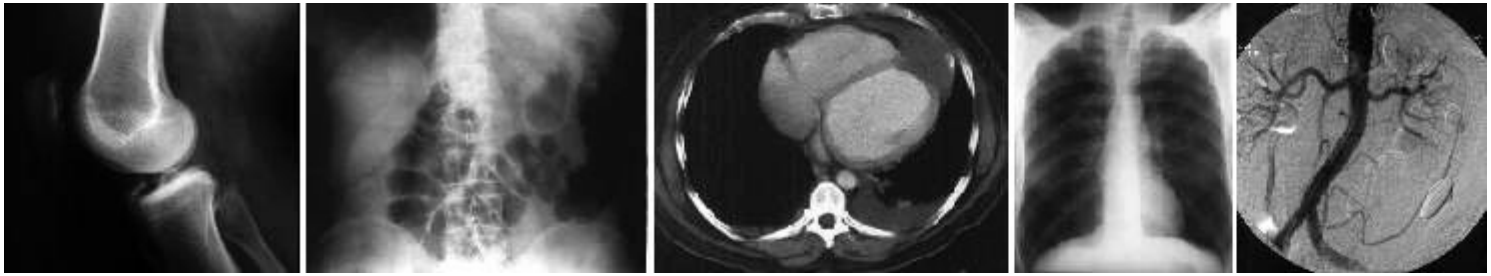


Source: uhrad.com.

Medical Imaging

“Seeing Through the Human Body”

History of medicine

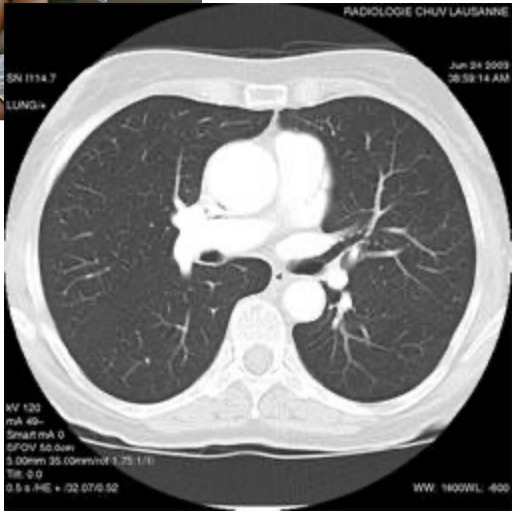
- From humours…

Until 19th century western medicine was based on Galen's theory of humours, or principal fluids: black bile, yellow bile, phlegm (strange liquid related to tumors), and blood

- …to auscultation

Stethoscope: Laennec in 1816

- … and imaging



It all started in 1845 with the first X-ray image

Roentgen’s wife

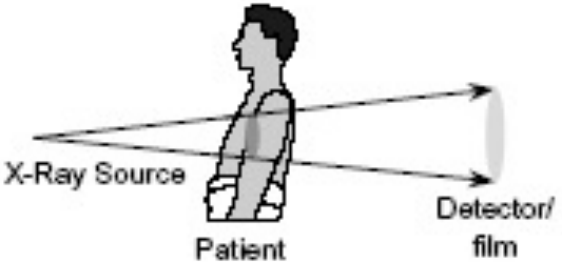
Von Kolliker

History of Medical Imaging

X Ray	• **1845**: Discovery of X-ray by **Wilhelm Conrad Röntgen**, german physicist. • **1972**: First scanner set up by **Allan Mc Cornack** et **Godfrey N. Hounsfield**, Nobel prize in 1979 for this work.
US	• **1915**: Ultrasound propagation principles for SONAR (SOund NAvigation Ranging). • **1955**: First echography by **Inge Edler** (1911-2001), swedish cardiologist.
MRI	• **1945**: Discovery of nuclear resonance under a magnetic field by **Edward Purcell** and **Felix Bloch**, both nobel prize winners in 1952. • **1973**: First MRI image on an animal by the american chemist **Paul Lauterbur.** P. Lauterbur and P. Mansfield won the Nobel Prize for Physiology or Medicine in 2003 for the development of MRI. • **1980**: Spectroscopy by magnetic resonance.
Nuclear	• **1934**: Discovery of natural radioactivity by **Henri Becquerel**, **Pierre** et **Marie Curie.** Discovery of artificial radioactivity by **Irène et Frédéric Joliot-Curie** • **1990**: Nuclear medicine development with scintigraphy and positron emission tomography.

Terminology

- **Transmission:** Photons passing through the body
- **Absorption:** Partial or total absorption of energy in the patient
- **Scatter:** Radiation diverted in a new direction



Source: Utrecht University, NL

- **Axial** - plane normal to a vector from head to toe.
- **Coronal** - plane normal to a vector from front to back
- **Sagittal** - plane normal to a vector from left to right.
- **Oblique** – otherwise.

Image types

- 2D:
  - A single slice.
  - A projection image.
- 3D:
  - A series of parallel slices with uniform spacing.
  - A series of slices with varying spacing and/or orientation.
  - A volumetric data set.

Imaging Support

Films
(hard copy)

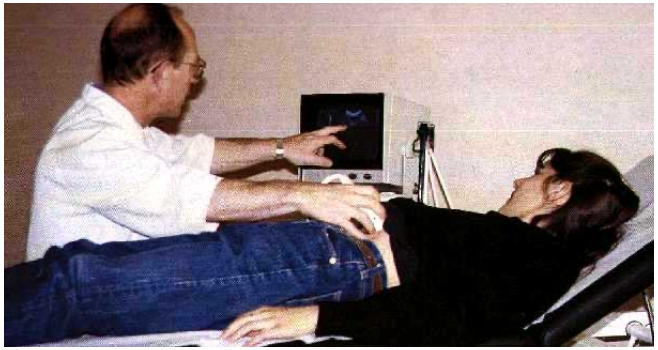
Digital Display
(soft copy)

Imaging Modalities

- X-Ray:
  - Traditional
  - Computerized Tomography (CT)
- Ultrasound (US)
- Magnetic Resonance Imaging (MRI)
- Nuclear Imaging

X-rays

CT



Ultrasound

MRI

etc.

A lot of differences

- Physical principles (important to correctly interpret the images!)
- Irradiation
- Resolution
- 2D / 3D
- Slice / projection
- Temporal sequences
- Differenciation of tissues
- Anatomy / function or metabolism
- Instrumentation
- …

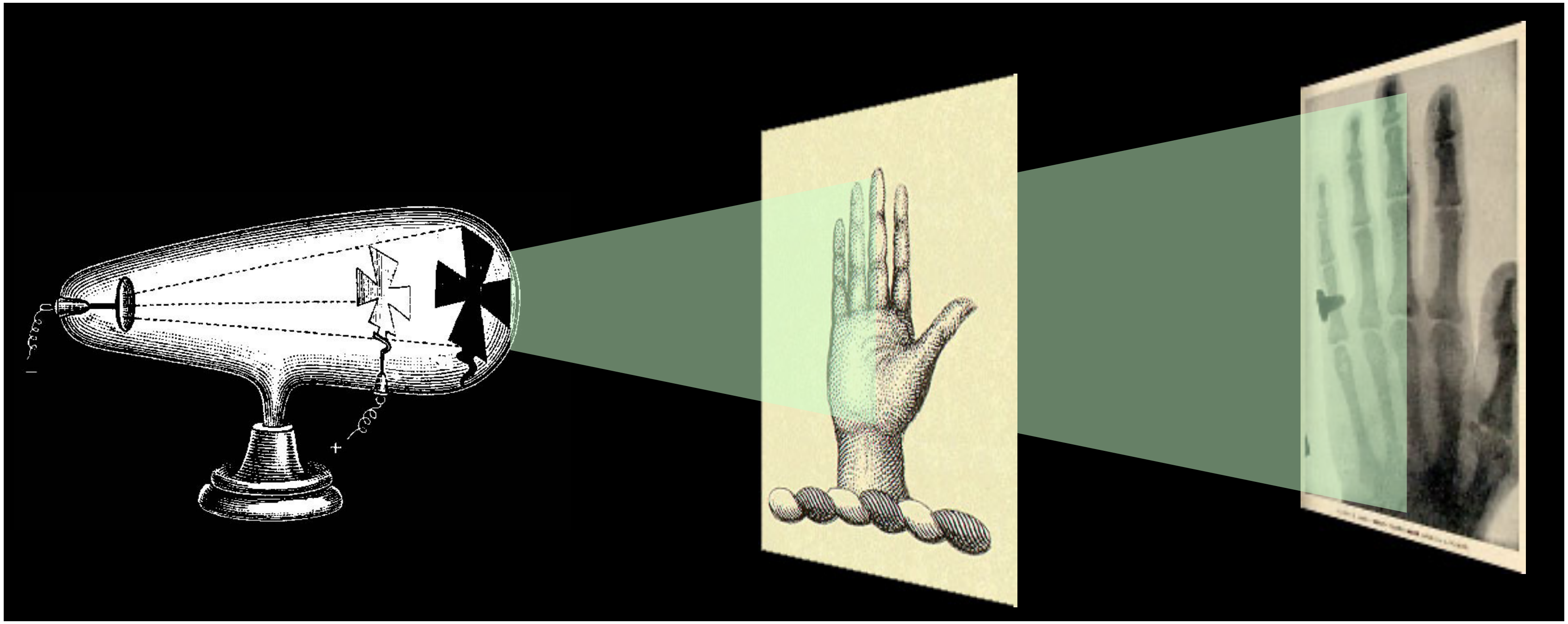
Research in image processing and understanding for medical applications

- Reconstruction
- Improve image quality
- Organ detection, classification, segmentation, recognition
- Pathology detection and recognition
- Quantitative measurements
- Modeling
- 3D visualization
- Registration and information fusion
- Functional analysis, neurosciences
- Aid to diagnosis, therapeutical or surgical planning
- Follow-up
- …

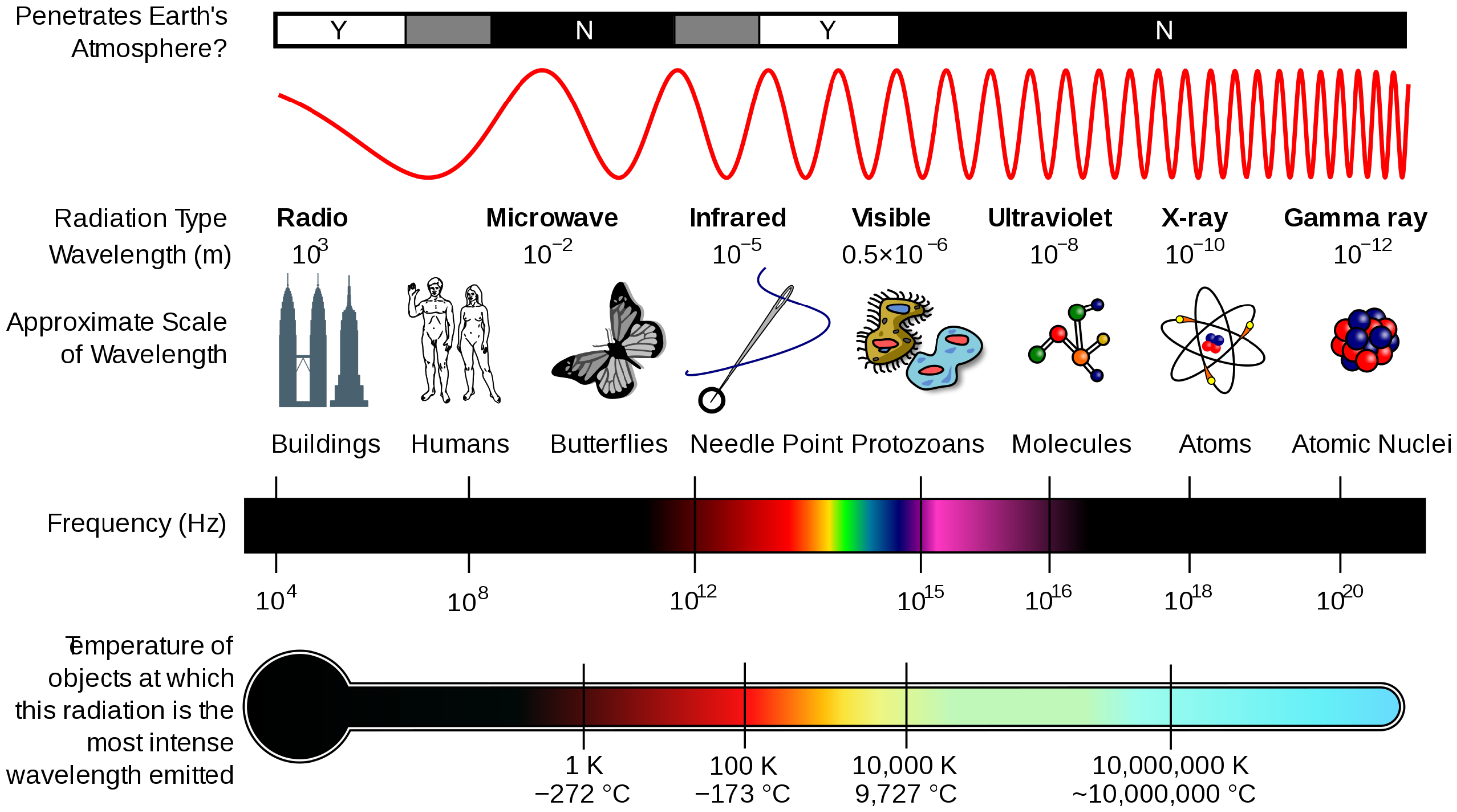
Complex and multi-disciplinary domain

- Physics
- Mathematics
- Computer science
- Biology
- Medicine, anatomy
- Neuroscience, psychology
- Clinical studies and research
- Strong interaction and communication needed among actors
- And the patient …

Principle of X-ray imaging



Electromagnetic spectrum



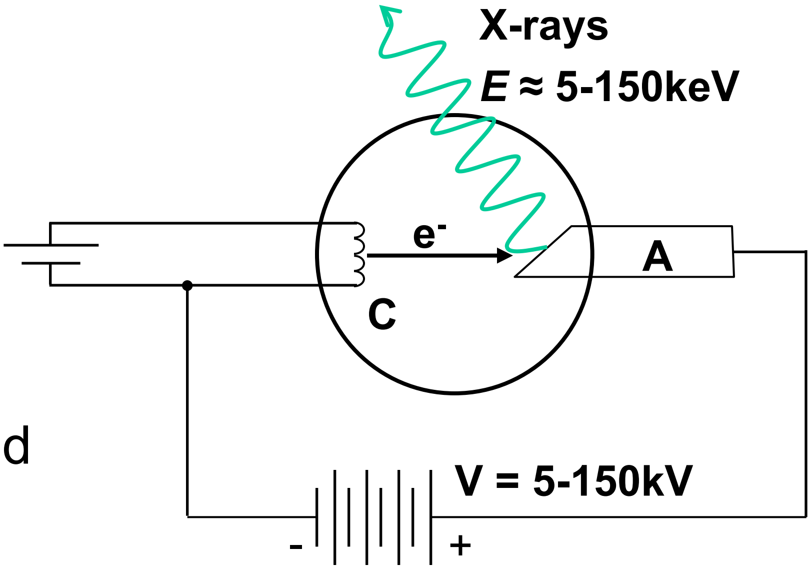
Source: Wikipedia

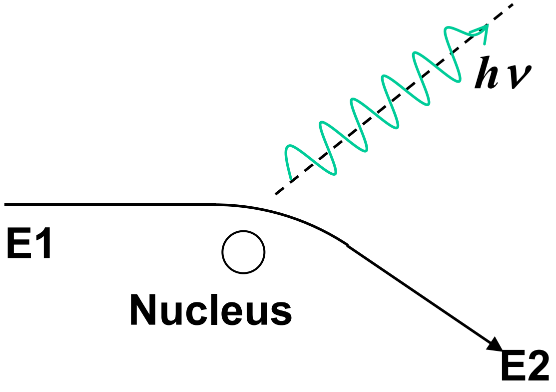
Conventional X-Ray

Conventional X-Ray

Physics Principles

- Accelerating & decelerating electrons generate electromagnetic radiation
- Bombardment of a target material with a beam of fast electrons
- Electrons are emitted thermally from a heated cathode (C) and are accelerated toward the anode target (A) by the applied voltage potential V (~kV).
- Electromagnetic radiation is produced by the quick deceleration of the electrons when hitting the target (Bremsstrahlung).
  - ~99% of energy converted into heat.
  - Few generated X-ray photons with wavelength set by the amount of energy loss $E=h\nu=E2-E1$

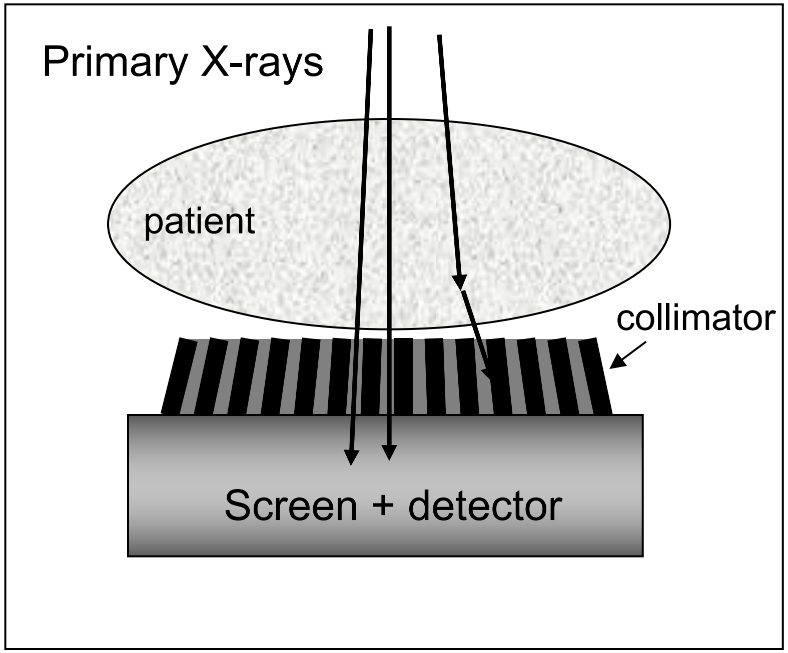




Conventional X-Ray

Image Formation

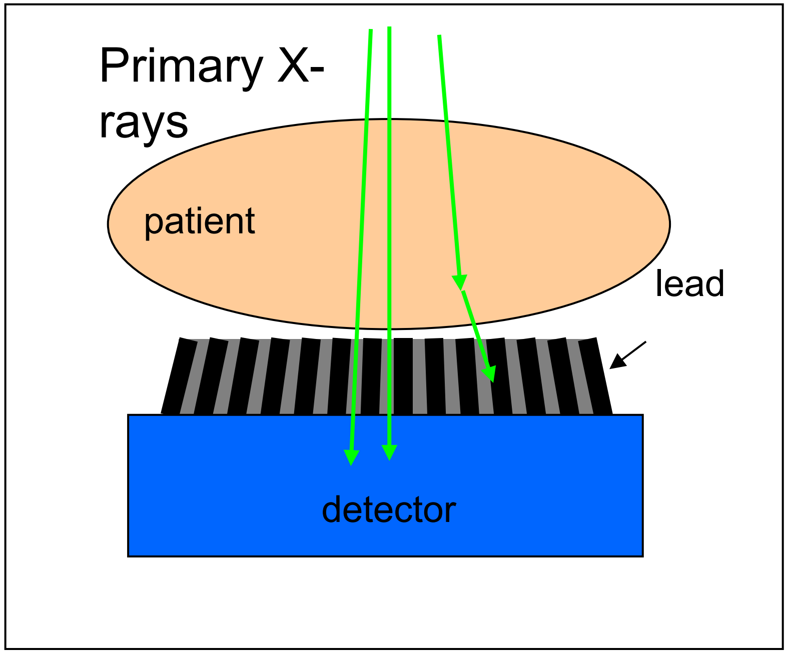
- X-ray beam goes though the patient, which decreases energy, depending on the absorption pattern inside the body.



Conventional X-Ray

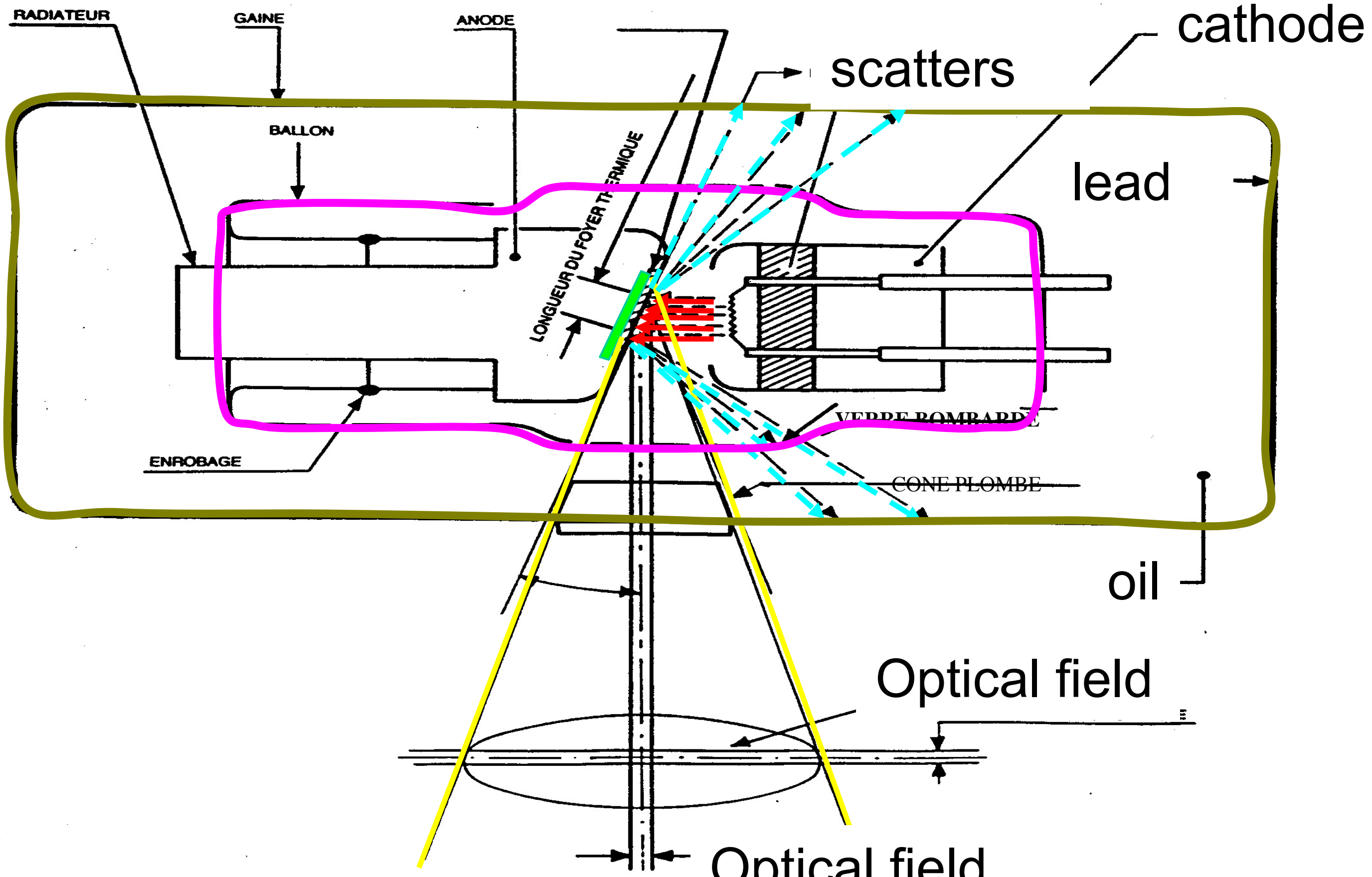
Image Capture

- Image captured on phosphor screen, with conversion to visible light.
- Recording on film (negative image)
- Display on video monitor (positive image)



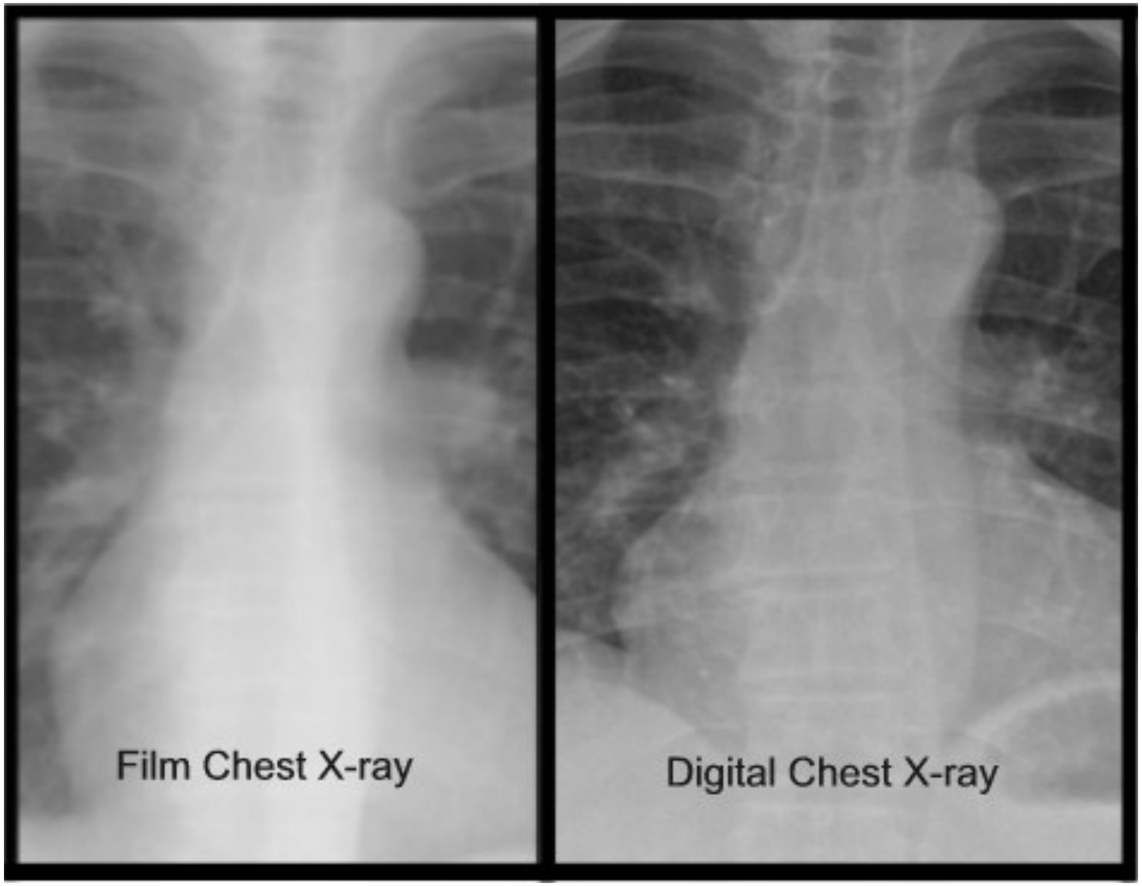
Conventional X-Ray

System Design



Conventional X-Ray

System Design



Conventional X-Ray

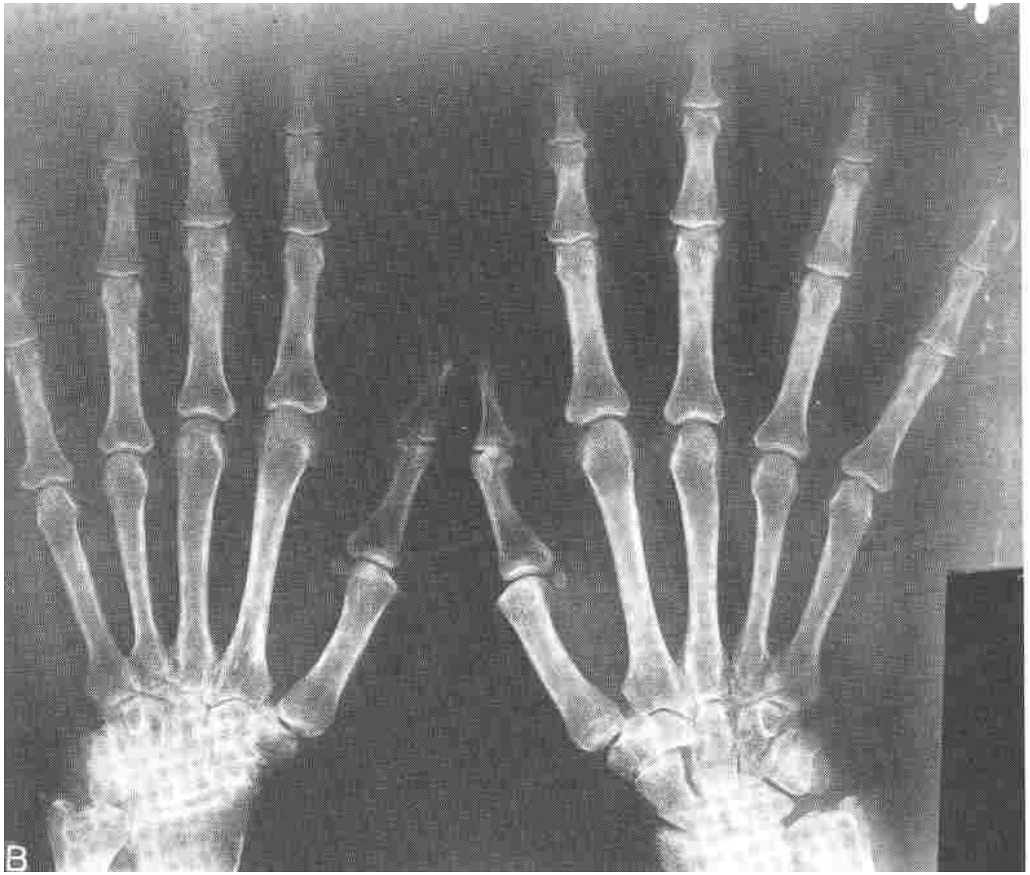
- **Advantages:**
  - Fast.
  - Inexpensive.
- **Disadvantages:**
  - Ionizing radiation involved.
  - Projection images.
  - Poor blood vessel and soft-tissue contrasts.

Conventional X-Ray

- **Applications:**
  - Lungs, breasts.
  - Gastro-intestinal track.
  - Blood vessels (contrast agent).
  - Bones, joints.

Conventional X-Ray

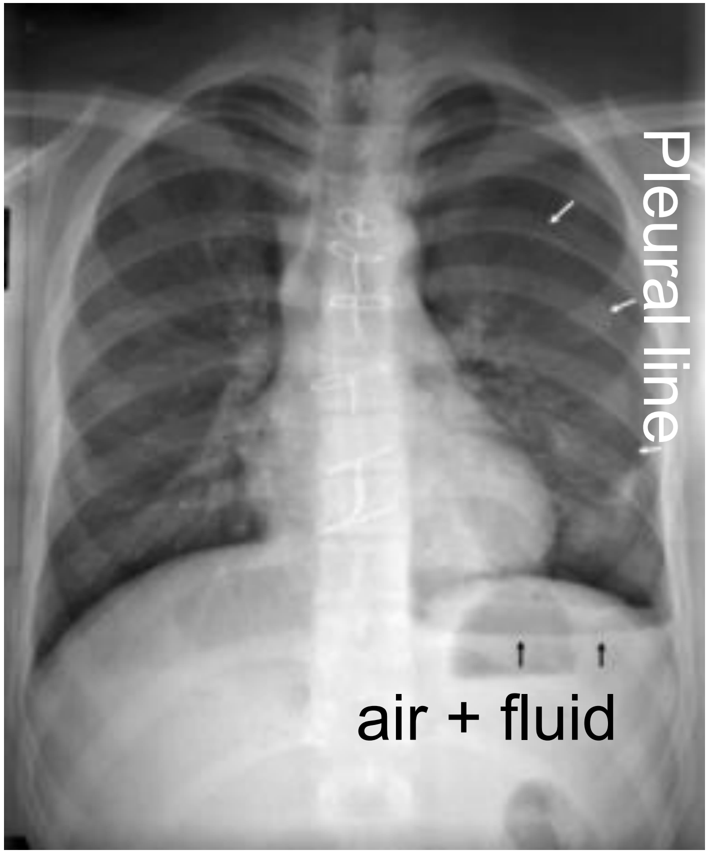
Examples: Bones



Conventional X-Ray

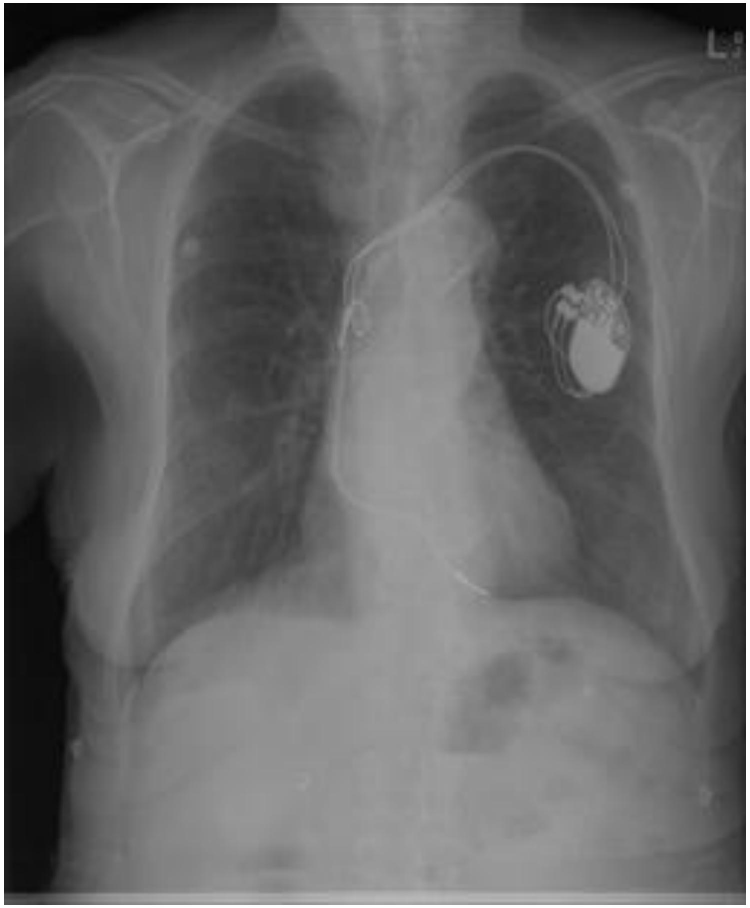
Examples: Lungs

Patient with hemo-pneumothorax



Source: www.mypacs.net

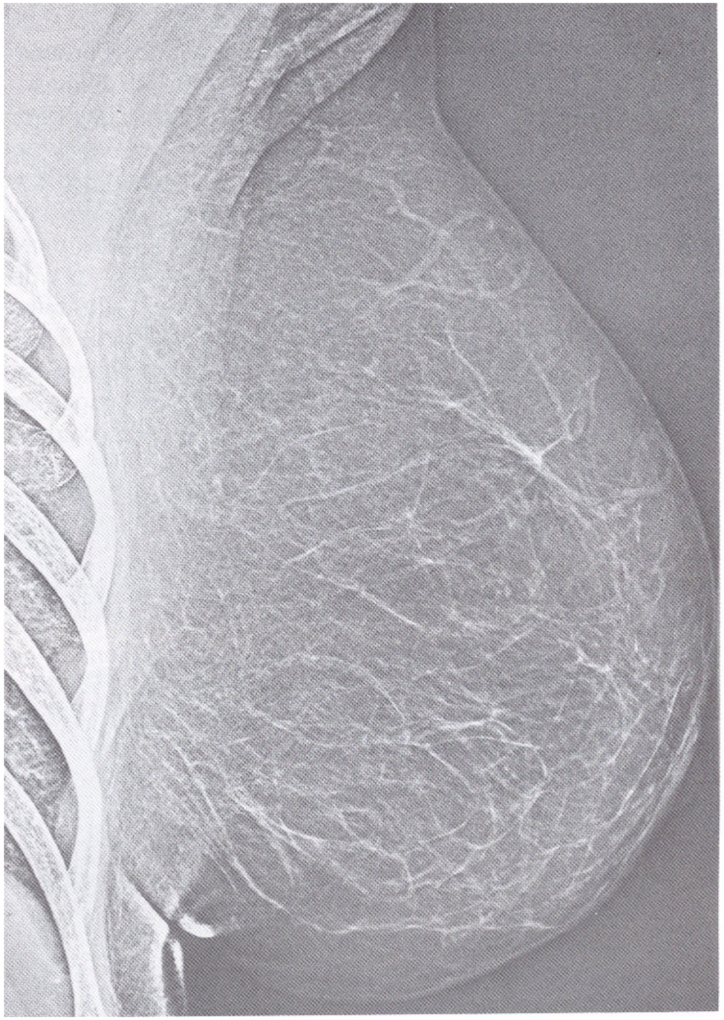
Patient with pacemaker



Conventional X-Ray

Examples: Mammography

- Low kV can be used (little attenuation) => sufficient photoelectric absorption to differentiate between normal tissue and pathology
- Dose must be limited.
- Breast must be compressed
  - To avoid motion.
  - To minimize focus/film distance.
  - To have equal tissue thickness.

