MEDICAL IMAGING METHODS

Image processing, X-ray, CAT scanning

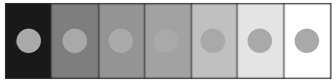
Miklós Kellermayer

I. The digital image

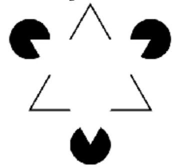
Seeing is believing!?

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

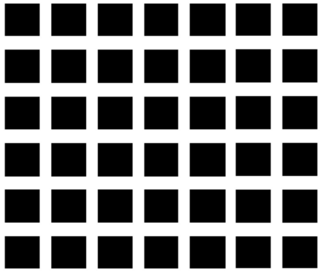
Optical illusions - intensity

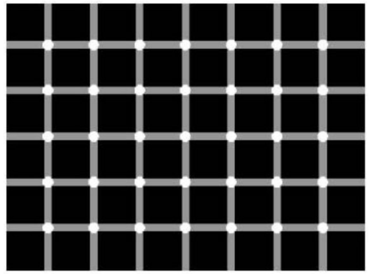


Mach bands



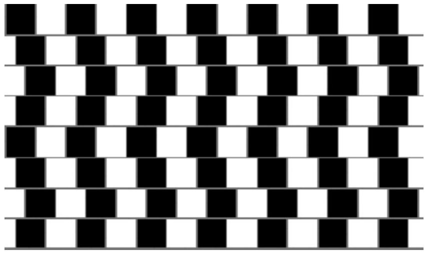
Kanizsa triangle



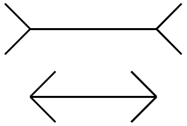


How many black circles can we count?

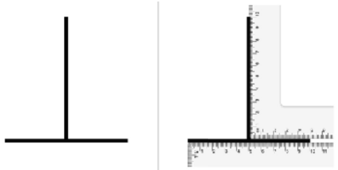
Optical illusions – direction, size



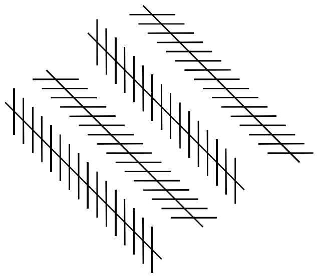
Café Wall illusion

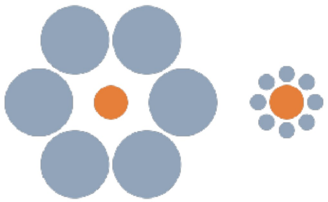


Müller-Lyer illusion



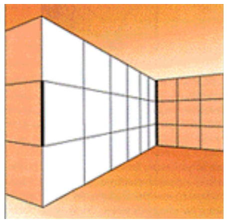
Vertical-horizontal illusion

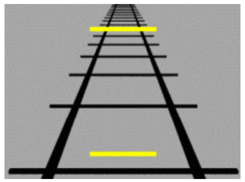




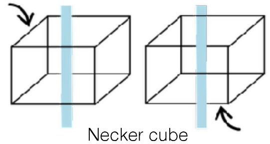
Ebbinghaus illusion

Optical illusions – space

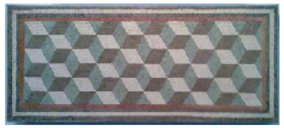




Ponzo illusion

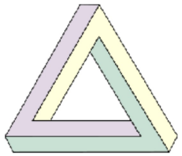


Necker cube

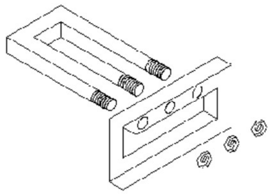


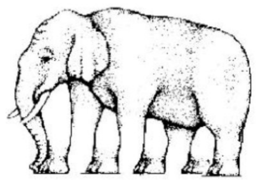
Necker cube effect on a Roman mosaic

"Impossible" geometries

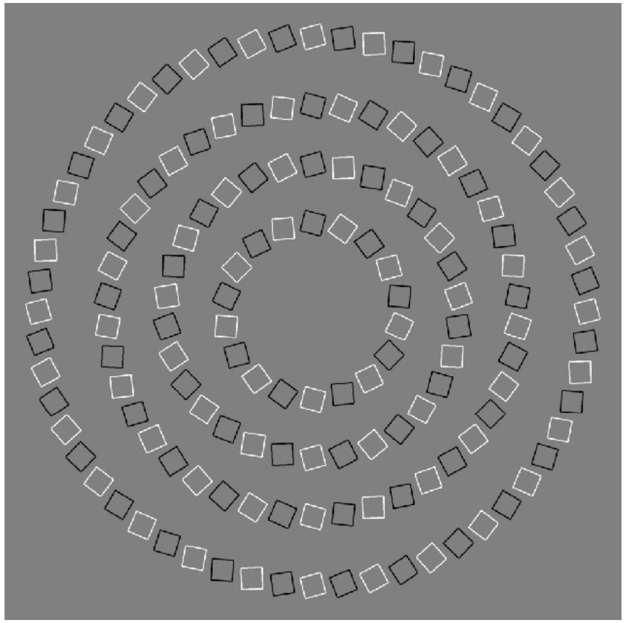


Penrose triangle





Optical illusions – geometry

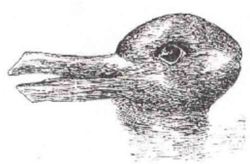


Pinna illusion:
Spiral, or
concentric
rings?

