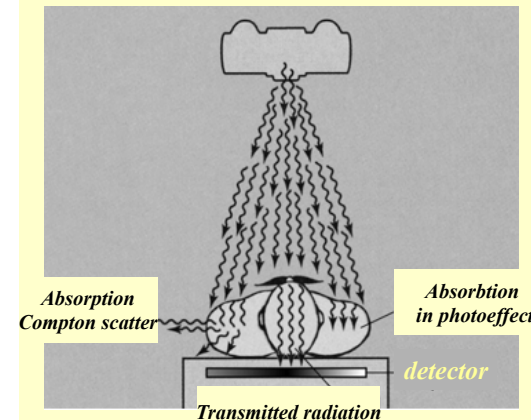


# Medical applications of X-rays

X-ray diagnostics and imaging

Diagnostic radiology

Basic principle of X-ray diagnostic  
is the absorption of radiation

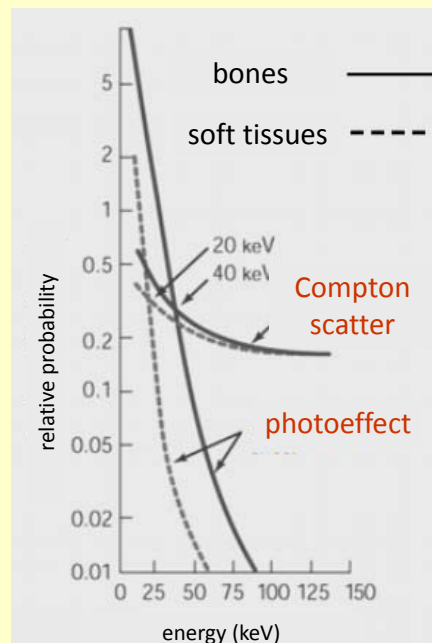


*Possible interactions:*

Compton scatter

photoeffect

no interaction



Attenuation decreases with  
increasing photon energy.

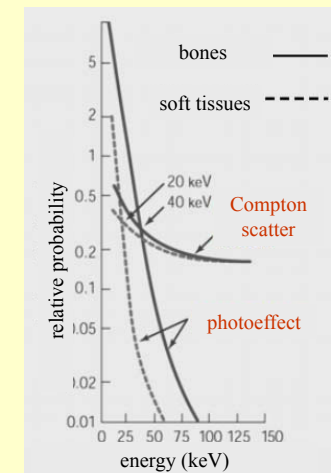
The decrease is more pronounced  
in the case of photoeffect.

At lower photon energies  $\tau_m$  is  
dominant.

$\tau_m$  strongly depends on the atomic  
number.

$$\tau_m \approx \lambda^3 Z^3$$

Spectral changes of radiation  
drastically modify the attenuation  
processes.



## Effective atomic number

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

$$\tau_m = C \lambda^3 Z_{eff}^3$$



matter	$Z_{eff}$
air	7,3
water	7,7
soft tissue	7,4
bone	13,8

## Summary of attenuation mechanisms

	Variation with E	Variation with Z	Energy range in tissues
$\tau_m$	$\sim 1/E^3$	$\sim Z^3$	10 – 100 keV
$\sigma_m$	Slightly falls with E	linear	0.5 – 5 MeV
$\kappa_m$	Rises slowly with E	$\sim Z^2$	>5 MeV

Main contrast mechanism in diagnostic X-ray:  
photoeffect ( $\sim Z^3$ )

