MEDICAL IMAGING METHODS

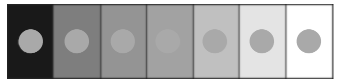
Miklós Kellermayer

I. The digital image

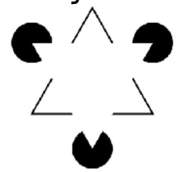
Seeing is believing!?

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

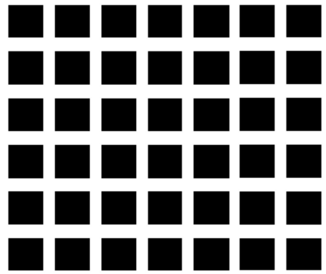
Optical illusions - intensity

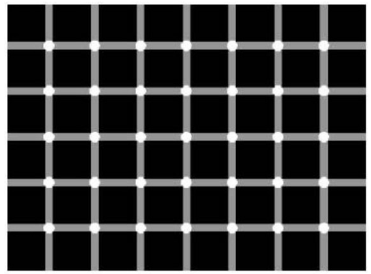


Mach bands



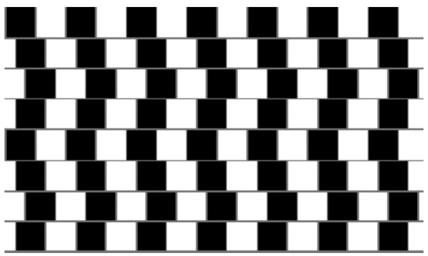
Kanizsa triangle



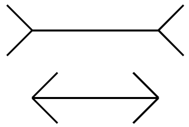


How many black circles can we count?

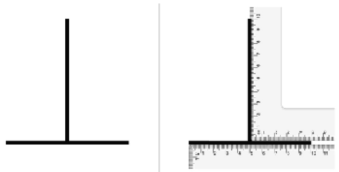
Optical illusions – direction, size



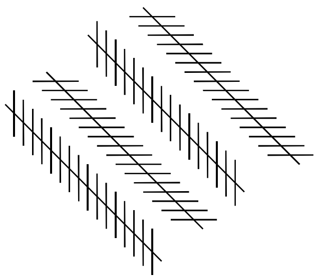
Café Wall illusion



Müller-Lyer illusion

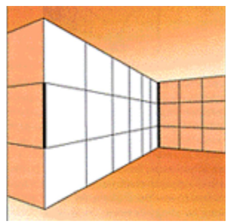


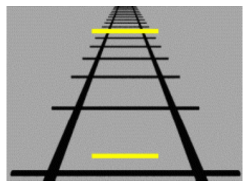
Vertical-horizontal illusion



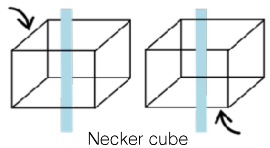
Ebbinghaus illusion

Optical illusions – space





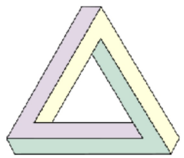
Ponzo illusion



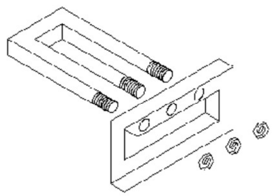
Necker cube

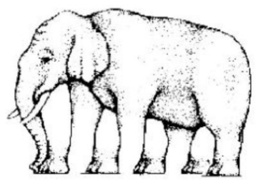
Necker cube effect on a Roman mosaic

“Impossible” geometries

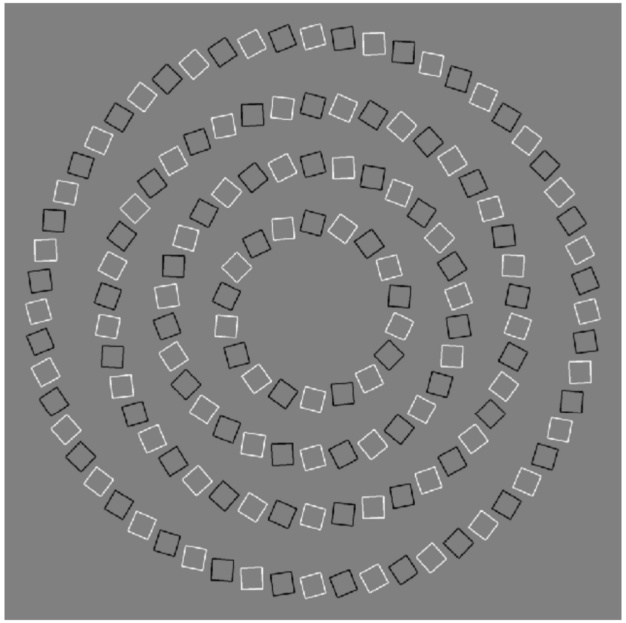


Penrose triangle





Optical illusions – geometry

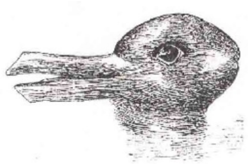


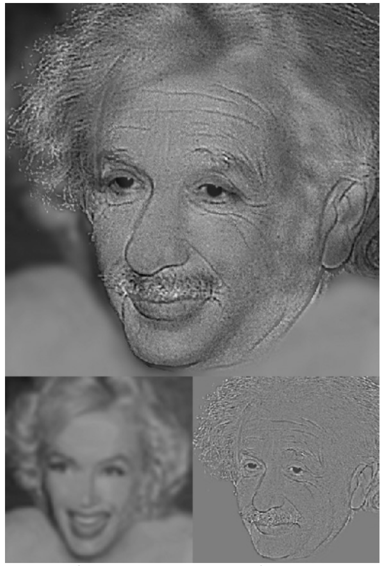
Pinna illusion:
Spiral, or
concentric
rings?

