

Functional Brain MRI

Christian Windischberger, PhD

CoE Highfield-MR
Medical University of Vienna, Austria



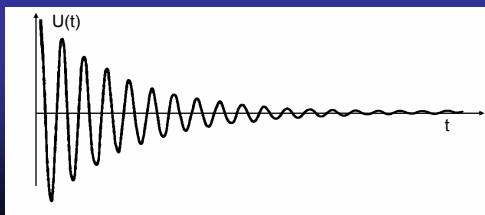
Outline

- Imaging concepts
 - Gradients
 - Slice excitation
 - Frequency encoding
 - Phase encoding

Free Induction Decay (FID)

Spin ensemble magnetization returns to thermal equilibrium after excitation

→ characteristic signal is emitted



NMR → MR: Why?



Field gradients

Spatial encoding via well-defined linear variation of the static magnetic field

$$\vec{G} = \begin{pmatrix} G_x \\ G_y \\ G_z \end{pmatrix} = \begin{pmatrix} \frac{dB_G}{dx} \\ \frac{dB_G}{dy} \\ \frac{dB_G}{dz} \end{pmatrix} \quad \vec{B}_G = B_G \cdot \hat{e}_z$$

Field gradients

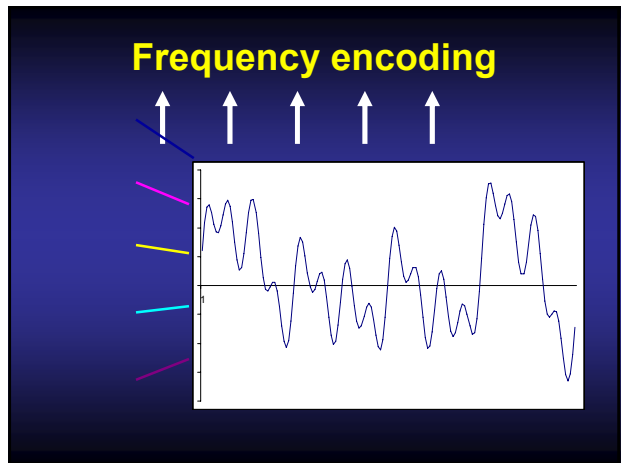
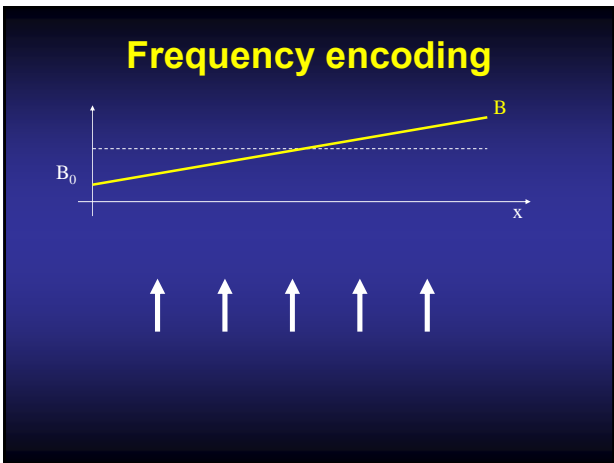
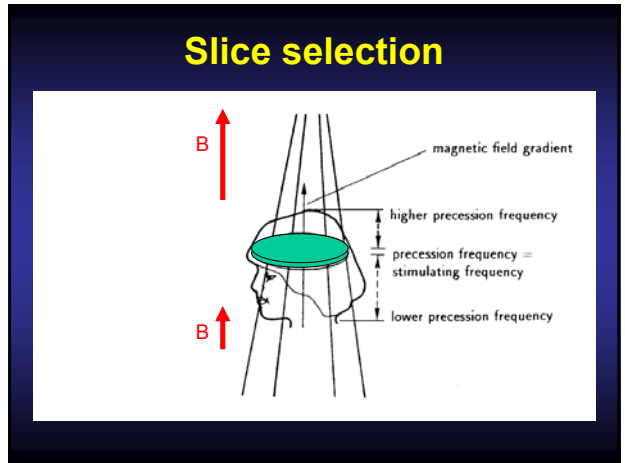
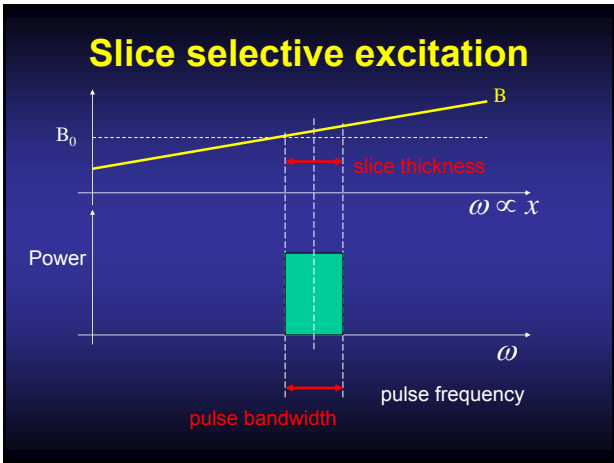
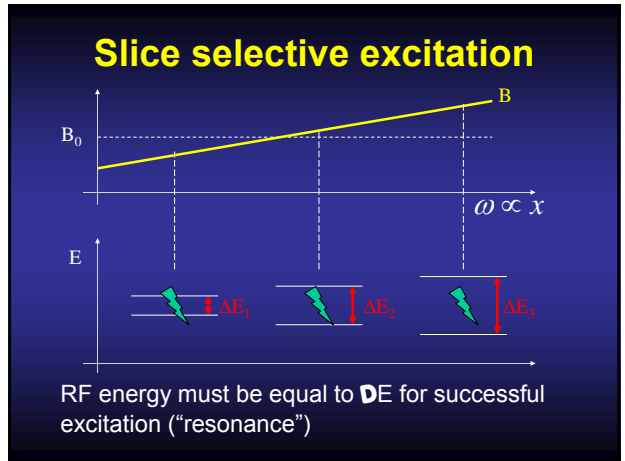
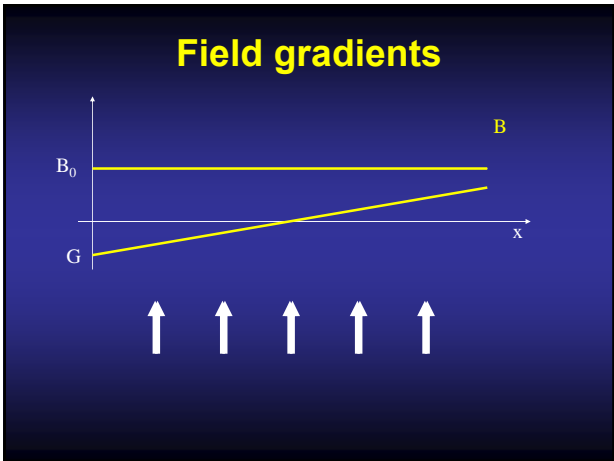
Spatially dependant field causes spatially dependant precession frequency

