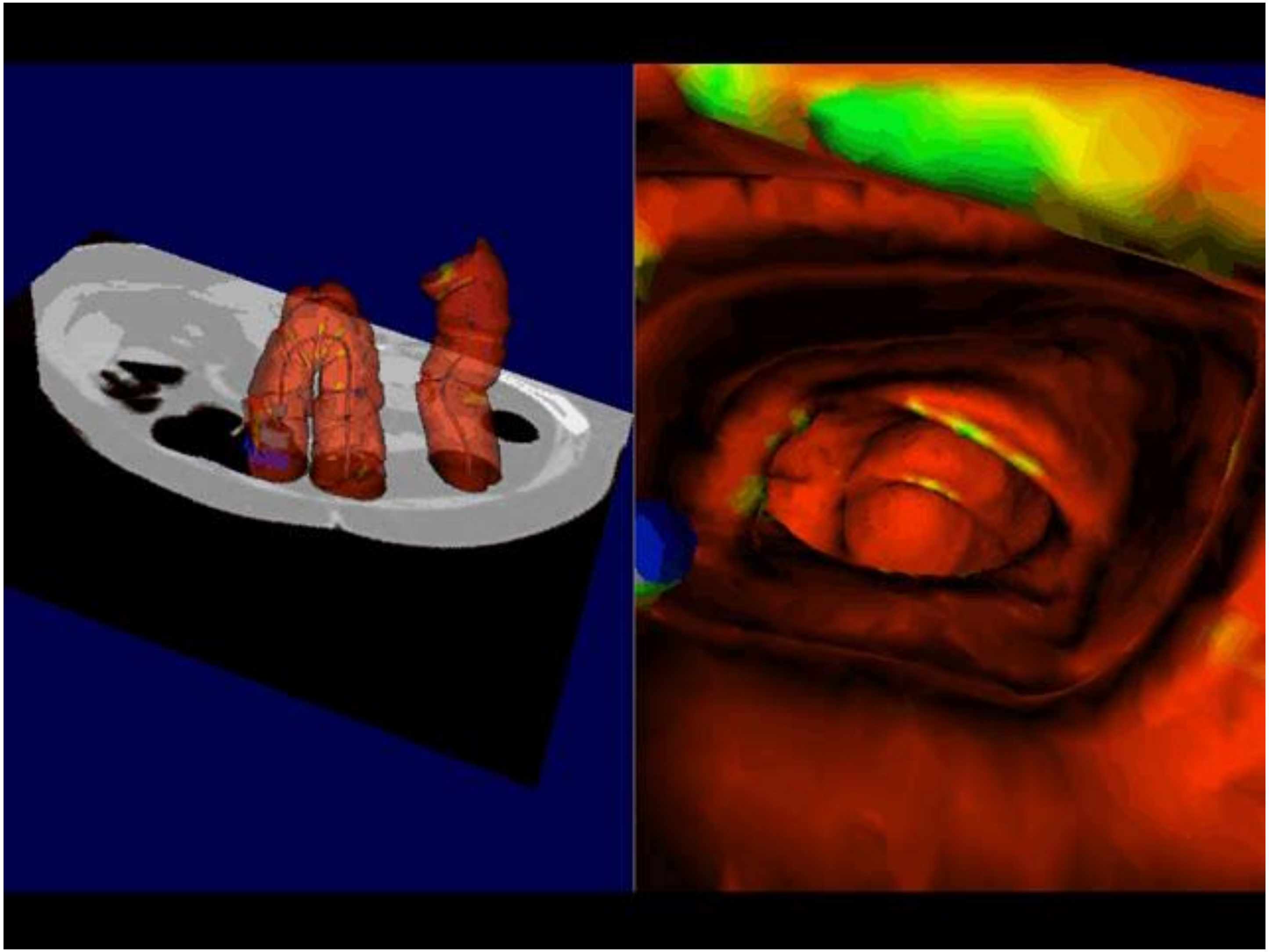
Virtual Endoscopy

Simulation of an endoscopy based on tomographic data

Method:

- Acquiring CT / MRI images of the patient
- Thresholds or manually set the interfaces between lumen and tissue
- 3D surface reconstruction
- Path of the virtual camera set
- Spatial impression through imaginary light source (reflections / shadows) and texturing of the surface

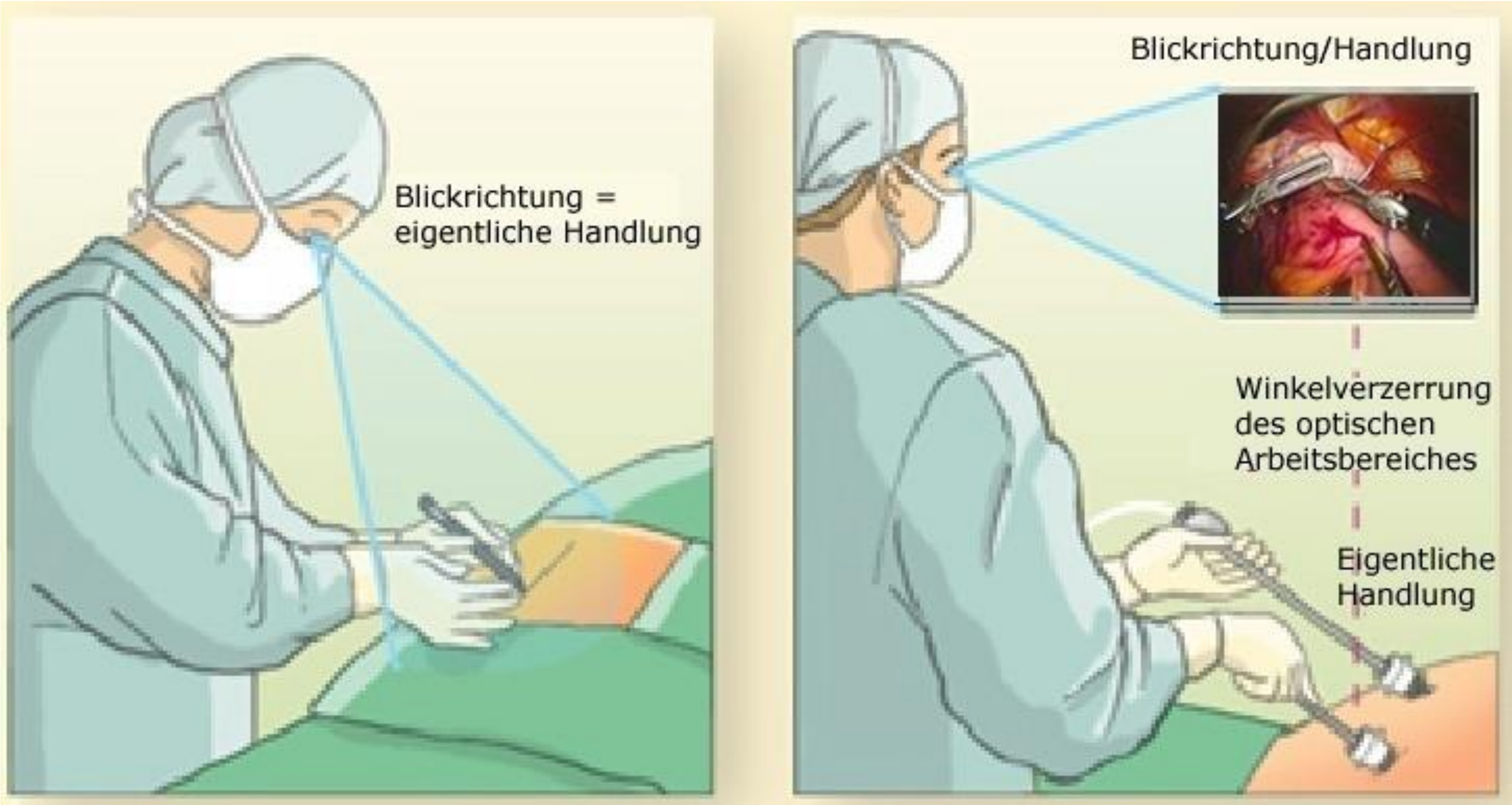
Virtual Endoscopy



Quelle: MIT AI Lab

Endoscopic usage in Surgery

Surgical techniques



Conventional

minimally invasive

Source:Websurg

Minimally Invasive Surgery: Examples

- **Laparoscopy:**
  - Minimally invasive procedure, in which the abdominal cavity and the organs inside are mirrored
  - For example: gallbladder removal, cecum, removal of intestine, liver, prostate ...