Optical illusions – shape

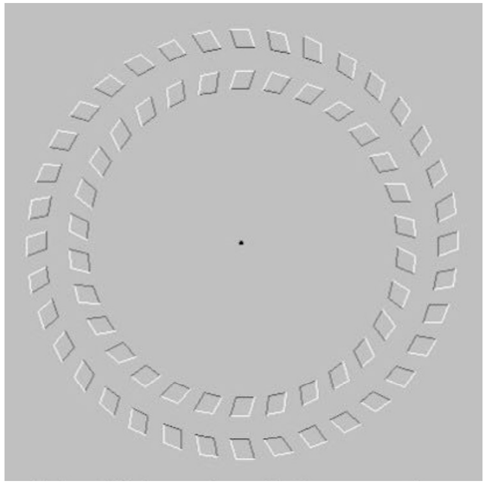
Reversible shapes, complementary shapes

Rubin vase illusion



"Gestalt" Contour

Optical illusions – motion



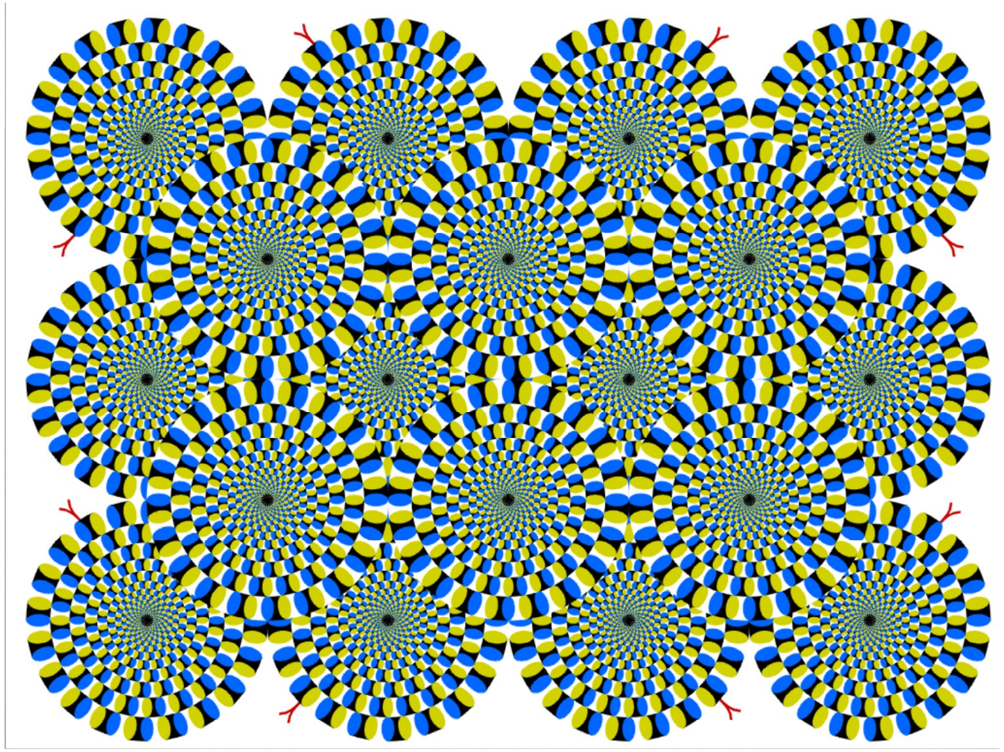
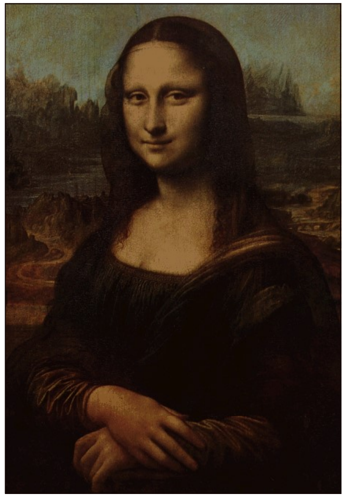
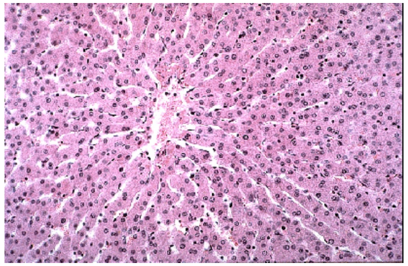


Image: what is the information carried?
Is it visible … or not?

