

MEDICAL IMAGING METHODS

Image processing, X-ray, CAT scanning

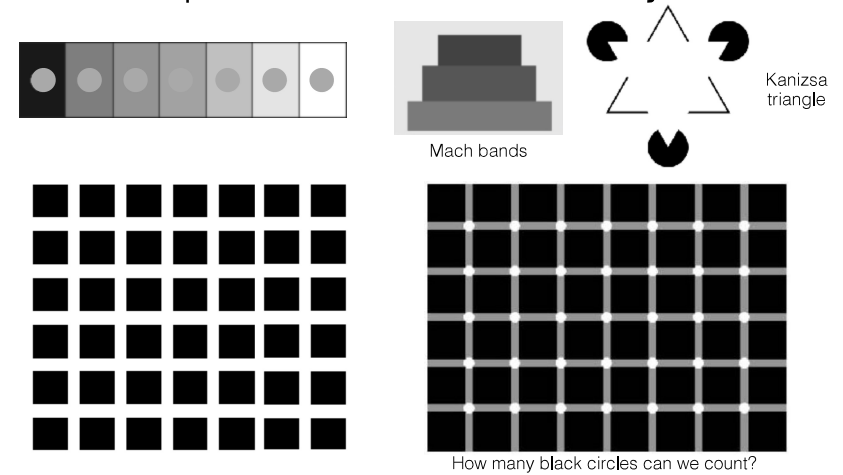
Miklós Kellermayer

I. The digital image

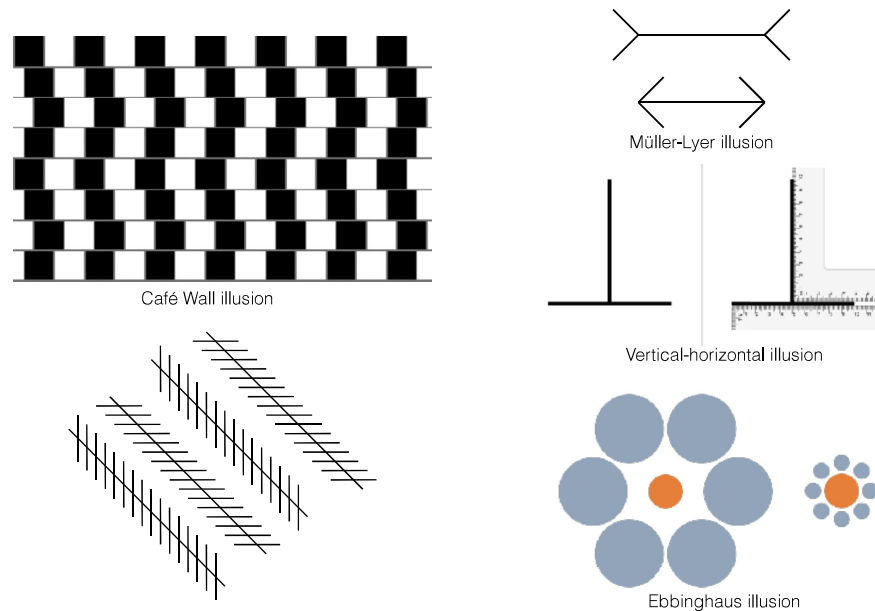
Seeing is believing!?

Vision is not only the detection of image information, but complex processing occurs as well

