Imaging using ionizing radiations

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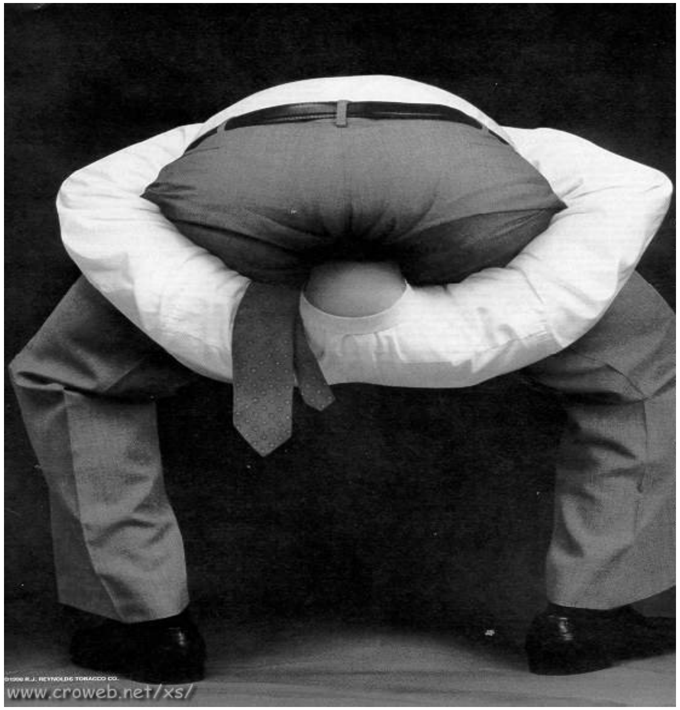
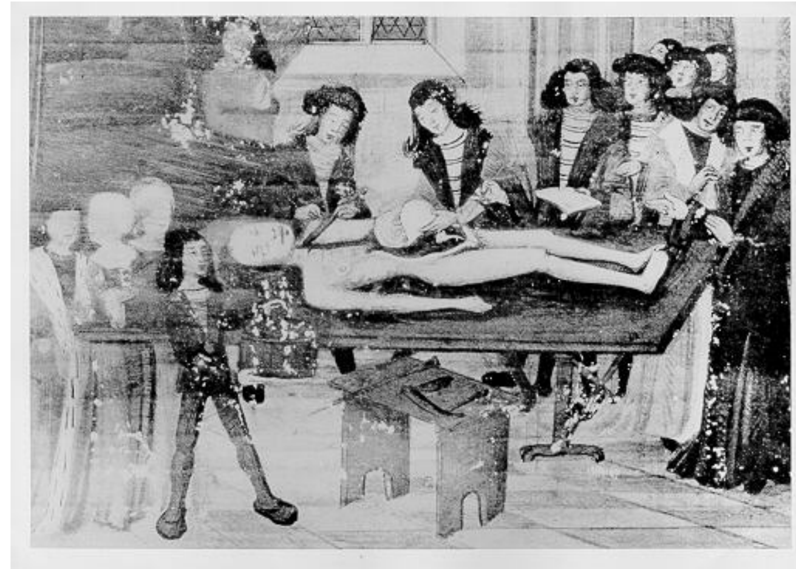
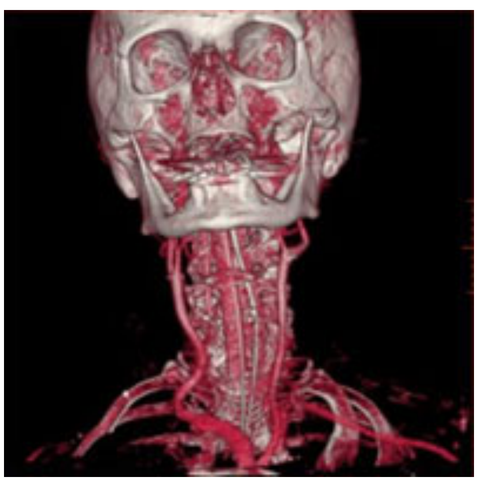
Some slides are courtesy of David Brasse

Curious to know how
we are made inside ?



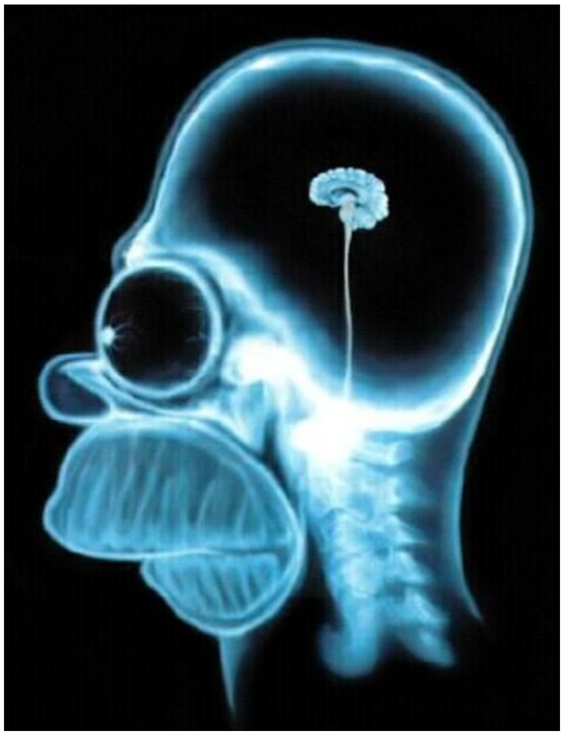
…however, without being sacrificed !

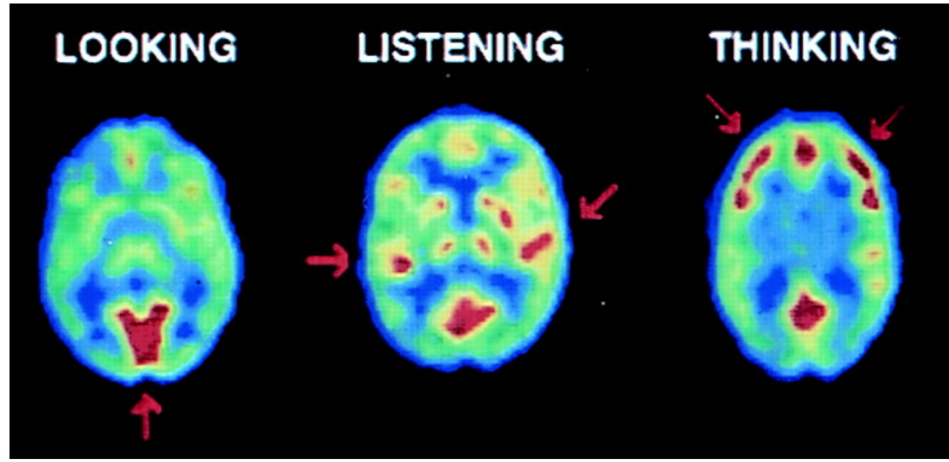


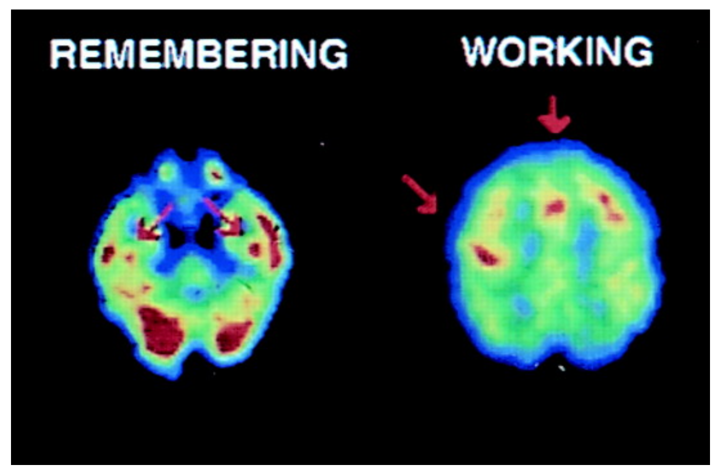


David Teplica, Birth of man with homage to Michelangelo (1987)

We are also curious to know how ...







...do our organs function?

Modality using X Rays or gamma rays

- Radiology (X rays)
  - *Standard radiology, mammography*
  - *Angiography*
  - *Computer Tomography (CT scanner)*

- Nuclear medicine
  - *Scintigraphy*
  - *Emission tomography*
    - *Simple photons*
    - *Positons*

- Radiotherapy

Morphology vs Functional

Emission vs Transmission

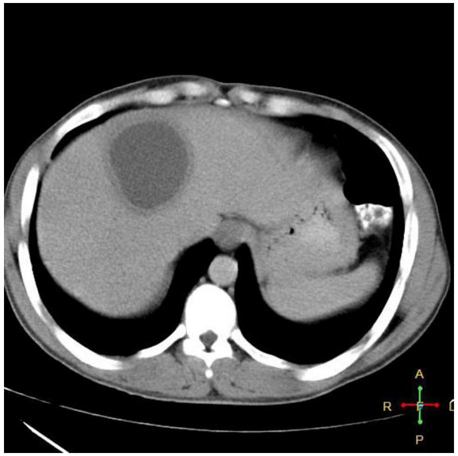
Real time vs Integration

Anatomical imaging

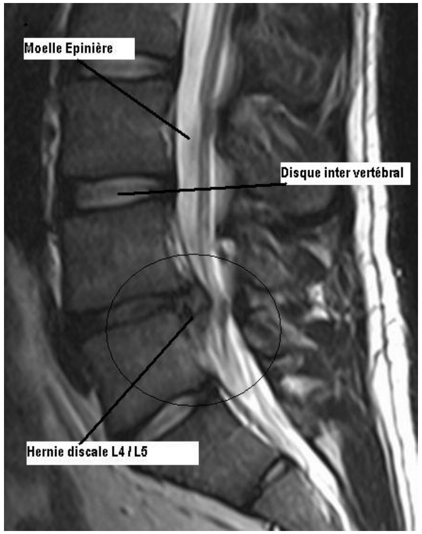
Visualisation of organs and tissues structures

- Surface
- Volume
- Distance

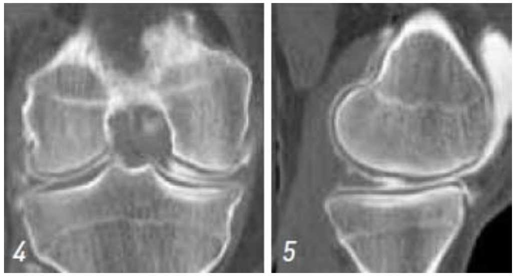
A broken tibia



Liver tumor



Discale Hernia

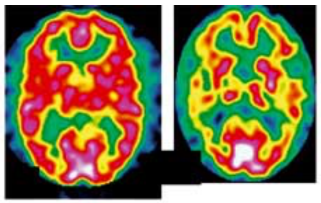


Knee Arthrosis

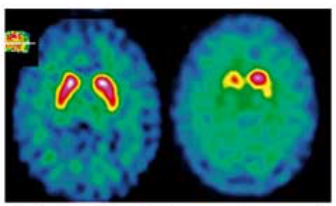
odienneosteopathe.fr
radiopaedia.org

Functional Imaging

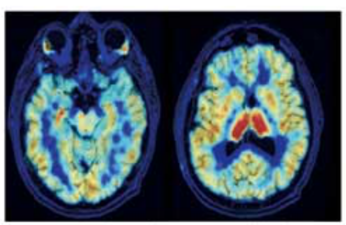
Study and evaluate the functioning of organs, metabolism, …



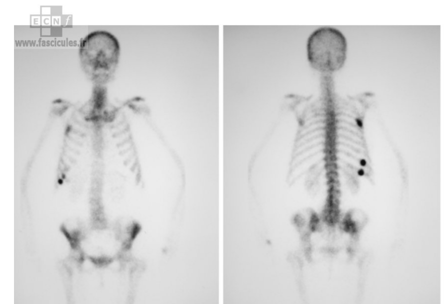
Exemple de scintigraphie de perfusion normale (à gauche) et pathologique (à droite) chez un patient présentant une maladie d'Alzheimer.



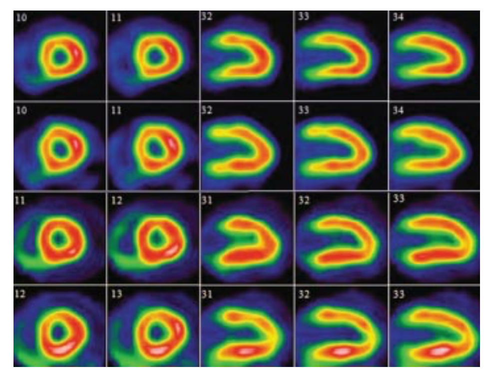
Scintigraphie des transporteurs de la dopamine : examen normal (à gauche) et chez un patient parkinsonien (à droite).



Exemple de radiotraceur utilisé en recherche : il s'agit ici d'un ligand des récepteurs cholinergiques de la nicotine, dont l'image scintigraphique a été fusionnée avec une IRM anatomique.