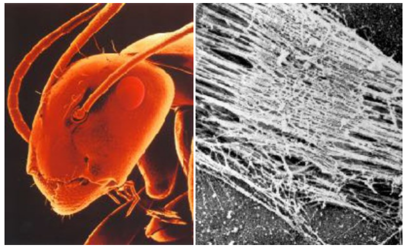


Method-dependent images

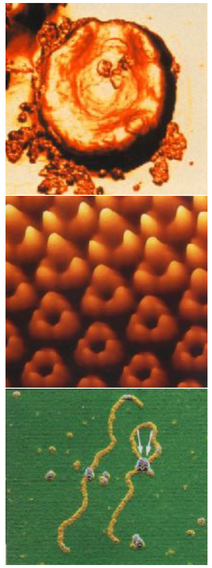
HE-stained section: hepatic lobule



Scanning electron microscopic images



Atomic force microscopic images

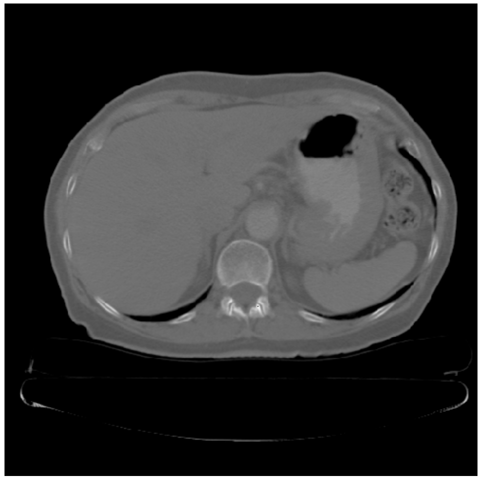


Red blood cell

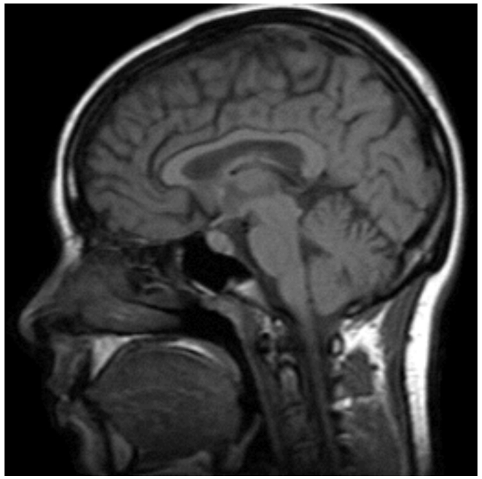
Bacteriorhodopsin

DNA-protein complex

Method-dependent images

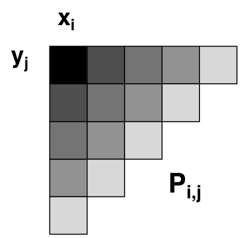


CT



MRI

The digital image



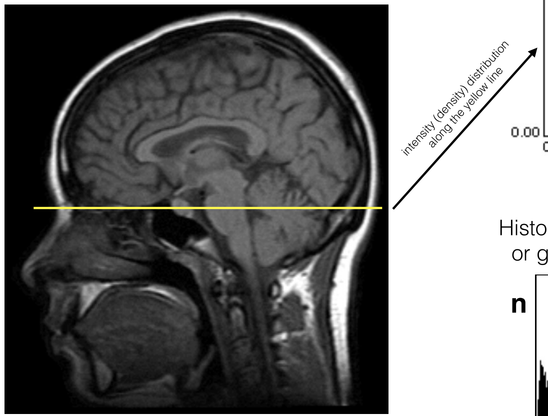
Digital image: information displayed at different discrete spatial points in the form of color. 2 or 3 dimensional array or matrix of picture elements.

Characteristics of the digital image:

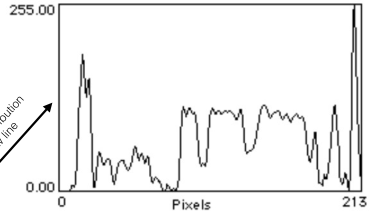
1. *Picture element: pixel (pix=picture; element)*
2. *Information associated with the pixel:*
   a. XY location: coordinates related to spatial resolution
   b. Color depth: intensities related to color (or grayscale)resolution
3. *Spatial resolution:*
   Number of resolved pixels in the X and Y directions.
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)



Resolved intensities may be displayed as a function



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

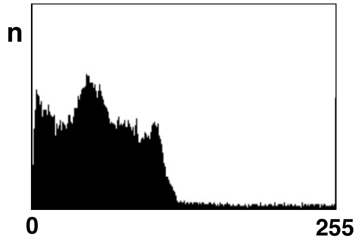
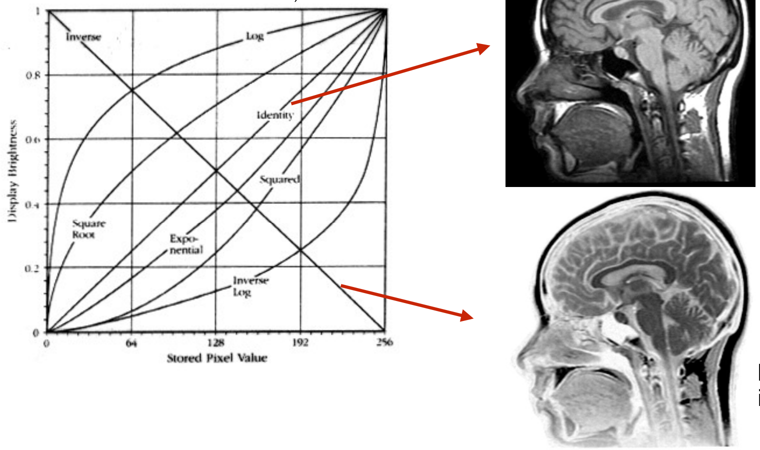


Image enhancement techniques: Contrast manipulation

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

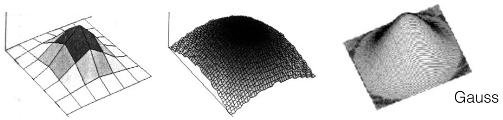
1	1	1
1	1	1
1	1	1

„smoothing" convolution

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

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):



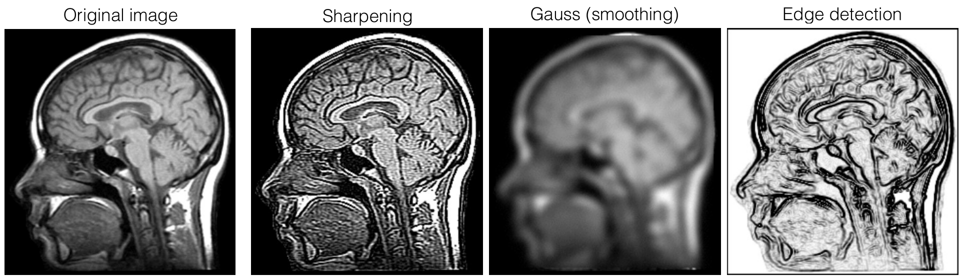
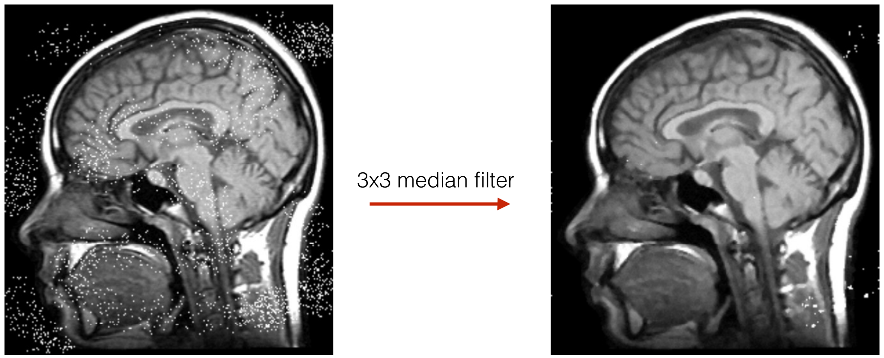


