Radio spectroscopies, NMR, ESR, MRI

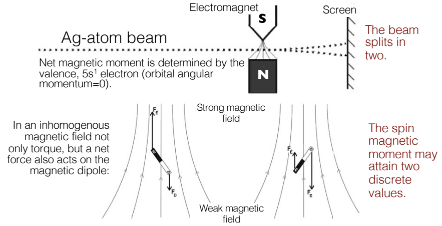
Miklós Kellermayer

Atomic, molecular systems may behave as elementary magnets

Stern-Gerlach experiment (1922)

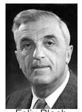

Otto Stern (1888-1969)

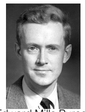

Walther Gerlach (1889-1979)



Nuclear magnetic resonance, (NMR) Nobel-prize, 1952


Isidor Rabi (1898-1988)

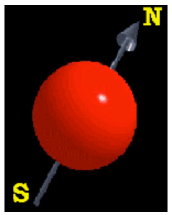

Felix Bloch (1905-1983)


Edward Mills Purcell (1912-1997)

Magnetic resonance: resonance-absorption of electromagnetic energy by a material placed in magnetic field.

Systems with net spin: elementary magnets

- Elementary particles (p, n, e) have their own *spin*.
- Depending on the number of elementary particles and organizational principles (e.g., Pauli principle), ***net spin*** emerges within the system.
- Atomic nucleus: odd mass number - half nuclear spin (^{1}H, ^{13}C, ^{15}N, ^{19}F, ^{31}P); even mass number, odd atomic number - whole nuclear spin; even mass and atomic number - zero nuclear spin.
- Electron: net electron spin within a molecular system containing a stable unpaired electron (e.g., free radicals).
- Because of *charge* and *net spin, magnetic moment* emerges.



Nuclear magnetic moment:

$$M_N = \gamma_N L$$

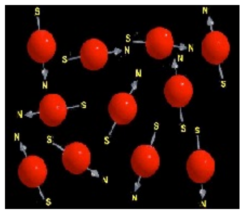
γ_N = gyromagnetic ratio (ratio of magnetic moment and angular momentum.)
L = nuclear spin ($L = \sqrt{l(l+1)}\hbar$), l= spin quantum number.

Magnetic moment of the electron:

$$M_e = -g\mu_\beta \sqrt{S(S+1)}$$

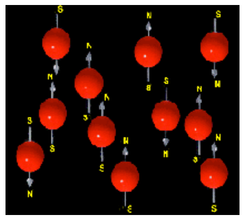
g = electron's g-factor (dimensionless number that describes the relationship between magnetic moment and gyromagnetic ratio)
μ_β = Bohr's magneton (unit of the electron's magnetic moment)
S = spin quantum number

In external magnetic field the elementary magnets orient

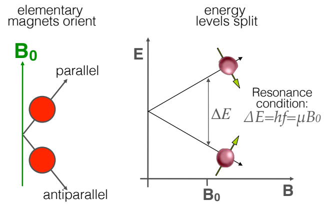


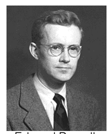
In absence of magnetic field:
random orientation of elementary magnets

Paramagnetism: magnetism emerging in external magnetic field (caused by the orientation of magnetic dipoles).



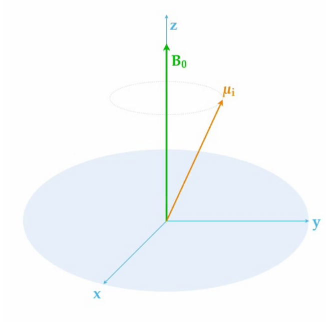
In magnetic field:




Edward Purcell, 1946

ented elementary magnets do precessional mo

Precession of a top



Precession of an elementary magnetic moment (μ_i) in magnetic field (B_0) within a reference *xyz* space

Precession or Larmor frequency:

$$\omega_0 = \gamma B_0$$

$$f_{Larmor} = \frac{\gamma}{2\pi} B_0$$

Resonance condition:

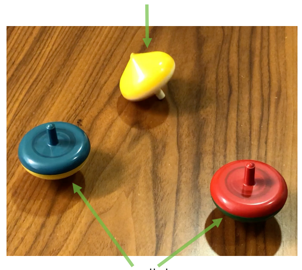
$$\Delta E = \frac{h\omega_0}{2\pi}$$

Felix Bloch, 1946

Net (macrosopic) magnetization

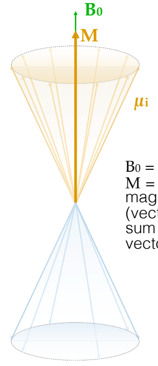
Due to spin access in different energy states

antiparallel



parallel

Low-energy state
parallel in case of proton (^{1}H)



