MEDICAL IMAGING METHODS

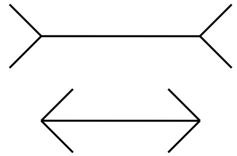
Miklós Kellermayer

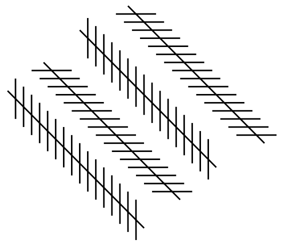
I. The digital image

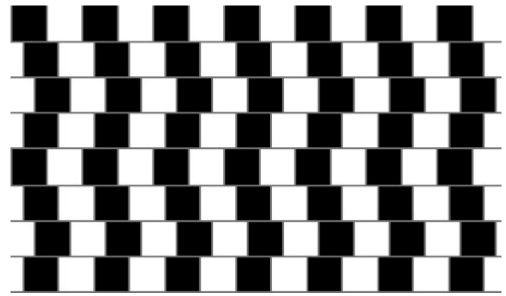
Seeing is believing!?

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

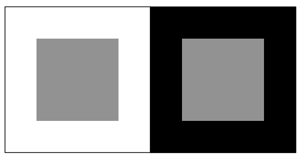
Optical illusions – size, direction

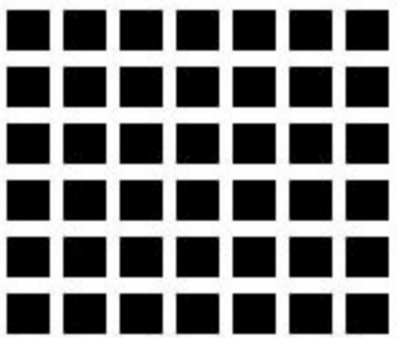


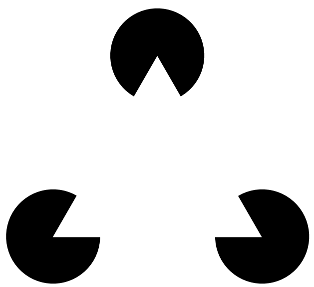




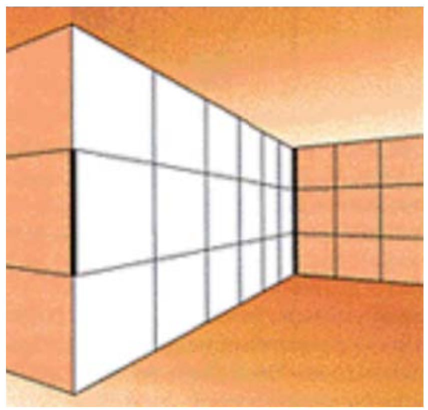
Optical illusions - intensity (color density)