Image enhancement techniques: Rank operations

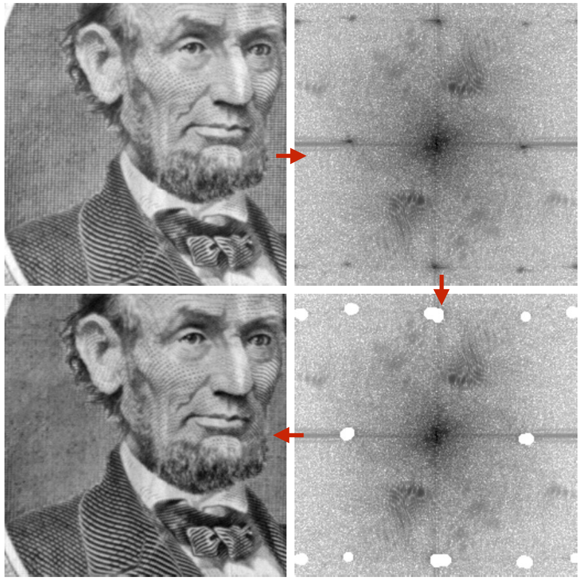
Principle: the pixel is exchanged for another from its ranked neighborhood (e.g., min, max, median)

Noise removal using median filtering:



Fourier transformation

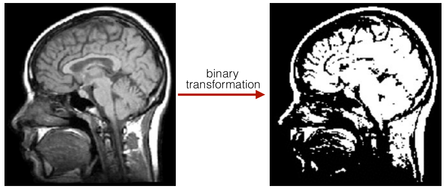
Fourier principle: any function may be generated as the sum of a sine function and its harmonics.
Fourier transform -> spectral density: displays the contribution of a given frequency.



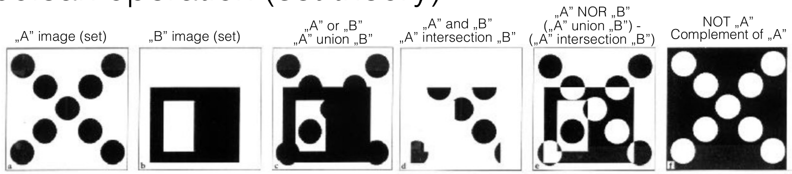
Binary image processing

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"

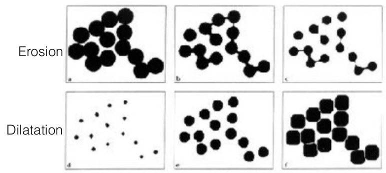


2. Boolean operation (set theory)

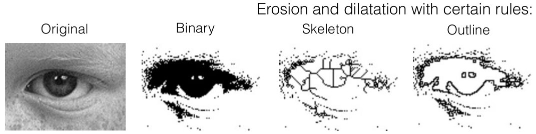


3. Erosion, dilatation, opening, closing

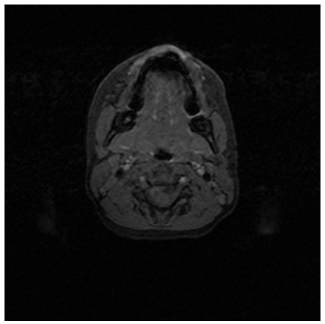
Moving pixels from the foreground to the background and *vice versa*

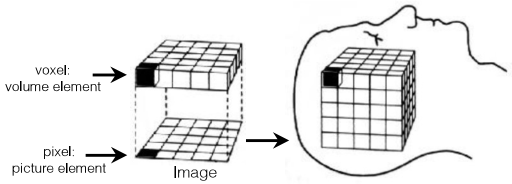


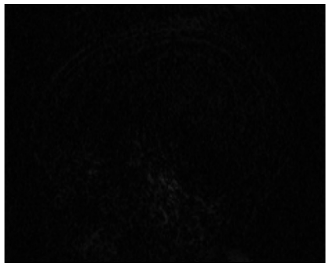
Erosion and dilatation with certain rules:

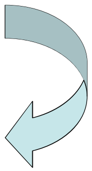


3D image processing









Spatial projection
(„volume rendering")

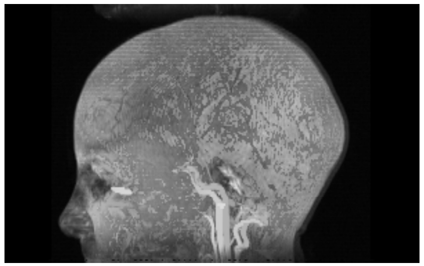
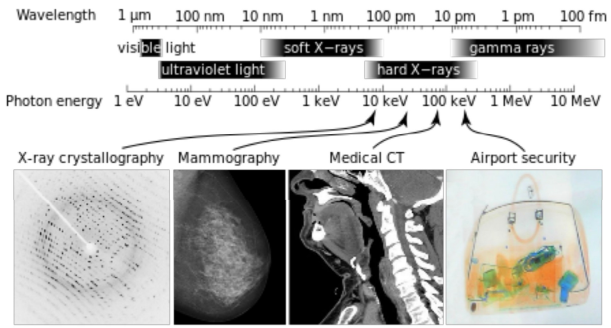


Image format of medical diagnostics: DICOM (Digital Imaging and Communications in Medicine)

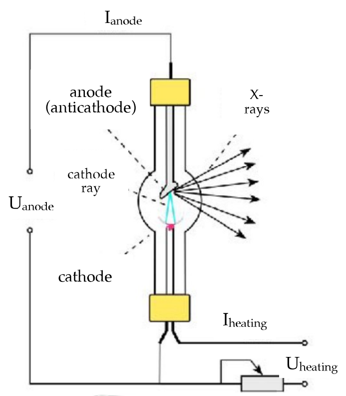
II. X-ray imaging

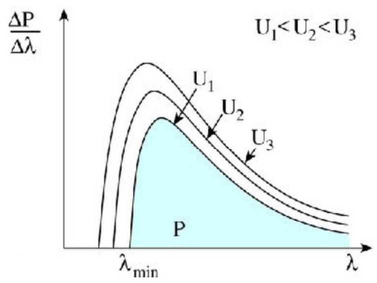
X-rays are electromagnetic waves

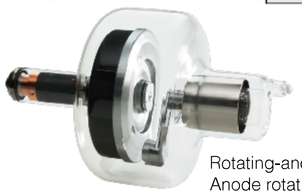


Wavelength 10 - 0.01 nm. ***Frequency*** 30×10^{15} - 30×10^{18} Hz. ***Energy*** 120 eV - 120 keV.
(petaherz - exahertz)

Generation of X-ray







Rotating-anode X-ray tube.
Anode rotation is used for cooling.