B_0 = magnetic field
M = net magnetization (vectorial quantity, sum of elementary vectors μ_i)

High-energy state
antiparallel in case of ^{1}H

Ratio of low- and high-energy spin polulations is determined by the Boltzmann distribution:

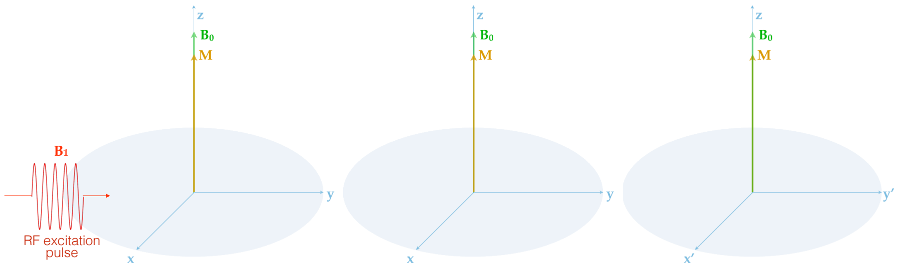
$$\frac{N_{antiparallel}}{N_{parallel}} = e^{-\frac{\Delta E}{k_B T}}$$

N.B.: magnetic field in MRI is 20-50-thousand times as strong as the earth's magnetic field.

Excitation

Resonance condition, Larmor frequency

Employed electromagnetic radiation: radiowaves (NMR, MRI), microwaves (ESR)



Excitation in the real coordinate system (x, y, z)

Concept of the rotating frame of reference: x', y', z coordinate system rotating around the z-axis, together with M

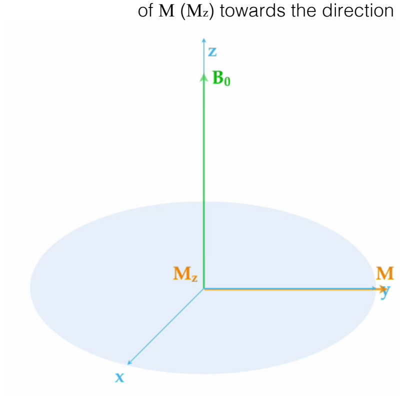
Excitation within the rotating frame of reference: the net magnetization vector (M) is tilted from its oriented state into the *xy*-plane (transverse plane)

B_0 = magnetic field
M = net magnetization
B_1 = irradiated radio frequency wave

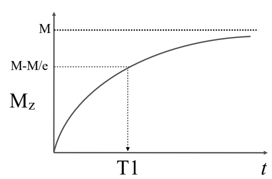
Spin-lattice relaxation

T1 or longitudinal relaxation

T1 relaxation process: return (relaxation) of the *z*-axis vectorial component of M (M_z) towards the direction of the external magnetic field



M_z: *z*-axis vectorial component of M

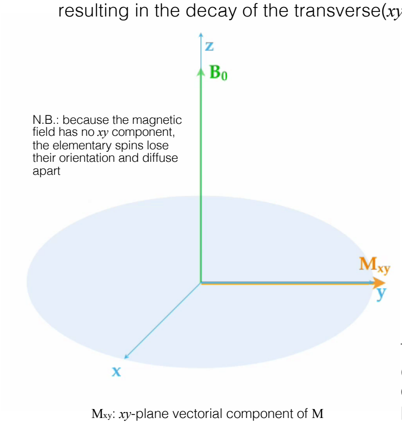


T1 relaxation time:
depends on interaction between elementary magnet (proton) and its environment (lattice)

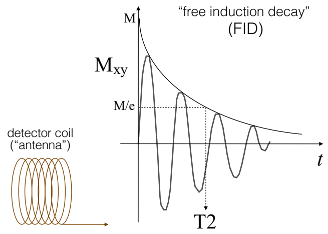
Spin-spin relaxation

T2 or transverse relaxation

T2 relaxation process: diffusion (spreading) of the elementary magnetic moments (μ_i) resulting in the decay of the transverse(xy)-plane vectorial component of M (M_{xy})



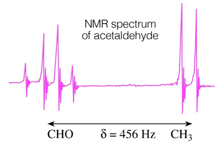
M_{xy}: xy-plane vectorial component of M



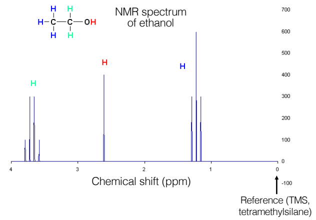
T2 relaxation time:
depends on interaction between elementary magnets (spins, protons); process occurs in the transverse (xy) plane

