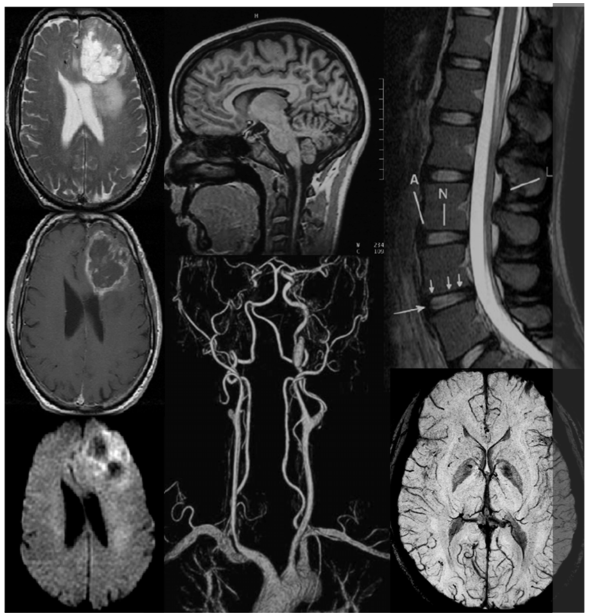

磁振影像學MRI
基本原理與設備

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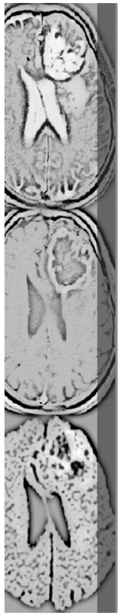
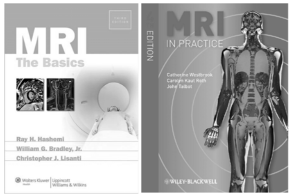
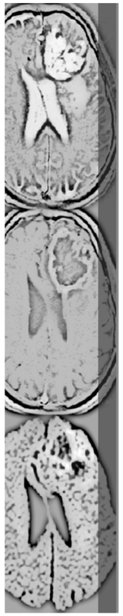


本週課程內容 http://cflu.lab.nycu.edu

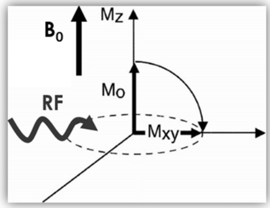
- 磁振原理
- 磁振造影設備 (上週內容複習)

- MRI The Basics (3rd edition)
  - Chapter 2: Basic Principles of MRI
- MRI in Practice, (4th edition)
  - Chapter 1: Basic Principles
  - Chapter 9: Instrumentation and equipment

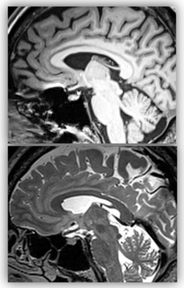




Procedure of MRI

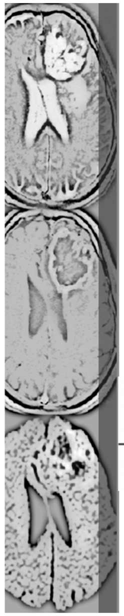


- 1. Alignment (magnetization) B_0
- 2. Precession $\omega_0 = \gamma B_0$
- 3. Resonance (given B_1 by RF with ω_2) $\omega_1 = \gamma B_1$, $B_1 \perp B_0$
  - The most effective resonance is produced when $\omega_0 = \omega_2$
- 4. MR signal (EMF, electromotive force)
- 5. Imaging (Pulse sequencing)
  - Image Contrast: Relaxation time
  - Spatial localization: Spatial Encoding