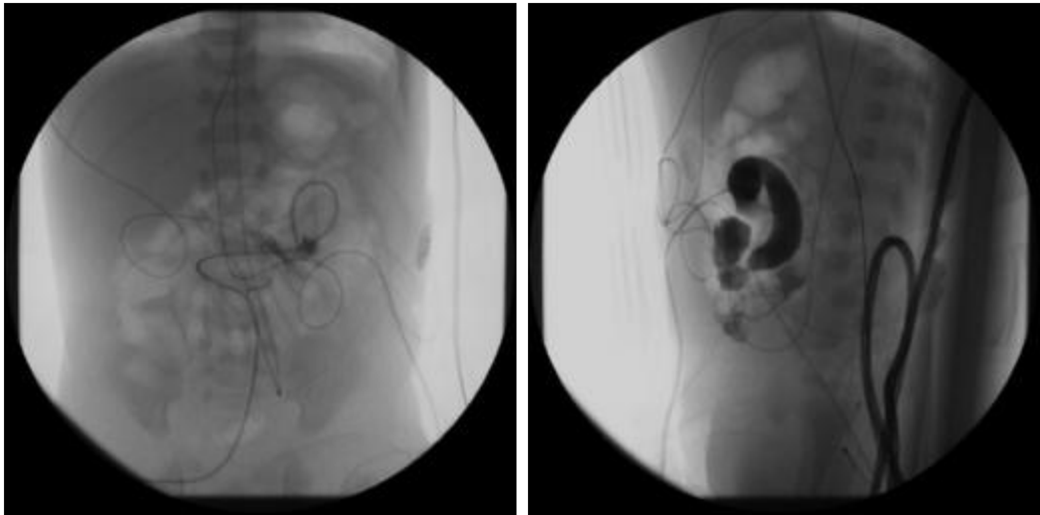


Conventional X-Ray

Examples: Fluoroscopy

- Real-time X-ray imaging.
- Direct visualization on screen.
- Used for guidance of interventions (mainly vascular and orthopedic).

Ex: Fluoroscopic guidance with umbilical catheter injecting contrast agent in the small bowel.



Source: www.mypacs.net

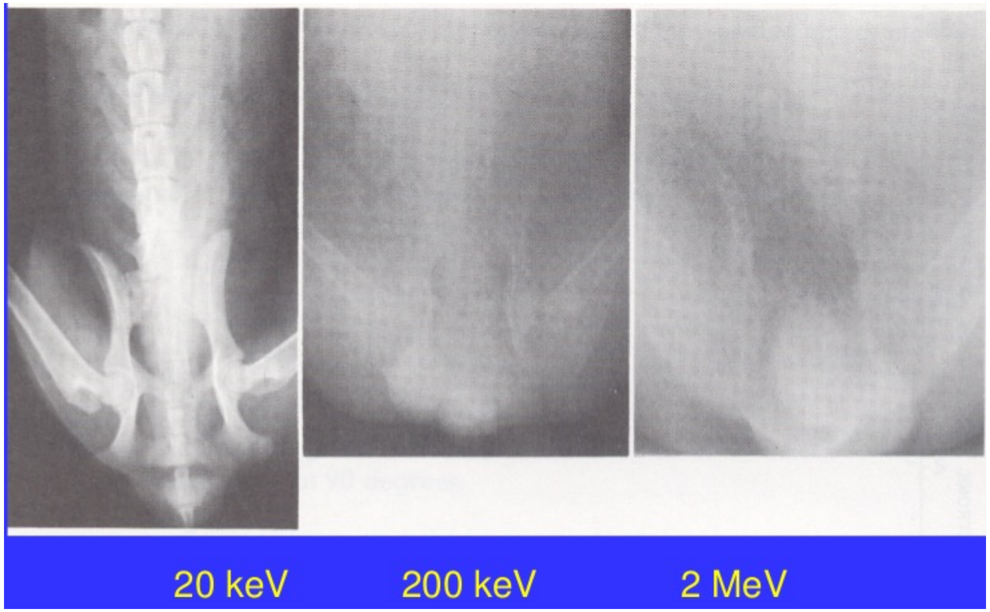
Conventional X-Ray

Examples: Fluoroscopy

Source: Utrecht University, NL

Conventional X-Ray

Influence of energy



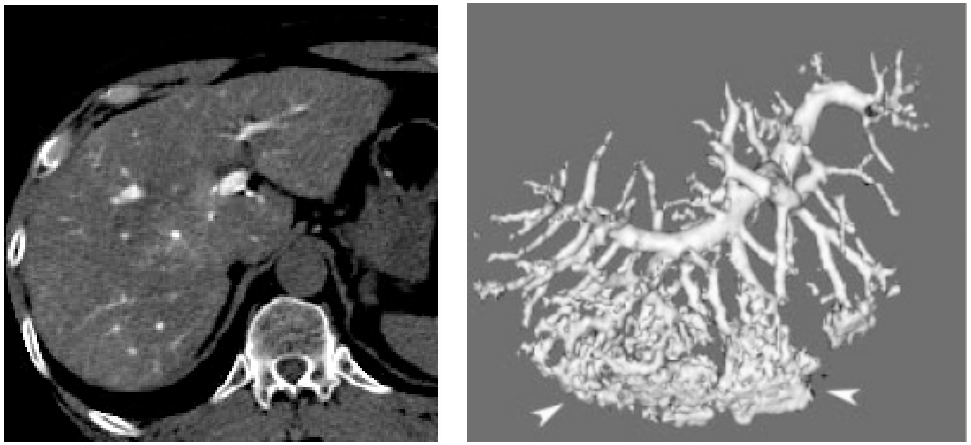
Less contrast when energy increases, and lower dose.

EOS Low Dose
$115.62\mu\mathrm{Gy}$

EOS Micro Dose
$14.64\mu\mathrm{Gy}$

EOS preview
$1.44\mu\mathrm{Gy}$

Computerized Tomography (CT)



CT

Physics Principles

- Same as X-ray.

Image Formation

- Same as X-ray.

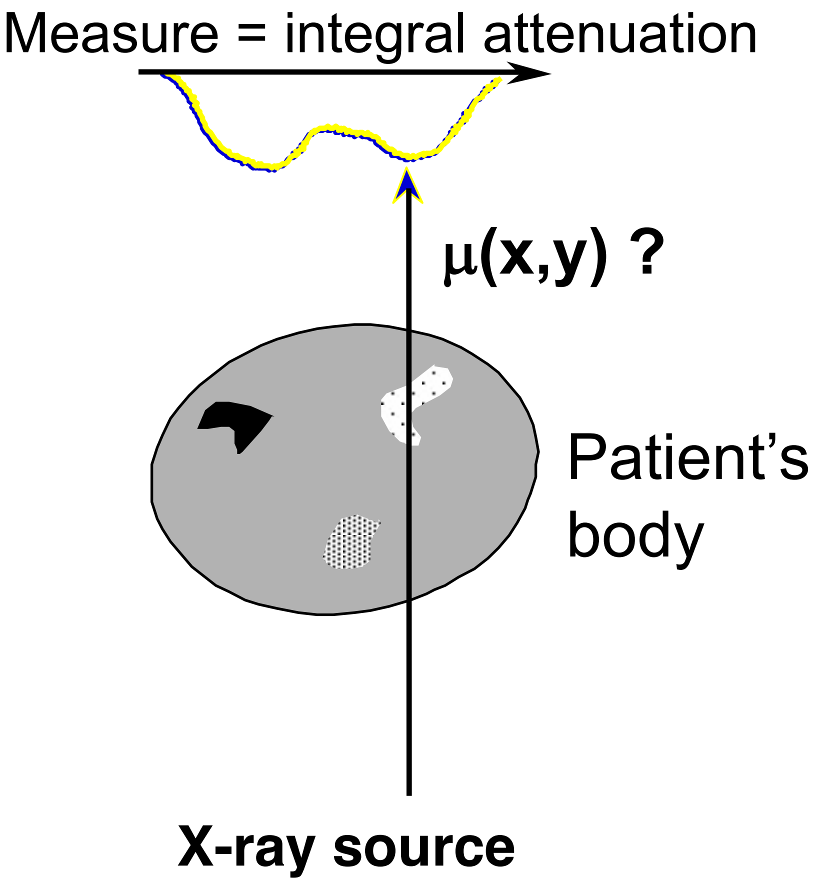
CT

Image Capture

- Generation of a sliced view of body interior (“T”)

(cf. tomos = slice in Greek).

- Computational intensive image reconstruction (“C”).



Measure = integral attenuation

$\mu(x,y)$?

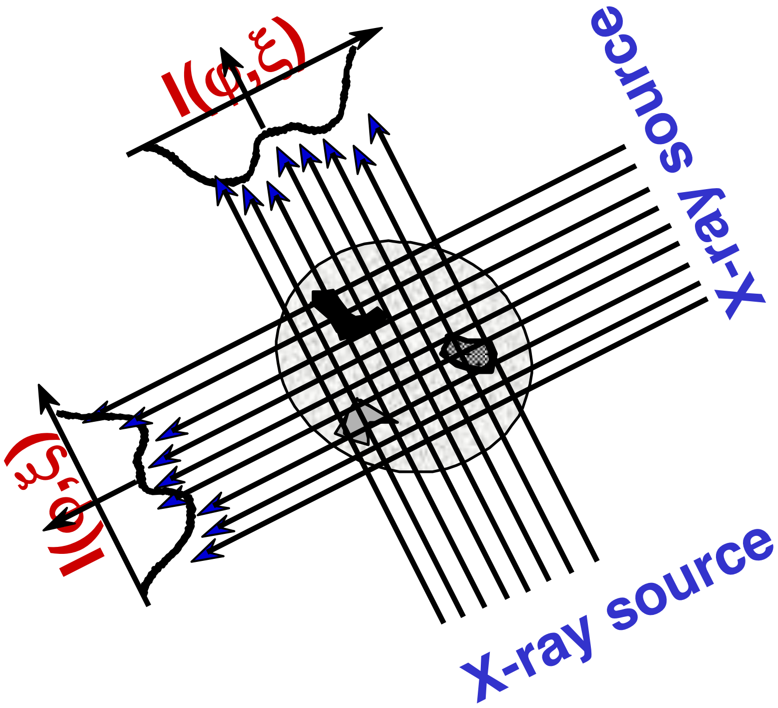
Patient’s body

X-ray source

CT

Image Capture

- Translation and rotation of integral measure of absorption.
- Reconstruction: see next lecture

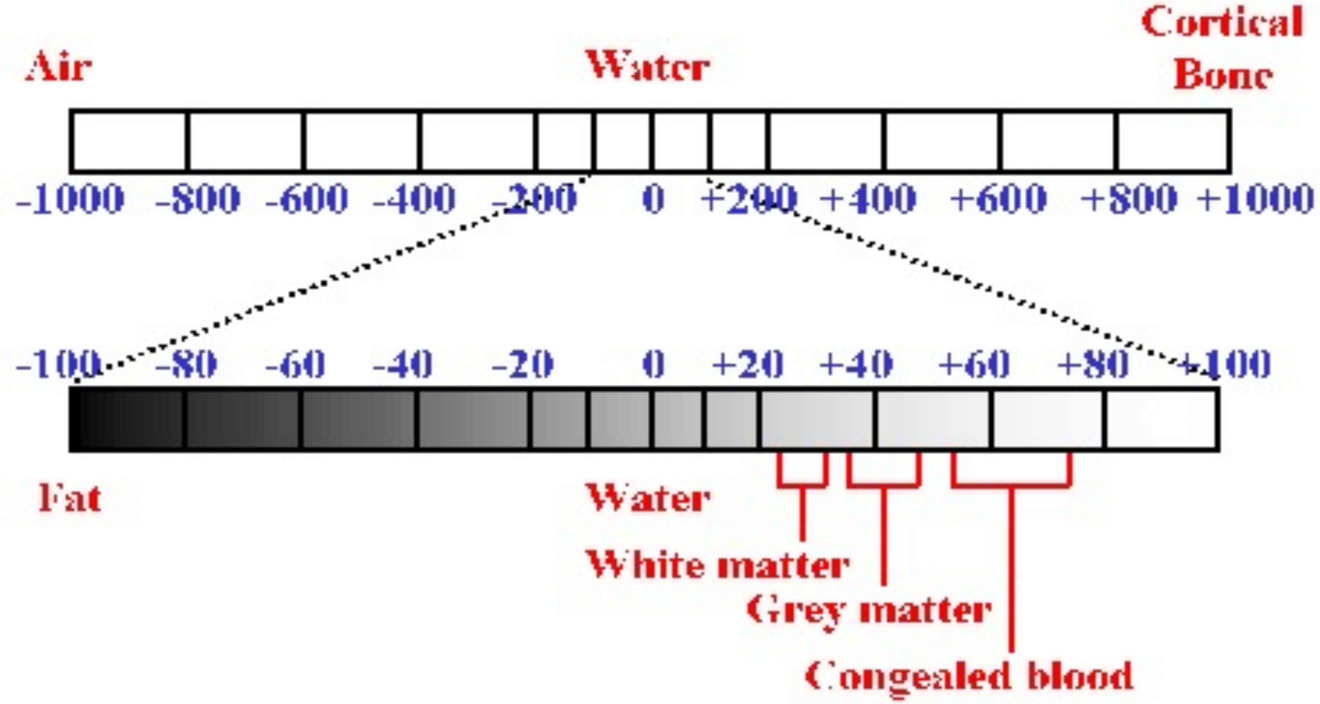


CT

Image Capture: Hounsfield Units

- Relates the linear attenuation coefficient of a local region μ to the linear attenuation coefficient of water, μ_W @ 70 keV (=E_{eff}).
- Based on measurements with the original EMI scanner invented by Hounsfield.

$$HU = 1000 \bullet \frac{\mu - \mu_W}{\mu_W}$$



- Assign calibrated values to gray scale of CT images -> allows for thresholding!

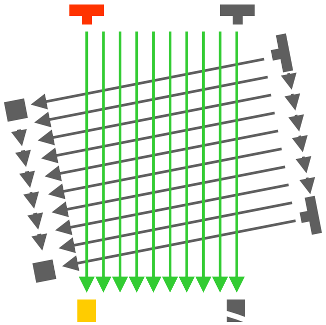
CT

System Design

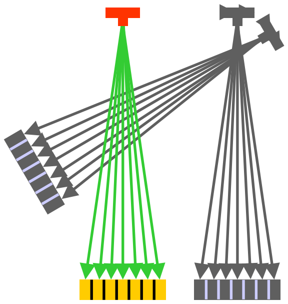
- **1st generation**: Original resolution: 80 × 80 pixels (ea. 3 × 3 mm^2), 13mm slice thickness, 5min scan time, 20min reconstruction.

- **2nd generation**: reduced number of view angles ⇒ scan time ~30 s.

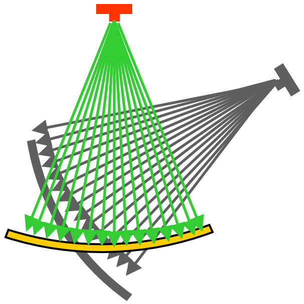
- **3rd generation**: scan time ~seconds (reduced dose, motion artifacts). Reconstruction time ~seconds.



Translation
& Rotation



Translation
& Rotation

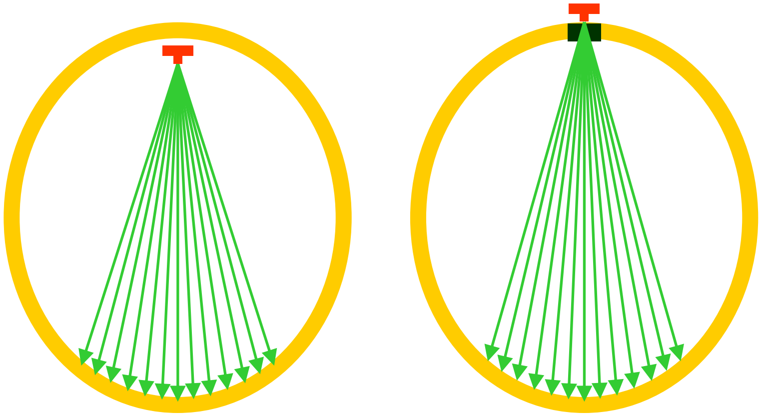


only
Rotation

CT

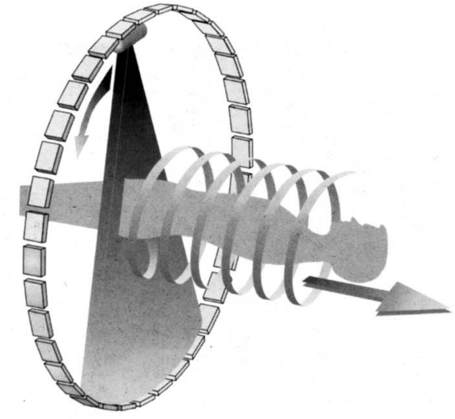
System Design

- **4th generation:** scan time, reconstruction time ~sec.



only Rotation of sources

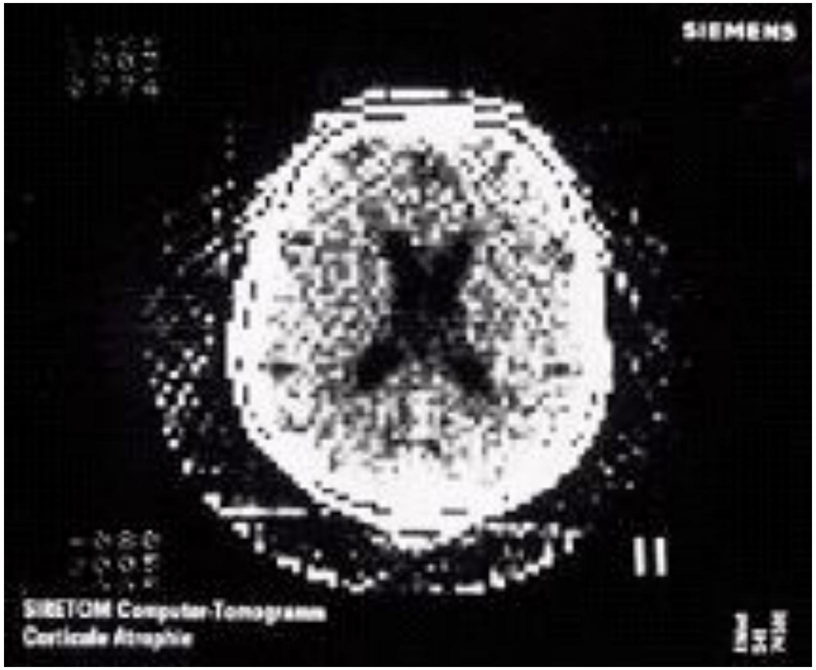
- **Spiral**: Continuous linear motion of patient table during multiple scans. Increased coverage volume per rotation.



CT

Example: Image quality

1975



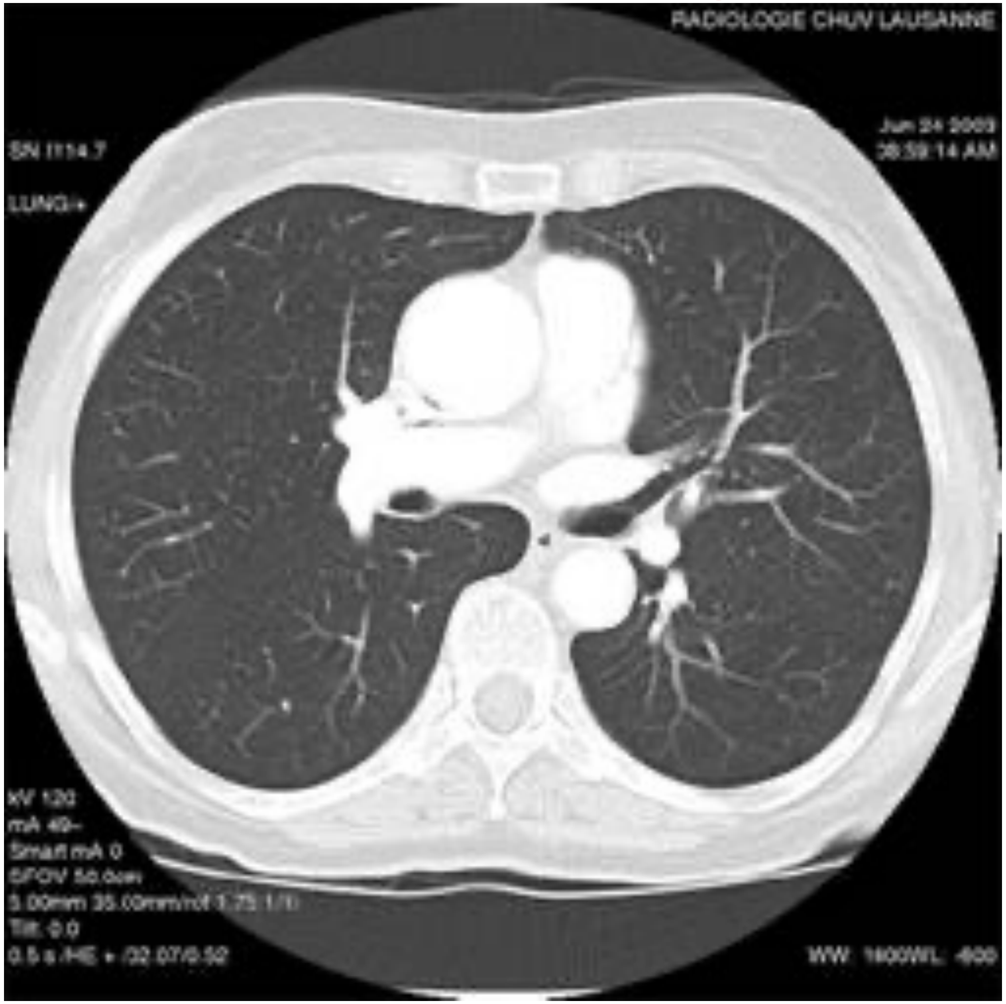
128x128 pixels, 1-4 hours acquisition, 1-5 days computation

2000

512x512pixels, 0.35 sec aquisition, <1sec computation

CT

Example: Lungs



CT

Example: Lungs

Source: www.mypacs.net

Ex: CT of right lung with active pulmonary tuberculosis: shows centrilobular lesions (nodules or branching linear structures 2-4 mm in diameter) in and around the small airways.