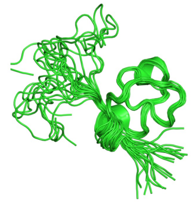
NMR spectroscopy

- NMR spectroscopy or Magnetic Resonance Spectroscopy (MRS)
- Spectroscopic method for measuring the local magnetic field around atomic nuclei. We measure the resonance frequencies of the nuclei positioned in the magnetic field.
- NMR spectrometer: superconducting magnet (cooled with liquid He), large magnetic field (spectral resolution is proportional to field strength).
- NMR spectrum: intensity of absorbed electromagnetic radiation as a function of frequency.
- The area under the "NMR-line" is proportional to the number of absorbing atomic nuclei.
- The electron cloud distorts the local magnetic field, therefore the frequency condition is shifted: "chemical shift". Chemical structure determination is possible.
- Protein NMR: possibility of measuring dynamics and the detection of disordered protein elements



900 MHz NMR, 21.1 T magnet



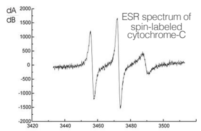


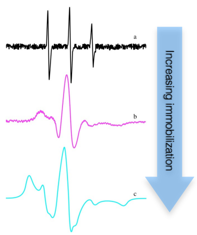
Somatomedin B domain (superimposed structures)

ESR spectroscopy

- Electron spin resonance (ESR) or electron paramagnetic resonance (EPR) spectroscopy.
- Spectroscopic method for investigating materials containing unpaired electron.
- EPR spectrum: intensity of electromagnetic radiation as a function of magnetic field.
- Magnetic field is lower, but radiation frequencies are greater (microwave) than in NMR.
- Spin-labeling: attachment of a chemical containing a stable unpaired electron. Site-directed spin labeling: spin labeling of reactive (mostly -SH) residues introduced into the targeted protein by molecular biological tools (point mutation).
- Dynamics of rotational motion can be measured ub the 10^{-4} - 10^{-2} s time range.

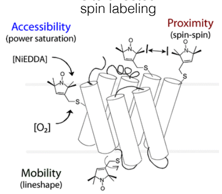
Jevgenyij Zavoisky, 1944

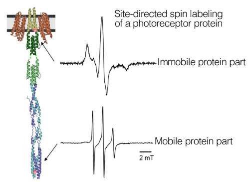




Effect of immobilization on the ESR spektrum

ESR spectroscopy workstation

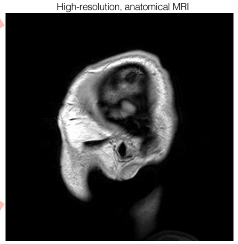




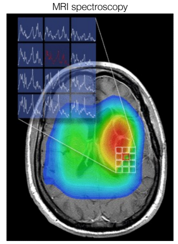
MRI: revolutionary device

Non-invasive

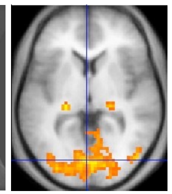
High-resolution, anatomical MRI



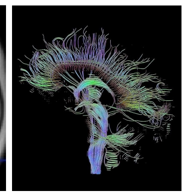
MRI spectroscopy



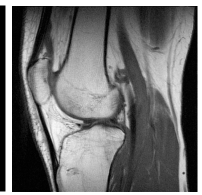
MRI angiography



Functional MRI (fMRI)

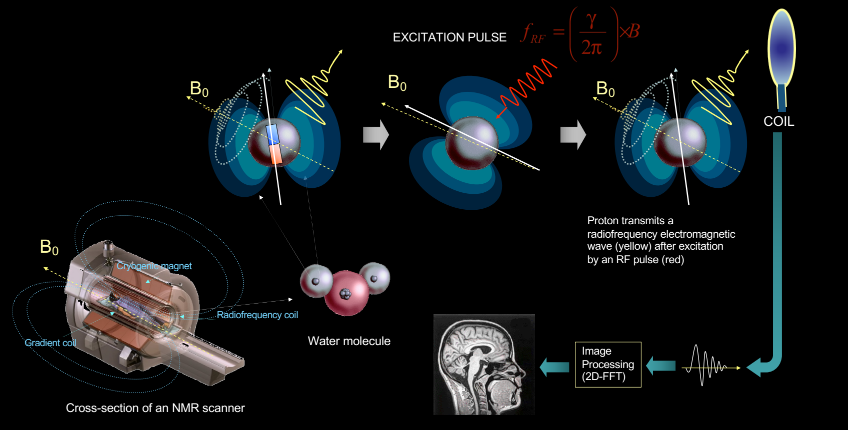


Diffusion MRI (tractography)