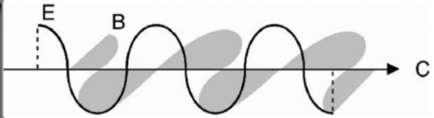
磁振原理

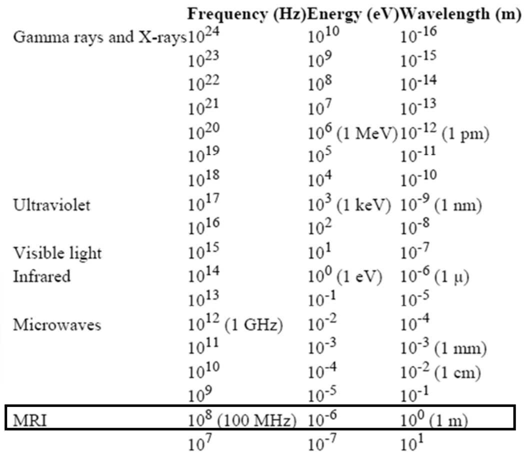
MR Principles



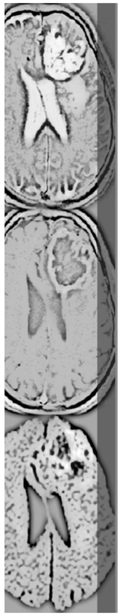
Electromagnetic Waves

- All travel at the speed of light c = 3 x 10^8 m/sec
- Maxwell's wave theory:
  - an electric field *E*
  - A magnetic field *B*



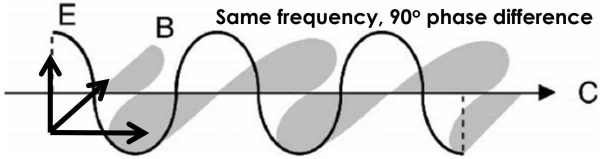


	Frequency (Hz)	Energy (eV)	Wavelength (m)
Gamma rays and X-rays	10^{24}	10^{10}	10^{-16}
	10^{23}	10^{9}	10^{-15}
	10^{22}	10^{8}	10^{-14}
	10^{21}	10^{7}	10^{-13}
	10^{20}	10^{6} (1 MeV)	10^{-12} (1 pm)
	10^{19}	10^{5}	10^{-11}
	10^{18}	10^{4}	10^{-10}
Ultraviolet	10^{17}	10^{3} (1 keV)	10^{-9} (1 nm)
	10^{16}	10^{2}	10^{-8}
Visible light	10^{15}	10^{1}	10^{-7}
Infrared	10^{14}	10^{0} (1 eV)	10^{-6} (1 μ)
	10^{13}	10^{-1}	10^{-5}
Microwaves	10^{12} (1 GHz)	10^{-2}	10^{-4}
	10^{11}	10^{-3}	10^{-3} (1 mm)
	10^{10}	10^{-4}	10^{-2} (1 cm)
	10^{9}	10^{-5}	10^{-1}
MRI	10^{8} (100 MHz)	10^{-6}	10^{0} (1 m)
	10^{7}	10^{-7}	10^{1}



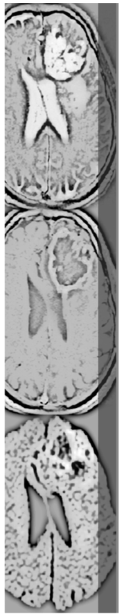
Electromagnetic Waves

- The angular frequency **ω=2π*f*,** *f* is linear frequency
- We are interested in the magnetic field rather than the electric field
  - Electric field generates heat



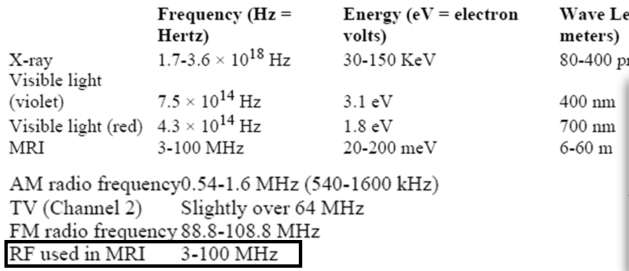
Same frequency, 90° phase difference

Changes in the E generates the B, and vice versa.



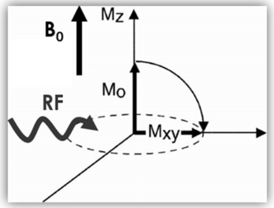
Radio frequency (RF) pulse

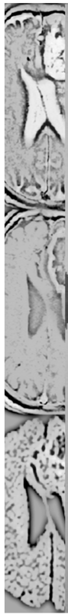
- The electromagnetic pulse used in MRI to get a signal is called an RF pulse.