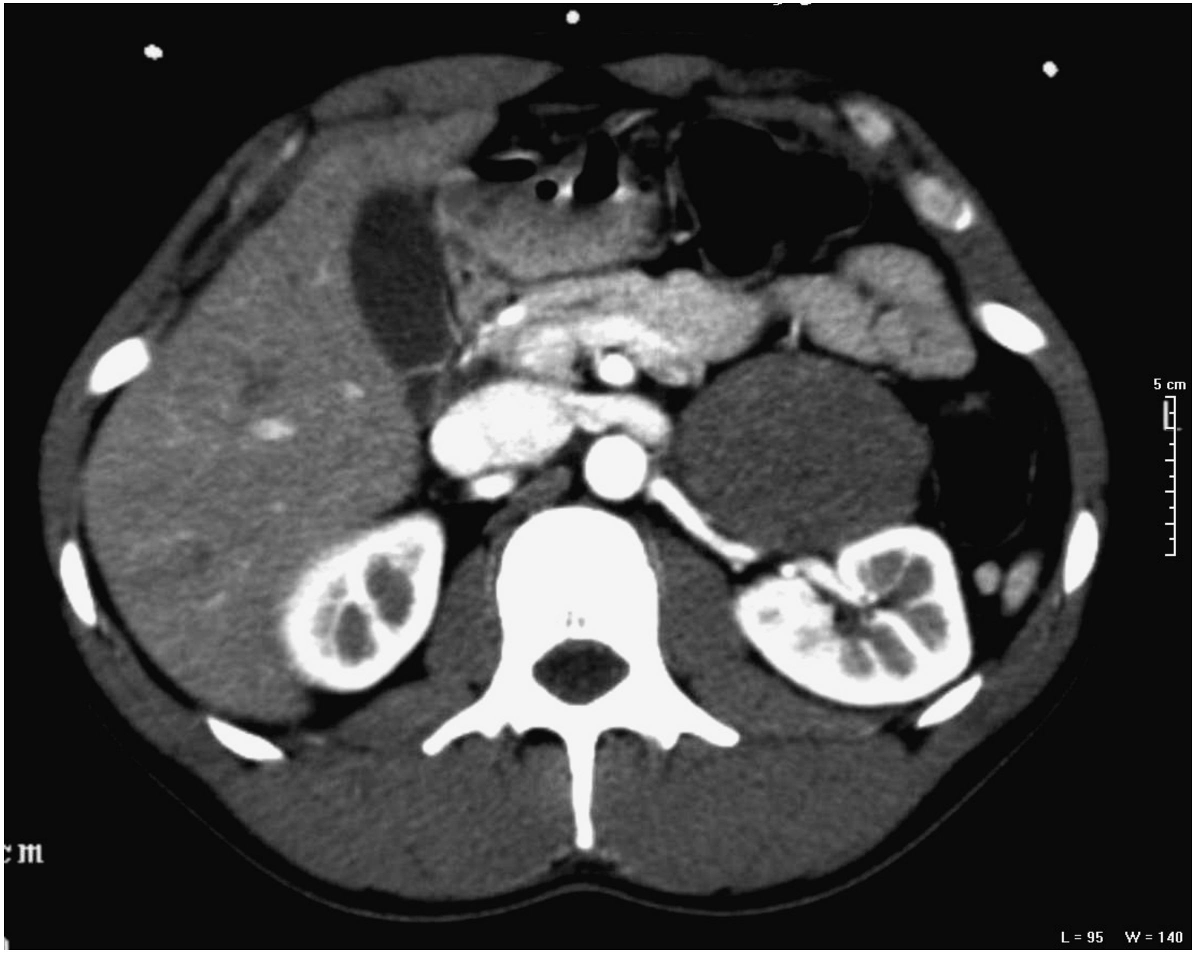
CT

Examples: Abdomen

Diagnosis of appendicitis

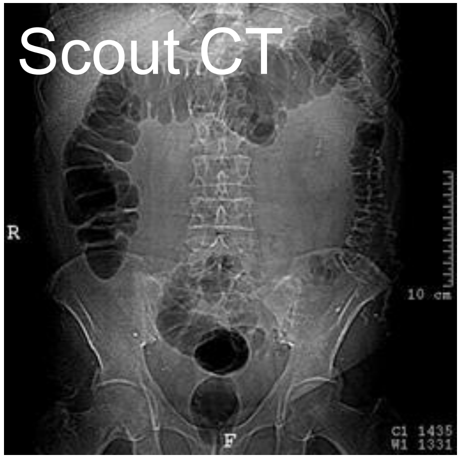
CT

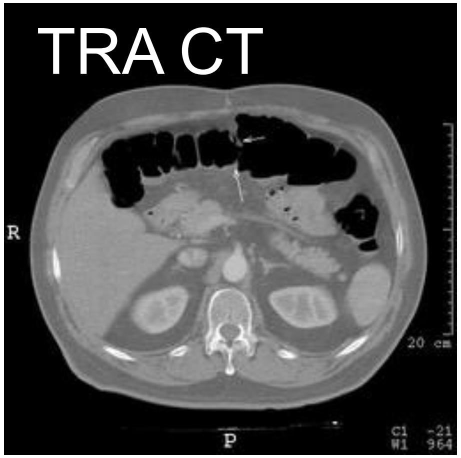
Examples: Abdomen

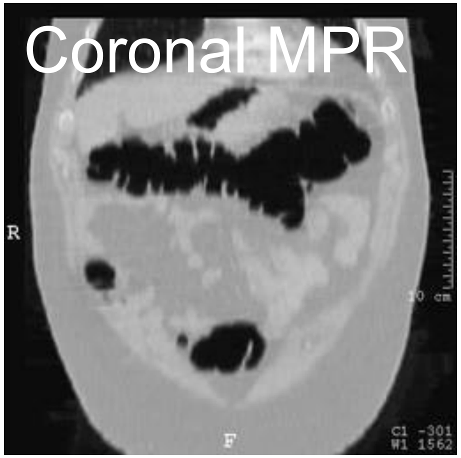


CT

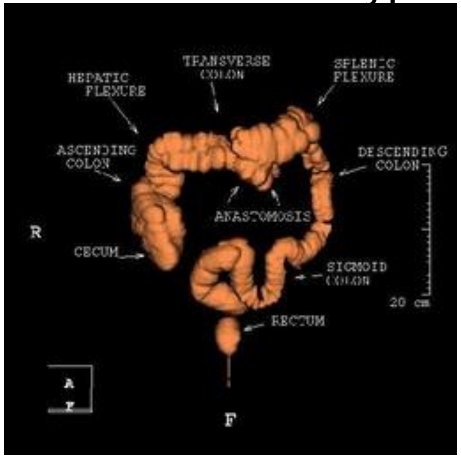
Example: Abdomen

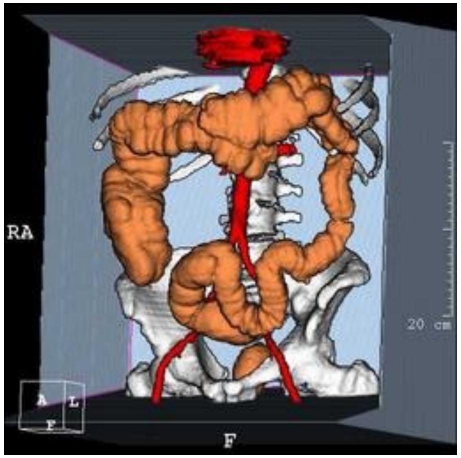

Scout CT

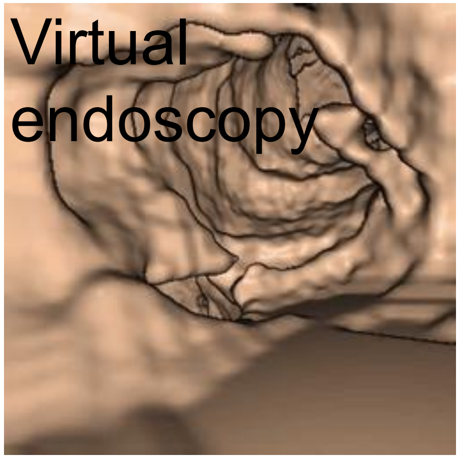

TRA CT


Coronal MPR

Source: www.mypacs.net





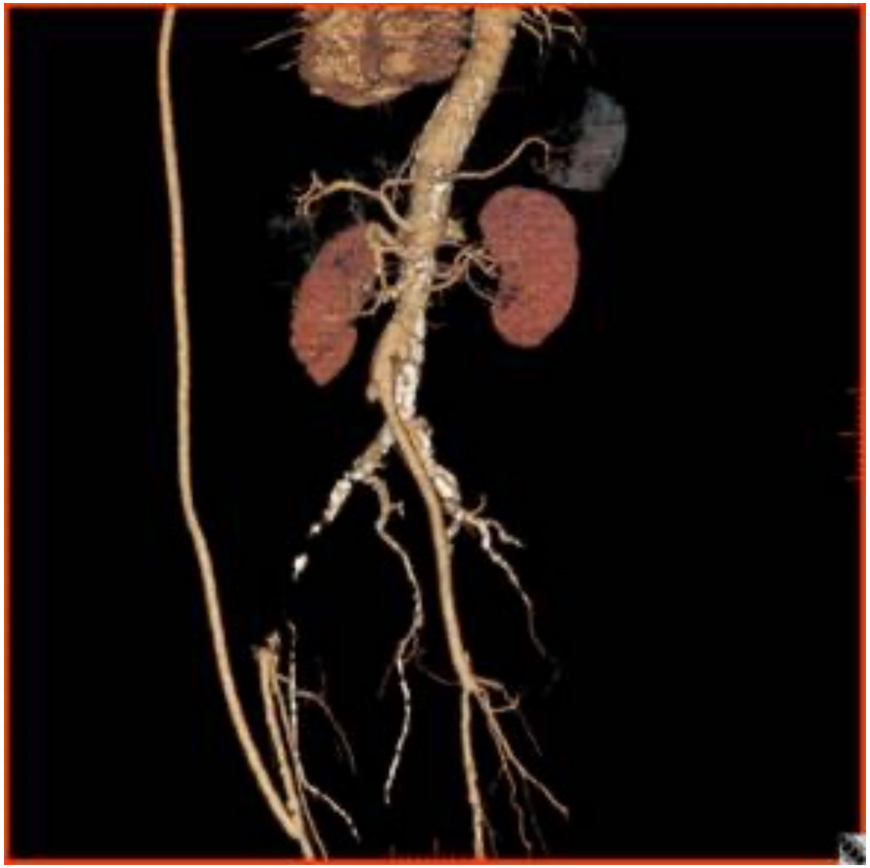

Virtual endoscopy

CT

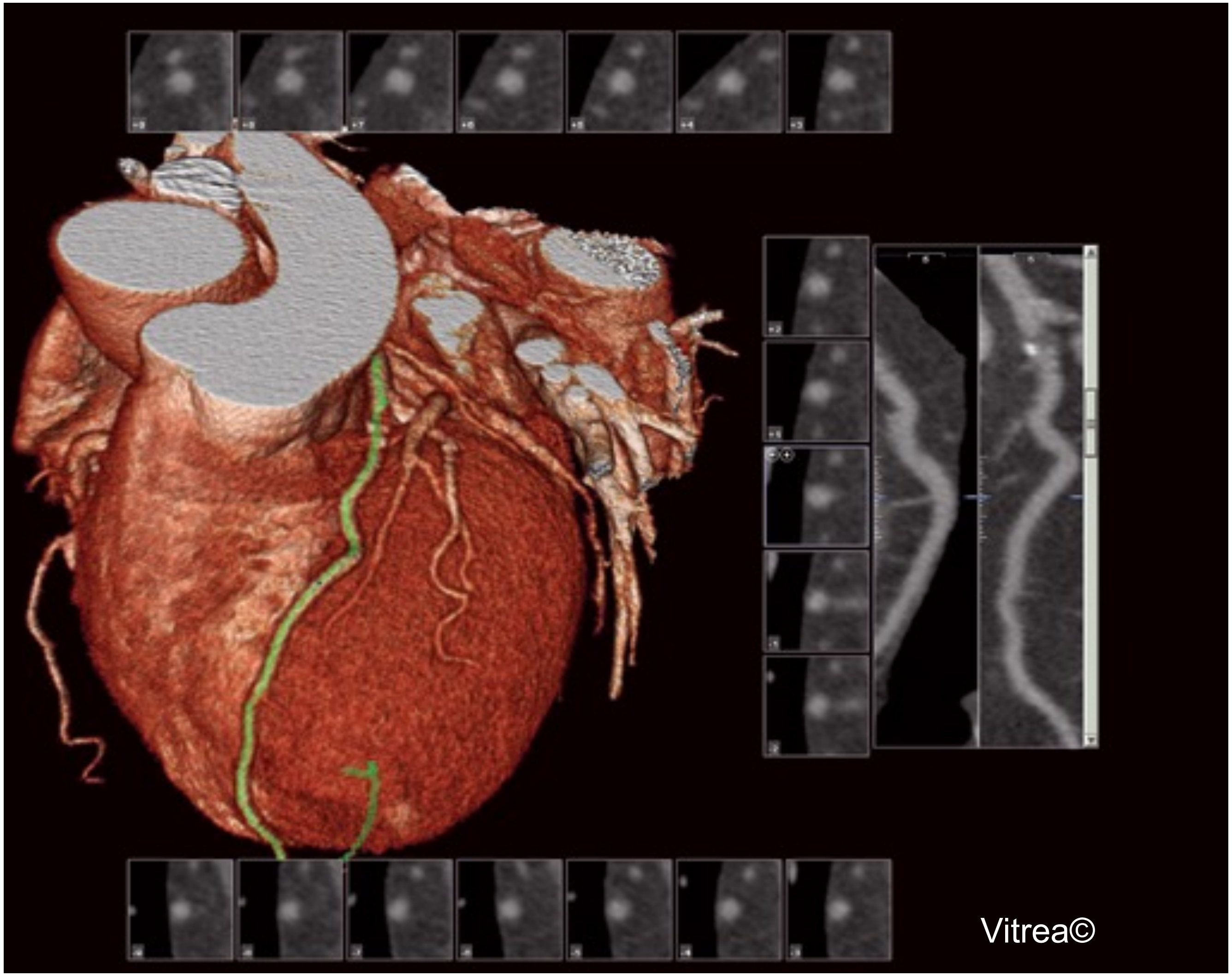
Example: Blood vessels

CT

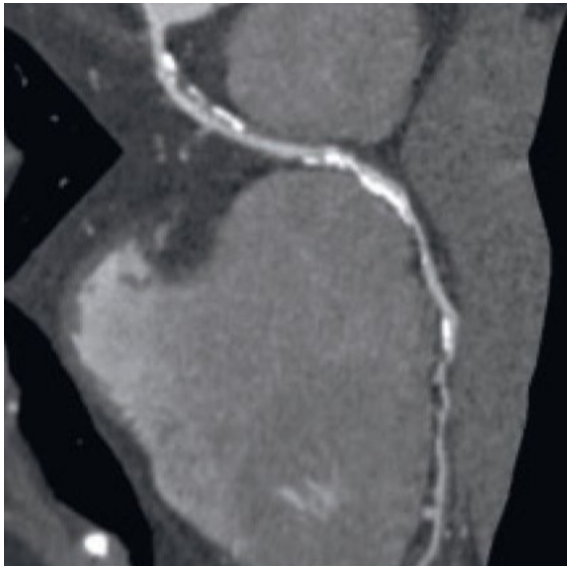
Example: Blood Vessels



CT

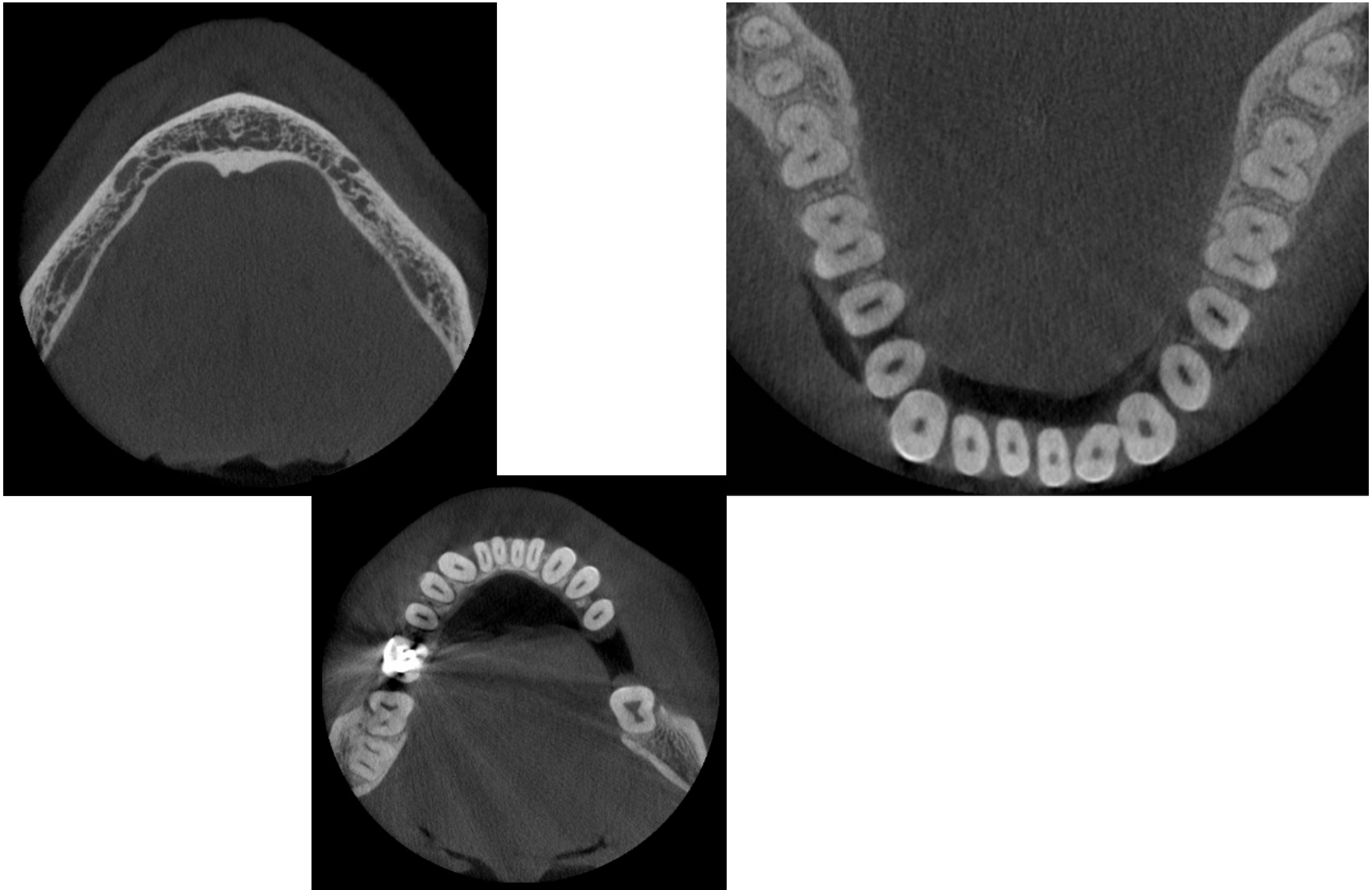


CT

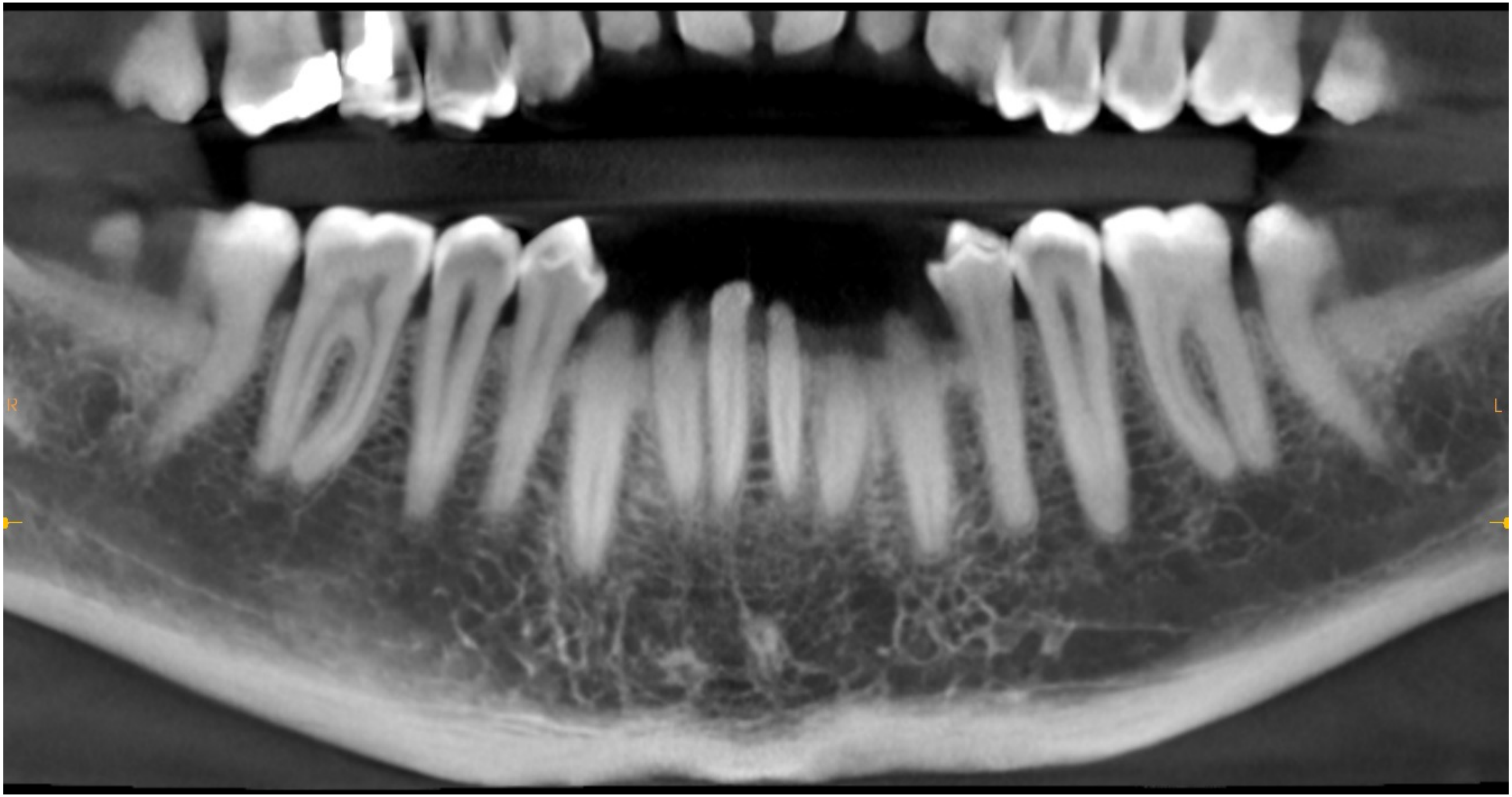


High resolution CT

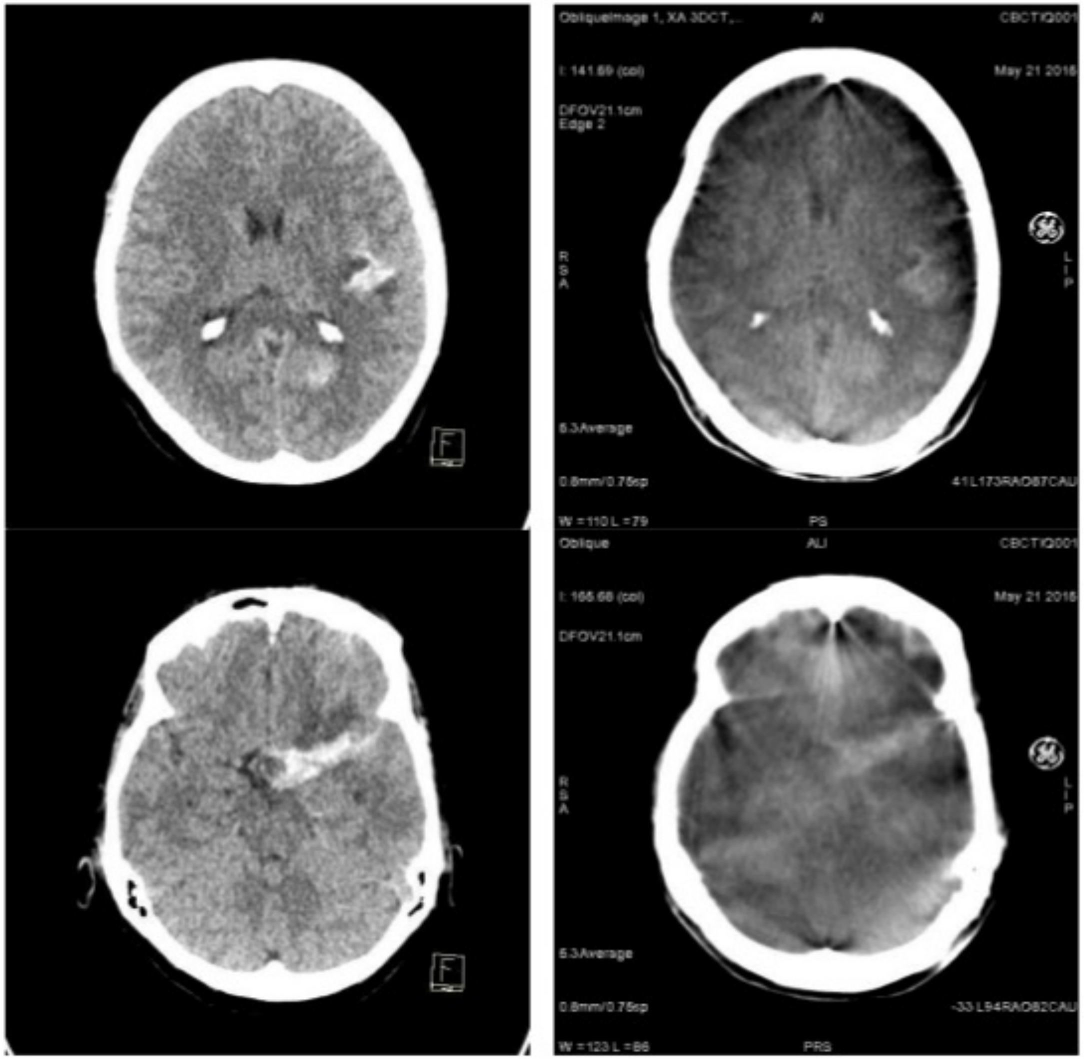
Cone Beam CT (CBCT)



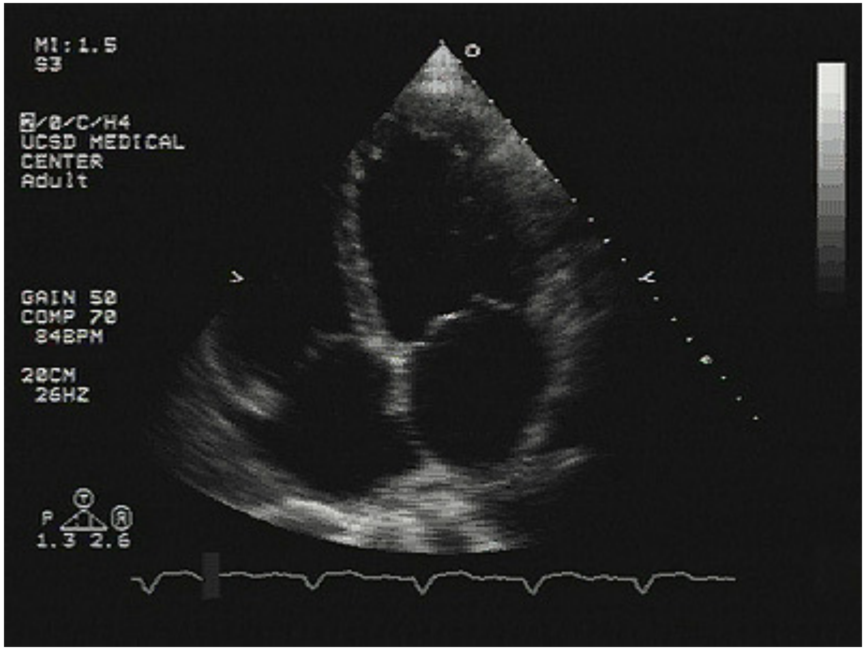
Cone Beam CT (CBCT)



CT **CBCT**


F
F
ObliqueImage 1, XA 3DCT,..
AI
CBCTIQ001
I: 141.69 (col)
May 21 2016
DFOV21.1cm
Edge 2
R
S
A
L
I
P
5.3Average
0.8mm/0.75sp
41L173RAO87CAU
W = 110 L = 79
PS
Oblique
ALI
CBCTIQ001
I: 165.68 (col)
May 21 2016
DFOV21.1cm
R
S
A
L
I
P
5.3Average
0.8mm/0.75sp
-33 L94RAO82CAU
W = 123 L = 86
PRS

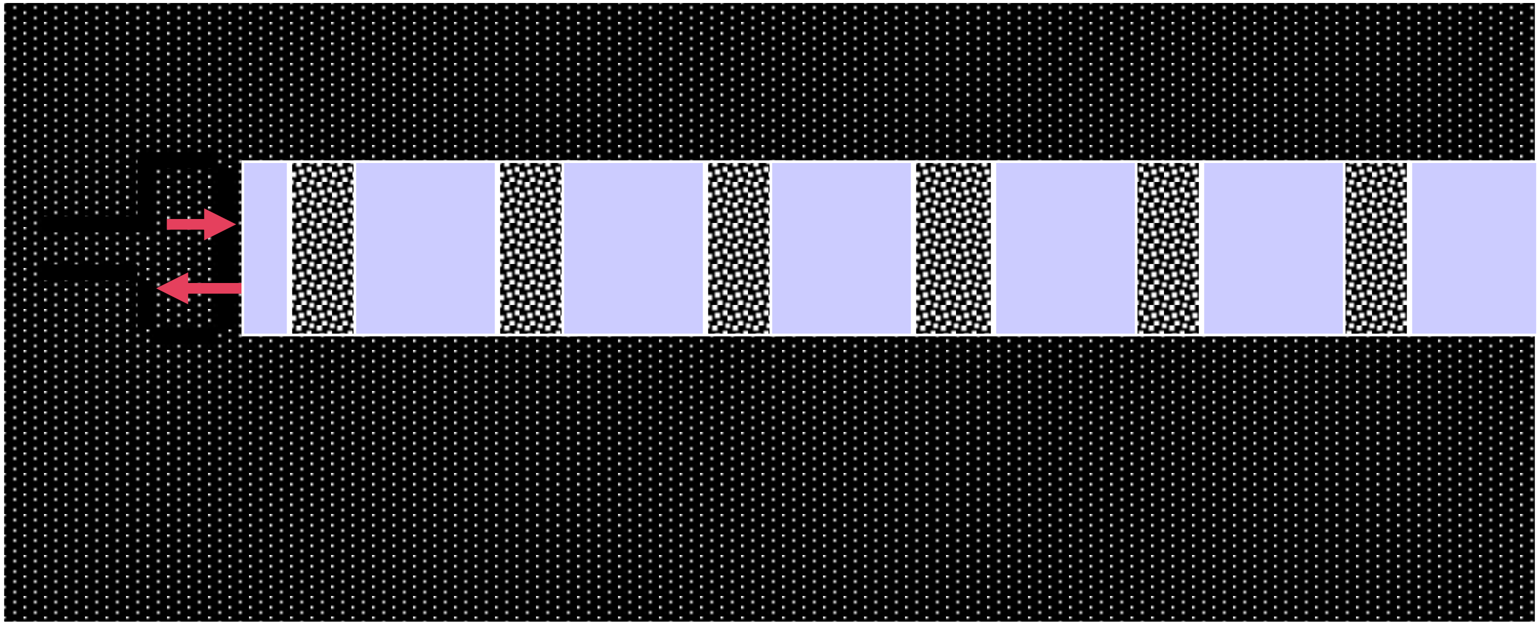
Ultrasound


MI:1.5
S3
/0/C/H4
UCSD MEDICAL
CENTER
Adult
GAIN 50
COMP 70
84BPM
20CM
26HZ
P
1.3 2.6

Ultrasound

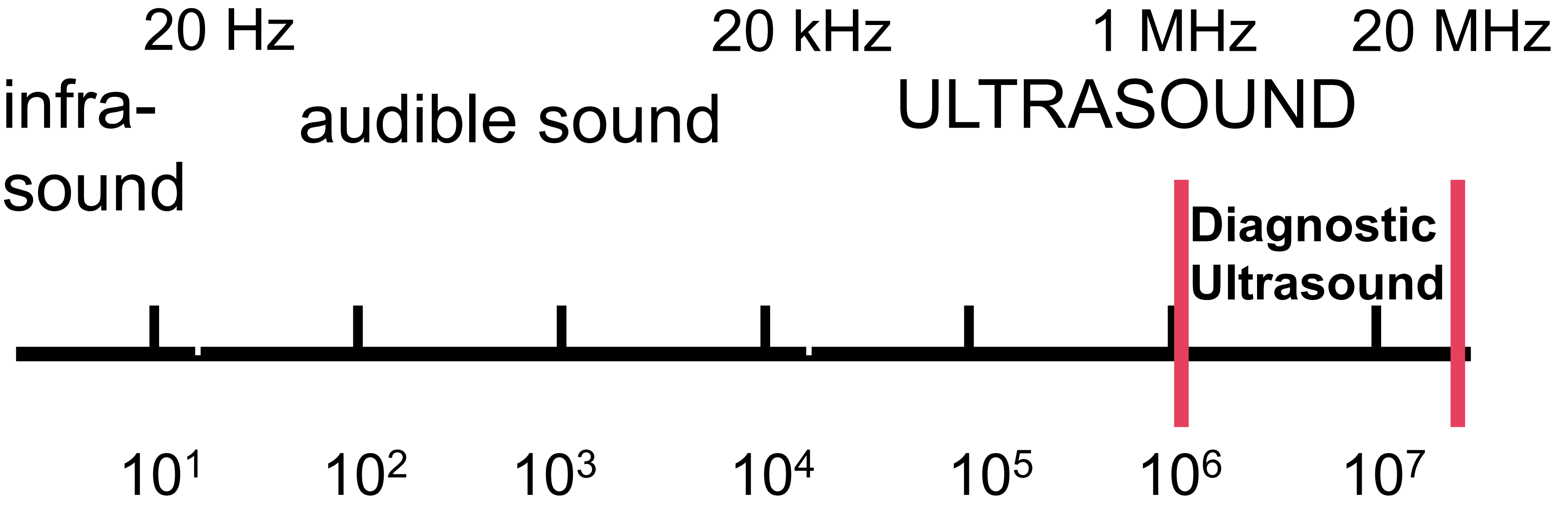
Physics Principle

- Traveling pressure waves through a medium.



Ultrasound

Physics Principle



20 Hz

20 kHz

1 MHz

20 MHz

infra-
sound

audible sound

ULTRASOUND

Diagnostic Ultrasound

10^1 10^2 10^3 10^4 10^5 10^6 10^7

Frequency f (Hz)

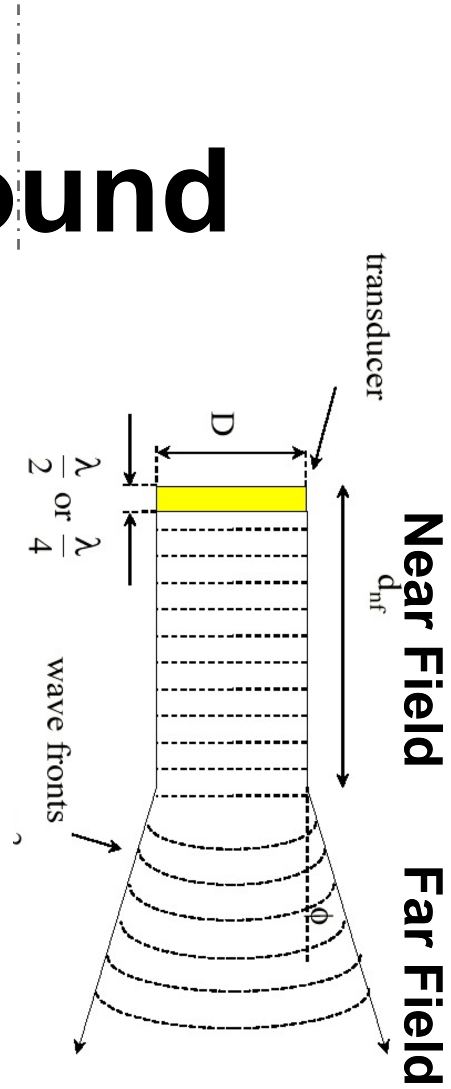
$f_{light} \sim 10^{15}$

$f_{xray} \sim 10^{18}$

Ultrasound

Image Formation

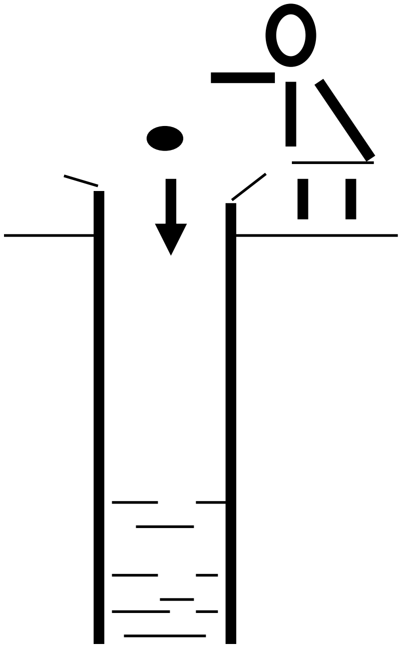
- Sound waves propagate through the body.
- At each interface, part is reflected, part is transmitted.
- Reflected waves are recorded back.

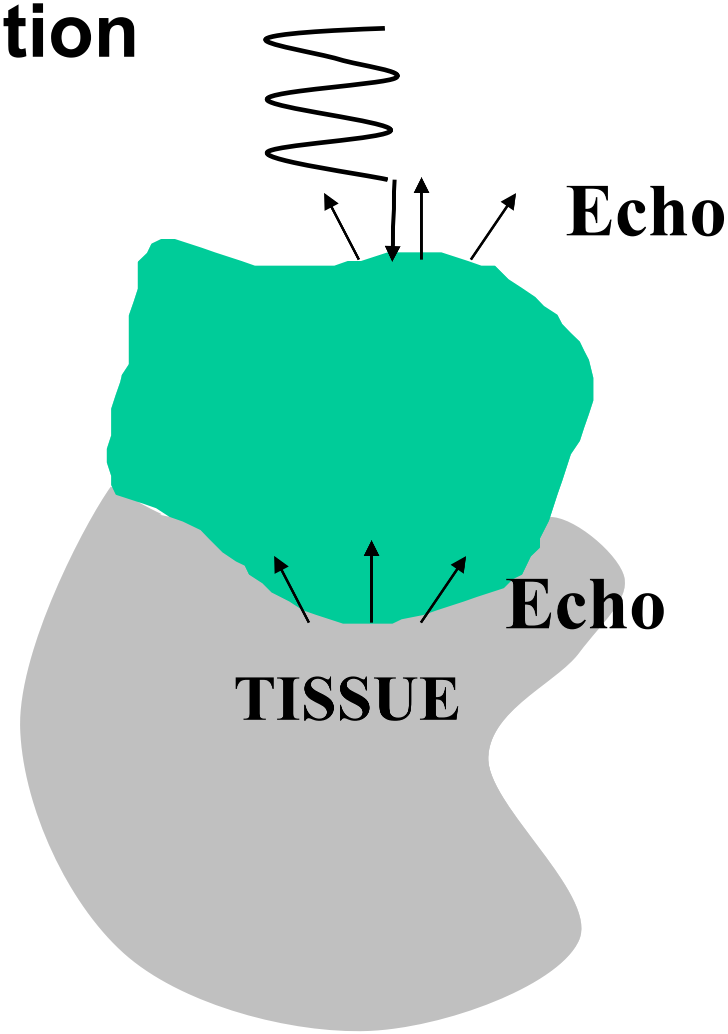


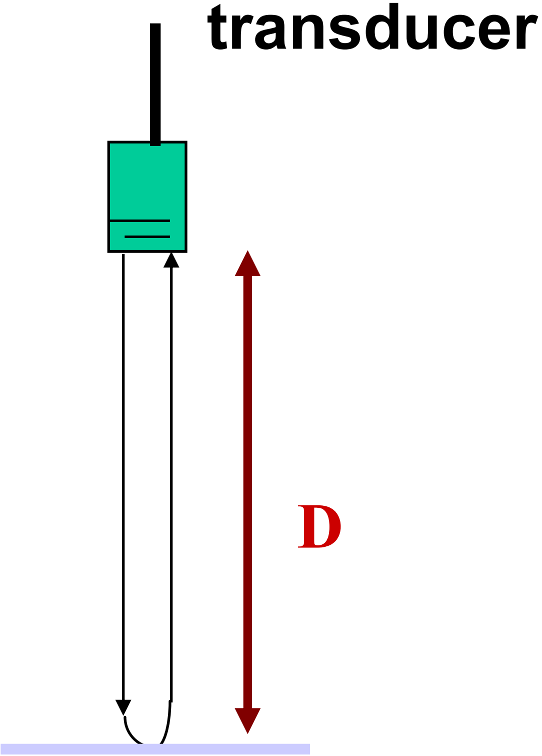
Source: The essential physics of Medical Imaging

Ultrasound

Image Formation





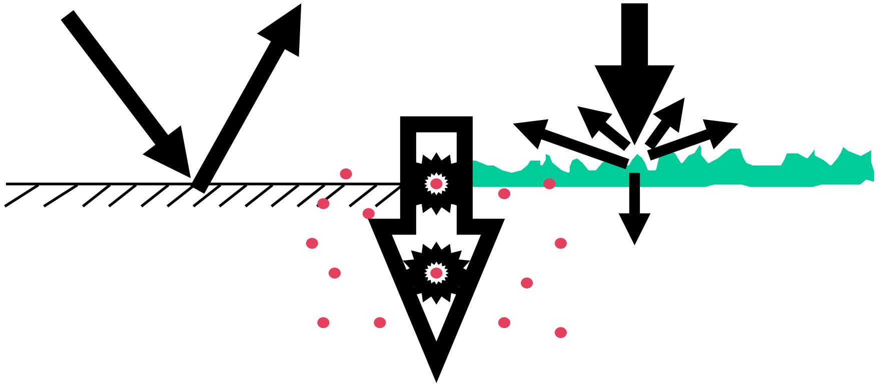


$D = c \cdot \mathrm{Time}/2$

$c = 1.54\ \mathrm{mm}/\mu\mathrm{s}$

Ultrasound

Image Capture

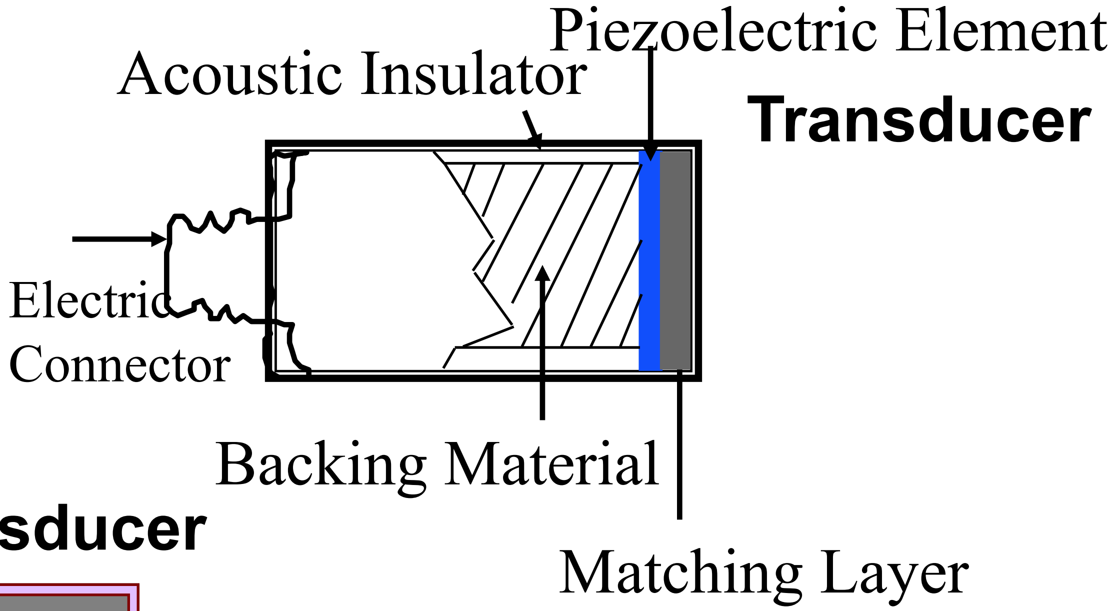


- **Recorded signals**:
  - Specular reflection, Diffuse scattering, Rayleigh scattering
- **Frame rate (FR)** =number of times per second a sweep of the ultrasound beam is performed.
  - The higher the frame rate, the better the temporal resolution.
  - Limited by:
    - Time delay from maximum depth.
    - Speed of sound.

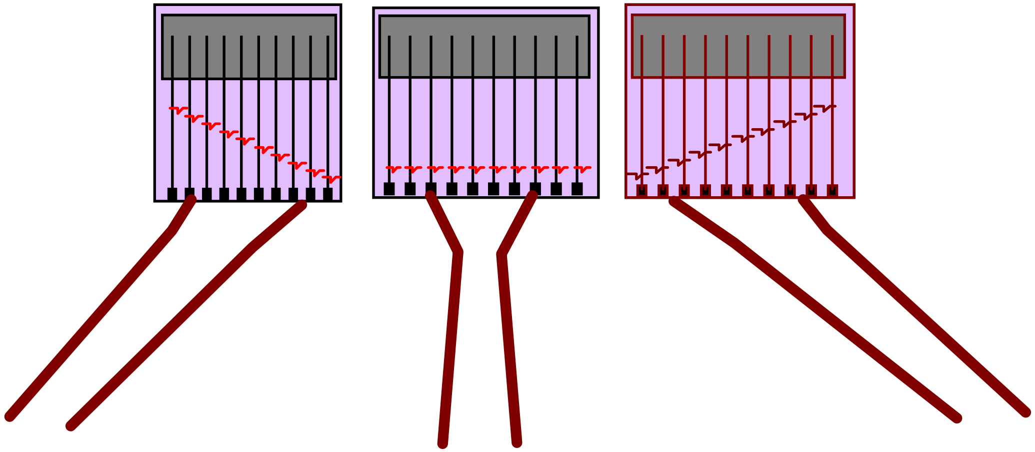
Ultrasound

System Design

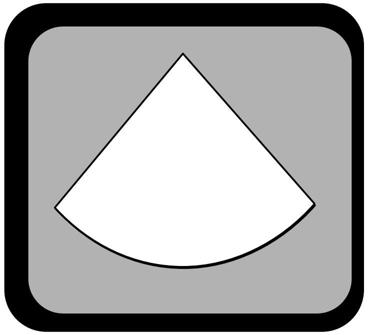
Transducer



Phased array transducer



Display



Ultrasound

- **Advantages:**
  - Portable.
  - Inexpensive.
  - Good spatial resolution (<1mm).
  - High temporal resolution.
- **Disadvantages:**
  - Poor image quality.
  - High level of noise.

Ultrasound

Applications

- Obstetric
- Heart
- Gastro-intestinal track (liver, gall bladder, pancreas)
- Urinary track (bladder, kidneys)
- Genital organs (prostate, testicles, ovaries, uterus).
- Blood vessels (Doppler).

Ultrasound

Example: Fetus

- Establish number of fetus.
- Check position of placenta.
- Determine fetal age and development.
- Check for congenital defects.
- Check fetus position.

Fetus at 9 weeks

Ultrasound

Example: Obstetric

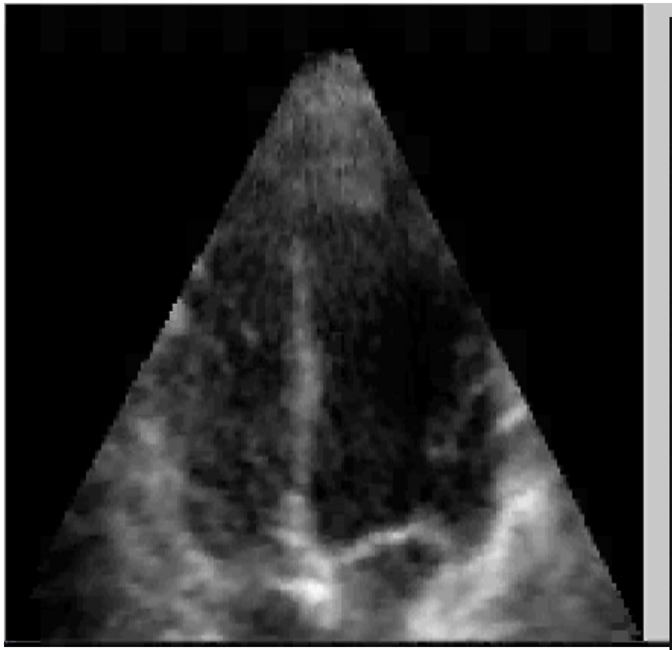
1961: First image of fetus

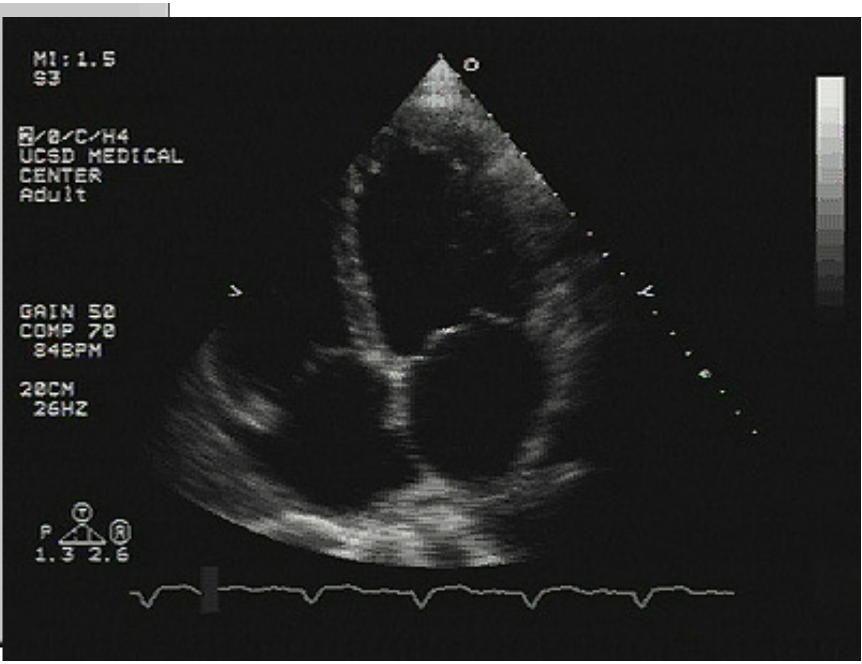
1990: First 3D visualization of fetus

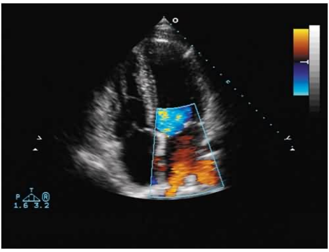
Ultrasound

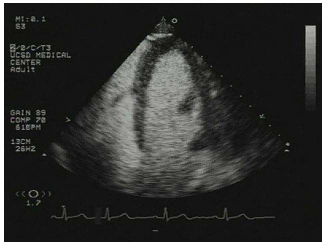
Example: Heart

- Valve diseases.
- Cardiac function (pumping efficiency).
- Blood clots in cardiac chamber.



