Medical Imaging: an introduction

Purpose: to look into the patient and identify the spatial distribution of parameters of interest like:

• morphology of tissues, bones, organs,.. eg radiography/magn. res

• regions where pathologies are localized

• physiological functionalities (and their time evolution)

Main techniques for medical imaging:

we see these in red, btw they use radiations

TAC

- X-ray radiography, X-ray computed tomography (CT)

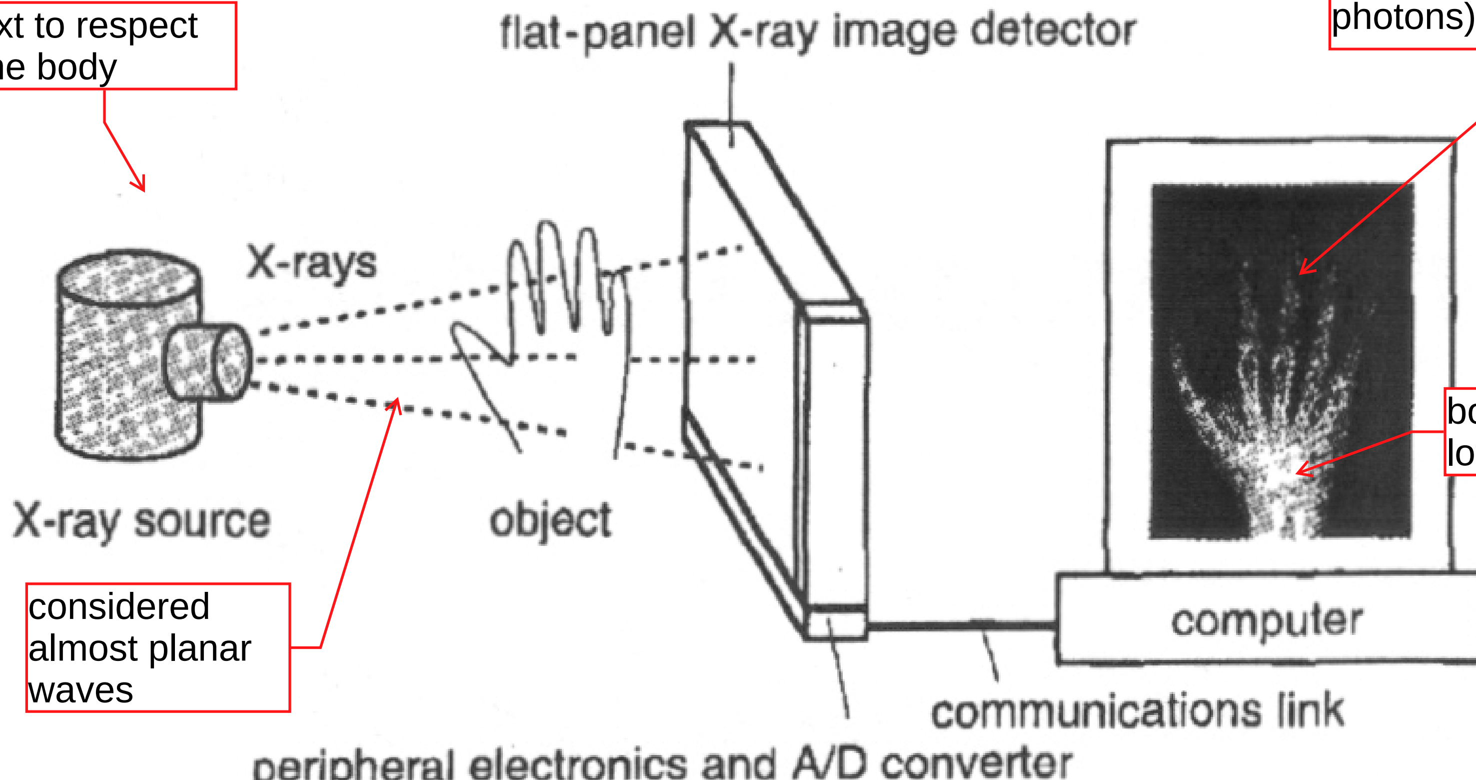
2 of nuclear imaging:

- SPECT (Single Photon Emission Computed Tomography)
- PET (Positron Emission Tomography)
- MRI (Magnetic Resonance Imaging) very senstive to soft tissue
- Ultrasound (Ecography)

Radiography (digital)

soft tissues: almost transparent => dark image (collecting more photons)

ext to respect the body

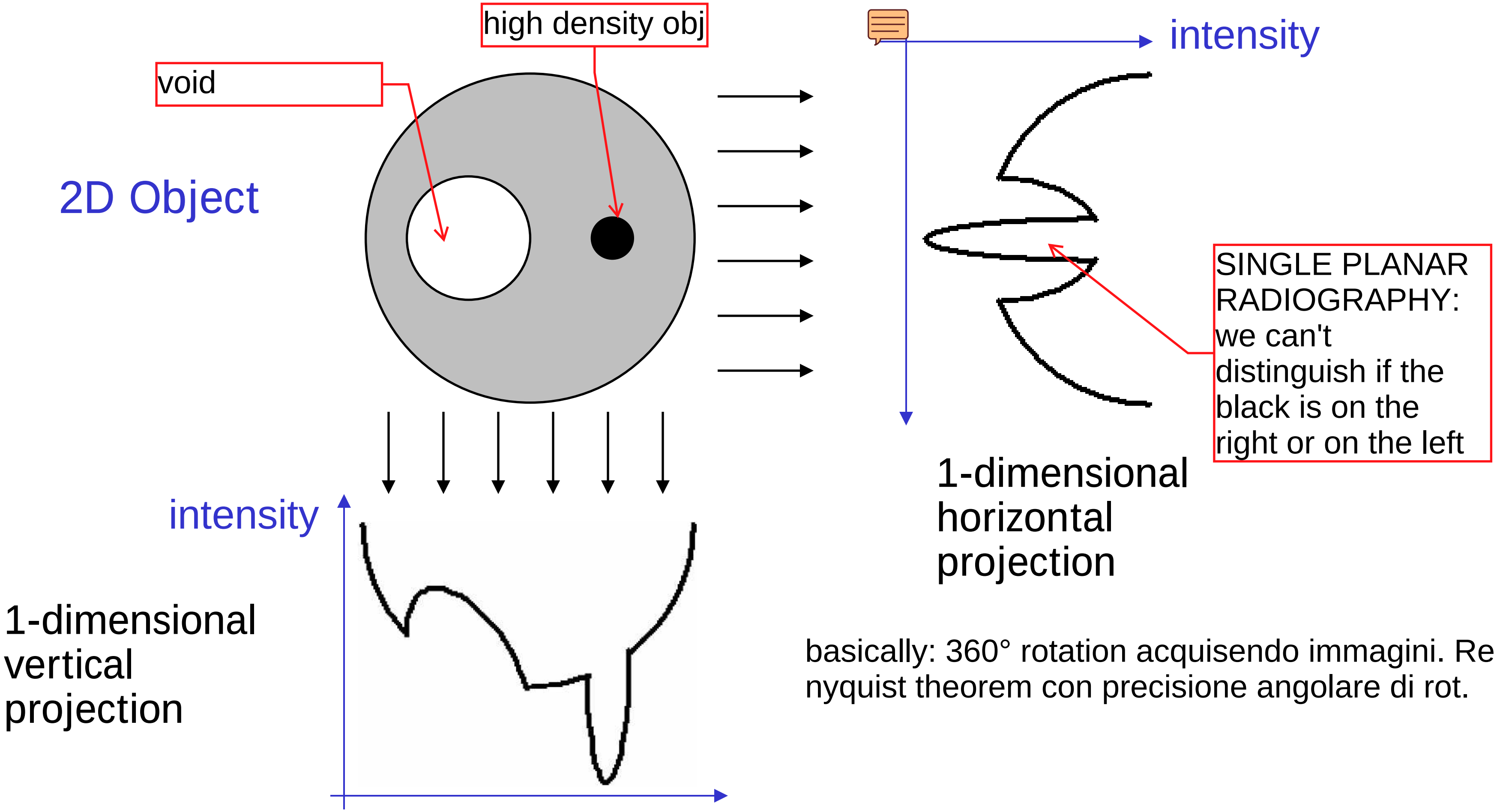


bone absorbs a lot of xrays

considered almost planar waves

we dont use film+chemical anymore, we encode in density of electrons in a sensor (so it's digital). (density elct proportional to intensity of xrays). Challenges for panels: good compromise b/w efficiency of sensor and PRICE. We need to cover a FOV of 40cmx40cm! We cant cover that much with the cost of Si sensors.. so we need an alternative technology

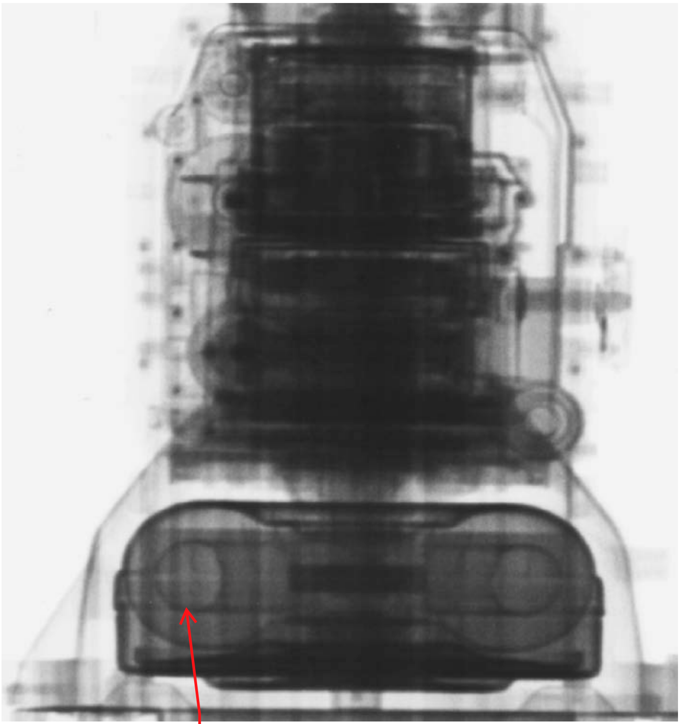
Computed Tomography: principle



basically: 360° rotation acquisendo immagini. Rel
nyquist theorem con precisione angolare di rot.