## Production of X-ray image

Representation of variations in  
attenuated intensity

in radiation sensitive film

on luminescent screen

in digitized image

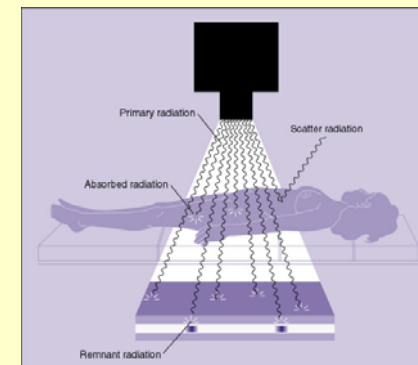


scalp



chest

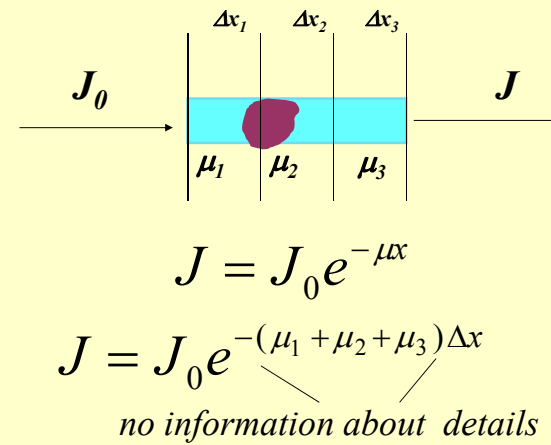
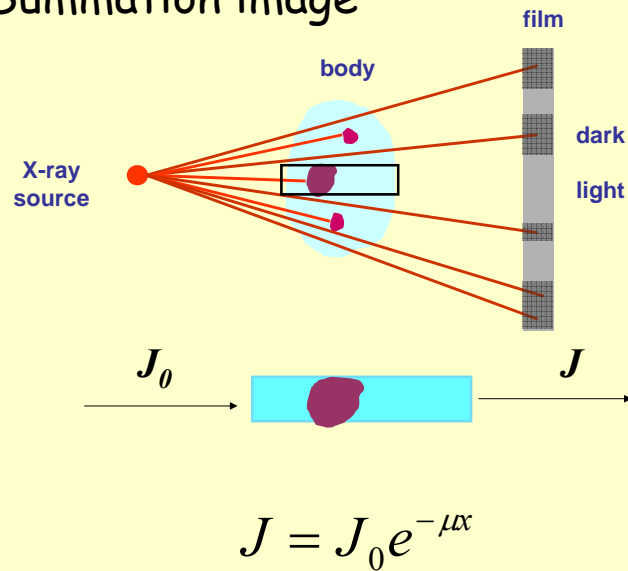
## Summation image



*“X-ray image”  
or  
“radiographic image”*

*Contrast arises due to relative attenuation*

## Summation image



$$D = \lg \frac{J_0}{J}$$

$$D = \sum_i D_i$$

## Radiographic contrast

If the differences between

$$\tau_m = C \lambda^3 Z_{eff}^3$$

or  
densities

of neighbouring tissues are not sufficient

**alteration of  $Z_{eff}$  or density**

	$Z_{eff}$	$\rho$ (g/cm <sup>3</sup> )	$\tau_m = C \lambda^3 Z_{eff}^3$
H <sub>2</sub> O	7.7	1	
soft tissues	7.4	1	
bones	13.8	1.7 - 2.0	
air	7.3	1.29 x 10 <sup>-3</sup>	

**Positive contrast → increased attenuation**

$$Z_{eff \text{ contrast}} > Z_{\text{surrounding}}$$

$$\mu_{\text{contrast}} > \mu_{\text{surrounding}}$$

$$\mu_{m \text{ contrast}} > \mu_{m \text{ surrounding}}$$

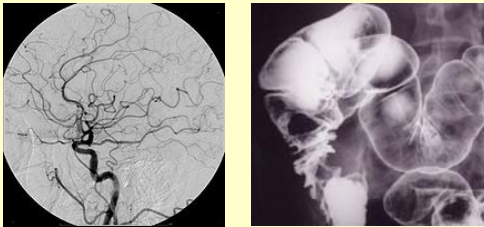
**Negative contrast → decreased attenuation**