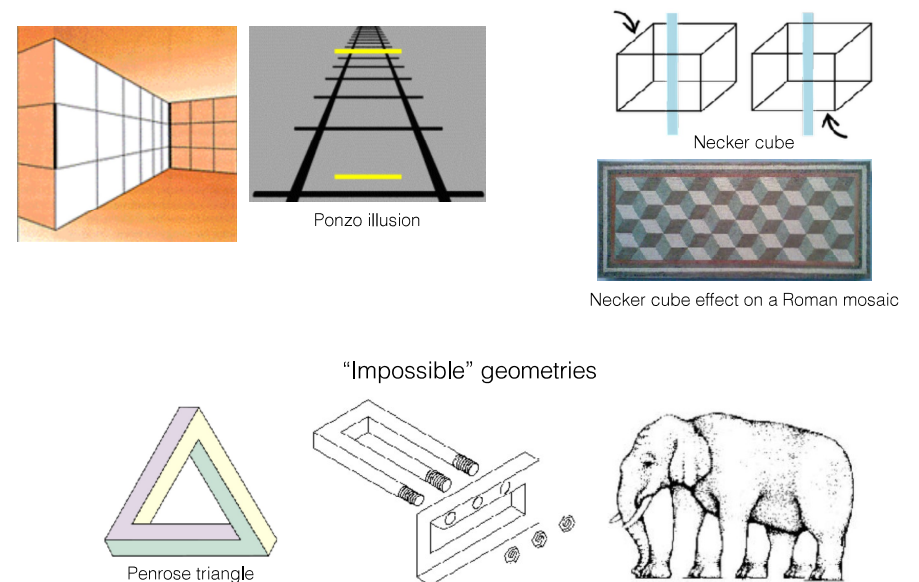
Optical illusions - intensity



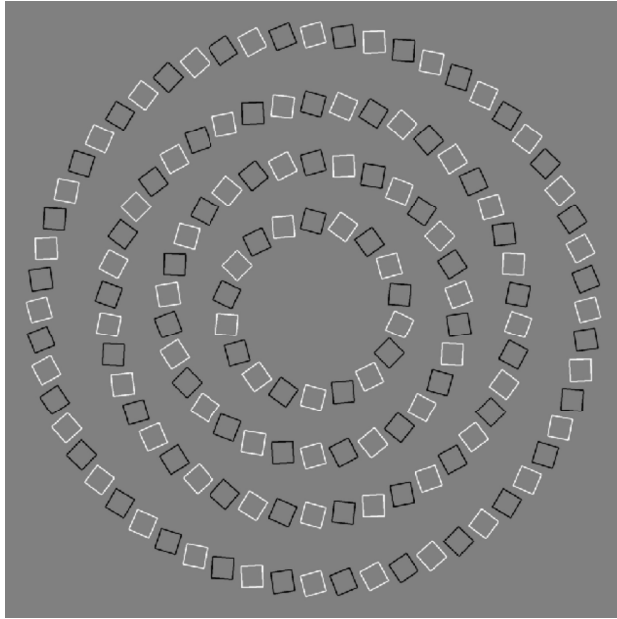
Optical illusions – direction, size



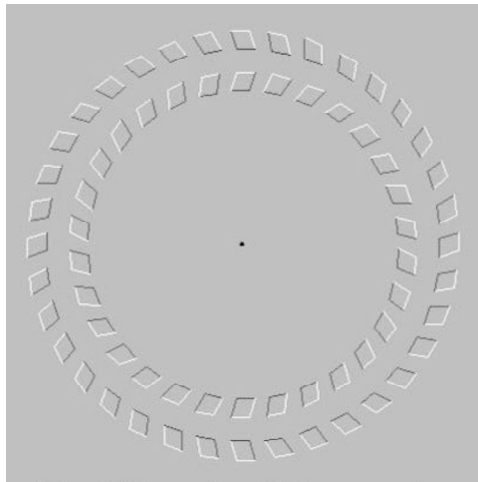
Optical illusions – space



Optical illusions – geometry



Optical illusions – motion

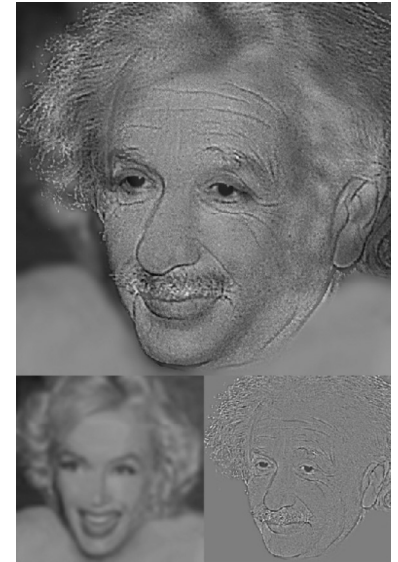
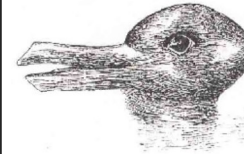


Optical illusions – shape

Reversible shapes, complementary shapes



Rubin vase illusion



"Gestalt"

Contour

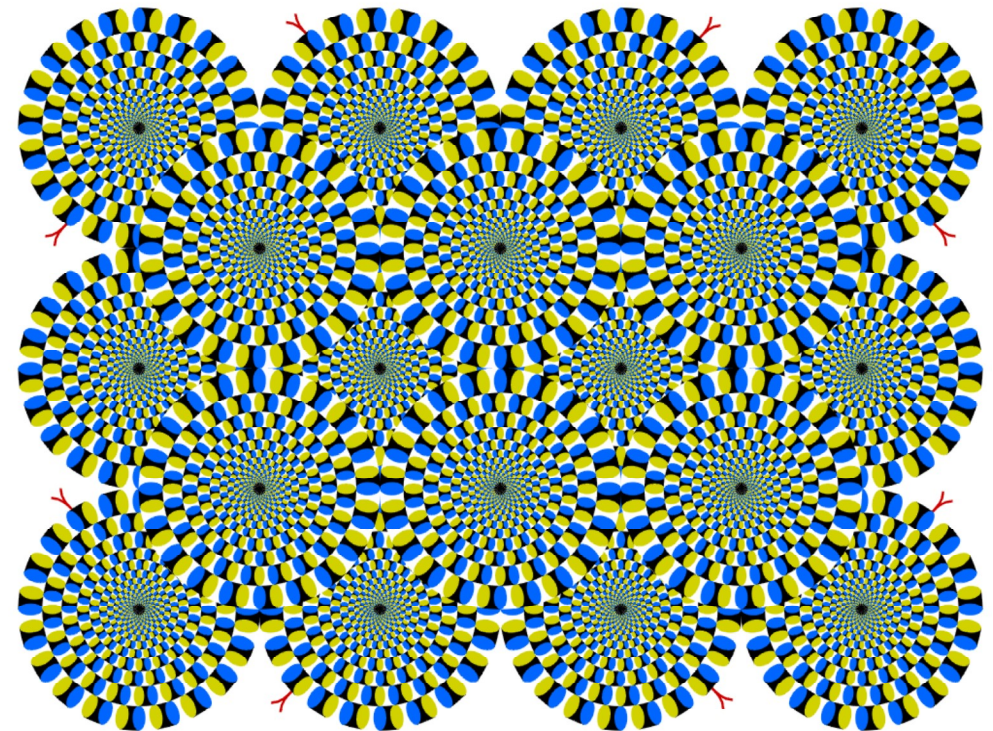
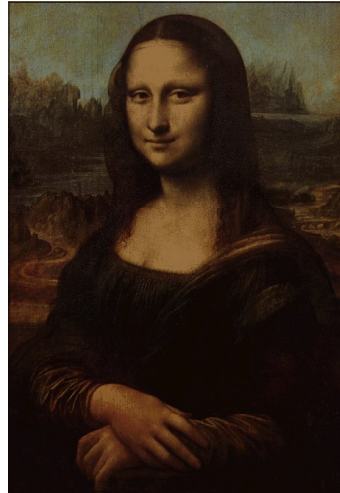
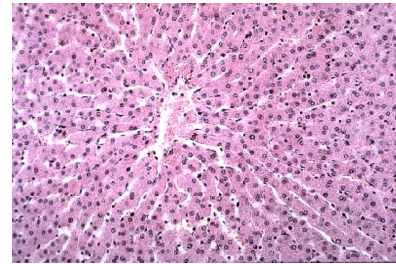


Image: what is the information carried?
Is it visible ... or not?

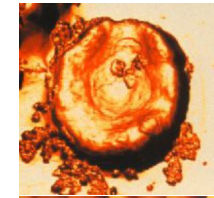


Method-dependent images

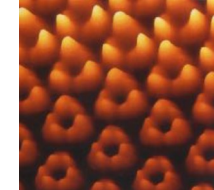
HE-stained section: hepatic lobule



Atomic force microscopic images



Red blood cell

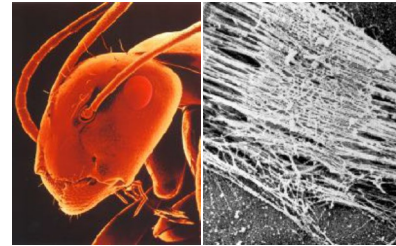


Bacteriorhodopsin

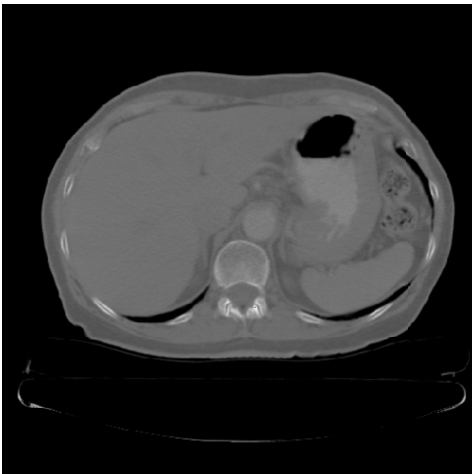


DNA-protein complex

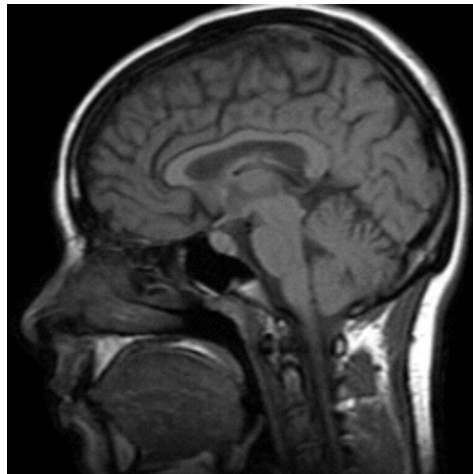
Scanning electron microscopic images



Method-dependent images



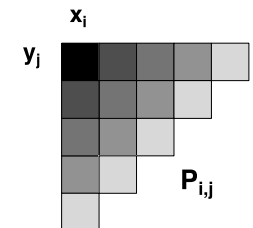
CT



MRI

The digital image

Digital image: information displayed at different discrete spatial points in the form of color. 2 or 3 dimensional array or matrix of picture elements.