- **Arthroscopy:**
  - Minimally invasive examination of joints with a special endoscope (Arthroscope)
  - For example: injuries in the knee, shoulder, hand and ankle ...

- **Minimally invasive cardiac surgery:**
  - Most of the patients are operated in the so-called "off-pump" technique (without Life-support-machine)
  - For example: bypass surgery, interventions on the atrium ...

Challenges of minimally invasive operations

- Altered surgical environment and posture of the surgeon
- Deviation between the enlarged 2D view and the actual 3D surgical field, missing depth perception
- Altered hand-eye coordination
- Special instruments and reduced tactile sensation
- Special surgical movements, movements are u. U. reversed or severely restricted

→ Intraoperative support of the surgeon useful (e.g. during navigation)

NCT

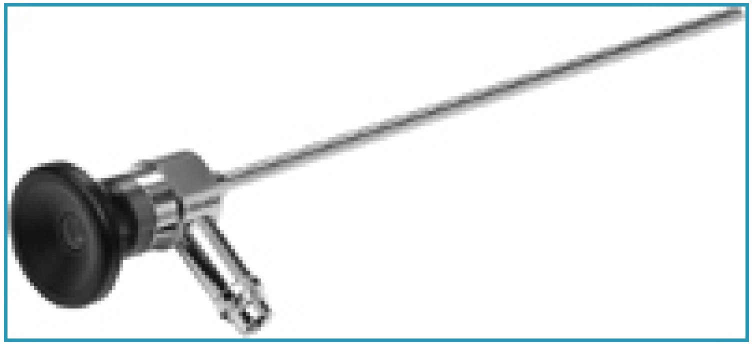
Endoscope: Technical Setup

Components:

- Lens and objectives
- Camera or eyepiece
- Image Transfer System
  - Optical
  - Electronic
- Light transmission system
- Flushing / instrument channel equipments
- Trocar, light source, instruments, monitor ...