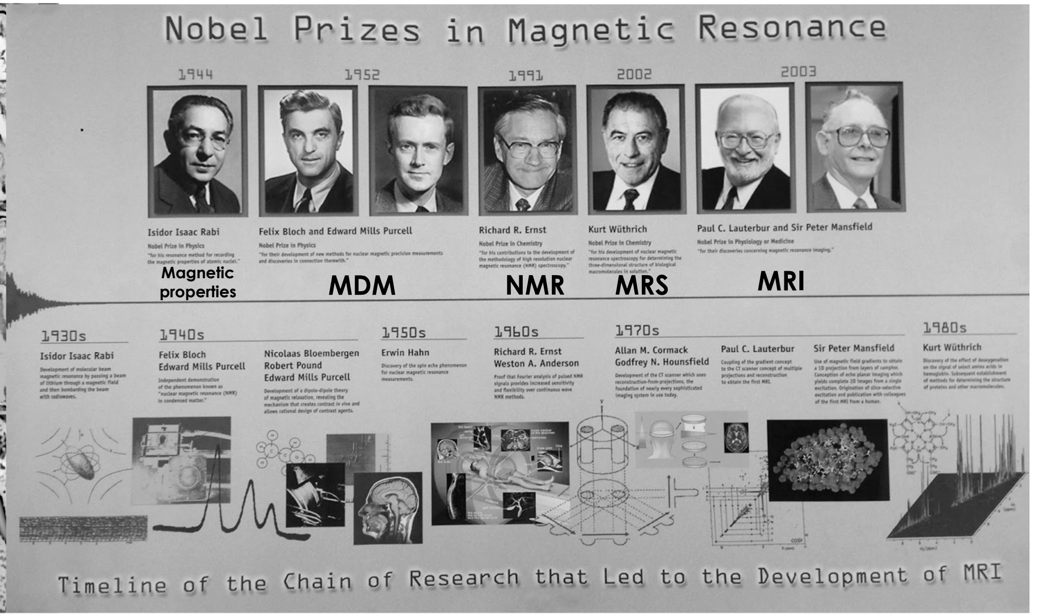


	Frequency (Hz = Hertz)	Energy (eV = electron volts)	Wave Length (m = meters)
X-ray	1.7-3.6 × 10^{18} Hz	30-150 KeV	80-400 pm
Visible light (violet)	7.5 × 10^{14} Hz	3.1 eV	400 nm
Visible light (red)	4.3 × 10^{14} Hz	1.8 eV	700 nm
MRI	3-100 MHz	20-200 meV	6-60 m

AM radio frequency	0.54-1.6 MHz (540-1600 kHz)
TV (Channel 2)	Slightly over 64 MHz
FM radio frequency	88.8-108.8 MHz
RF used in MRI	3-100 MHz







Nobel Prizes in Magnetic Resonance

1944

Isidor Isaac Rabi

Nobel Prize in Physics

"for his resonance method for recording the magnetic properties of atomic nuclei."

Magnetic properties

1952

Felix Bloch and Edward Mills Purcell

Nobel Prize in Physics

"for their development of new methods for nuclear magnetic precision measurements and discoveries in connection therewith."

MDM

1991

Richard R. Ernst

Nobel Prize in Chemistry

"for his contributions to the development of the methodology of high resolution nuclear magnetic resonance (NMR) spectroscopy."

NMR

2002

Kurt Wüthrich

Nobel Prize in Chemistry

"for his development of nuclear magnetic resonance spectroscopy for determining the three-dimensional structure of biological macromolecules in solution."

MRS

2003

Paul C. Lauterbur and Sir Peter Mansfield

Nobel Prize in Physiology or Medicine

"for their discoveries concerning magnetic resonance imaging."

MRI

1930s

Isidor Isaac Rabi

Development of molecular beam magnetic resonance by passing a beam of lithium through a magnetic field and then bombarding the beam with radiowaves.

1940s

Felix Bloch
Edward Mills Purcell

Independent demonstration of the phenomenon known as "nuclear magnetic resonance (NMR) in condensed matter."