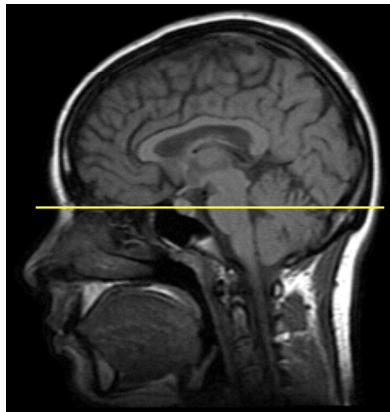


Characteristics of the digital image:

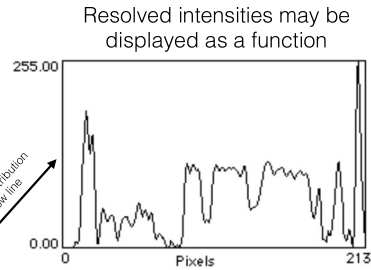
1. *Picture element: pixel (pix=picture; element)*
2. *Information associated with the pixel:*
 - a. XY location: coordinates related to spatial resolution
 - b. Color depth: intensities related to color (or grayscale) resolution
3. *Spatial resolution:*
Number of resolved pixels in the X and Y directions.
4. *Grayscale/color depth:*
Number of resolved colors/grayscale intensities (bit)
(BUT: color is not necessarily real; e.g. AFM, CT, MRI)

Color histogram

(intensity histogram, density histogram, "grayscale" histogram)



intensity (density) distribution
along the yellow line



Histogram: relative frequency of colors or grayscale intensities in the image

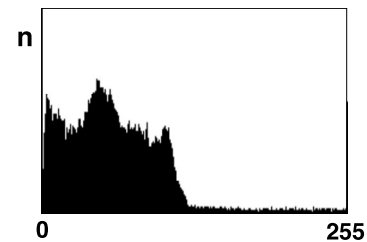
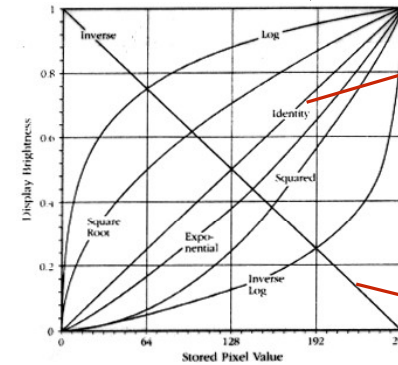


Image enhancement techniques: Contrast manipulation

Contrast transfer function:
assigns color to pixel densities (expressed in numerical values)



Negative image

Image enhancement techniques: Convolution

Special transformation between two functions (the image and the kernel; "kernel operations")

„smoothing“ kernel

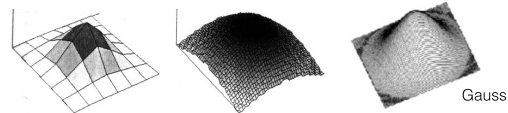
1	1	1
1	1	1
1	1	1

$$P_{x,y}^* = \frac{\sum_{i,j=-m}^{+m} W_{i,j} \cdot P_{x+i,y+j}}{\sum_{i,j=-m}^{+m} W_{i,j}}$$

„smoothing“ convolution

P=original pixel intensity
x,y=coordinates of the pixel on which operation is being executed
P*=modified pixel intensity
±m=size of kernel (distance from x,y coordinate)
W=weight of kernel at a given i,j coordinate
i,j=coordinates within kernel (integers between -m and +m)

Various kernel shapes (shape depends on the numerical content of the matrix):



Original image

Sharpening

Gauss (smoothing)

Edge detection

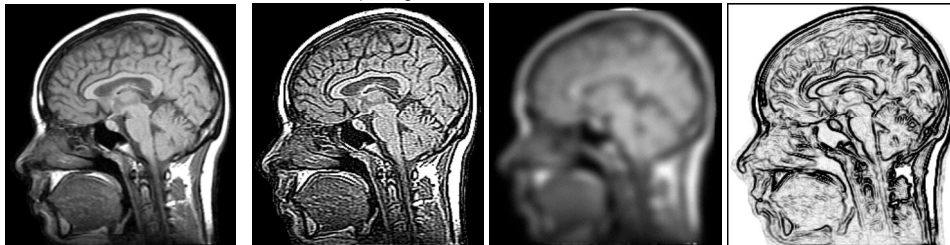
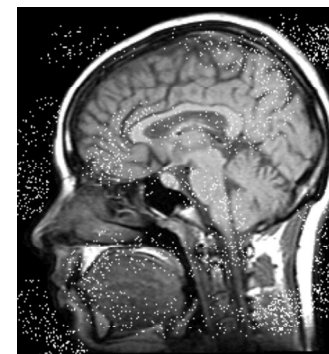


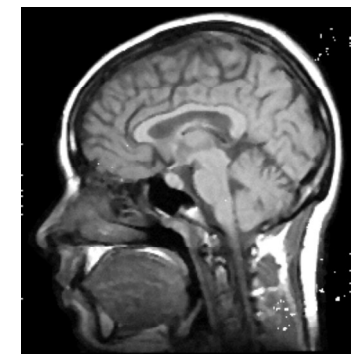
Image enhancement techniques: Rank operations

Principle: the pixel is exchanged for another from its ranked neighborhood (e.g., min, max, median)

Noise removal using median filtering:

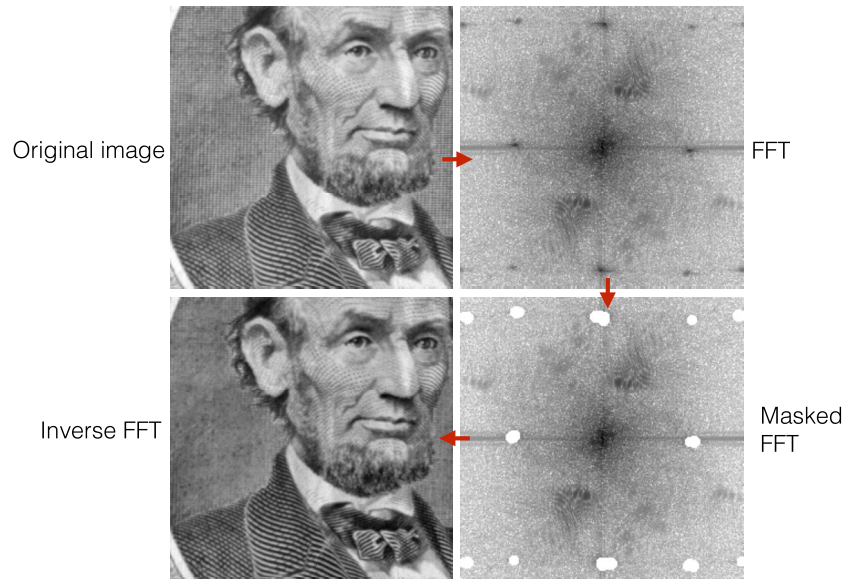


3x3 median filter



Fourier transformation

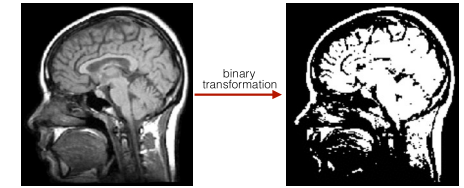
Fourier principle: any function may be generated as the sum of a sine function and its harmonics.
Fourier transform -> spectral density: displays the contribution of a given frequency.