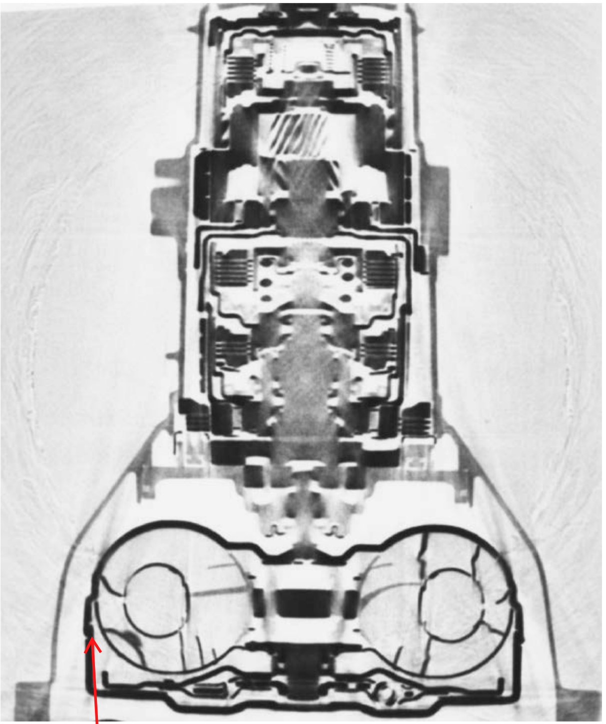
By measuring 1D projections along different angles, it is possible to reconstruct the 2D distribution of the object density

Planar X-Ray



overlapped :(

Computed Tomography



"slice" of CT

CT - TAC

TUBE

translate the patient along this side

improvement: elicoidale

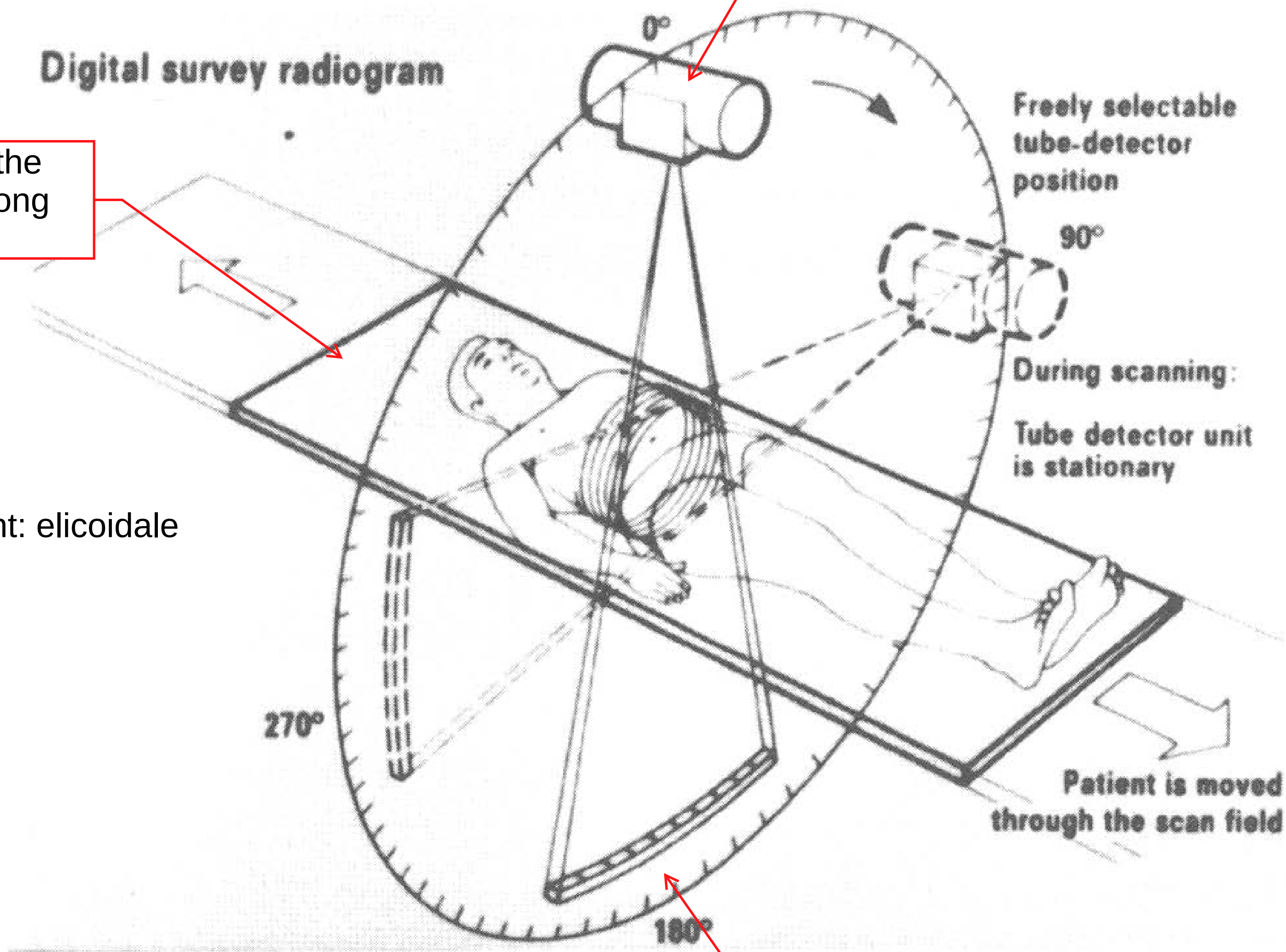


image sensor

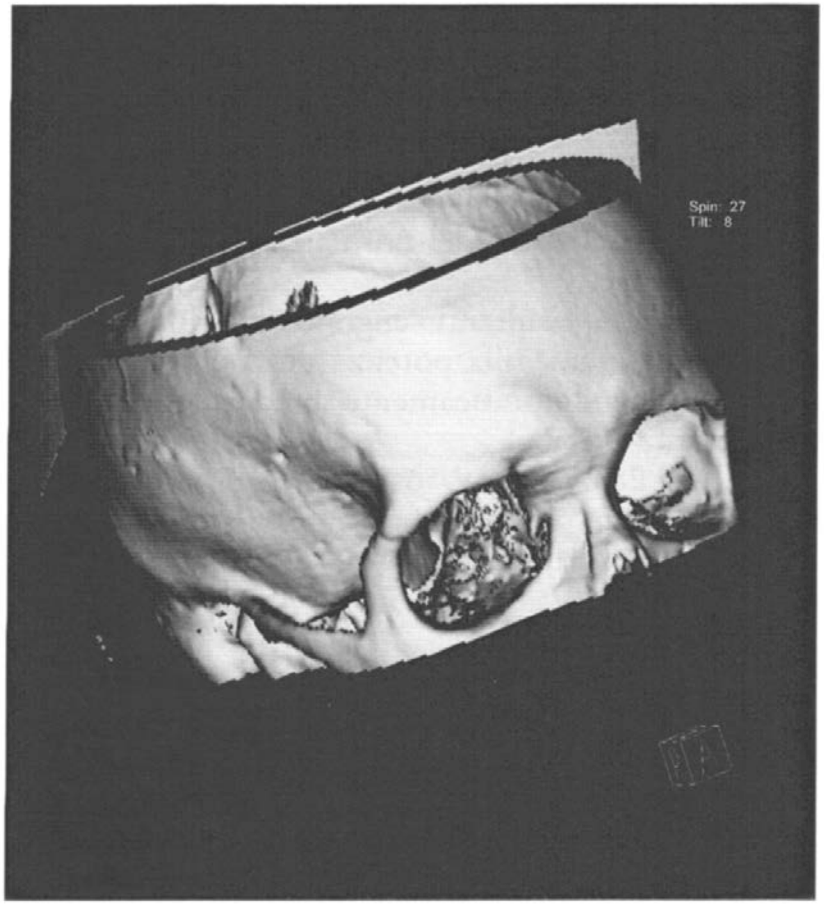


Fig. 28.26 – Articolazione Temporo-mandibolare; Ricostruzione 3D da TC Spirale.

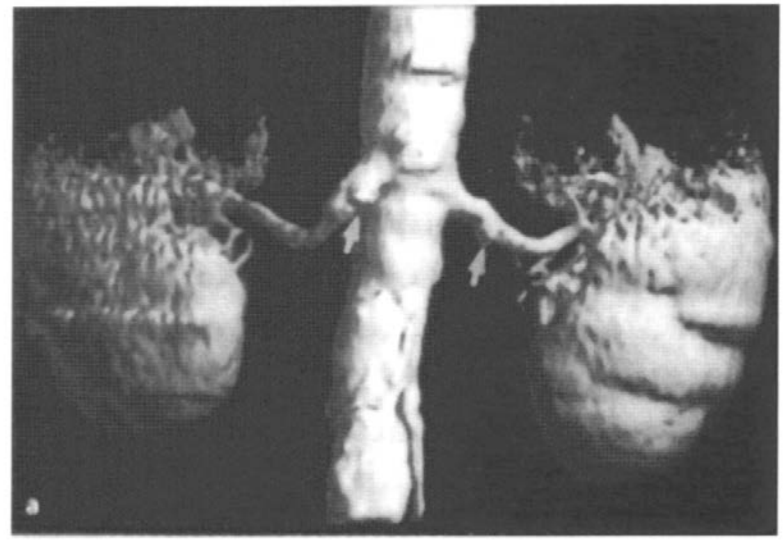


Fig. 28.28A – TC Angiografia; distretto Renale; ricostruzione 3 D-SSD.