Nicolaas Bloembergen
Robert Pound
Edward Mills Purcell

Development of a dipole-dipole theory of magnetic relaxation, revealing the mechanism that creates contrast in vivo and allows rational design of contrast agents.

1950s

Erwin Hahn

Discovery of the spin echo phenomenon for nuclear magnetic resonance measurements.

1960s

Richard R. Ernst
Weston A. Anderson

Proof that Fourier analysis of pulsed NMR signals provides increased sensitivity and flexibility over continuous wave NMR methods.

1970s

Allan M. Cormack
Godfrey N. Hounsfield

Development of the CT scanner which uses reconstruction-from-projections, the foundation of nearly every sophisticated imaging system in use today.

Paul C. Lauterbur

Coupling of the gradient concept to the CT scanner concept of multiple projections and reconstruction to obtain the first MRI.

Sir Peter Mansfield

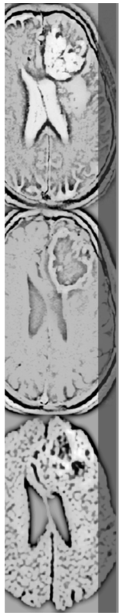
Use of magnetic field gradients to obtain a 1D projection from layers of camphor. Conception of echo planar imaging which yields complete 2D images from a single excitation. Origination of slice-selective excitation and publication with colleagues of the first MRI from a human.

1980s

Kurt Wüthrich

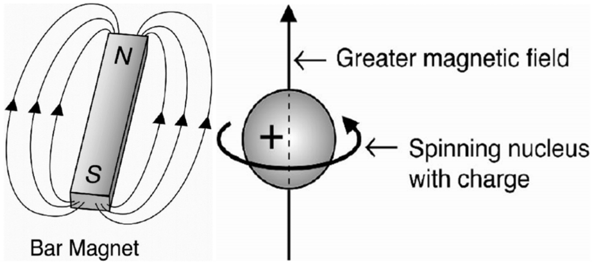
Discovery of the effect of deoxygenation on the signal of select amino acids in hemoglobin. Subsequent establishment of methods for determining the structure of proteins and other macromolecules.

Timeline of the Chain of Research that Led to the Development of MRI



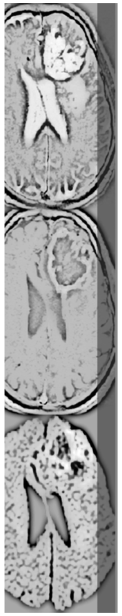
Spins and electromagnetic field

- **Felix Bloch** (Standard University, Nobel prize in physics, 1952)
  - Any spinning charged particle (such as the **hydrogen nucleus**) creates an electromagnetic field.



Magnetic dipole moment (MDM)

1905.10.23~1983.09.10



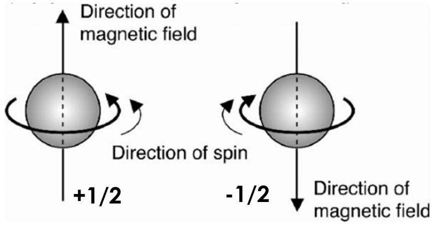
Quantum theory: Energy levels

- The hydrogen nucleus (a proton) has a **spin quantum number (S)**

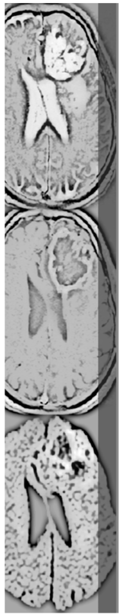
$S\,(^1H)=1/2$

- The number of energy states of a nucleus

\# of energy states = 2S+1 (for ^1H = 2)