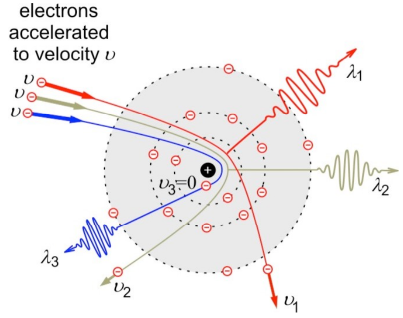
Duane-Hunt formula:

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

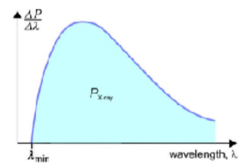
h: Planck's constant
c: speed of light
e=: elementary charge

Mechanisms of X-ray generation

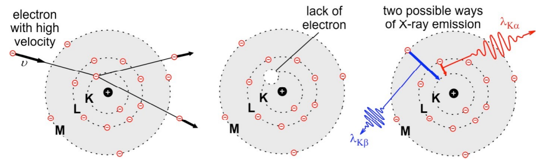
1. "Bremsstrahlung"
Breaking radiation
Deceleration radiation



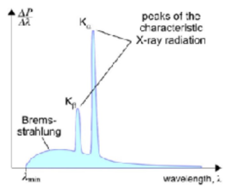
Continuous energy spectrum



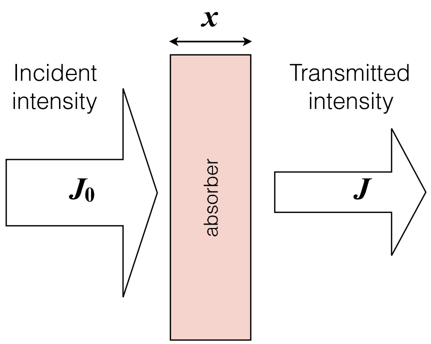
2. Characteristic radiation (X-ray fluorescence)



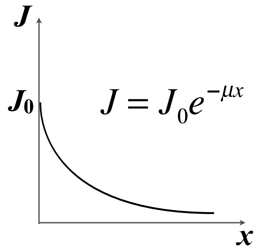
Linear energy spectrum



X-ray absorption



Exponential attenuation principle



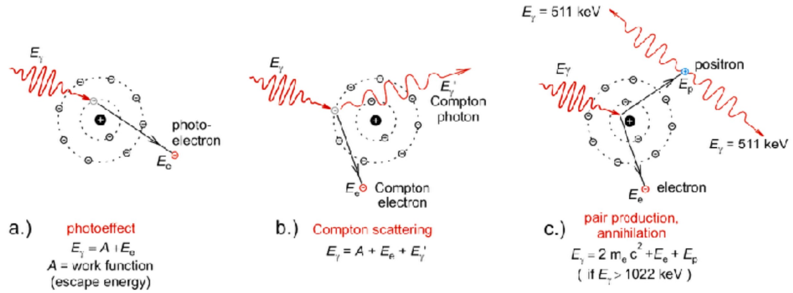
$$J = J_0 e^{-\mu x}$$

$$\mu = \mu_m \rho$$

μ : attenuation coefficient
μ_m : mass attenuation coefficient (cm²/g)
ρ : density (g/cm³)

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

Attenuation mechanisms



$\tau = \tau_m \rho$ $\sigma = \sigma_m \rho$ $\kappa = \kappa_m \rho$

τ_m, σ_m, κ_m: mass attenuation coefficients, ρ: density

$$\mu_m = \tau_m + \sigma_m + \kappa_m$$

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	~1 / ε³	~Z³	10 - 100 keV
Compton scatter	falls gradually with ε	~Z/A (A: mass number)	0.5 - 5 MeV
Pair production	rises slowly with ε	~ Z²	> 5 MeV

Diagnostic X-ray:
1. Contrast mechanism between soft tissue and bone: photoeffect (~Z^3)
2. Contrast mechanism within soft tissue: Compton-scatter (~ρ)

Imaging with X-ray

Wilhelm Konrad
Röntgen
(1845-1923)

Sitzungs-Berichte
der
Physikalisch-medicinischen Gesellschaft
zu
WÜRZBURG.

Jahrgang 1895. | Der Abonnementspreis pro Jahrgang beträgt ℳ 4.—. Die Nummern werden einzeln nicht abgegeben. Grössere Beiträge erscheinen in Sonderdrucken. | No. 9.

Am 28. Dezember wurde als Beitrag eingereicht:

W. C. Röntgen: Ueber eine neue Art von Strahlen.

(Vorläufige Mittheilung.)

1. Lässt man durch eine *Hittorf*'sche Vacuumröhre, oder einen genügend evacuirten *Lenard*'schen, *Crookes*'schen oder ähnlichen Apparat die Entladungen eines grösseren *Ruhmkorff*'s gehen und bedeckt die Röhre mit einem ziemlich eng anliegenden Mantel aus dünnem, schwarzem Carton, so sieht man in dem vollständig verdunkelten Zimmer einen in die Nähe des Apparates gebrachten, mit Bariumplatincyanür angestrichenen Papierschirm bei jeder Entladung hell aufleuchten, fluoresciren, gleichgültig ob die angestrichene oder die andere Seite des Schirmes dem Entladungsapparat zugewendet ist. Die Fluorescenz ist noch in 2 m Entfernung vom Apparat bemerkbar.

Man überzeugt sich leicht, dass die Ursache der Fluorescenz vom Entladungsapparat und von keiner anderen Stelle der Leitung ausgeht.