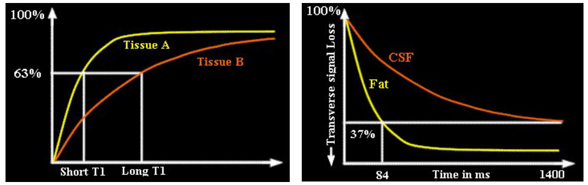
Musculoskeletal MRI

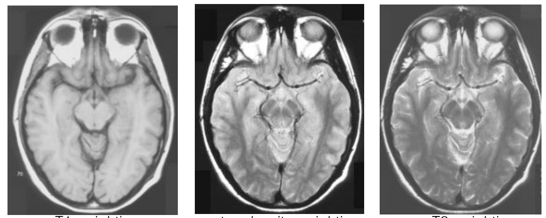
MRI: the human body is macroscopically magnetized



MRI 1: contrast

Color contrast based on spin density (proton density, PD) and relaxation times (T1, T2)

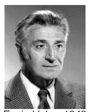




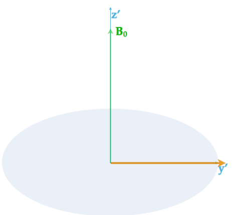
T1-weighting | proton density-weighting | T2-weighting

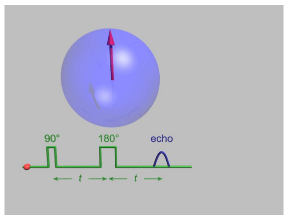
Measuring relaxation time: the spin-echo experiment

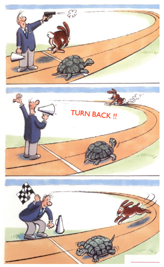
Repeating excitation, refocusing and "echo" pulses: spin-echo sequence



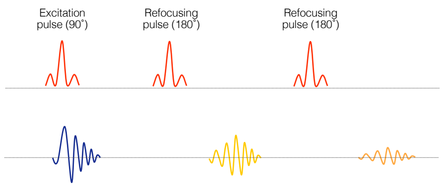
Erwin Hahn, 1949

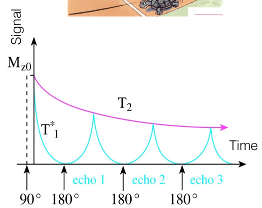




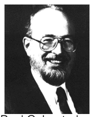


Knocking sounds in MRI: pulse generation

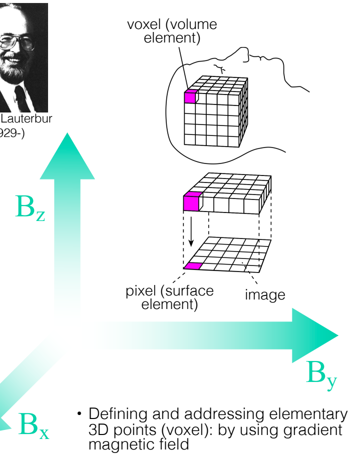




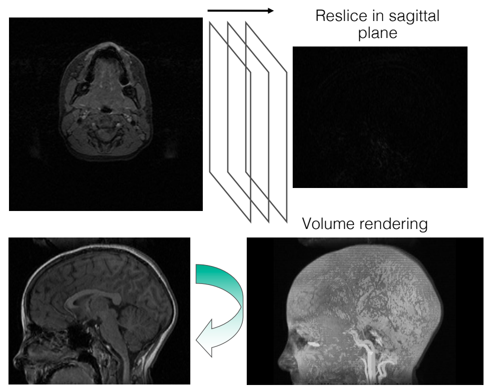
MRI 2: spatial encoding

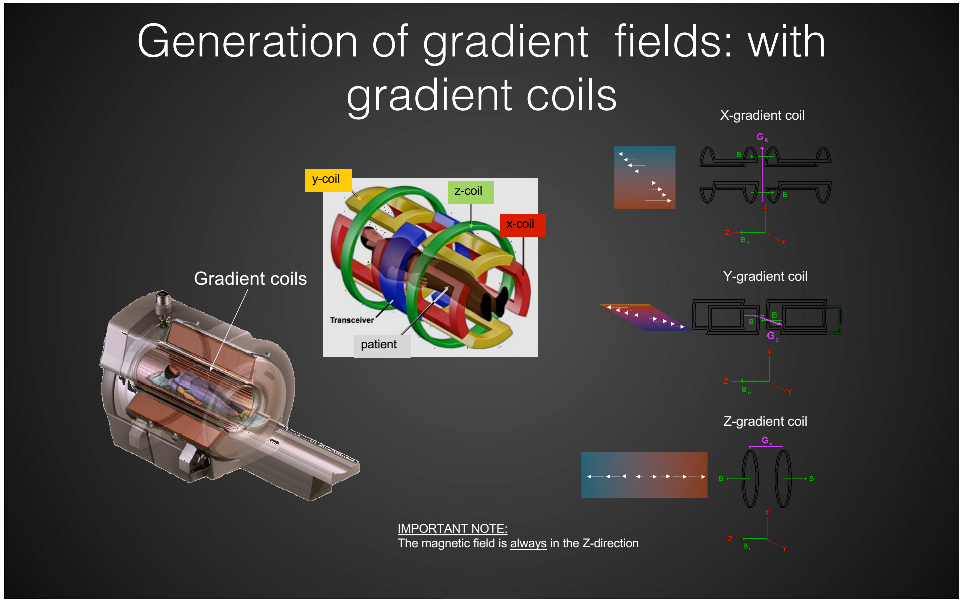


Paul C. Lauterbur (1929-)