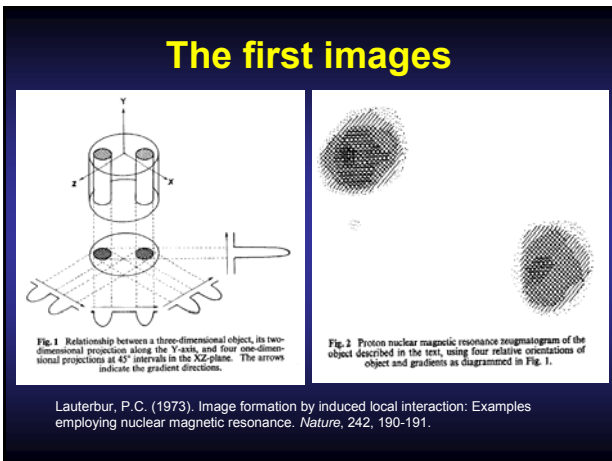
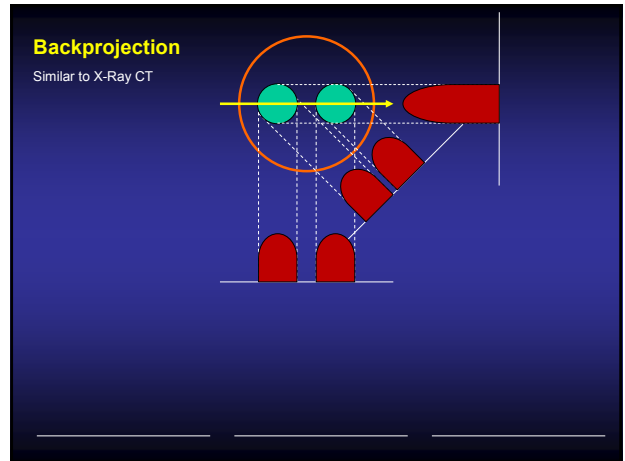
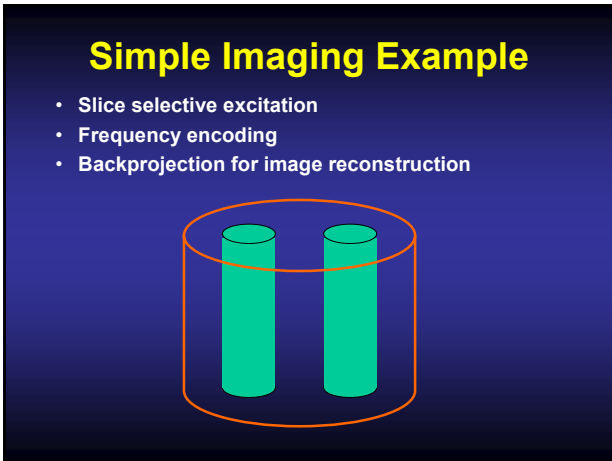
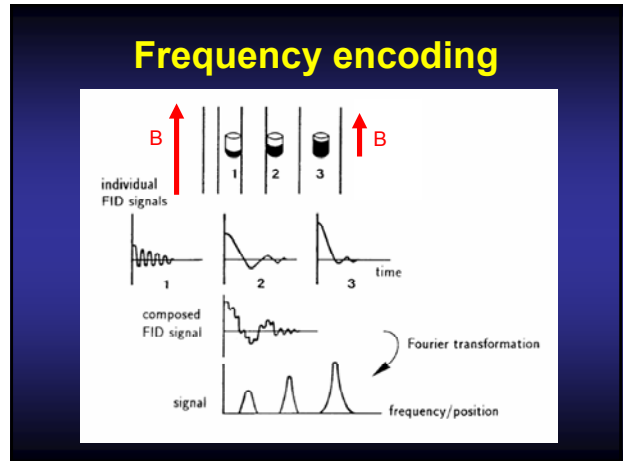
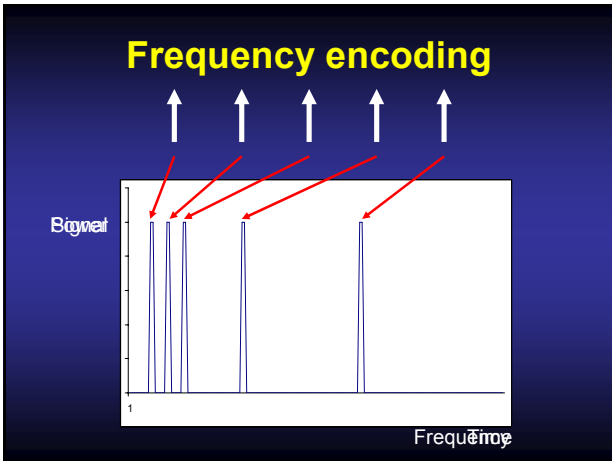
$$B = B_0 + \vec{G} \cdot \vec{r}$$

$$B = B_0 + G_x \cdot x + G_y \cdot y + G_z \cdot z = B(\vec{r})$$

$$\omega = \gamma B_0 + \gamma \vec{G} \cdot \vec{r} = \omega_0 + \omega_G(\vec{r})$$

$$\vec{B}_0 = B_0 \cdot \hat{e}_z; \quad \vec{B}_G = B_G \cdot \hat{e}_z; \quad \vec{B} = B \cdot \hat{e}_z$$



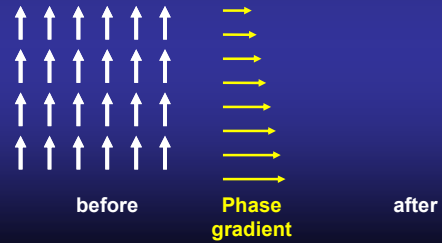


The last dimension: Phase

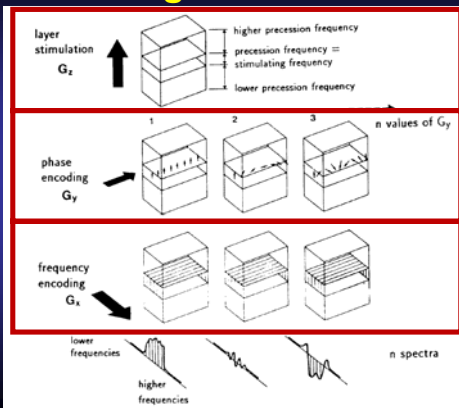
- Slice selective excitation
- Frequency encoding
 - Gradient during data acquisition
 - “readout” gradient
- Phase encoding
 - Short gradient pulse between excitation and readout