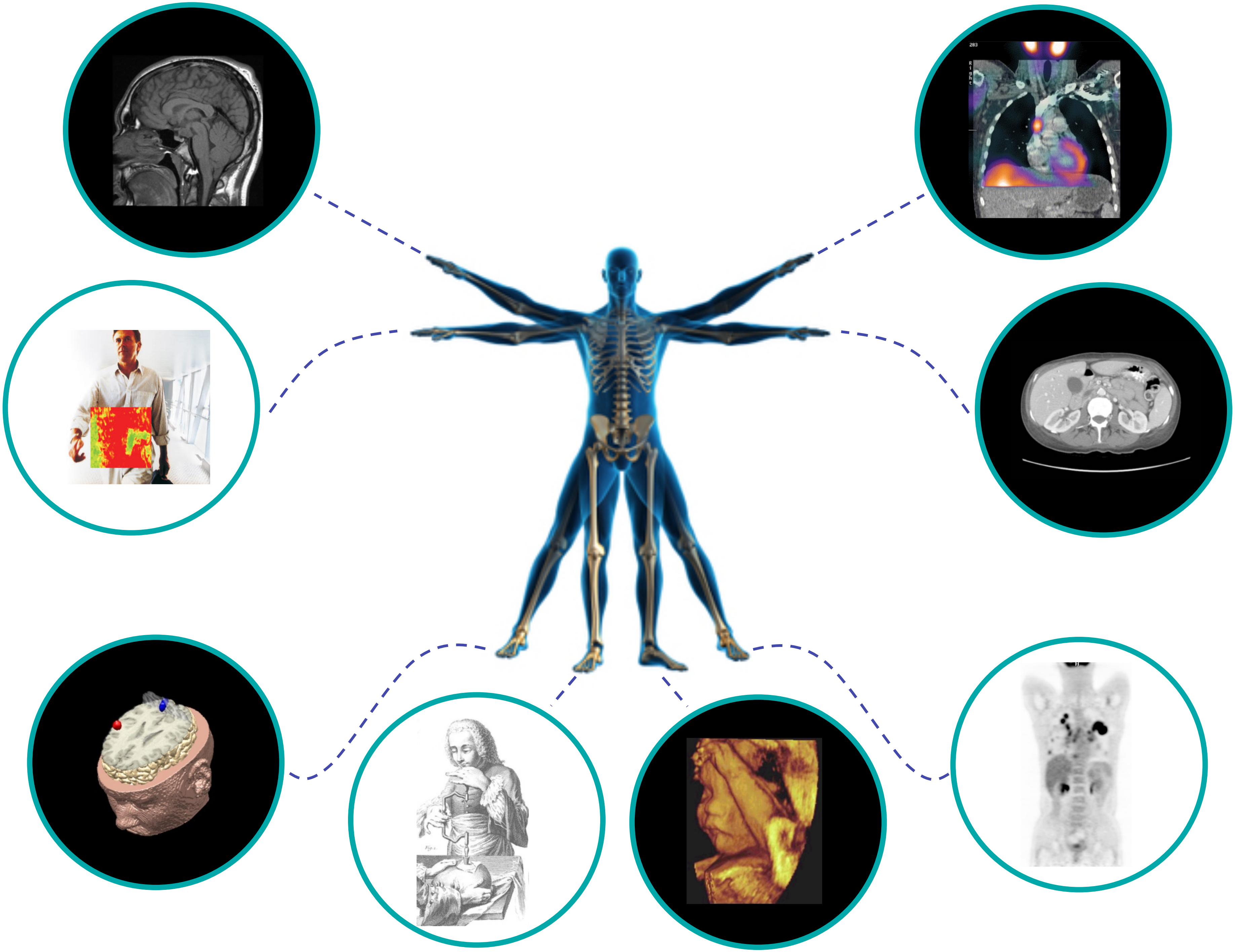


Bone Scintigraphy

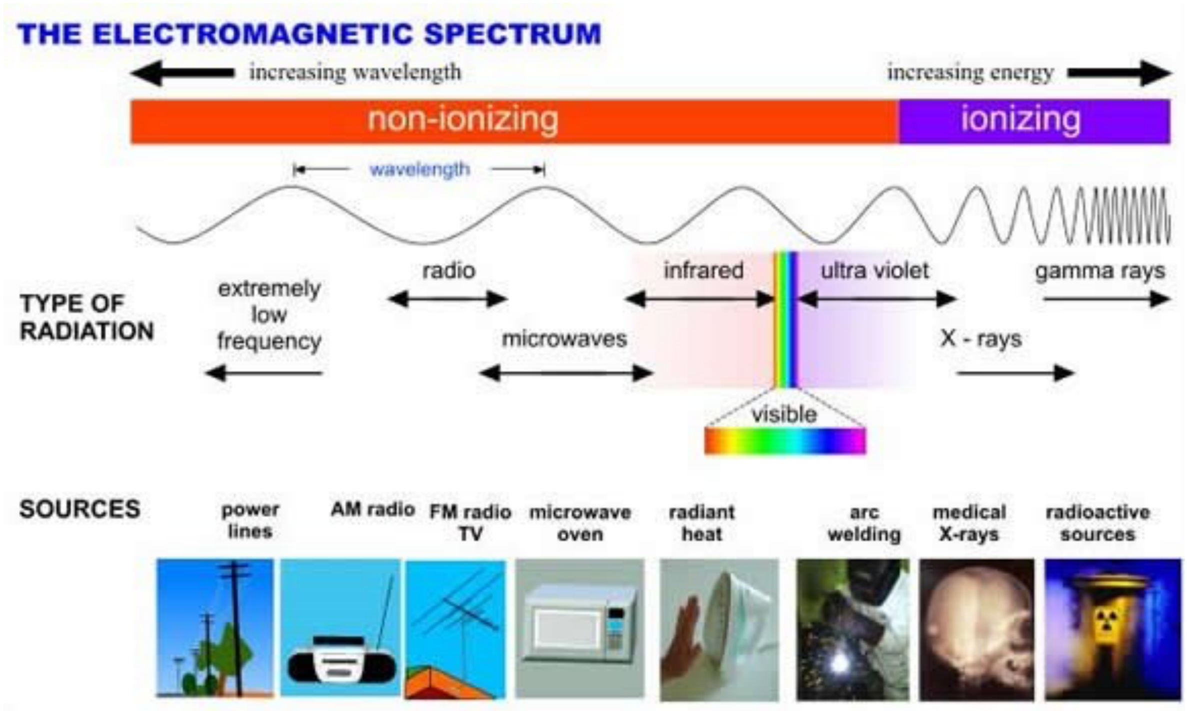


Cardiac perfusion

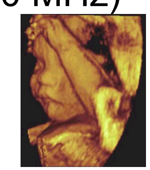
http://imed.jussieu.fr



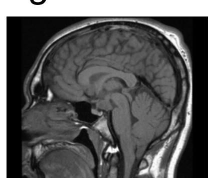
Ionising and non-ionizing radiations



Ecography (Ultra Sound: 1-10 MHz)

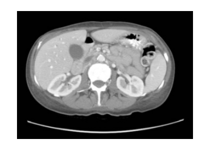


Magnetic resonance Imaging



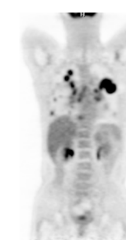
RadiographY

X-ray scanner

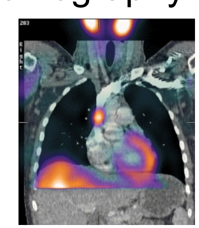


Single Photon Scintigraphy

Single Photon Emission Computed Tomography

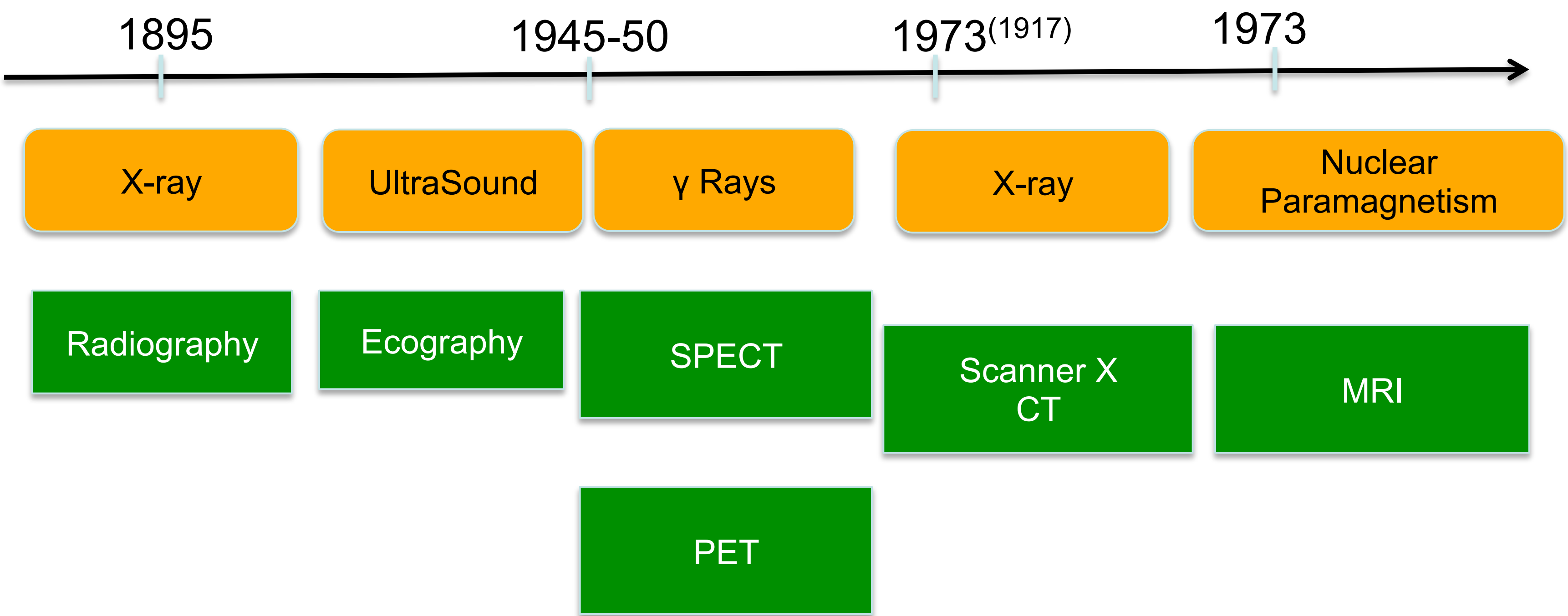


Position Emission Tomography



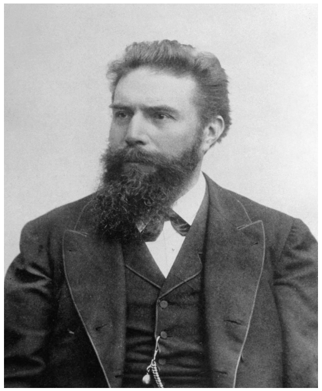
https://www.pmfias.com/radioactive-pollution-ionizing-non-ionizing-radiation/

History

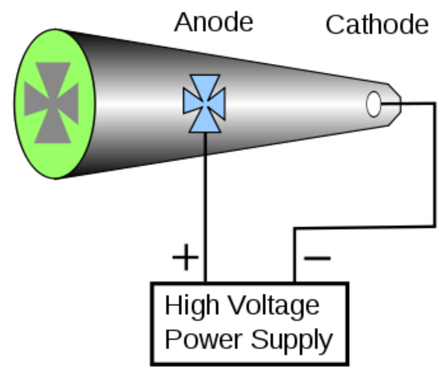

1895
1945-50
1973 (1917)
1973
X-ray
UltraSound
γ Rays
X-ray
Nuclear Paramagnetism
Radiography
Ecography
SPECT
Scanner X CT
MRI
PET

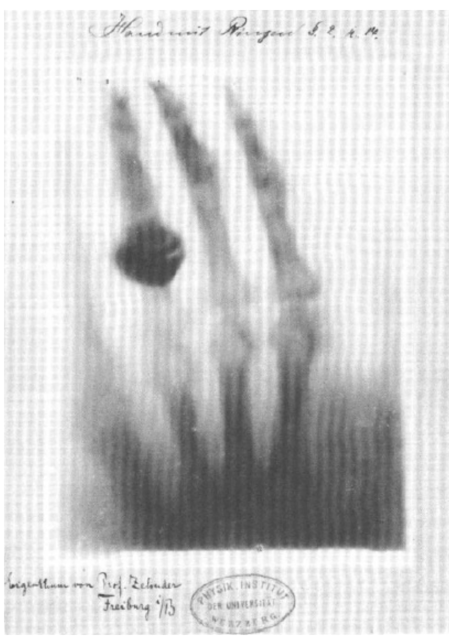
X-ray Imaging

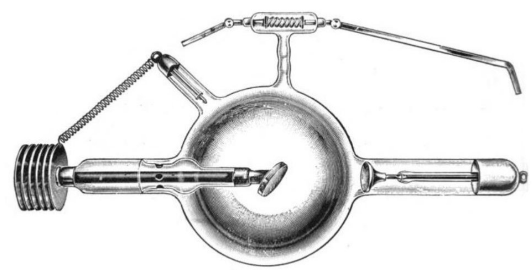
X-ray discovery (1895)



de Wilhelm Conrad Röntgen
(1845–1923)







Crookes tube
(~1910)

https://fr.wikipedia.org/wiki/Tube_de_Crookes

X-ray production

Electromagnetic radiations
Two ways of production:
- Synchrotron
- X-ray tube

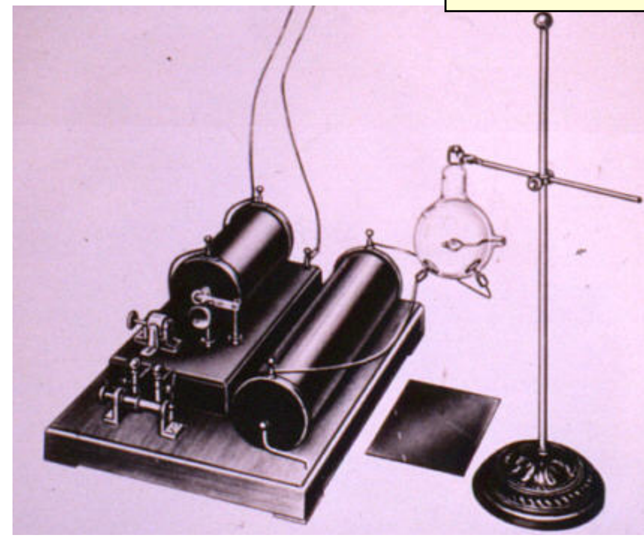
Electrons generation:
- Tungsten filament
- Thermo-ionic Effect

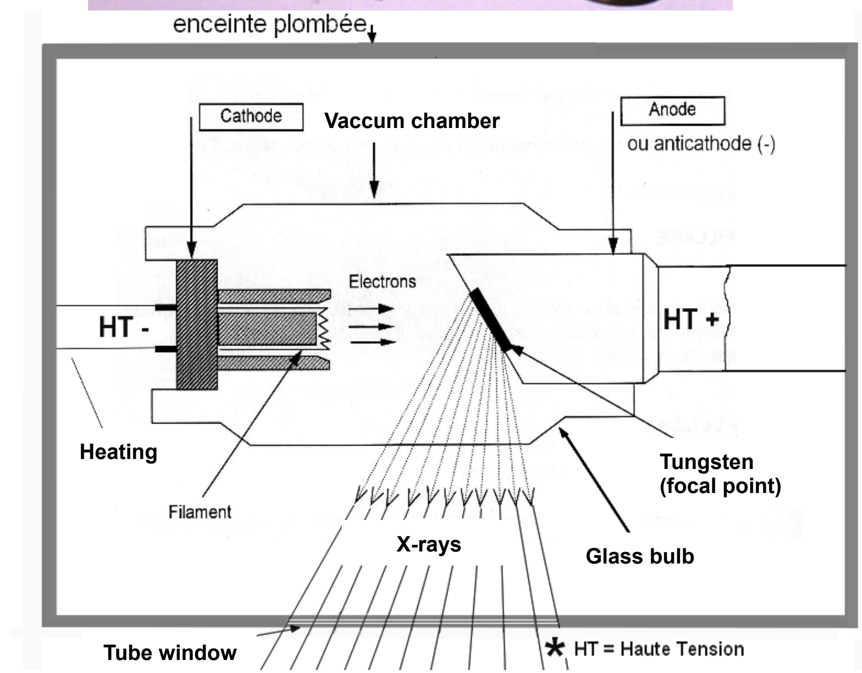
Electrons Acceleration

Metallic target (anode)
- Static or rotating plate

Interaction electron/matter

Heating





X-ray production

Electrons generation

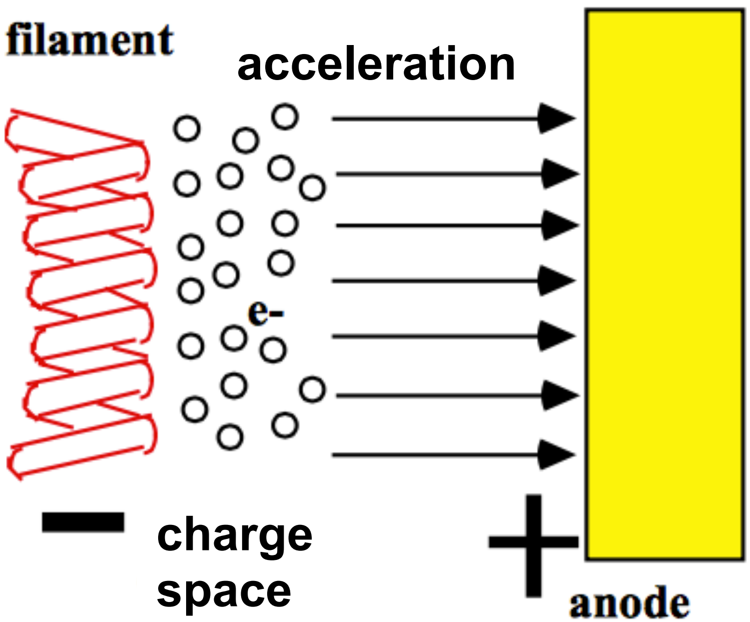
Energy supply → Heat a filament
Joule Effect: $W=RI^2t$ → Electronic cloud

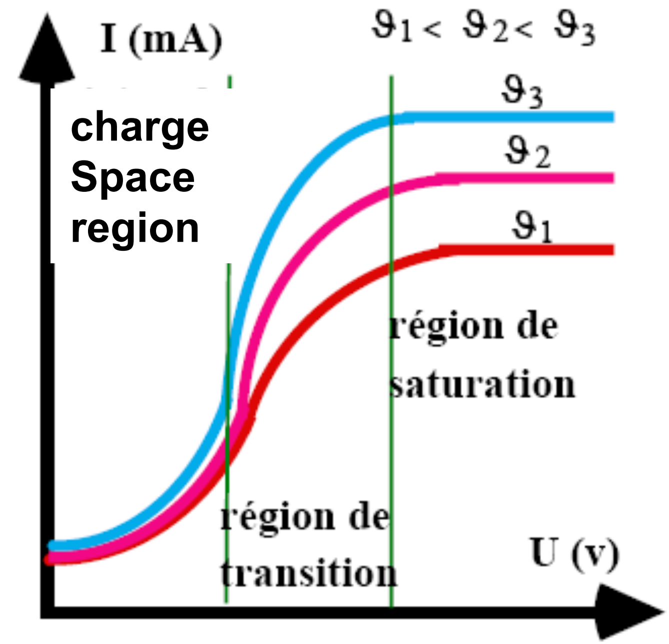
=

Thermo-ionic effect

Or

EDISON effect





In the saturation region, the current intensity depends only on the filament temperature.