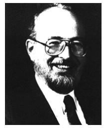
- Defining and addressing elementary 3D points (voxel): by using gradient magnetic field
- Foundations: resonance condition



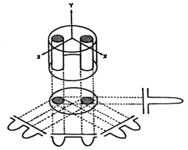


MRI 3: image reconstruction

1. Back projection
- as in CT scanning

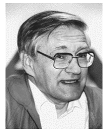

Paul Lauterbur, 1973, Illinois

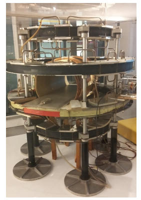

Peter Mansfield, 1973, Nottingham

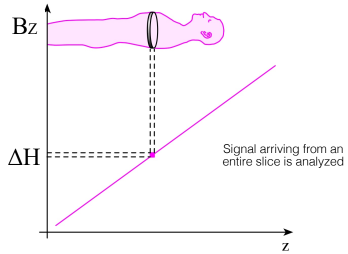

Principle of back projection

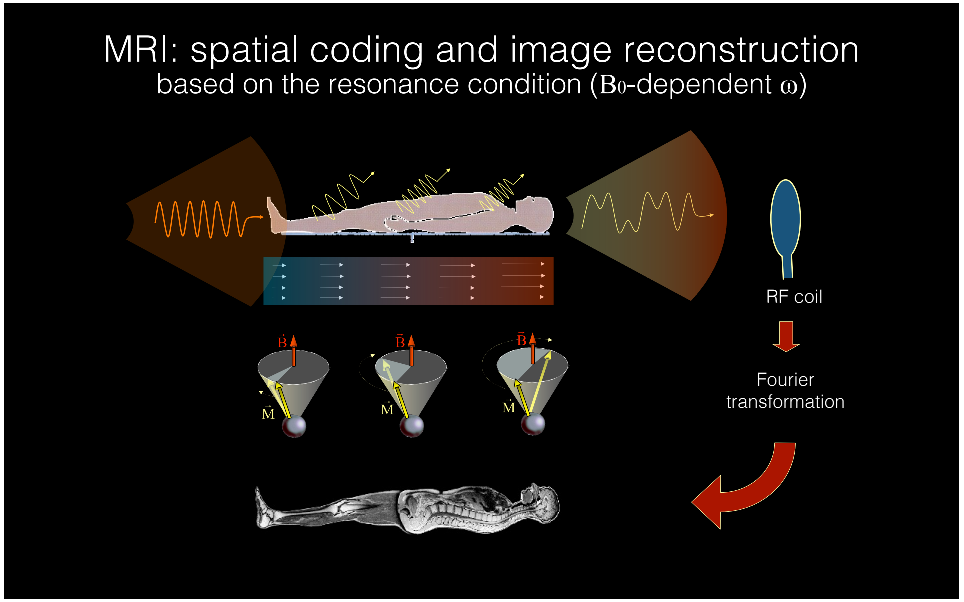

Reconstructed image (cross section of two test tubes)

2. 2D Fourier transformation
- currently used method
- „NMR Fourier Zeugmatography"


Richard Ernst, 1974, Zürich

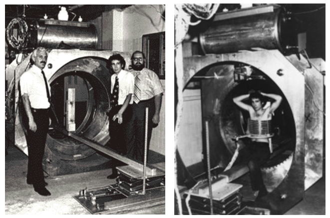

"MRI Scanner Mark One", Aberdeen, Scotland

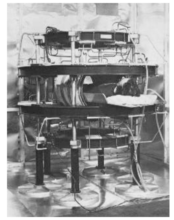




MRI 4: scanners

Early times


Indomitable (Damadian)


MRI Scanner Mark One (Ernst)