Phase encoding

- Apply well-defined phase shift according to spatial position

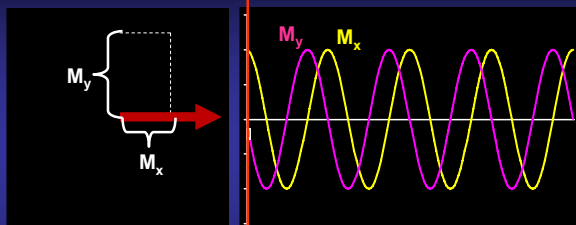


All together now ...



And now the REAL thing: k-space

Single spin after excitation



$$M_x = M_0 \cos(\omega t)$$

$$M_y = -M_0 \sin(\omega t)$$

Spin rotation

$$M_x = -M_0 \sin(\omega t)$$

$$M_y = M_0 \cos(\omega t)$$

$$M = M_0(\cos(\omega t) - i \sin(\omega t))$$

$$M = M_0 \cdot e^{-i\omega t}$$

$$\omega = \gamma B$$

$$M = M_0 \cdot e^{-i\gamma B_0 t}$$

Single spin $M = M_0 \cdot e^{-i\gamma B_0 t}$

Induction $S \propto \frac{dB}{dt} \propto \frac{dM}{dt}$

Induced signal $S(t) = C \cdot M_0 \cdot e^{-i\gamma B_0 t}$

What happens if we use gradients?

Magnetic field $B(\vec{r}) = B_0 + \vec{G} \cdot \vec{r}$

$$B(\vec{r}) = B_0 + G_x \cdot x + G_y \cdot y + G_z \cdot z$$

$$S(t) = C \cdot M_0 \cdot e^{-i\gamma B_0 t}$$

$B(\vec{r}) = B_0 + \vec{G} \cdot \vec{r}$

$$S(t, \vec{r}) = C \cdot M_0 \cdot e^{-i\gamma(B_0 + \vec{G} \cdot \vec{r})t}$$

$$S(t, \vec{r}) = C \cdot M_0 \cdot e^{-i\gamma B_0 t} \cdot e^{-i\gamma \vec{G} \cdot \vec{r} t}$$

Resonance frequency

Signal induced by spins with magnetization M_0 at position \vec{r}

$$S(t, \vec{r}) = C \cdot M_0 \cdot e^{-i\gamma \vec{G} \cdot \vec{r} t}$$

What happens if there are more spins?

$$S(t, \vec{r}) = C \cdot M_0 \cdot e^{-i\gamma \vec{G} \cdot \vec{r} t}$$

Add up all signals

$$S(t) = C \cdot \iiint_V M(\vec{r}) \cdot e^{-i\gamma \vec{G} \cdot \vec{r} t} d\vec{r}$$

Magic trick: $\vec{k} = \gamma \vec{G} t$

$$k_x = \gamma G_x t \quad k_y = \gamma G_y t \quad k_z = \gamma G_z t$$

Heureka!

$$S(t) = C \cdot \iiint_V M(\vec{r}) \cdot e^{-i\gamma \vec{G} \cdot \vec{r} t} d\vec{r} \quad \vec{k} = \gamma \vec{G} t$$

$$S(\vec{k}) = C' \cdot \iiint_V M(\vec{r}) \cdot e^{-i\vec{k} \cdot \vec{r}} d\vec{r}$$

Fourier Transformation (FT)