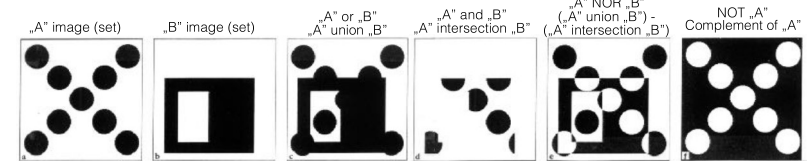
Binary image processing

1. Thresholding, segmentation

Principle: The image is partitioned according to certain parameters.
Implementation:
1. Select a certain grayscale range of the image
2. The selected pixels form the "foreground"
3. The rest of the pixels form the "background"



2. Boolean operation (set theory)



3. Erosion, dilatation, opening, closing

Moving pixels from the foreground to the background and vice versa



3D image processing

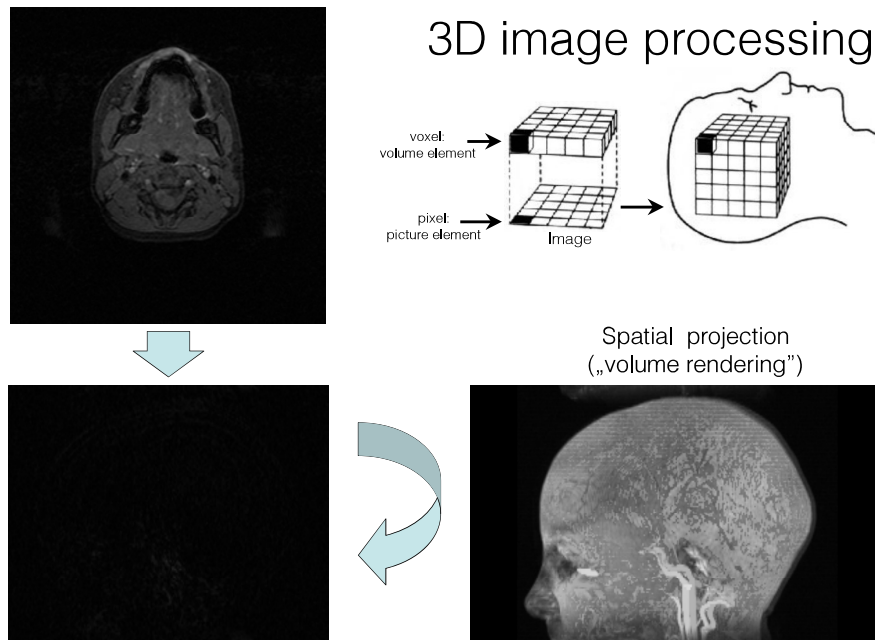
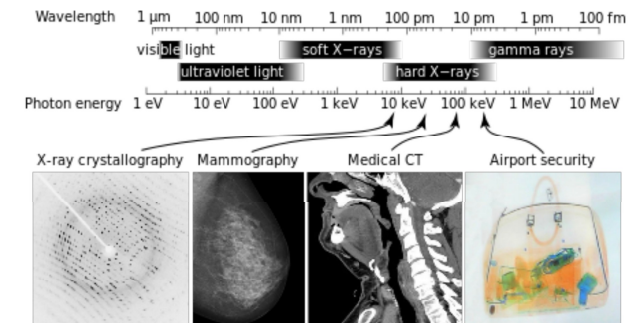


Image format of medical diagnostics: DICOM (Digital Imaging and Communications in Medicine)

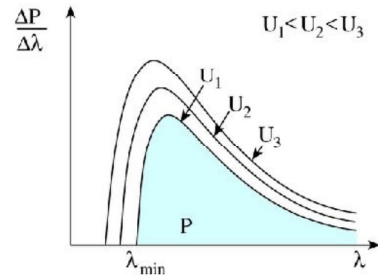
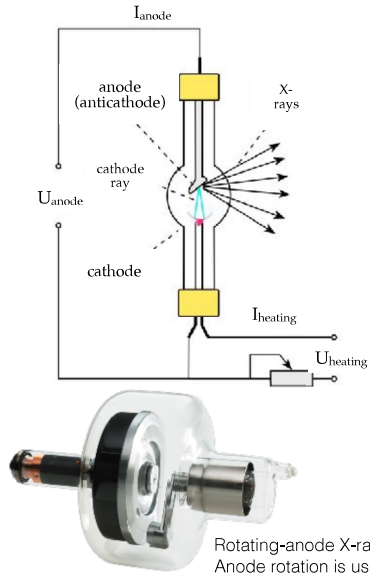
II. X-ray imaging

X-rays are electromagnetic waves



Wavelength 10 - 0.01 nm, **Frequency** 30x10¹⁵ - 30x10¹⁸ Hz, **Energy** 120 eV - 120 keV, (petahertz - exahertz)

Generation of X-ray



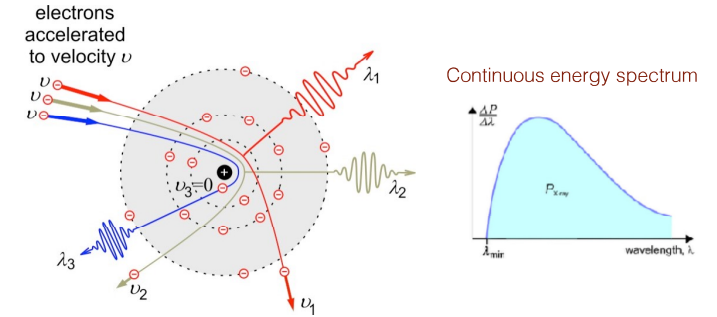
Duane-Hunt formula:

$$\lambda_{\min} = \frac{hc}{e} \cdot \frac{1}{U_{\text{anode}}}$$

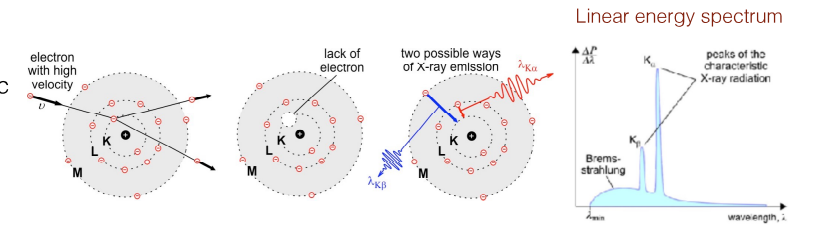
h : Planck's constant
 c : speed of light
 e : elementary charge