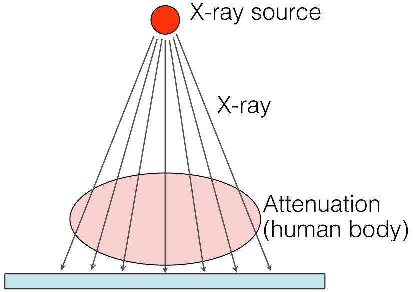
2. Das an dieser Erscheinung zunächst Auffallende ist, dass durch die schwarze Cartonhülse, welche keine sichtbaren oder ultravioletten Strahlen des Sonnen- oder des elektrischen Bogenlichtes durchlässt, ein Agens hindurchgeht, das im Stande ist, lebhafte Fluorescenz zu erzeugen, und man wird deshalb wohl zuerst untersuchen, ob auch andere Körper diese Eigenschaft besitzen.

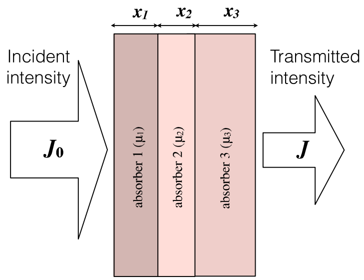
Man findet bald, dass alle Körper für dasselbe durchlässig sind, aber in sehr verschiedenem Grade. Einige Beispiele führe ich an. Papier ist sehr durchlässig:[1] hinter einem eingebun-

[1] Mit „Durchlässigkeit" eines Körpers bezeichne ich das Verhältniss der Helligkeit eines dicht hinter dem Körper gehaltenen Fluorescenzschirmes zu derjenigen Helligkeit des Schirmes, welcher dieser unter denselben Verhältnissen aber ohne Zwischenschaltung des Körpers zeigt.

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 Zehnder 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



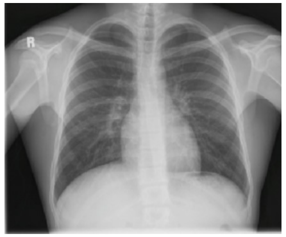


$$J = J_0 e^{-(\mu_1 x_1 + \mu_2 x_2 + \mu_3 x_3 + \ldots)}$$

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

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

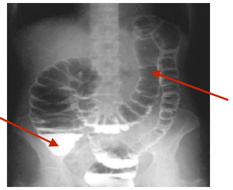
The X-ray image is a **summation image** ("X-ray image", "radiographic image", "roentgenogram"). Contrast arises due to spatially varying attenuation.



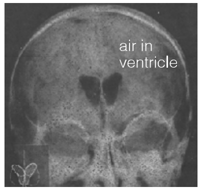
Improving X-ray imaging I.

Increasing contrast: contrast agents

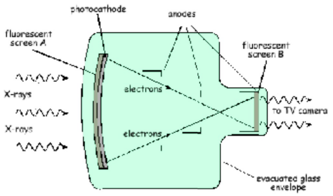
Positive contrast (large *Z*, e.g., Ba)



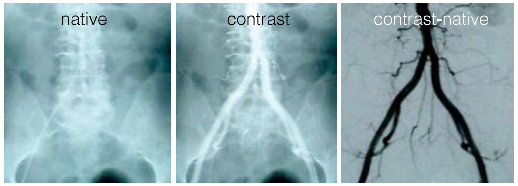
Negative contrast (small effective *Z*, e.g., air)



Enhancing sensitivity: intensifier

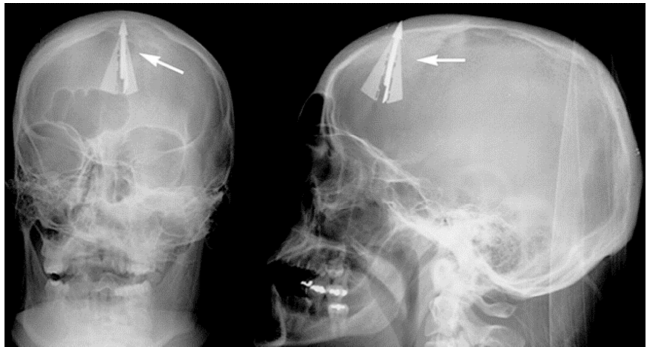


Background subtraction: "Digital Subtraction Angiography" (DSA)



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.

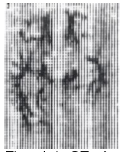
Improving X-ray imaging: the CAT scanner

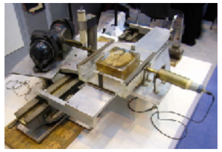
History

- 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


Godfrey Hounsfield

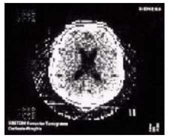

Allan Cormack


First, lab CT of a brain slice

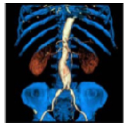

Prototype CAT scanner (EMI)

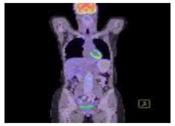
„Siretom" head scanner (1974)

128x128 pixel image (1975)

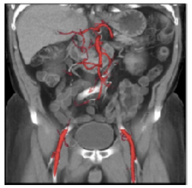


Multi-modal (combined) images



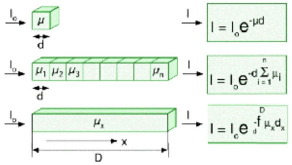


Current CAT scanner



Foundations and steps of CAT

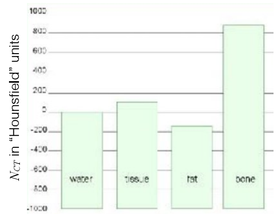
Objective: to determine the attenuation coefficient (μ_x) of the individual volume elements (voxels)



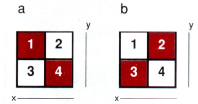
Based on μ the voxel "density" ("CT-number, N_{CT}) can be determined:

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

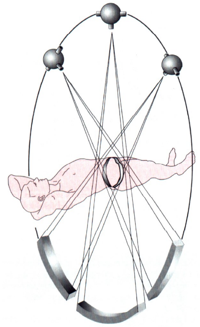
μ: voxel attenuation coefficient
μ_w: water attenuation coefficient