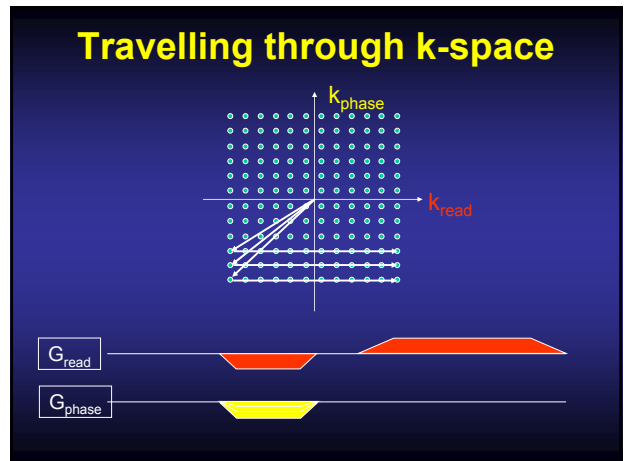
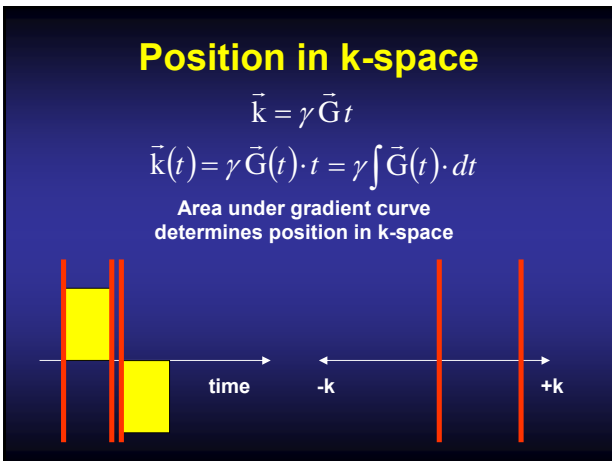
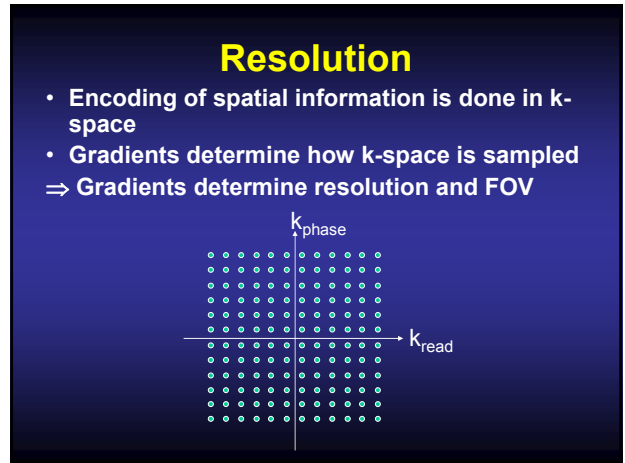
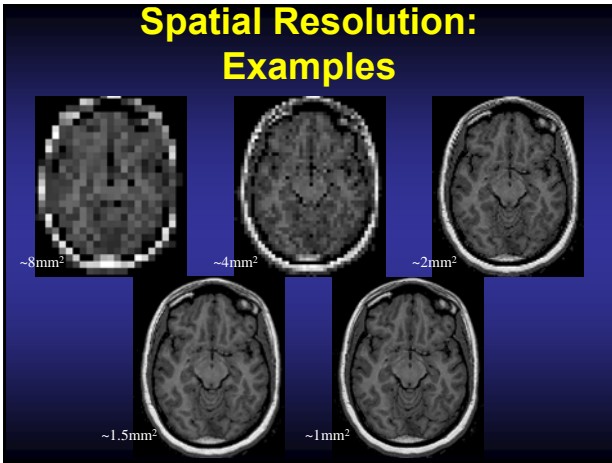
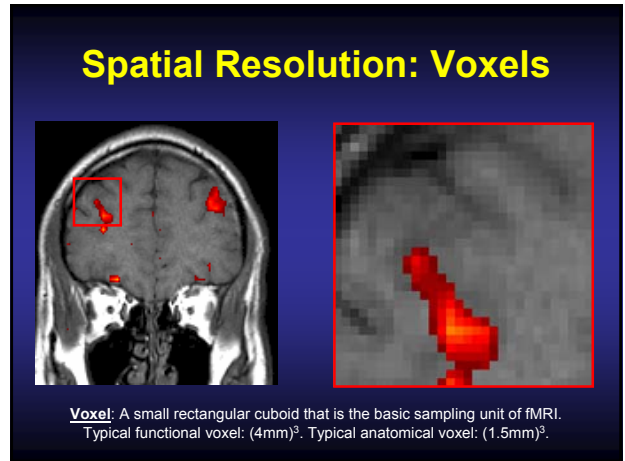
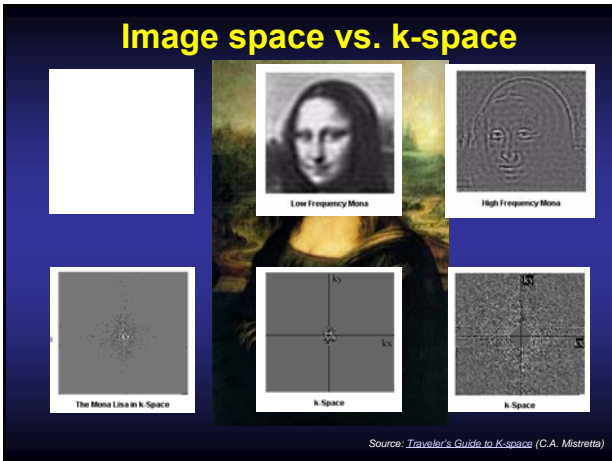
$$M(\vec{r}) = C'' \cdot \iiint_k S(\vec{k}) \cdot e^{i\vec{k} \cdot \vec{r}} d\vec{k}$$

Image real space Signal k-space

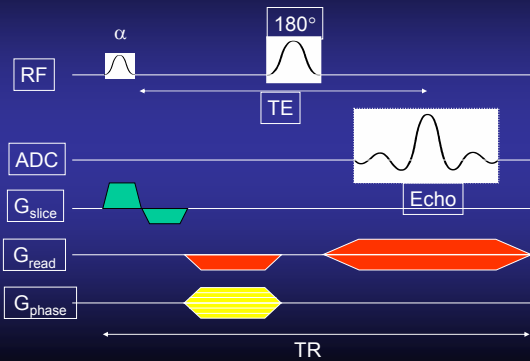
k-space

- Sampling of MR data is done in k-space
- (re)construction of image is performed by fourier transformation (FT) of k-space data

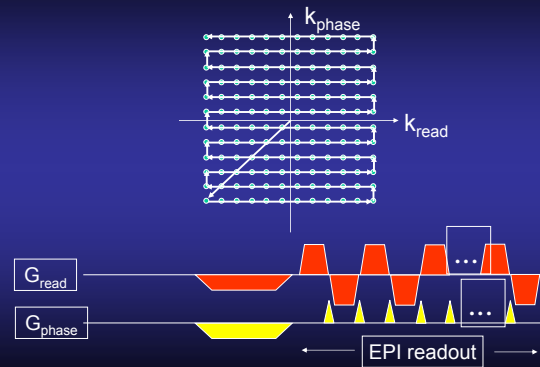
k-space properties



Gradient/Spin-Echo sequence

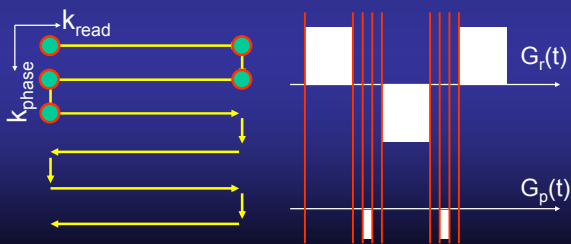


Travelling through k-space

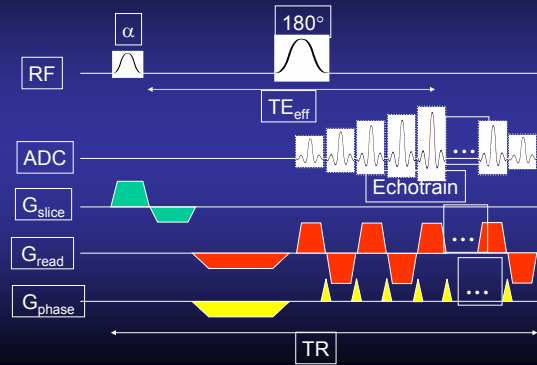


Ultra-fast Imaging

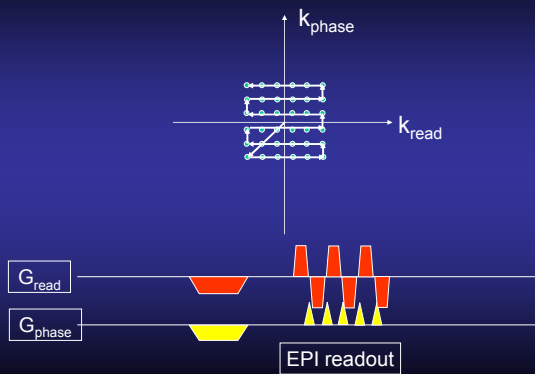
Echo-Planar-Imaging (in 2 dimensions)