Optical illusions – shape

Reversible shapes, complementary shapes

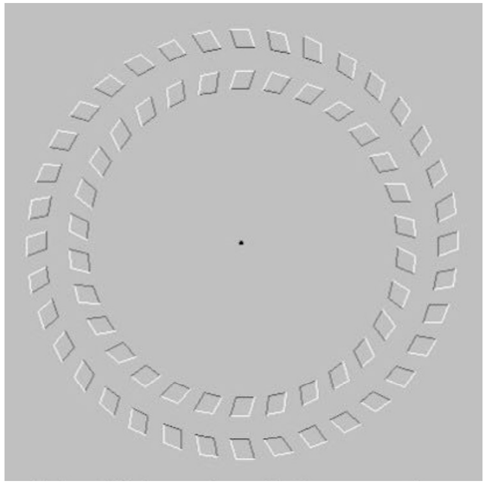
Rubin vase illusion





"Gestalt" Contour

Optical illusions – motion



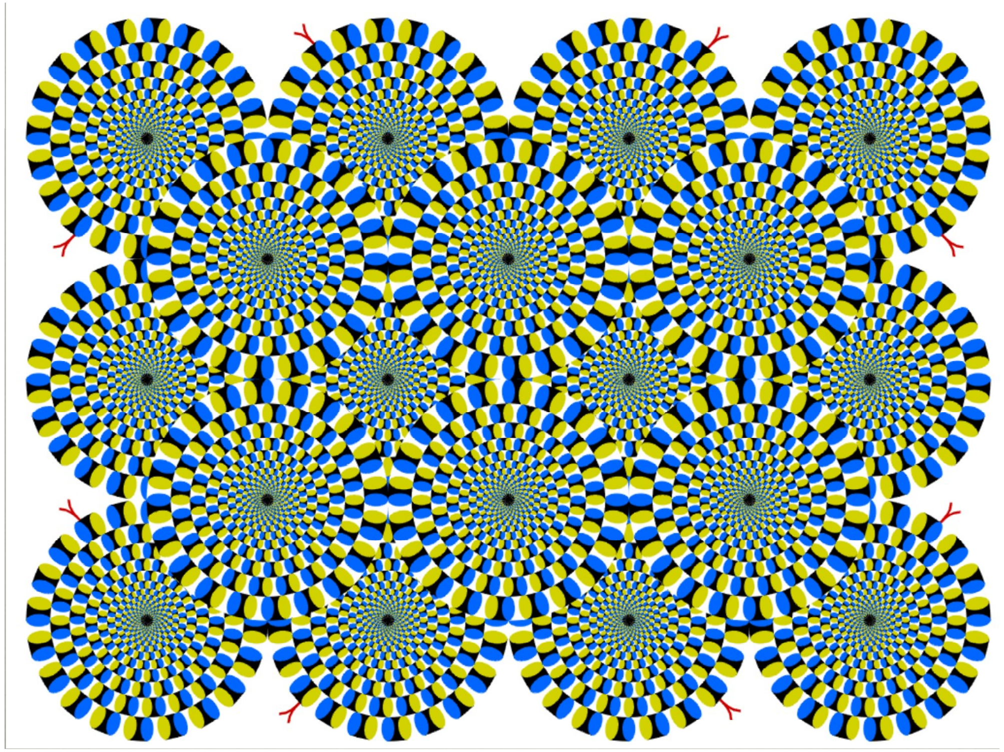
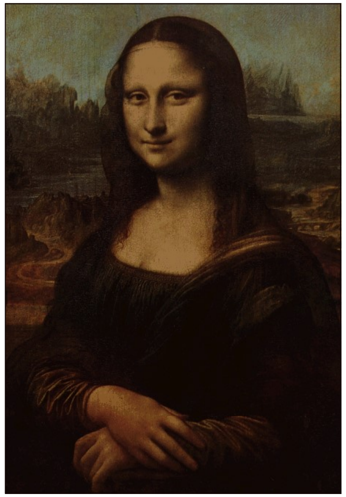
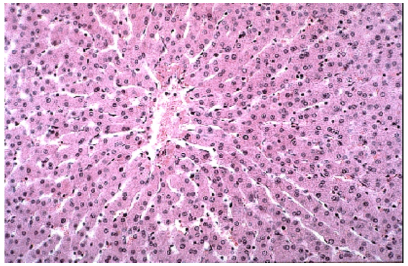


Image: what is the information carried?
Is it visible … or not?