Present


3T MRI


Open MRI unit

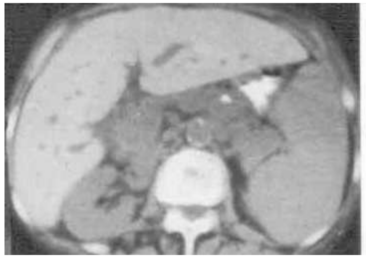

Interventional MRI unit


Mobile MRI

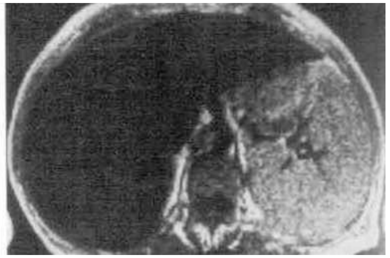
MRI 5: contrast agents

Positive: paramagnetic elements (T1 contrast): Gd, Mn

Negative: superparamagnetic, ferromagnetic (T2 contrast): FeIII, MnII



CT

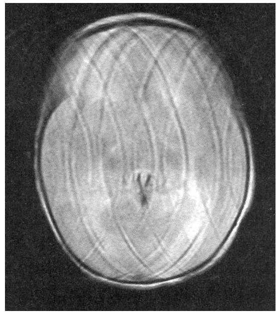


MR T2

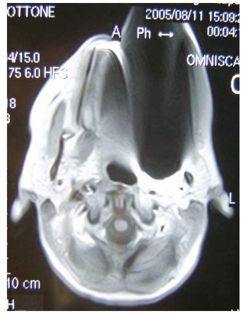
Haemochromatosis hepatis (iron accumulation in liver)

MRI 6:artefacts

- Motion
- Metals (implants, injury)



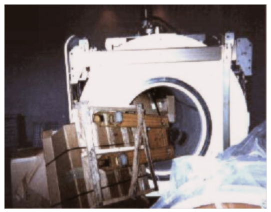
Motion artefact



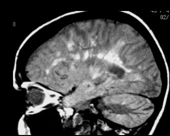
Metal in the orbit of the eye

MRI 7: dangers, contraindications

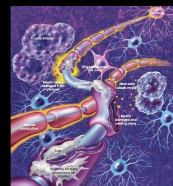
- Static magnetic field - metal objects
  Contraindications: implanted devices (pacemaker, defibrillator, hearing aids, drug delivery devices), neurostimulators, brain aneurysm clamps, early cardiac valve implants
- Gradient field - induced current
- Radio frequency field - thermal effects (lens, testis)



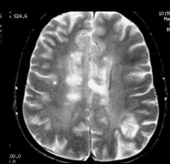
Applications: Anatomical imaging - Multiple sclerosis



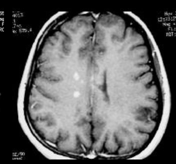
Proton density (sagital)



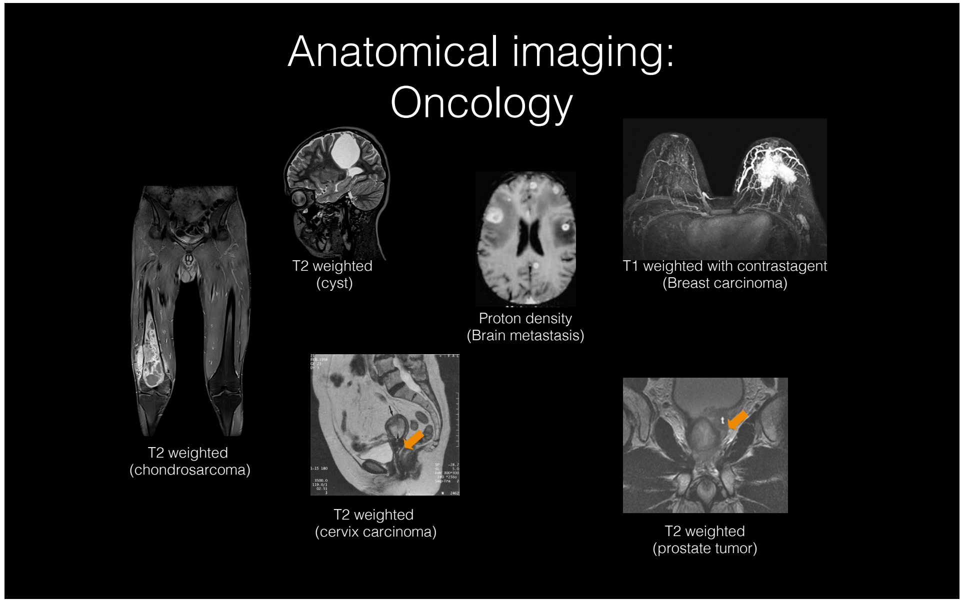
Proton density (transverse)