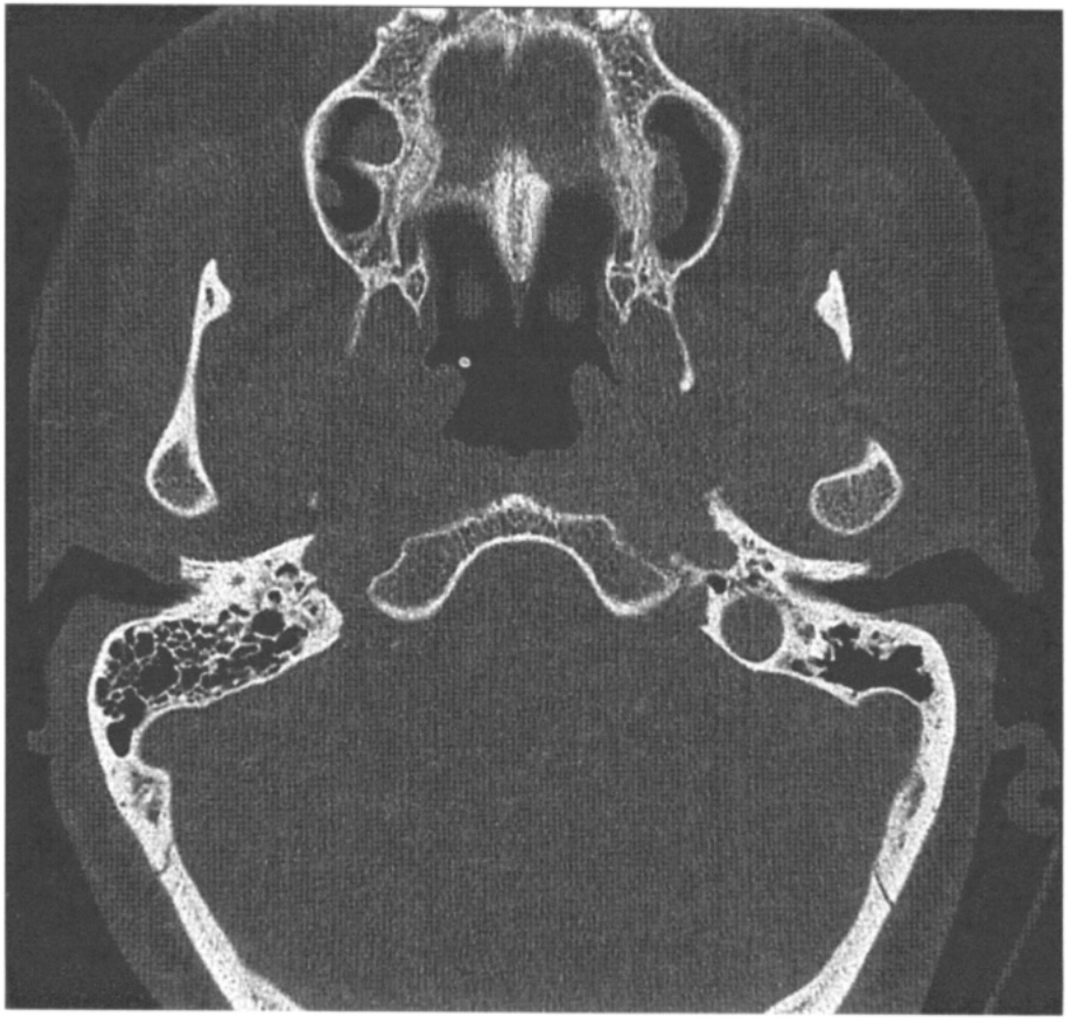
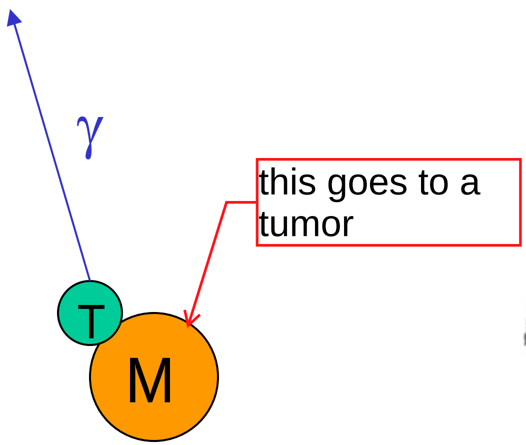


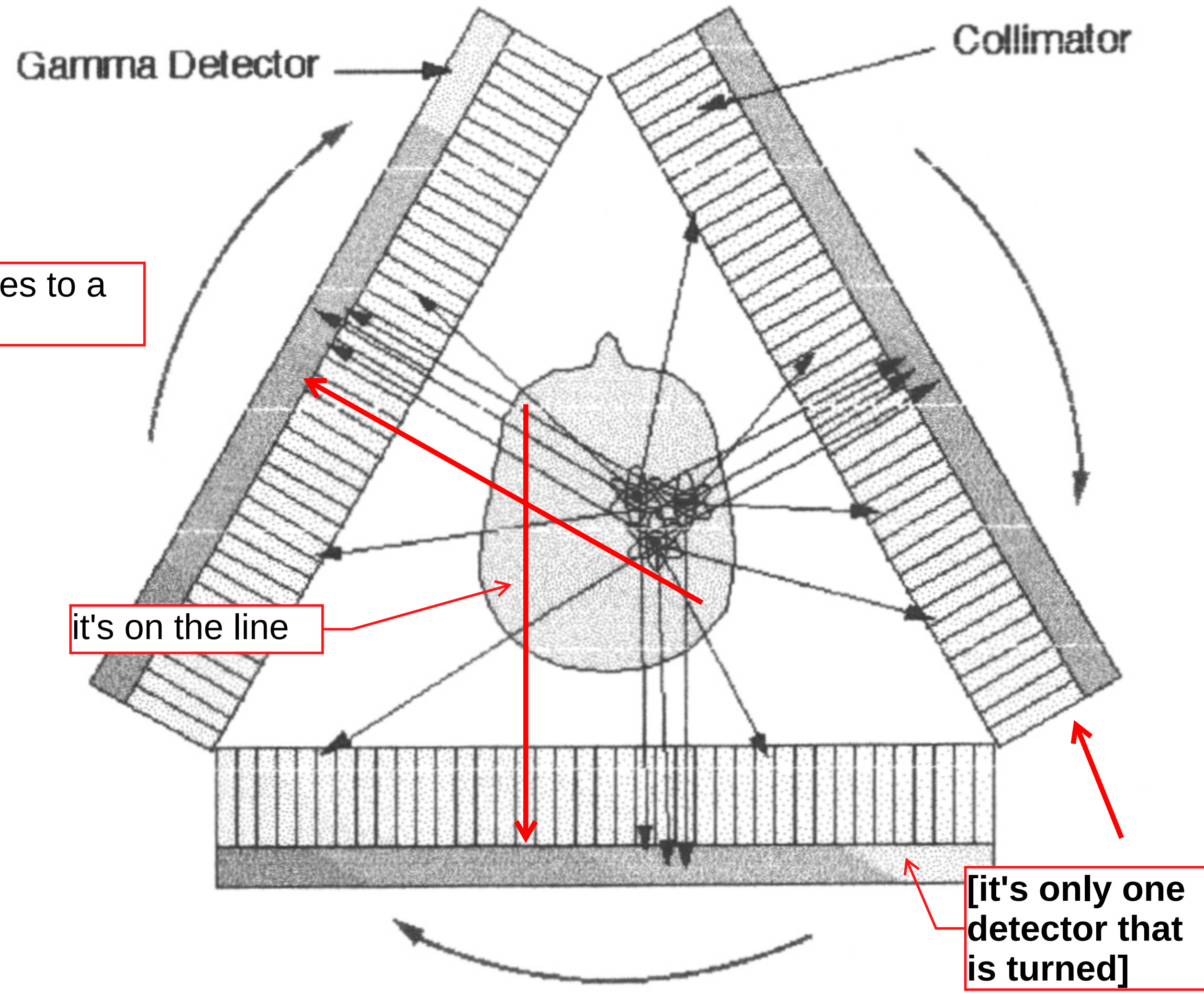
Fig. 28.6 – Immagine Cranio assiale, alta risoluzione; spessore strato 1 mm.; T = 2 sec.