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

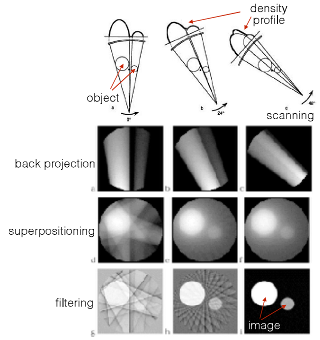


It is not possible to distinguish **a** from **b** in a bi-directional image

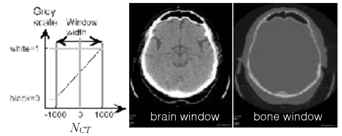


Scanning along as large angular resolution as possible is necessary

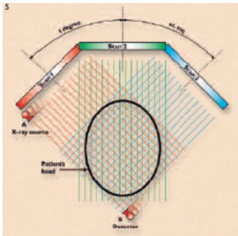
Image reconstruction and manipulation



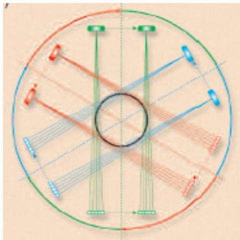
The CAT scan is a density matrix, the color scale of which can be manipulated ("windowing") to increase specific local contrast



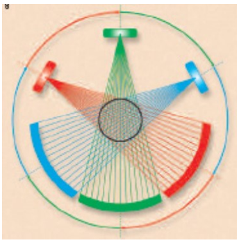
Scanning techniques evolved through generations



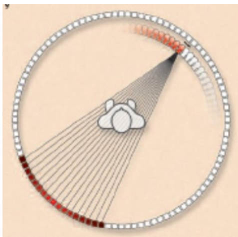
I. Generation.
There is a single moving source and a single moving detector, each translating linearly, then rotated.



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.

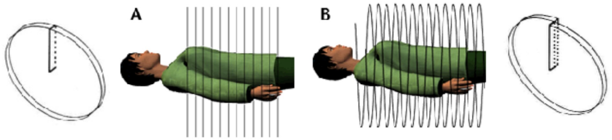


IV. Generation.
There are an intermediate number of X-ray beams (approximately 50 to 200) in a wide fan configuration with a rotating X-ray tube and a stationary circular array of approximately 600 to 2,400 detectors surrounding the patient.

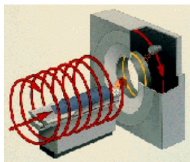
Current CT's use spiral (helical) scanning

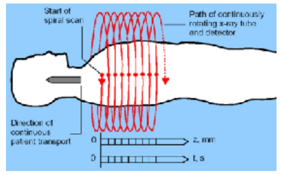
Source-detector pair rotates constantly

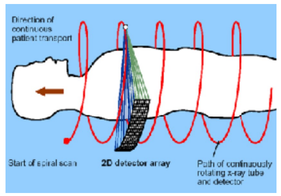
Conventional CT slice



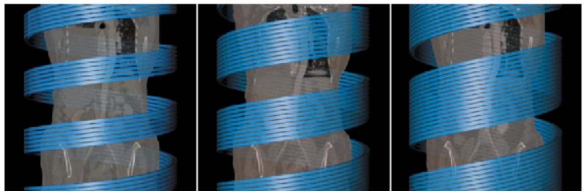
Spiral CT slice





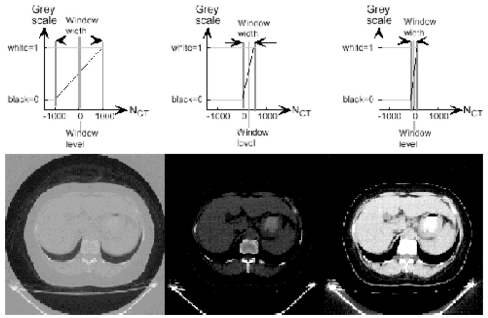


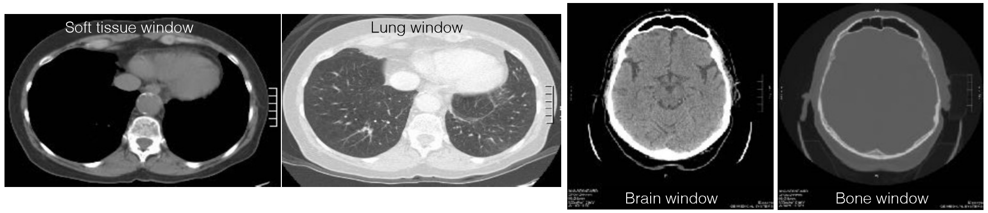
Multi-detector CT (MDCT)



Multi-slice CT (MSCT)

Contrast manipulation of CT Image
„Windowing”



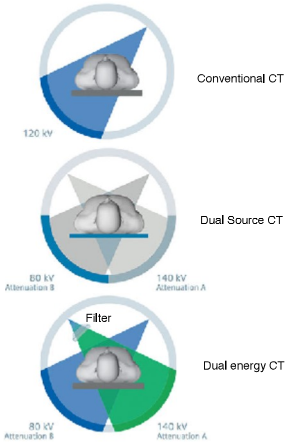


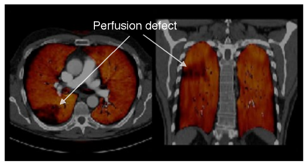
Summary of CT scanning (CAT)

- 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

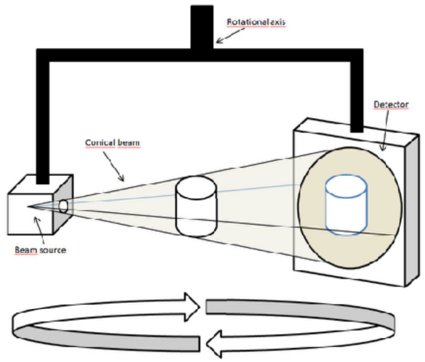


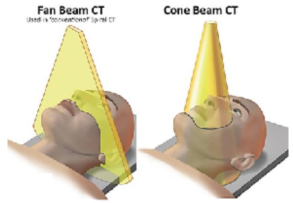


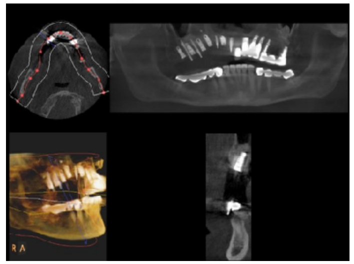
Lung perfusion image with dual-energy CT. Based on iodine contrast agent distribution recorded with time delay