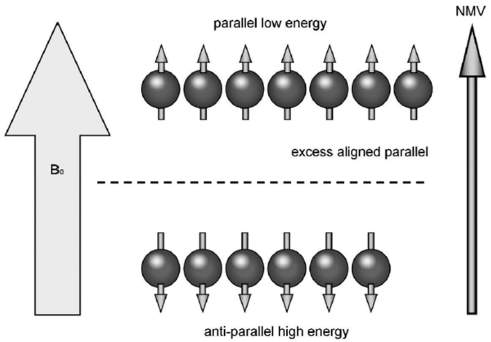


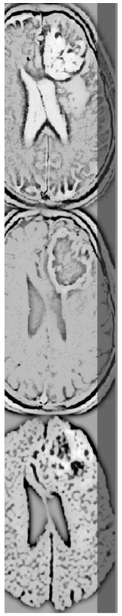
$S\,(^{23}Na)=3/2$
\# of energy states = 2 (3/2) +1
= 4
(-3/2, -1/2, 1/2, 3/2)



Net Magnetic Vector (NMV)

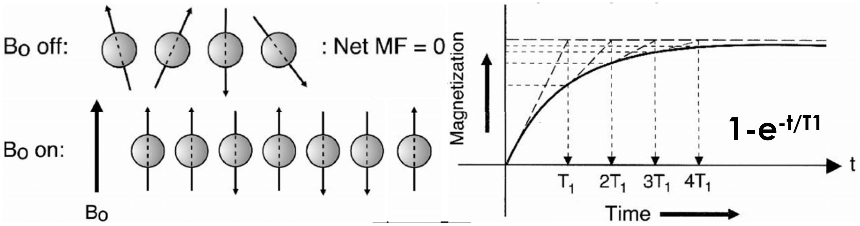
- With B_0, protons line up and approximately half spin-up (parallel, low energy) and half spin-down (anti-parallel, high energy).
- About one in a million more protons point in the direction of B_0.
- ppm (parts per million)

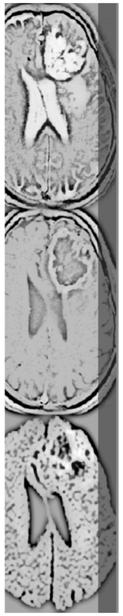




Alignment & T1 Relaxation time

- At time t = 0, proton spins are distributed randomly and net magnetic field is zero.
- Immediately after B_0 is presented, magnetization increases over time.



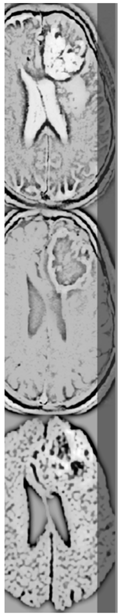


Spin and Precession

- Wheel rolling: spin
- Gravity: B_0

- Spiral precession

Magritek videos on youtube (6:33)!!



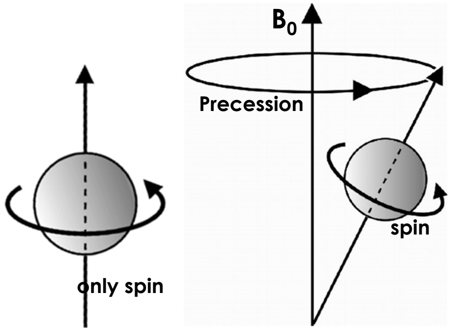
Precession

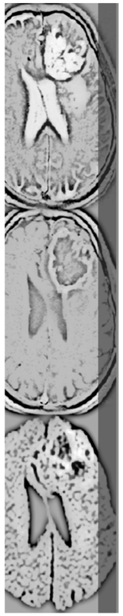
- With B_0, the proton not only spins about its own axis, but also precesses about the axis of the B_0.
- Each proton spins much faster about its own axis than it rotates around the axis of the B_0.
- **Larmor equation (frequency)**

$\omega = \gamma B_0$

γ is gyromagnetic ratio (MHz/T)

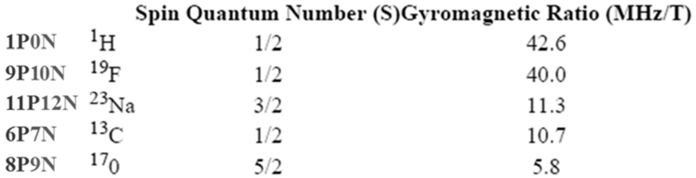
For B_0 from 1.5T → 3T
ω = 42.6 x 1.5T = 63.9 MHz
= 42.6 x 3.0T = 127.8 MHz
The RF range for MRI !!