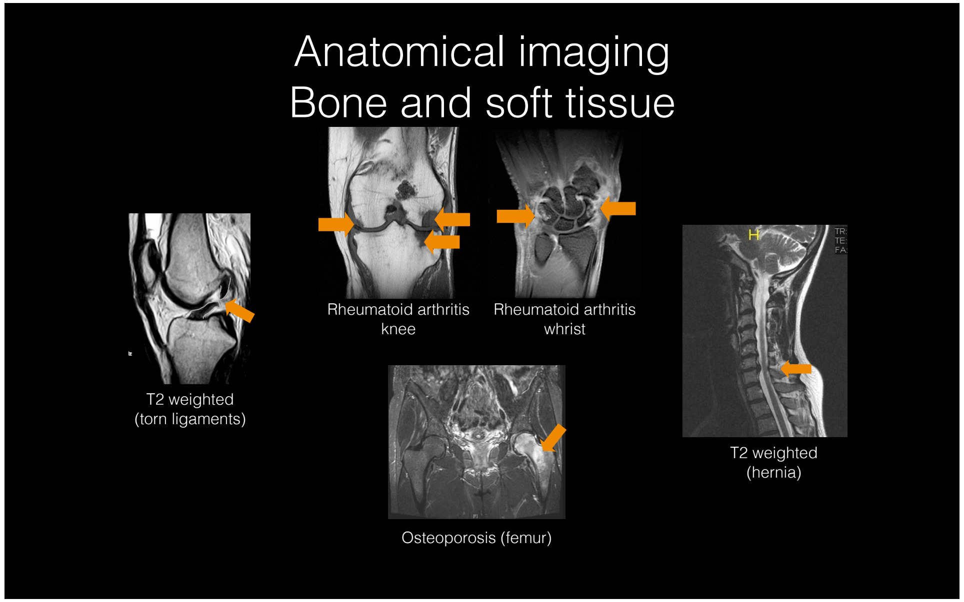
T2 weighted (transverse)