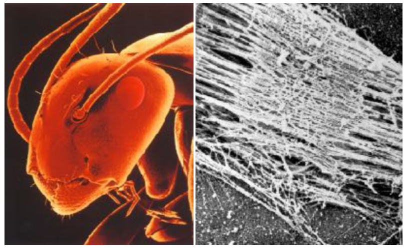


Method-dependent images

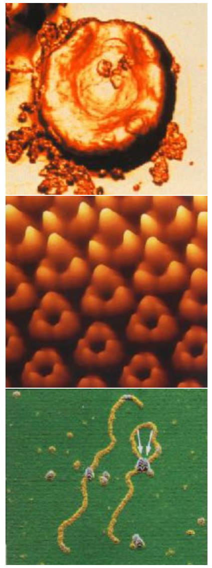
HE-stained section: hepatic lobule



Scanning electron microscopic images



Atomic force microscopic images

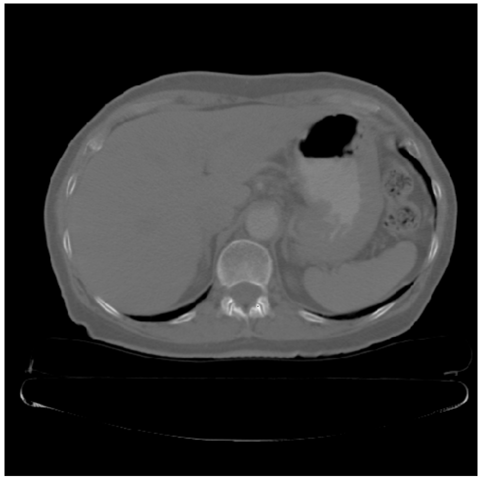


Red blood cell

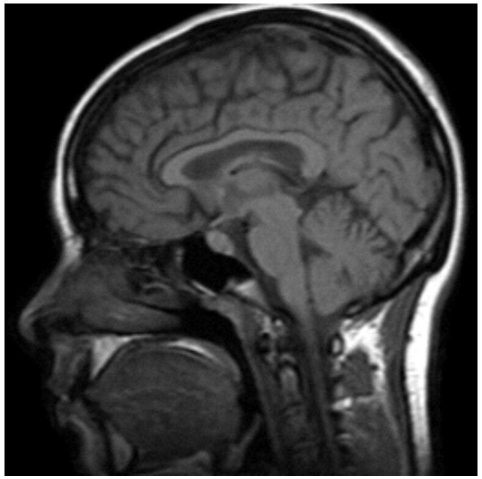
Bacteriorhodopsin

DNA-protein complex

Method-dependent images

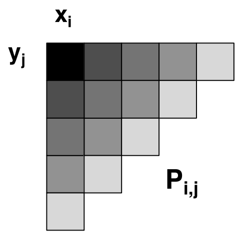


CT



MRI

The digital image



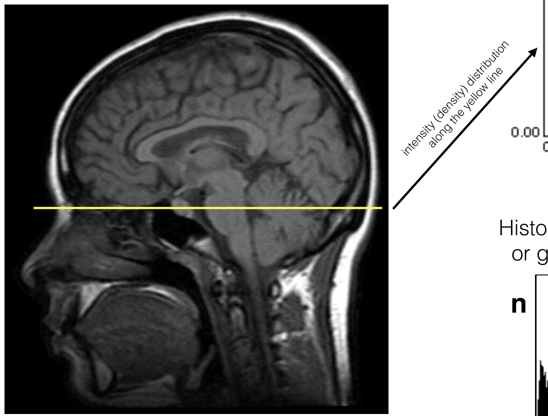
Digital image: information displayed at different
discrete spatial points in the form of color.
2 or 3 dimensional array or matrix
of picture elements.

Characteristics of the digital image:

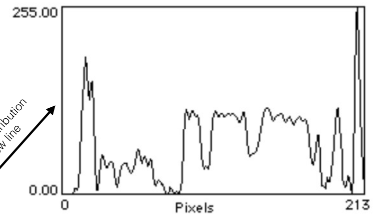
1. *Picture element: pixel (pix=picture; element)*
2. *Information associated with the pixel:*
   a. XY location: coordinates related to spatial resolution
   b. Color depth: intensities related to color (or grayscale)resolution
3. *Spatial resolution:*
   Number of resolved pixels in the X and Y directions.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

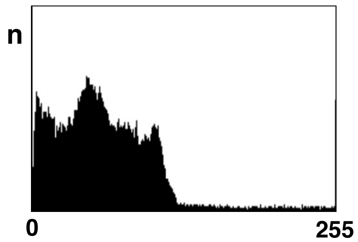
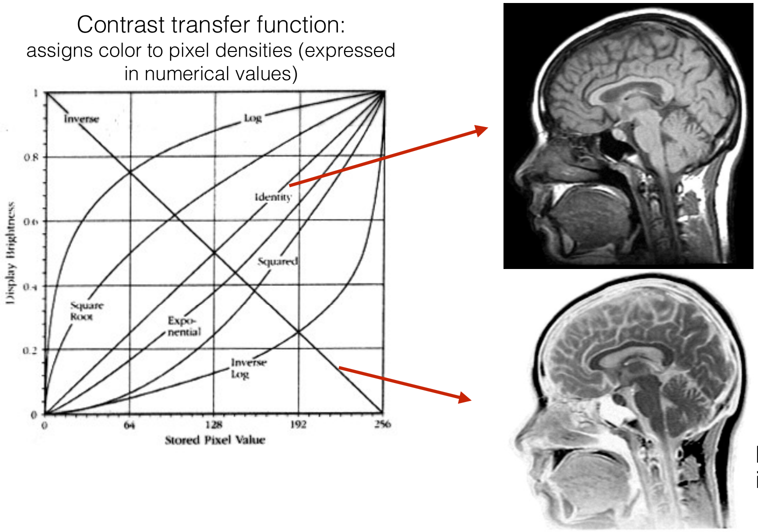


Image enhancement techniques: Contrast manipulation

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

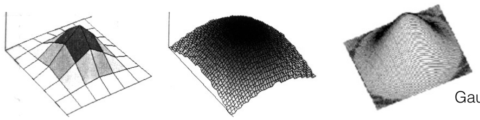
1	1	1
1	1	1
1	1	1

„smoothing" convolution

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

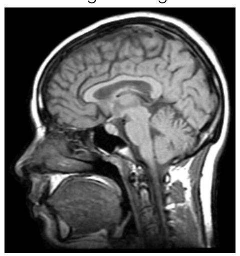
P=original pixel intensity
x,y=coordinates of the pixel on which operation is being executed
P*=modified pixel intensity
±m=size of kernel (distance from x,y coordinate)
W=weight of kernel at a given i,j coordinate
i,j=coordinates within kernel (integers between -m and +m)

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



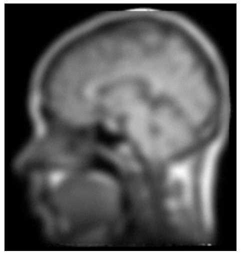
Gauss

Original image



Sharpening

Gauss (smoothing)



Edge detection

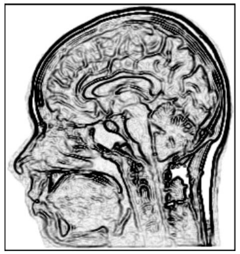
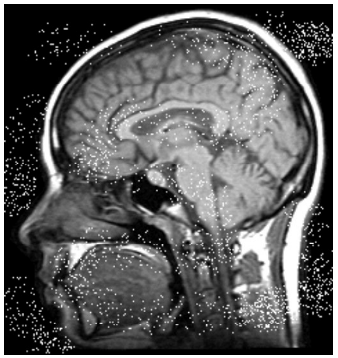