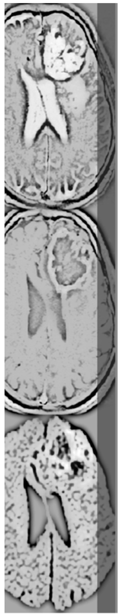
Magnetic dipole moment (MDM)

- An MDM is found in any nucleus with **an odd number of protons, neutrons, or both**.
- MDM is the signal source of MRI.



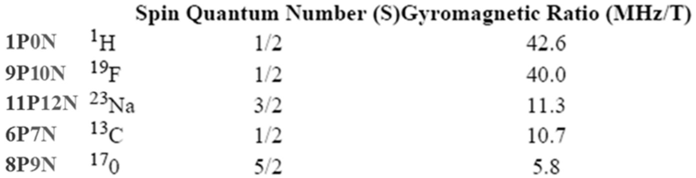
		Spin Quantum Number (S)	Gyromagnetic Ratio (MHz/T)
1P0N	^{1}H	1/2	42.6
9P10N	^{19}F	1/2	40.0
11P12N	^{23}Na	3/2	11.3
6P7N	^{13}C	1/2	10.7
8P9N	$^{17}0$	5/2	5.8

$S \neq 0$, can be MR signal source



Hydrogen Nucleus (^{1}H)

- We use hydrogen for imaging because of...
  - its abundance (about 60~70% of body is water)
  - Hydrogen protons (^{1}H) in water (H_2O) and fat ($-CH_2-$)
  - its high MR sensitivity (high gyromagnetic ratio, γ = 42.58 MHz/T)



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8P9N	$^{17}0$	5/2	5.8

Magnetic Susceptibility, χ

- χ is the measure of magnetizability of a substance.
- The χ is defined as the ratio of the induced magnetic field (M) to the applied magnetic field H:

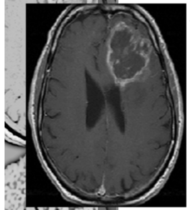
$$M = \chi H \quad \text{or} \quad \chi = M/H.$$

- The *magnetic induction field* or *magnetic flux density*, B, is the net magnetic field effect caused by an external magnetic field H:

$$B = \mu H = (1+\chi)H = H + M.$$

μ represents the *magnetic permeability*.

Magnetic Substances



- **Diamagnetic**
  - No unpaired orbital electrons
  - Under an external B_0, a weak M is induced in the opposite direction to B_0 ($\chi<0$ and $\mu<1$).
  - Most tissues in body are diamagnetic.
- **Paramagnetic**
  - Unpaired orbital electrons
  - M is in the same direction as B_0 ($\chi>0$ and $\mu>1$).
  - Become demagnetized once the B_0 has been turn off.
  - Dipole-dipole (proton-proton and proton-electron) interactions cause T1 shortening (bright signal on T1-weighted images)
  - gadolinium (Gd) – contrast agent
- **Superparamagnetic**
  - breakdown products of hemoglobin: deoxyhemoglobin, methemoglobin, hemosiderin

---

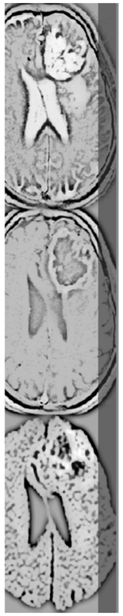
Magnetic Substances

- **Ferromagnetic**
  - Become permanently magnetized even after the magnetic field has been turned off ($\chi>>0$ and $\mu>>1$).
  - Iron (Fe), cobalt (Co), and nickel (Ni)
  - Aneurysm clips and shrapnel

potential projectiles! Safety issue!