X-ray production

Electrons beam

Potential difference between anode et cathode ⇒ Electrons acceleration

Electrons energy: $$T_0 = eU = \frac{1}{2}mv^2$$

e: electron charge
U: Potentiel difference in V
m: electron mass
v: electron velocity

Consider that :
- All the electrons have the same energy
- If $U = 120\ kV,\ T_0 = 120\ keV$

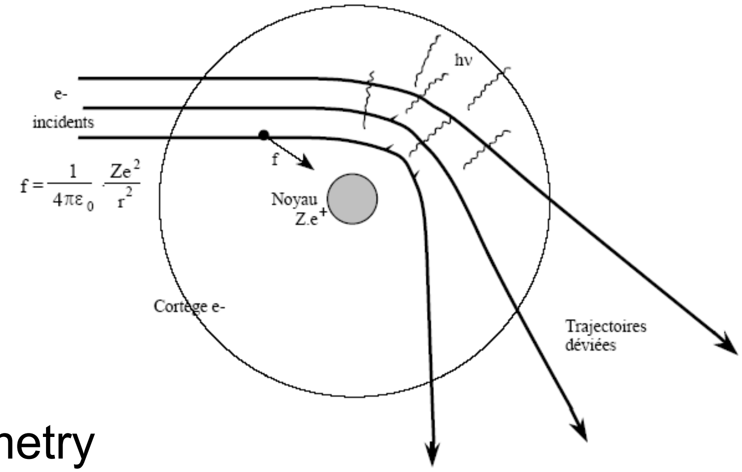
X-rays production

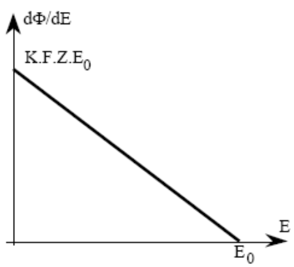
Electron/matter interaction

Two types of interaction:

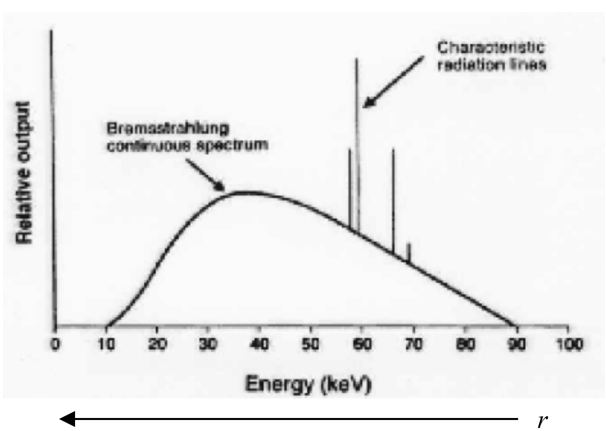
Energy supply

Passing at the proximity of the nucleus
→ Attraction by the positive nuclear charge
→ Centripetal acceleration interaction
→ Energy emission by means of photons
→ Electron slowing down
→ Bremsstrahlung radiation





K is a constant depending on geometry
F is the electrons fluence
Z is the target atomic number
E_0 is the electron maximum energy

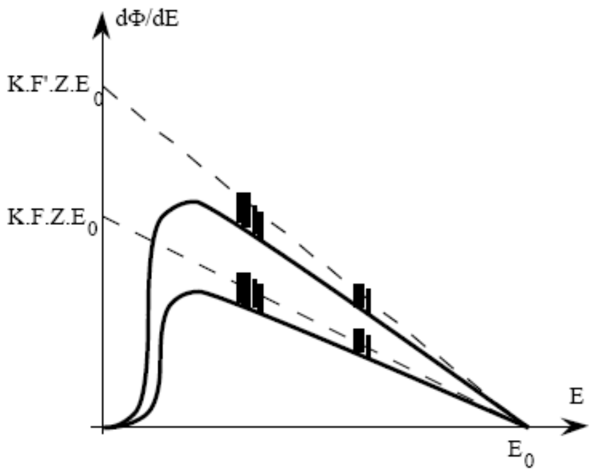


→ Characteristics rays

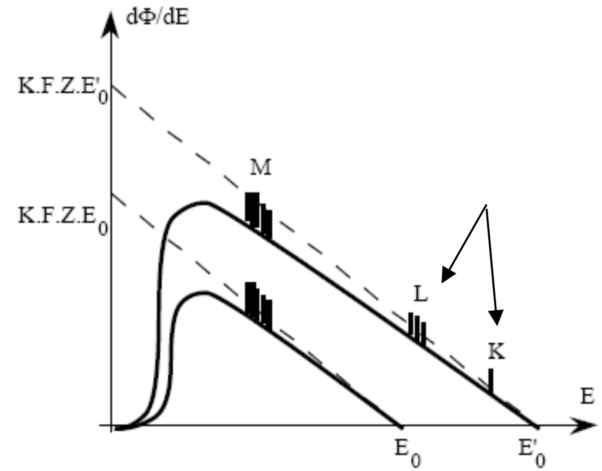
X-ray production

Spectra shape

Filament current intensity role



Acceleration voltage role



Global energetic fluence $\Phi = \frac{1}{2} K \cdot F \cdot Z \cdot E_0^2$

Bremsstrahlung radiation theoretical yield:

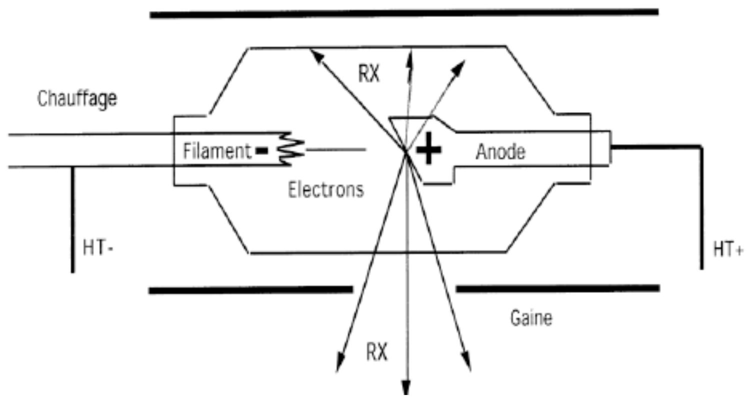
$$\rho = \frac{\Phi}{F \cdot E_0} = \frac{K \cdot F \cdot Z \cdot E_0^2}{2F \cdot E_0} = k \cdot Z \cdot U$$

Is is function:
- of the target (Z),
- of the acceleration voltage (U),
- Geometrical factor (k).

Example of a tungsten anode:
Z = 74, U = 100 kV, ρ *= 1,2 %*
The rest is dissipated in form of heat

X-ray production

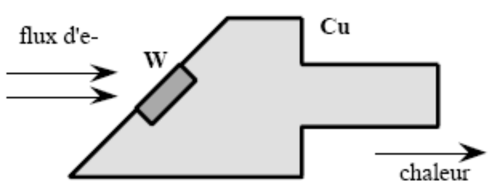
Tubes



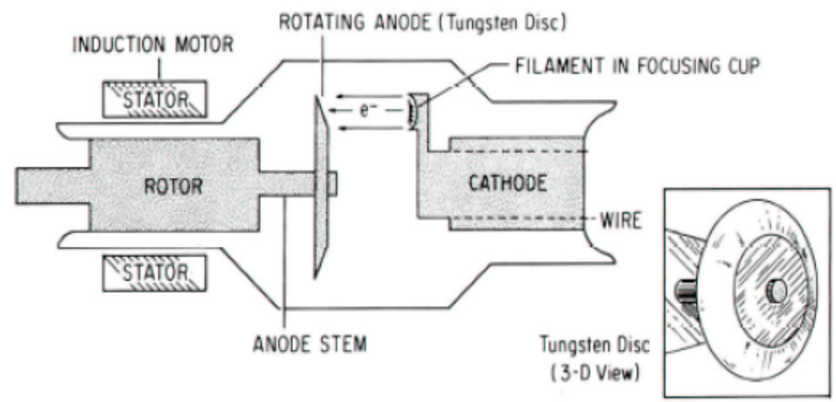
Two major problems :
- Yield
- Heat

→ Anode capacity overtaking and destruction.
Glass and filament aging and bulb destruction

Cooling circuit based on mineral oil.
Rotating anode instead of fixed one.



Heat dissipation by copper



X-rays production

Rotating anode

Rotating anode advantages are:

→ Heat spreading on a larger surface (1000-1500°C).

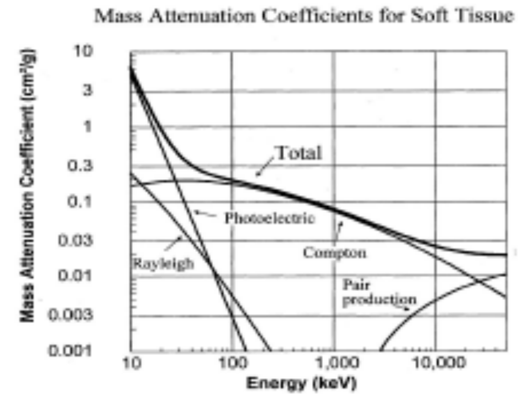
→ Increasing the X-rays yield which means the increasing of the generator power (15-20 kW)

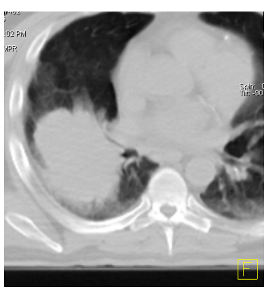
→ Reducing the focal point size which improves the image quality in terms od spatial resolution.

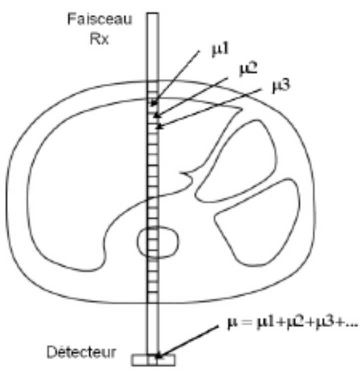
Photon/matter interaction

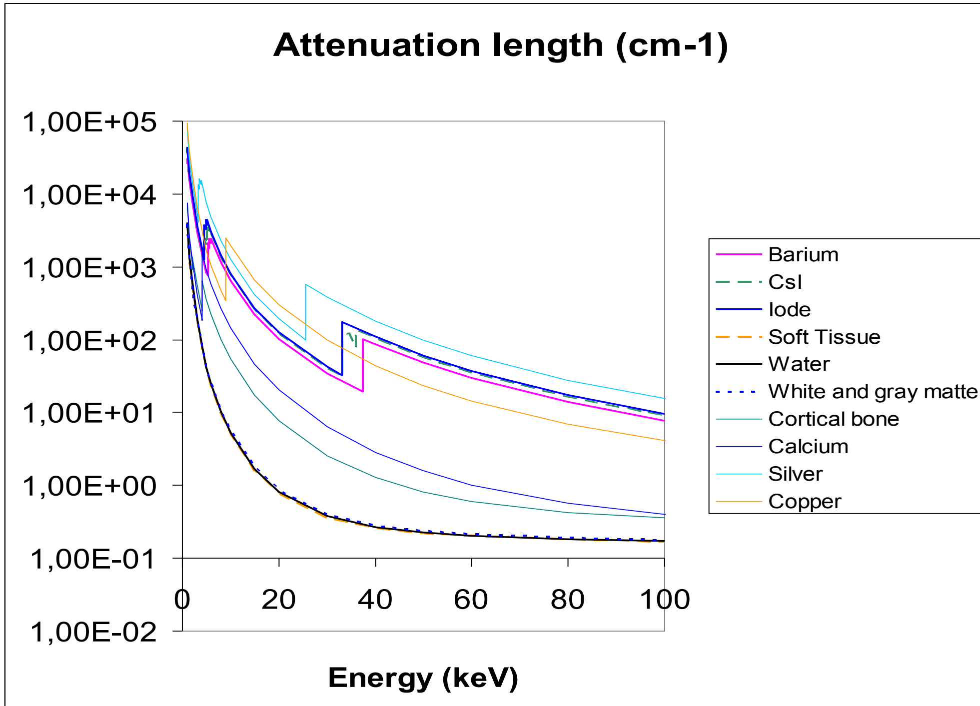
$$\mu = \tau + \sigma + \pi$$

$$N(x) = N_0 e^{-\mu x}$$





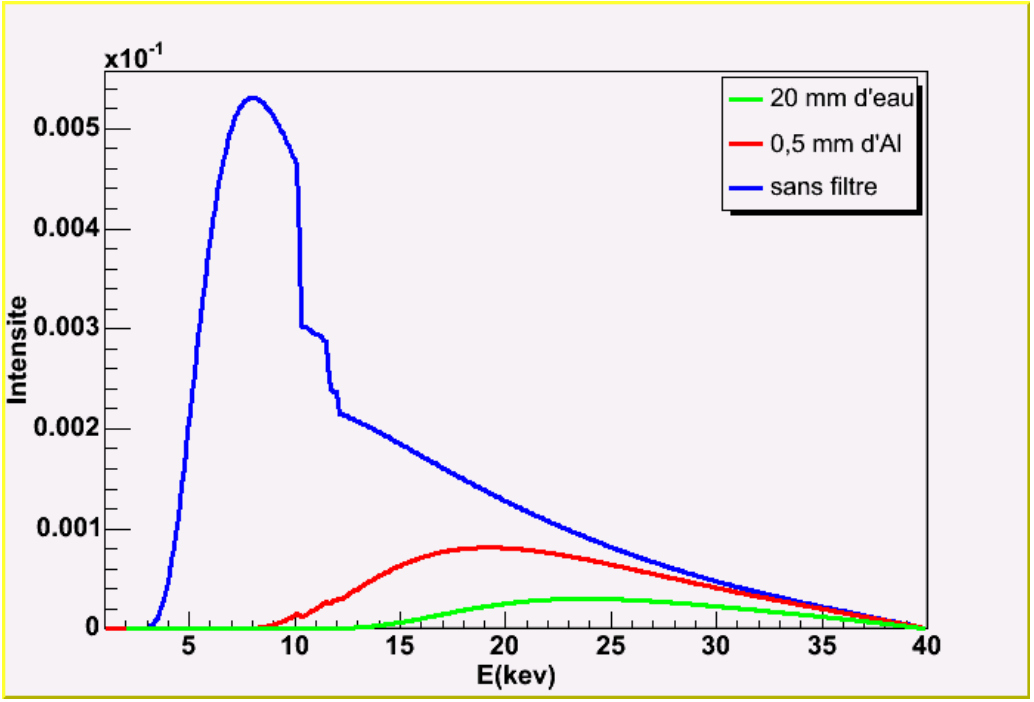




$$I = I_0 e^{-\int_L \mu_E(x,y,z)\,dL}$$

Hypothèse: E constante

Photon/matter interaction



Beam hardening

Mean fluence:

$$F_m = \frac{K \cdot I \cdot t \cdot Z \cdot U^5}{d^2}$$

Distance to anode

Photon/matter interaction

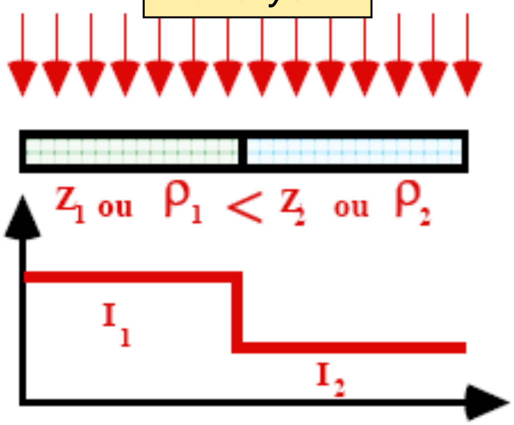
Image contrast

Contrast between two regions can be expressed as follows:

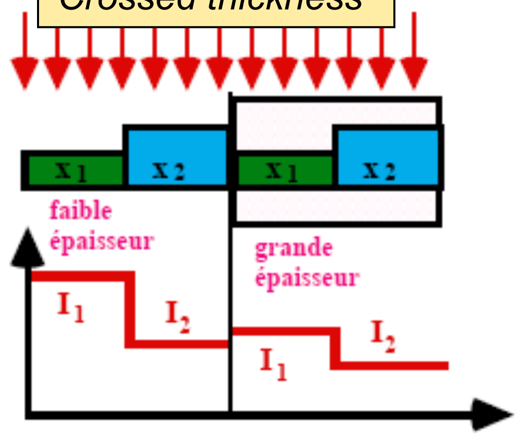
$$C = \frac{I_2 - I_1}{I_2 + I_1}$$

It depends on many factors:

Density / Z



Crossed thickness



Photons energy

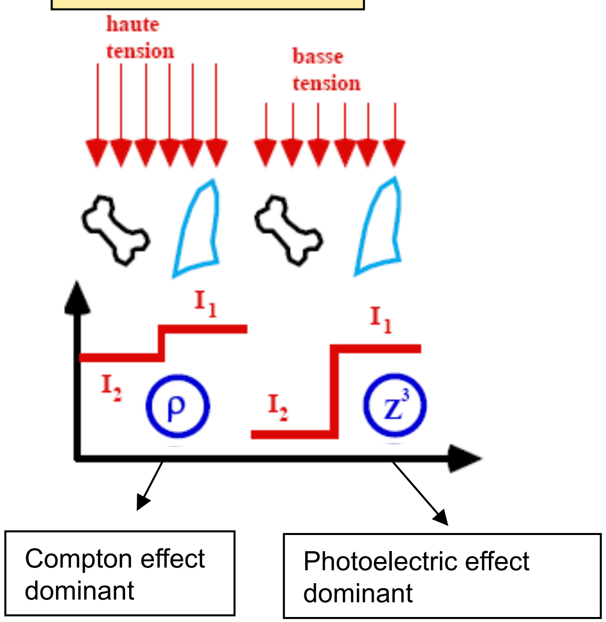
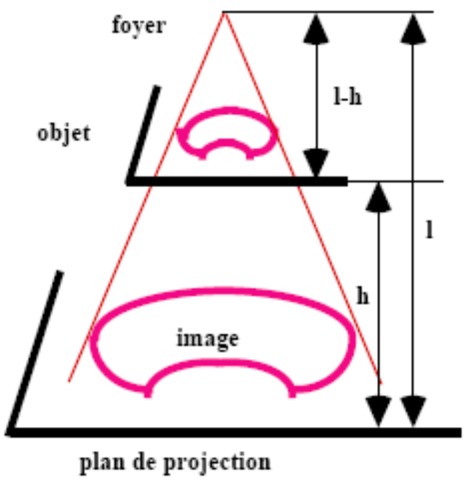
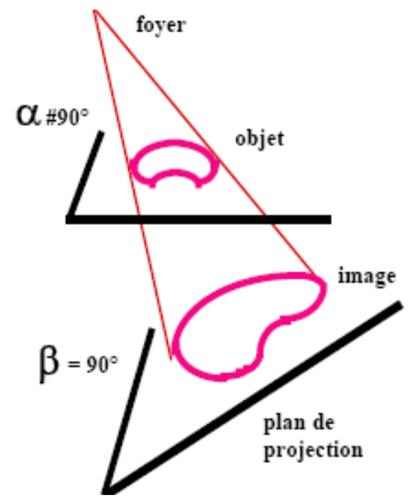


Image formation

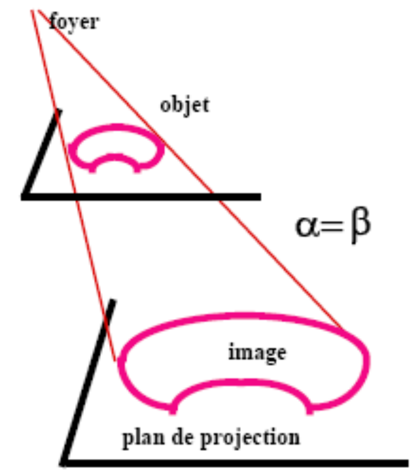
Conical projections law:



$$M = \frac{l}{l - h}$$



Deformation if incidence angle is different from projection angle



No deformation if incidence angle and projection angle are the same

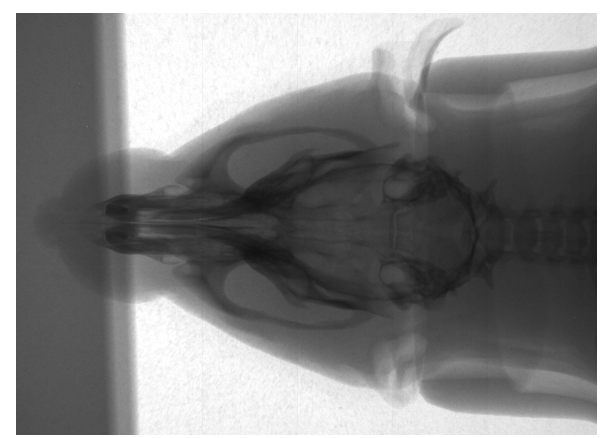
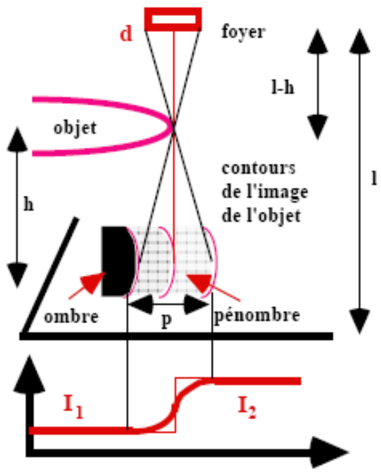


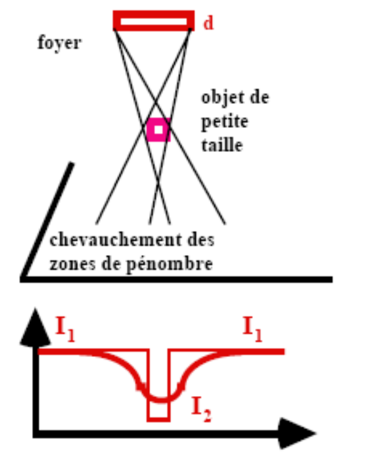
Image formation

Blurr

- <u>geometrical</u>: focal point size

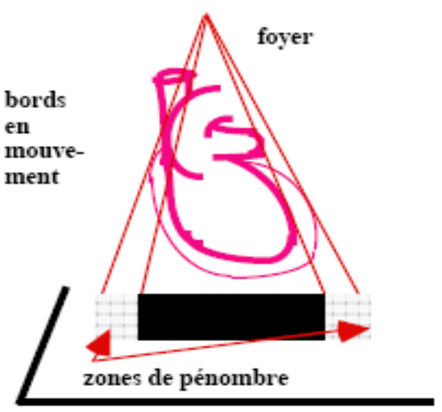


Le flou géométrique



Le flou géométrique efface les détails

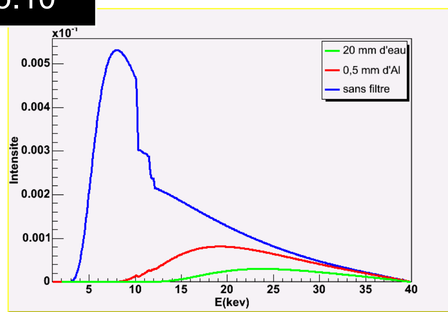
- <u>Kinetic</u>: Organs movement / Pause time



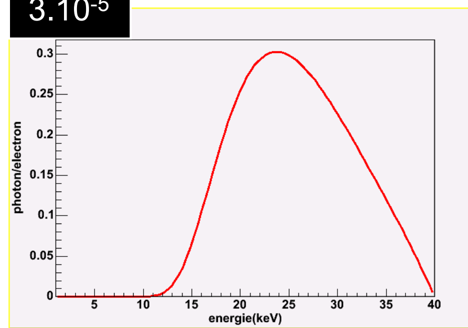
Formation de l' image

Incident beam filtration:

5.10^{-4}

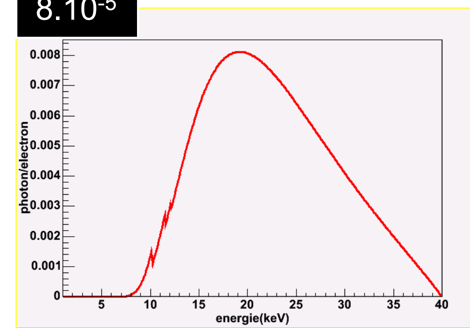


3.10^{-5}



25mm d' eau

8.10^{-5}



0,5mm d' Al

$$F_m = \frac{K \cdot I \cdot t \cdot Z \cdot U^5}{d^2}$$

Change the voltage of the mAs

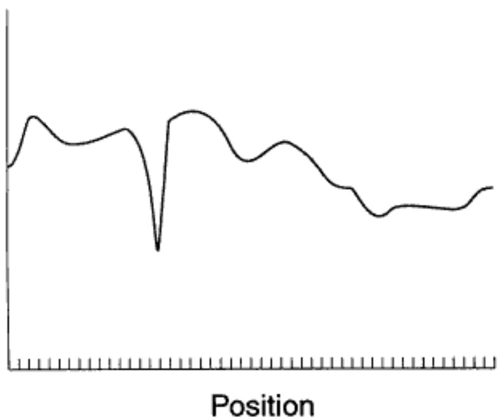
From analogical to numerical

http://www.chu-poitiers.fr/en/pole-imagerie-radiologie-radiologie/

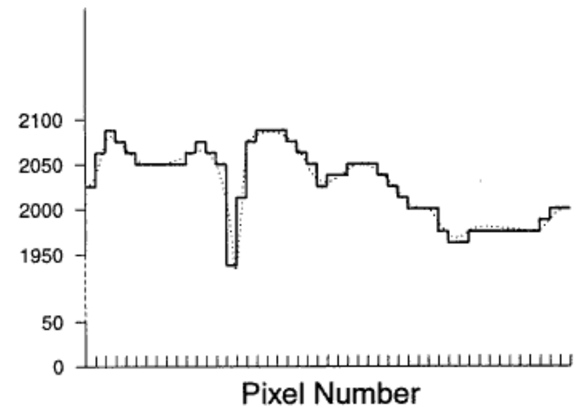
Numerical detection system

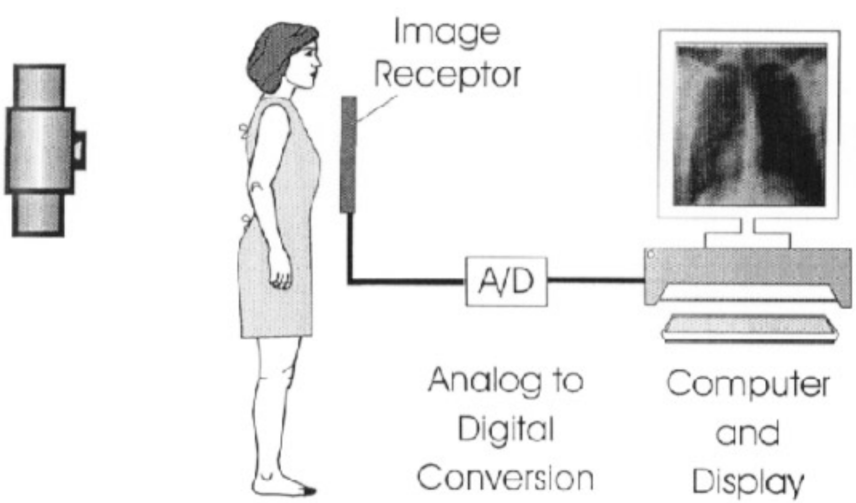
Numerical image

Analogical signal



Numerical signal





Two parameters:
- Pixel size
- Signal depth

*Yaffe and Rowland, X-ray detectors for digital radiography, Phys Med Biol **42** (1997) 1-39*

Numerical detection system

Detector properties

Field of view

The field of view should be adapted to the region of interest:

Thorax radiography: 35cm x 43cm

Mammography: 18cm x 24cm ou 24cm x 30cm

Geometrical characteristics

Filling ratio: ratio between active zone and dead zone

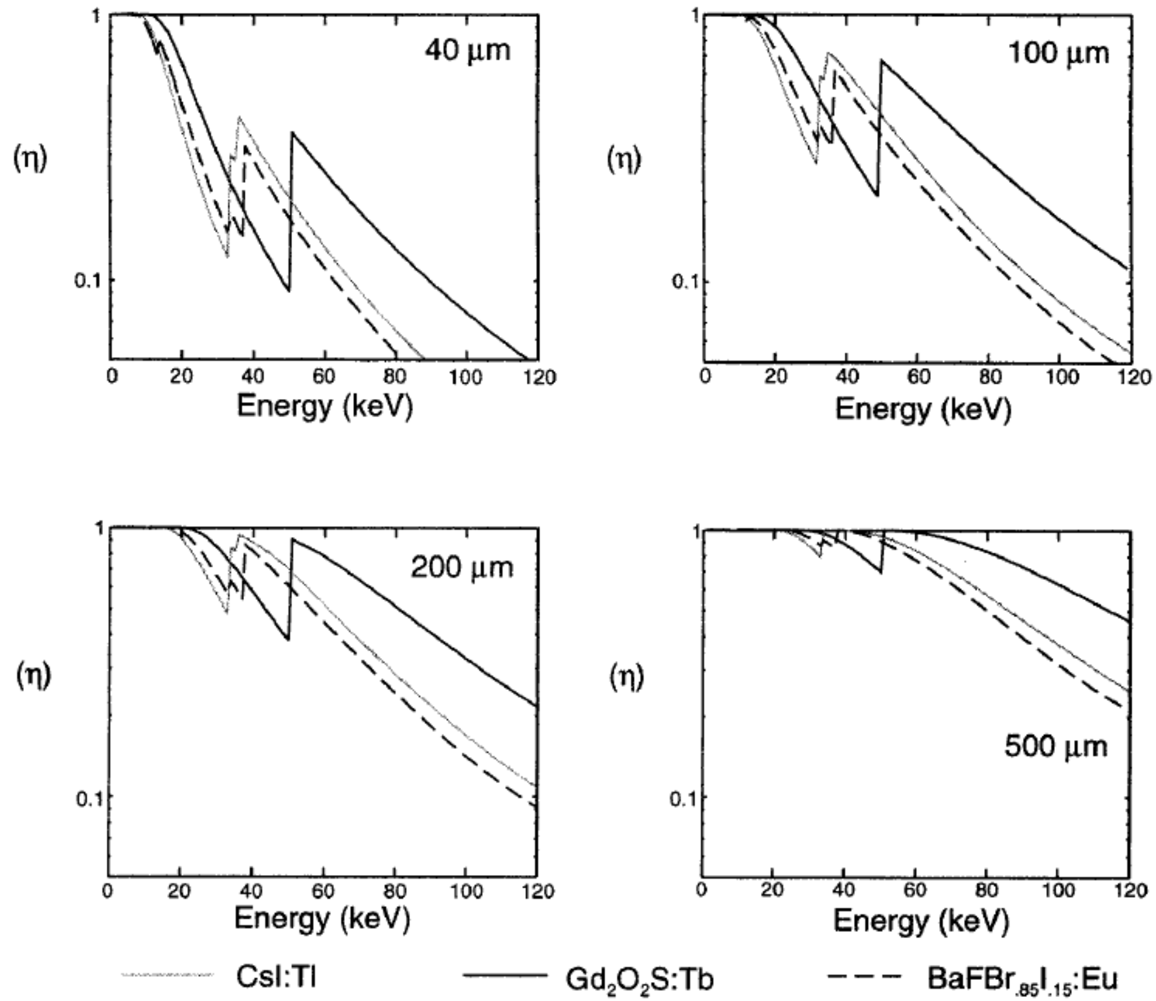
Distorsion: for scale adaptation

Numerical detection system

Detector properties

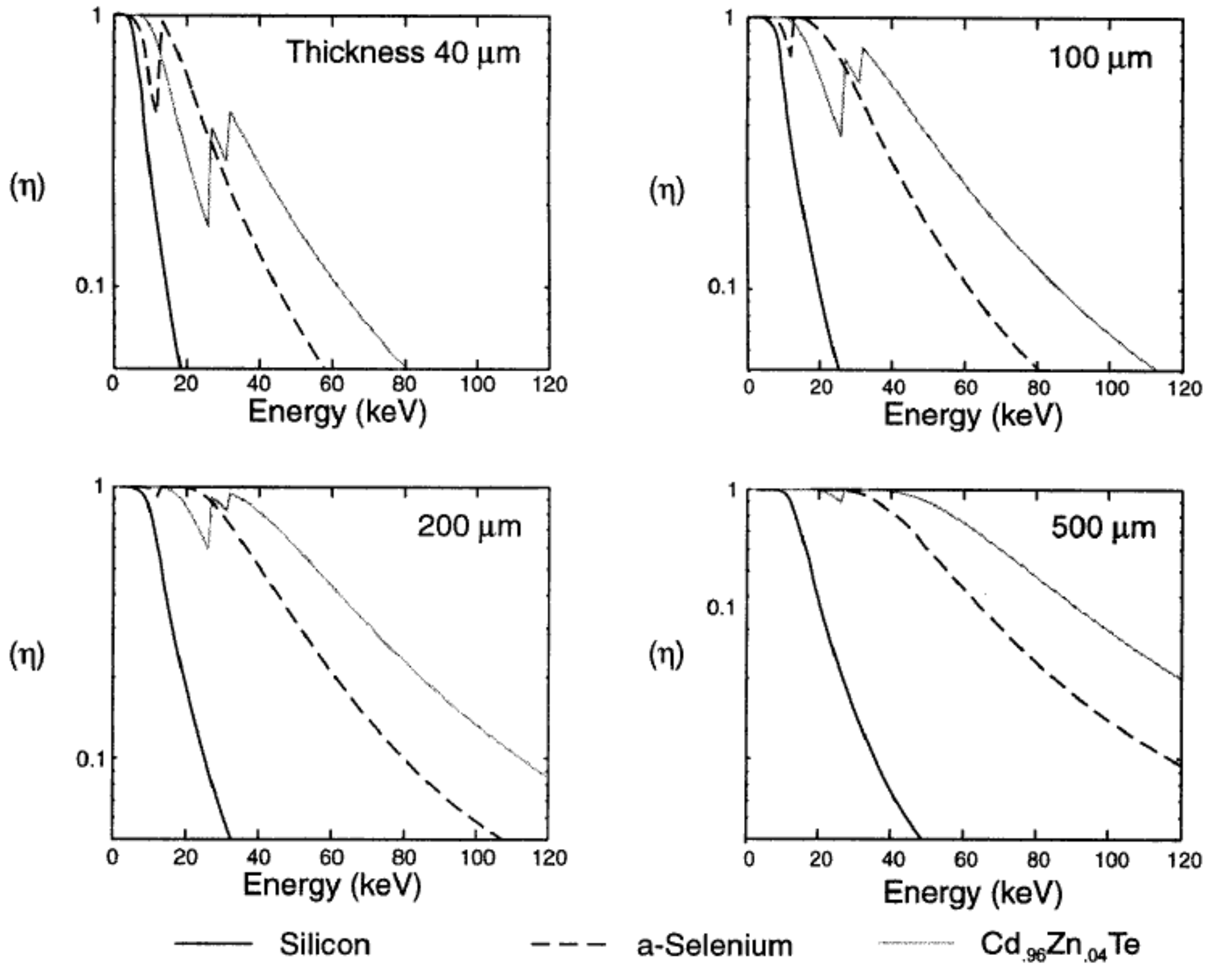
Detection efficiency

$$\eta = 1 - e^{-\mu(E)x}$$



Numerical detection system

Detector properties



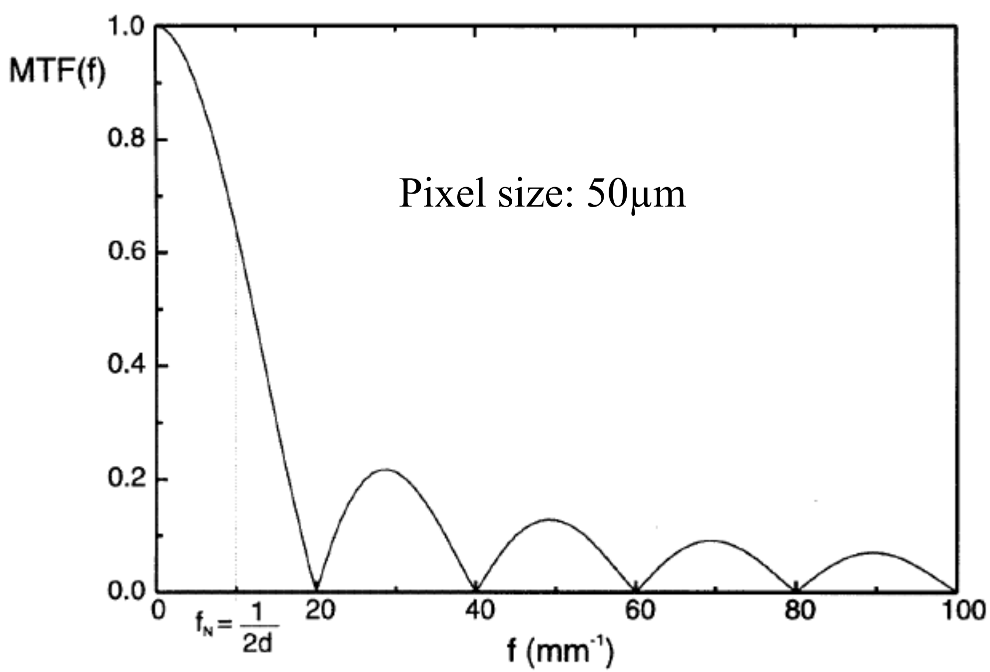
Numerical detection system

Detector properties

Spatial resolution: the smallest distance between two distinguishable points

<u>Detector related factors:</u>
- Size of a detection element (pixel),
- Distance between two pixels,
- Scatter (physics, read-out etc)

<u>Exterior factors:</u>
- Focal point,
- Magnification factor,
- Movement,
- etc…



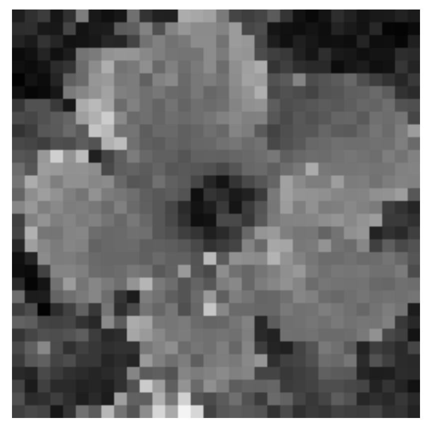
Nmerical image (pixellisation)

48	49	46	42	44
110	79	54	47	48
190	192	190	153	99
150	166	189	203	183
131	140	145	161	165

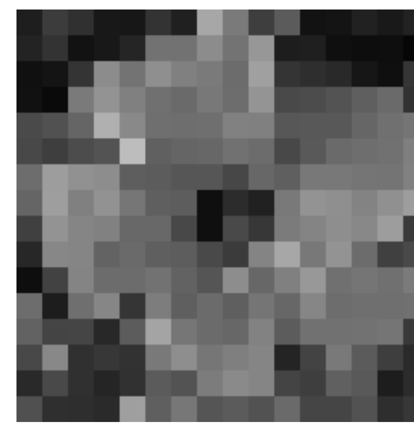
Pixel value : 0 – 255 (256 values)

One line/column over 2

One line/column over 4



One line/column over 8



One line/column over 16

http://images.math.cnrs.fr/Le-traitement-numerique-des-images.html

Numerical detection system

Detector properties

Noise

$$\sigma = \sqrt{N}$$ Emission X: Poisson law

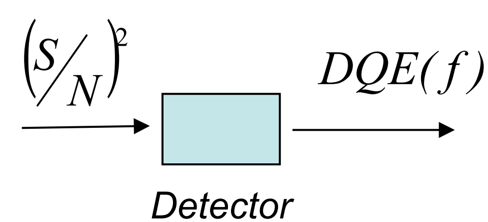
$$\sigma = \sqrt{\eta N}$$ After interaction: Statistic according to Poisson law

After magnification: $$q = \eta N \bar{g}$$

Mean gain

Variance: $$\sigma_q^2 = N\eta\left(\bar{g}^2 + \sigma_g^2\right)$$

« Detective quantum efficiency » $DQE(f)$
Ideally, $DQE(f) = \eta$ for all frequencies



Numerical detection system

Detector properties

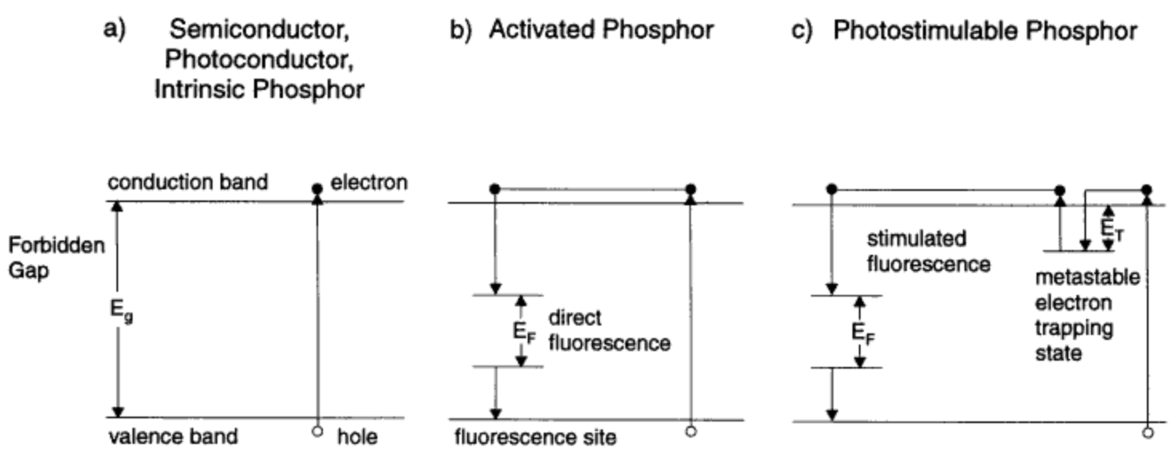
Yield

1 photon X → ? électrons

Required energy to create:
An optical photon (cristal) or
An electron-hole pair (semi-conducteur)

Material	Z	E_K (keV)	w (eV)	ω_K (approx.)[a]
CdTe	48/52	26.7/31.8	4.4	0.85–0.88
High-purity Si	14	1.8	3.6	$<$ 0.05
Amorphous selenium	34	12.7	50 (at 10 V μm^{-1})[b]	0.6
CsI(Tl)	55/53	36.0/33.2	19	0.87
Gd_2O_2S	64	50.2	13	0.92
BaFBr (as photostim. phosphor)	56/35	37.4/13.5	50–100[c]	0.86

Probability to have a Characteristic ray

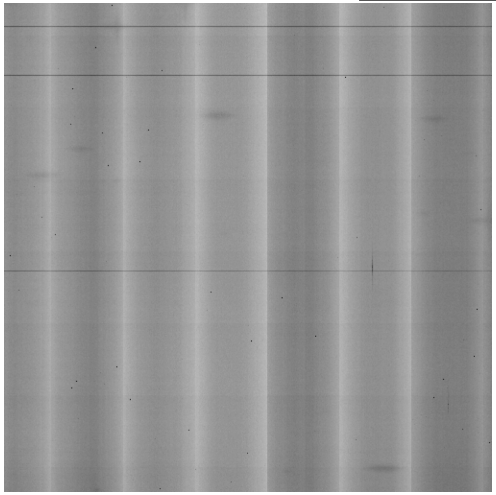


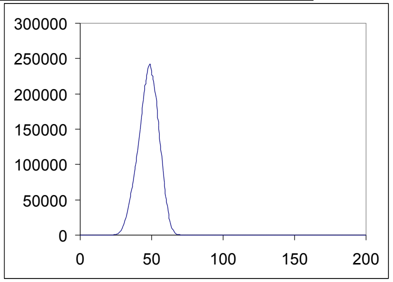
Numerical detection system

Detector properties

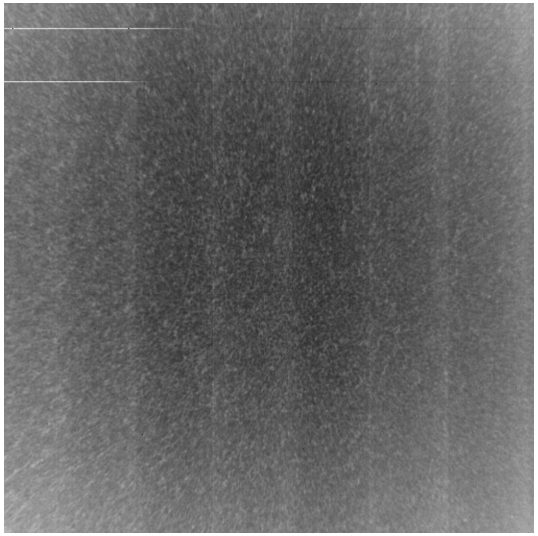
Signal dynamic

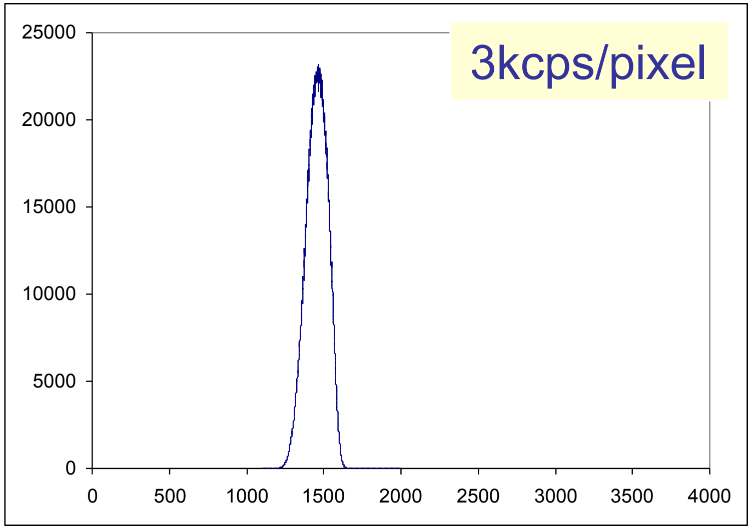
$$Dynamic = \frac{X_{\max}}{X_{bruit}}$$