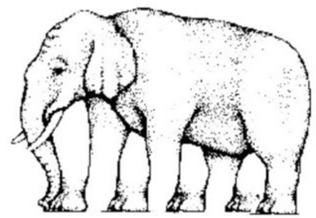


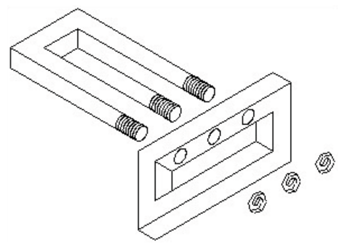




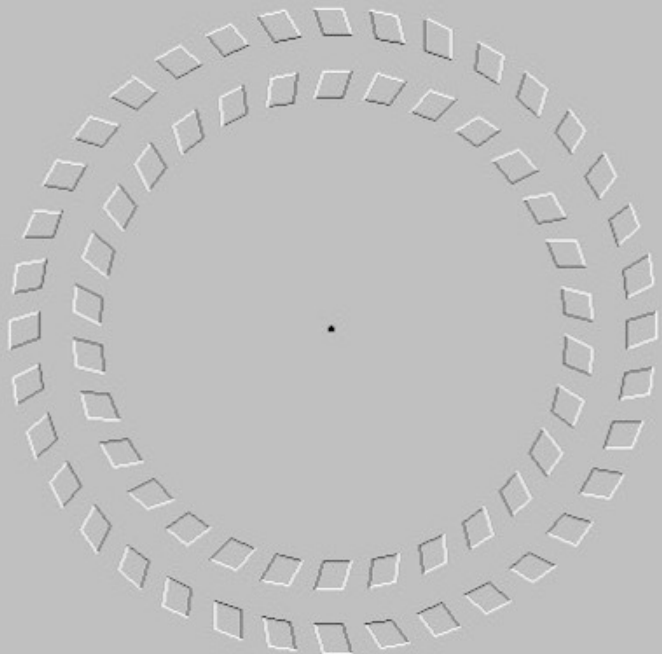
Optical illusions – space







Optical illusions – motion



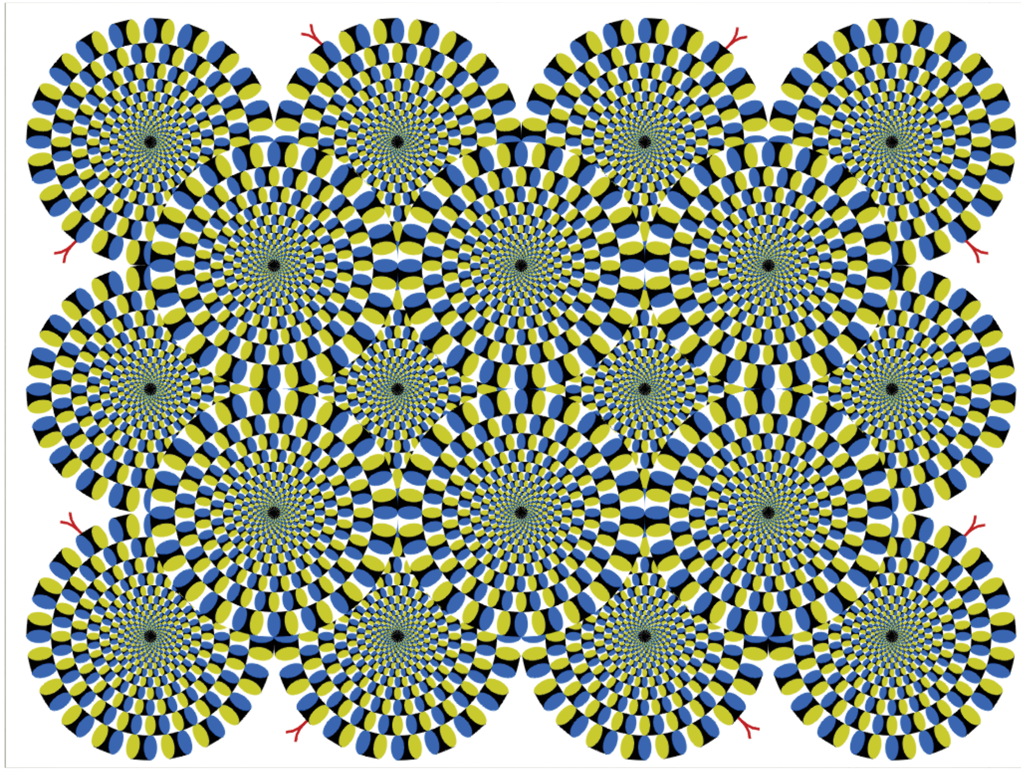
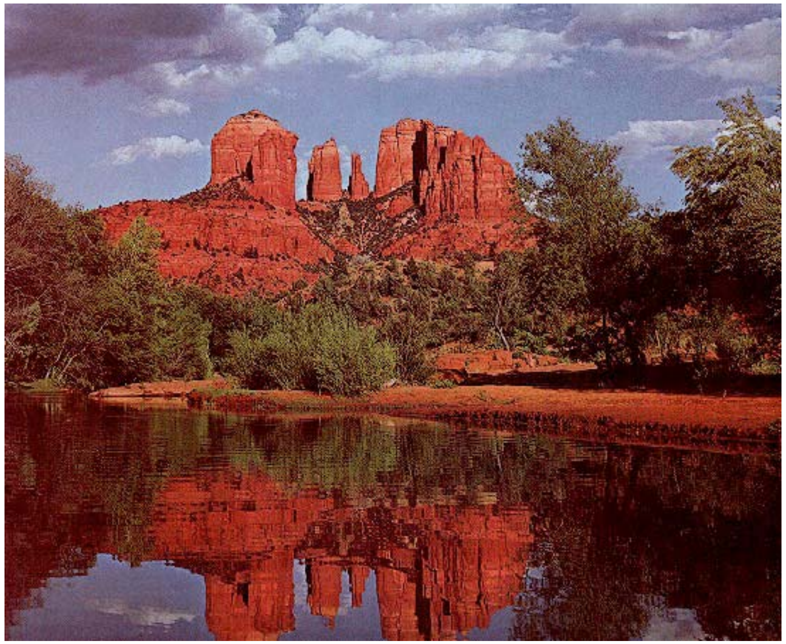
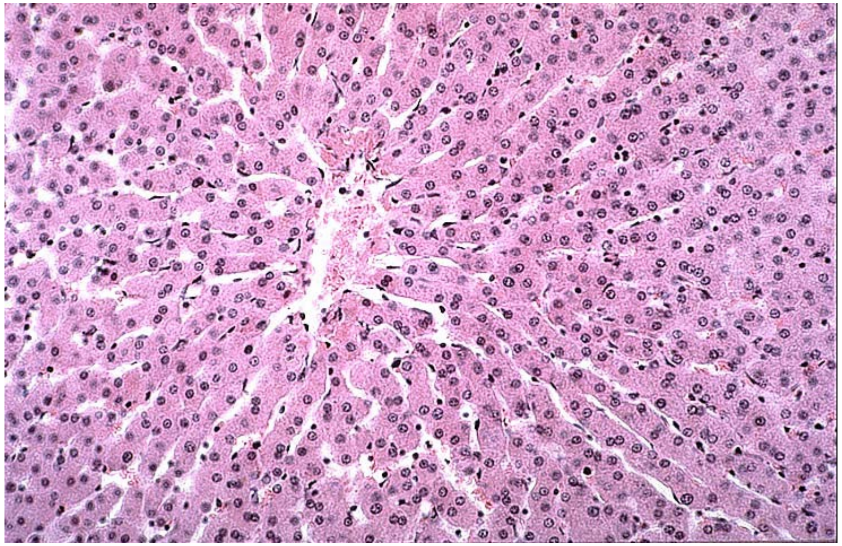


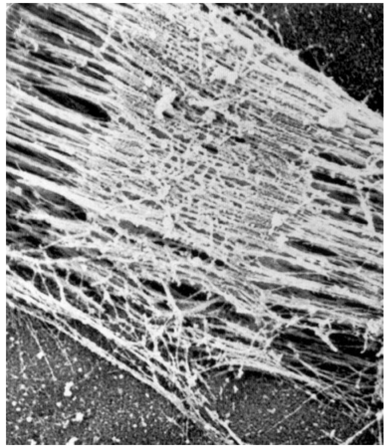
Image: information that is visible … or not?



Light microscopic image
Hepatic lobule

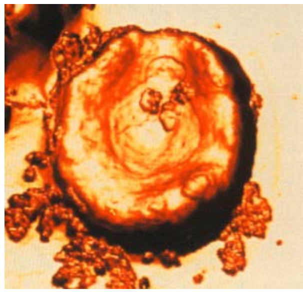


Scanning electron microscopic images

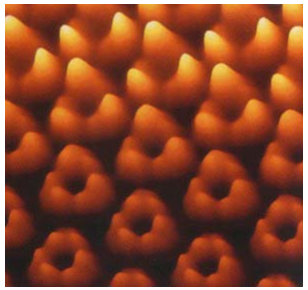


Atomic force microscopic images

Red blood cell

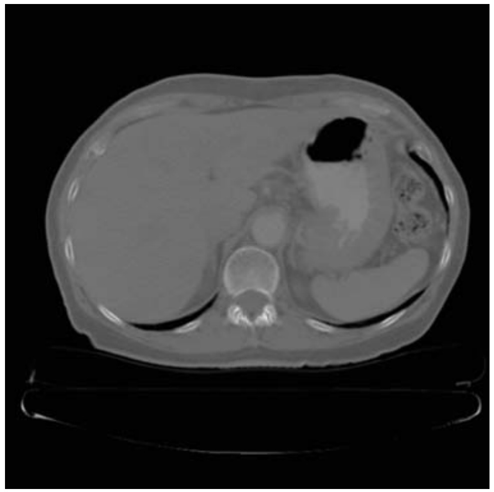


bacteriorhodopsin

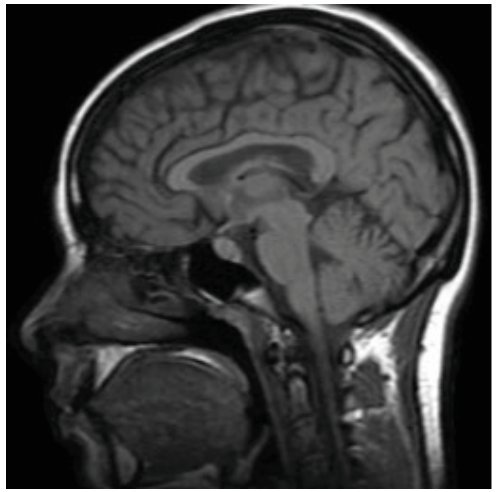


DNA

CT



MRI



Digital Image Analysis

1. The digital image
    a. Generation
    b. Characteristics

2. Image enhancement techniques
    a. Contrast manipulation
    b. Convolution
    c. Rank operations

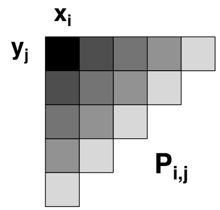
3. Geometric transformations

4. Fourier transformation

5. Thresholding and segmentation

6. 3D image analysis

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.