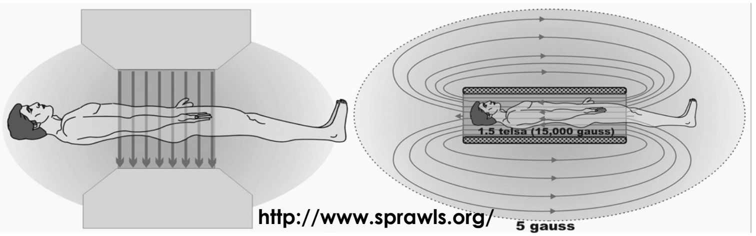
磁振造影設備

MRI Instrument

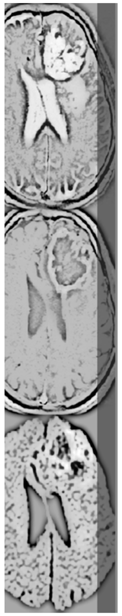


External B_0 Magnetic Field

- On the order of 1 Tesla (1T) = 10000 Gauss (0.5 Gauss for earth's magnetic field in average)
- Required magnetic uniformity is less than 5 ppm (parts per million), which can be achieved by shimming and shielding.



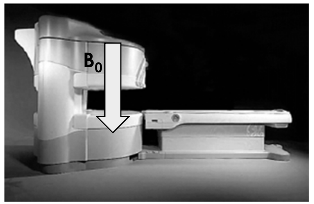
http://www.sprawls.org/

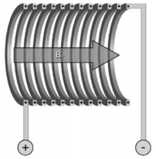


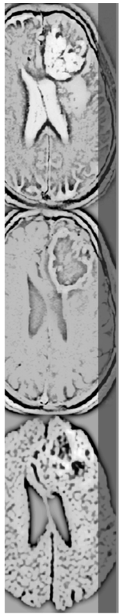
Types of Magnets

alnico alloy: 鋁aluminum(Al)、鎳nickel(Ni)、鈷cobalt(Co)合金

- Permanent magnets (for open MRI scanners), always stay on
- Resistive magnets (for low field MRI), can be turned on/off
- Superconducting magnets (the most common today)
  - operate near absolute zero temperature
  - generate a high B_0 without generating significant heat
  - require cryogens (interior 4^oK liquid helium; outer 77^oK liquid nitrogen), very expensive !!
  - Niobium-titanium alloy (鈮鈦合金)





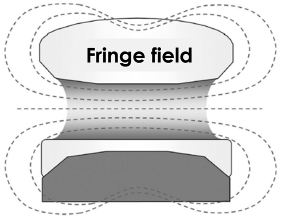


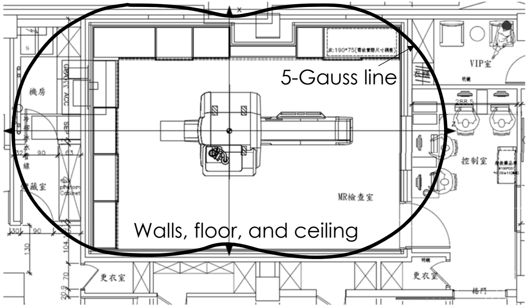
(屏蔽)

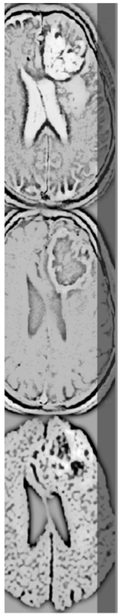
Shielding

1) Prevent extraneous electromagnetic waves from contaminating/distorting the MR signal
2) Reduce electromagnetic field generated by the MR scanner

- **Passive (magnetic) shielding**: scanner room with galvanized steel plates
  - RF shielding is accomplished by lining the scan room walls with copper.
- **Active shielding**: additional solenoid electromagnets located around the outside of the main magnet coil.
- **5 Gauss line** – safety zone







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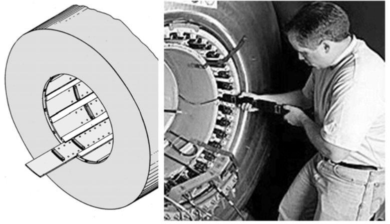
Shimming

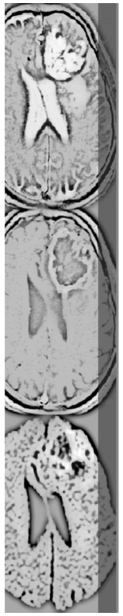
Generally **passive shimming** is used to get the magnetic field to a particular level of homogeneity and then **active shimming** is used to optimize for each patient examination.