Electronic noise





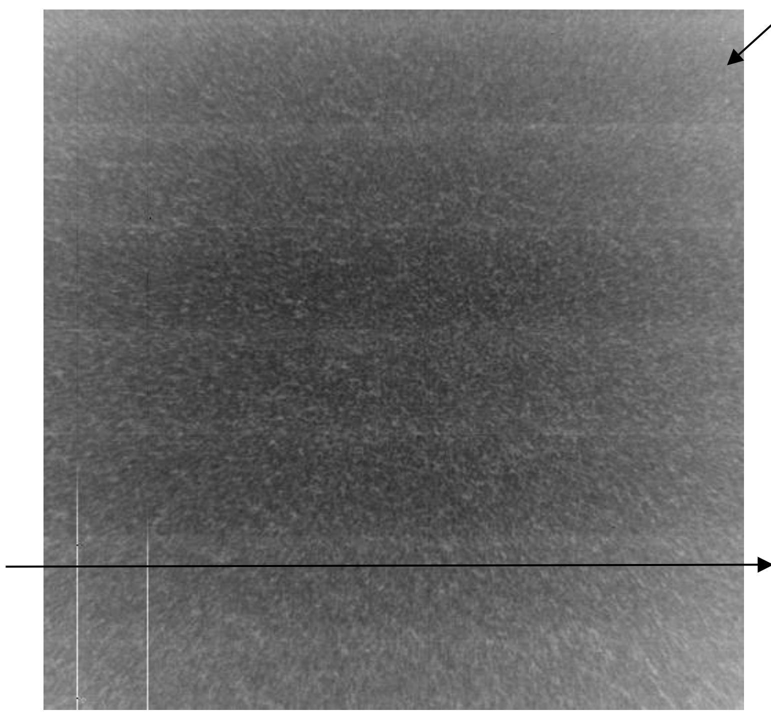
Full fluence (40kV, 250µA, 0,5mm Al, 470ms)

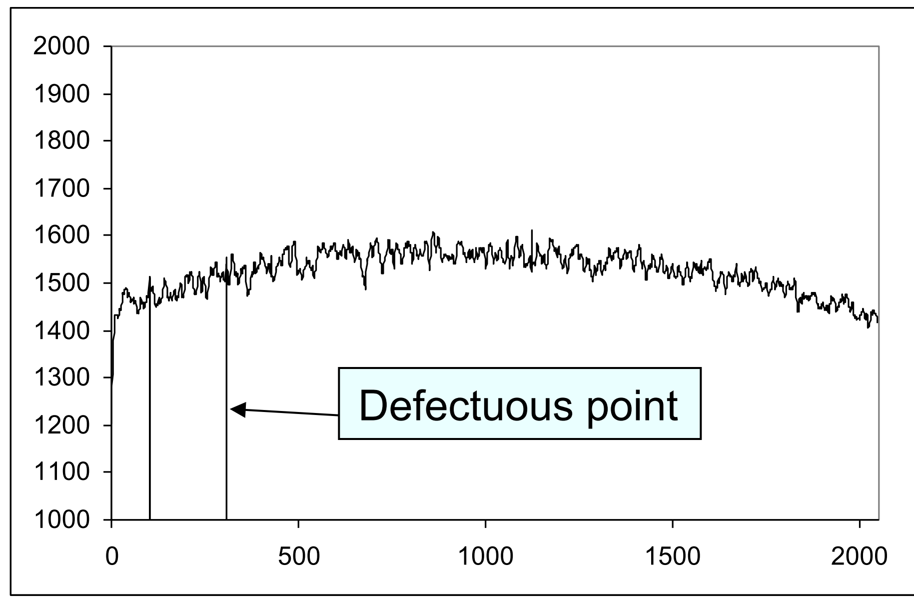
Numerical detection system

Detector properties

Uniformity

Read-out band

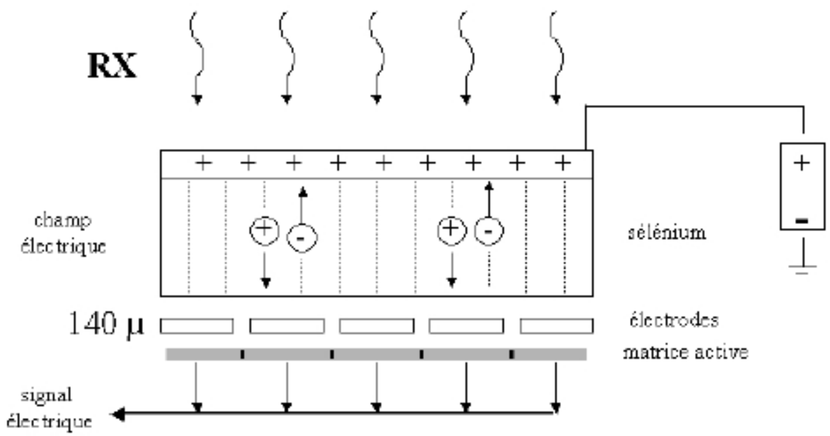




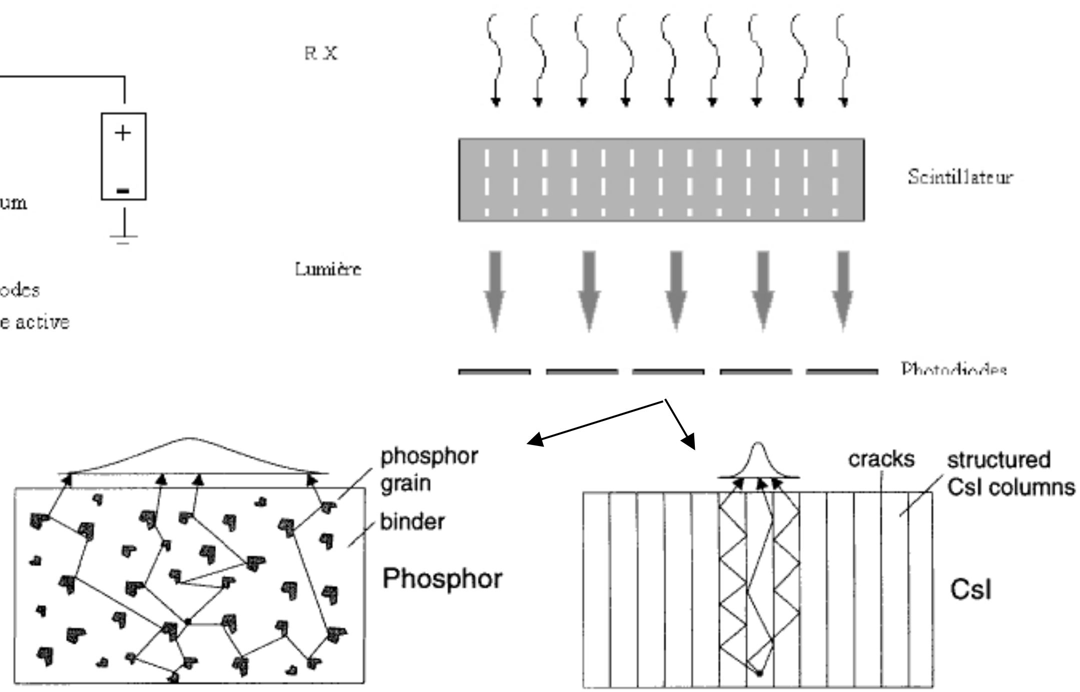
Numerical detection system

Conversion of the radiant image can be direct or indirect

Direct electric conversion

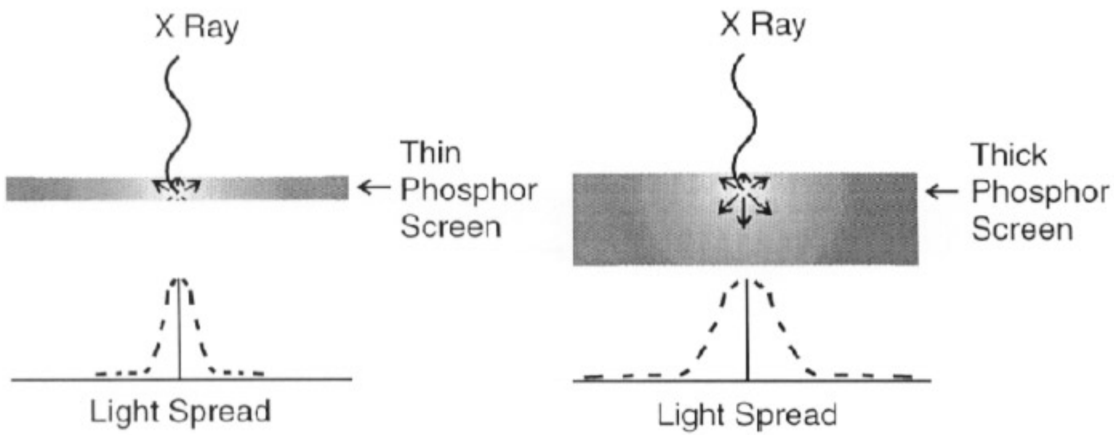


Indirect electric conversion



Numerical detection system

Indirect method



Coupling with a photodetector

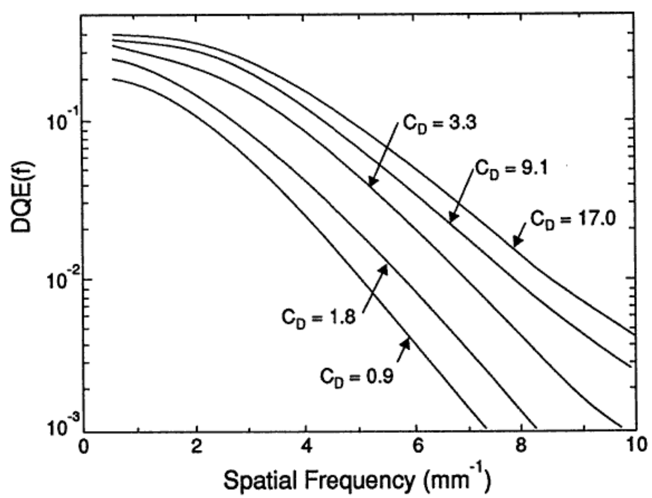


Figure 11. Effect of optical coupling efficiency on $DQE(f)$ of a phosphor–fibre optic–CCD detector. C_D is the number of electrons produced in the CCD per x-ray interacting in the phosphor. (From Maidmont and Yaffe 1994.)

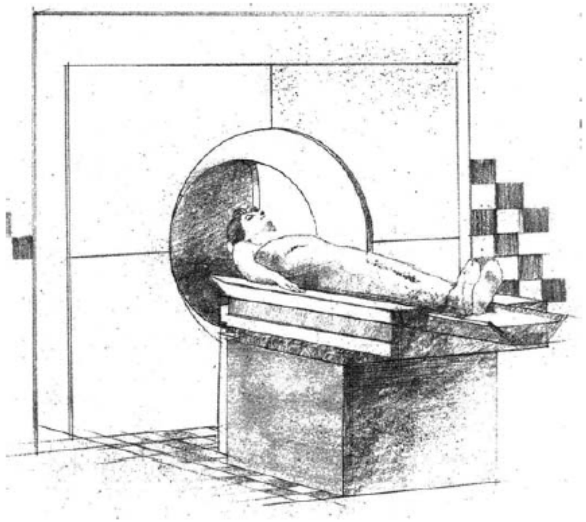
X-ray scanner

Historical overview

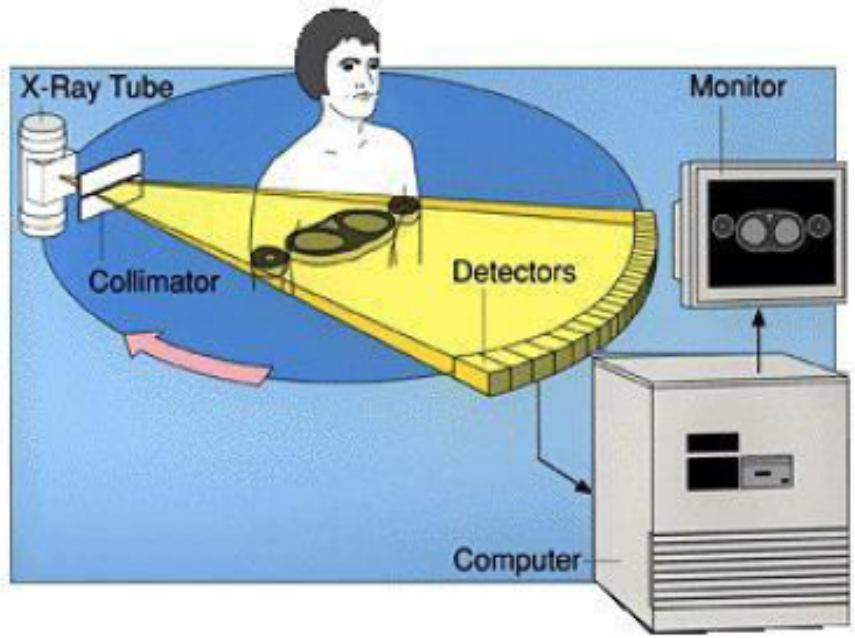
1971 : First brain scanner exam
1974 : First full-body apparatus
1979 : Nobel price in medicine attributed to Allan MacLeod and Godfrey N. Hounsfield for the first scanner set-up
1989 : Helicoïdal acquisition
1992 : Simultaneous acquistion of two slices by rotation
1998 : Multi-slices acquisition

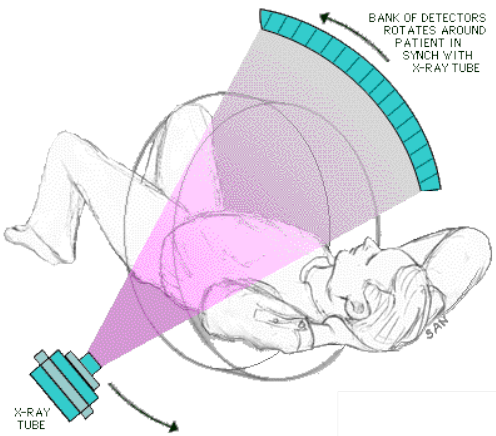
In summary, during these 30 years, progess allowed to :