Single Photon Emission Computed Tomography (SPECT)

efficiency: Reaching/Emitted ~10^-4



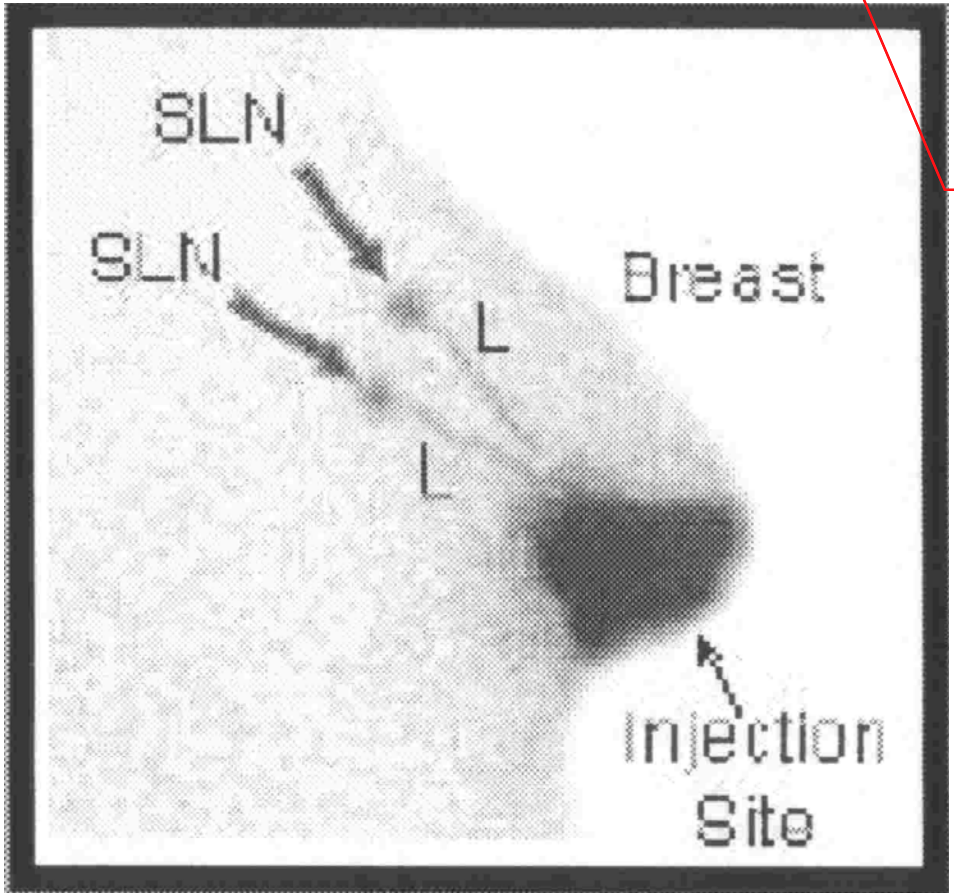
radioactive γ-ray emitter bound to a molecule



application in scintigraphy:
example: identification of the sentinel lymphnode into radioguided surgery

has a tumor spread to the body? it could use the linfatic system.. so we monitor it. Network of linfonodi, we monitor the nearest linfonode to the pathology. If during imaging it contains Tec99 it means there are still tumoral cells.

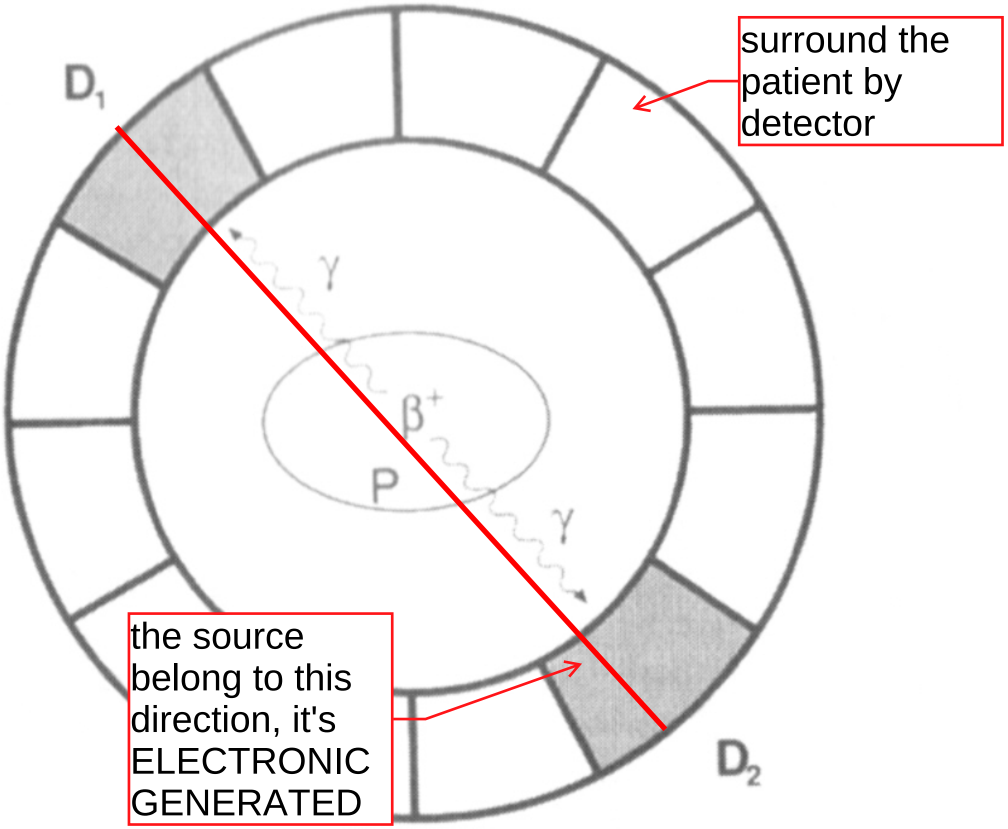
With this we can limit the surgery only where's the pathology

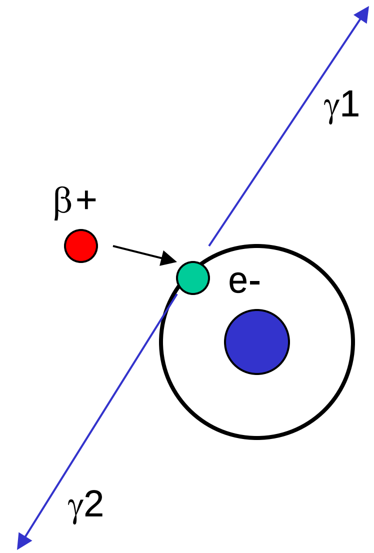


NO physical collimation=> NO LOSS, in principle 100% efficiency

Positron Emission Computed Tomography (PET)

From E=mc^2 => each g-ray: 511keV



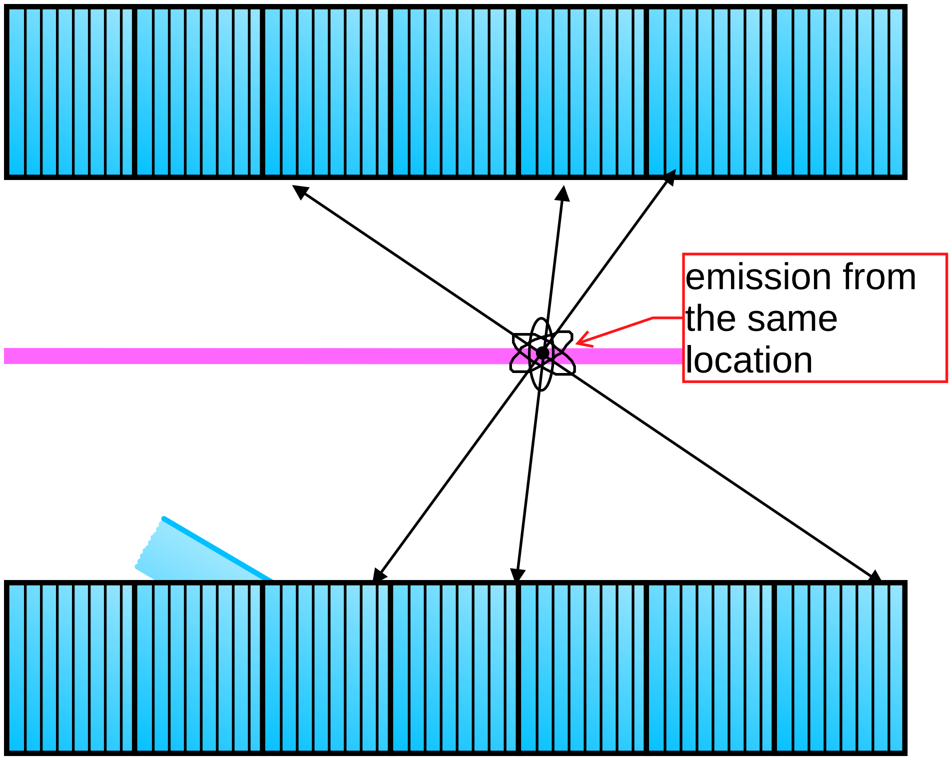


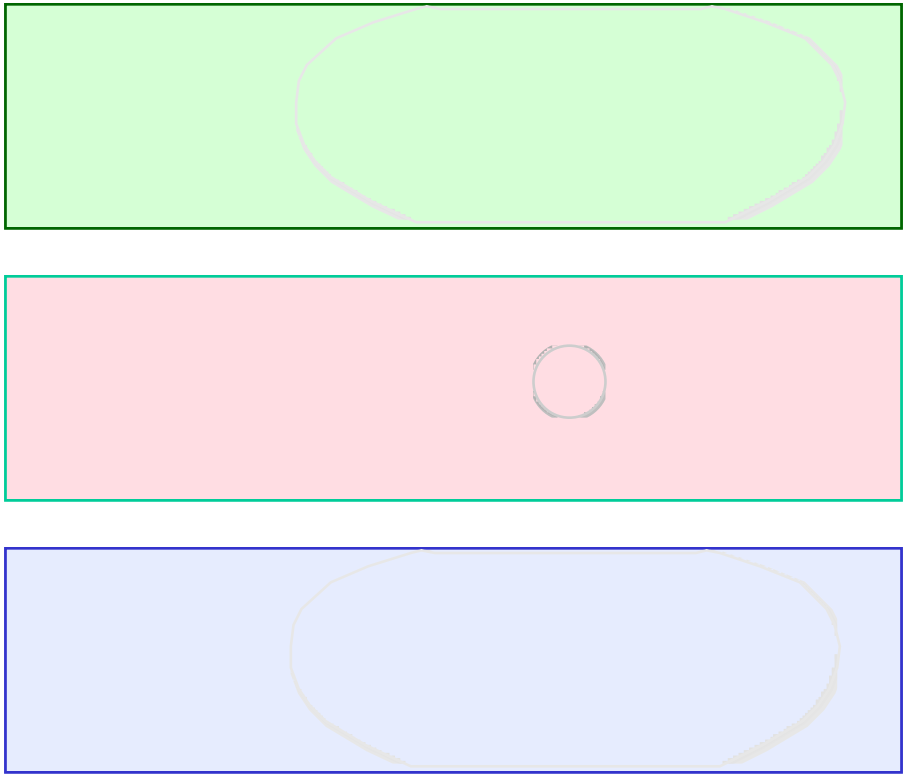
radioactive β+ emitter bound to a molecule

with respect to SPECT: higher efficiency, lower spatial resolution

Reality: efficiency 10^-2. due to scattering and also not all actually detected.
[Problem] lifetime of radiotracer in minutes! 10 minutes, so it has to be generated in the hospital.