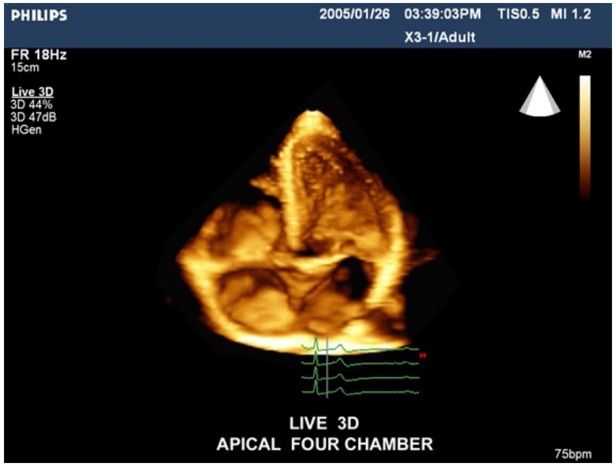


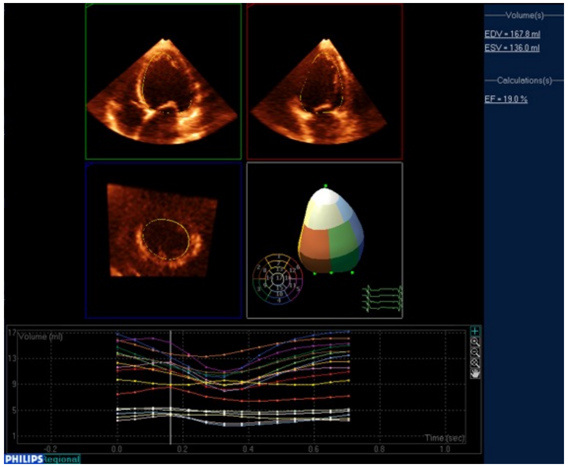




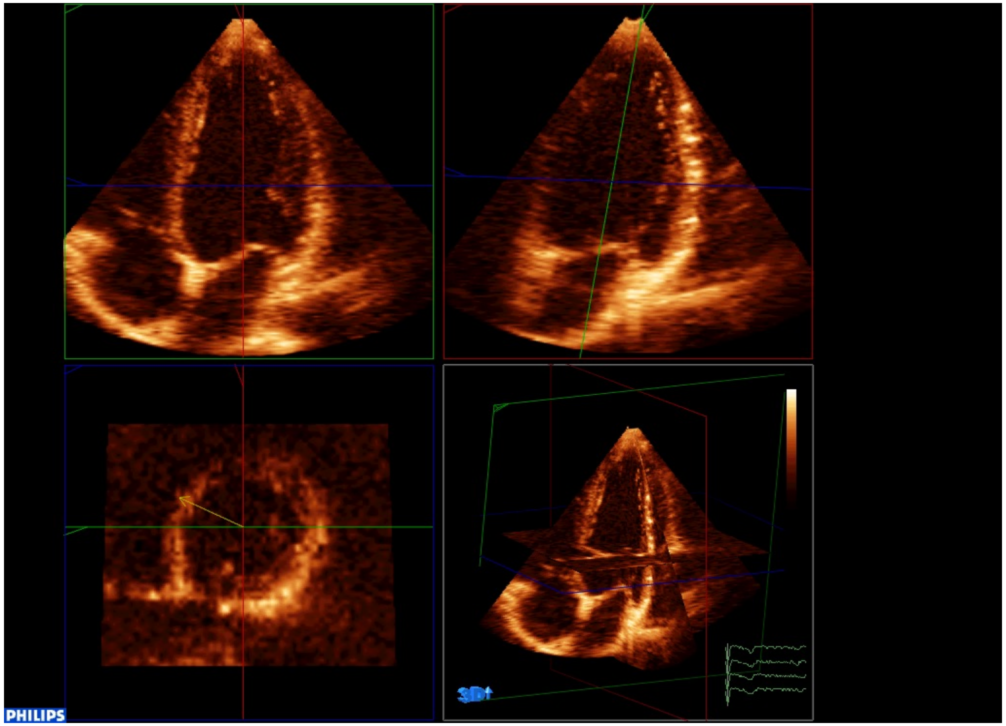
Ultrasound

Example: Heart





EDV = 167.8 ml
ESV = 136.0 ml
EF = 19.0 %



- Real-Time 3D Ultrasound

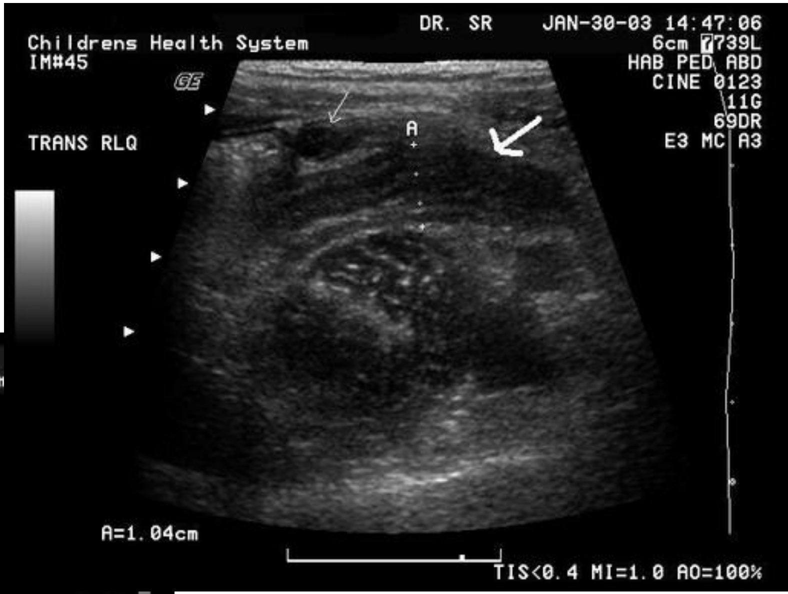
Ultrasound

Examples: Abdomen

- Biopsy guidance.
- Diagnosis of abdominal pains, kidney stones, inflamed appendicitis.

kidney

liver

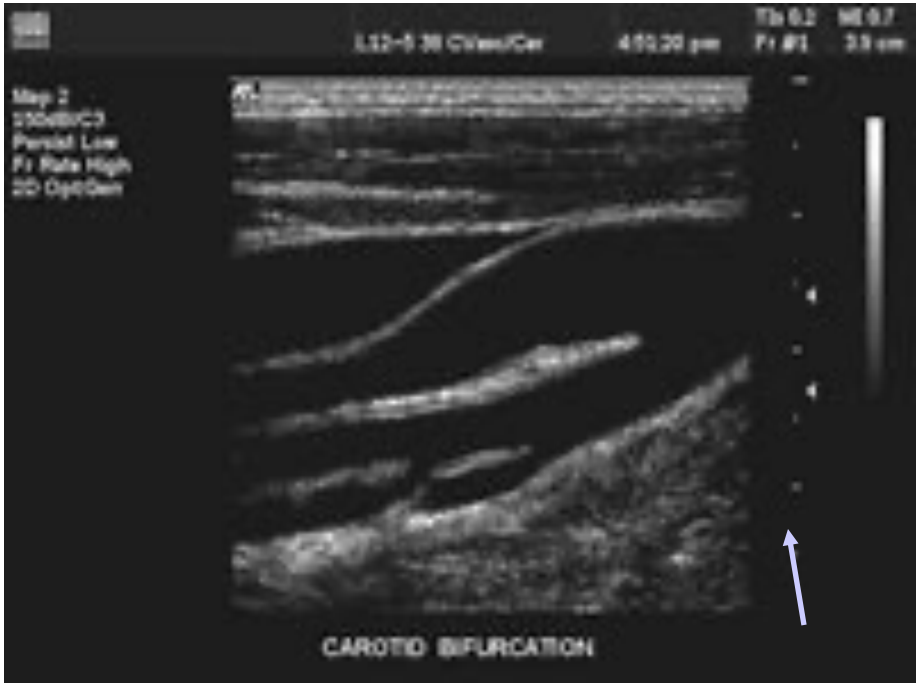


appendicitis

Ultrasound

Example: Blood vessels

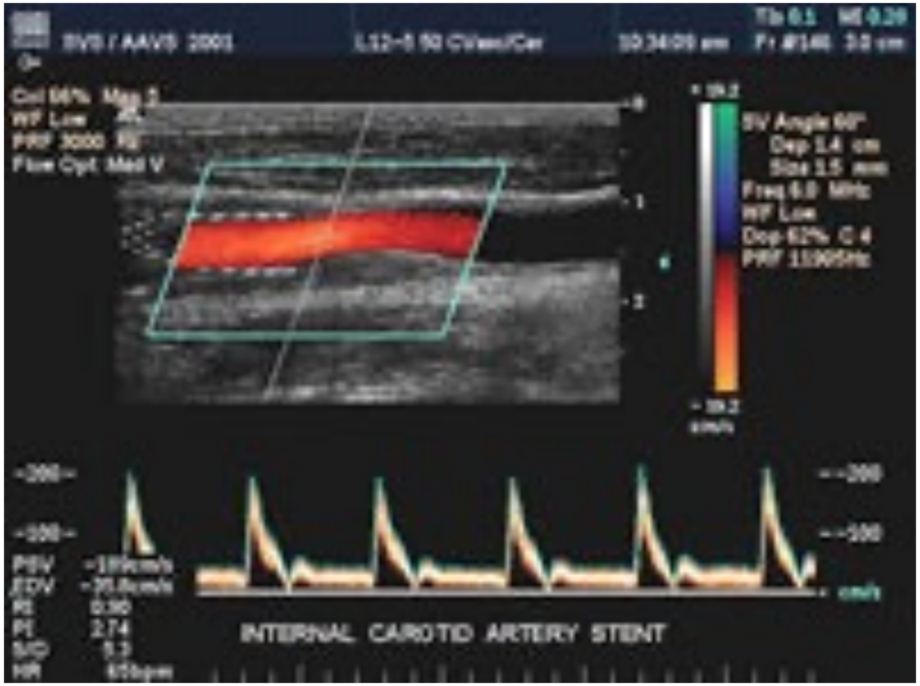
- Artery blockage from blood clots.
- Arteriosclerosis (plaques).
- Stent position



Ultrasound

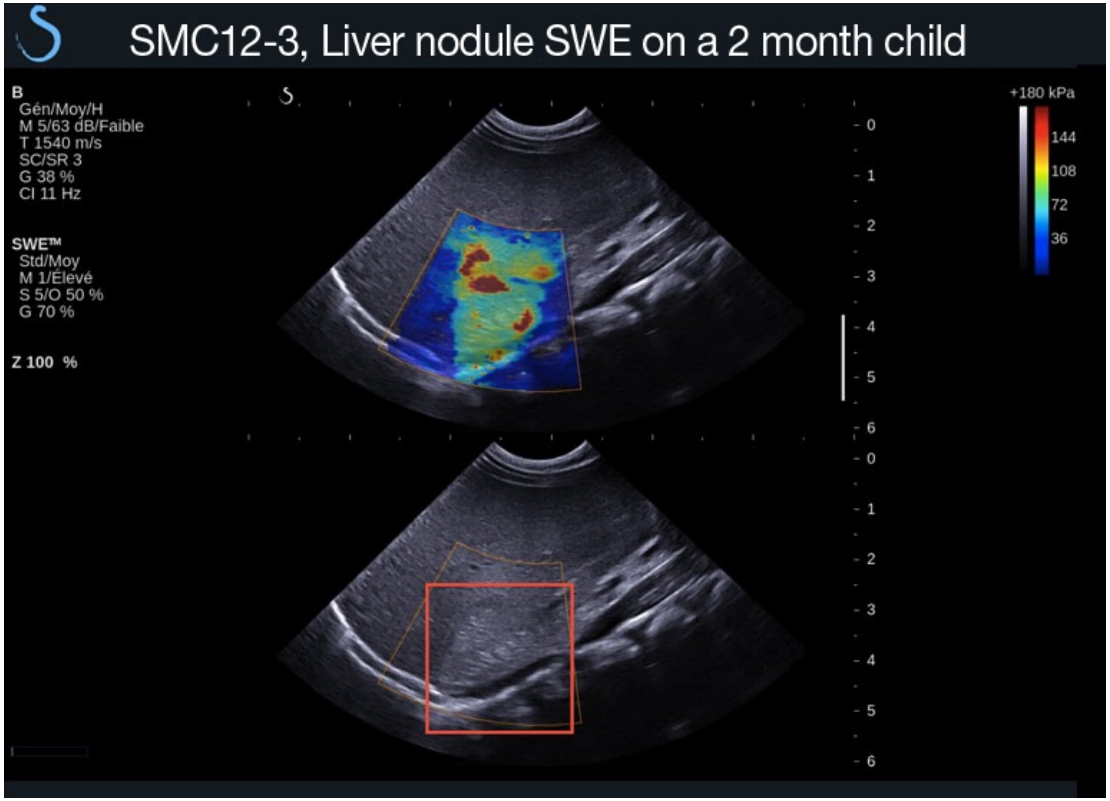
Example: Blood vessels

- Doppler



Ultrasound

Elastography



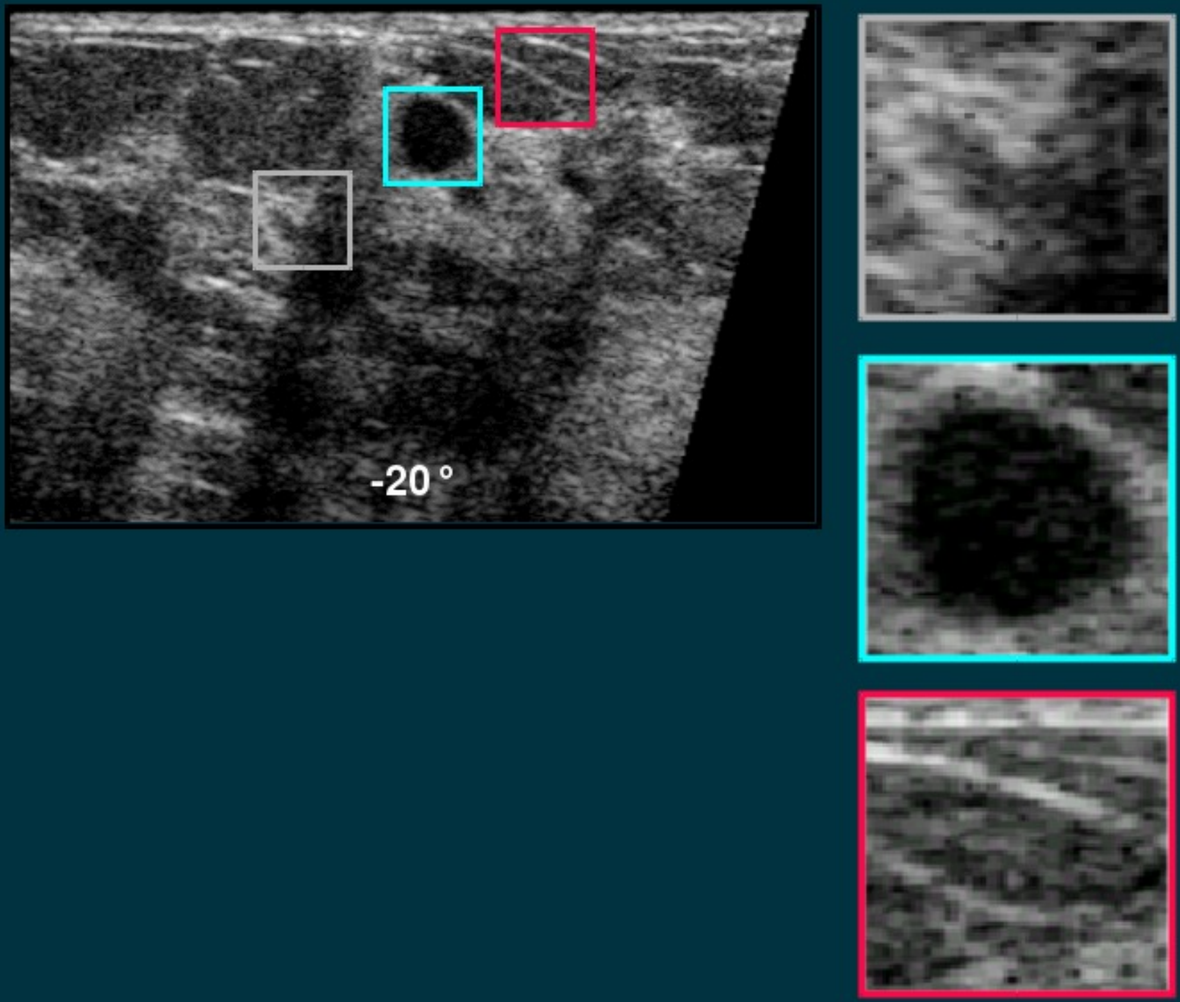
SMC12-3, Liver nodule SWE on a 2 month child

B
Gén/Moy/H
M 5/63 dB/Faible
T 1540 m/s
SC/SR 3
G 38 %
CI 11 Hz

SWE™
Std/Moy
M 1/Élevé
S 5/O 50 %
G 70 %

Z 100 %

2D Spatial Compounding Example

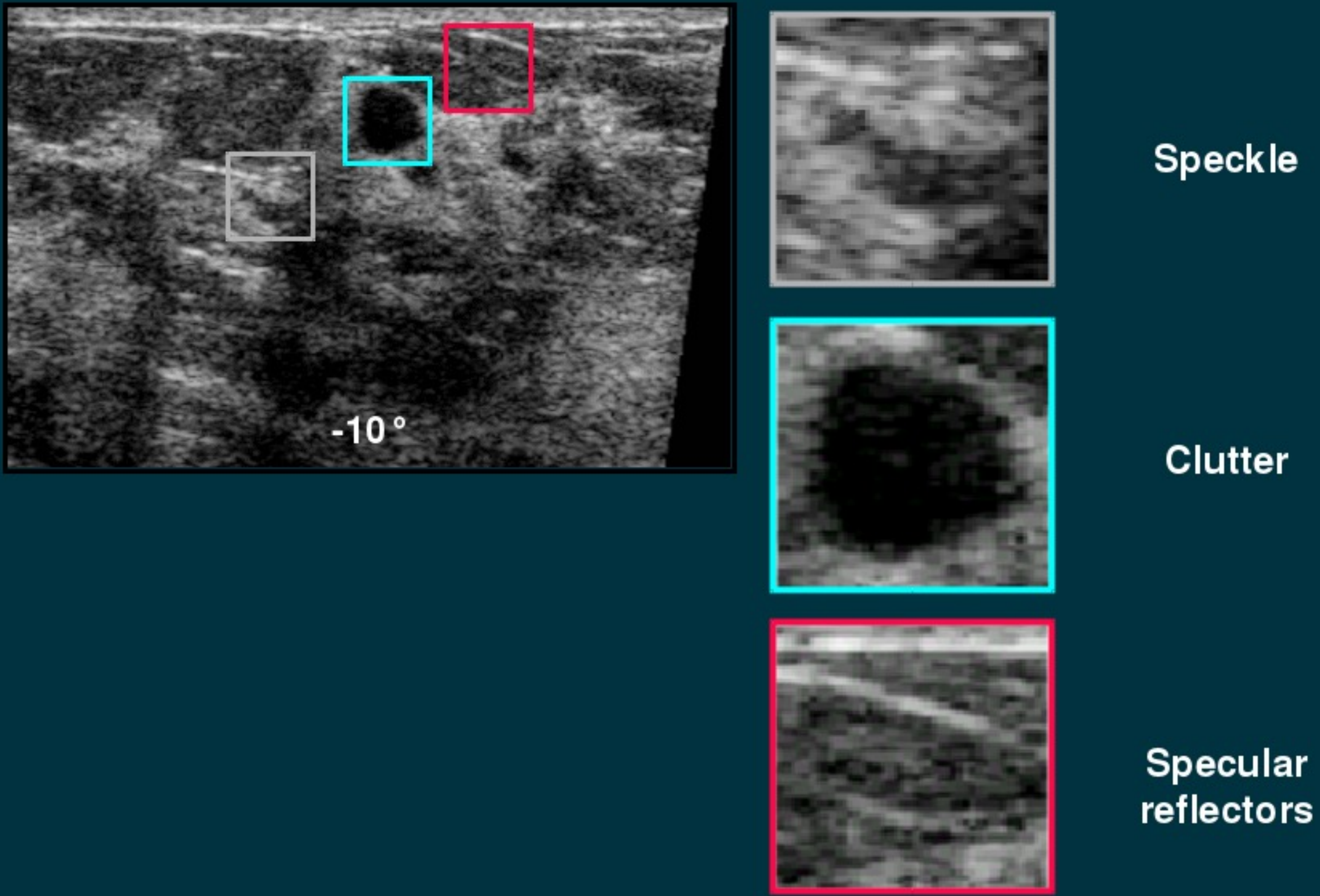


Speckle

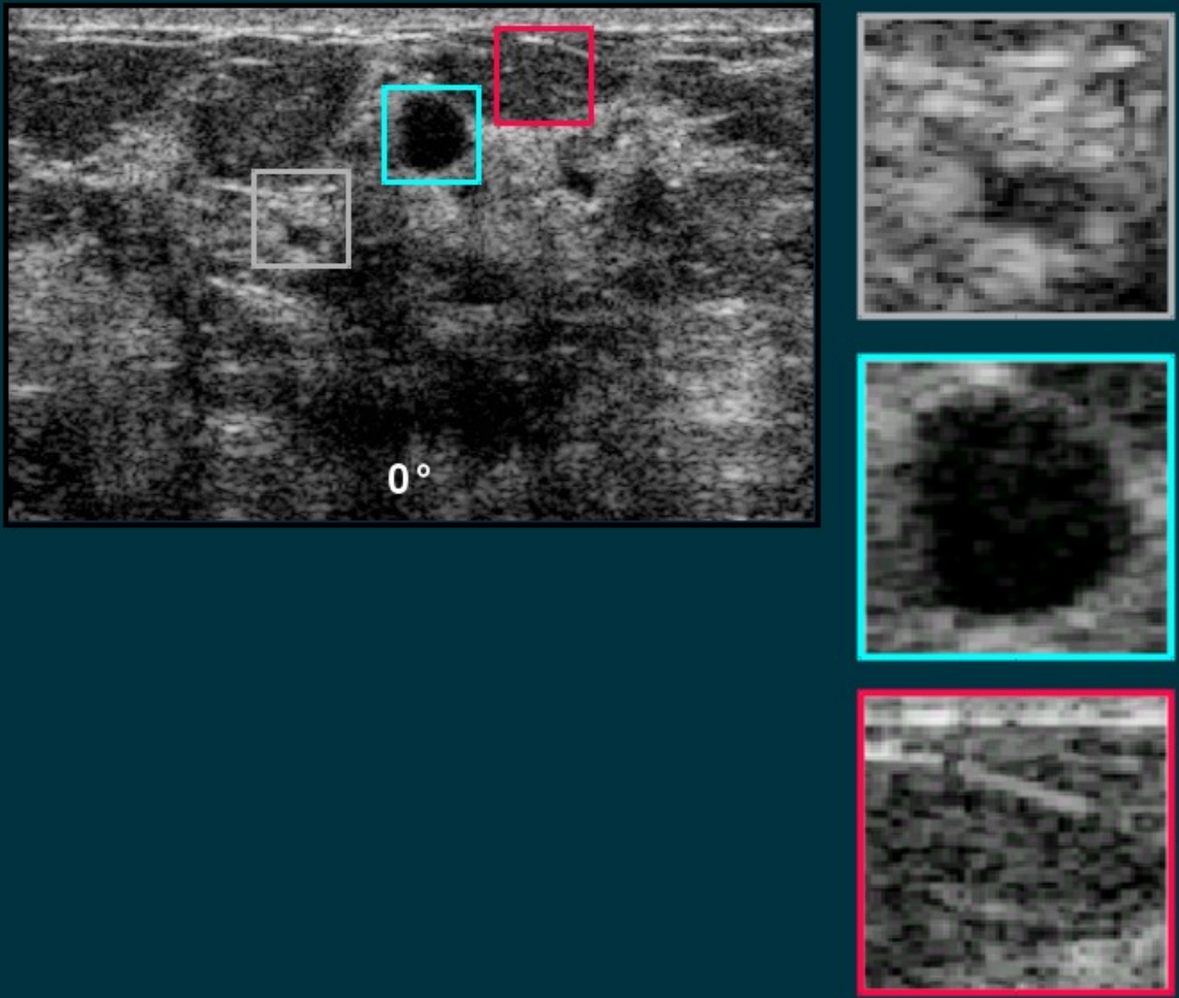
Clutter

Specular reflectors

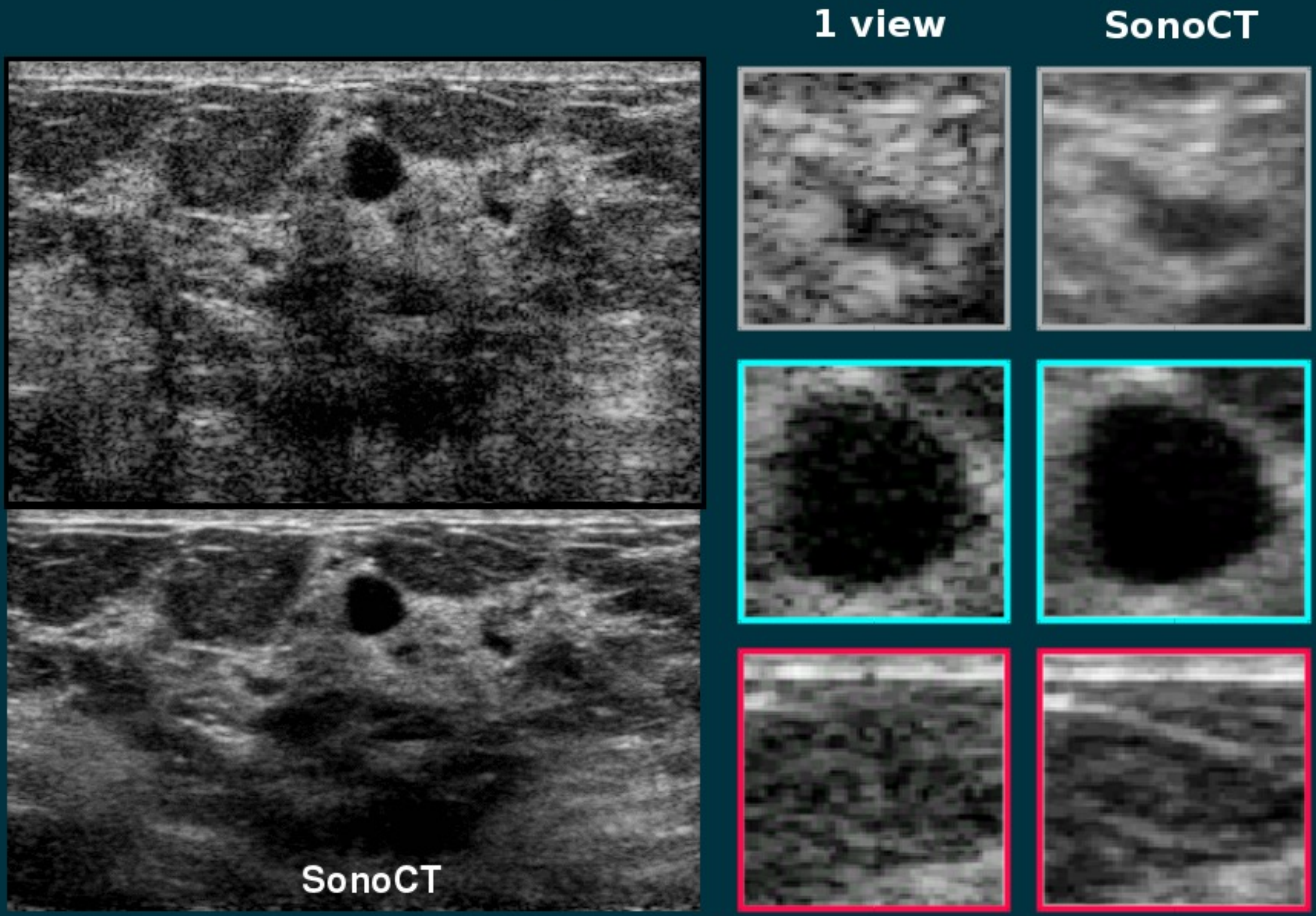
2D Spatial Compounding Example



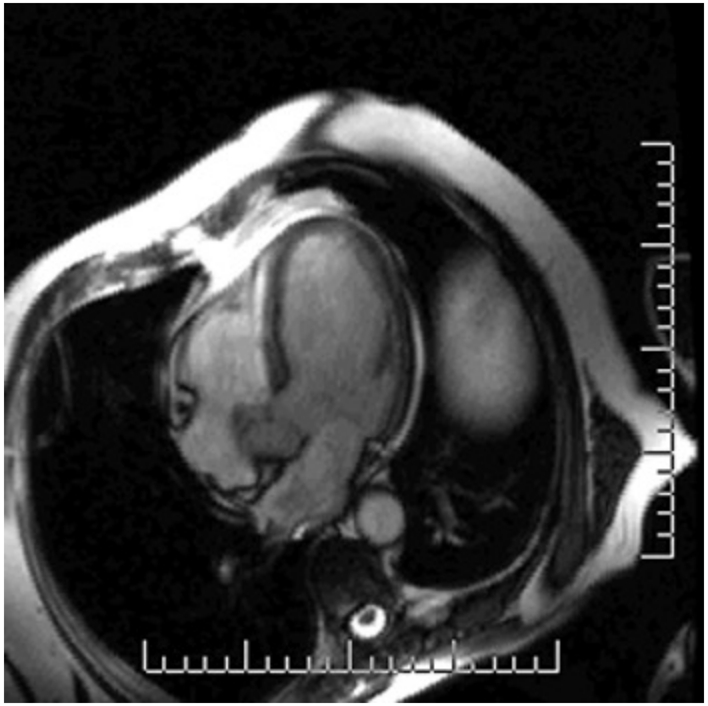
2D Spatial Compounding Example



2D Spatial Compounding Example



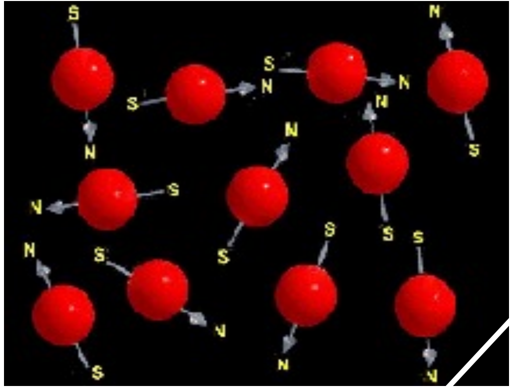
Magnetic Resonance Imaging (MRI)



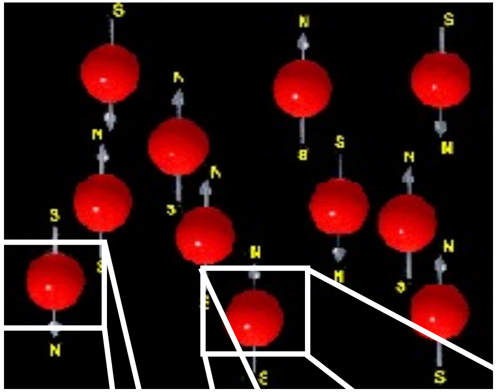
MRI

Physics Principle

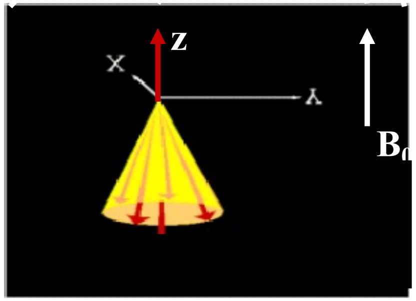
No magnetic field

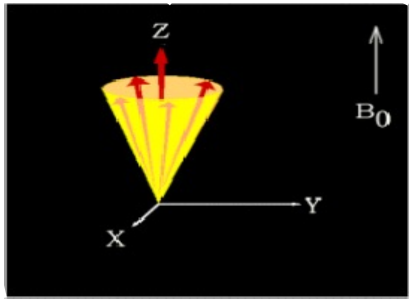


Magnetic field



- Nuclei with magnetic dipoles (H).
- Magnetic field $\mathbf{B_0}$ makes nuclei precess along its direction.
- The precession rate is the Larmor frequency.
- $f_L = \gamma \mathbf{B_0}$ (43⍰1.5 = 64 MHz for Hydrogen into a 1.5T magnet).

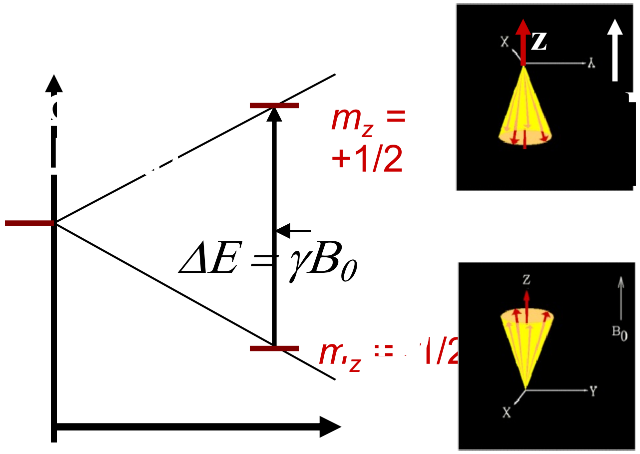




Source: Hielscher, Columbia Univ.

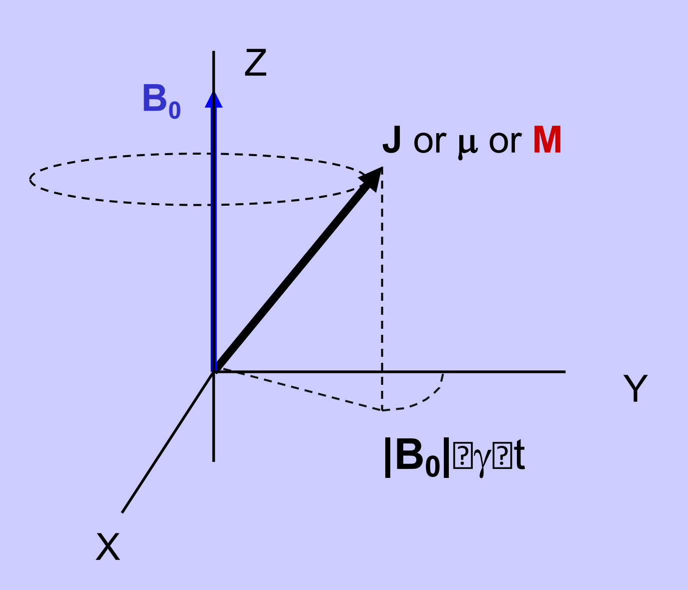
MRI

Image Formation



- For every 1,000,000 nuclei in upper state (mz=+1/2) there are 1,000,001 nuclei in lower state (mz=-1/2).
- This difference is enough to result in macroscopic net magnetization of material.

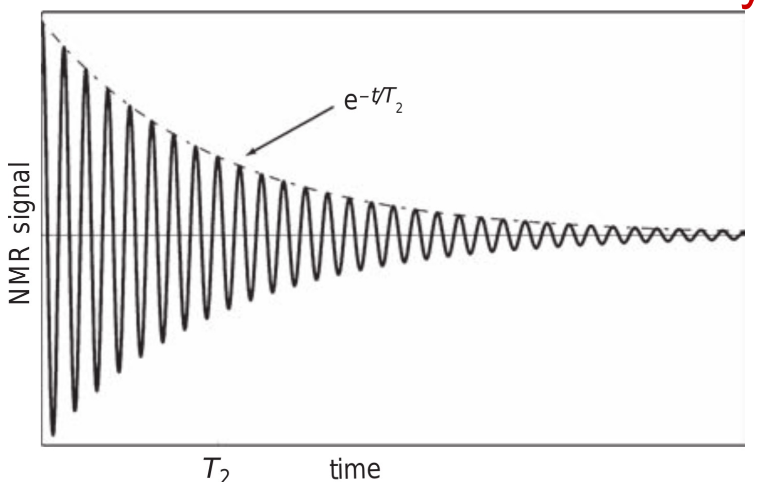
- Nuclei with magnetic dipole moment μ, and angular momentum **S**.
- Net magnetization **M** = density of μ.
- Tip **M** away from **B_0** ⇨ Precession at frequency γB_0, producing a measurable RF magnetic field.