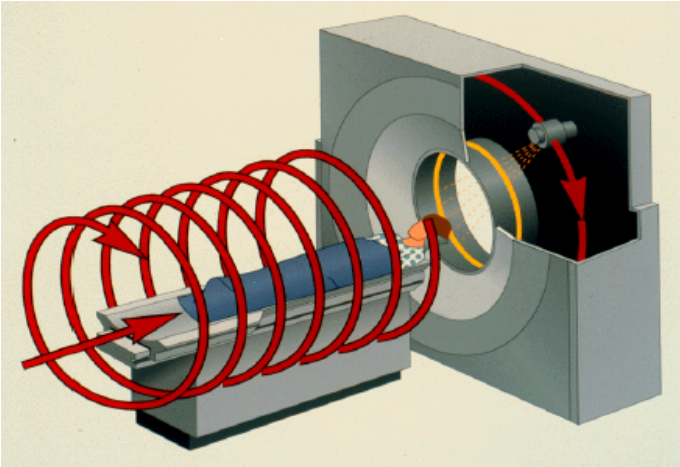
- Gain a factor of 1000 in acquisition speed and reconstruction
- Gain a factor of 30 in terms of spatial resolution and to improve considerably the contrast
- Improve the patient comfort by reducing the exam duration



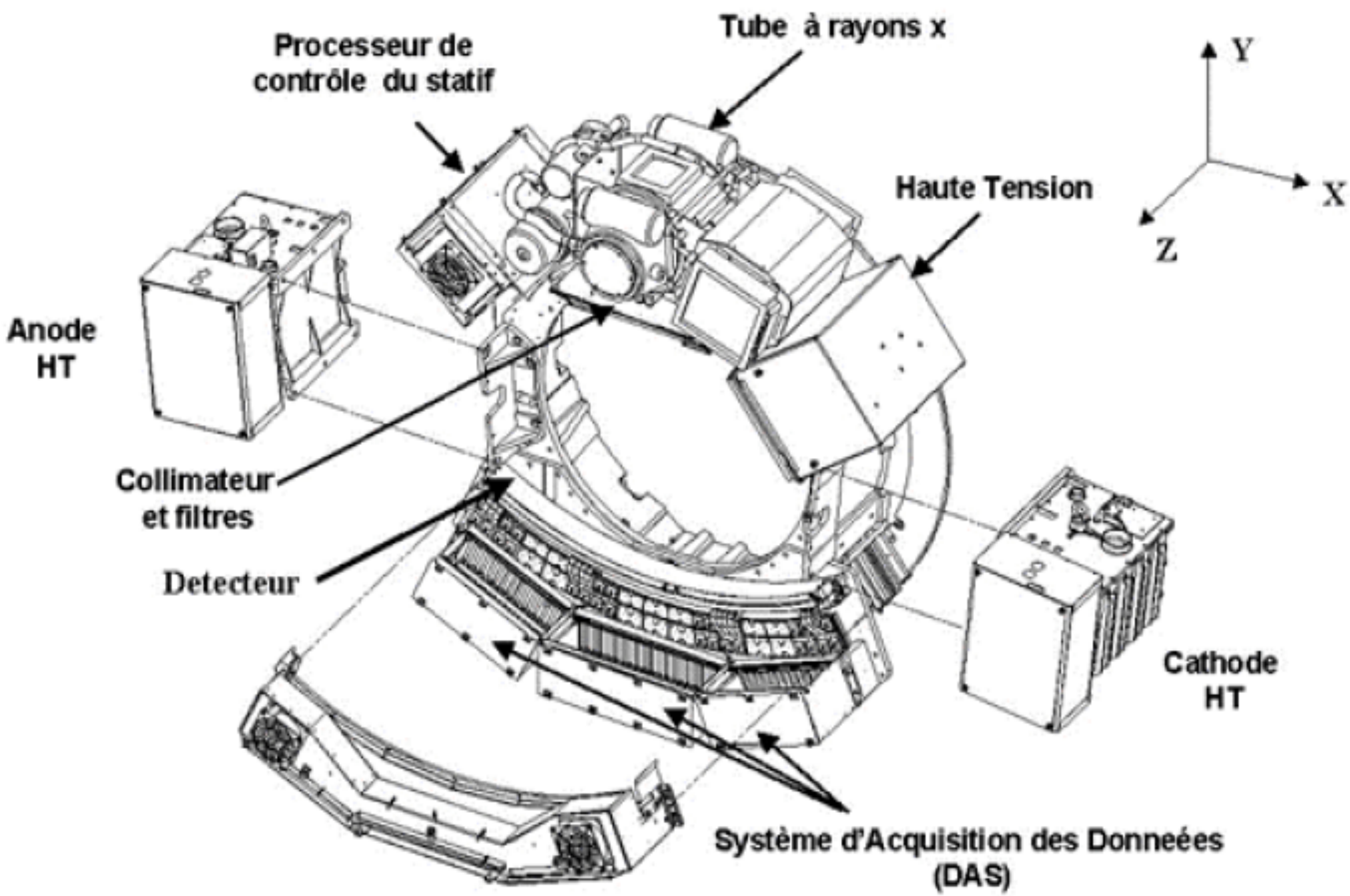
X-ray scanner



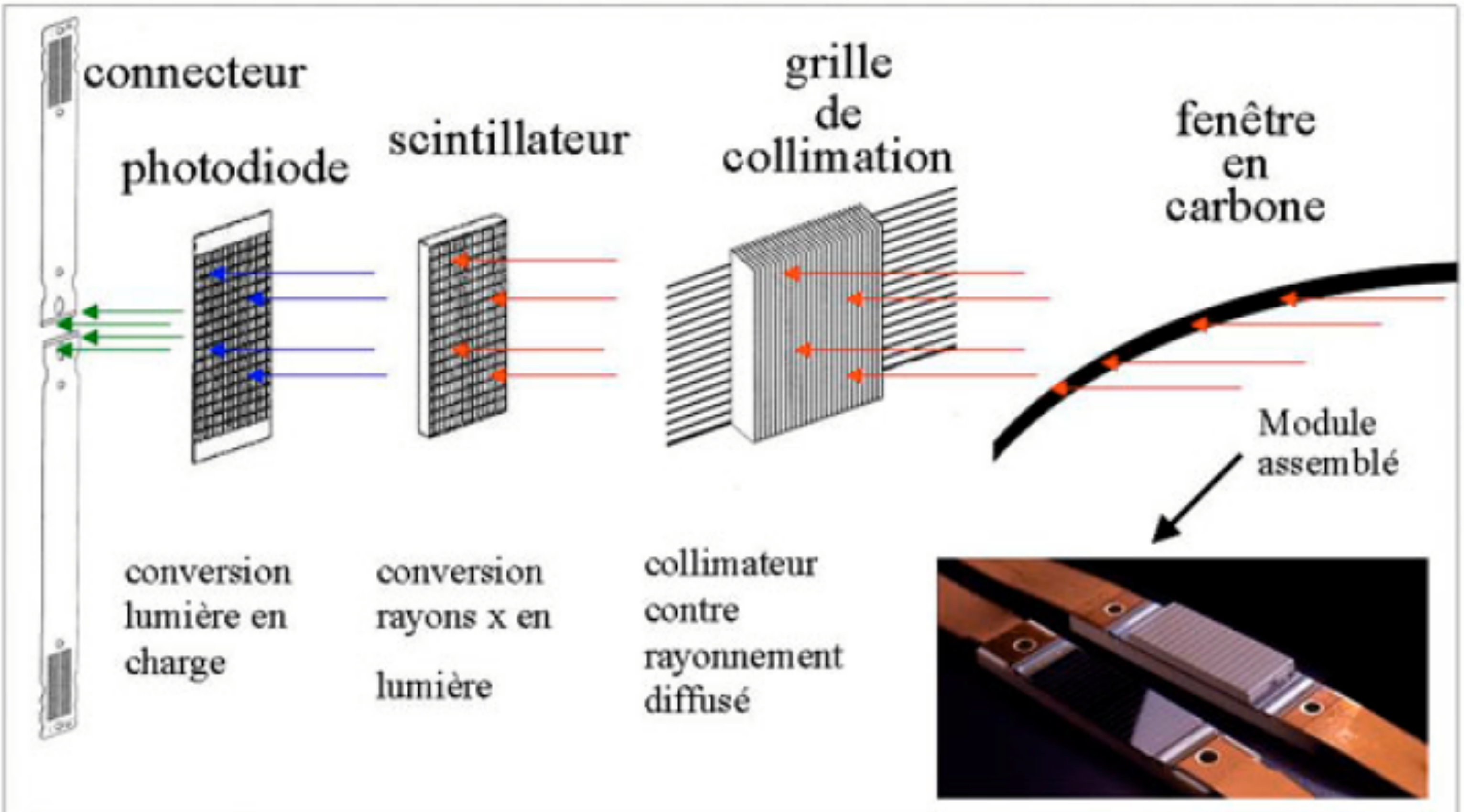




X-ray scanner

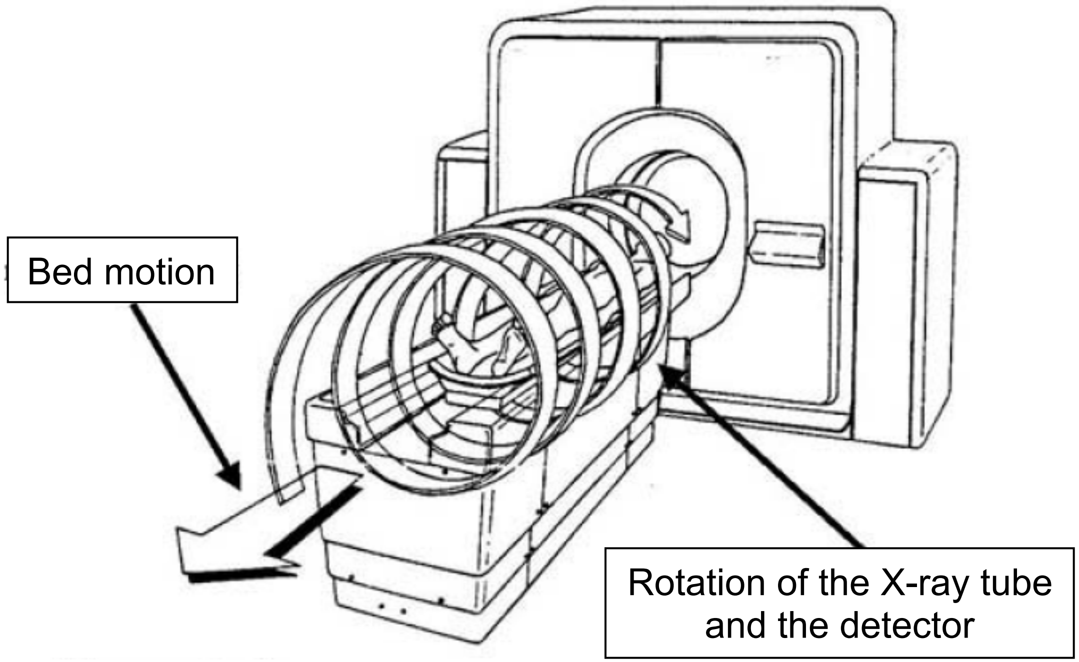


X-ray scanner



X-ray scanner

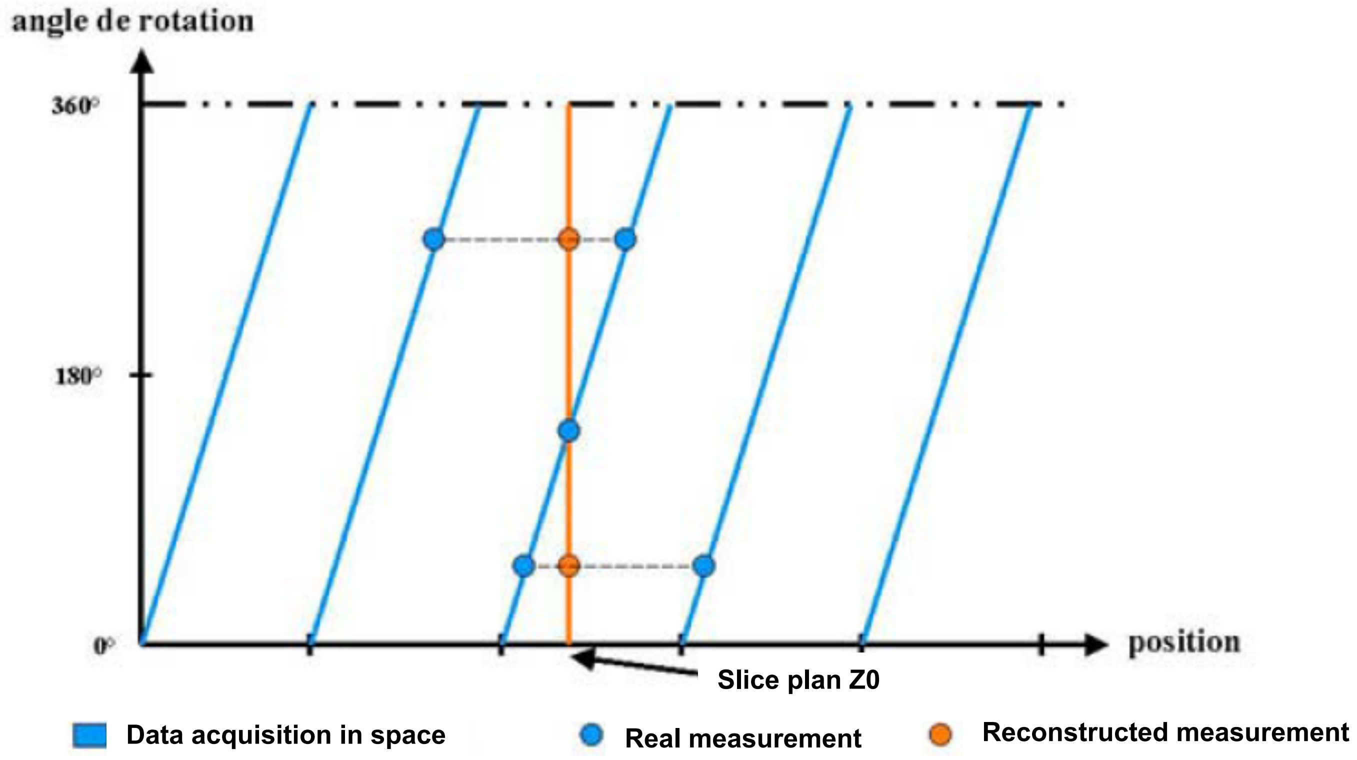
Spiral acquisition



Collimation opening window width : It is the physical width of the collimation in the center of the acquisition.
Table displacement velocity during acquisition (in mm/sec),
The pitch : It is the ratio between the distance crossed by the table during a 360° rotation and the collimator width (ex : during an acqusition of a pitch 1, the exam table would move by a distance equal to the collimator opening window width.
Effective slice thickness: It is the Full Width Half Measurement (FWHM) of a slice profile.