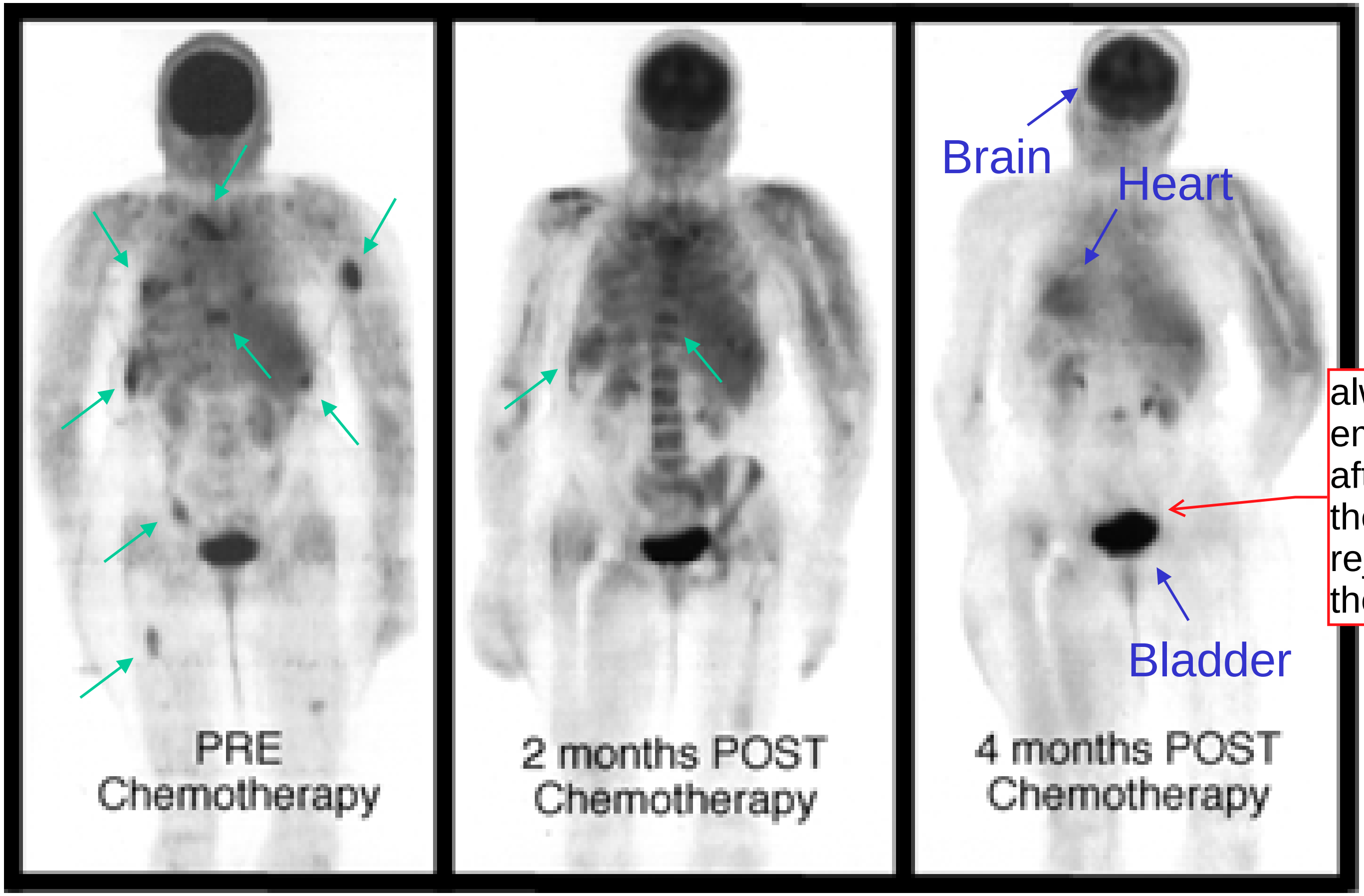
g-ray emitted in all direction, but always as a couple





no details of body, HOT SPOTS that identify regions where the radiotracer has localized

PET Images of Breast Cancer Patient

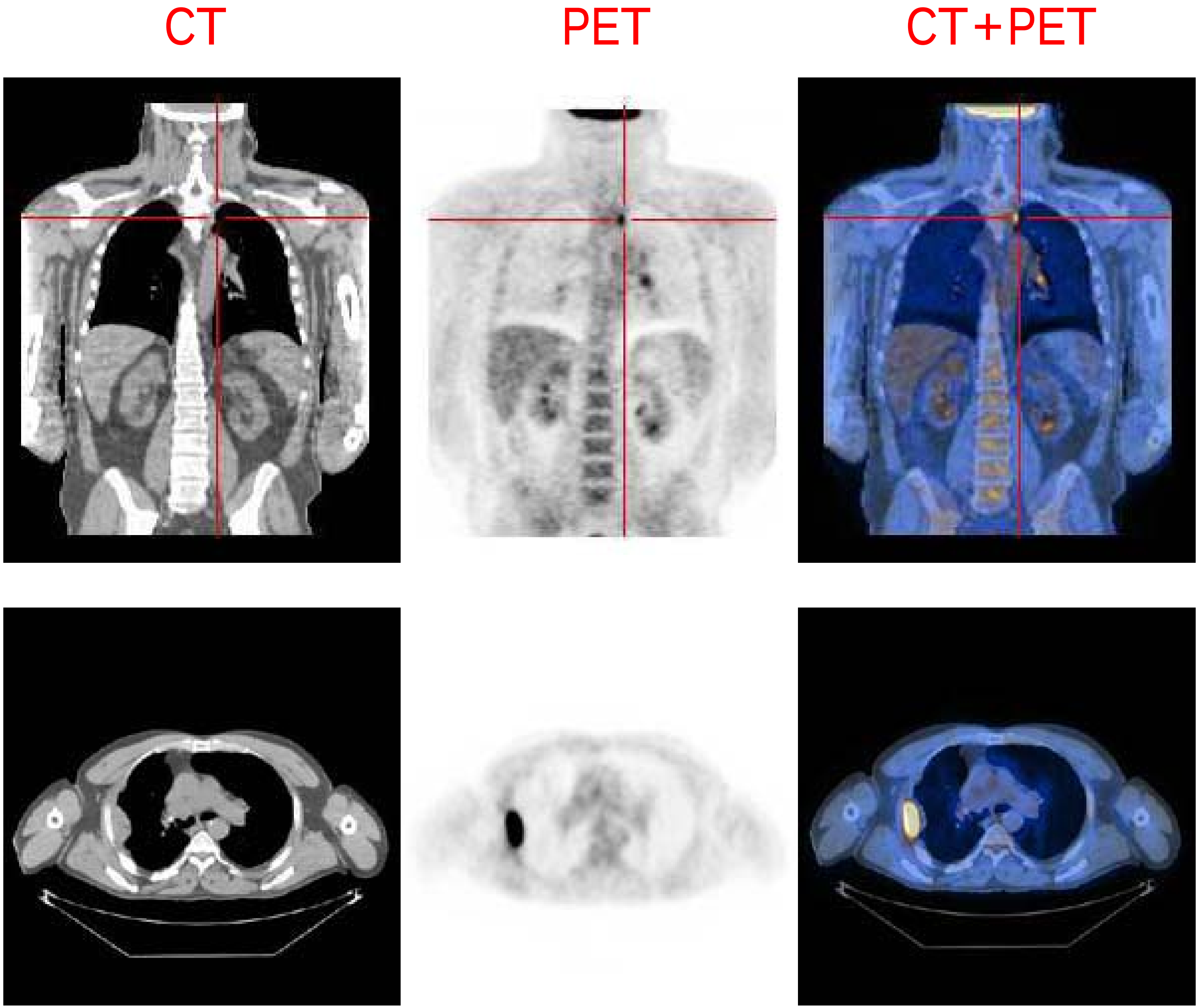


always high emitter.. the RT. after flowing in the body is rejected thorugh the bladder

Metastases Shown with Green Arrows

Normal Uptake in Other Organs Shown in Blue

Trend: COMBINE MORPHOLOGY(CT) + eg PET



Fundamental for radiotherapy. Also combining PET+MRI(1° better image thanTAC, 2° less radiations).

The choice of the imaging technique depends on the parameter which has to be visualized

Figures of merit:

Sensitivity: efficiency of the imaging system to detect the parameter of interest eg. to loc of Tec99 => collect any g-rays coming from it.

Selectivity (specificity): capability of the system to distinguish the parameter of interest from other possible signals b/c it could collect also OTHER things.. but I don't want it.