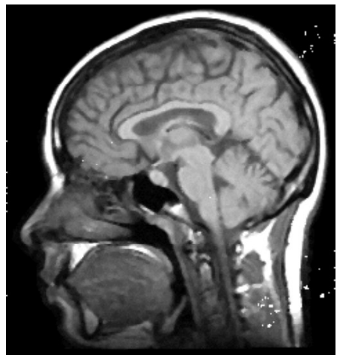
Image enhancement techniques: Rank operations

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

Noise removal using median filtering:



3x3 median filter

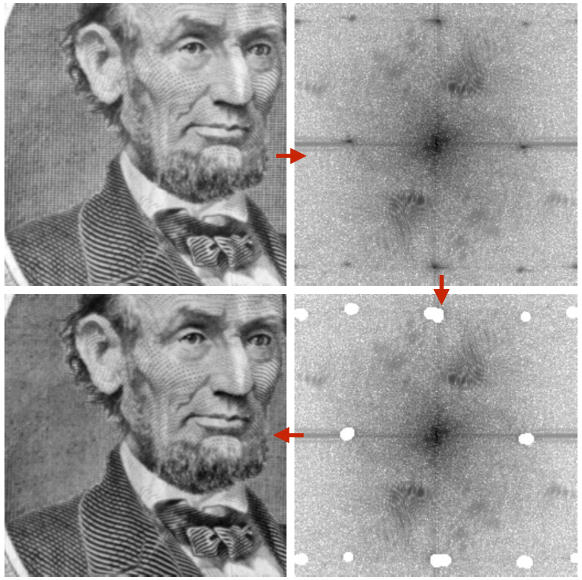


Fourier transformation

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.

Original image

FFT



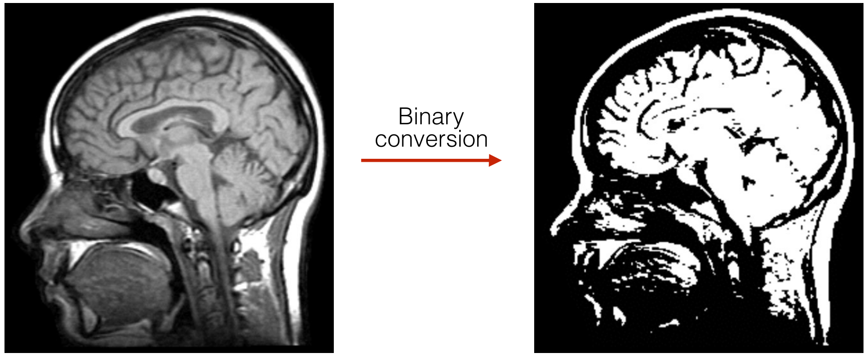
Inverse FFT

Masked FFT

Binary transformation: Thresholding, segmentation

Principle: The image is partitioned according to certain parameters.

Execution:
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"

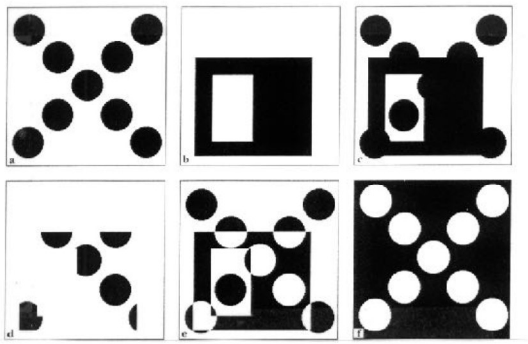


Binary operations: Boolean functions

„A" image

„B" image

„A" OR „B"
„A" union „B"



„A" AND „B"
„A" intersection „B"

„A" NOR „B"
(„A" union „B") -
(„A" intersection „B")

NOT „A"
Complement of „A"

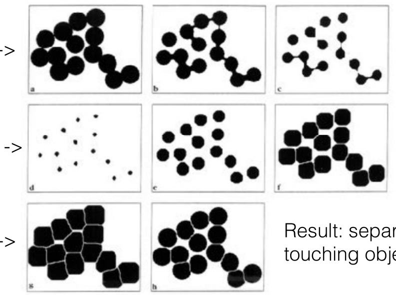
Binary operations: Erosion, dilatation, Opening, Closing

Moving pixels from the foreground to the background and vice versa

Erosion ->

Dilatation ->

Boolean operation ->



Result: separation of touching objects

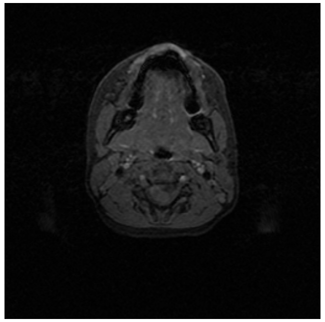
Erosion and dilatation with certain rules:

Original image

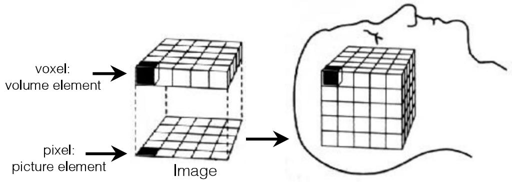
Binary image

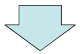
Skeletonized image

Outlined image



3D image processing





Spatial projection
(„volume rendering")