Mechanisms of X-ray generation

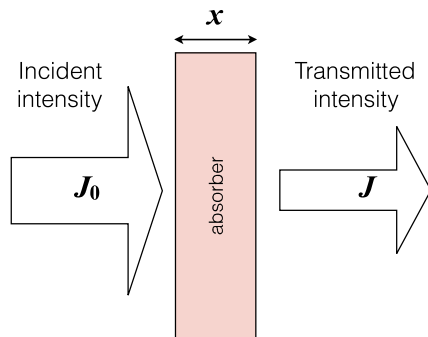
1. "Bremsstrahlung"
Breaking radiation
Deceleration radiation



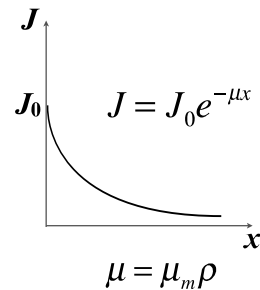
2. Characteristic
radiation (X-ray
fluorescence)



X-ray absorption



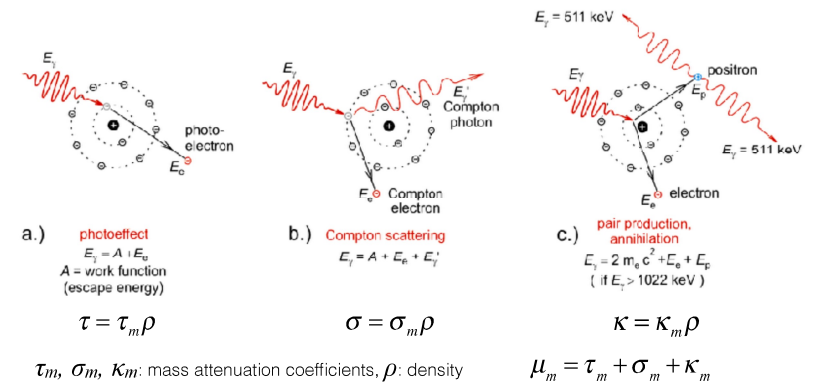
Exponential attenuation
principle



μ : attenuation coefficient
 μ_m : mass attenuation coefficient (cm^2/g)
 ρ : density (g/cm^3)

μ_m is the sum of the mass attenuation coefficients
of the different absorption mechanisms.

Attenuation mechanisms



Mechanism	Photon energy (ϵ) dependence of the mass attenuation coefficient	Atomic number (Z) dependence of the mass attenuation coefficient	Relevant energy range in soft tissue
Photoeffect	$\sim 1 / \epsilon^3$	$\sim Z^3$	10 - 100 keV
Compton scatter	falls gradually with ϵ	$\sim Z/A$ (A : mass number)	0.5 - 5 MeV
Pair production	rises slowly with ϵ	$\sim Z^2$	$> 5 \text{ MeV}$

Diagnostic X-ray:

1. Contrast mechanism between soft tissue and bone: photoeffect ($\sim Z^3$)
2. Contrast mechanism within soft tissue: Compton-scatter ($\sim \rho$)

Imaging with X-ray

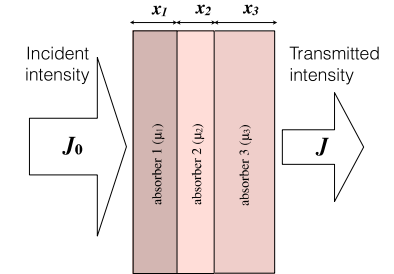
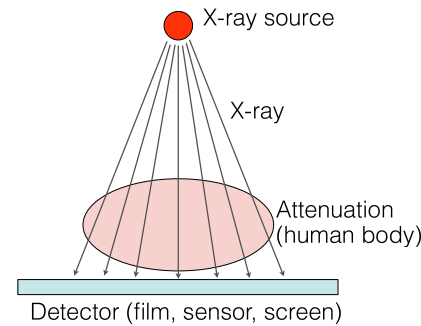


Wilhelm Konrad
Röntgen
(1845-1923)



Hand mit Ringen (Hand with Ring): print of Wilhelm Röntgen's first "medical" X-ray, of his wife's hand, taken on 22 December 1895 and presented to Professor Ludwig Zehender of the Physik Institut, University of Freiburg, on 1 January 1896. The dark oval on the third finger is a shadow produced by her ring.

Principles of X-ray imaging

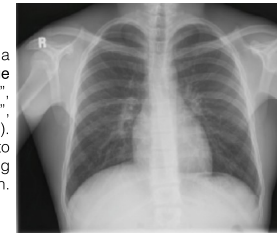


$$J = J_0 e^{-(\mu_1 x_1 + \mu_2 x_2 + \mu_3 x_3 + \dots)}$$

$$\lg \frac{J_0}{J} = (\mu_1 x_1 + \mu_2 x_2 + \mu_3 x_3 + \dots) \cdot \lg e$$

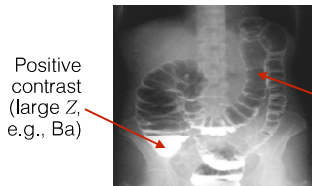
μ_n : n^{th} absorber's attenuation coefficient
 x_n : n^{th} absorber's thickness

The X-ray image is a summation image ("X-ray image", "radiographic image", "roentgenogram"). Contrast arises due to spatially varying attenuation.

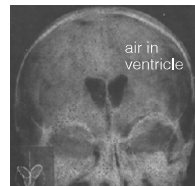


Improving X-ray imaging I.