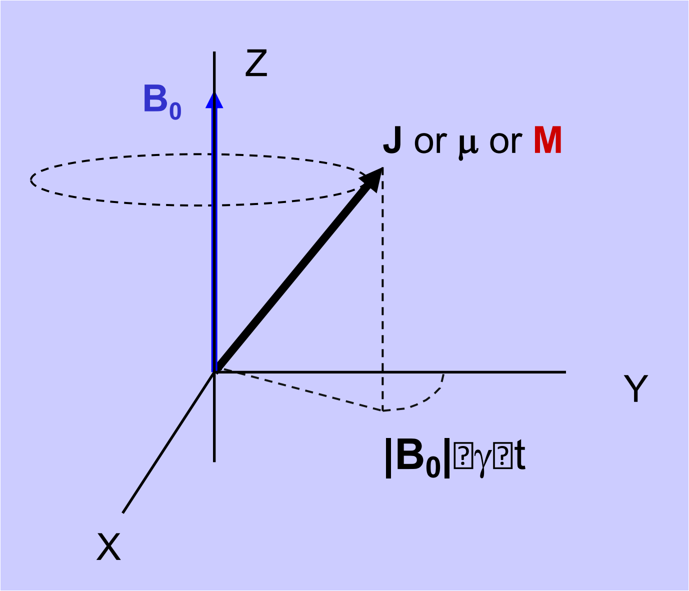


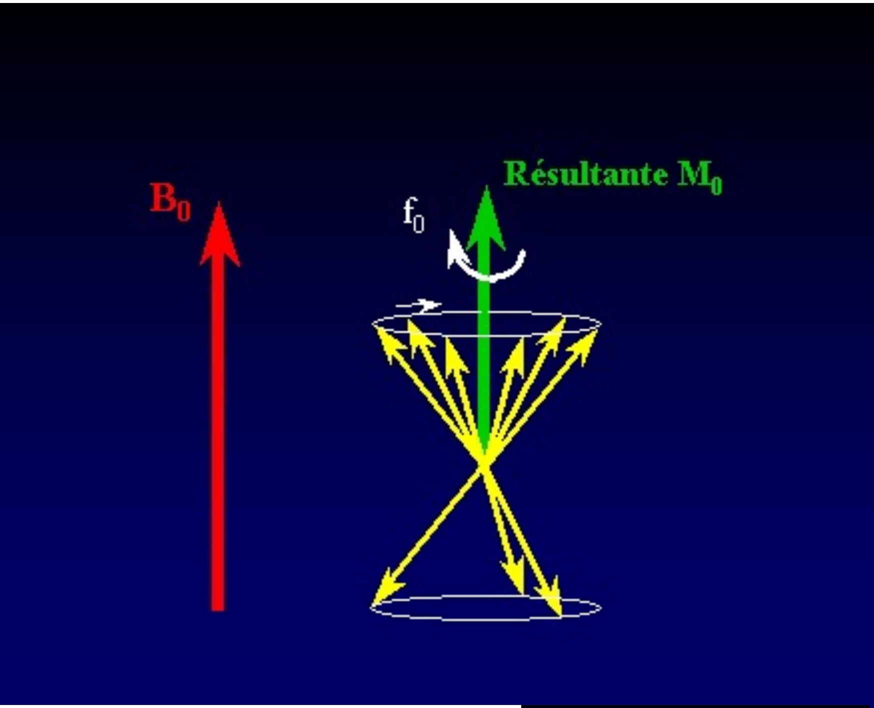
MRI

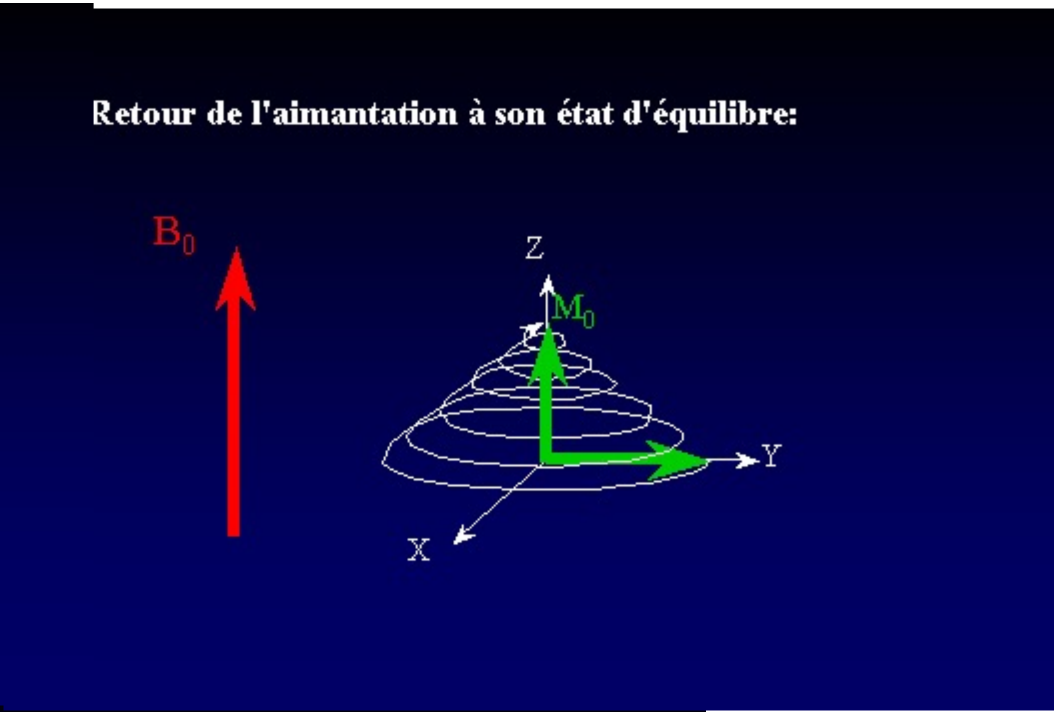
Image Capture

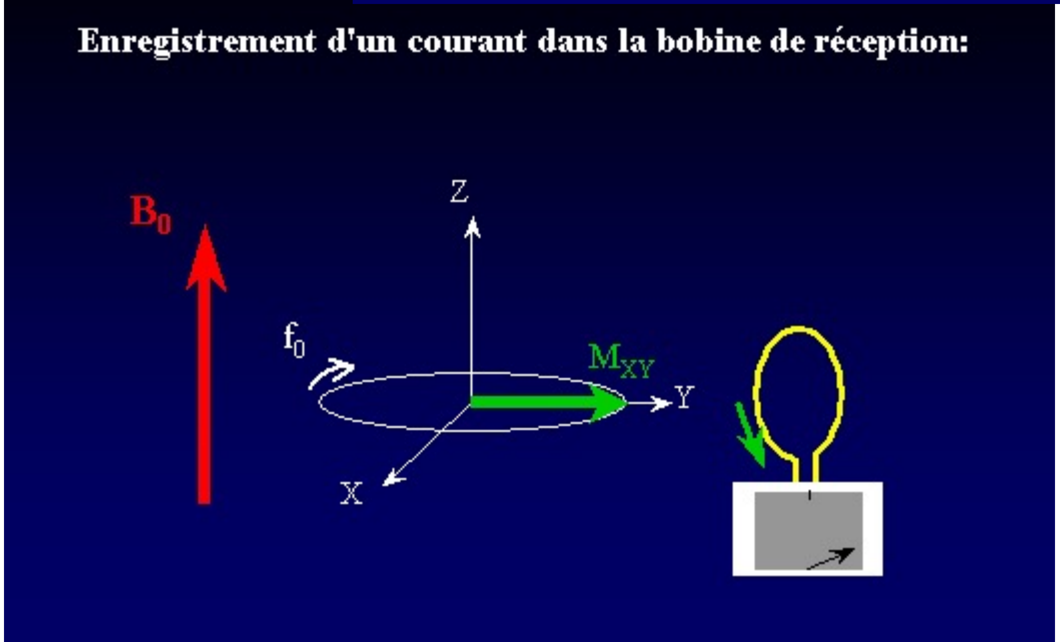
- As the magnetization precesses it creates its own RF magnetic field.
- This field is much smaller than the exciting RF field.
- It can be detected with a standard radio receiver (e.g. RF coils used to tip M away from B_0)
- The resulting signal from precession is called the Free Induction Decay or FID.





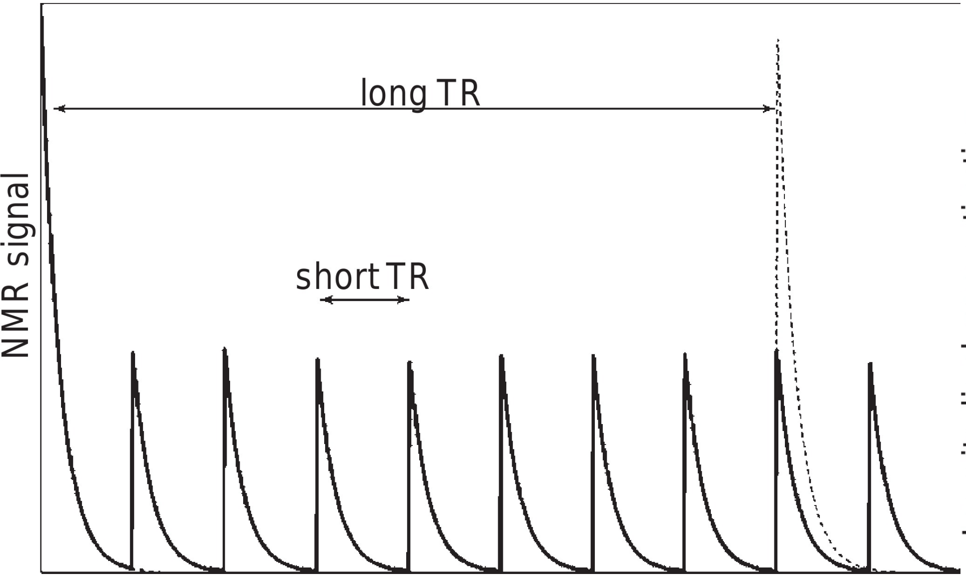


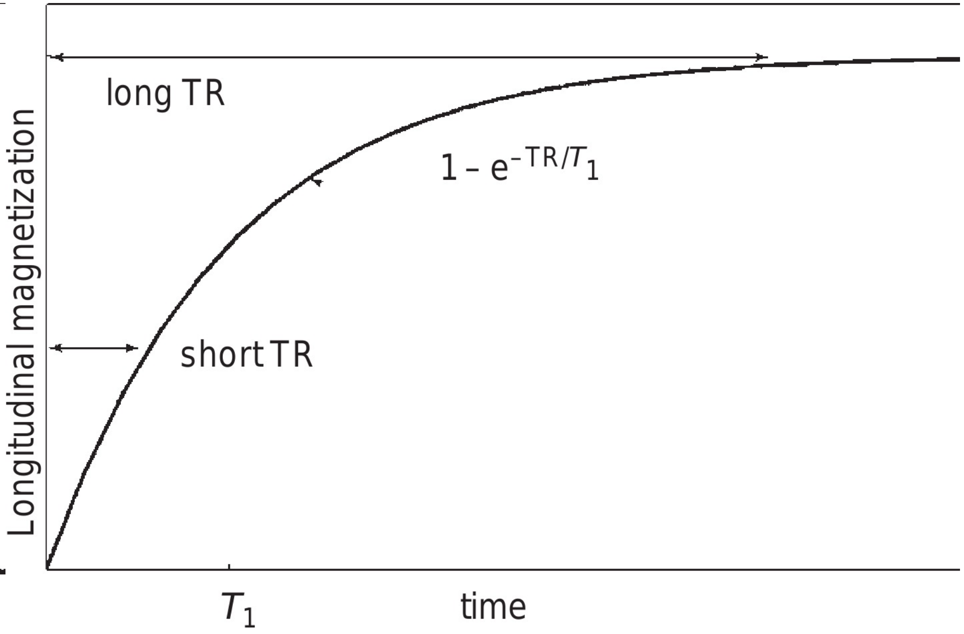

Retour de l'aimantation à son état d'équilibre:


Enregistrement d'un courant dans la bobine de réception:

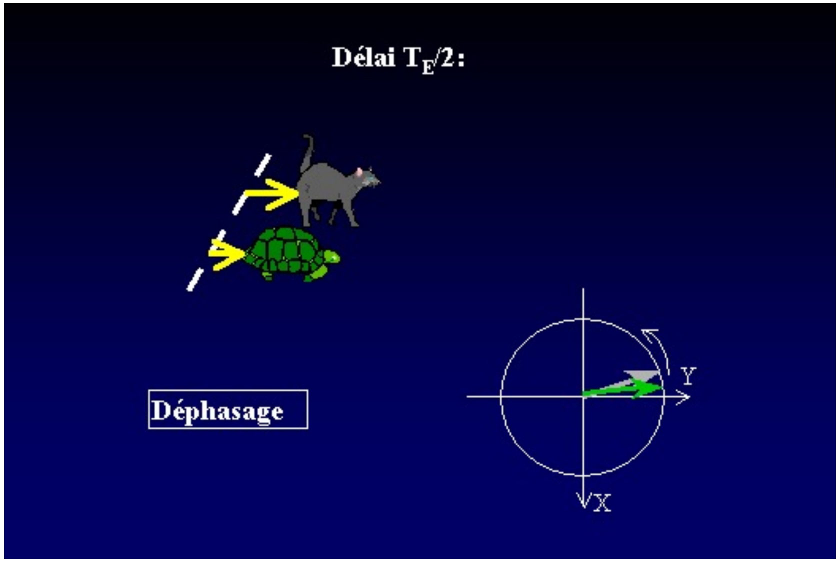
TR = repetition time (between consecutive RF pulses)

If the recovery of the first FID in not complete (TR < T1), the next FID signal will be reduced.



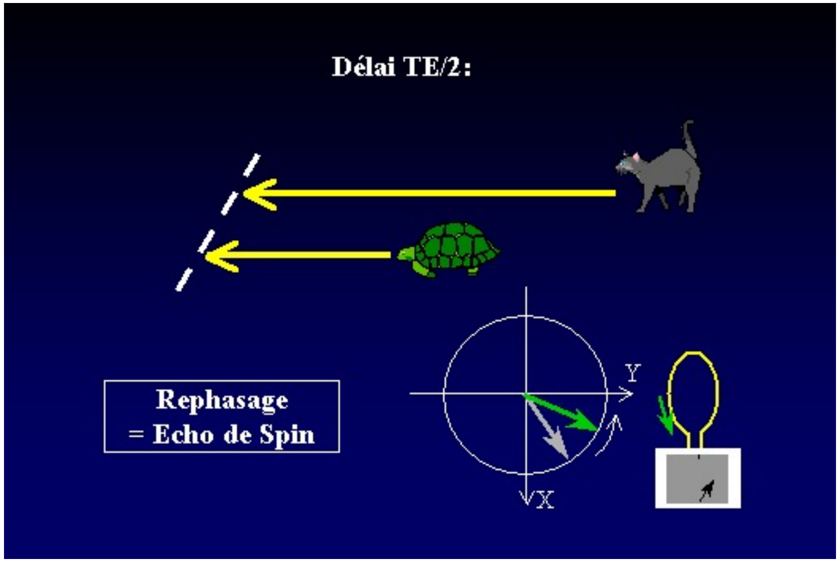


TE = spin echo time



Délai $T_E/2$:

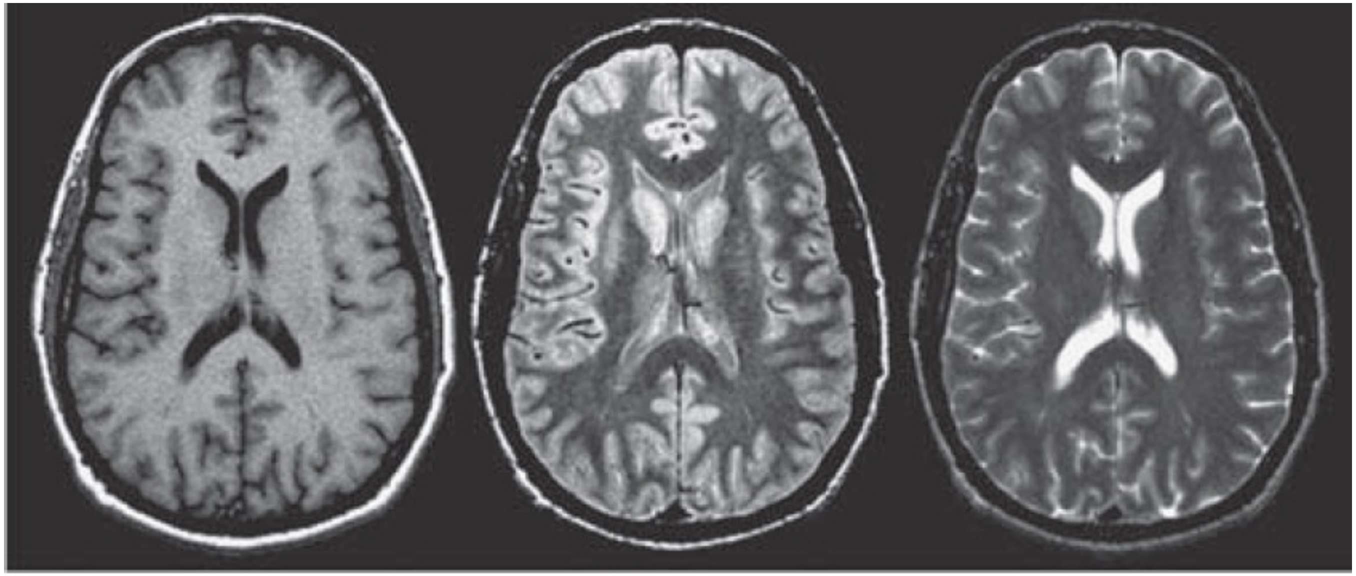
Déphasage



Délai TE/2:

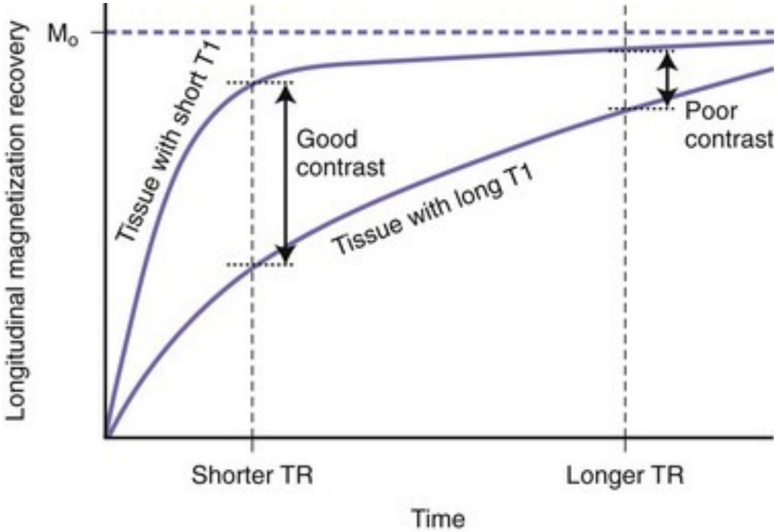
Rephasage
= Echo de Spin

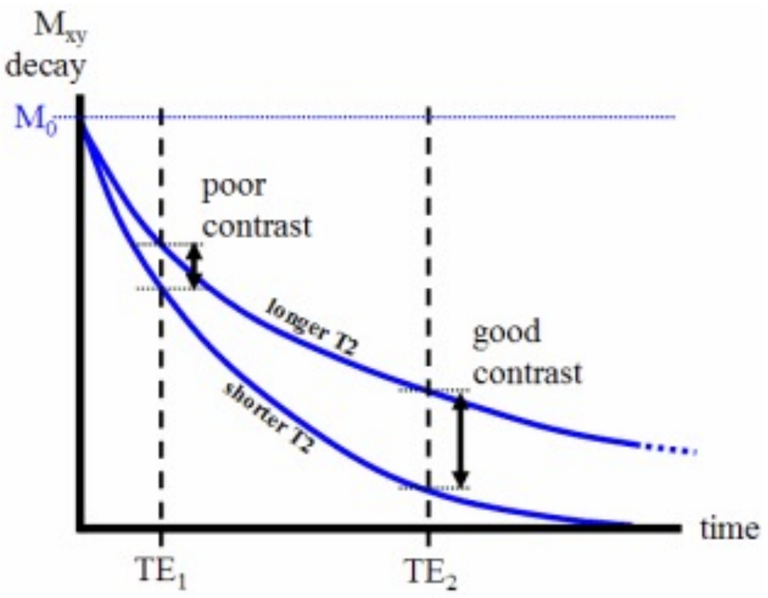
Image contrast:

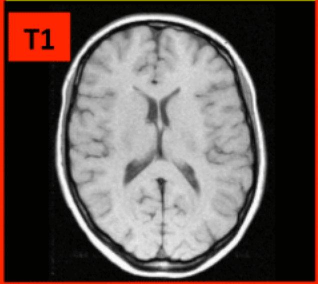
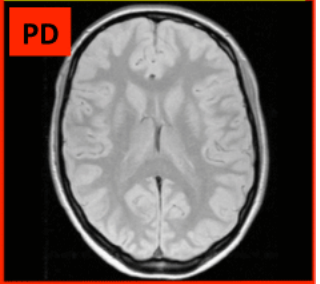


T_1-weighted (TR = 600, TE = 11) | Density-weighted (TR = 3000, TE = 17) | T_2-weighted (TR = 3800, TE = 102)

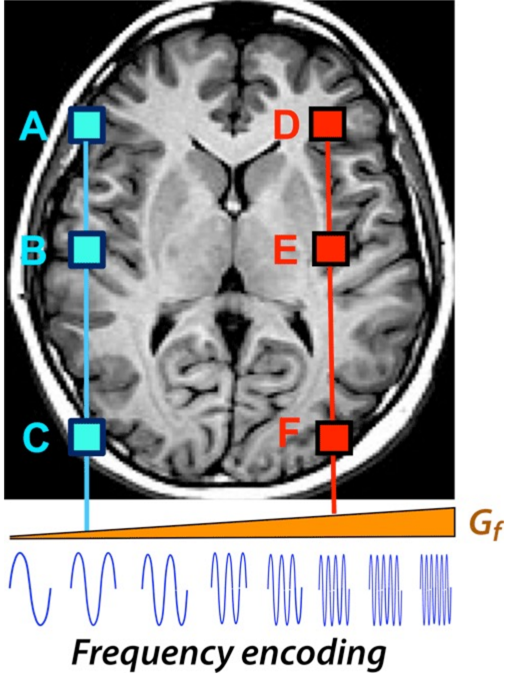
Image contrast:

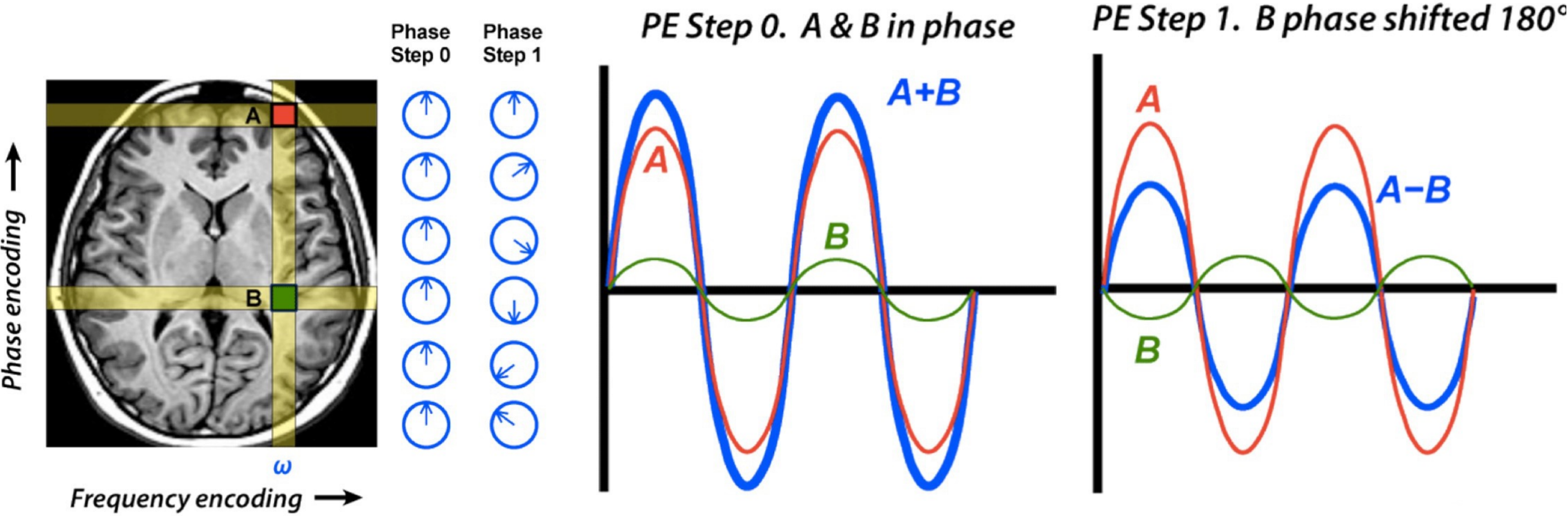




	Short TR	**Long TR**
Short TE		
Long TE		

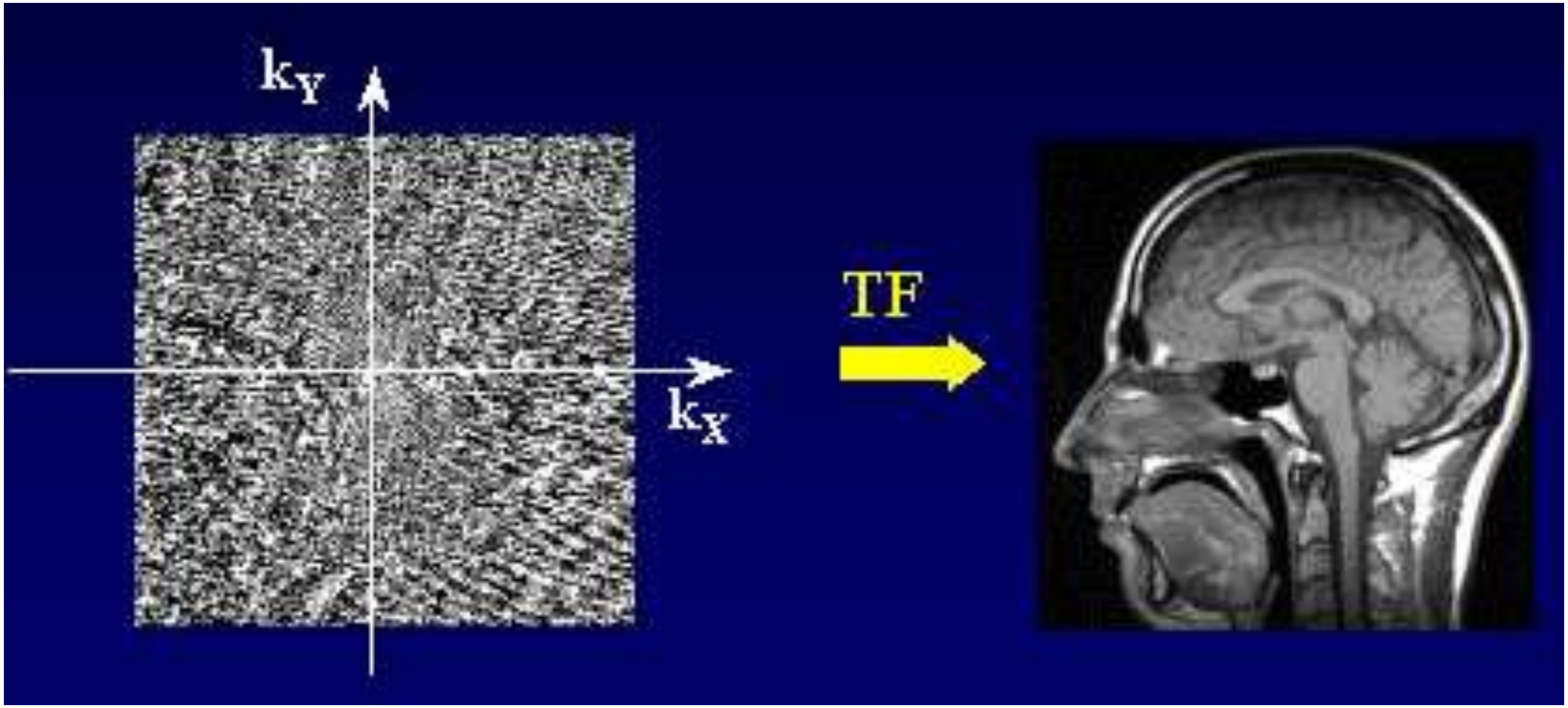
Spatial localization: using gradient field, frequency encoding and phase encoding





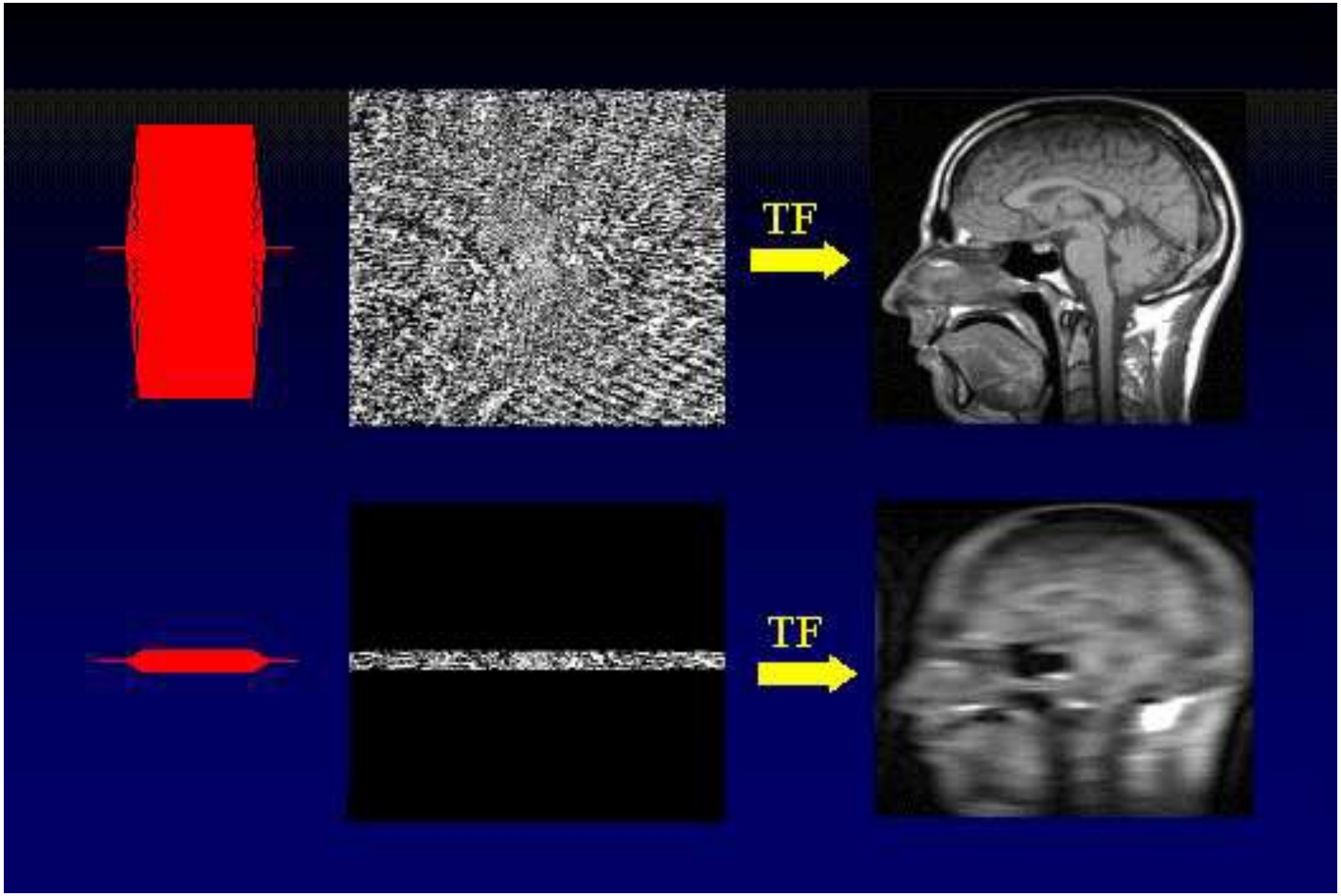
signal = sum of the contributions from all the locations

= Fourier transform of the image (k-space)



signal = sum of the contributions from all the locations

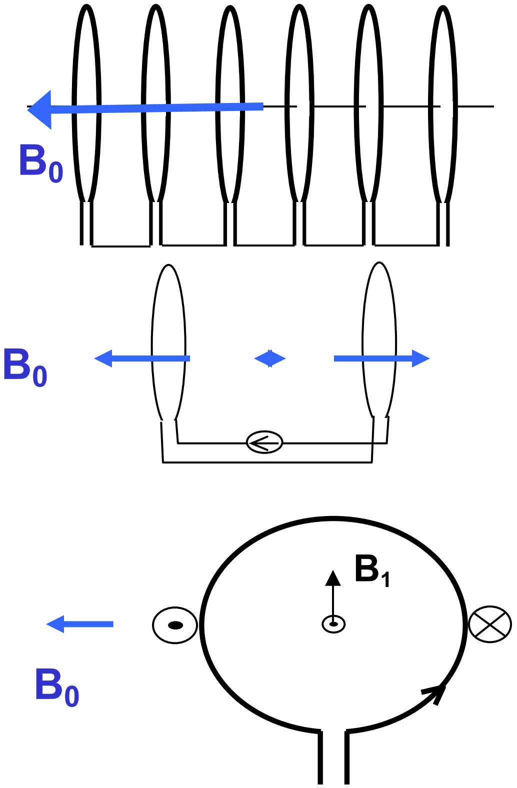
= Fourier transform of the image (k-space)



MRI

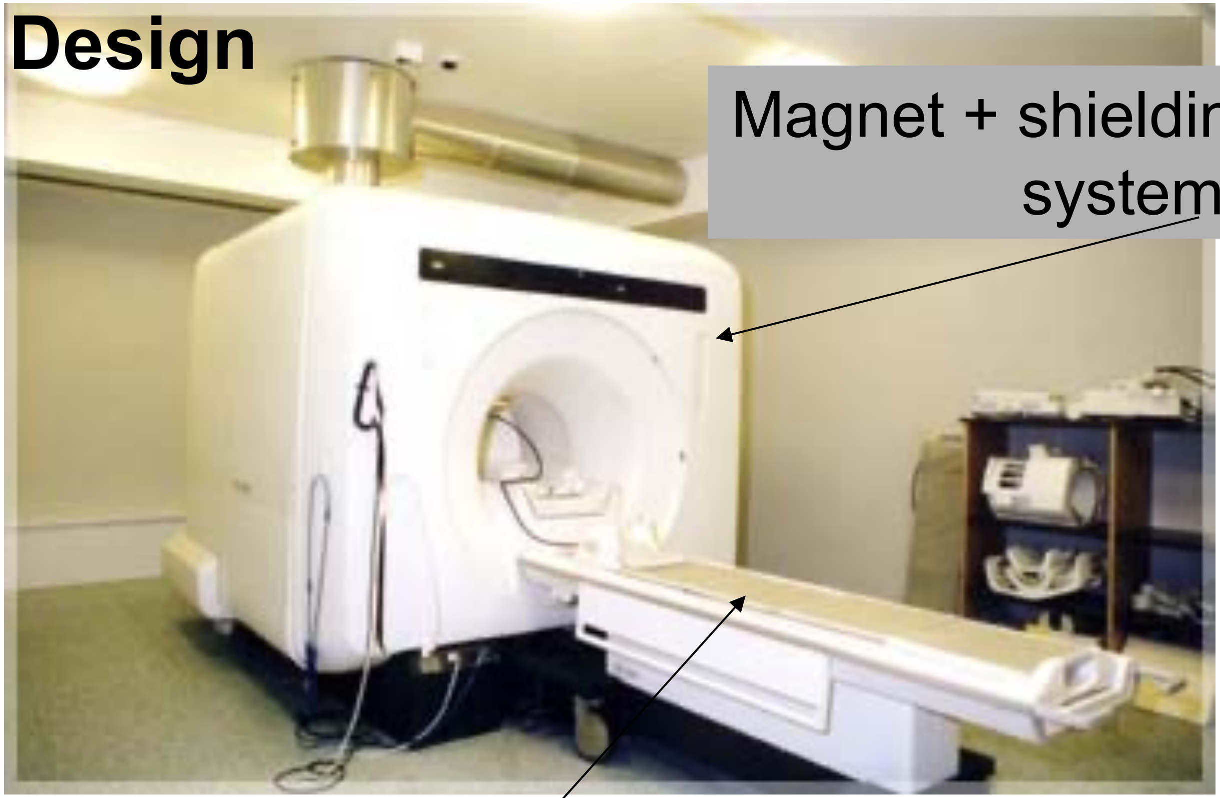
System Design

- **Main Magnet**
  - High, constant,Uniform Field, B_0.
- **Gradient Coils**
  - Produce pulsed, linear gradients in this field: G_x, G_y, & G_z
  - <u>spatial localization</u>
- **RF coils**
  - Transmitter: B_1 Excites NMR signal to generate Free Induction Decay (FID).
  - Receiver: Senses FID.