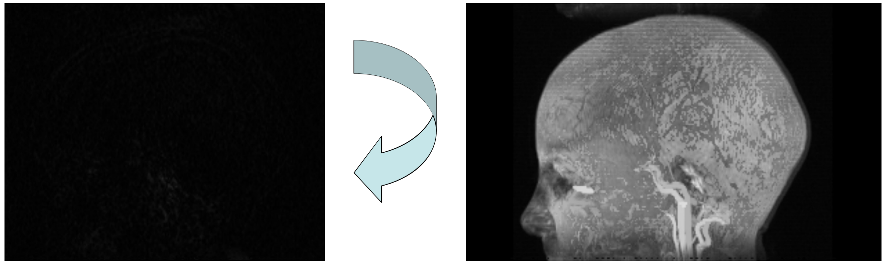
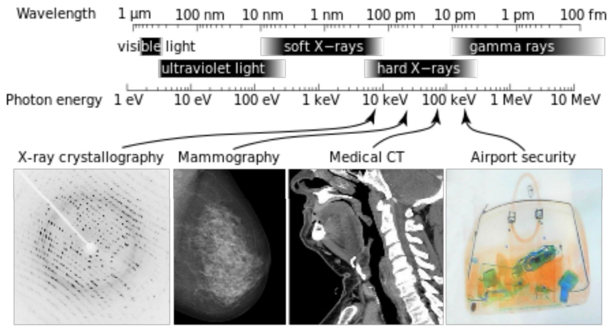


Image format of medical diagnostics: DICOM (Digital Imaging and Communications in Medicine)

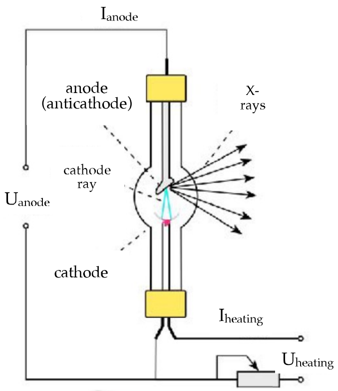
II. X-ray imaging

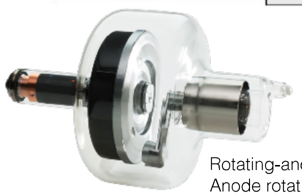
X-rays are electromagnetic waves



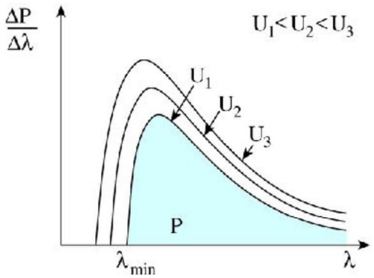
Wavelength 10 - 0.01 nm. ***Frequency*** 30×10^{15} - 30×10^{18} Hz. ***Energy*** 120 eV - 120 keV.
(petaherz - exahertz)

Generation of X-ray





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



Duane-Hunt formula:

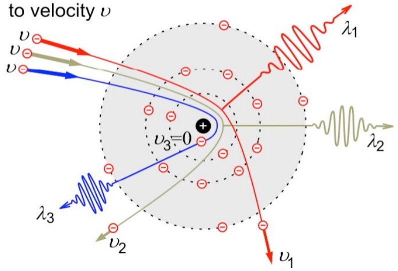
$$\lambda_{min} = \frac{hc}{e} \cdot \frac{1}{U_{anode}}$$

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

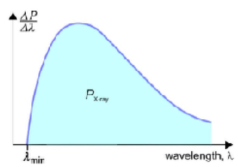
Mechanisms of X-ray generation

1. "Bremsstrahlung"
Breaking radiation
Deceleration radiation

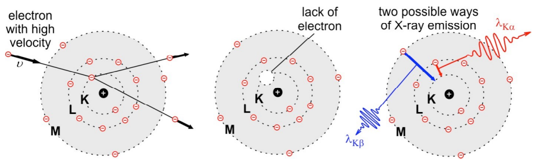
electrons
accelerated
to velocity υ



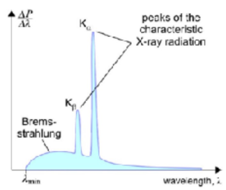
Continuous energy spectrum



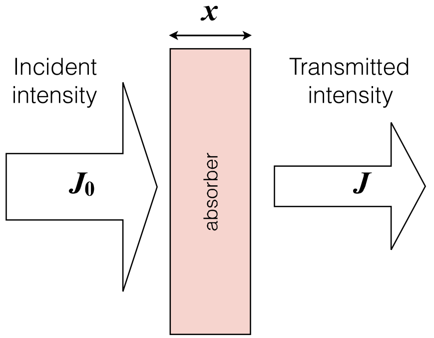
2. Characteristic radiation (X-ray fluorescence)



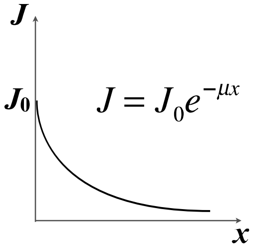
Linear energy spectrum



X-ray absorption



Exponential attenuation principle



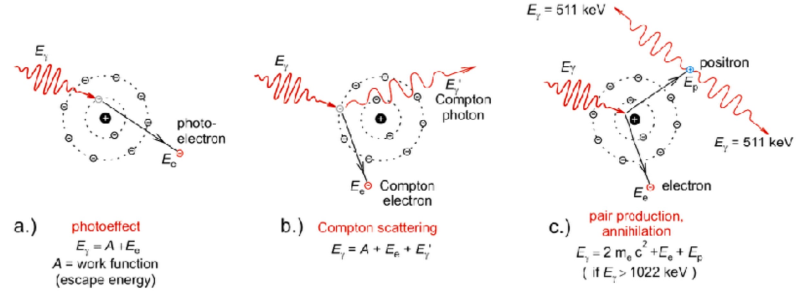
$$J = J_0 e^{-\mu x}$$

$$\mu = \mu_m \rho$$

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



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

$\tau_m, \sigma_m, \kappa_m$: 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. | No. 9.

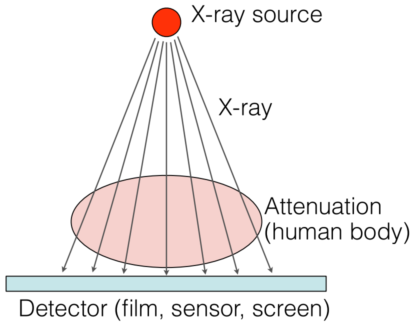
Am 28. Dezember wurde als Beitrag eingereicht:

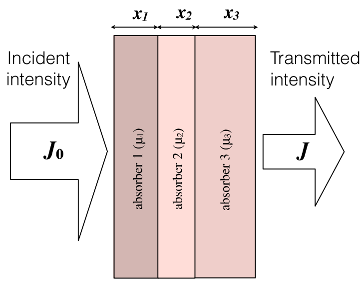
W. C. Röntgen: Ueber eine neue Art von Strahlen.