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)

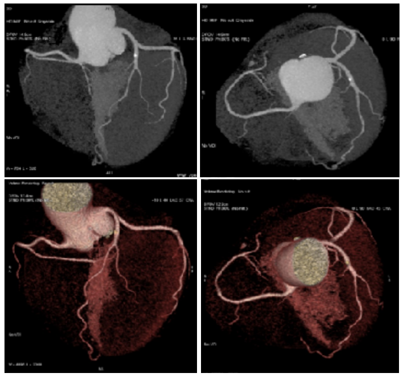
Renal artery aneurysm CTA 8 detector-array spiral CT

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

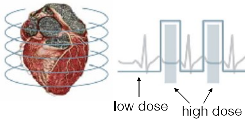
Solutions:
- reduce heart rate (beta blockers, 65 bpm)
- sort images according to cardiac cycle (ECG gating)

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

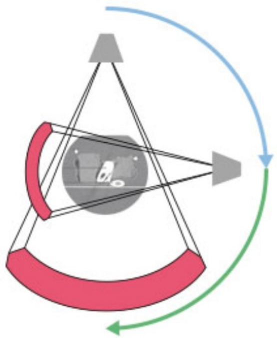


Prospective ECG-triggered sequential CT
- patient ECG is monitored
- scan started after predefined time from R wave
- limitations: severe arrhythmia

Cardiac CT II.

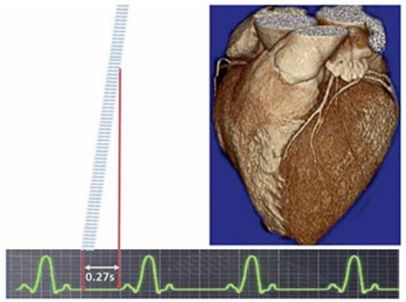
Dual-source cardiac CT imaging

- 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



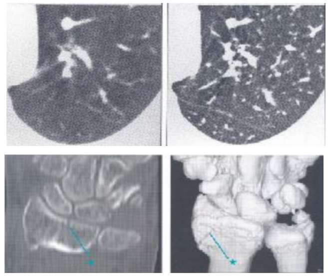
Flash mode

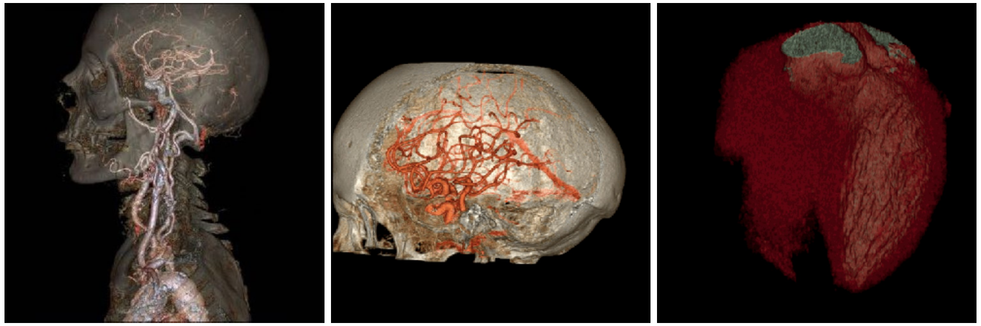
- ECG triggering
- fast patient table movement
- entire heart scan within one heartbeat



HRCT (High Resolution CT)

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



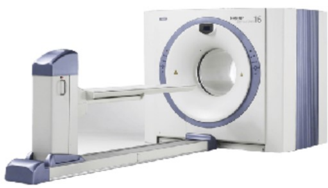


Limitations of CAT scanning

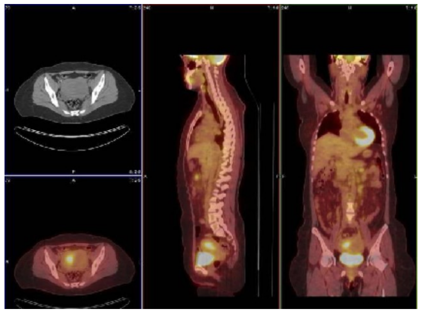
- Ionizing radiation
- Irradiation dose up to 50-100 times that of conventional X-ray imaging!
- direct exposure to radiation
- + scattered radiation (its intensity is 1-2 orders of magnitude smaller)

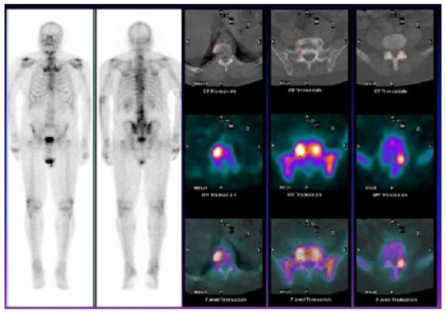
Combination of CT with functional (isotope-based) imaging

PET/CT



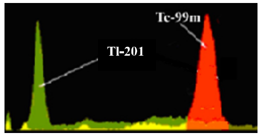
SPECT/CT



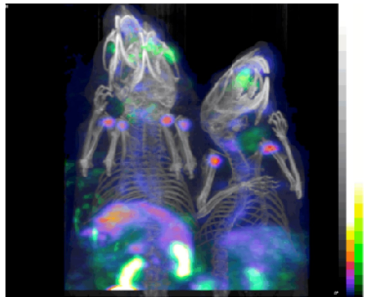


Hybrid technologies in research: NanoSPECT/CT

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



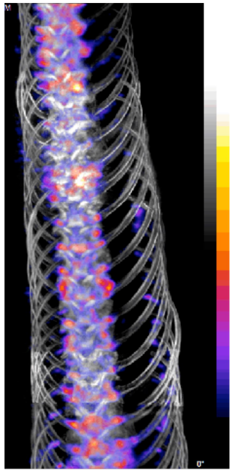
"Dual-channel" SPECT



^{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)