EPI sequence



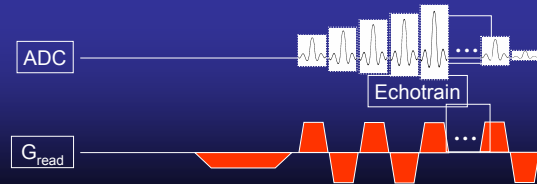
Low resolution

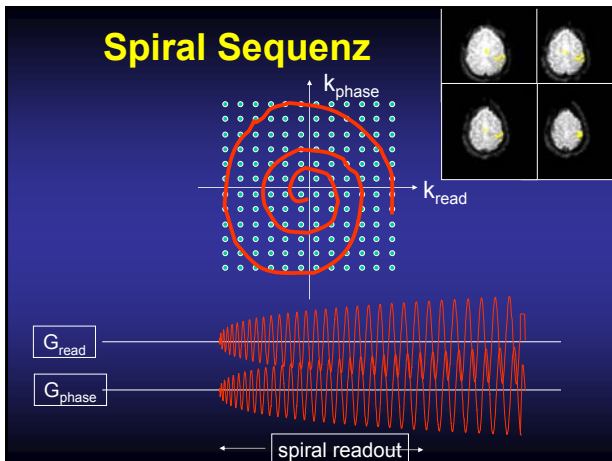


Resolution - Gradients

Long EPI readout:

- long effective TE
- little signal left at the end of EPI-readout
- T_2^* decay during EPI-readout additionally degrades resolution \Rightarrow effective resolution is worse





Resolution - Gradients

High performance gradients needed

- fast ramping times ($< 300\mu\text{s}$)
- high peak amplitudes ($>25\text{T/m}$)
- low eddy currents

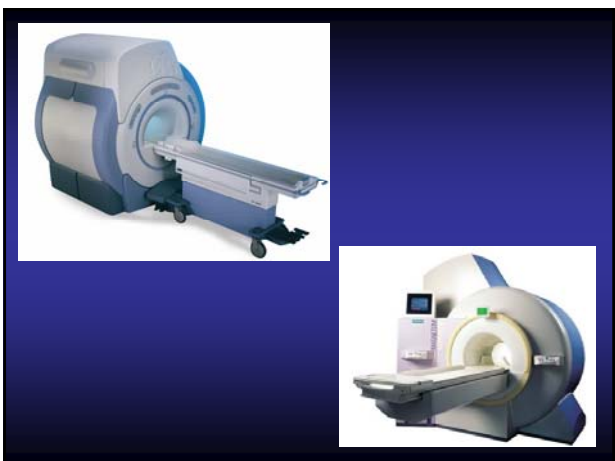
BUT!

- ! patient comfort may be reduced by noise
- ! very fast switching may cause peripheral nerve stimulation

MRI Scanners

Technical Prerequisites

- Huge (superconducting) coil to achieve a very strong magnetic field (~ 10000 times stronger than the earth's magnetic field)
- RF-Coils for application of Radiofrequency - approx. several tens of MHz (Hertz - unit of frequency 1/s)
- Magnetic field gradient coils for imaging to obtain spatial information
- Fast computers for Image calculation using Fourier-Transform
- Especially for fMRI: Physiological monitoring, stimulus display, and behavioral recording hardware
- And of course ... Protons (e.g. human body)



Shimming Coils

- **Used to compensate for magnetic field inhomogeneities**
 - May be first order (X or Y) or of higher orders (X²)
 - May be along single gradient or multiple gradients (XY)
- **Types of shim systems at 3.0T scanner**
 - Passive: Large number of metal rods w/ adjustable weights
 - Adjusted infrequently (i.e., after ramping up)
 - Superconducting: Coils surrounded by cryogens
 - Expensive, adjusted infrequently
 - Resistive: Coils at room-temperature
 - Cheaper, adjusted for each subject

MRI Safety

Issue: The appropriate risk level for a research participant is much lower than for a clinical patient, because the latter receives benefit from the MR examination.

Hospital Nightmare Boy, 6, Killed in Freak MRI Accident

July 31, 2001 — A 6-year-old boy died after undergoing an MRI exam at a New York-area hospital when the machine's powerful magnetic field jerked a metal oxygen tank across the room, crushing the child's head. ...

ABCNews.com

MR Incidents

- **Pacemaker malfunctions leading to death**
 - At least 5 as of 1998 (Schenck, JMIRI, 2001)
 - E.g., in 2001 an elderly man died in Australia after being twice asked if he had a pacemaker
- **Blinding due to movements of metal in the eye**
 - At least two incidents (1985, 1990)
- **Dislodgment of aneurysm clip (1992)**
- **Projectile injuries (most common incident type)**
 - Injuries (e.g., cranial fractures) from oxygen canister (1991, 2001)
 - Scissors hit patient in head, causing wounds (1993)
- **Gun pulled out of policeman's hand, hitting wall and firing**
 - Rochester, NY (2000)

Issues in MR Safety

- **Known acute risks**
 - Projectiles, rapid field changes, RF heating, claustrophobia, acoustic noise, etc.
- **Potential risks**
 - Current induction in tissue at high fields
 - Changes in the developing brain
- **Epidemiological studies of chronic risks**
 - Extended exposure to magnetic fields
- **Difficulty in assessing subjective experience**
 - In one study, 45% of subjects exposed to a 4T scanner reported unusual sensations (Erhard et al., 1995)

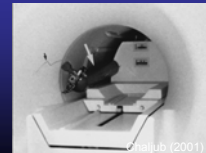
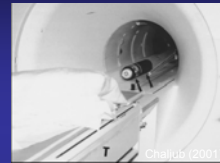
Possible Effects of Magnetic Fields

- **Physiological**
 - Red blood cells (especially sickled) may alter shape in a magnetic field
 - Some photoreceptors may align with the field.
- **Sensory (generally reported in high-field)**
 - Vertigo
 - Metallic taste
 - Magnetophosphenes

Risks of MRI

- Projectile Effects: External
- Projectile Effects: Internal
- Radiofrequency Energy
- Gradient field changes
- Claustrophobia
- Acoustic Noise
- Quenching

Projectile Effects: External



"Large ferromagnetic objects that were reported as having been drawn into the MR equipment include a defibrillator, a wheelchair, a respirator, ankle weights, an IV pole, a tool box, sand bags containing metal filings, a vacuum cleaner, and mop buckets."