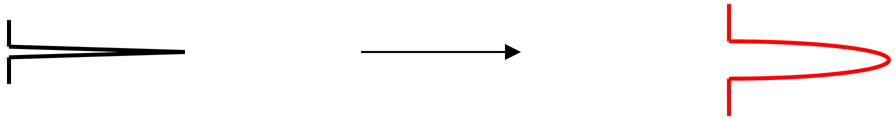
===>High sensitive but only to what I'm looking for

Resolution and contrast: capability of the system to distinguish details of the distribution very close each other and separate regions with different concentrations (to improve contrast, specific contrast agents can be employed)

Resolution: distinguish details very close to each other.
Contrast: distinguish region of SLIGHTLY different intensities (tipical problem of soft tissue)

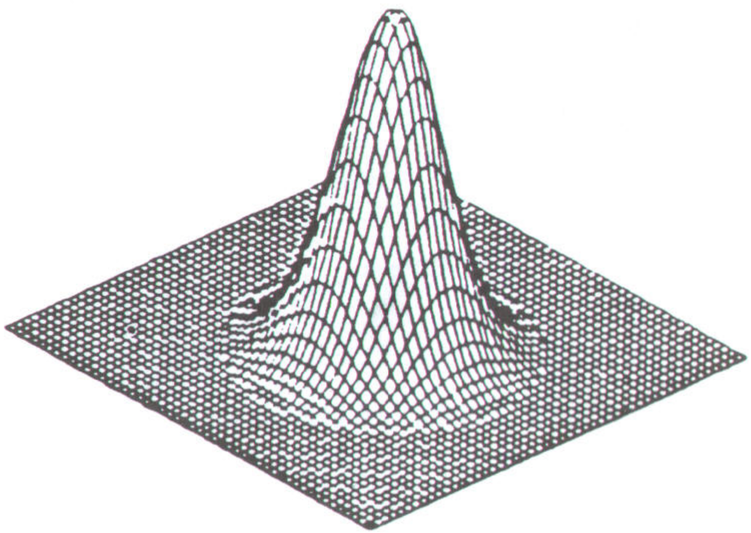
RESOLUTION: we want details

Spatial resolution: the Point Spread Function (PSF)



point, δ-like source

image



MARGIN FIGURE 17-3
The point spread function PSF (x, y).

PSF: RESPONSE OF THE IMAGING SYSTEM to a delta source. You'd like in output a very small spot, not true in real life, we have a broad response.

$$I(x,y) = O(x,y) * h(x,y) \qquad h(x,y)\text{: PSF}$$

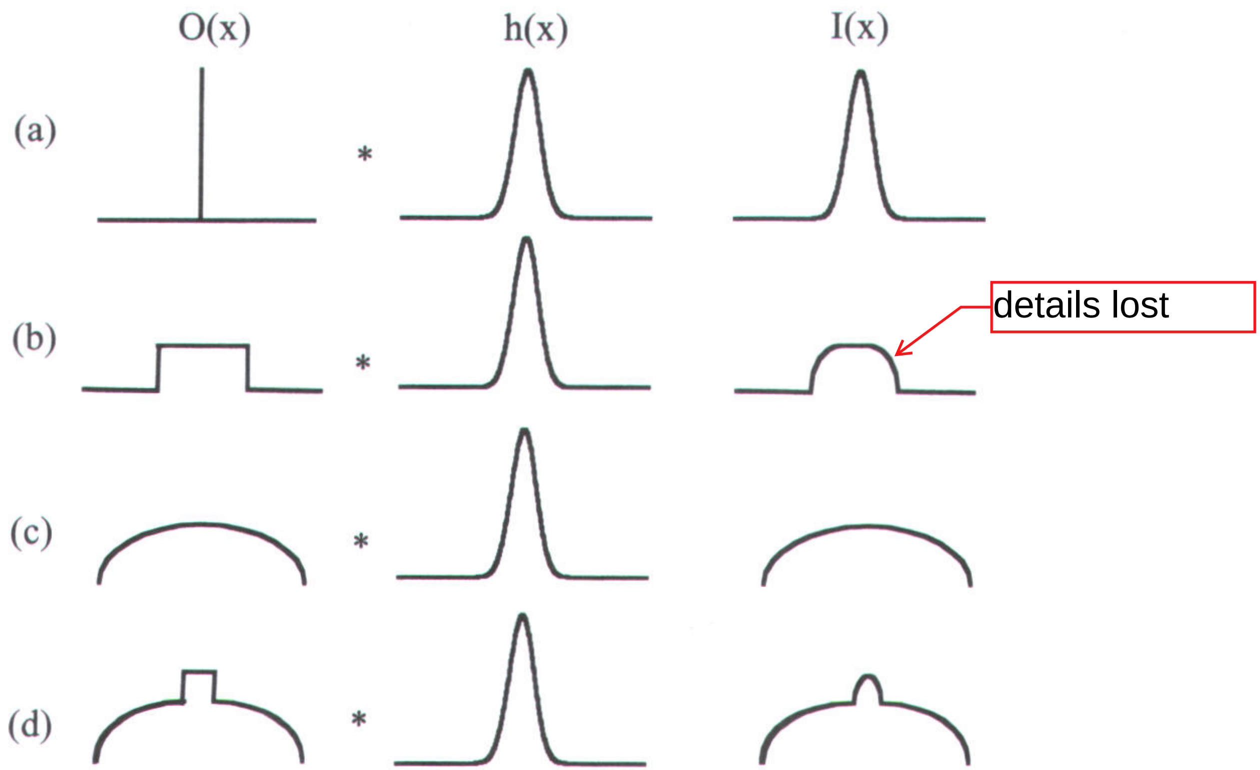


FIGURE 5.3. *Projections I (x) resulting from the convolution of different one-dimensional objects O(x) with a one-dimensional Gaussian PSF, h(x). (a) If O(x) is a delta function I (x) and h(x) are identical, and thus the acquired image can be used to estimate h(x). (b) Sharp edges and boundaries in the object are blurred in the image I (x). (c) If the image is very smooth, then the overall effect of h(x) is small, but if, within the smooth structure, there are sharp boundaries, as in (d), then these boundaries appear blurred in the image.*

Output is the convolution between image and PSF (impulse response).

SPATIAL RESOLUTION IS FWHM

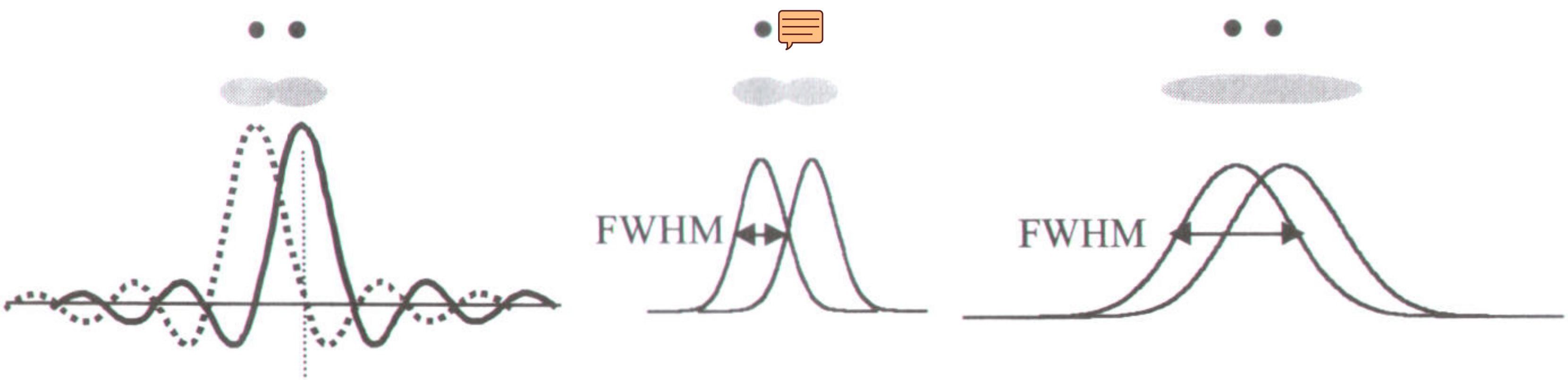


FIGURE 5.4. (Left) For a sinc PSF, the signals from the two point sources can be resolved when the separation between them is less than half the width of the main lobe of the sinc function. (Center) For an arbitrary form of the PSF, the two point sources can be resolved when their separation is less than the FWHM of the function. (Right) The two point sources can no longer be resolved due to the broad FWHM of the PSF.

Popular shape: gaussian. We can actually fit the PSF with a gaussian..

$$h(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x-x_0)^2}{\sigma^2}\right)$$

Gaussian PSF
(or Gaussian approx. of PSF)

$$\mathrm{FWHM} = 2\sqrt{2\ln 2}\sigma \cong 2.36\sigma$$

Full-Width-at-Half-Maximum

resolution :)

Line Spread Function (LSF) and Edge Spread Function (ESF)

Resolution along only one direction

defines the sharpness of the imaging system in distinguish edges. Another way to identify res.