Endoscope: Basic Types

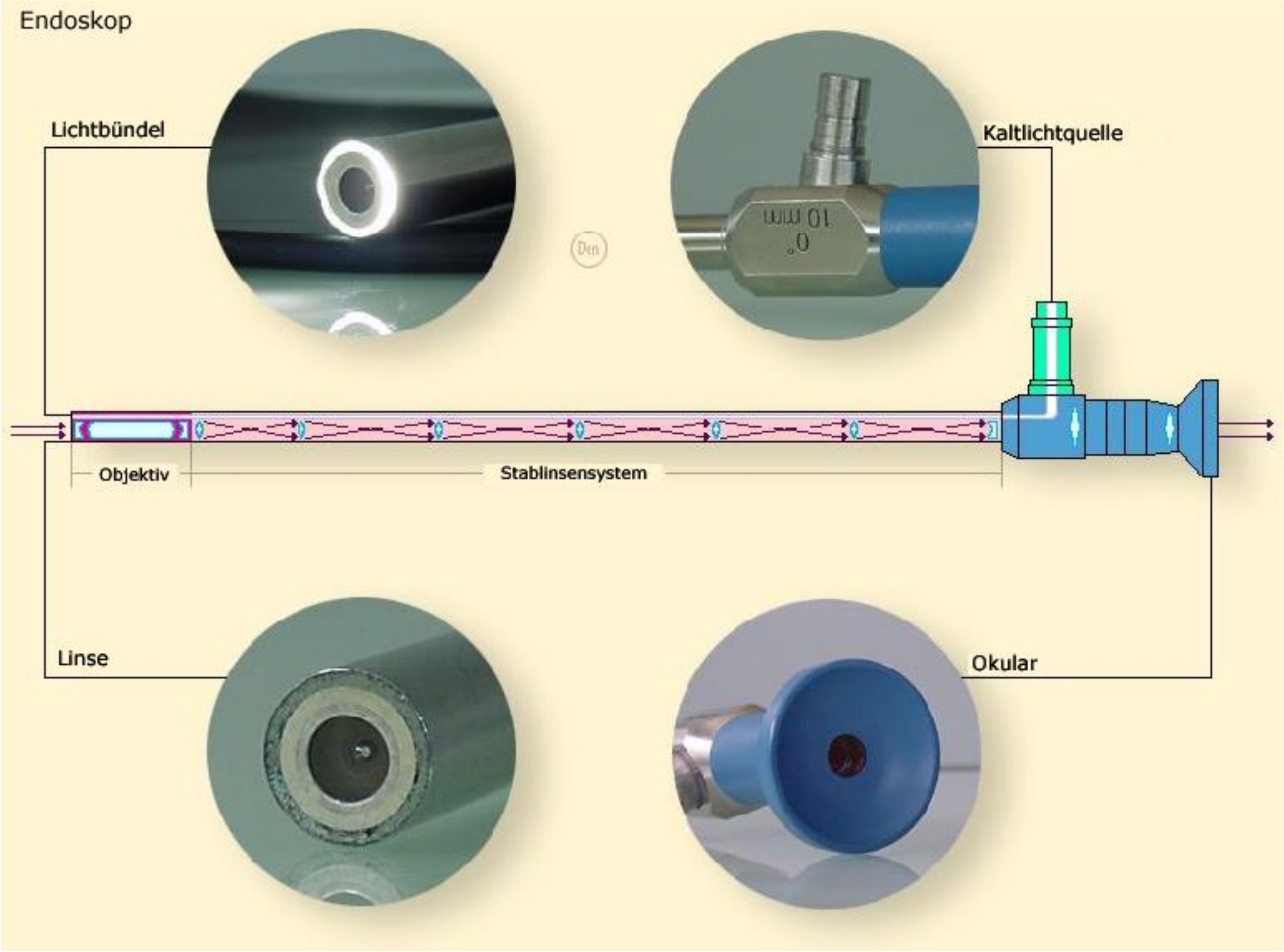
- Rigid endoscope
  - In the rigid endoscope, the optical system consists of a series of successively arranged prisms and lenses



- Flexible endoscope
  - Follows the course of natural body openings, optical system consists of glass fiber bundles

- Videoscope
  - The eyepiece image is forwarded to a monitor or an image processing system with the aid of a placement camera

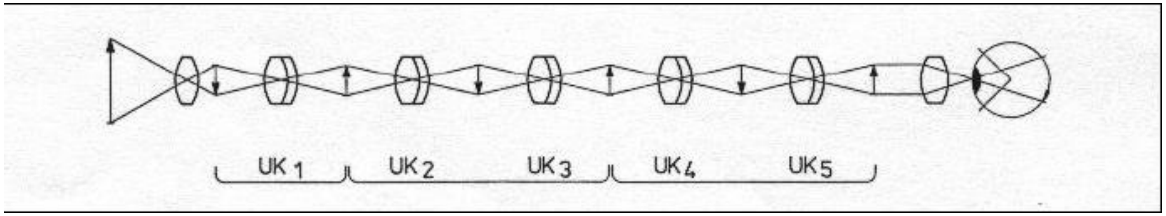
Rigid Endoscopes



Source:Websurg

Rigid Endoscopes

- Imaging optics necessary to obtain a good view despite the extreme ratio of length to visible cross-section: image transfer with rod lens system (reversal system)