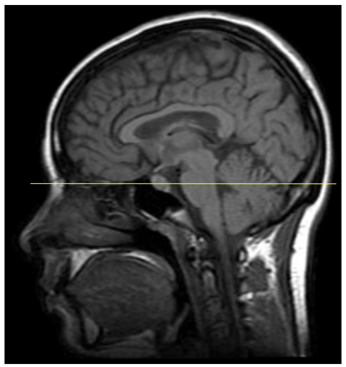
4. Grayscale/color depth:

Number of resolved colors/grayscale intensities (bit)

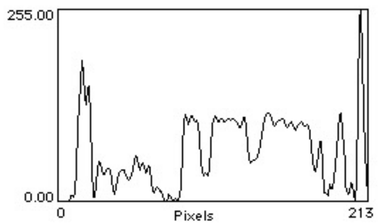
(BUT: color is not necessarily real; e.g. AFM, CT, MRI)

THE COLOR HISTOGRAM

(intensity histogram, "grayscale" histogram)



Resolved intensities may be displayed as a function



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

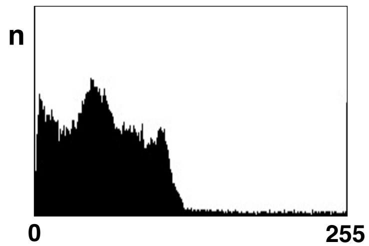
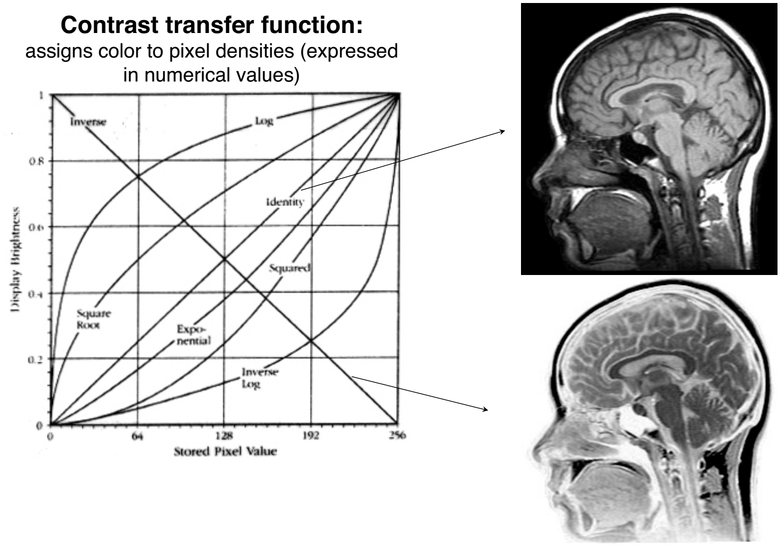


Image enhancement techniques I.

Contrast manipulation A.

Contrast transfer function:

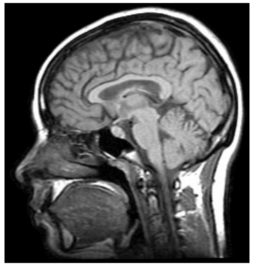
assigns color to pixel densities (expressed in numerical values)

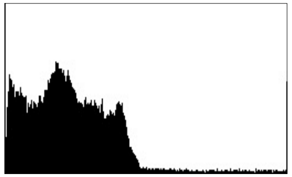


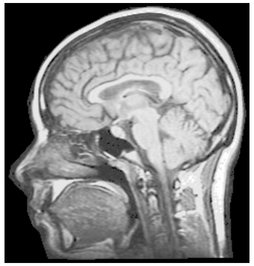
Contrast manipulation B.

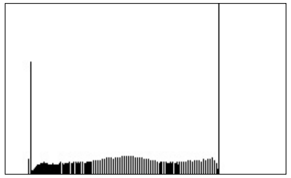
Histogram equalization

Goal: best use of the available color/grayscale range









The cumulative histogram of the image is used as its contrast transfer function

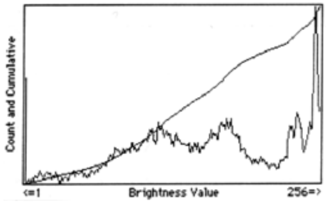


Image enhancement techniques II.

Convolution

Special transformation between two functions (the image and the kernel)

Kernel operations

„smoothing" kernel

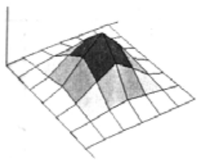
1	1	1
1	1	1
1	1	1

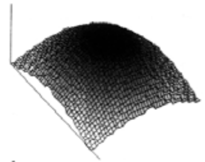
„smoothing" convolution

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

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 kernels


a


b

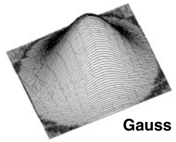
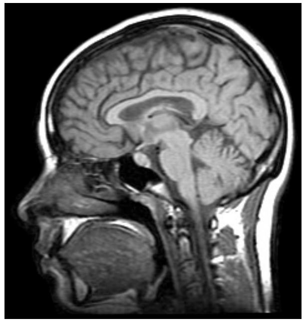

Gauss

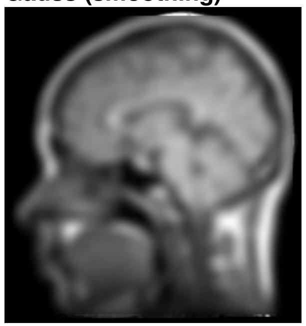
Image enhancement techniques II. Convolution

Original image



Sharpening

Gauss (smoothing)



Edge detection

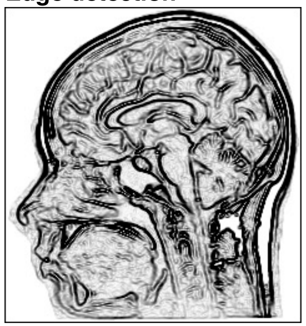
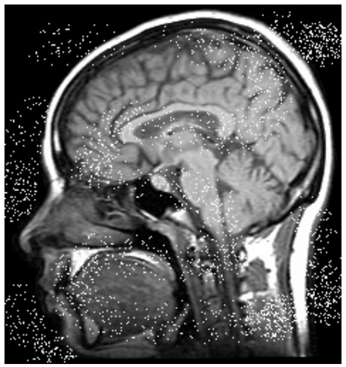


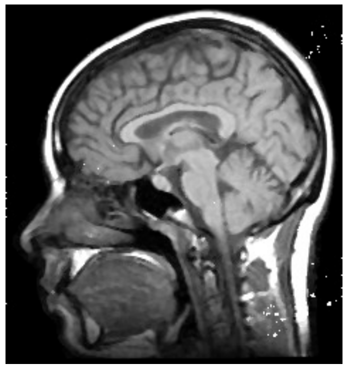
Image enhancement techniques III. Rank operations

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

Noise removal using median filtering:

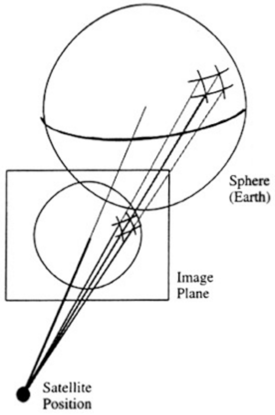


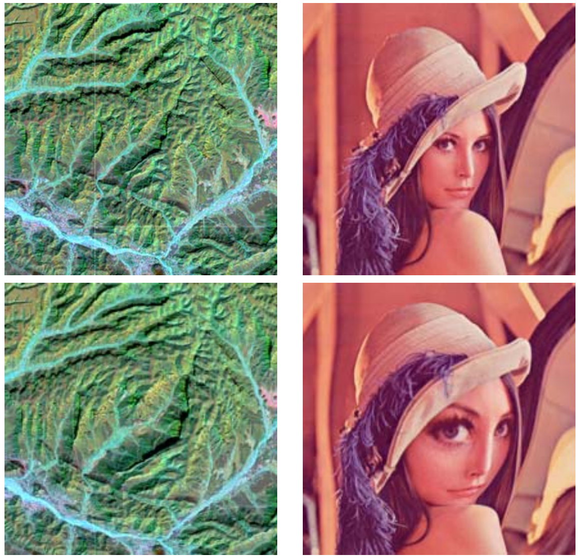
3x3 median filter →



Geometric transformations

Basic problem: 2D image from 3D object





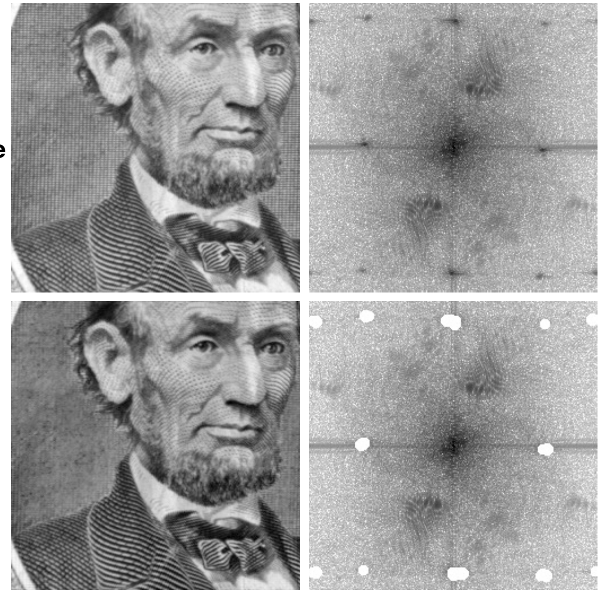
IV. Fourier transformation

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

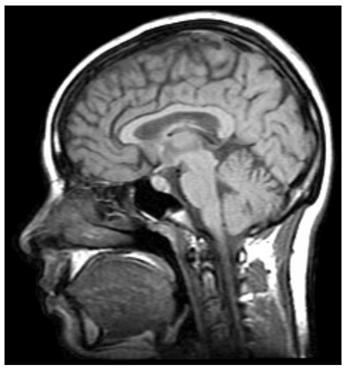
Masked FFT

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 image →

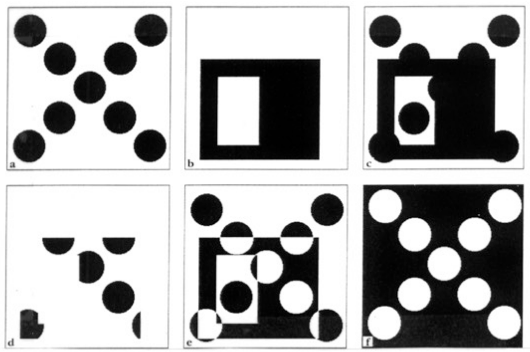
Binary operations I.

Boolean operations

„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 II.

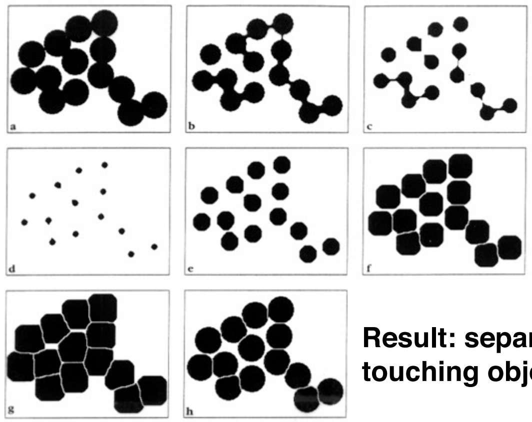
Erosion, dilatation, Opening, Closing

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

Erosion ->

Dilatation ->

Boolean operation ->



Result: separation of touching objects

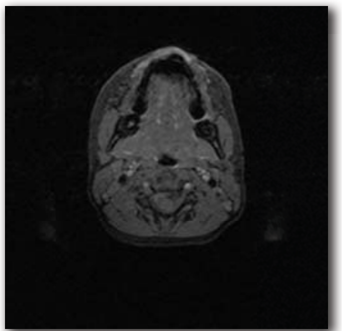
Binary operations III.

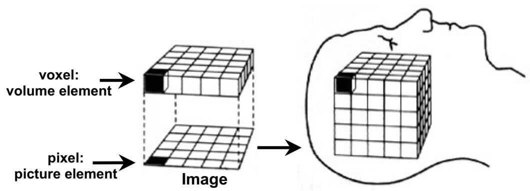
Skeletonization, Outlining

Erosion and dilatation with certain rules

Original image	Binary image	Skeletonized image	Outlined image

3D image processing





Spatial projection („volume rendering")

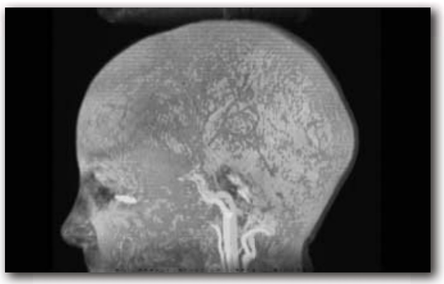
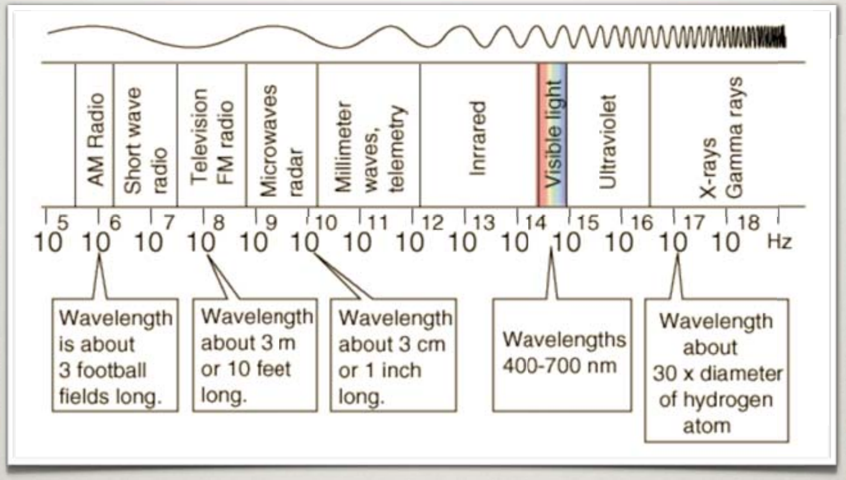


Image format of medical diagnostics: DICOM (Digital Imaging and Communications in Medicine)

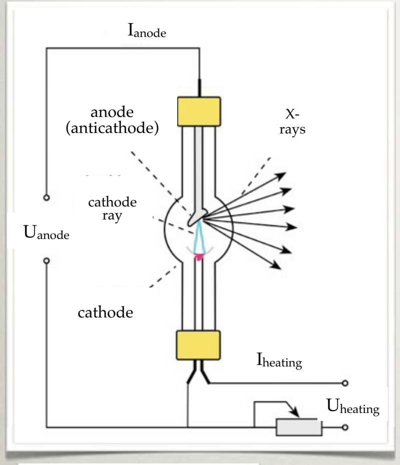
II. X-ray imaging

X-rays are electromagnetic waves

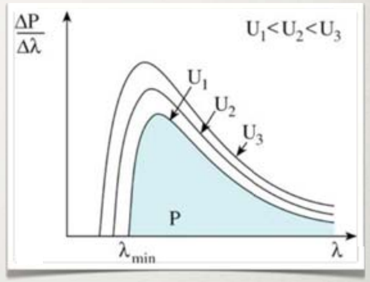


Wavelength 10 - 0.01 nm. ***Frequency*** 30×10^{15} - 30×10^{18} Hz. ***Energy*** 120 eV - 120 keV.