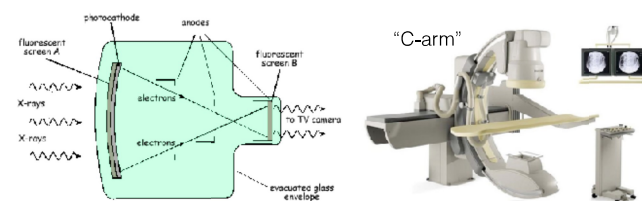
Increasing contrast:
contrast agents



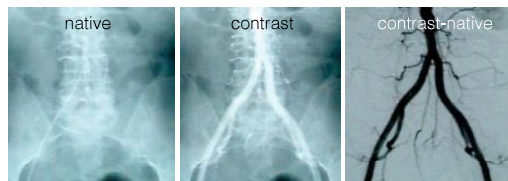
Negative contrast (small effective Z, e.g., air)



Enhancing sensitivity:
intensifier

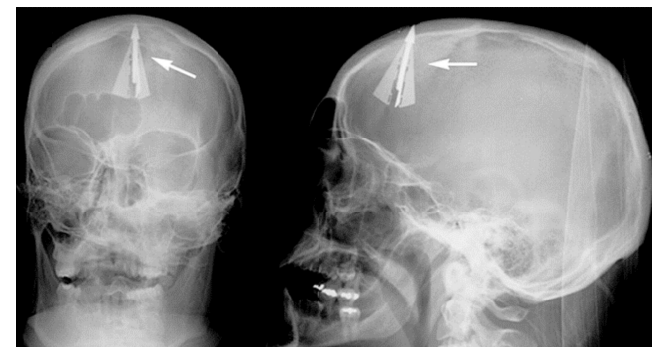


Background subtraction:
"Digital Subtraction Angiography" (DSA)



Improving X-ray imaging II. Spatial resolution

Bi-directional X-ray imaging

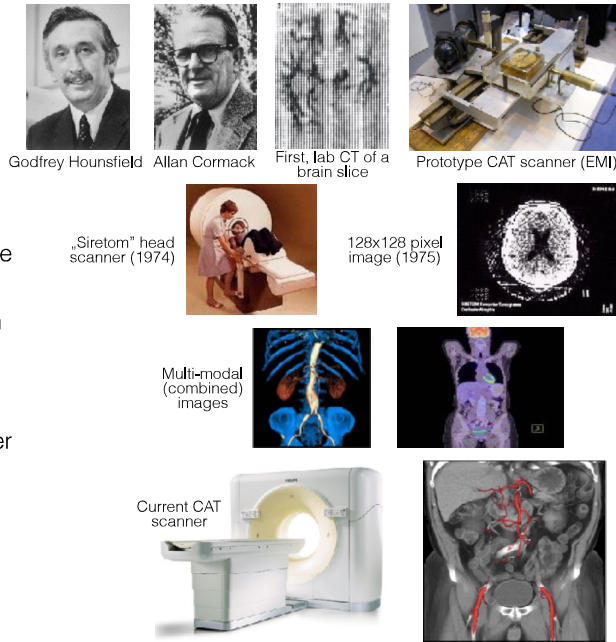


Bi-directional cranial X-ray of an individual who tried to commit suicide with a crossbow.

Improving X-ray imaging: the CAT scanner

History

- Röntgen, Hounsfield and Cormack
- 1967: first CAT scan
- 1972: prototype
- 1974: first clinical CAT image (head)
- 1976: whole body CAT scan
- 1979: Nobel-prize
- 1990: spiral CAT scanner
- 1992: multislice CAT scanner
- 2006: 64 slice (and more...)
- multiple and hybrid modes: SPECT-CT, PET-CT, Dual-source CT



Foundations and steps of CAT

Objective: to determine the attenuation coefficient (μ_x) of the individual volume elements (voxels)

$$I = I_0 e^{-\mu d}$$

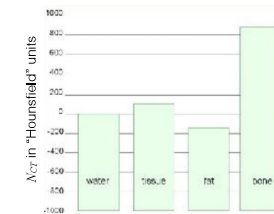
$$I = I_0 e^{-\sum_{i=1}^n \mu_i d_i}$$

$$I = I_0 e^{-\int \mu_x dx}$$

Based on μ the voxel "density" ("CT-number, N_{CT}) can be determined:

$$N_{CT} = 1000 \frac{\mu - \mu_w}{\mu_w}$$

μ : voxel attenuation coefficient
 μ_w : water attenuation coefficient



Scanning in transaxial tomographic slices ("tomos") is needed

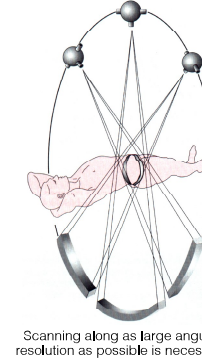
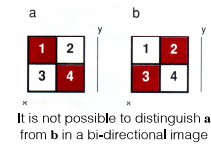
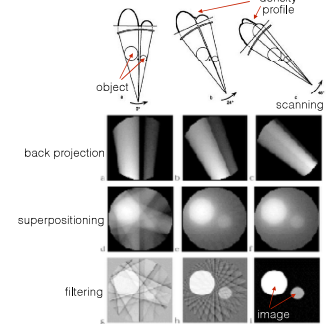
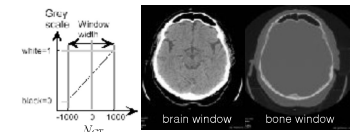


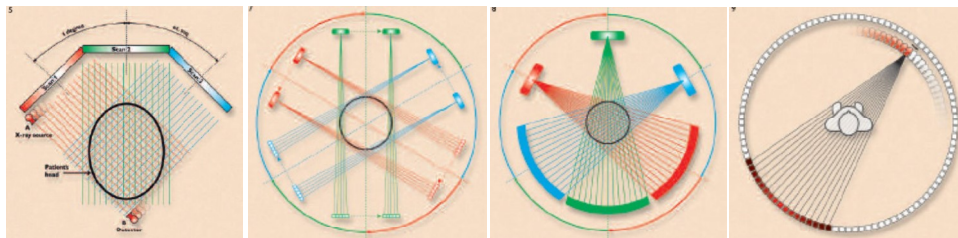
Image reconstruction and manipulation



The CAT scan is a density matrix, the color scale of which can be manipulated ("windowing") to increase specific local contrast



Scanning techniques evolved through generations



I. Generation.

There is a single moving source and a single moving detector, each translating linearly, then rotated.

II. Generation.

There are a small number of beams (approximately 8 to 30) in a narrow fan configuration with the same translate-rotate motion used in first generation machines. Each linear traverse produces several projections at differing angles, one view for each X-ray beam.

III. Generation.

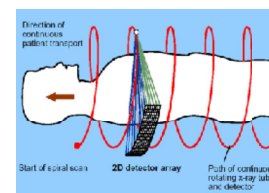
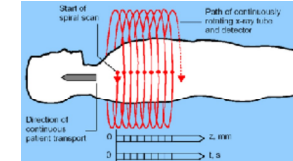
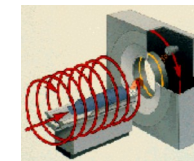
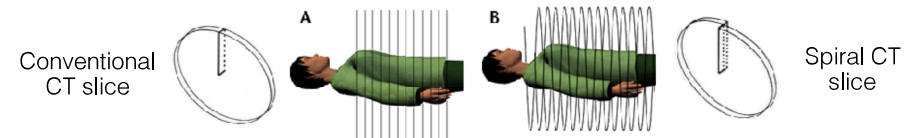
There are a large number of X-ray beams (approximately 500 to 700) in a wide fan configuration. Both the X-ray tube and the detectors rotate.