MRI

System Design



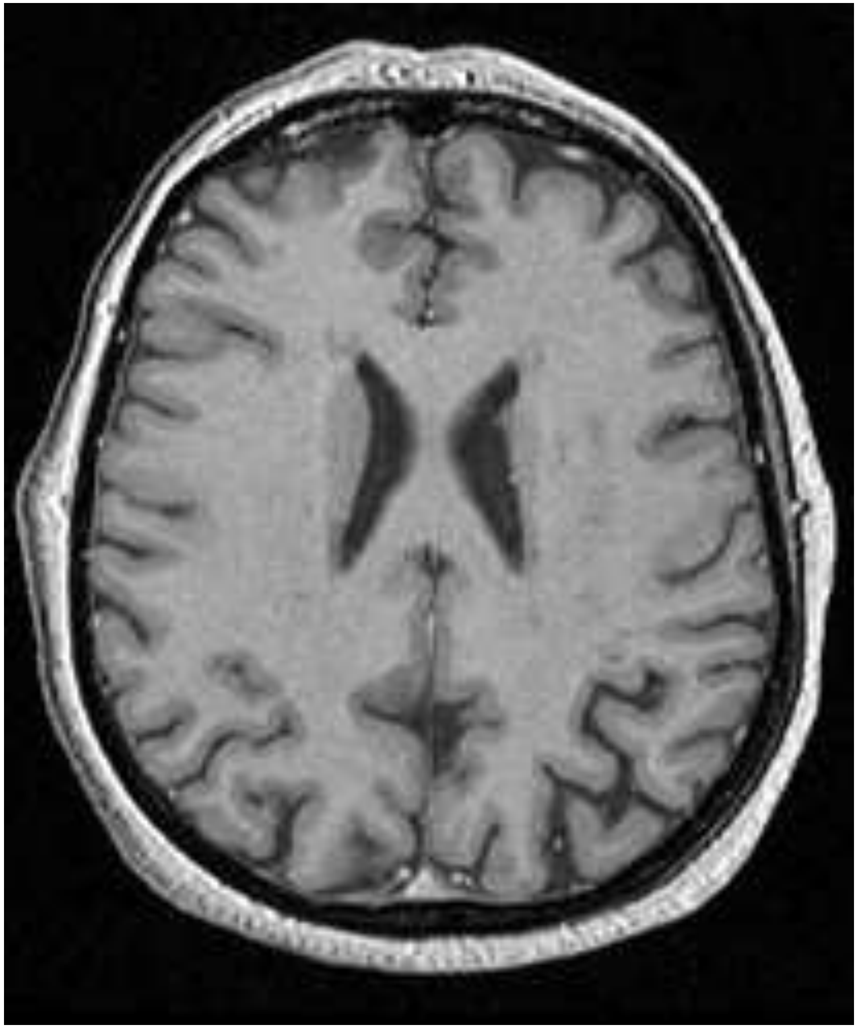
Magnet + shielding + cooling systems

gantry

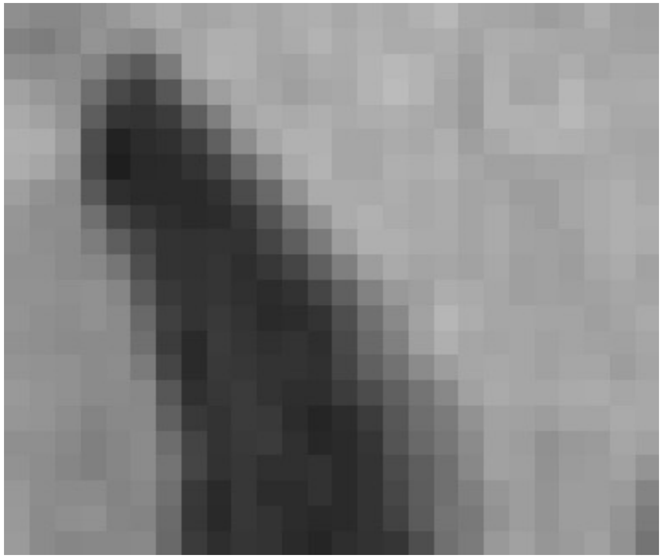
MRI

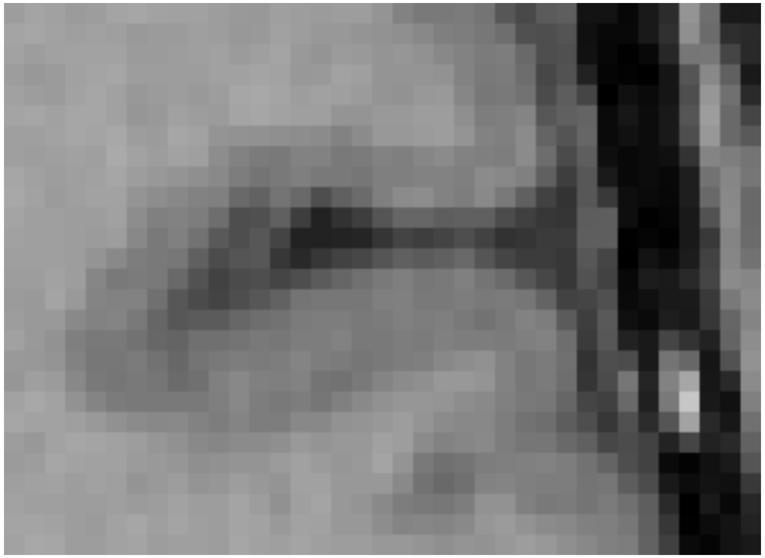
- **Advantages:**
  - High image quality.
  - Good spatial resolution (~1mm).
  - Almost all tissues.
  - Can provide information on both anatomy and function.
- **Disadvantages:**
  - Very expensive scanners.
  - Some patients cannot be imaged (pacemaker, claustrophobia).

Chemical shift:



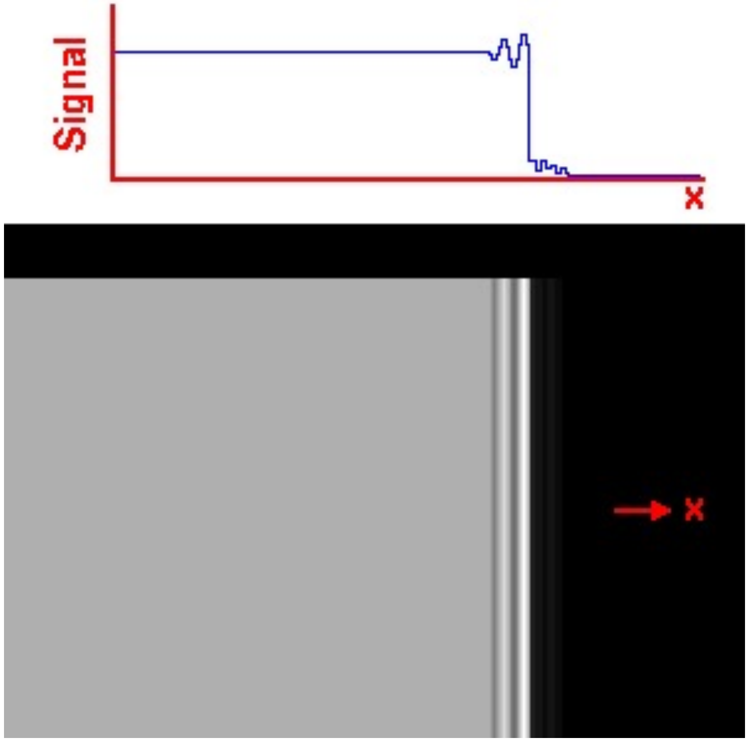
Partial volume effect:

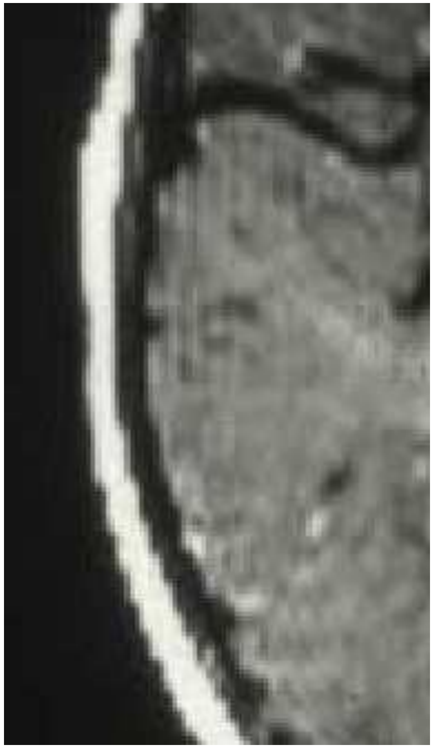




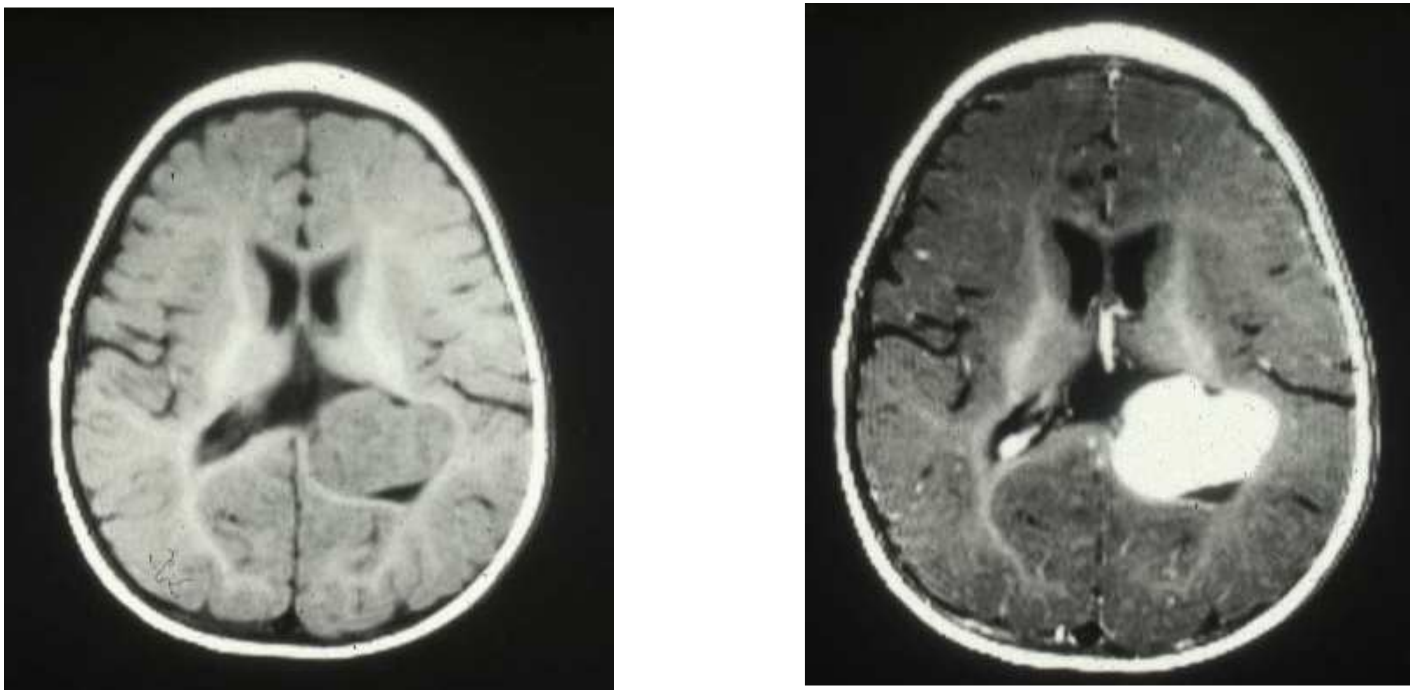
Local antenna:

Gibbs effect:





Contrast agent: Gd-DTPA (paramagnetic) – Reduces T1



MRI

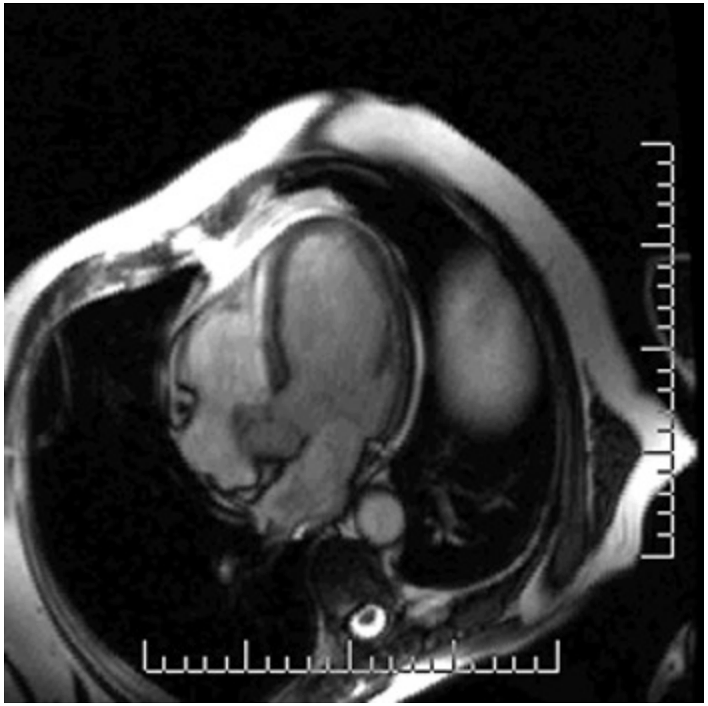
Applications

- Brain (Multiple sclerosis, Alzheimer’s disease, epilepsy, tumors)
- Spine
- Muscles, tendons.
- Blood vessels: angiography (strokes, aneurism)
- Heart
- Soft tissues

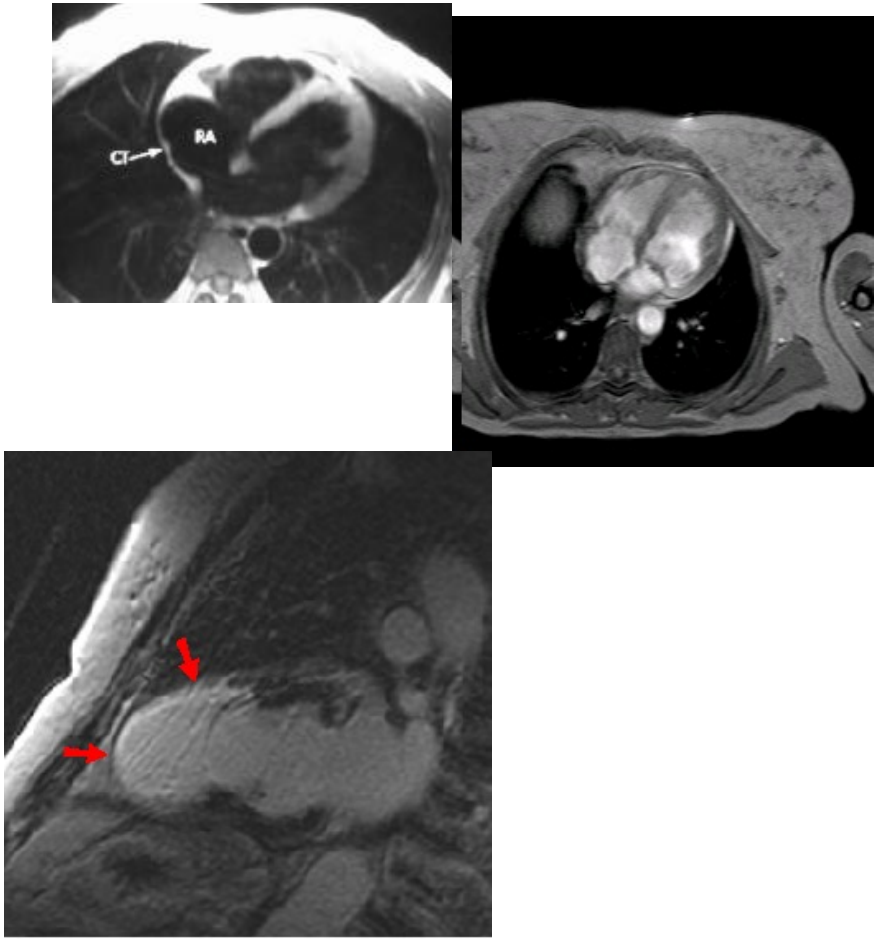
MRI

Example: Heart

- CINE MRI

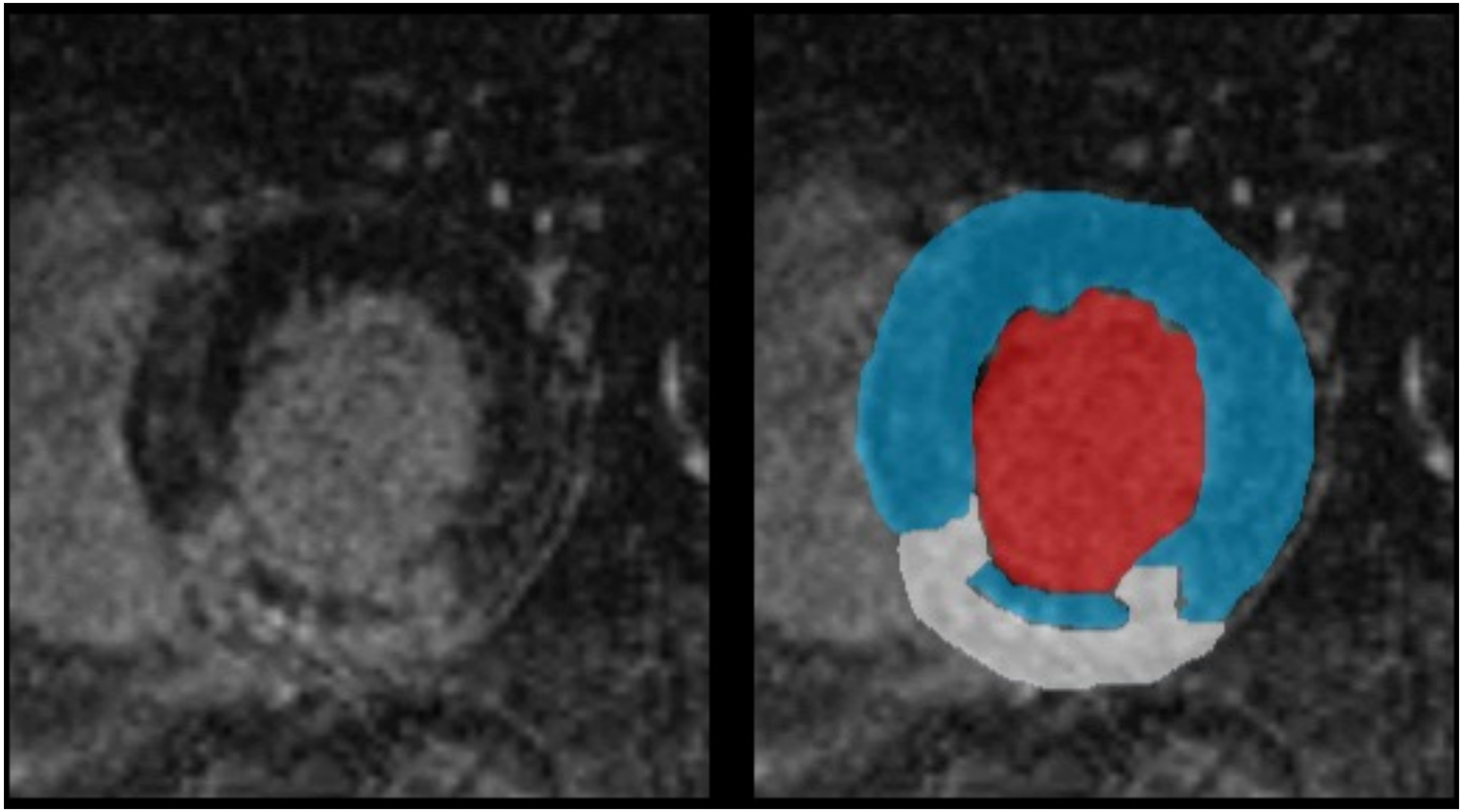


Courtesy of Robert R. Edelman



MRI

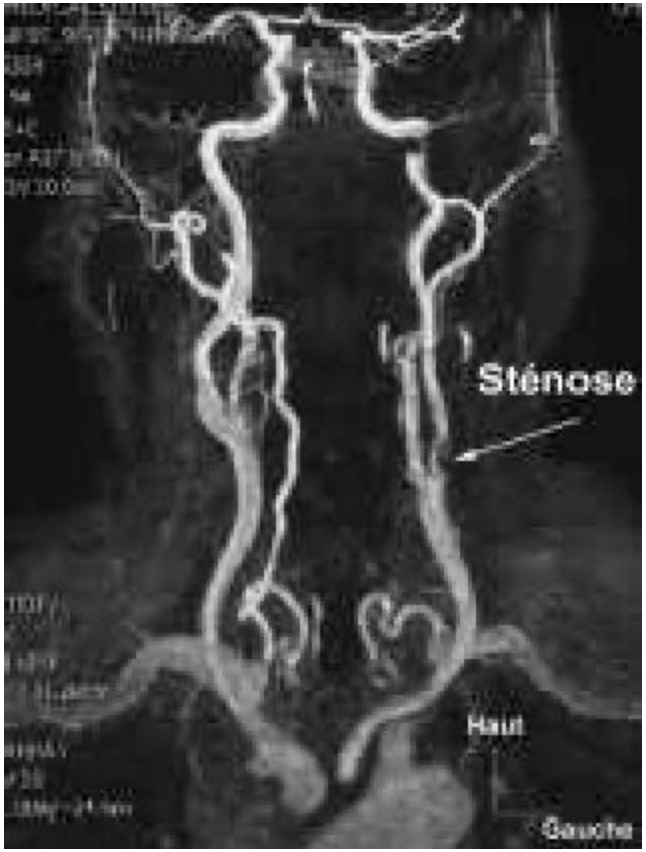
Example: Heart



MRI for myocardial perfusion

MRI

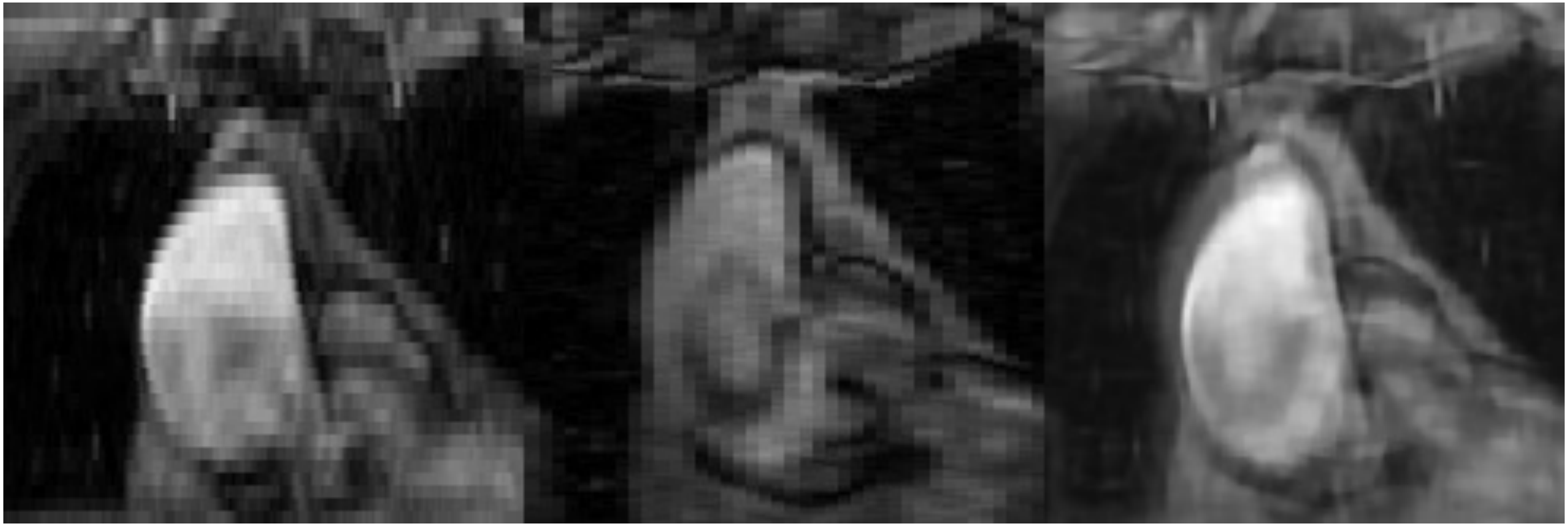
Example: Blood vessels



Magnetic Resonance Angiography

MRI

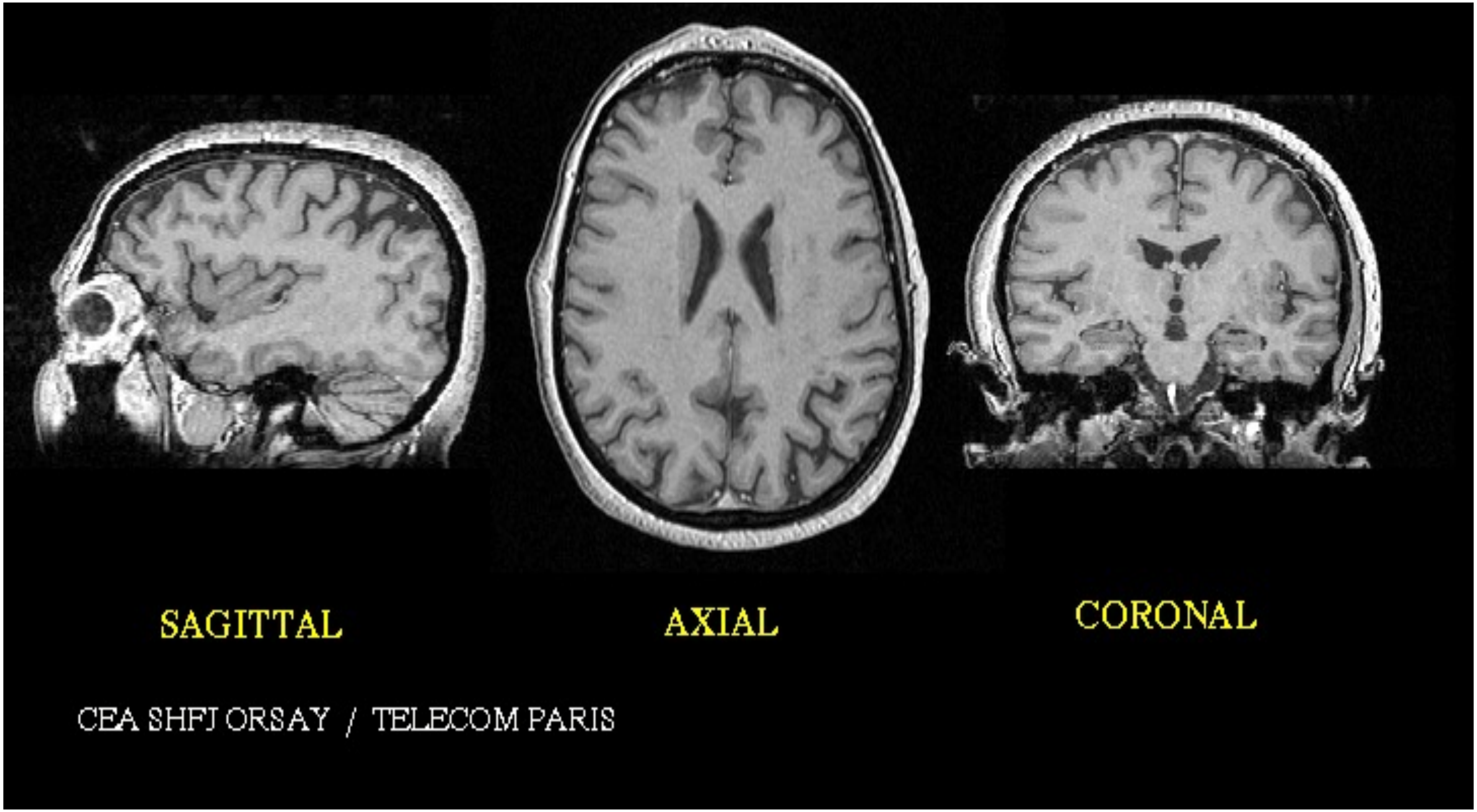
Example: Blood vessels



Aorta

MRI

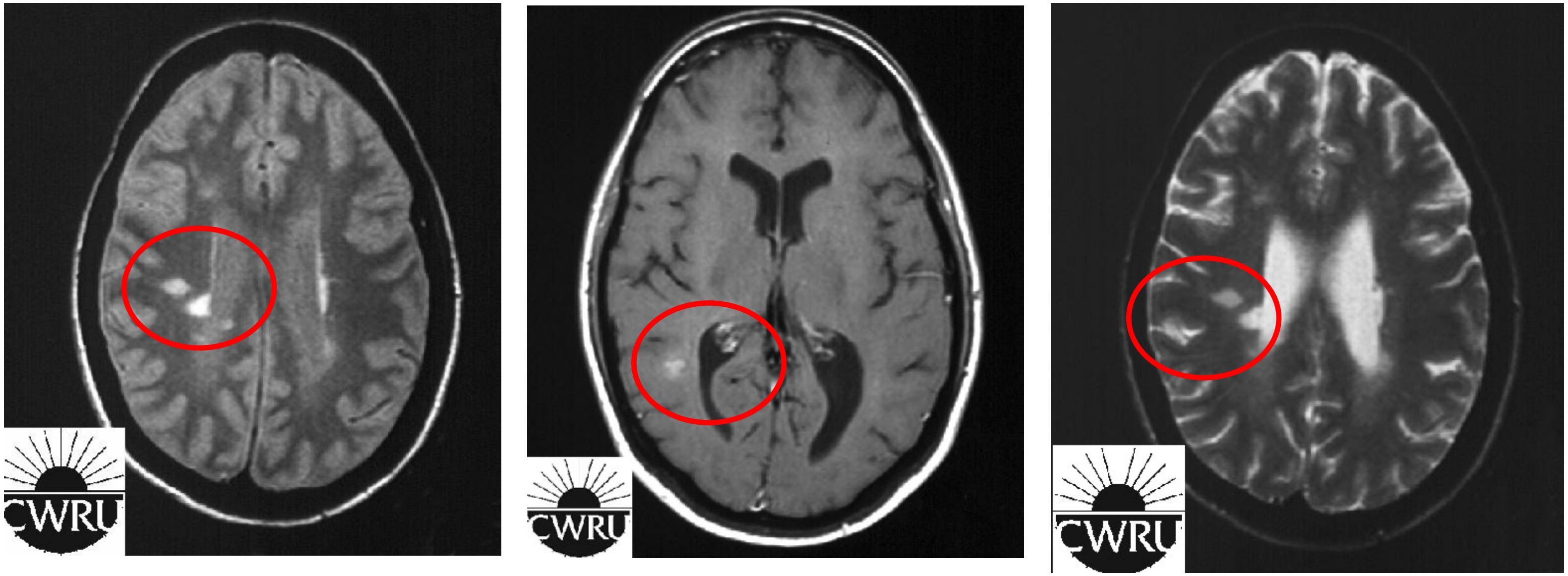
Example: Brain



MRI

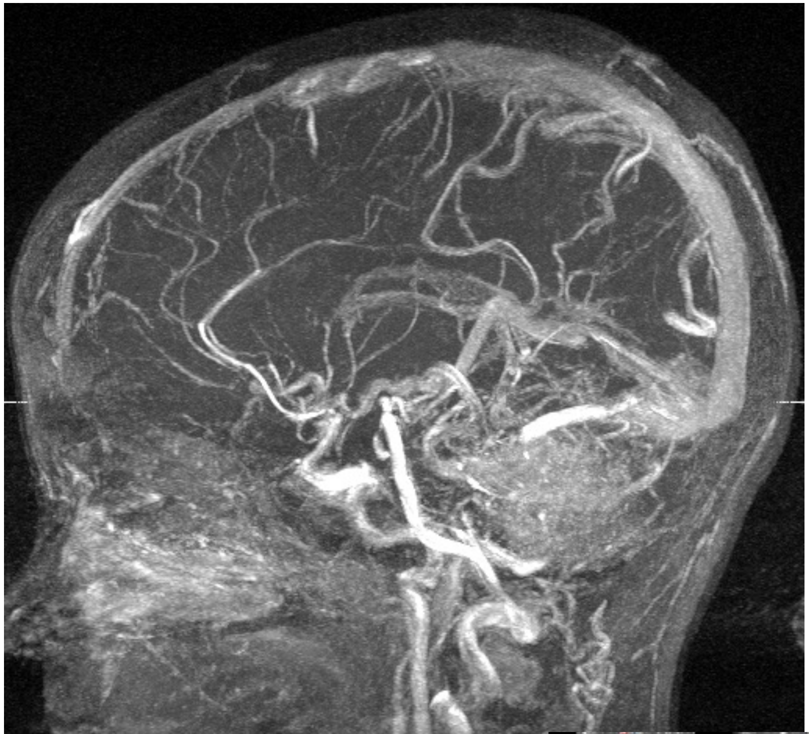
Example: Brain

- Diagnosis of Alzheimer’s and Parkinson’s disease.

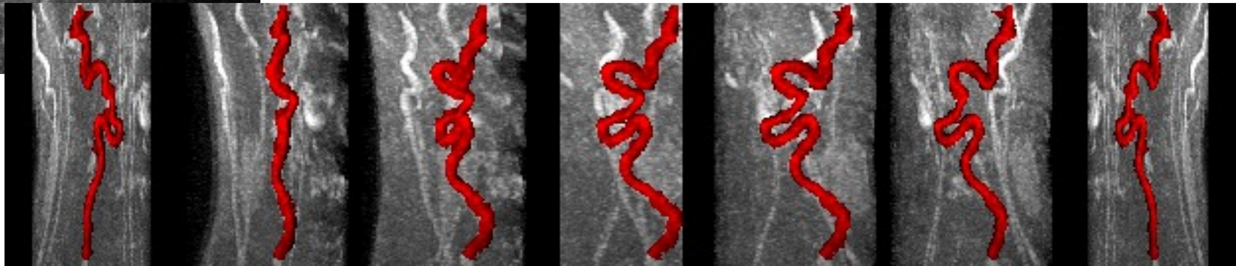


MRI

Example: Blood vessels

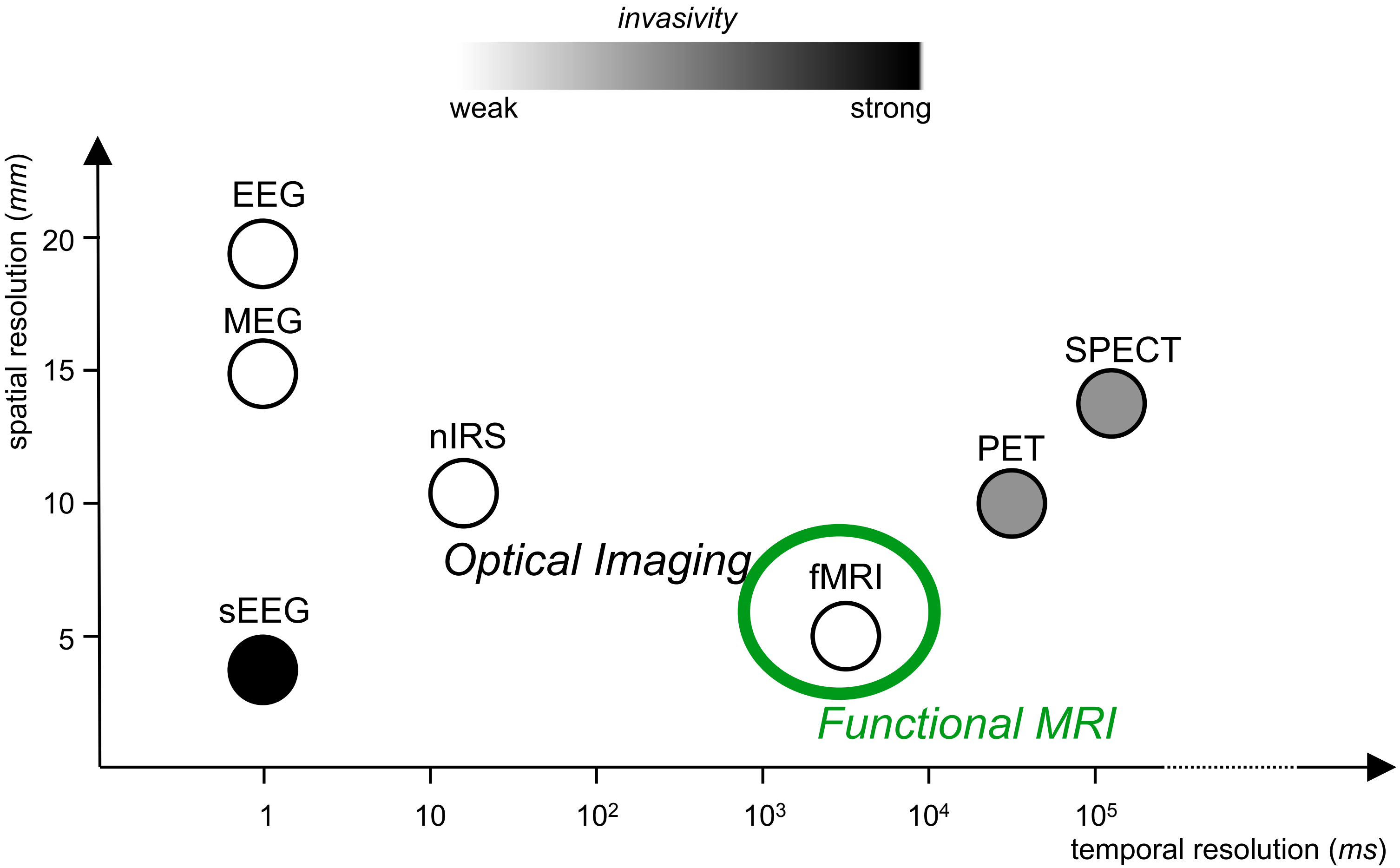


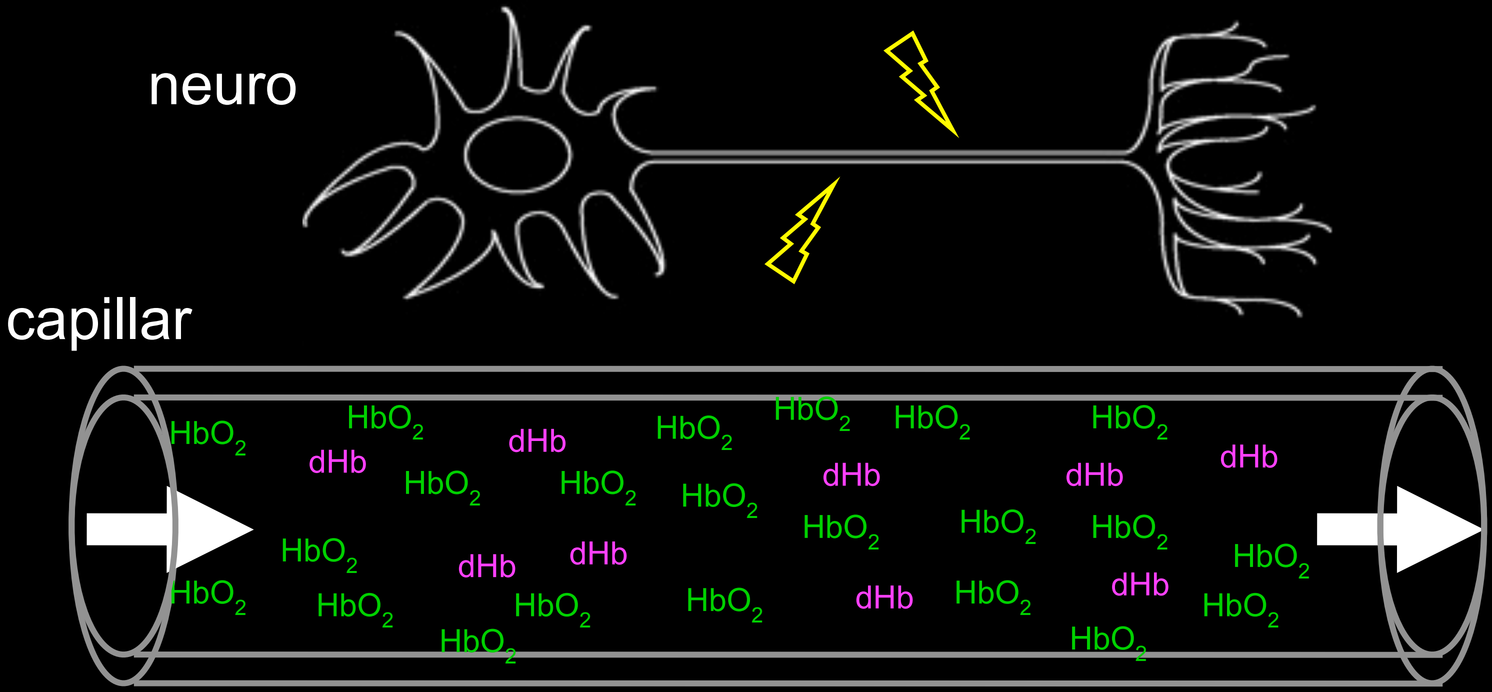
MR Angiography



fMRI

Functional neuroimaging modalities





↑ O_2 metabolism

↑ blood flow

↑ blood volume

↓ [dHb]