Generation of X-ray



Rotating anode X-ray tube

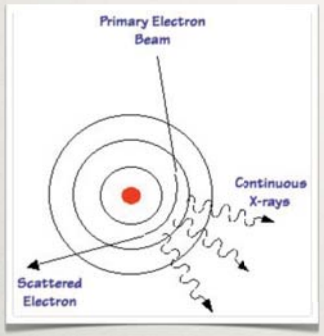


Duane-Hunt formula:

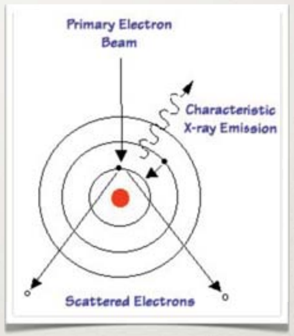
$$\lambda_{min} = \frac{hc}{e} \cdot \frac{1}{U_{anode}}$$

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

Mechanisms of X-ray generation



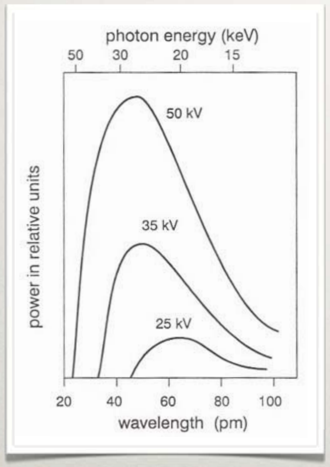
"Bremsstrahlung"
Breaking radiation
Deceleration radiation



Characteristic radiation
X-ray fluorescence

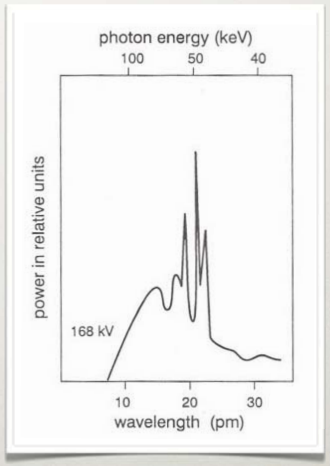
Spectral features of X-ray

"Bremsstrahlung"



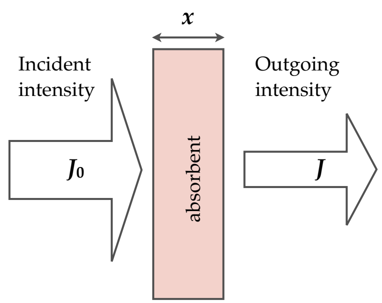
Continuous spectrum

Characteristic radiation

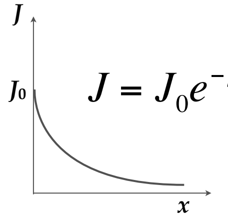


Linear spectrum

X-ray absorption



Exponential attenuation principle

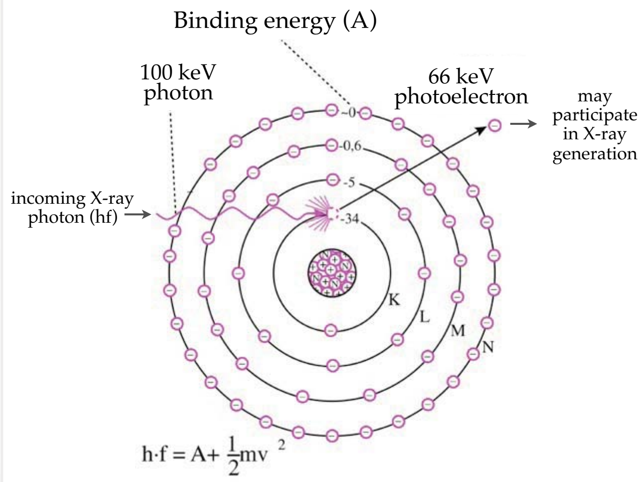


$$J = J_0 e^{-\mu x}$$

$$\mu = \mu_m \rho$$

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

X-ray photoeffect

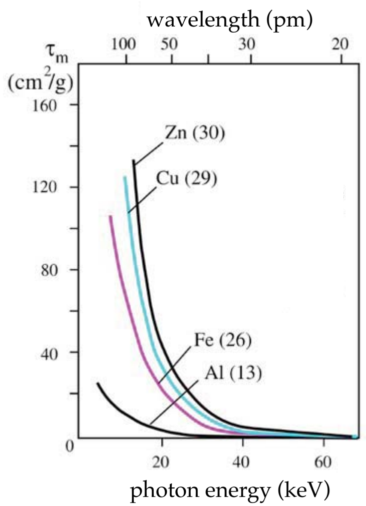


Main effect in diagostic X-ray!

Photoeffect attenuation coefficient:

$$\tau = \tau_m \rho$$

Photoeffect attenuation depends strongly on atomic number



$$\tau_m = const \cdot \frac{Z^3}{\varepsilon^3} = C \cdot \lambda^3 \cdot Z^3$$

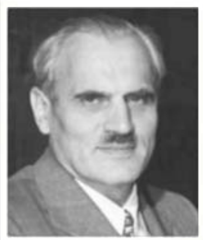
For multi-component system:
"effective atomic number" (Z_{eff})

$$Z_{eff} = \sqrt[3]{\sum_{i=1}^{n} w_i Z_i^3}$$

ε=photon energy
Z=atomic number
w=mole fraction
n=number of components

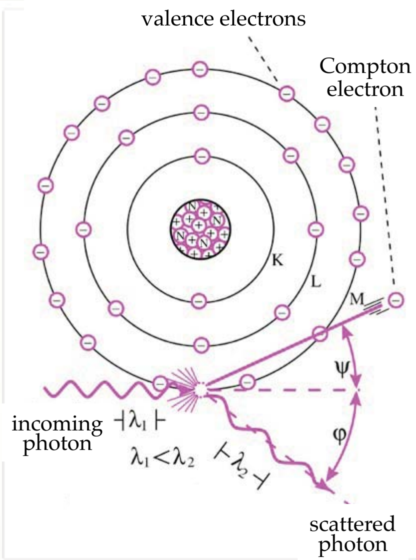
Material	Z_{eff}
Air	7.3
Water	7.7
Soft tissue	7.4
Bone	13.8

Compton scatter

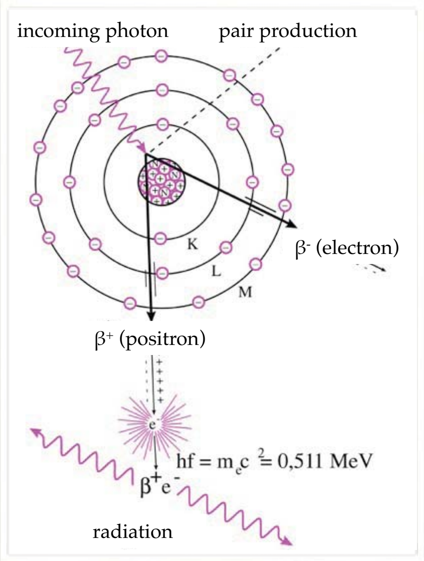


Arthur Holly Compton (1892-1962)

$$hf = A + hf_{scatt} + E_{kin}$$



Pair production



Energy balance:

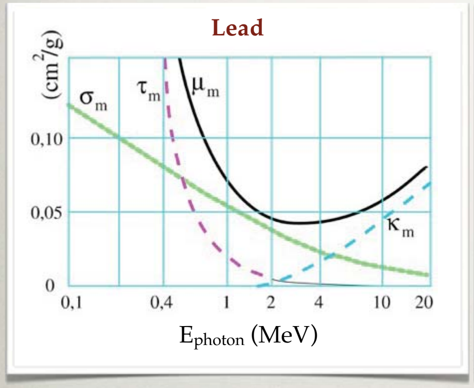
$$hf = 2m_e c^2 + 2E_{kin}$$

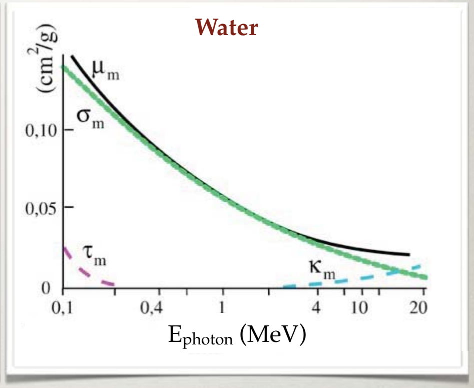
m_e=mass of electron
c=speed of light

Pair production relevant in high-energy X-ray photons, γ-radiation.