$$Z_{eff \text{ contrast}} < Z_{\text{surrounding}}$$

$$\mu_{\text{contrast}} < \mu_{\text{surrounding}}$$

## Positive contrast

increased  $Z_{\text{eff}}$



E.g., I- or Ba-compounds  
 $^{56}\text{BaSO}_4$ ,  $^{53}\text{J}$

## Negative contrast

$$\rho_{\text{contrast}} < \rho_{\text{surrounding}}$$



air,  
 $\text{CO}_2$

## Digital Subtraction Angiography (DSA)



*contrast*

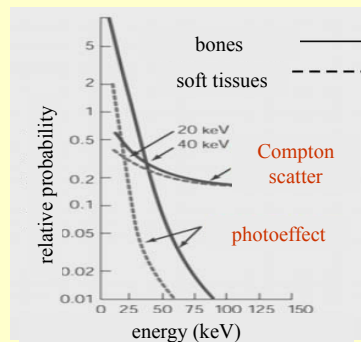
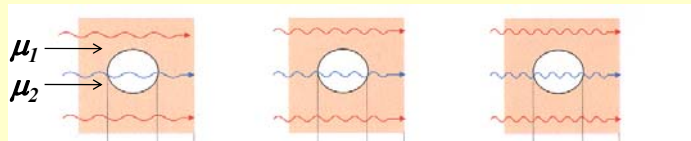
*native*

*contrast - native*

*images*

## Photon energy and image quality

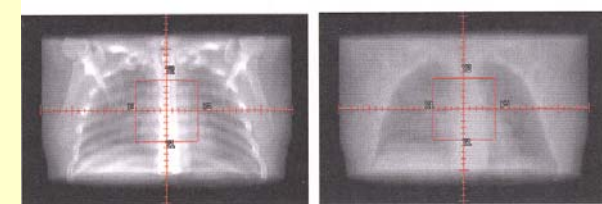
$$U_1 < U_2 < U_3$$



## Photon energy and image quality

$$U_1 < U_2$$

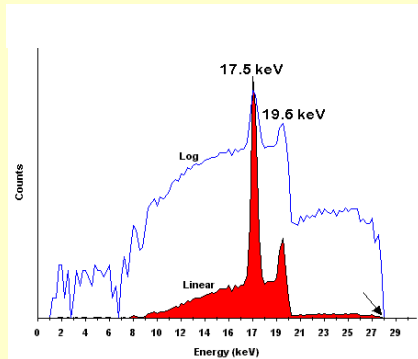
(30 keV) (2 MeV)



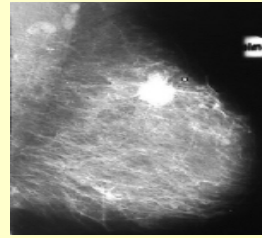
<i>Photo effect</i>	36%	0%
<i>Compton scatter</i>	51%	99%
<i>Pair production</i>	0%	1%

*Average values*

## Typical spectrum used in mammography



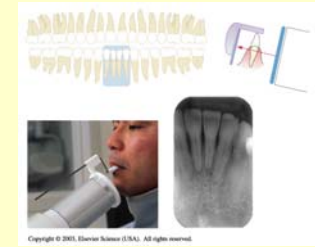
Characteristic lines of Molybdenum



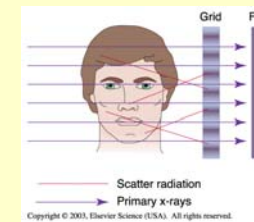
*Malignant tissue in a mammogram*



## Intra-oral radiography

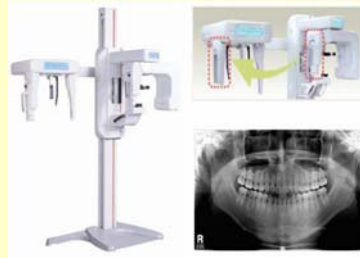


## Extra-oral radiography



## Dental panoramic radiography

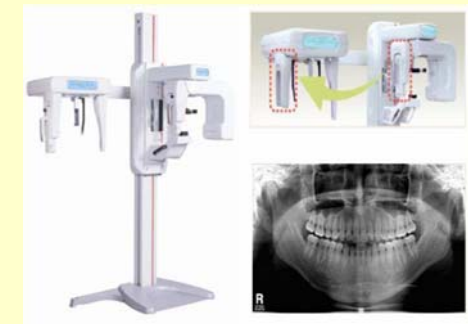
The equipment consists of a horizontal rotating arm which holds an X-ray source and a moving film mechanism (carrying a film) arranged at opposed extremities.