(Vorläufige Mittheilung.)

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



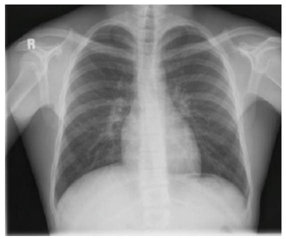


$$J = J_0 e^{-(\mu_1 x_1 + \mu_2 x_2 + \mu_3 x_3 + \ldots)}$$

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

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

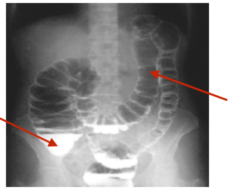
The X-ray image is a **summation image** ("X-ray image", "radiographic image", "roentgenogram"). Contrast arises due to spatially varying attenuation.



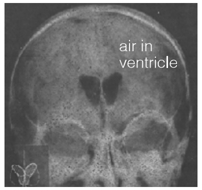
Improving X-ray imaging I.

Increasing contrast: contrast agents

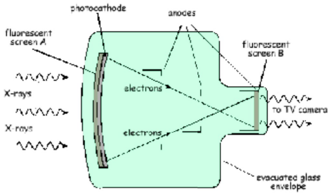
Positive contrast (large *Z*, e.g., Ba)



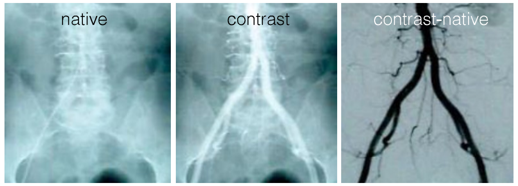
Negative contrast (small effective *Z*, e.g., air)



Enhancing sensitivity: intensifier

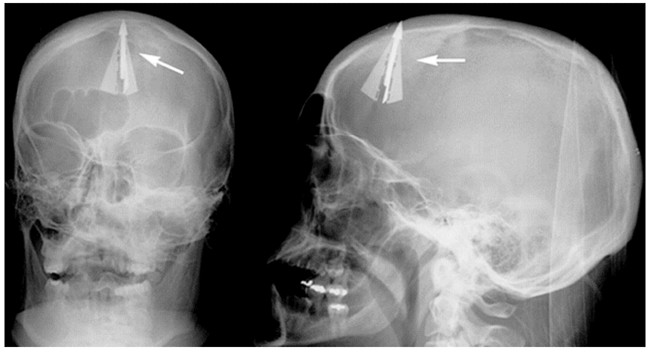


Background subtraction: "Digital Subtraction Angiography" (DSA)



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.

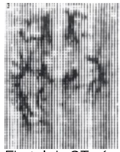
Improving X-ray imaging: the CAT scanner

History

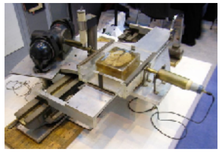
- Röntgen, Hounsfield and Cormack
- 1967: first CAT scan
- 1972: prototype
- 1974: first clinical CAT image (head)
- 1976: whole body CAT scan
- 1979: Nobe-prize
- 1990: spiral CAT scanner
- 1992: multislice CAT scanner
- 2006: 64 slice (and more…)
- multiple and hybrid modes: SPECT-CT, PET-CT, Dual-source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

Godfrey Hounsfield

Allan Cormack



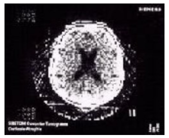
First, lab CT of a brain slice



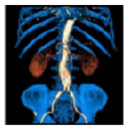
Prototype CAT scanner (EMI)

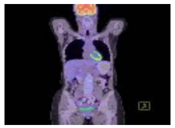
„Siretom" head scanner (1974)

128x128 pixel image (1975)



Multi-modal (combined) images

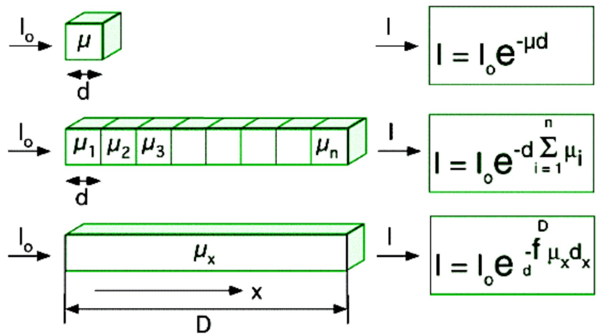




Current CAT scanner

CT Foundations I

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



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

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

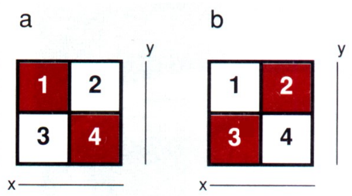
$I = I_0 e^{-\int_0^D \mu_x d_x}$

μ_x: linear attenuation coefficient

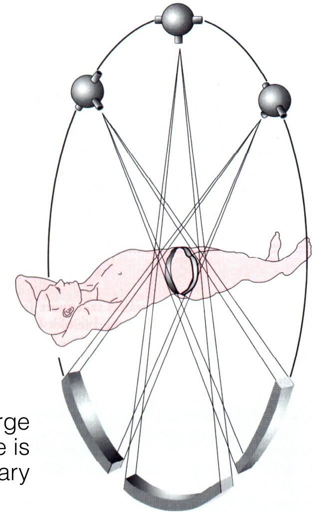
d_x: size of the voxel

CT Foundations II

Scanning in transaxial tomographic slices

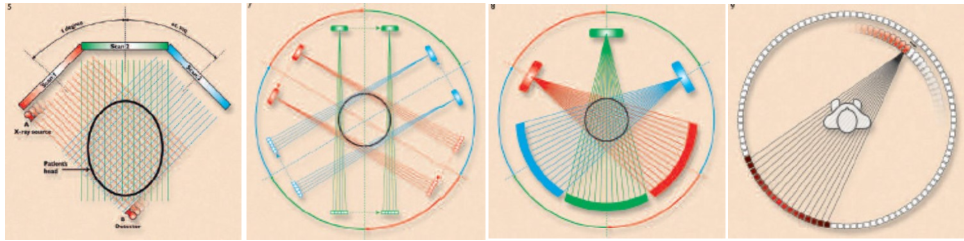


It is not possible to distinguish **a** from **b** in a bi-directional image



Scanning along as large angular resolution as possible is necessary

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.