Attenuation mechanisms

Dependence on photon energy and material





$$\mu = \tau + \sigma + \kappa$$

μ_m=mass attenuation coefficient
σ_m=Compton effect mass attenuation coefficient
τ_m=photoeffect mass attenuation coefficient
κ_m=pair production mass attenuation coefficient

Summary of attenuation mechanisms

Mechanism	Variation of μ_m with E	Variation of μ_m with Z	Energy range in tissue
Rayleigh	~ 1 / E	~Z^2	1 - 30 keV
photoelectric	~1 / E^3	~Z^3	10 - 100 keV
Compton	falls gradually with E	independent ~Z	0.5 - 5 MeV
pair production	rises slowly with E	~ Z^2	> 5 MeV

Main contrast mechanism in diagnostic X-ray: photoelectric effect (~Z^3)

Imaging with X-ray

Wilhelm Konrad Röntgen (1845-1923)

Sitzungs-Berichte
der
Physikalisch-medicinischen Gesellschaft
zu
WÜRZBURG.

Jahrgang 1895.

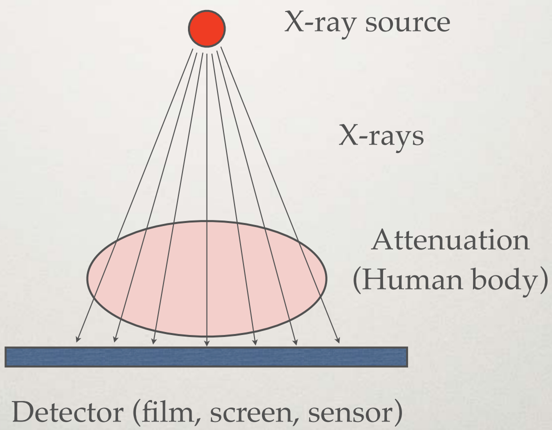
Am 28. Dezember wurde als Beitrag eingereicht:

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.

Principle of X-ray imaging



The X-ray image

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

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

μ and x are attenuation coefficient and thickness of elementary volume unit lying in the direction of X-ray beam.

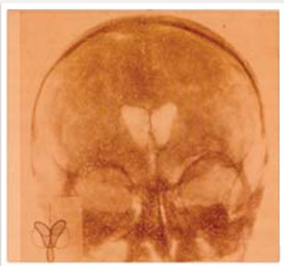
X-ray image is summation image.

"X-ray image", "radiographic image", "roentgenogram".

Contrast arises due to relative attenuation.

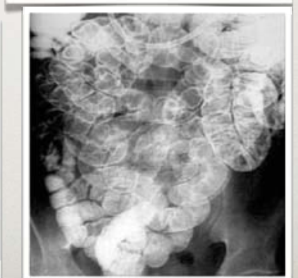
Radiographic contrast

Bowels (positive contrast)



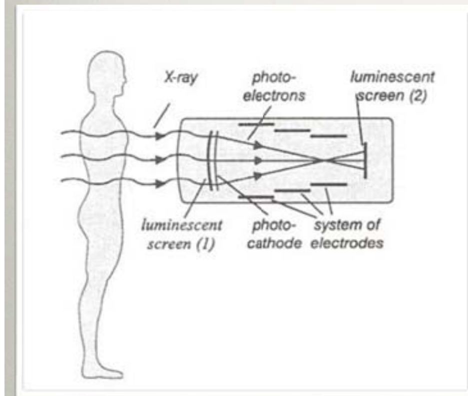
Air (negative contrast)

Large intestine (double contrast)



Small intestine (double contrast)

Improving the X-ray image
The image intensifier



Possibility of image digitization.

Digital Subtraction Angiography (DSA)

Image 1
native

Image 2
contrast

DSA image
contrast-native

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

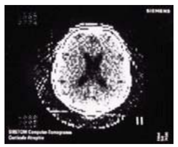
History

- 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

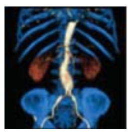
Godfrey Hounsfield

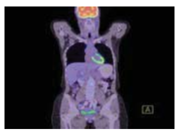
Allan Cormack

„Siretom" head scanner (1974)

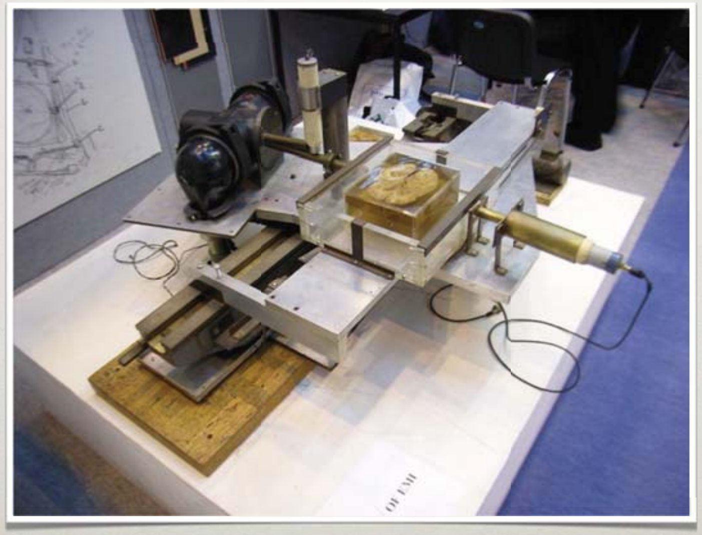


128x128 pixel image (1975)



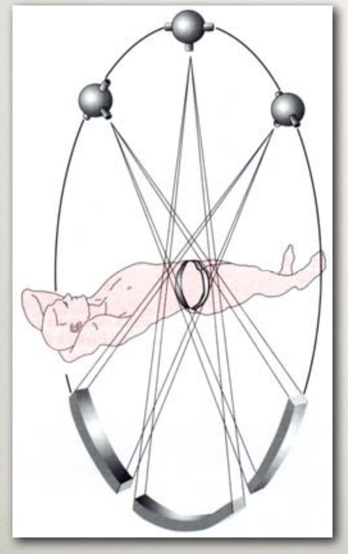


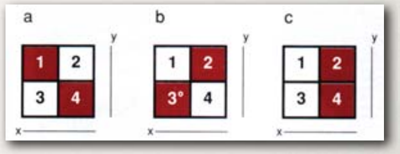
Prototype CT scanner

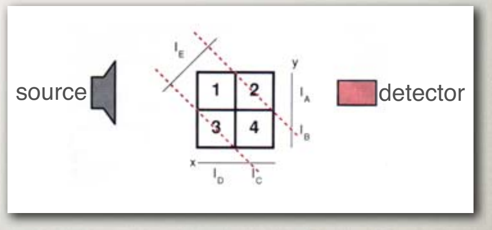


The very first ct scanner prototype. Invented by Houndsfield at EMI.