-Chaljub et al., (2001) AJR

Radiofrequency Energy

- **Tissue Heating**
 - Specific Absorption Rate (SAR; W/kg)
 - Pulse sequences are limited to cause less than a one-degree rise in core body temperature
 - In the US Scanners can be operated at up to 4 W/kg (with large safety margin) for normal subjects, 1.5 W/kg for compromised patients (infants, fetuses, cardiac)
 - Weight of subject critical for SAR calculations
- **Burns**
 - Looped wires can act as RF antennas and focus energy in a small area
 - Most common problem: ECG leads
 - Necklaces, earrings, piercings, pulse oximeters, any other cabling

Projectile/Torsion Effects: Internal

- **Motion of implanted medical devices**
 - Clips, shunts, valves, etc.
- **Motion or rotation of debris, shrapnel, filings**
 - Primary risk: Metal fragments in eyes
- **Swelling/irritation of skin due to motion of iron oxides in tattoo and makeup pigments**

Acoustic Noise

- **Potential problem with all scans**
 - Short-term and long-term effects
- **Common sound levels of MR scanners**
 - ≈ 98 dB (EPI)
- **Earplugs reduce these values by 14-29 dB.**

Gradient noise: Why?

- Gradients are created by currents through wires in the gradient coil — up to 100 Amperes
- Currents immersed in a magnetic field have a force on them — the Lorentz force — pushing them sideways
- Switching currents back and forth rapidly causes force to push back and forth rapidly
- Force on wires causes coil assembly to vibrate rapidly
- Frequency of vibration is audio frequency
 - about 1000 Hz = switching rate of frequency encode gradients
 - scanner is acting like a (low-fidelity) loudspeaker

Gradient Field Changes (dB/dt)

- **Peripheral nerve stimulation**
 - May range from distracting to painful
 - Risk greatly increased by conductive loops
 - Arms clasped
 - Legs crossed
- **Theoretical risk of cardiac stimulation**
 - No evidence for effects at gradient strengths used in MRI

Claustrophobia

- **Most common subject problem**
 - About 10% of patients
 - About 1% of our subjects
- **Can be reduced with comfort measures**
 - Talking with subject
 - Air flow through scanner
 - Panic button
 - Slow entry into scanner

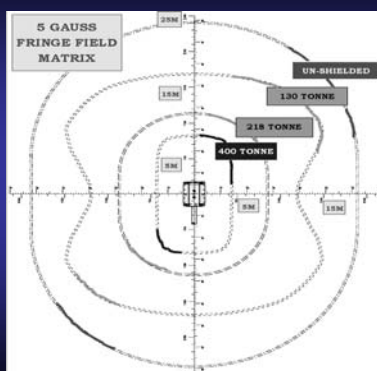
Quenching

- **Definition: Rapid decrease in magnetic field strength due to loss of superconductivity**
 - Only initiated voluntarily due to danger for participant's life or health
- **Effects**
 - Magnets heat up with loss of current
 - Cryogenic fluids (Helium) boil off and fill the scanner room
 - Displaces breathable air from room
 - Cooling of room, condensation reduces visibility
 - Physical damage to the scanner may occur
 - Safety personnel must be cognizant of room conditions

Future Perspectives in Vienna

- **01/2007: Construction start of the new 7T building**
- **06/2007: 7T Installation**
- **12/2007: Opening ceremony**

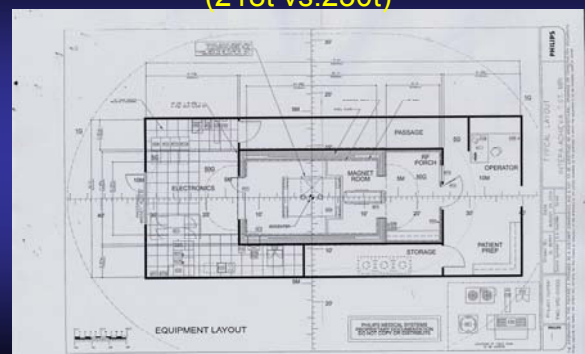
5G Contour Map

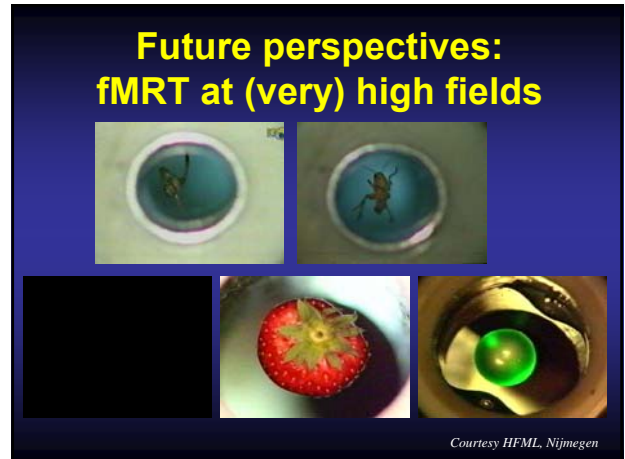
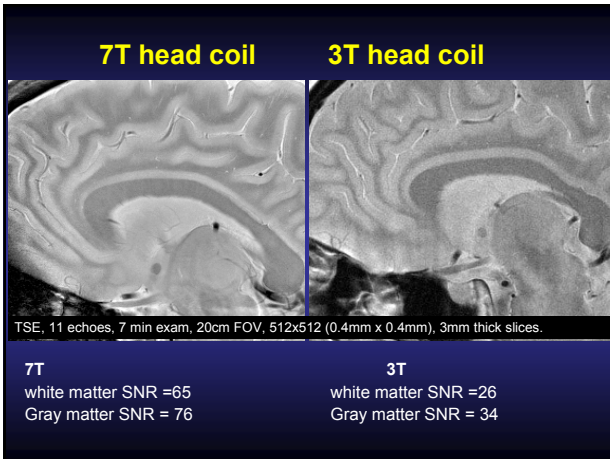