$$LSF(y) = \int PSF(x, y)\, dx$$

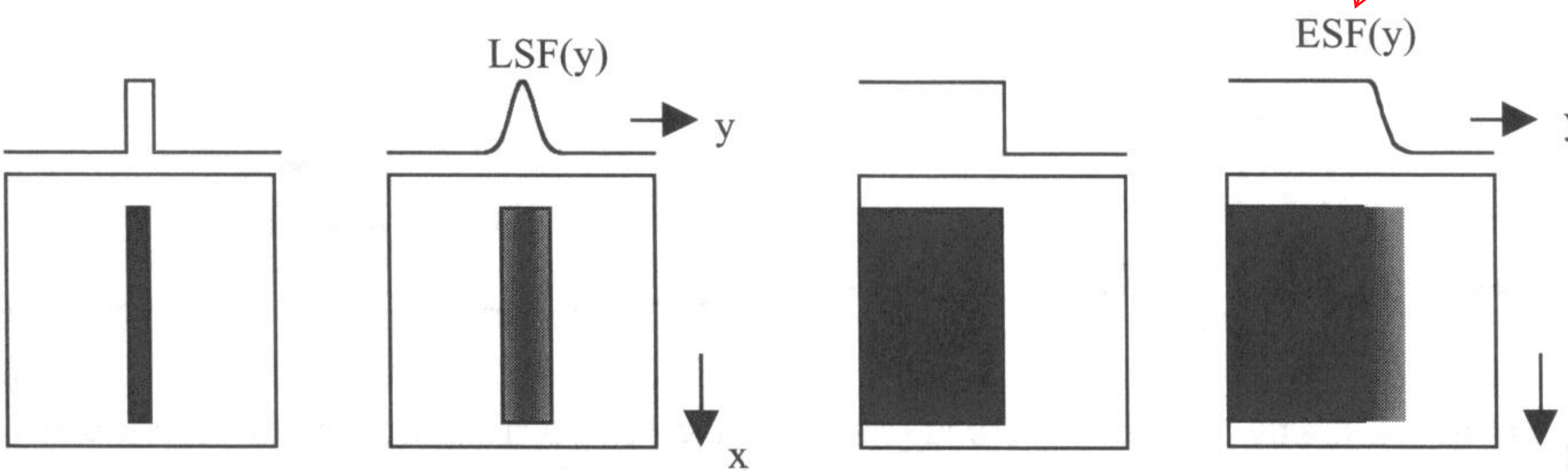


FIGURE 5.5. *Illustration of the concept of (left) the line spread function (LSF) and (right) the edge spread function (ESF). For measuring the LSF, the object consists of a thin line, with the one-dimensional projection of the object in the y dimension shown above. The actual image is broadened, with the LSF defined by the one-dimensional y projection of the image. (Right) For measurement of the ESF, a wide object with a sharp edge is used.*

FREQUENCY RESPONSE, fourier transform of the PSF. SPATIAL frequency domain.

Modulation Transfer Function (MTF)

$$\mathrm{MTF}(k_x, k_y, k_z) = \int\int\int \mathrm{PSF}(x, y, z) e^{-j2\pi k_x x} e^{-j2\pi k_y y} e^{-j2\pi k_z z}\, dx\, dy\, dz$$

cut off in **spatial frequency: how frequent I may have lines to be distinguished. Freq. of lines I can distinguish.**

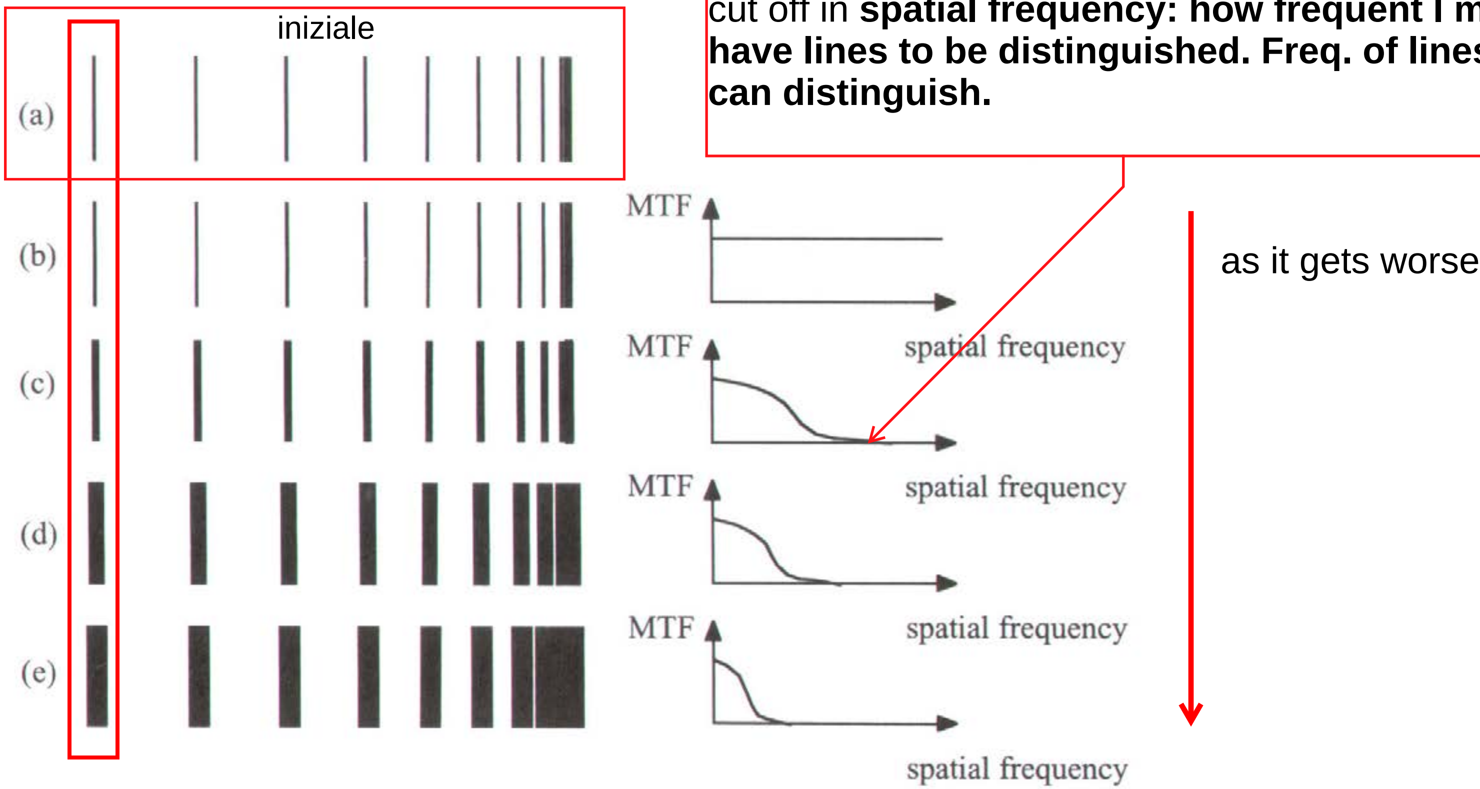


FIGURE 5.6. (a) A schematic of a line phantom used to measure the MTF of an imaging system. (b–e) The images produced from the phantom by imaging systems with the MTF shown on the right. As the MTF becomes progressively narrower (corresponding to a broader LSF), the image becomes more blurred.

sharper the response.. wider is the frequency of transfer function.

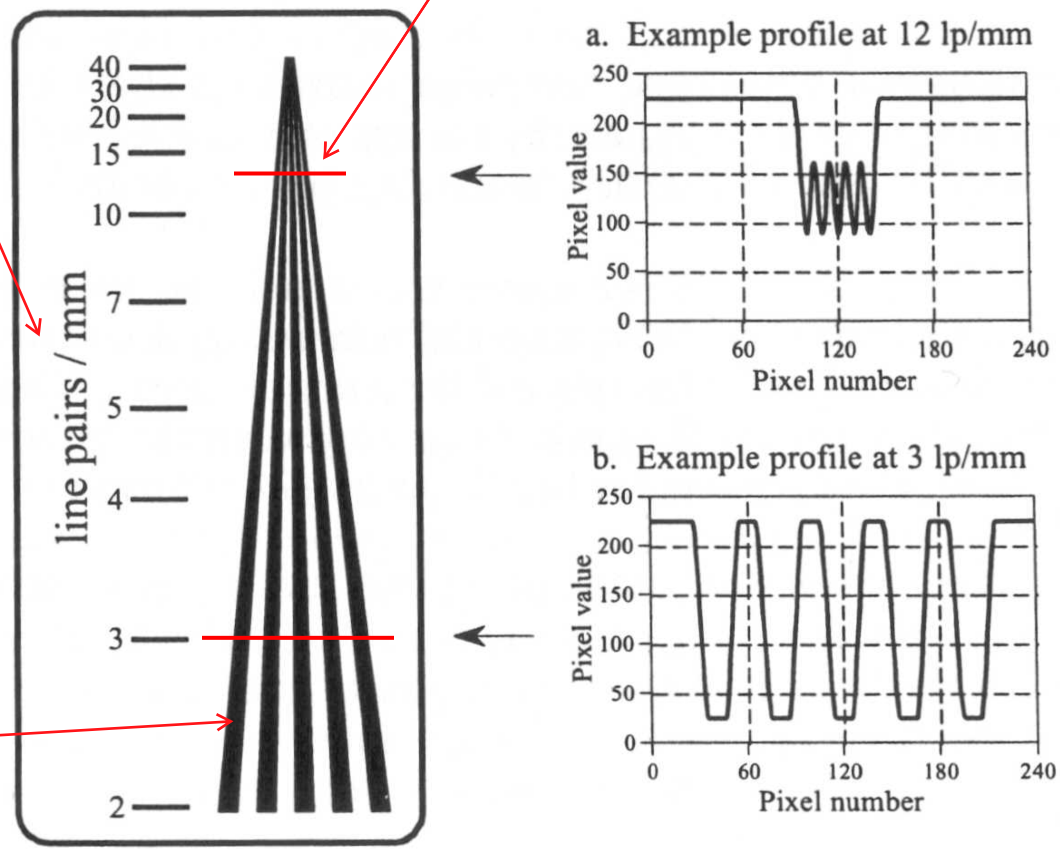
Spatial resolution: line pairs per *mm*

Quality: which is the highest density we can distinguish?

depending on the cut the line freq. increases
(here, 5 lines in 10mm)
under, 5 lines in 3mm.