IV. Generation.

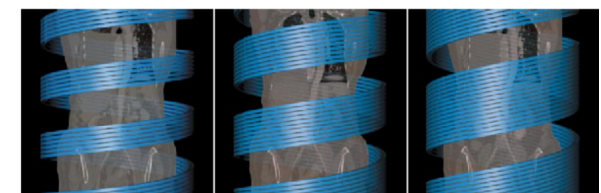
There are an intermediate number of X-ray beams (approximately 50 to 200) in a wide fan configuration with a rotating X-ray tube and a stationary circular array of approximately 600 to 2,400 detectors surrounding the patient.

Current CT's use spiral (helical) scanning

Source-detector pair rotates constantly

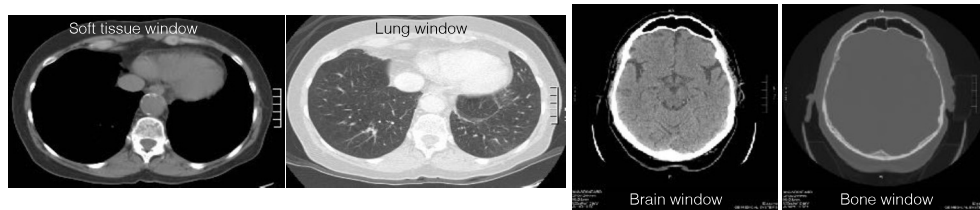
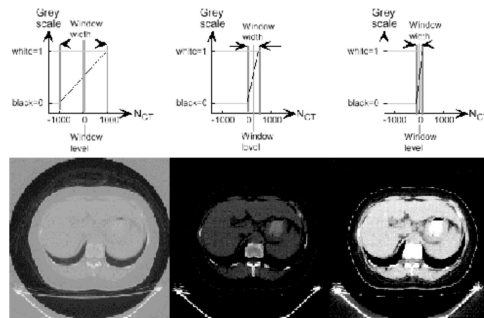


Multi-detector CT (MDCT)



Multi-slice CT (MSCT)

Contrast manipulation of CT Image „Windowing”

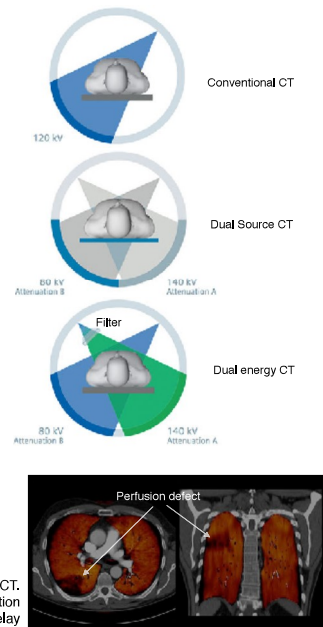


Summary of CT scanning (CAT)

- Tomographic digital imaging method that uses X-rays
- Principle: displaying differences in X-ray absorbance by the different points of the tomographic slice
- Conventional (outdated) technique:
one slice – 2 - 4 sec,
entire examination: 5 - 15 perc
- Spiral CT technique:
one slice – 1 - 1.5 sec,
entire examination: 30 - 60 sec (+ preparation)
- Multidetector spiral CT (4-64 detector array):
one slice – 0.4 - 1 sec,
entire examination: 5 - 15 sec

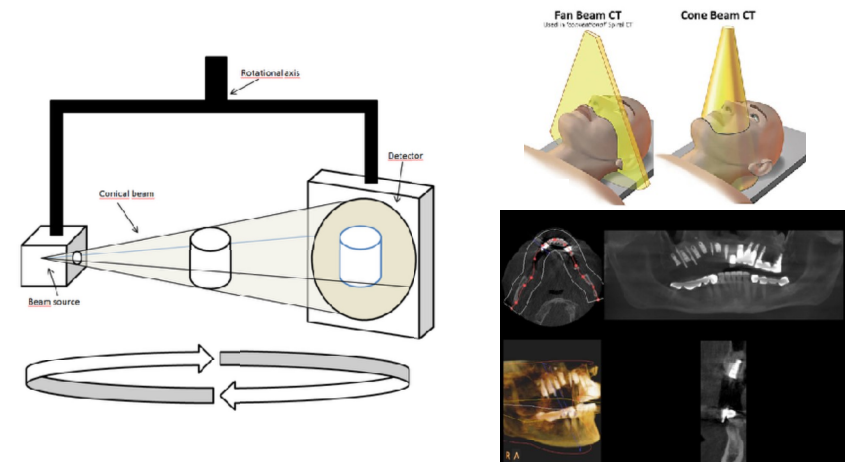
Dual Source CT (DSCT)

- Simultaneous use of two different X-ray sources and detectors.
- The two tubes are positioned perpendicular to each other, the detectors work in synchrony.
- If the sources are operated at identical accelerating voltage, 90° rotation is sufficient to generate a tomographic slice.
- The sources may also be operated at different accelerating voltages (“dual-energy mode”, 80 and 140 kV). 180° rotation is required to generate an image slice.
- In dual-energy mode two image slices with different information content are generated, due to the different tissue absorbance of the X-ray photons with different energies



Cone beam CT

- Cone-beam computed tomography (CBCT), C-arm CT, cone beam volume CT, flat panel CT
- X-ray beam is conical
- Volumetric dataset is provided; digital image reconstruction is required
- Dental, interventional, radiotherapeutic applications



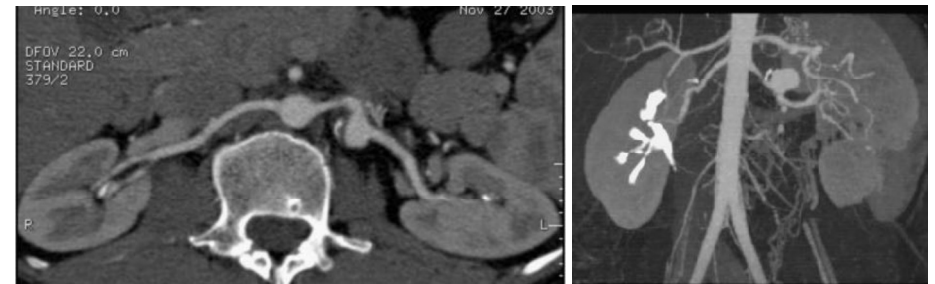
CT contrast agents

- Water soluble, iodine-containing macromolecule causing enhanced absorbance (hence color density) at the sites of accumulation
- Ionic contrast agent – outdated (abandoned since the 1990s)
- Non-ionic (monomeric or dimeric, low osmolality)
- Filtration through the kidney (nephrotropic). Its filtration begins immediately.
- Applications: every X-ray based imaging method

Imaging blood vessels - CT angiography

- Native CT: limited applications. Only in case of severely calcified vessel walls
- With intravenous contrast agents:
"conventional" technique - vessels with $d \geq 1$ cm (aorta)
- Spiral CT-angiography:
Single-detector array spiral CT - aorta branches ($d \geq 2-3$ mm)
Multidetector array spiral CT - peripheral vessels ($d \geq 1$ mm)

Renal artery aneurysm CTA 8 detector-array spiral CT



Cardiac CT I.