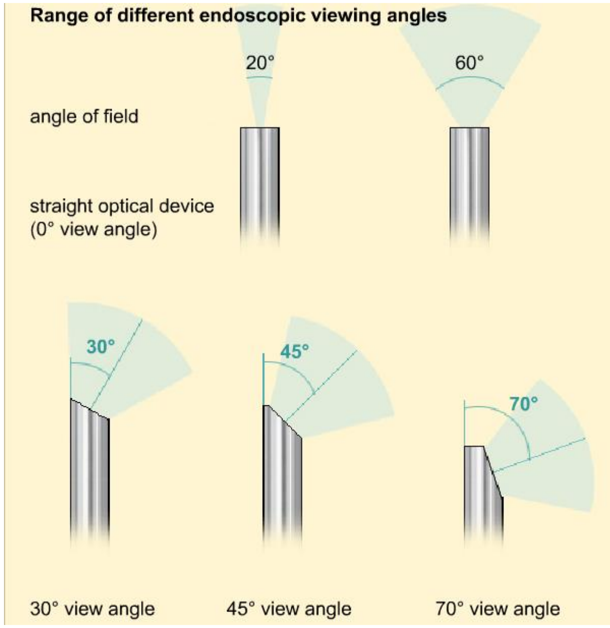


- Monocular endoscopes:
  - most common used in minimally invasive surgery

Viewing direction: 0 ° -120 °

Field of view: 20 ° - 60 °

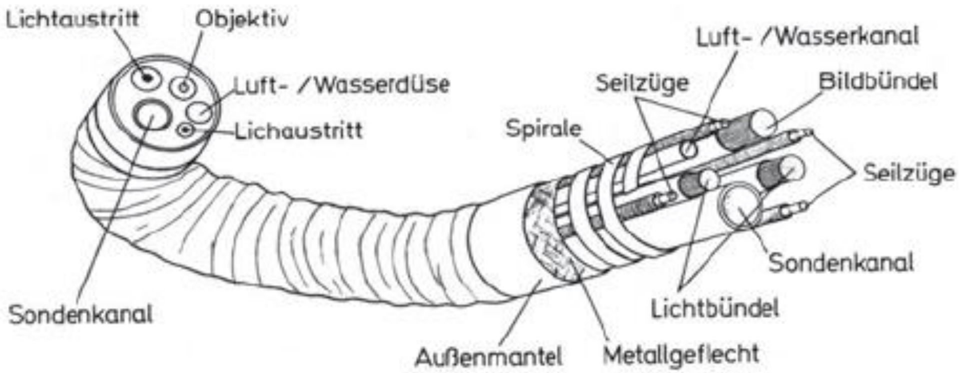
Caliber: 3mm-12mm



Source :Websurg

Flexible Endoscopes

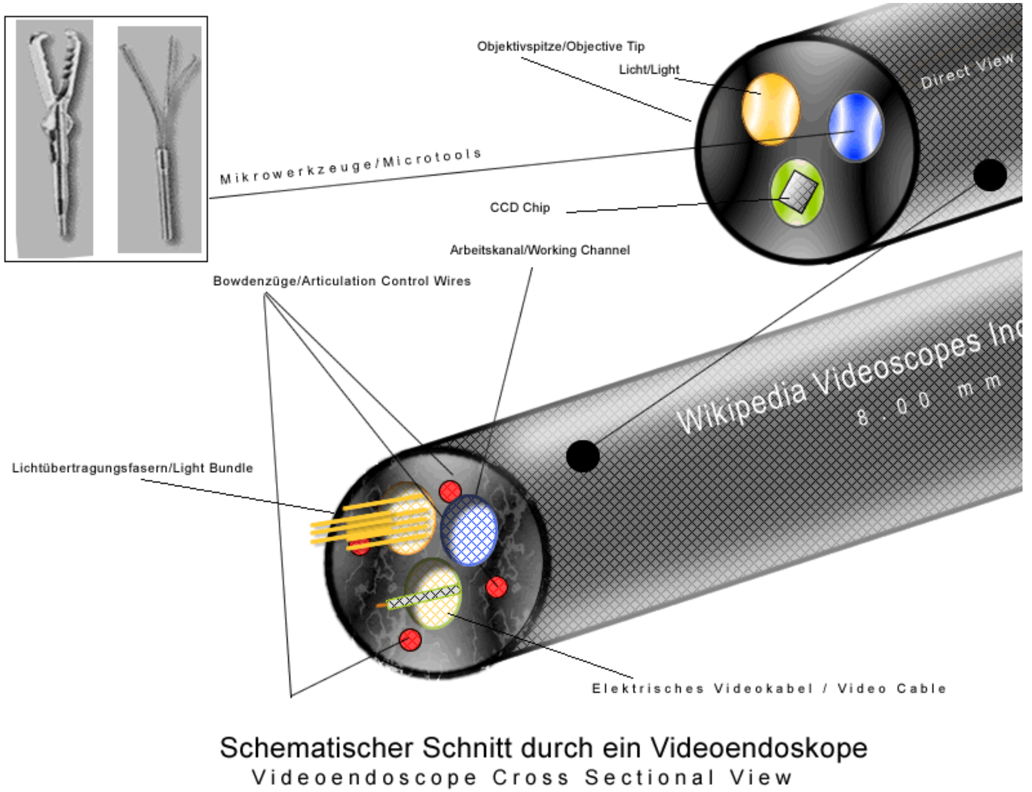
- Light and image transmission via fiber optic conductors, ordered at the image guide (about 30 000 fibers), disordered at the light guide
- Flushing and aspiration via internal channels, which are controlled by valves