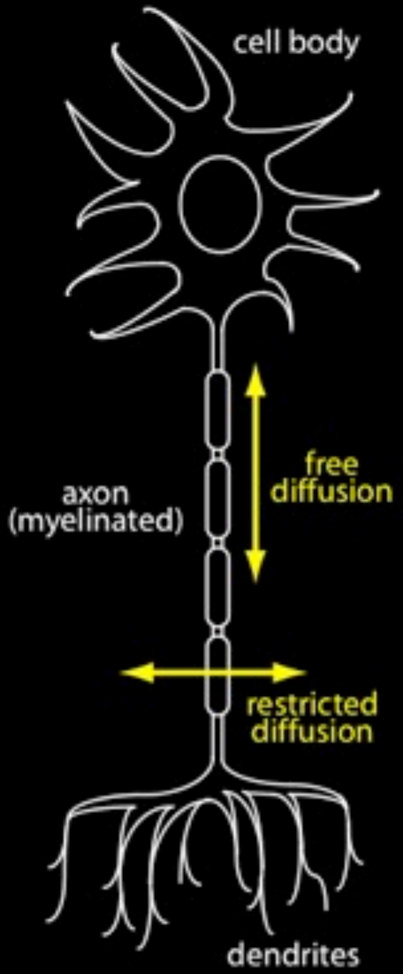
dHb = deoxyhemoglobin

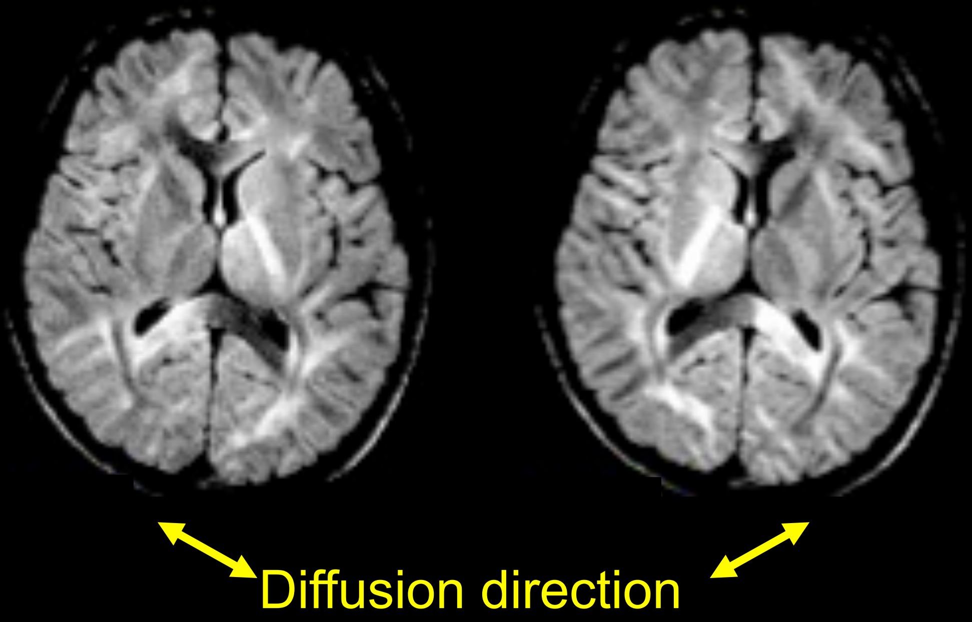
paramagnetic

HbO_2 = oxyhemoglobin

diamagnetic

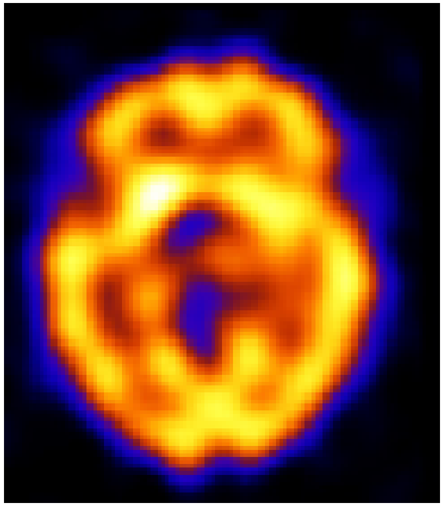
Diffusion MRI



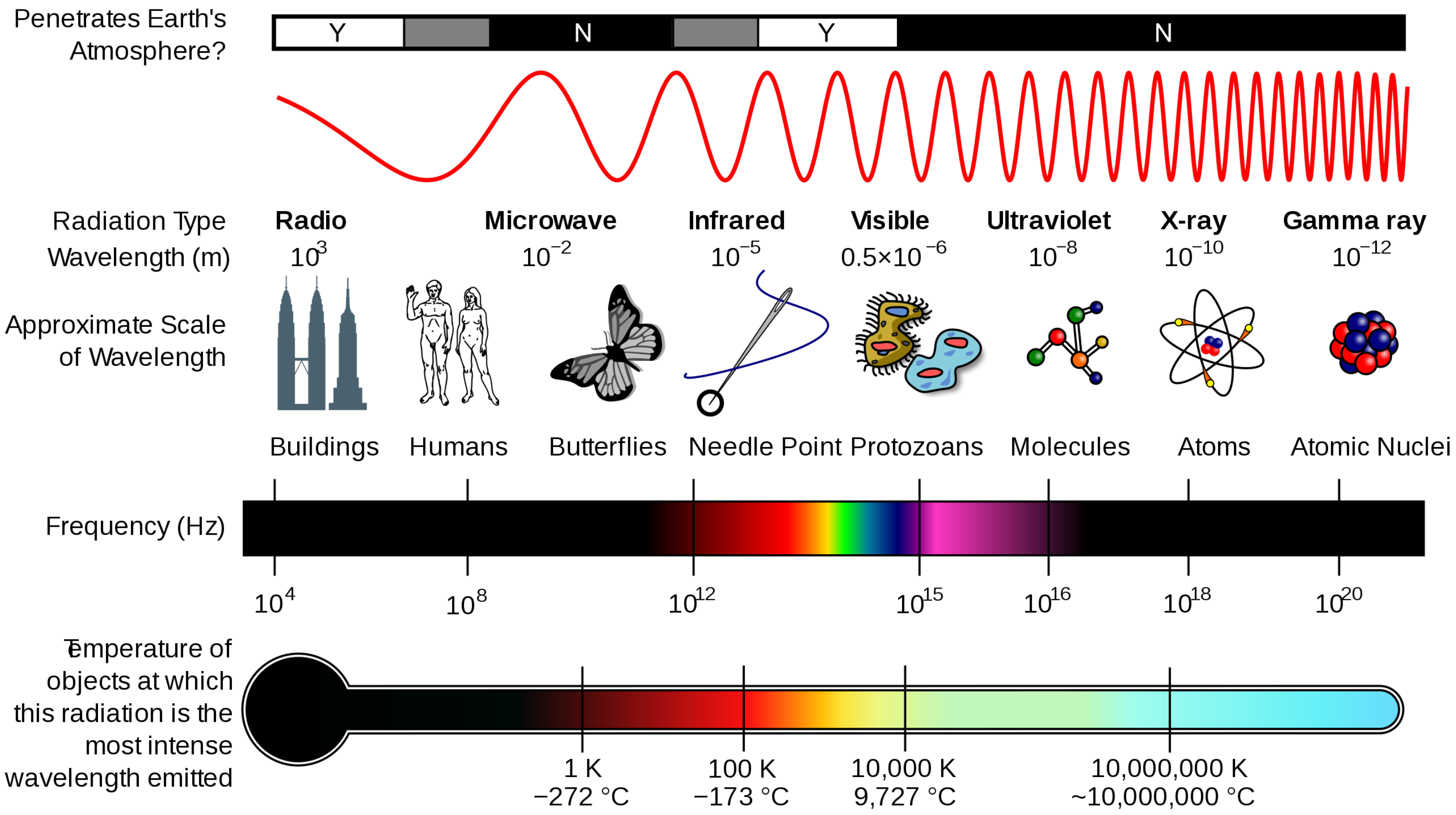


- Water diffusion restricted along white matter
- Sensitize signal to diffusion in different directions
- Measure along all directions, infer tracts

Nuclear Imaging (SPECT, TEP)



Electromagnetic spectrum

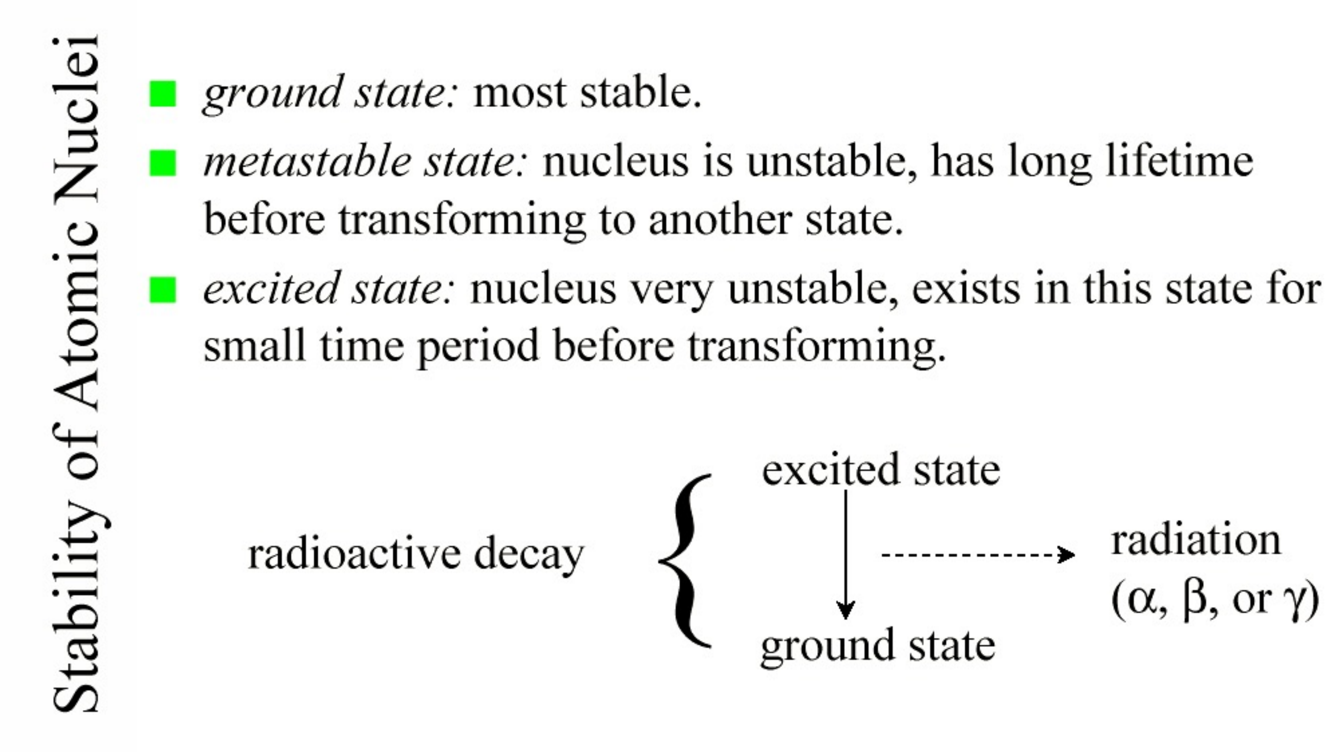


Source: Wikipedia

Nuclear Imaging

Physics Principle

Nuclear imaging is the use of radioactive materials for imaging structures and function inside the body.



Stability of Atomic Nuclei

- *ground state:* most stable.
- *metastable state:* nucleus is unstable, has long lifetime before transforming to another state.
- *excited state:* nucleus very unstable, exists in this state for small time period before transforming.

radioactive decay

excited state

ground state

radiation (α, β, or γ)

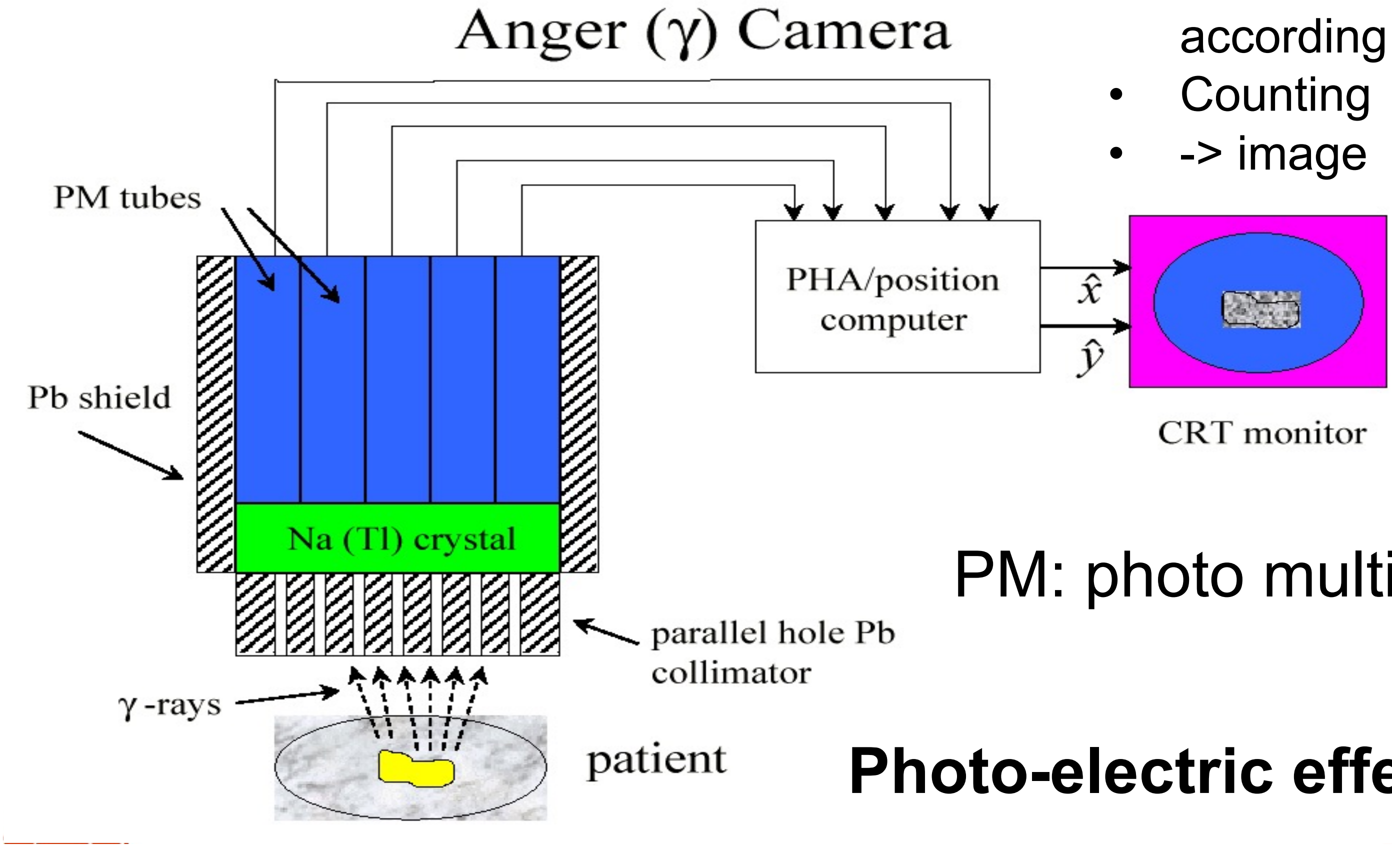
Nuclear Imaging

	Energy (in keV)	Half-life (in hours)
Technétium ^{99m}Tc	140	6
Iode ^{123}I	159	13
Thallium ^{201}Tl	75 et 135	73
Xénon ^{133}Xe	81	127
Indium ^{111}In	173 et 247	67

Nuclear Imaging

System Design

- Energy-based selection
- Localization according to PM
- Counting
- -> image



PM: photo multiplier

Photo-electric effect

\+ Compton (undesirable)

Nuclear Imaging

SPECT (single photon emission computerized tomography)

- Several projections
- Reconstruction (as for CT, see next lecture)
- Attenuation correction

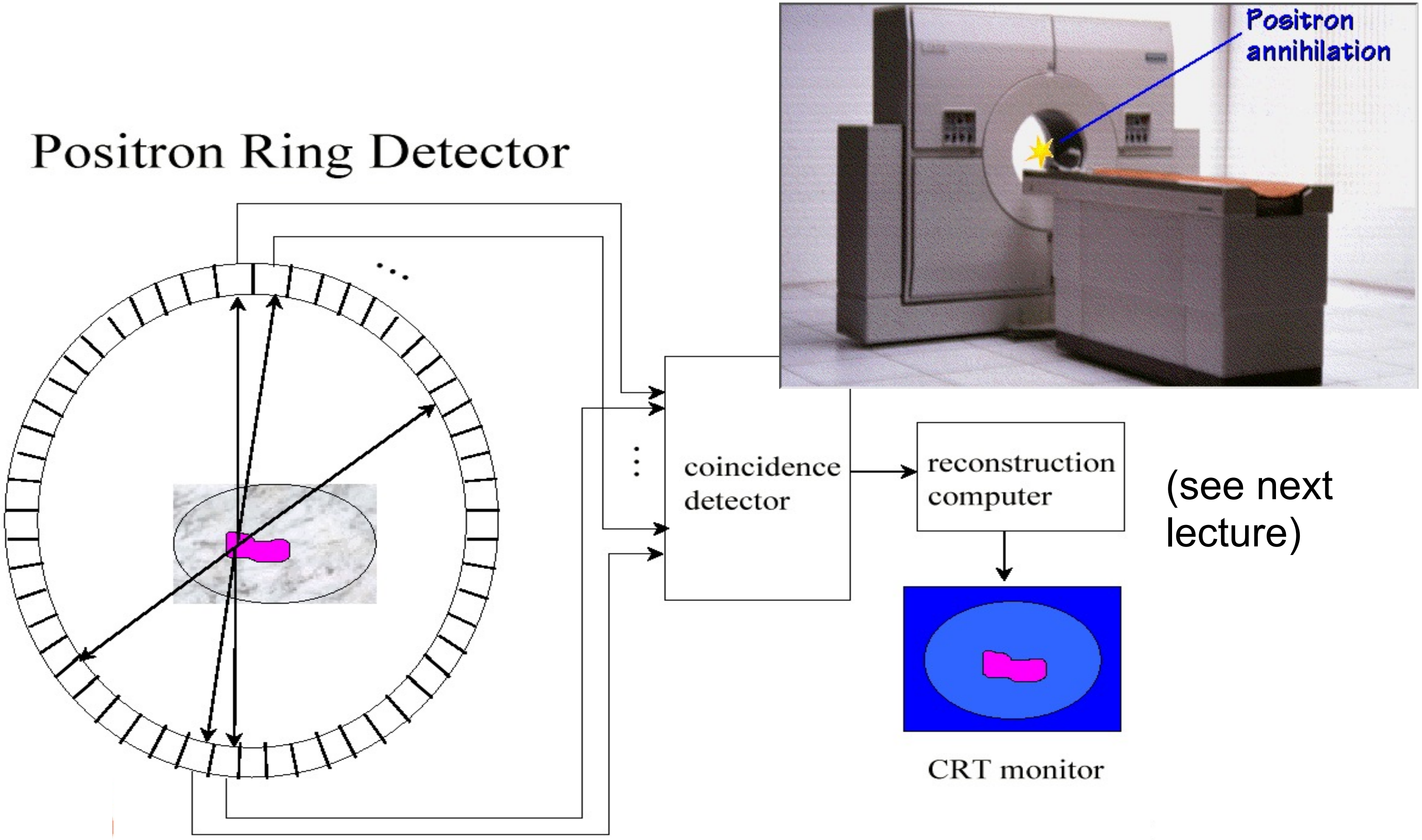
Nuclear Imaging

PET (positron emission tomography)

- In unstable nucleus, (more protons than neutrons) proton converts to neutron under emission of positron.
- Positron travels limited distance in tissue.
- Positron can combine with electron of nearby atom and emits two 511 keV X-ray photons (γ rays) that travel in opposite directions.

	^{15}O	^{13}N	^{11}C	^{18}F
Half-life (in min)	2	10	20	110

Nuclear Imaging



Positron Ring Detector

(see next lecture)

Nuclear Imaging

- **Advantages**
  - Functional imaging: metabolism, immunology, function, flux (not an anatomical imaging technique!).
- **Disadvantages**
  - Poor spatial resolution (a few mm).
  - High level of noise.
  - Expensive hardware.
  - Need of cyclotron.

Nuclear Imaging

Applications

- Heart
- Lungs
- Kidneys
- Bladder
- Gastro-intestinal Track
- Endocrine system (hormones)
- Immune system (white blood cells)
- Tumors (ex: FDG)

Nuclear Imaging

New developments

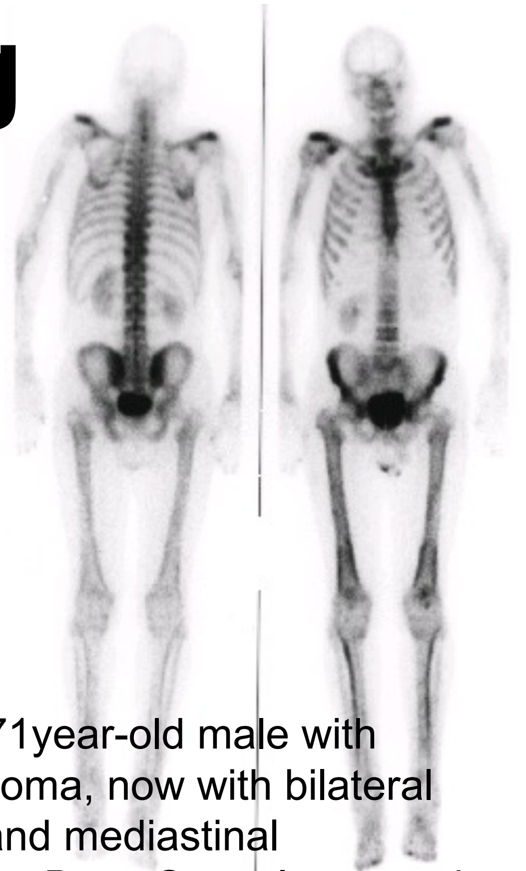
- Detection using semi-conductors
- Combined machines:
  - PET/CT
  - PET/MRI

Nuclear Imaging

Whole Body

Figure 1. Whole-body gallium-67 scan showing lymphoma in the chest, the spleen, the abdomen, and the groin. The chest and spleen sites were known before the scan. The abdominal and groin uptakes were detected only by the scan.

Source: http://www.nucmednet.com/galymph.htm



Clinical History: A 71year-old male with history of lung carcinoma, now with bilateral pulmonary nodules and mediastinal adenopathy.**Findings:** Bone Scan: Increased radiopharmaceutical uptake along cortical margins of the bilateral femurs and tibias. No evidence of bony metastases.

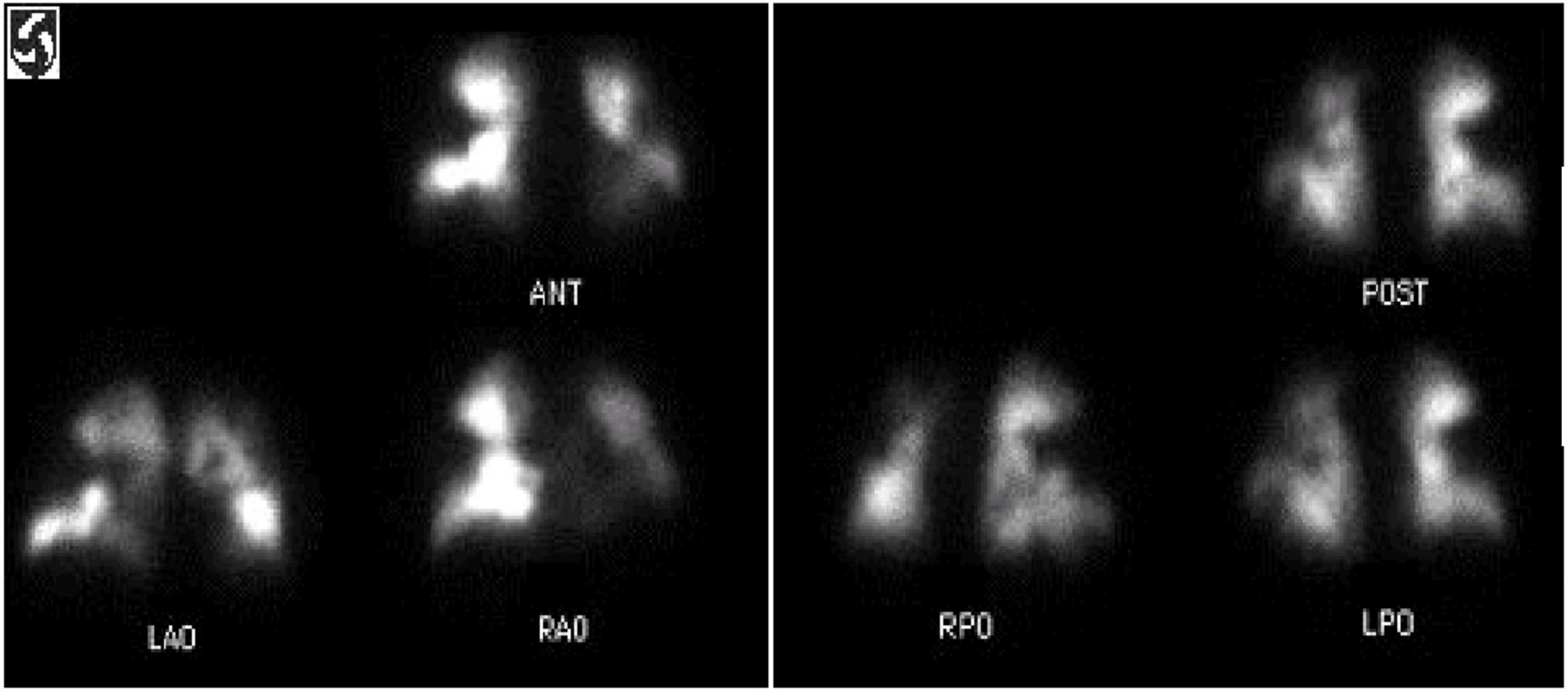
Diagnosis: Hypertrophic osteoarthropathy

http://www.uhrad.com/spectarc.htm

Nuclear Imaging

Example: Lung

SPECT scan for lung perfusion (pulmonary embolism)



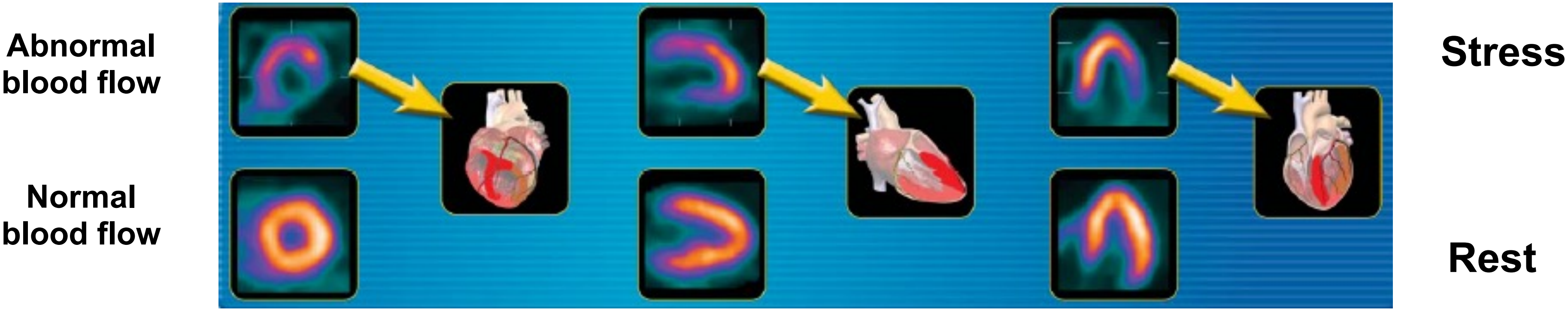
Source: Brigham & women's Hospital

Nuclear Imaging

Example: Heart

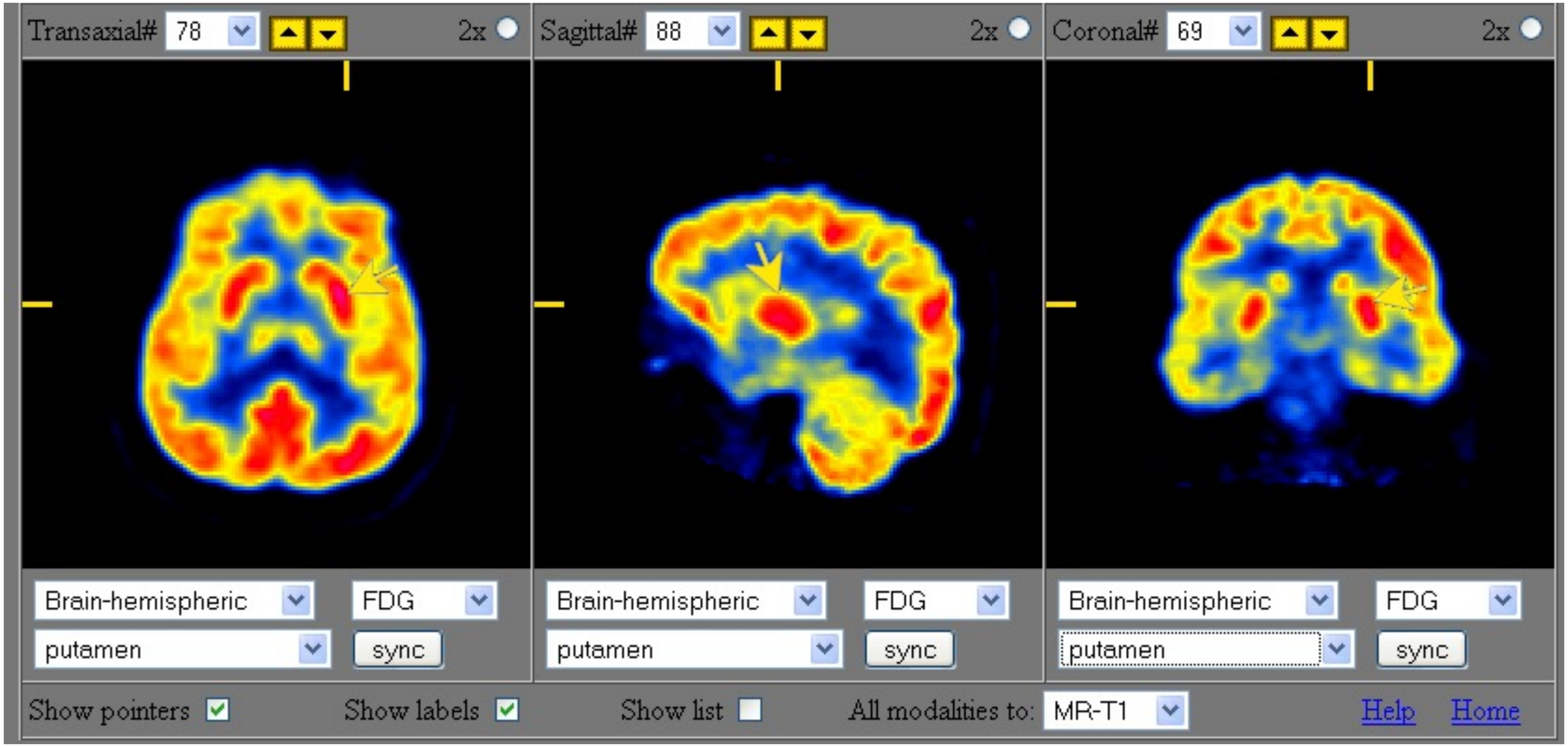
- Perfusion Imaging

Stress exams



Nuclear Imaging

Example: Brain



Transaxial# 78

Sagittal# 88

Coronal# 69

Brain-hemispheric FDG putamen

Brain-hemispheric FDG putamen

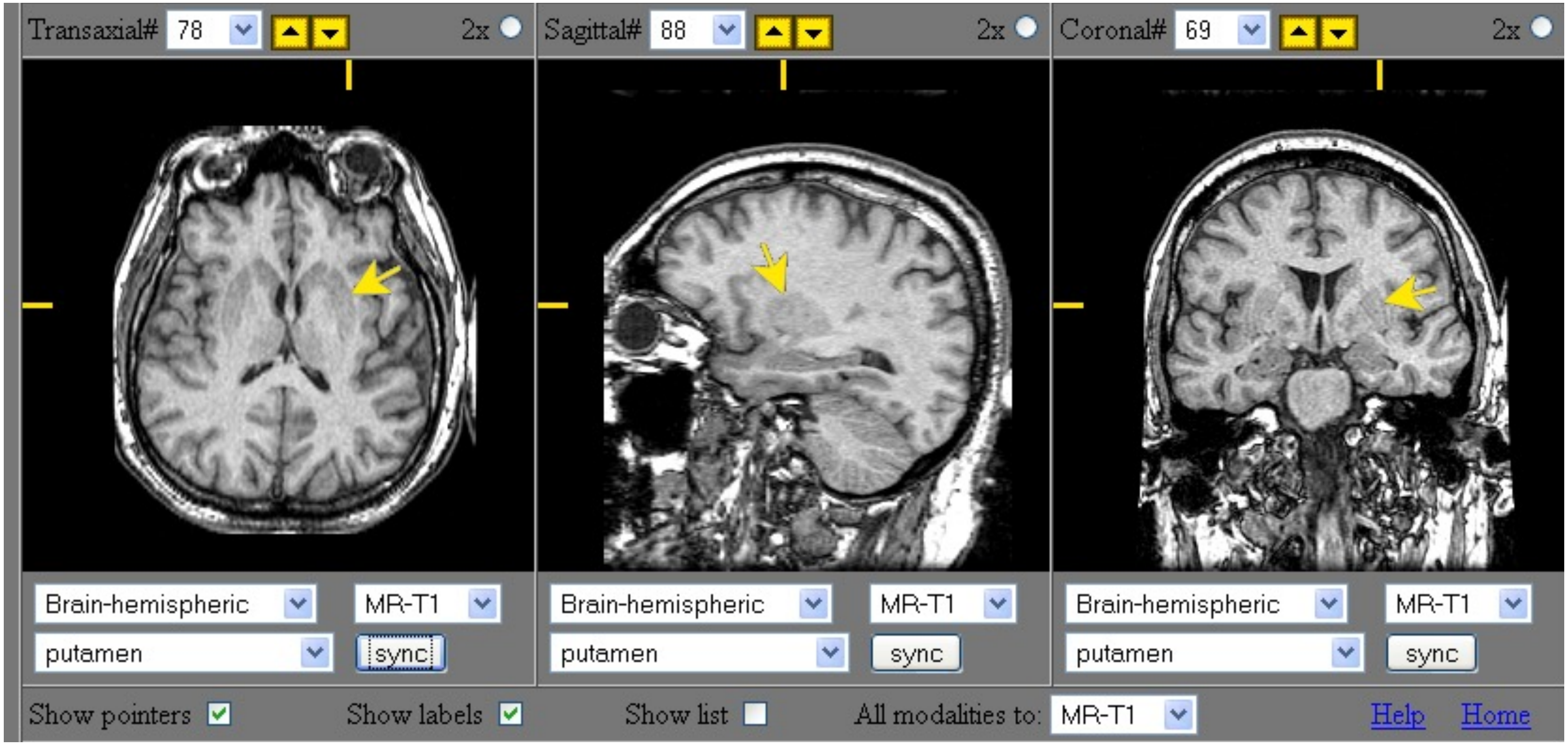
Brain-hemispheric FDG putamen

Show pointers ☑ Show labels ☑ Show list ☐ All modalities to: MR-T1

Source: www.med.harvard.edu/AANLIB

Nuclear Imaging

Example: Brain



Transaxial# 78

Sagittal# 88

Coronal# 69

Brain-hemispheric — MR-T1 — putamen

Brain-hemispheric — MR-T1 — putamen

Brain-hemispheric — MR-T1 — putamen

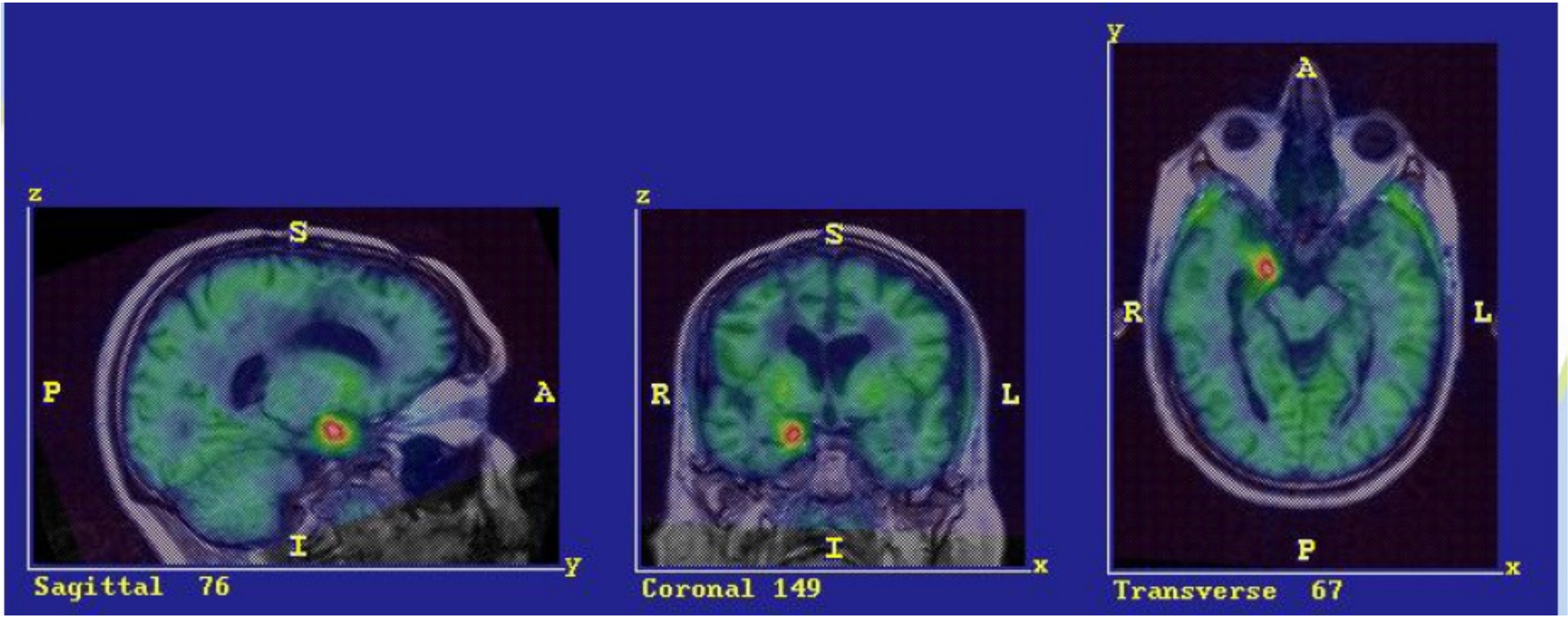
Show pointers ☑ Show labels ☑ Show list ☐ All modalities to: MR-T1