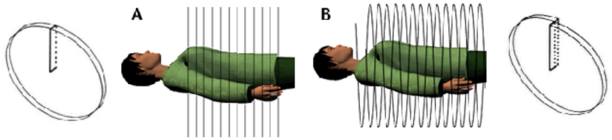
III. Generation.
There are a large number of X-ray beams (approximately 500 to 700) in a wide fan configuration. Both the X-ray tube and the detectors rotate.

III. 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.

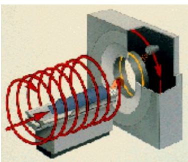
Current CT's use spiral (helical) scanning

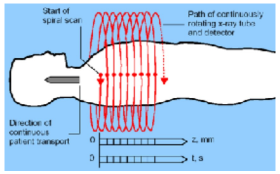
Source-detector pair rotates constantly

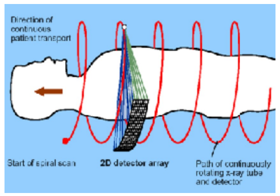
Conventional CT slice



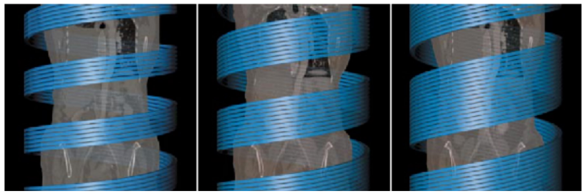
Spiral CT slice







Multi-detector CT (MDCT)



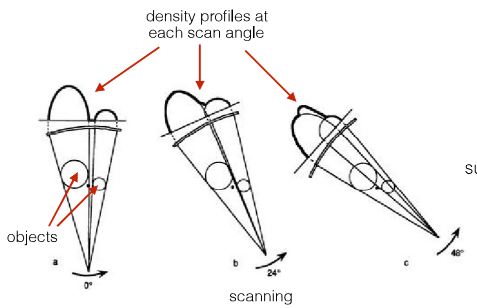
Multi-slice CT (MSCT)

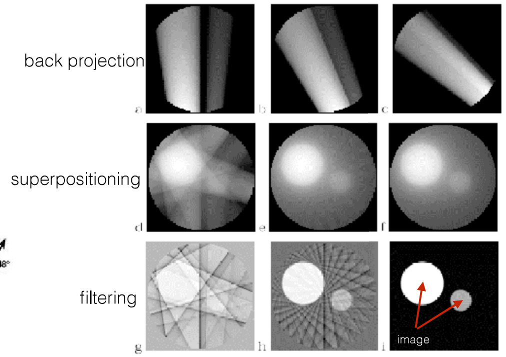
Summary of CT scanning (CAT)

- 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

CT Image Reconstruction

1. Algebraic reconstruction techniques
2. Direct Fourier reconstruction
3. „Filtered Back Projection" (current method)

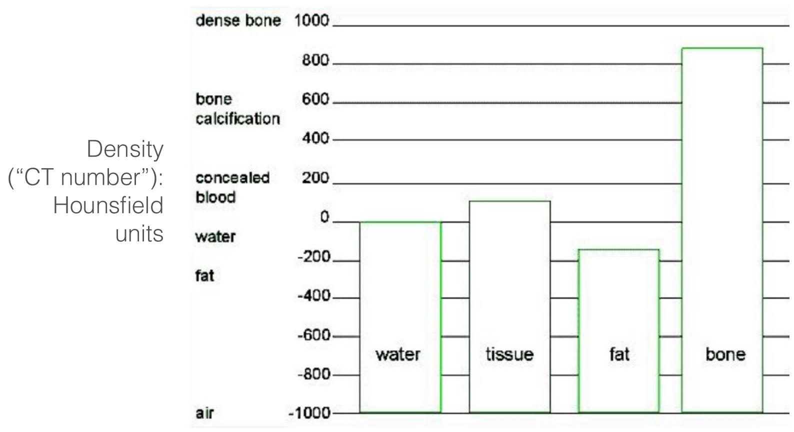




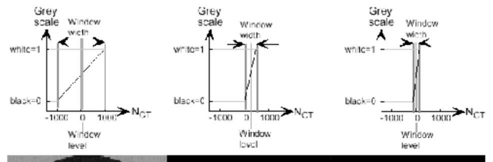
CT Image:
Density matrix

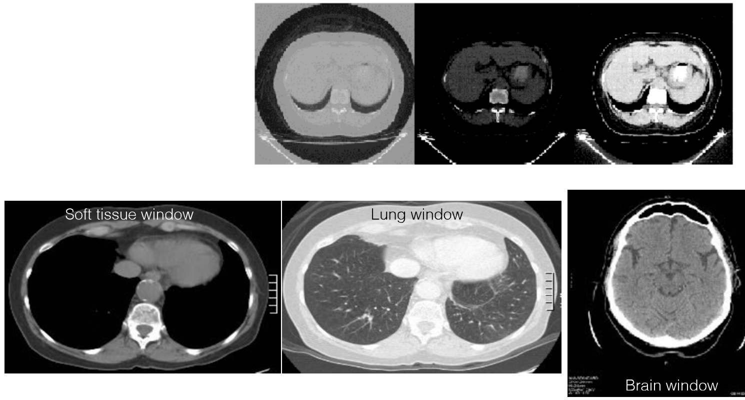
$$N_{CT} = 1000\frac{\mu - \mu_w}{\mu_w}$$