- Passive shimming
  - involving the use of ferromagnetic materials, typically iron or steel, placed in a regular pattern at specific locations along the inner bore of the magnet.
- Active shimming
  - performed by an electro-magnetic coil and can be used to shim the system for each patient or even each sequence within a protocol.

Passive shimming

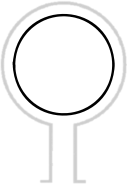


12-24 sliding trays arranged symmetrically with metallic shims
http://mriquestions.com/passive-shimming.html



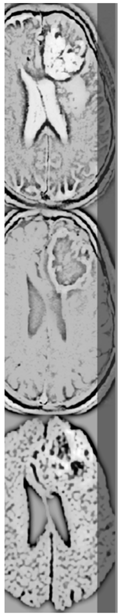
Coils

- Gradient coils
  - Shim coil – increase B_0 homogeneities
  - Imaging gradient coil – intentional perturbation for spatial encoding
- Transmit and/or receive RF coils
  - Linear phase or quadrature (receive or transmit)
  - Surface or volume (Helmholtz or solenoid)
  - Single or phased-array



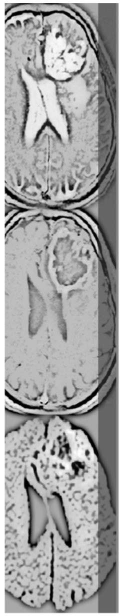
Solenoid coil

Helmholtz coil



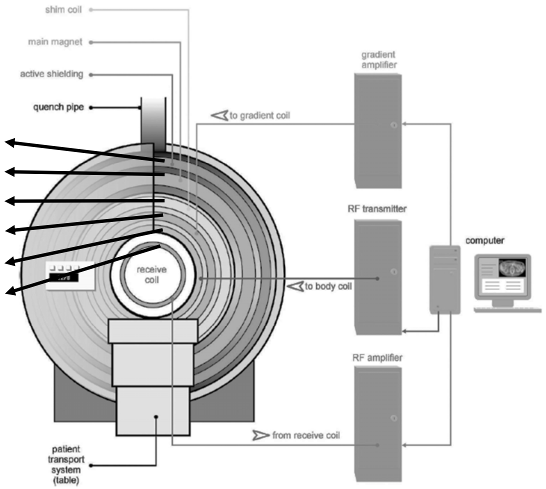
RF Coils

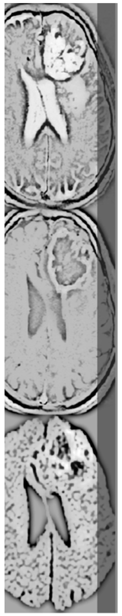
- A transmitter coil transmits an RF pulse
- A receiver coil receives an RF pulse
- Types of coils
  - Body coils: both transmitters and receivers, a part of magnet
  - Head coils: both transmitters and receivers, a helmet-like device
  - Surface coils: just receivers, imaging joints
- Quadrature-phased array coils
  - Multiple elements of coils, larger FOV and better SNR



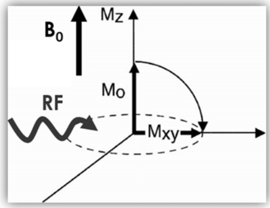
Setup

- Outer → inner
  - Active shielding
  - Main magnet
  - Shim coil
  - Gradient coil
  - Body coil
  - Receive coil

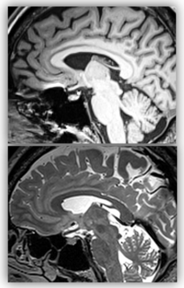




Procedure of MRI



- ☑ Alignment (magnetization) B_0
- ☑ Precession $\omega_0 = \gamma B_0$
- ☐ Resonance (given B_1 by RF with ω_2) $\omega_1 = \gamma B_1$, $B_1 \perp B_0$
  - The most effective resonance is produced when $\omega_0 = \omega_2$
- ☐ MR signal (EMF, electromotive force)
- ☐ Imaging (Pulse sequencing)
- ☐ • Image Contrast: Relaxation time
- ☐ • Spatial localization: Spatial Encoding



THE END

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