Source: www.med.harvard.edu/AANLIB

Nuclear Imaging

Example: Brain

PET with FDG tracer for diagnosis of brain tumor

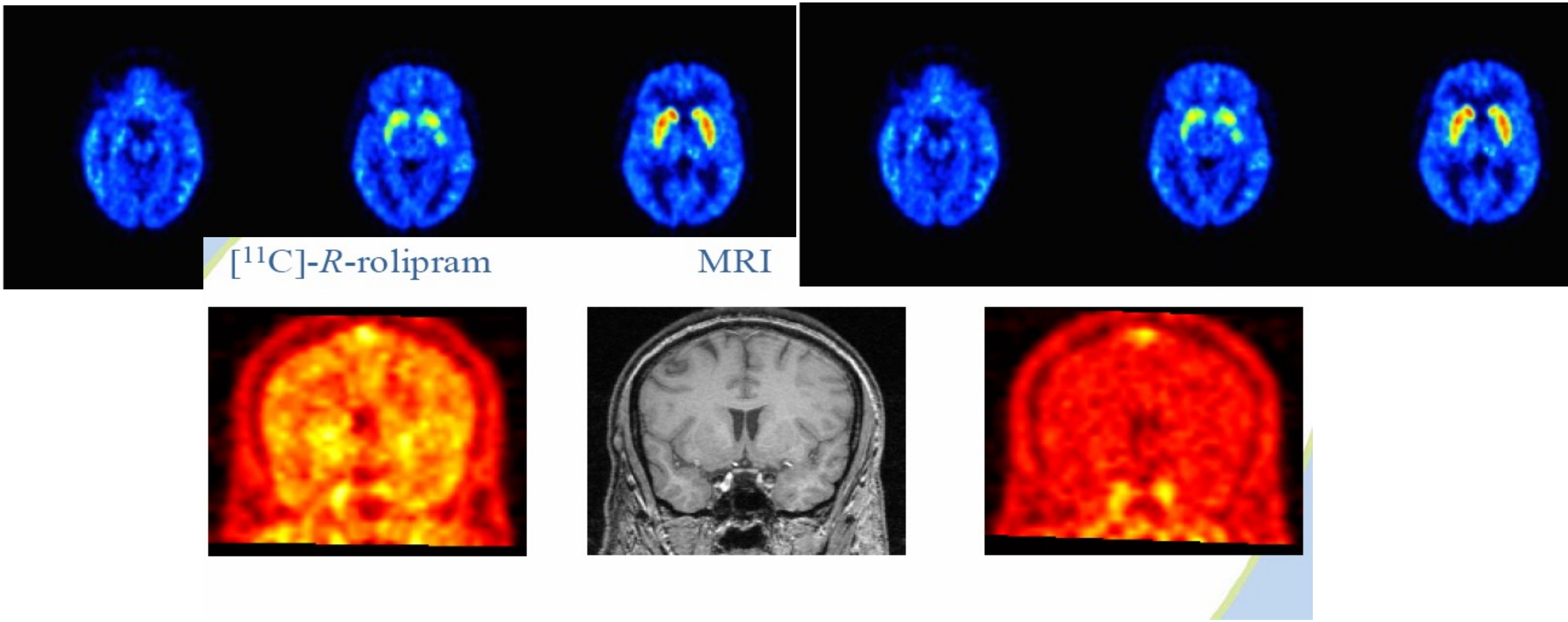


Source: V. Cunningham, GlaxoSmithKline.

Nuclear Imaging

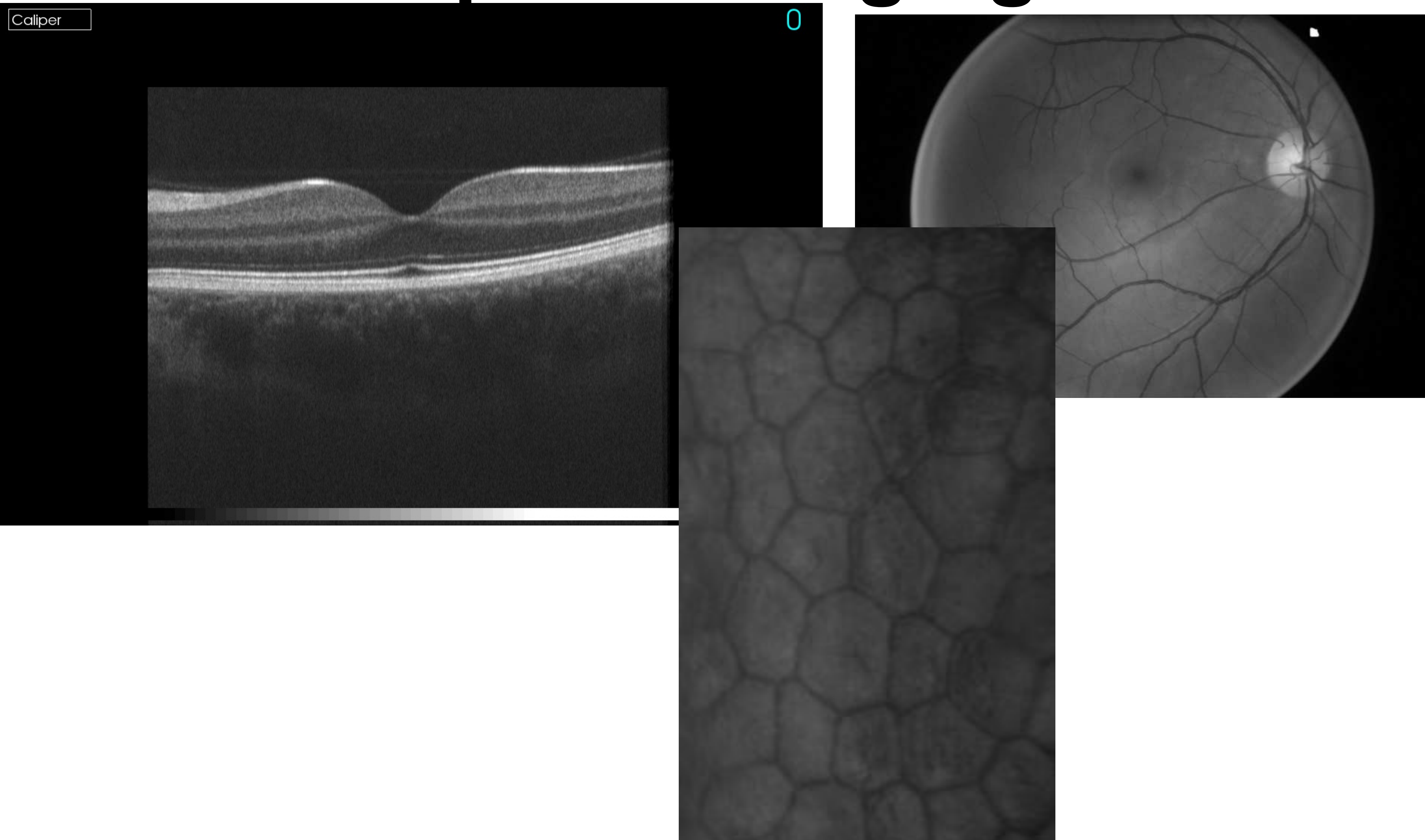
Example: Brain

PET for in-vivo testing of new drugs



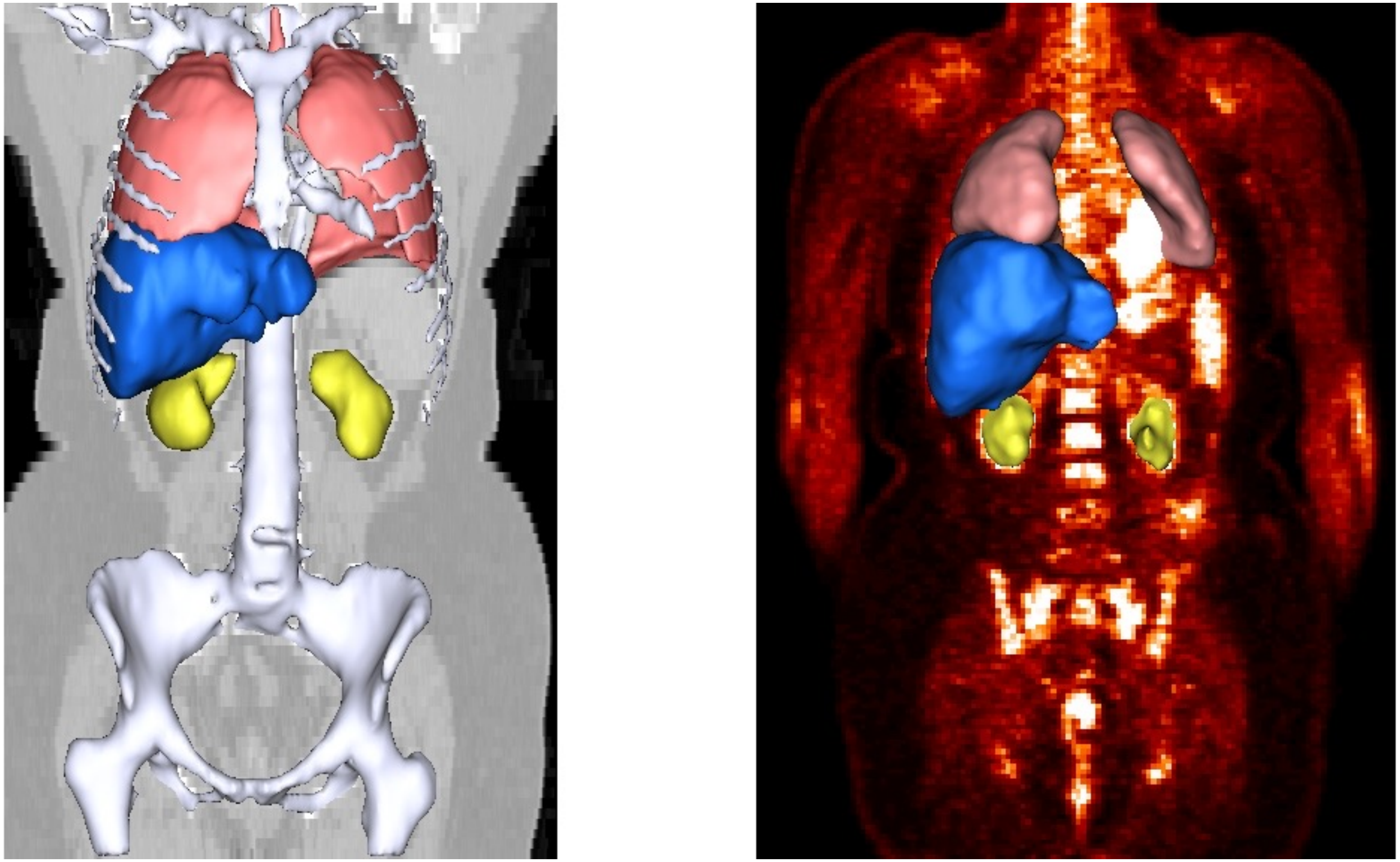
Source: V. Cunningham, GlaxoSmithKline.

Optical imaging

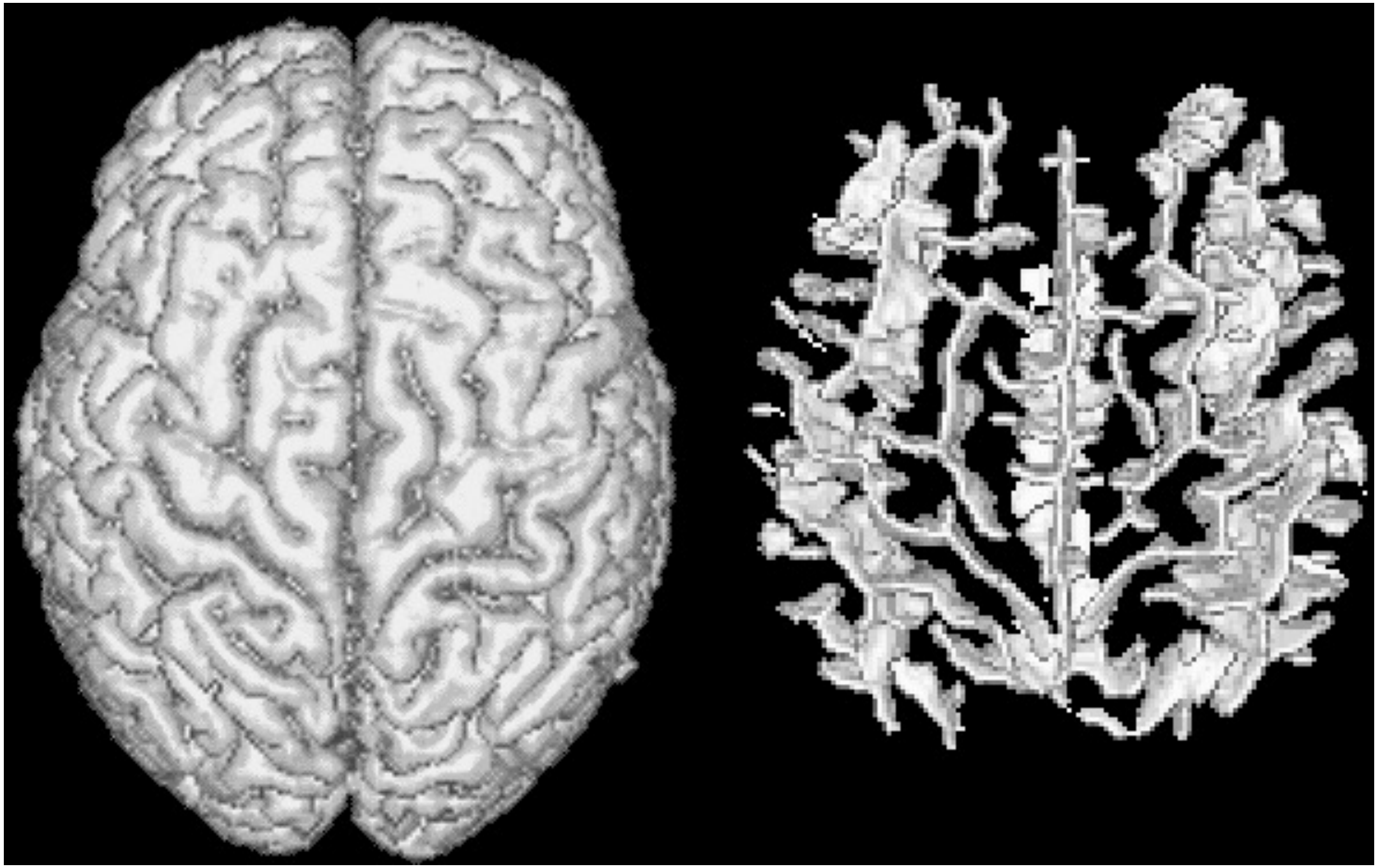


Research in Medical Imaging: a few examples

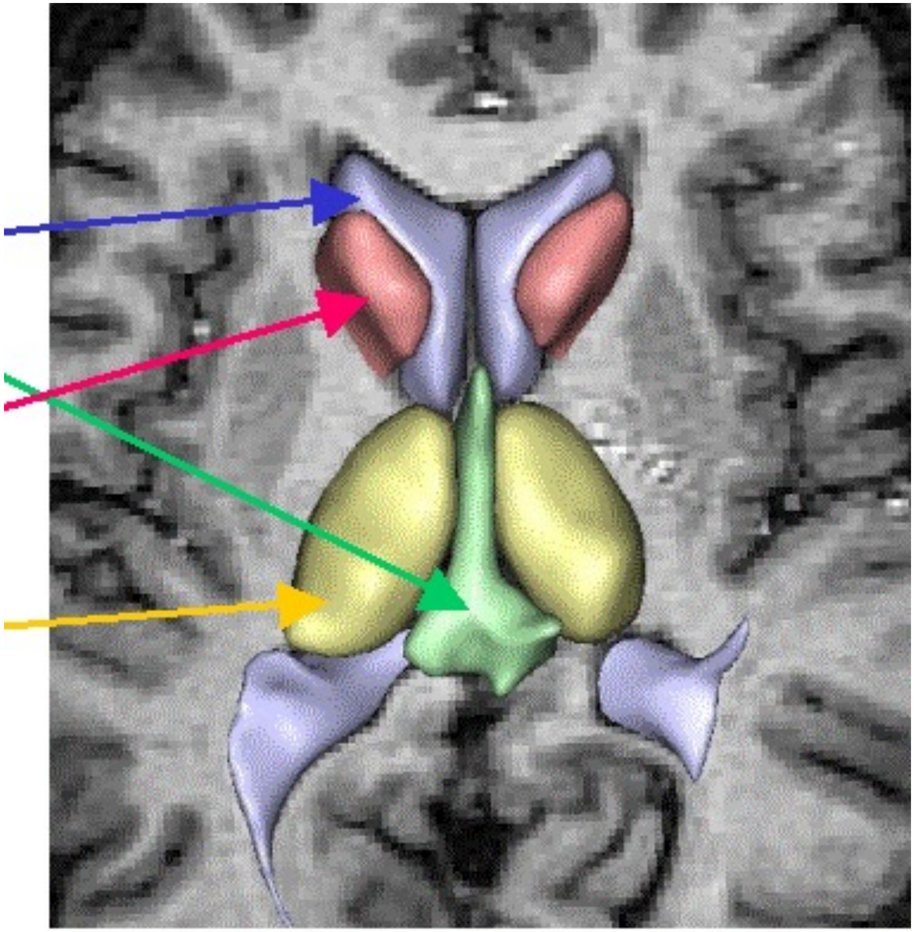
Registration of MRI and PET abdomen images



Segmentation of cortical brain structures



Segmentation of sub-cortical structures



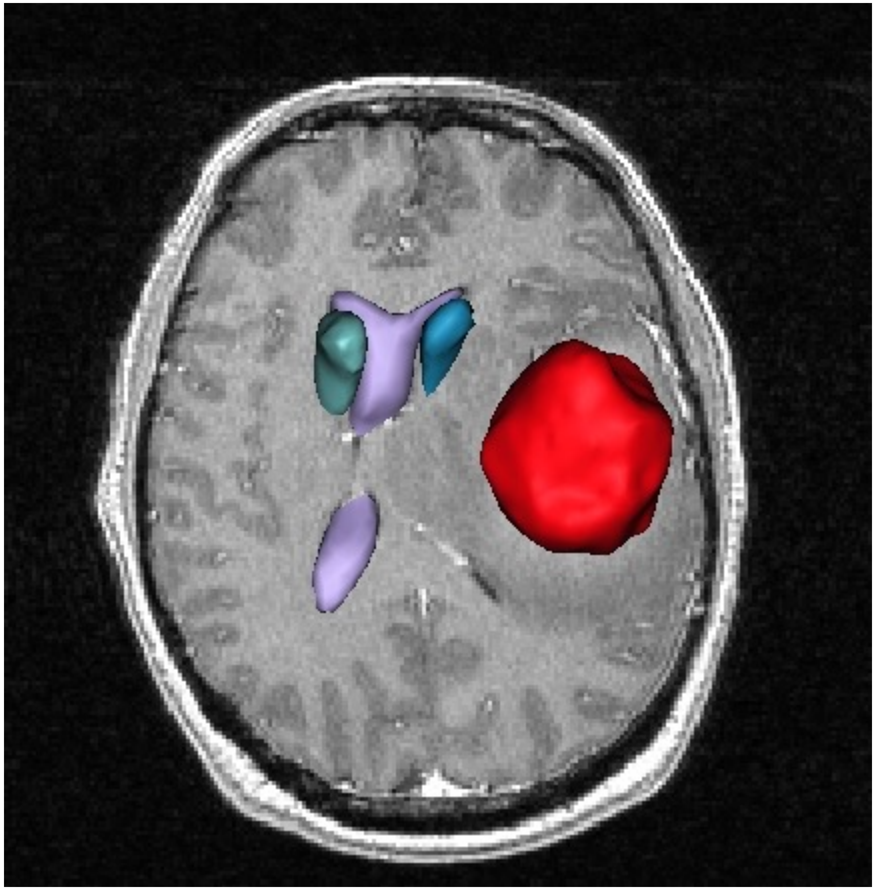
Lateral ventricles

Third ventricle

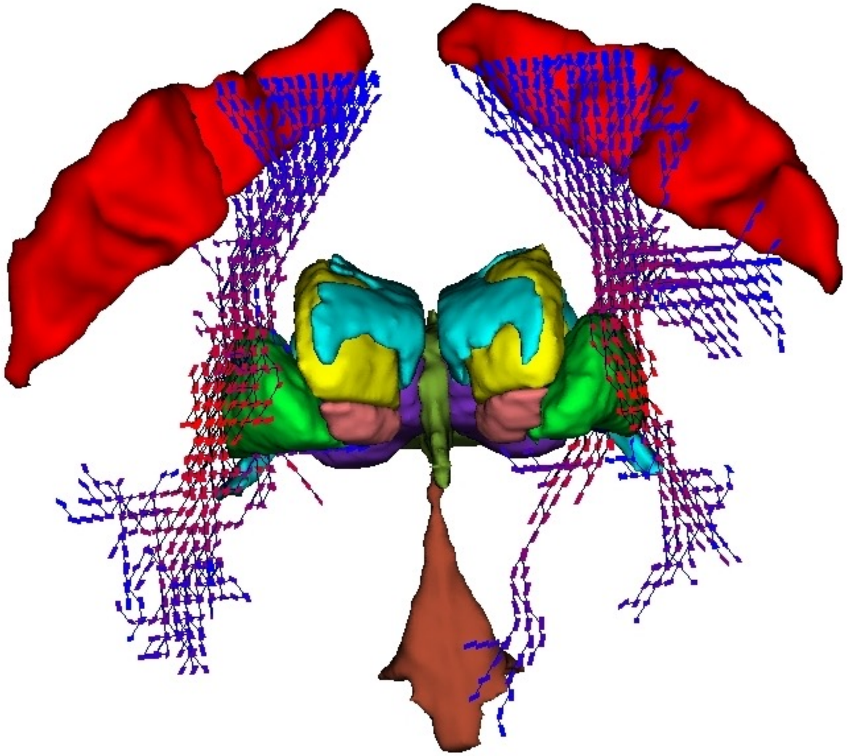
Caudate nucleus

Thalamus

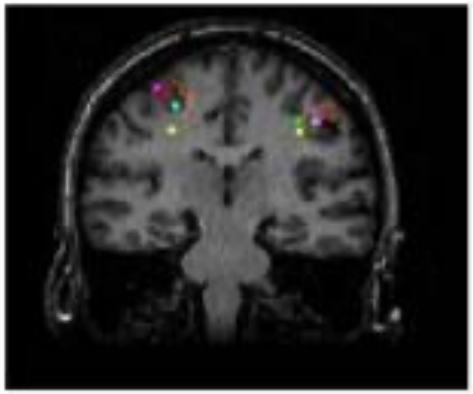
Segmentation of sub-cortical structures and tumors



Diffusion Tensor MRI for Brain White Matter Fibers

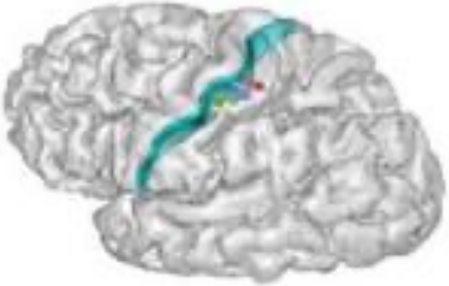


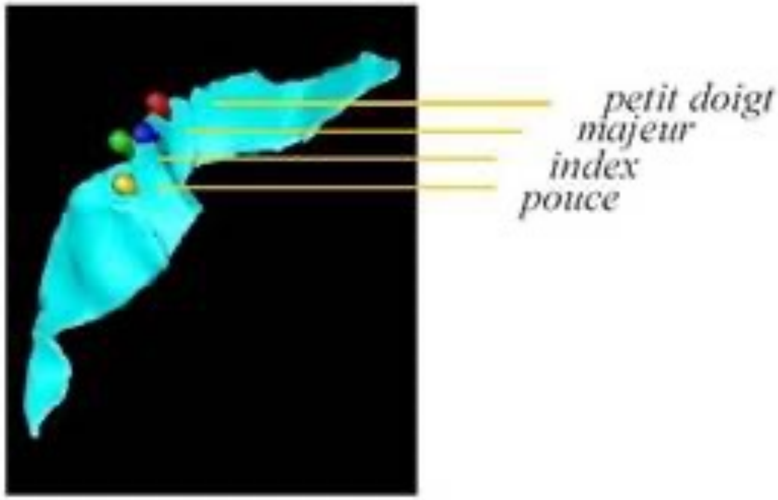
Functional Brain MRI



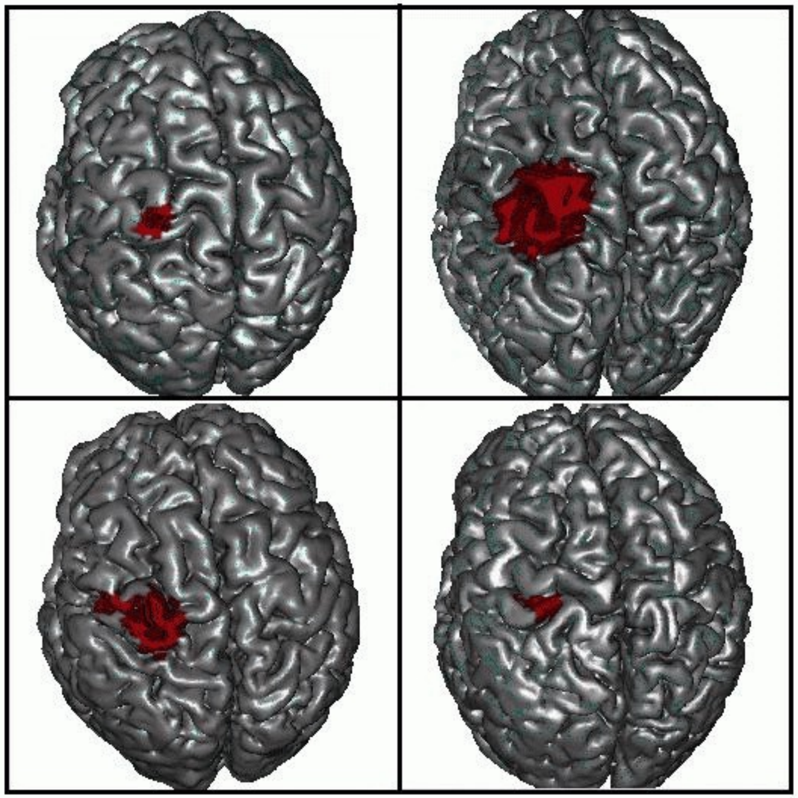
Distance entre doigt ~ 0.9 cm
Distance I - V ~ 1.5 cm

Motor control of fingers



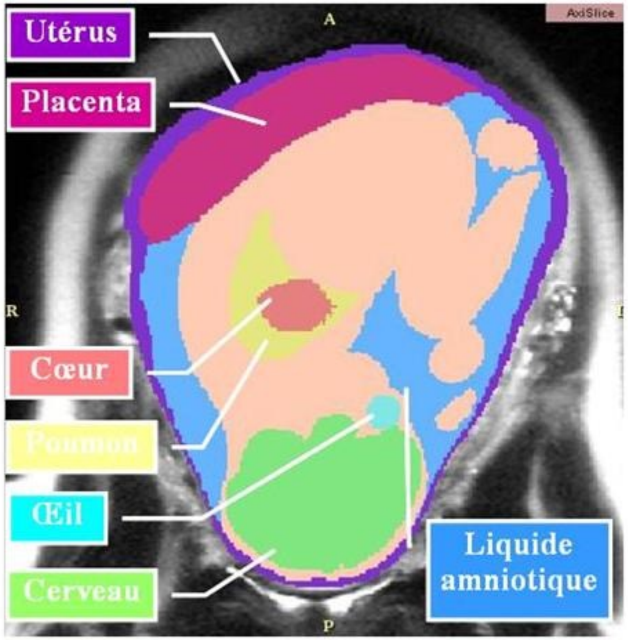


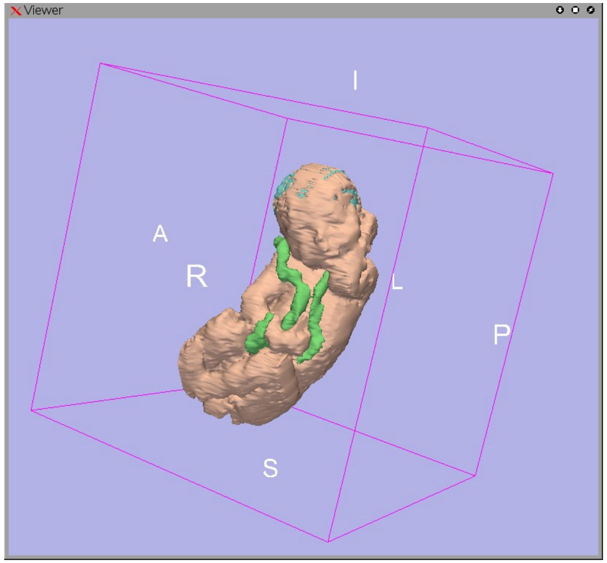
Functional MRI



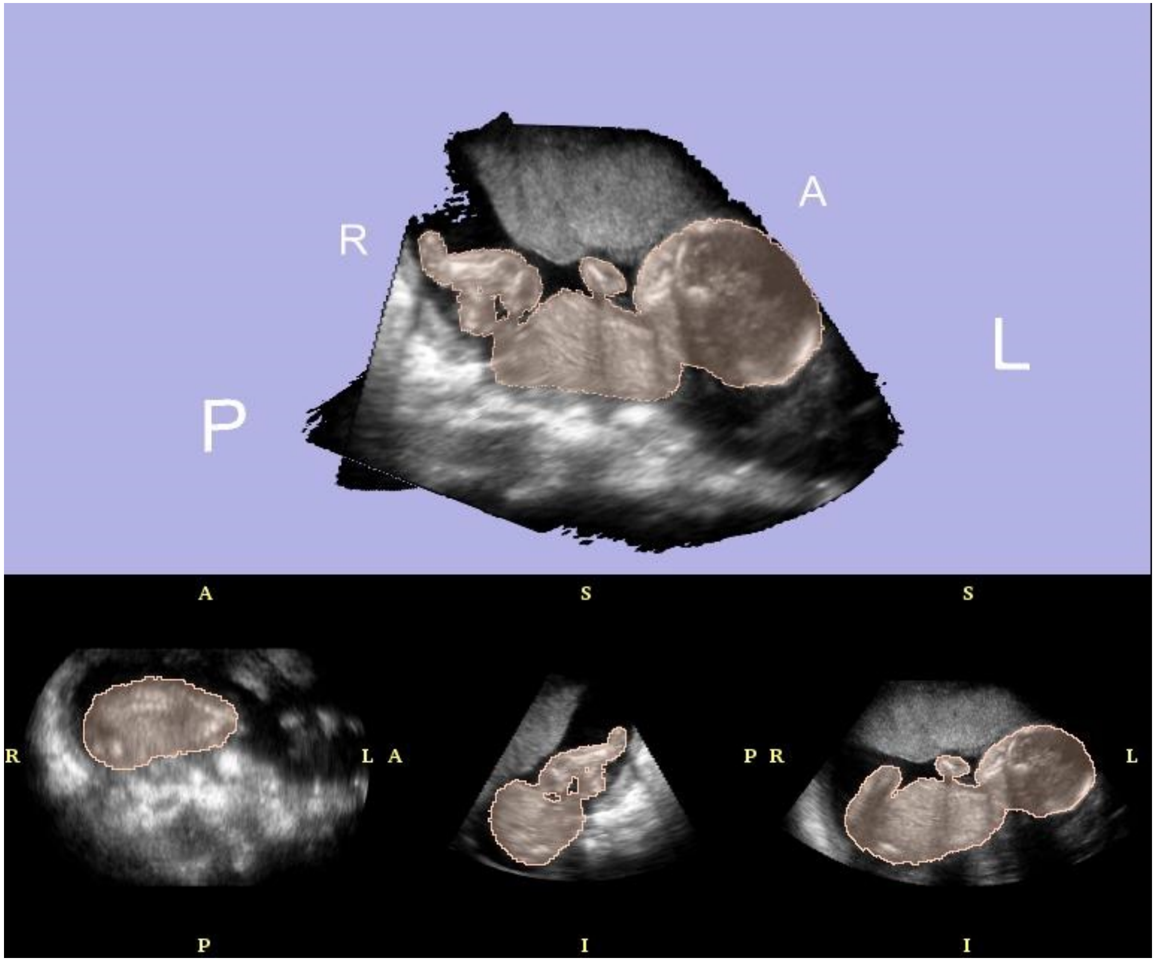
Motor control of right hand

Fetal Imaging



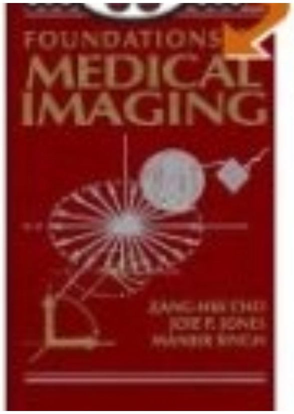


Fetal Imaging



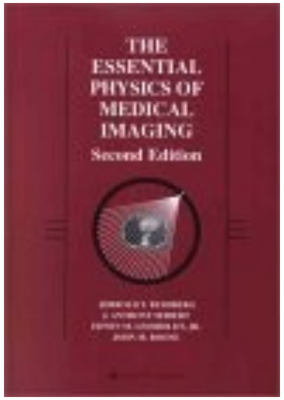
Books

- **Foundation of Medical Imaging**, Z.H. Cho, J.P. Jones, M. Singh, John Wiley &Sons, Inc., New York 1993, ISBN 0-471-54573-2.



- **Principles of Medical Imaging**, K.K. Shung, M.B. Smith, B. Tsui, Academic Press, San Diego 1992, ISBN 0-12-640970-6.

- **The Essential Physics of Medical Imaging (2nd Edition)** ,Jerrold T. Bushberg, J. Anthony Seibert, Edwin M. Leidholdt Jr., John M. Boone, Lippincott Williams & Wilkins; 2nd edition, ISBN 0683301187.



- **Image Reconstruction in Radiology**, J.A. Parker, CRS Press, Boca Raton, FL 1990, ISBN 0-8493-0150-5/90.

- **Principles of Magnetic Resonance Imaging,** Zhi-Pei Liang, P.C. Lauterbur IEEE Press, New York, NY 2000, ISBN 0-7803-4723-4.