Quelle:Biomedizinische Technik, Hutten

Videoendoscopes

- Camera instead of eyepiece
- Allows to display the the image on the monitor
- Rigid or flexible systems
- Mostly mono, few stereo systems
- Further processing of the images is possible
- Modern endoscopes with chip in the top

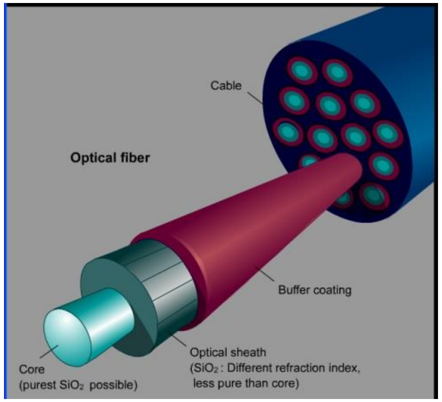


Source:Wikipedia

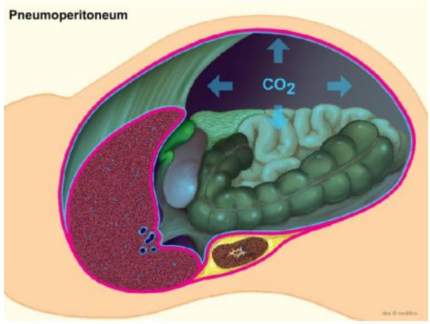
NCT

Light source and Insufflator

- Light source:
  - Halogen or xenon lamps whose light has a high proportion of white.
  - Light is generated externally and coupled as cold light into a light bundle of glass fibres.



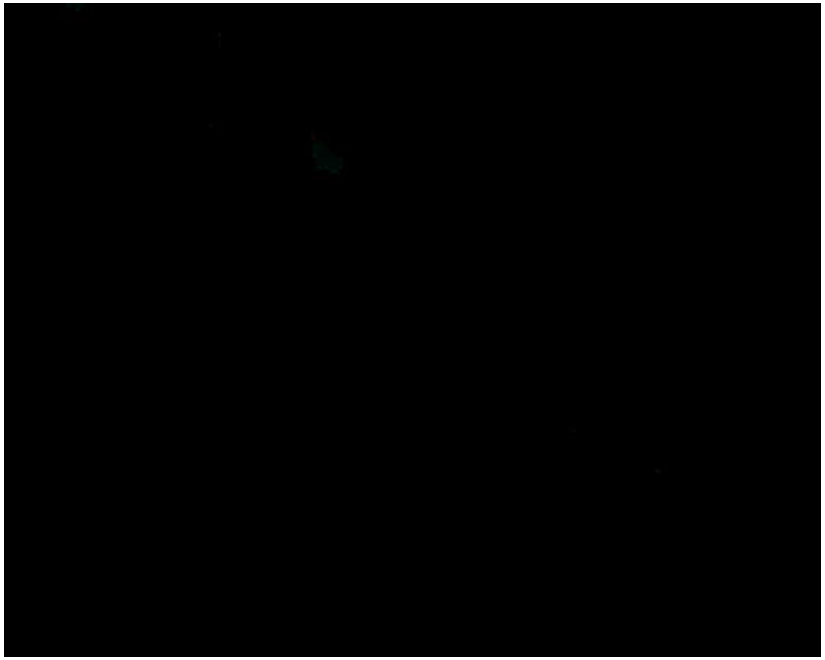
- Insufflator:
  - Generation and maintenance of pneumoperitoneum (working space between organs and abdominal wall)
  - Pressure control (<12 mm Hg)
  - Constant gas exchange