Lines/mm:
density of lines

FIGURE 25-2
Line pair gauge. The line pair gauge is a tool used to measure the resolution of imaging systems. A series of black and white ribs move together, creating a continuum of spatial frequencies. The resolution of a system is taken as the frequency where the eye can no longer distinguish the individual ribs. This example line pair gauge is shown several times larger than the calibrated scale indicates.



fixed number of
lines spread

All this is related to the MTF cutoff. Just to say the physical meaning

DIFFERENT PSF of different imaging, compared

pillbox:pixelated system, like photocamera

freq. response very different! even tho' the FWHM is the same

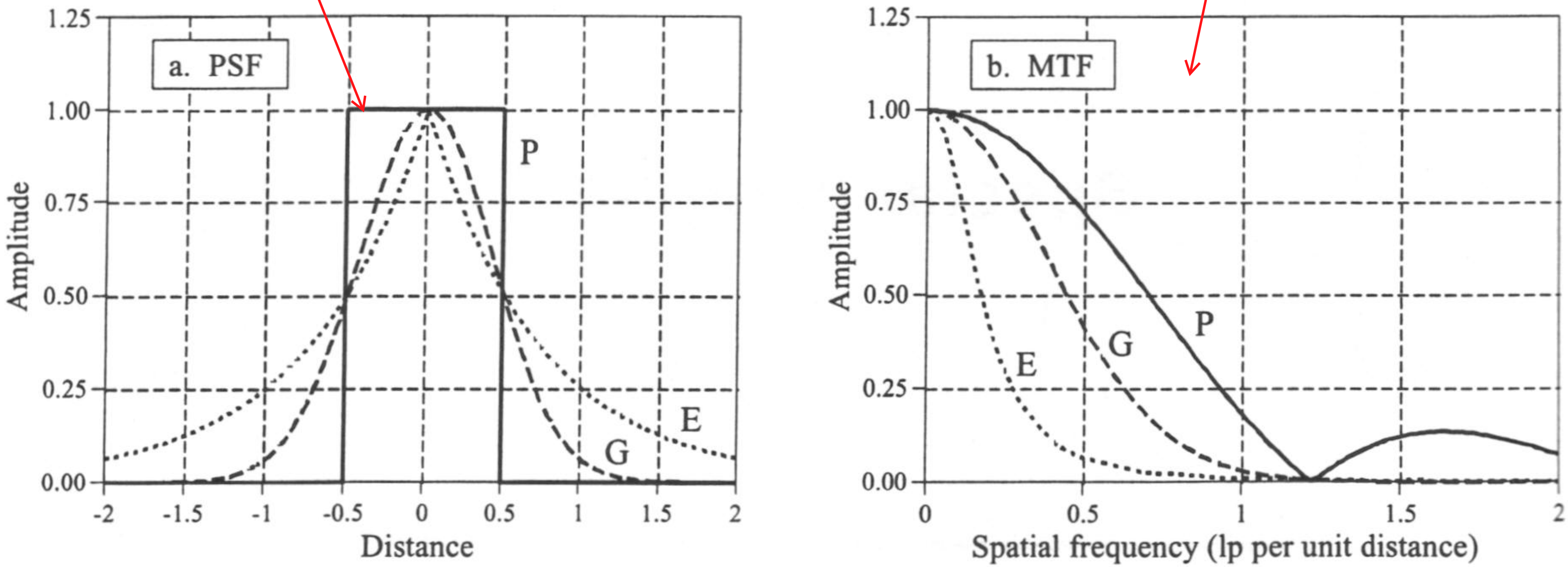


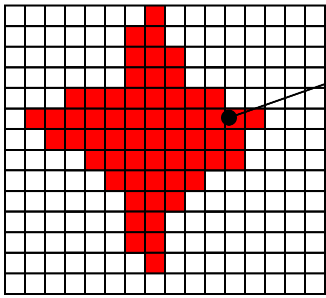
FIGURE 25-1
FWHM versus MTF. Figure (a) shows profiles of three PSFs commonly found in imaging systems: (P) pillbox, (G) Gaussian, and (E) exponential. Each of these has a FWHM of one unit. The corresponding MTFs are shown in (b). Unfortunately, similar values of FWHM do not correspond to similar MTF curves.

p: if it falls on the pixel you get it, otherwise is 0 (100% inside, 0% outside). The others doesnt have 0 probability to get it [outside?]
FWHM: ok very pratical, but to be more precise use MTF

[audio]

SNR (Signal-to-Noise Ratio): the Poisson statistics

pixelated detector for simplicity

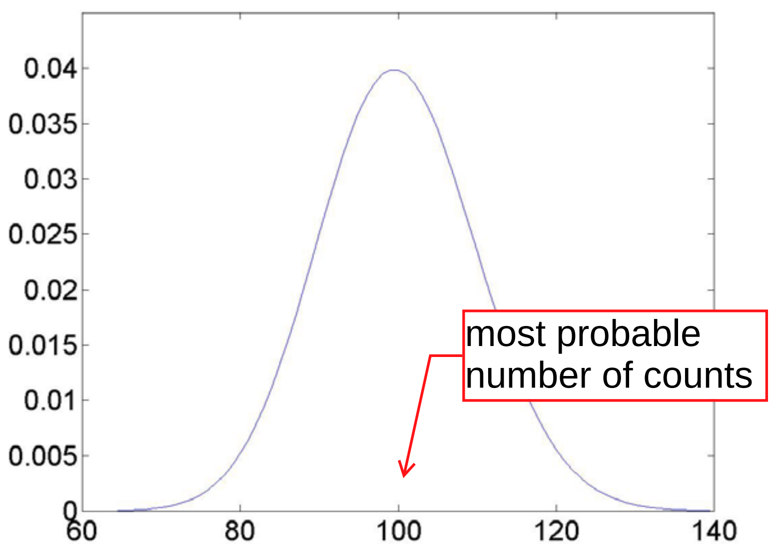


counts in a pixel acquired in the time T

$$P(N) = \frac{\mu^N e^{-\mu}}{N!}$$

how many xrays has been collected in each pixel?

ISTOGRAMMA XRAYS COLLECTED



P(N): probability to have N counts given an average μ of counts acquired in the time T

$\sigma^2 \sim \mu$ variance

$\sigma \sim \sqrt{\mu}$ r.m.s

*quelli che stanno arrivando

*quelli dati dal rumore

$$\boxed{\mathrm{SNR} = N/\sigma \sim \mu/\sigma \sim \sqrt{\mu}}$$

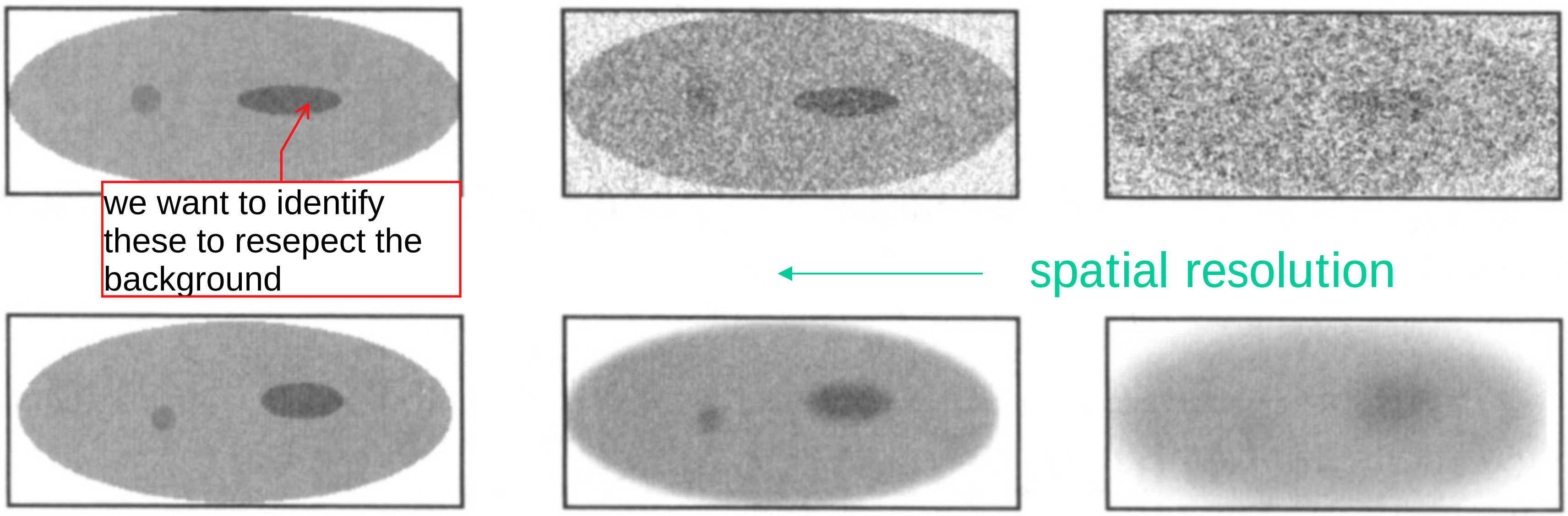
Another parameter of quality: "how many events my image system actually collects". our med.imaging: at the end we count the number of photons (xrays/grays) which are composing the image. (in radiography we usually dont count but integrate, while we count in PET and SPECT). Duration of xray on: 1 second. The number of photons actually fluctuates according to poisson statistics.

Image contrast

Capability to distinguish in the image the different tissues (e.g. bones vs. soft tissues, healthy tissues vs. pathologies)

image noise (statistics)

*avg reduced



we want to identify these to resepect the background

spatial resolution

FIGURE 5.9. *(Top left-to-right) As the noise level increases in an image with high intrinsic contrast, the CNR degrades such that structures within the image can no longer be discerned. (Bottom left-to-right) As the spatial resolution of the image decreases, then the image contrast becomes worse, particularly for small objects within the body.*

In the quality of an image, resolution and counting statistics both matter, we must find a compromise b/w good spatial resolution and a decent counting statistics. Bottom: image is processed with bad PSF which is larger and larger, the details are going to disappear [**same** total number of counts, but they get spread (diluiti), so it's more difficult to identify with a threshold to respect the background].