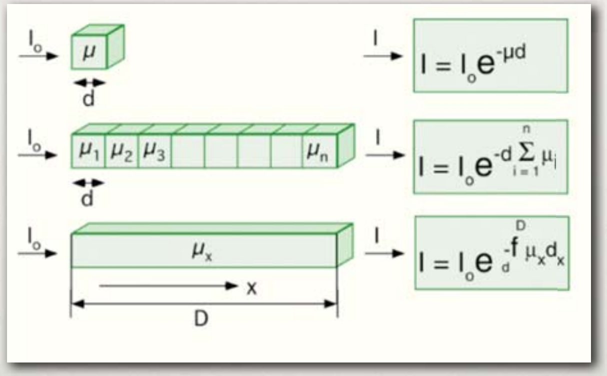
CT Foundations I





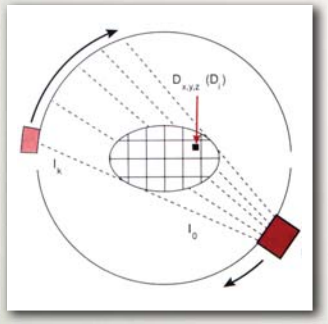


CT Foundations II

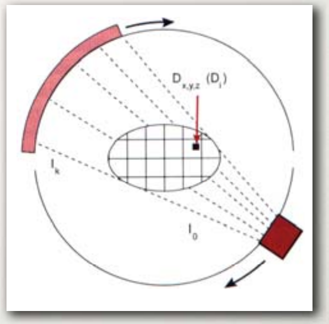


μ_x: linear attenuation coefficient

Scanning I

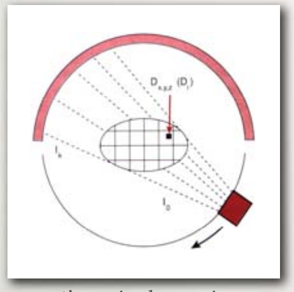


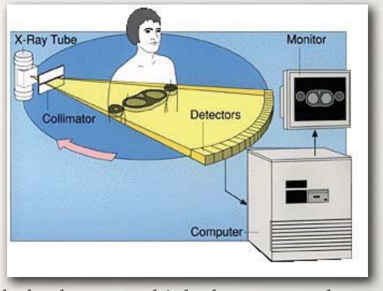
I. generation
Single moving source
Single moving detector



II. generation
Single moving source
Narrow fan-beam
Multiple moving detectors

Scanning II





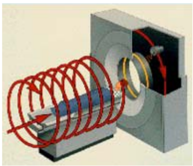
III-IV. generation: single moving source, wide fan-beam, multiple detectors or detector ring

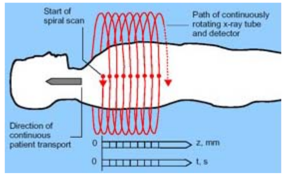
closed gantry

open gantry

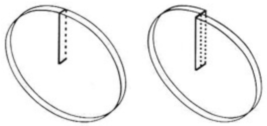
Spiral (helical) CAT scaning

Source-detector pair rotates constantly

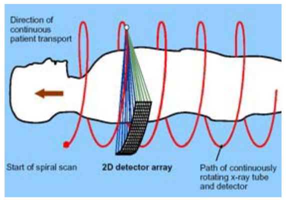




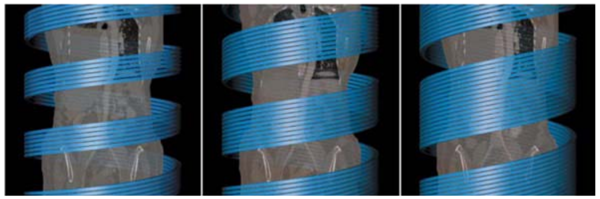
Conventional CT slice



Spiral CT slice



Multi-detector CT (MDCT)



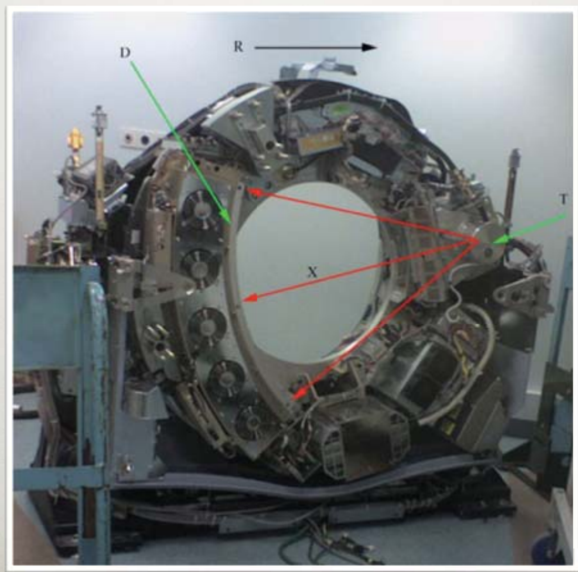
Multi-slice CT (MSCT)