Source:Websurg

Trocar

Instrument for opening a body cavity, to introduce the endoscopes and instruments

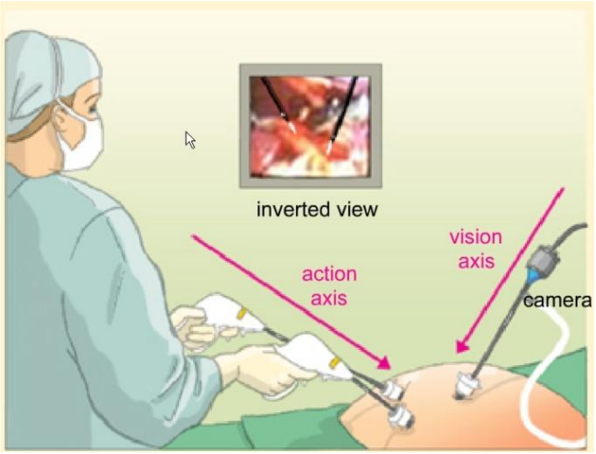


Source:Websurg

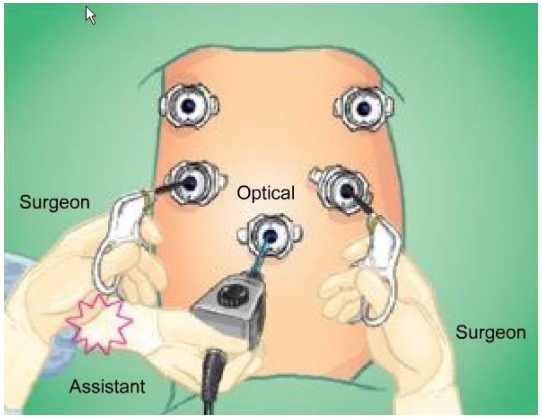
Trocar Positioning

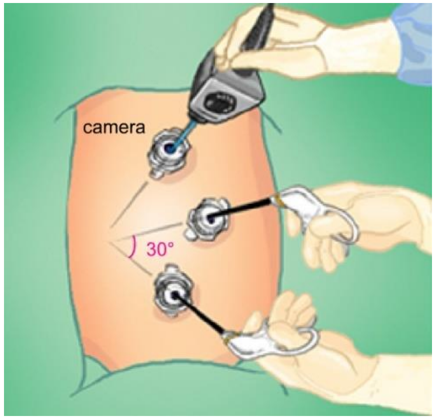
Each procedure has special trocar positioning, however, there are basic principles independent of intervention:

- Surgeon should face the target organ and make a line with lens and monitor
- Instruments that face the optics are difficult to use