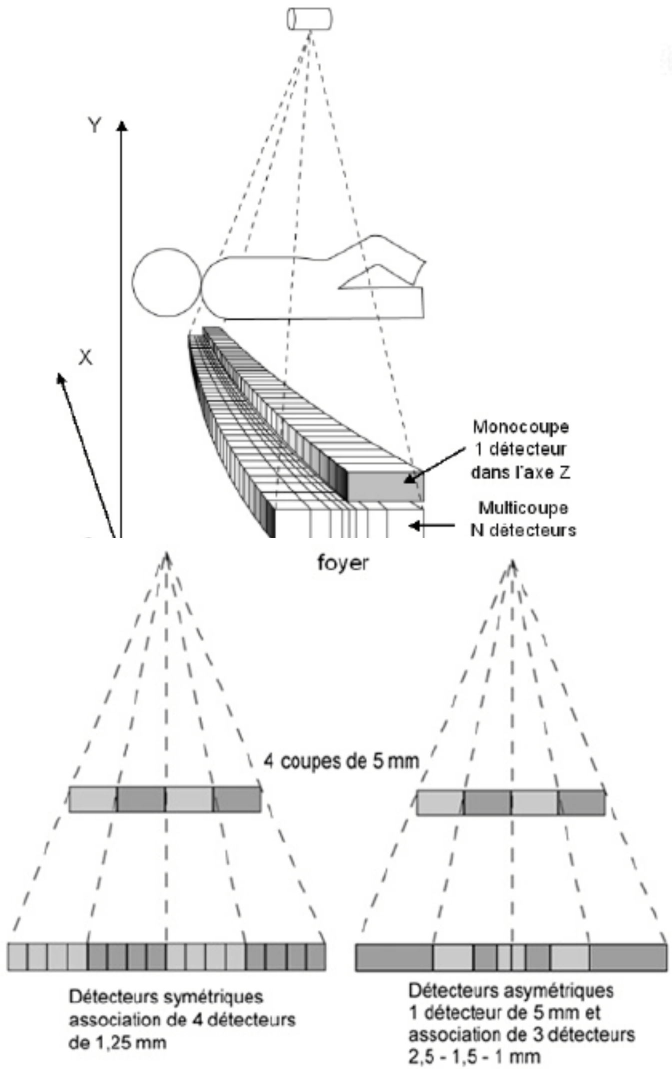
X-ray scanner

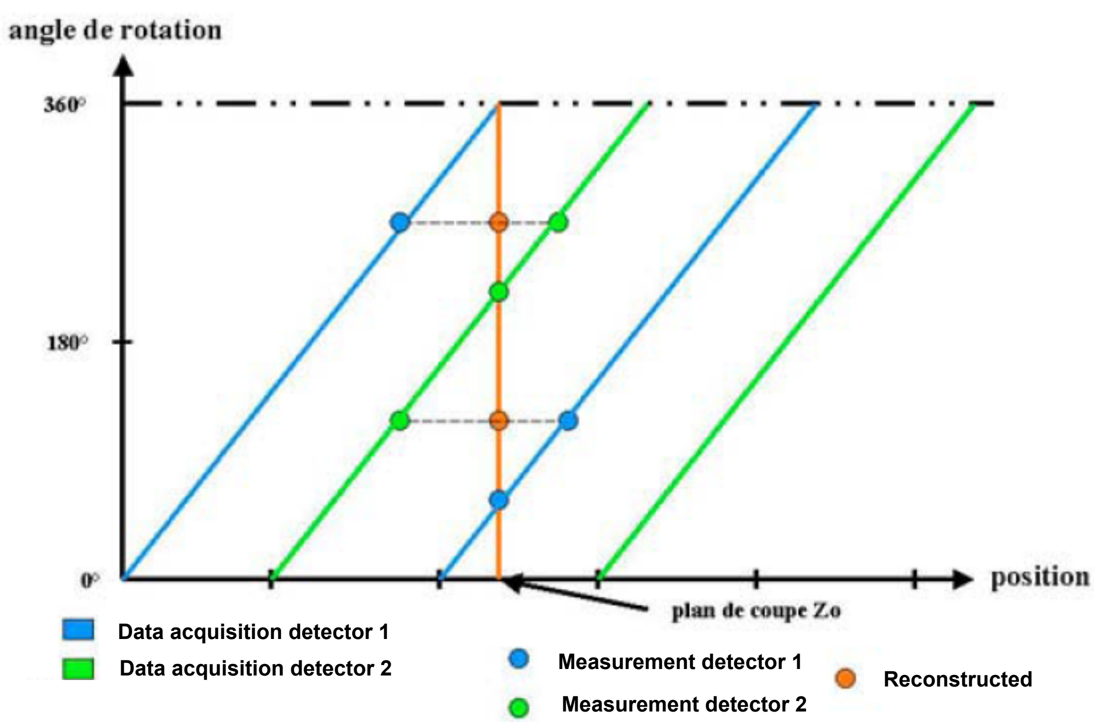
Spiral Acquisition



X-ray scanner

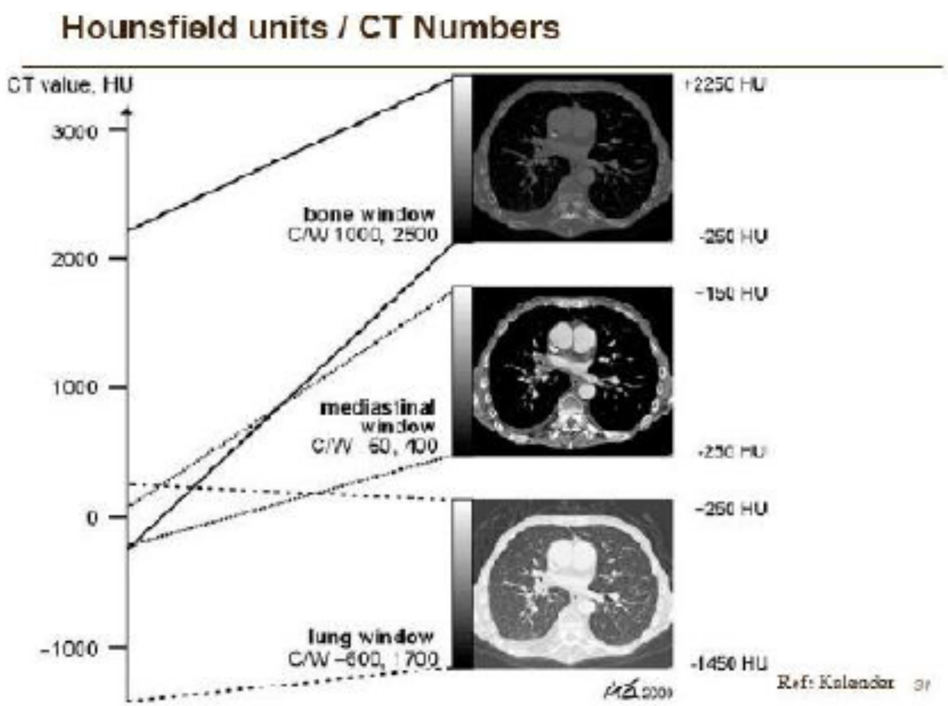
Spiral acquisition, multi barrettes

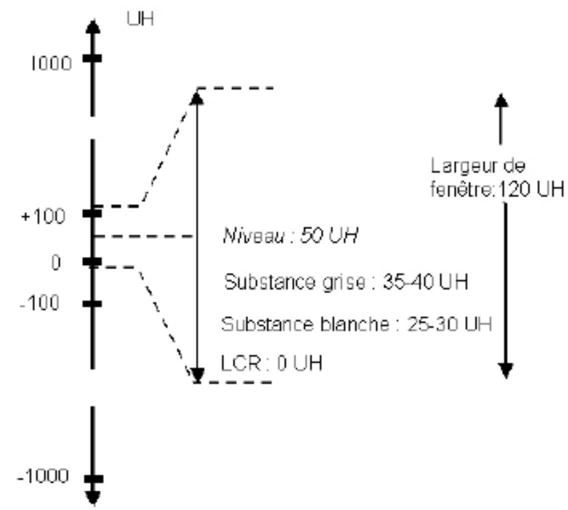




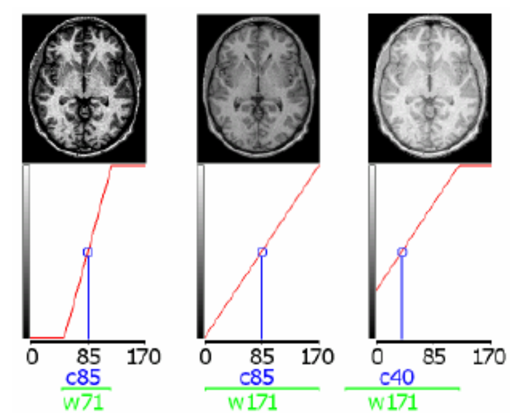
X-ray scanner

$$H = \frac{\mu - \mu_{eau}}{\mu_{eau}}.1000$$





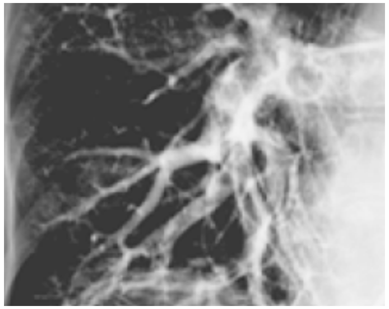
Exemple de niveau et de largeur de fenêtre pour l'étude du parenchyme cérébral



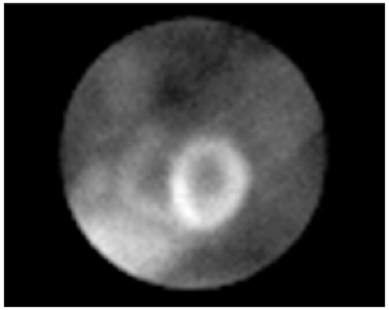
Exemple: Projection vs Tomography

Projection

Pulmonar radiology

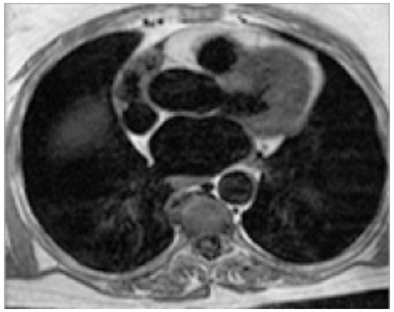


Angiography

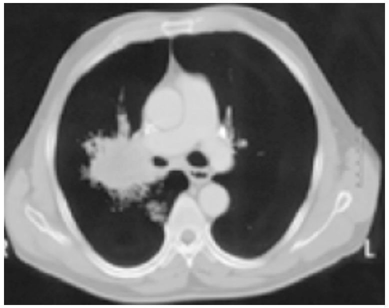


Cardiac Scintigraphy

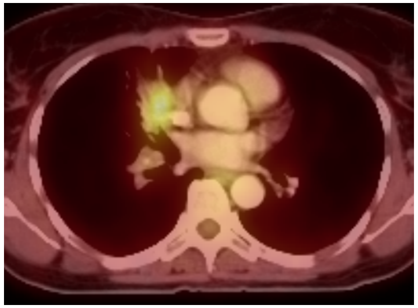
Tomography



IRM

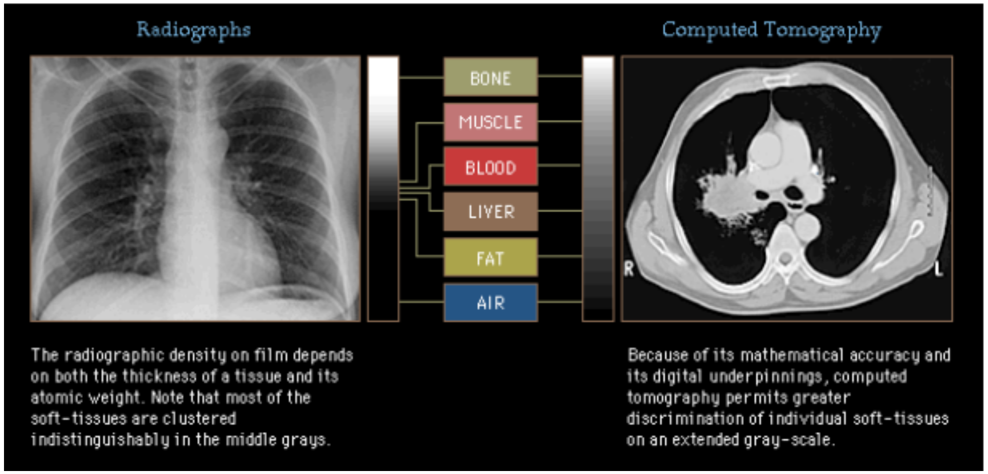


Scanner



Pet/Scanner

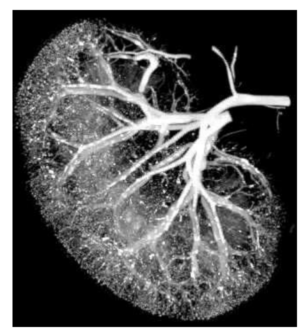
X-ray scanner



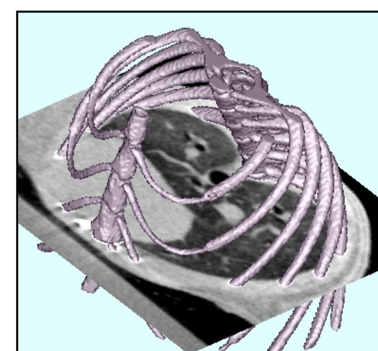
ischémie

angiography

Cardiac exam

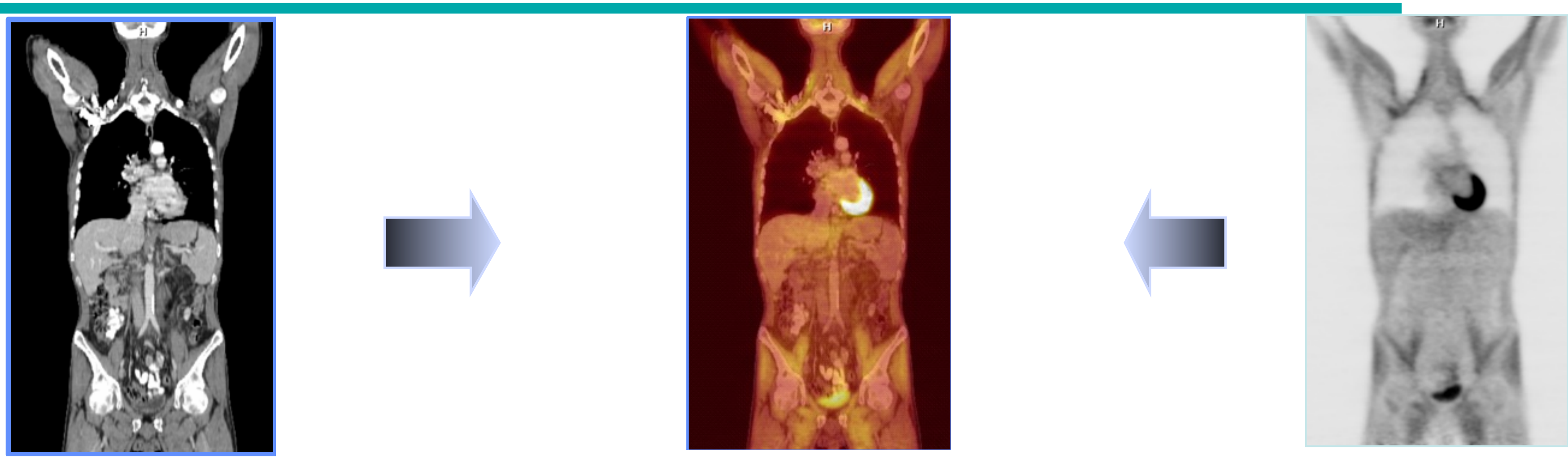


Kidney (rat)



Rib cage (mouse)

X-ray scanner



PET/CT fusion

Anatomy reference system