218-T Shield Design
axial 11m
radial 9m

410-T Shield Design
axial 8m
radial 4m

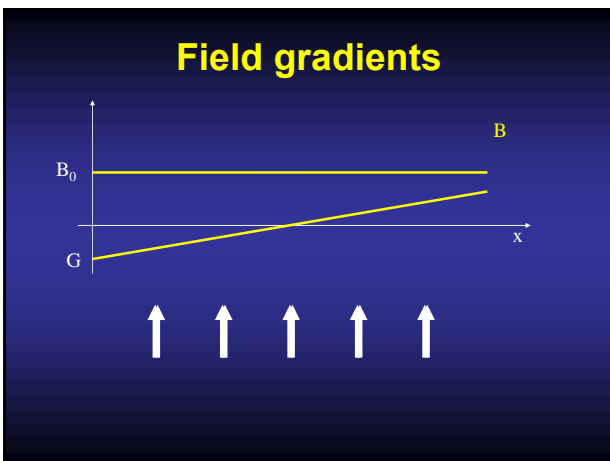
Magnet, RF- and iron shielding (218t vs.230t)





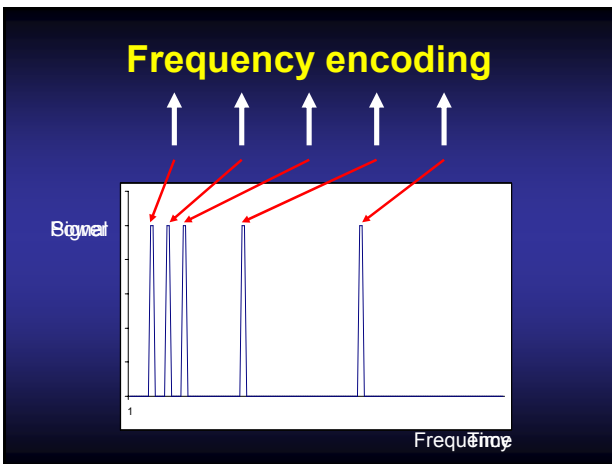
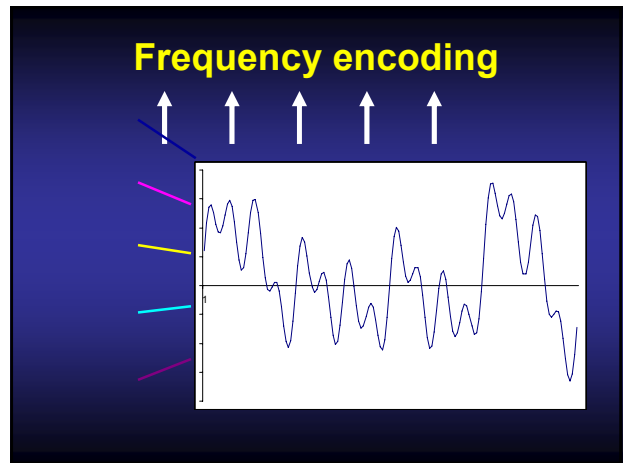
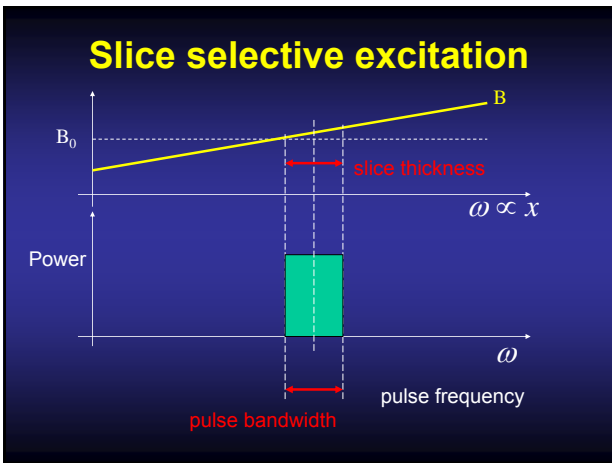
Repetition

Imaging & Safety

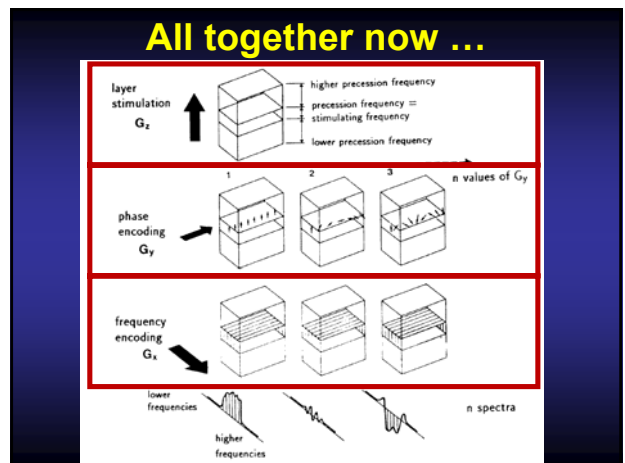
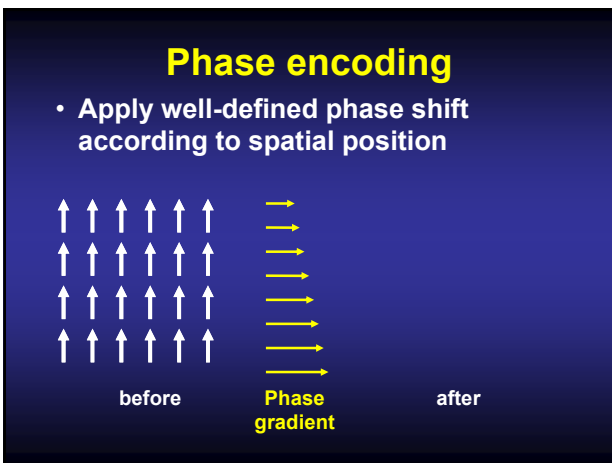


Course Schedule

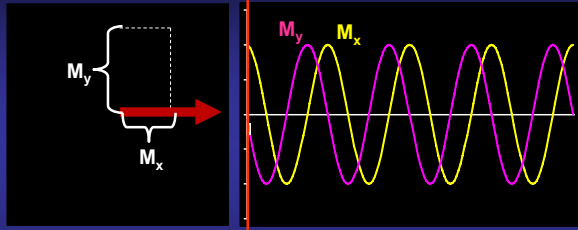
- Today, Wednesday, 2-5 pm
- Tomorrow, Thursday, 11 am – 2 pm
- Friday
 - Scanner Demo from 10:30
 - Lecture 1 – 4 pm



- ### The last dimension: Phase
- Slice selective excitation
 - Frequency encoding
 - Gradient during data acquisition
 - “readout” gradient
 - Phase encoding
 - Short gradient pulse between excitation and readout



Single spin after excitation



$$M_x = M_0 \cos(\omega t)$$

$$M_y = -M_0 \sin(\omega t)$$

Spin rotation

$$M_x = -M_0 \sin(\omega t)$$

$$M_y = M_0 \cos(\omega t)$$

$$M = M_0 (\cos(\omega t) - i \sin(\omega t))$$

$$M = M_0 \cdot e^{-i\omega t}$$

$$\omega = \gamma B$$

$$M = M_0 \cdot e^{-i\gamma B_0 t}$$

Single spin $M = M_0 \cdot e^{-i\gamma B_0 t}$

Induction $S \propto \frac{dB}{dt} \propto \frac{dM}{dt}$

Induced signal $S(t) = C \cdot M_0 \cdot e^{-i\gamma B_0 t}$

What happens if we use gradients?