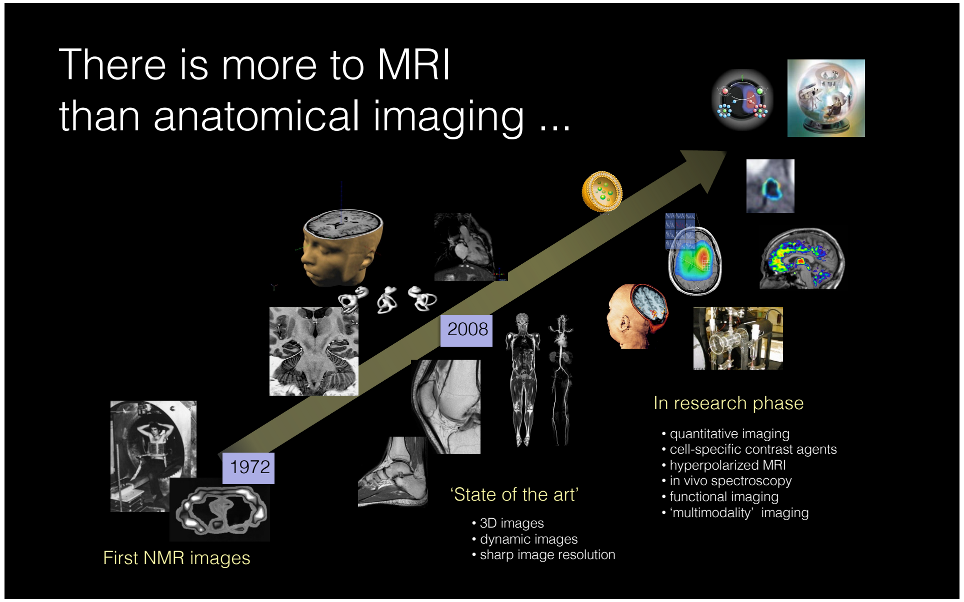
T1 weighted With contrast agent



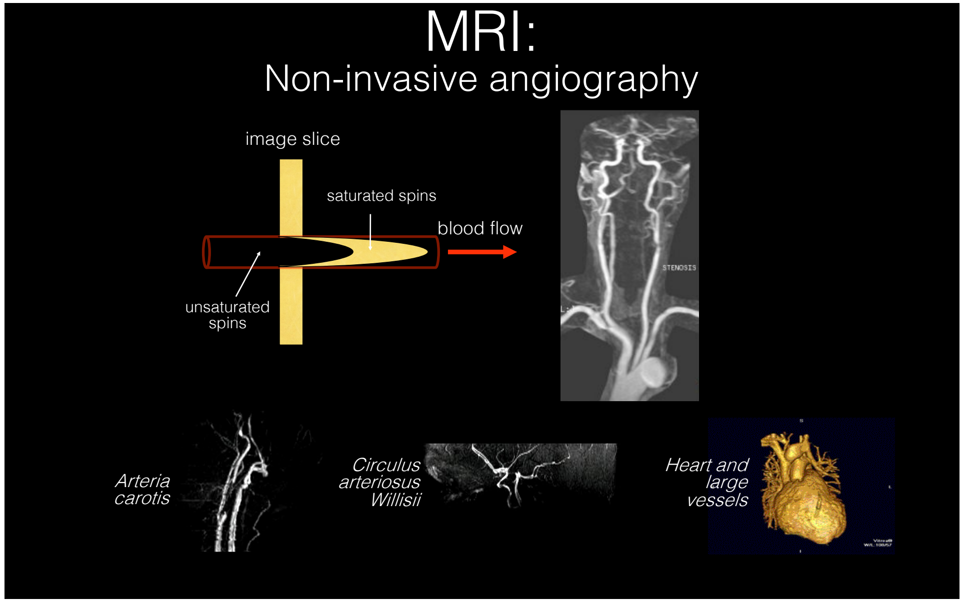
Anatomical imaging:
Oncology
T2 weighted
(cyst)
Proton density
(Brain metastasis)
T1 weighted with contrastagent
(Breast carcinoma)
T2 weighted
(chondrosarcoma)
T2 weighted
(cervix carcinoma)
T2 weighted
(prostate tumor)



Anatomical imaging
Bone and soft tissue
Rheumatoid arthritis
knee
Rheumatoid arthritis
whrist
T2 weighted
(torn ligaments)
T2 weighted
(hernia)
Osteoporosis (femur)

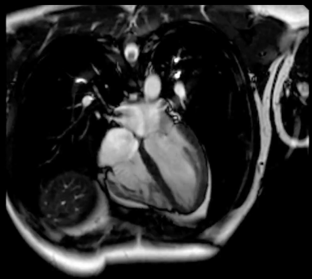


There is more to MRI
than anatomical imaging ...
2008
1972
First NMR images
'State of the art'
• 3D images
• dynamic images
• sharp image resolution
In research phase
• quantitative imaging
• cell-specific contrast agents
• hyperpolarized MRI
• in vivo spectroscopy
• functional imaging
• 'multimodality' imaging



MRI:
Non-invasive angiography
image slice
saturated spins
blood flow
unsaturated
spins
Arteria
carotis
Circulus
arteriosus
Willisii
Heart and
large
vessels

Time-resolved MRI
(ECG-gating required)

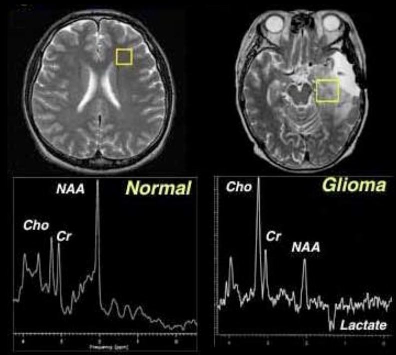


Blood flow across the cardiac chambers

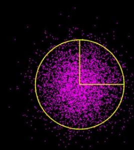
Opening and closing of aorta valve

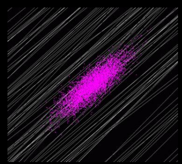
MR Spectroscopy

- Chemical shift
- Identification of metabolites
- Tumor diagnostics

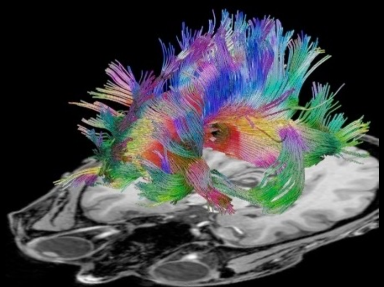


Diffusion imaging





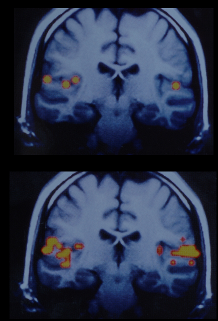
Anisotropic water diffusion: contrast generation



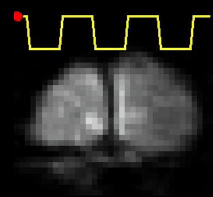
Imaging neural tracts: tractography

Corpus callosum

Functional MRI (fMRI)
High time resolution images recorded synchronously with physiological processes

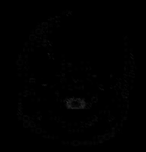


Activation in the acoustic cortex

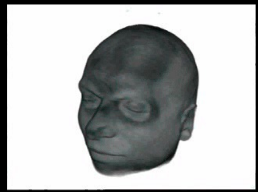


Effect of light pulses on the visual cortex

Superposition of MRI and PET



Intracranial tumor



PET signal: cortical areas activated during eye movement
Volume rendering

Feedback

https://feedback.semmelweis.hu/feedback/pre-show-qr.php?type=feedback&qr=TQ3LPVV6ILE8T5PN