Source:Websurg



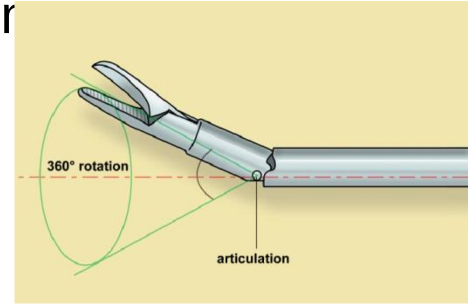


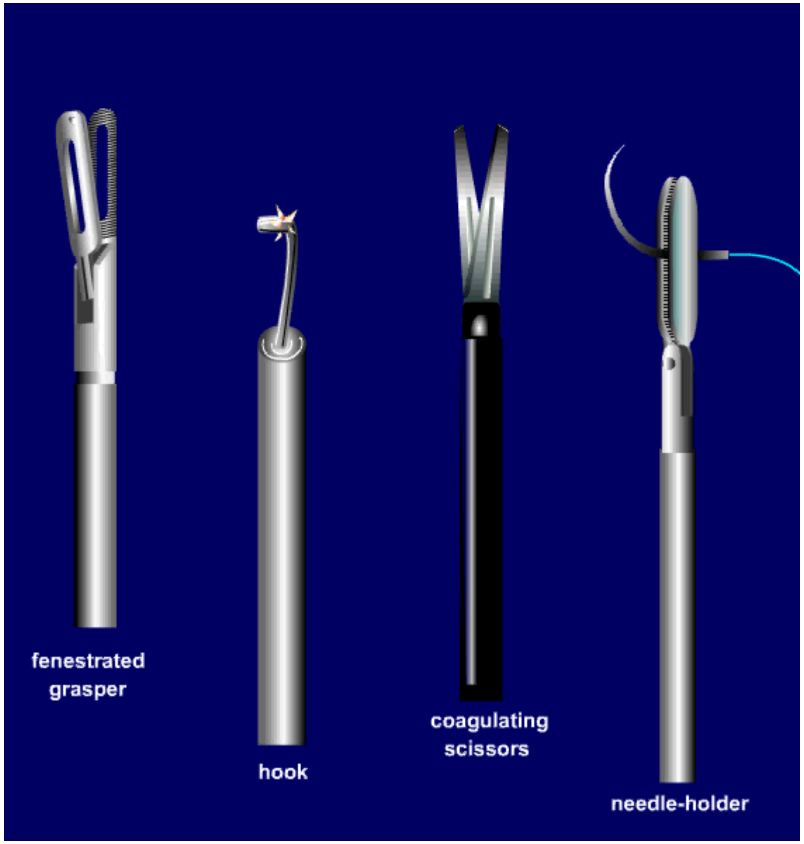
Instruments

- Every surgical procedure has special requirements to which the instruments are adapted

- Most of the instruments fit through 5mm-10mm trocars and have a length of 18cm - 45cm

- Degrees of freedom: 360 ° rotation, usually 4 degrees of freedo[m]





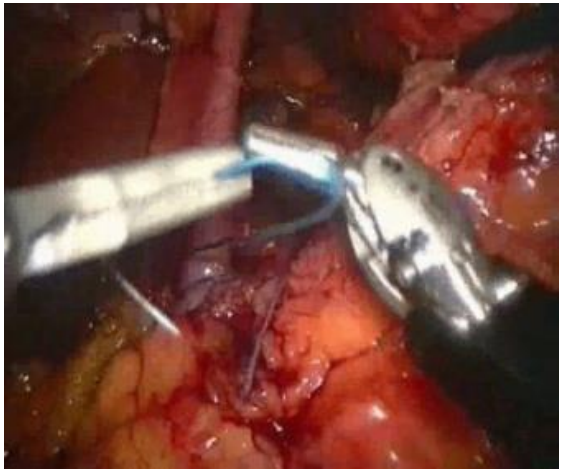
Quelle:Websurg

DaVinci-Telemanipulator

Source: Intuitive Surgical

Computer-assisted Endoscopy

Motivation: Intraoperative support of the surgeon



What can be seen in the image?

Where is a particular structure?

Does a planning exist?

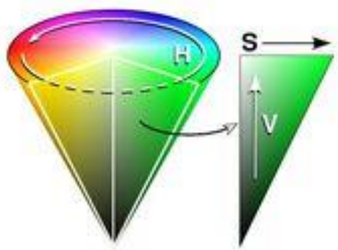
Is the tumour completely removed?

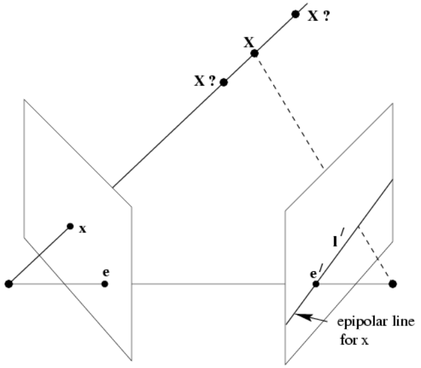
Lecture: Image Processing in Endoscopy and
Visualisation / augmented reality

Upcoming Lecture

Basic Computer Vision I

- Modelling of cameras
- Image representation
- 3D reconstruction methods
- Epipolar geometry





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