Magnetic field $B(\vec{r}) = B_0 + \vec{G} \cdot \vec{r}$

$$B(\vec{r}) = B_0 + G_x \cdot x + G_y \cdot y + G_z \cdot z$$

$$S(t) = C \cdot M_0 \cdot e^{-i\gamma B_0 t} \quad \vec{B}(\vec{r}) = B_0 + \vec{G} \cdot \vec{r}$$

$$S(t, \vec{r}) = C \cdot M_0 \cdot e^{-i\gamma (B_0 + \vec{G} \cdot \vec{r}) t}$$

$$S(t, \vec{r}) = C \cdot M_0 \cdot e^{-i\gamma B_0 t} \cdot e^{-i\gamma \vec{G} \cdot \vec{r} t}$$

Resonance frequency

Signal induced by spins with magnetization M_0 at position \vec{r}

$$S(t, \vec{r}) = C \cdot M_0 \cdot e^{-i\gamma \vec{G} \cdot \vec{r} t}$$

What happens if there are more spins?

$$S(t, \vec{r}) = C \cdot M_0 \cdot e^{-i\gamma \vec{G} \cdot \vec{r} t}$$

Add up all signals

$$S(t) = C \cdot \iiint_V M(\vec{r}) \cdot e^{-i\gamma \vec{G} \cdot \vec{r} t} d\vec{r}$$

Magic trick: $\vec{k} = \gamma \vec{G} t$

$$k_x = \gamma G_x t \quad k_y = \gamma G_y t \quad k_z = \gamma G_z t$$

Heureka!

$$S(t) = C \cdot \iiint_V M(\vec{r}) \cdot e^{-i\gamma \vec{G} \cdot \vec{r} t} d\vec{r} \quad \vec{k} = \gamma \vec{G} t$$

$$S(\vec{k}) = C \cdot \iiint_V M(\vec{r}) \cdot e^{-i\vec{k} \cdot \vec{r}} d\vec{r}$$

Fourier Transformation (FT)

$$M(\vec{r}) = C^{-1} \cdot \iiint_k S(\vec{k}) \cdot e^{i\vec{k} \cdot \vec{r}} d\vec{k}$$

Image real space

Signal k-space

Position in k-space

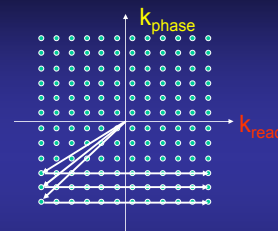
$$\vec{k} = \gamma \vec{G} t$$

$$\vec{k}(t) = \gamma \vec{G}(t) \cdot t = \gamma \int \vec{G}(t) \cdot dt$$

Area under gradient curve determines position in k-space

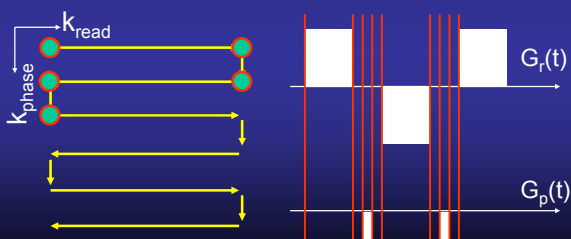


Travelling through k-space

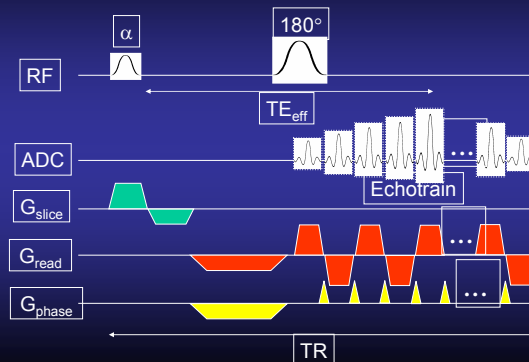


Ultra-fast Imaging

Echo-Planar-Imaging (in 2 dimensions)



EPI sequence



Resolution - Gradients

High performance gradients needed

- fast ramping times ($< 300\mu\text{s}$)
- high peak amplitudes ($> 25\text{mT/m}$)
- low eddy currents

BUT!

- ! patient comfort may be reduced by noise
- ! very fast switching may cause peripheral nerve stimulation

Technical Prerequisites

- Huge (superconducting) coil to achieve a very strong magnetic field (~ 10000 times stronger than the earth's magnetic field)
- RF-Coils for application of Radiofrequency - approx. several tens of MHz (Hertz - unit of frequency 1/s)
- Magnetic field gradient coils for imaging to obtain spatial information
- Fast computers for Image calculation using Fourier-Transform
- Especially for fMRI: Physiological monitoring, stimulus display, and behavioral recording hardware
- And of course ... Protons (e.g. human body)

Hospital Nightmare Boy, 6, Killed in Freak MRI Accident

July 31, 2001 — A 6-year-old boy died after undergoing an MRI exam at a New York-area hospital when the machine's powerful magnetic field jerked a metal oxygen tank across the room, crushing the child's head. ...

ABCNews.com

MR Incidents

- **Pacemaker malfunctions leading to death**
 - At least 5 as of 1998 (Schenck, JMIR, 2001)
 - E.g., in 2001 an elderly man died in Australia after being twice asked if he had a pacemaker
- **Blinding due to movements of metal in the eye**
 - At least two incidents (1985, 1990)
- **Dislodgment of aneurysm clip (1992)**
- **Projectile injuries (most common incident type)**
 - Injuries (e.g., cranial fractures) from oxygen canister (1991, 2001)
 - Scissors hit patient in head, causing wounds (1993)
- **Gun pulled out of policeman's hand, hitting wall and firing**
 - Rochester, NY (2000)

Risks of MRI

- **Projectile Effects: External**
- **Projectile Effects: Internal**
- **Radiofrequency Energy**
- **Gradient field changes**
- **Claustrophobia**
- **Acoustic Noise**
- **Quenching**