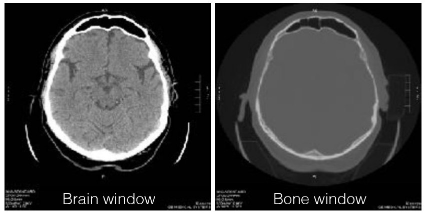
μ: attenuation coefficient of voxel
μ_w: attenuation coefficient of water



Contrast manipulation of CT Image
„Windowing"







Dual Source CT

- 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

CT contrast agents

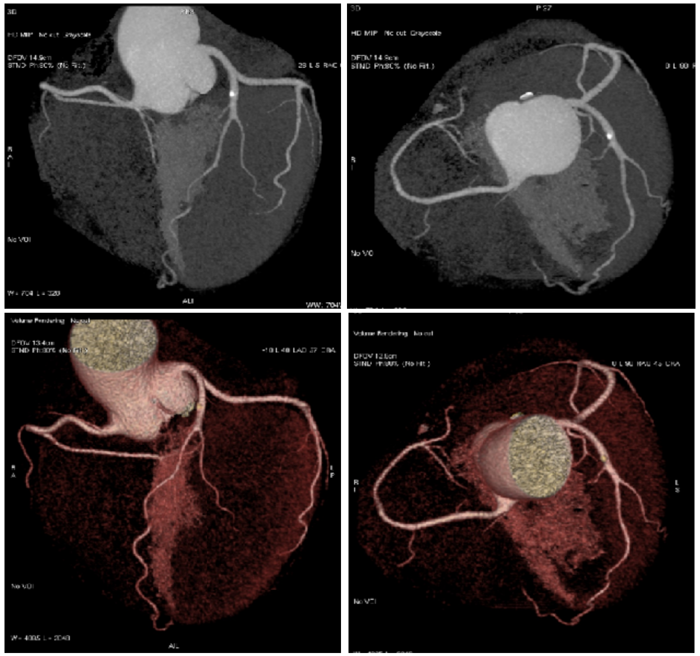
- Water soluble, iodine-containing macromolecule causing enhanced absorbance (hence color density) at the sites of accumulation
- Ionic contrast agent – outdated (abandoned since the 1990s)
- Non-ionic (monomeric or dimeric, low osmolality)
- Filtration through the kidney (nephrotropic). Its filtration 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 ≥ 1 cm (aorta)
- Spiral CT-angiography:
  Single-detector array spiral CT - aorta branches (d ≥ 2-3 mm)
  Multidetector array spiral CT - peripheral vessels (d ≥ 1 mm)

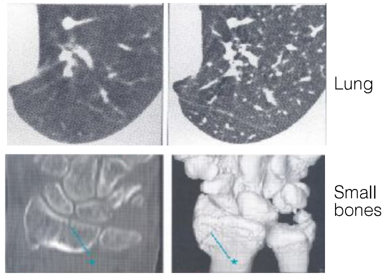
Renal artery aneurysm CTA 8 detector-array spiral CT

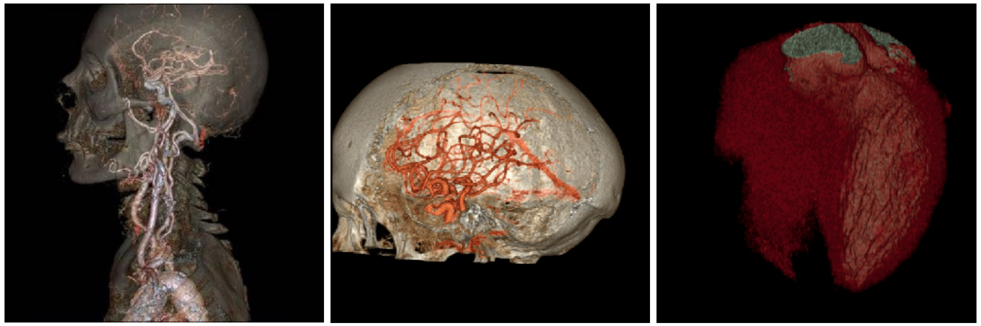
Coronary CT-angiography (CTCA) 64-slice MDCT



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.

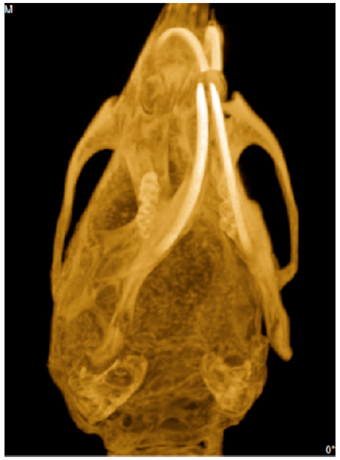




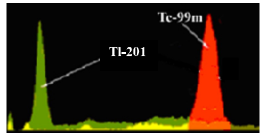
Limitations of CAT scanning

- 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)

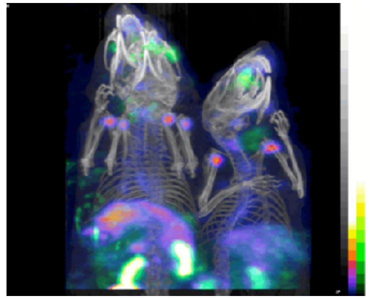
Hybrid technologies: NanoSPECT/CT



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



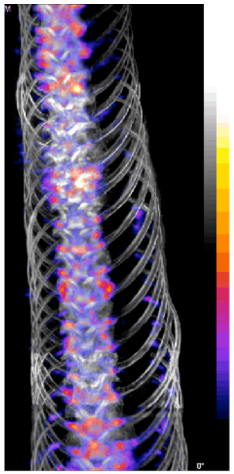
“Dual-channel” SPECT



^{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)