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 scanner operation

Detectors



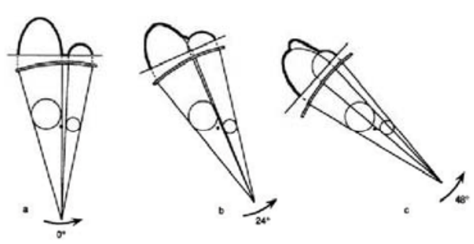
Rotation

Tube

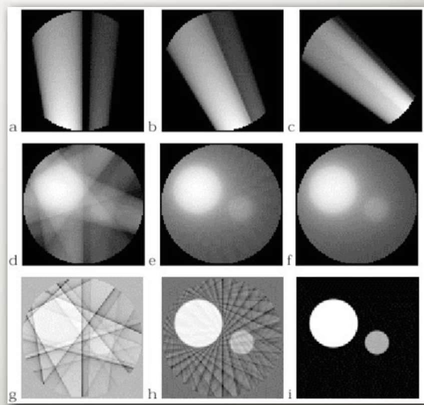
X-ray beams

CT Image Reconstruction

1. Algebraic reconstruction techniques
2. Direct Fourier reconstruction
3. „Filtered Back Projection"



CT image:
4000 detectors
1000 projections
512x512 matrix
16 bit color depth

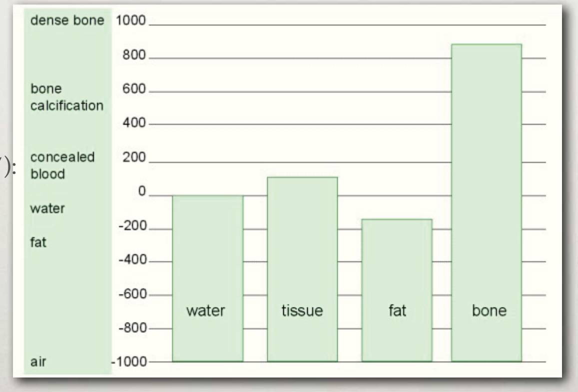


CT Image: Density matrix

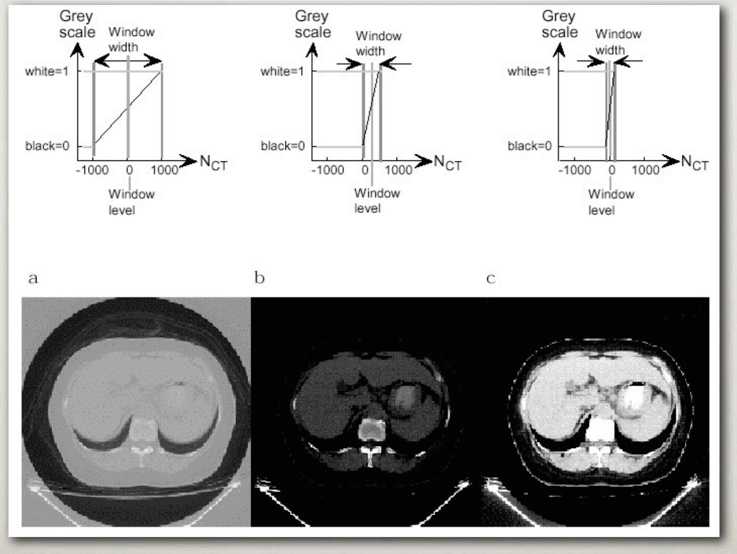
$$N_{CT} = 1000 \frac{\mu - \mu_w}{\mu_w}$$

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

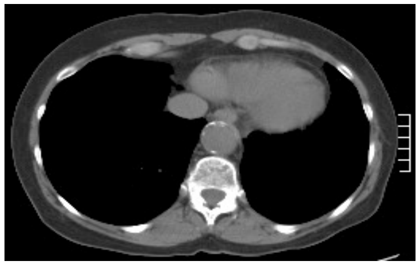
Density ("CT number"): Hounsfield units



Contrast manipulation of CT Image „Windowing"



Manipulation of CT contrast
„Windowing"



Soft tissue window

Lung window

Brain window

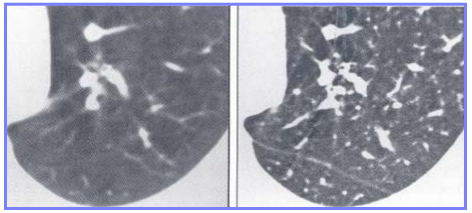
Bone window

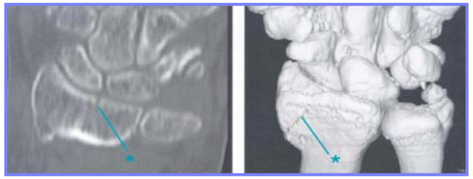
Limitations of CAT scanning

- 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)

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





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

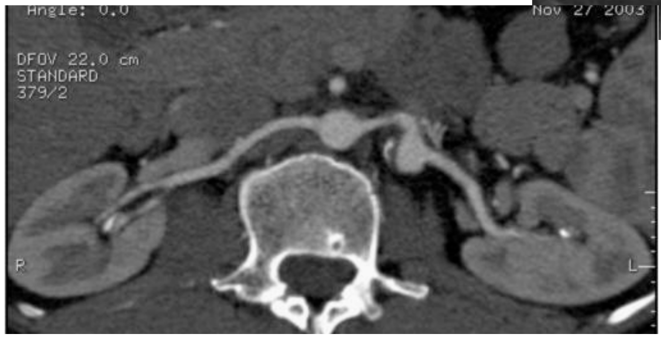
- Water soluble, iodine-containing macromolecule causing enhanced absorbance (hence color density) at the sites of accumulation
- Ionic contrast agent – outdated (abandoned since the 1990s)
- Non-ionic (monomeric or dimeric, low osmolality)
- Filtration through the kidney (nephrotropic). Its filtration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

Imaging blood vessels - CT angiography

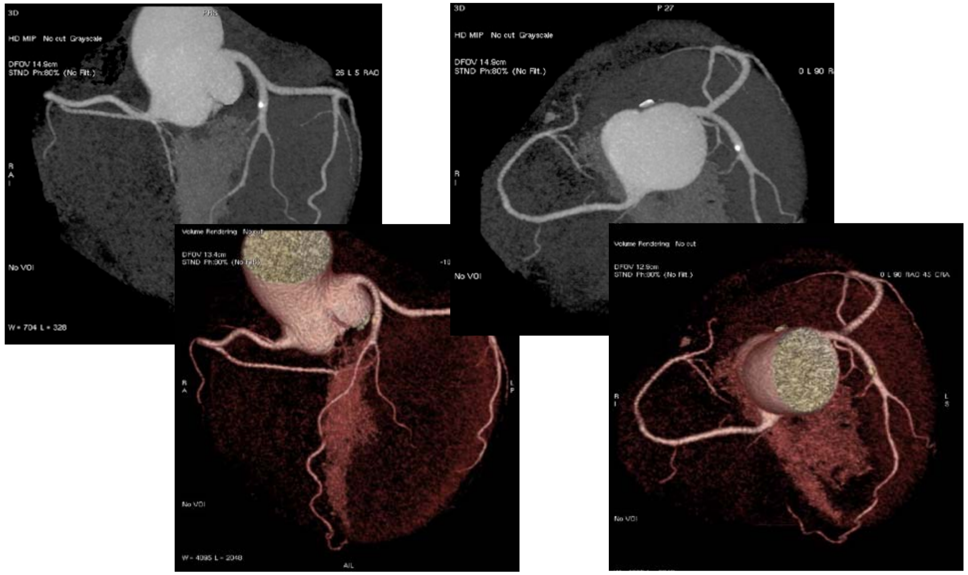
- Native CT: limited applications. Only in case of severely calcified vessel walls
- With intravenous contrast agents:
  ”conventional” technique - vessels with d ≥ 1 cm (aorta)
- Spiral CT-angiography:
  Single-detector array spiral CT - aorta branches (d ≥ 2-3 mm)
  Multidetector array spiral CT -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

Renal artery aneurysm

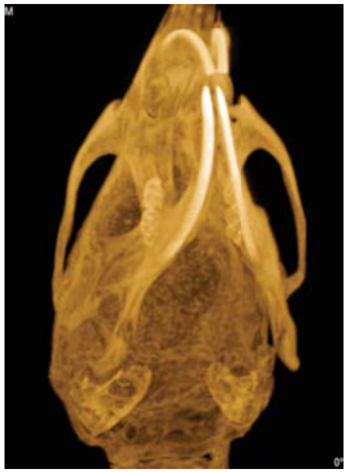
CTA 8 detector-array spiral CT



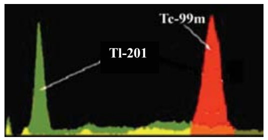
Coronary CT-angiography (CTCA) 64-slice MDCT



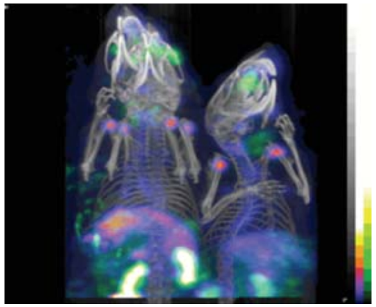
Hybrid technologies: NanoSPECT/CT



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



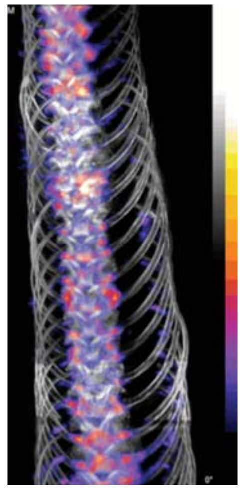
"Dual-channel" SPECT



^{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)