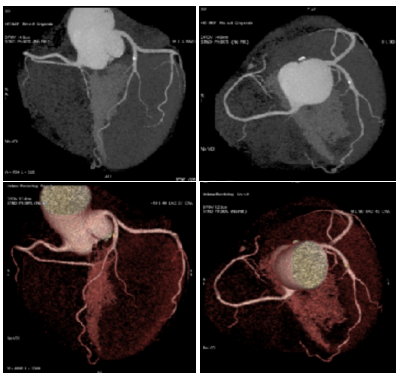
Challenges:

- to freeze the moving heart to avoid motion blurring
- for successful CT image reconstructions several projections from a 180° rotation are required, during which the heart must be in essential standstill

Solutions:

- reduce heart rate (beta blockers, 65 bpm)
- sort images according to cardiac cycle (ECG gating)

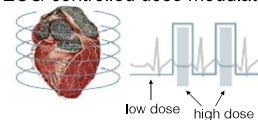
Coronary CT-angiography (CTCA) 64-slice MDCT



Retrospective ECG gating

- images are collected in all phases of the cardiac cycle
- user decides which phase to use for reconstruction
- disadvantage: very large x-ray dose

ECG-controlled dose modulation



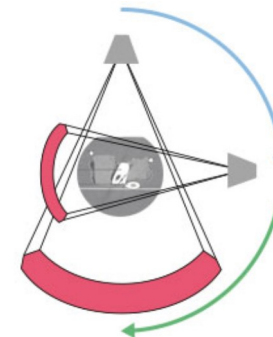
Prospective ECG-triggered sequential CT

- patient ECG is monitored
- scan started after predefined time from R wave
- limitations: severe arrhythmia

Cardiac CT II.

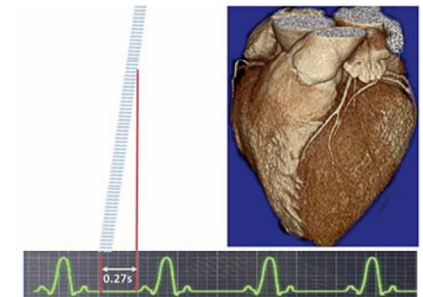
Dual-source cardiac CT imaging

- Hi temporal resolution
- low x-ray dose
- two x-ray tubes and two detectors positioned 90° apart
- 90° rotation of each detector makes up for 180° total rotation



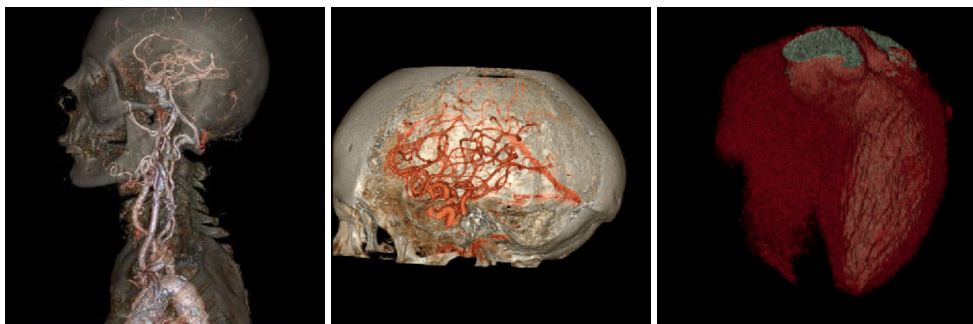
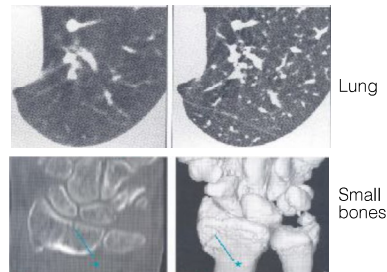
Flash mode

- ECG triggering
- fast patient table movement
- entire heart scan within one heartbeat



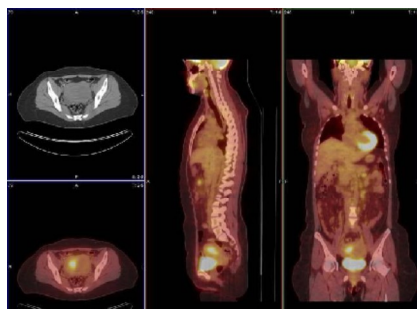
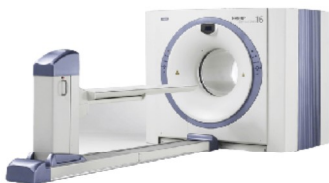
HRCT (High Resolution CT)

- Very thin (1-2 mm) slices, very high contrast resolution.
- Important in case of large contrast differences (e.g., bone - lung).
- Image processing: by using dedicated algorithms
- One of the most important development aims is increasing spatial resolution.

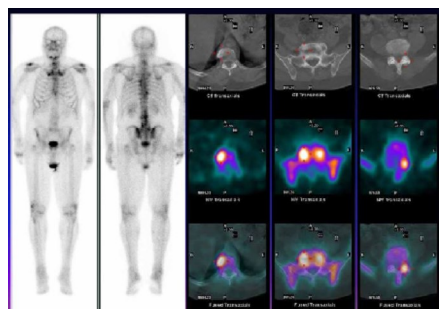


Combination of CT with functional (isotope-based) imaging

PET/CT



SPECT/CT



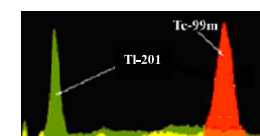
Limitations of CAT scanning

- Ionizing radiation
- Irradiation dose up to 50-100 times that of conventional X-ray imaging!
- direct exposure to radiation
- + scattered radiation (its intensity is 1-2 orders of magnitude smaller)

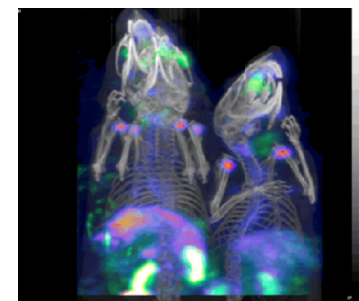
Hybrid technologies in research: NanoSPECT/CT



CT: 36 μ m voxel size
Real-time CT reconstruction (GPU)



"Dual-channel" SPECT

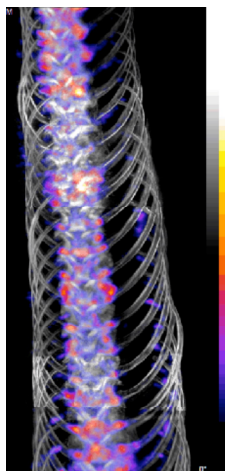


^{99m}Tc -DTPA: diethylenetriaminepentaacetic (BBB) - blue/red
 ^{99m}Tc -HMPAO: hexamethylpropyleneamine oxime (perfusion) - blue/red
 ^{201}Tl -DDC: diethylthiocarbamate (perfusion) - green

NanoSPECT/CT



Boa constrictor



*Osteomyelitis, ^{99m}Tc -MDP
(methylene-diphosphonate)*