overlapping individual images projected on the film

## Dental panoramic radiography

overlapping individual images projected on the film



a composite picture of the maxillo-facial block is created

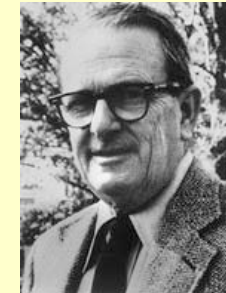
## Limitations of conventional radiography

- **Superimposition** – inability to resolve spatially structures along the X-ray propagation axis resulting in loss of depth information (flat picture), because the three-dimensional body is projected on to a two-dimensional receptor.
- Difficulty in **distinguishing** between homogenous objects of **non-uniform thickness**.
- Inability to distinguish soft body tissue because of **limited contrast**.

## X-Ray Transmission Computed Tomography



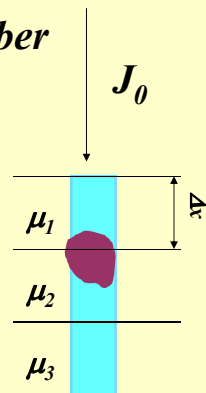
Godfrey Hounsfield



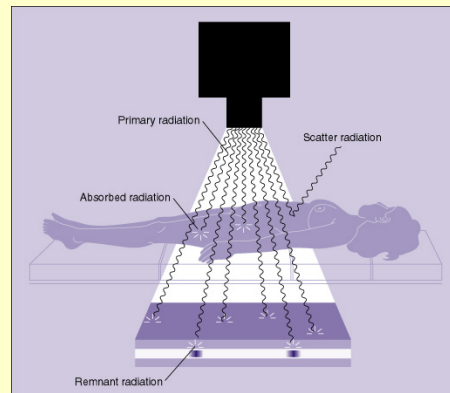
Allan Cormack

1979 Nobel-prize in Medicine

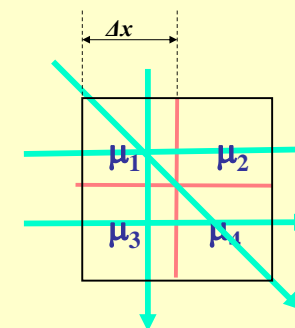
*remember*



$$J = J_0 e^{-(\mu_1 + \mu_2 + \mu_3) \Delta x}$$



## Mathematical interpretation with a simple example



$$J = J_0 e^{-(\mu_1 + \mu_3) \Delta x}$$

$$J = J_0 e^{-(\mu_1 + \mu_2) \Delta x}$$

$$J = J_0 e^{-(\mu_3 + \mu_4) \Delta x}$$

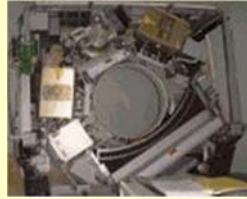
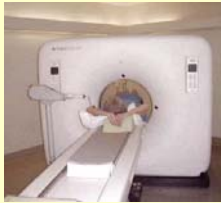
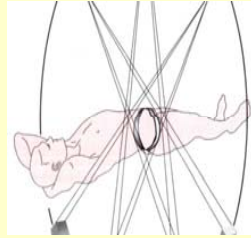
$$J = J_0 e^{-(\mu_1 + \mu_4) \Delta x}$$

4 independent equations, 4 unknowns



## New – axial – arrangement

The 2D CT image corresponds to a 3D section of the patient



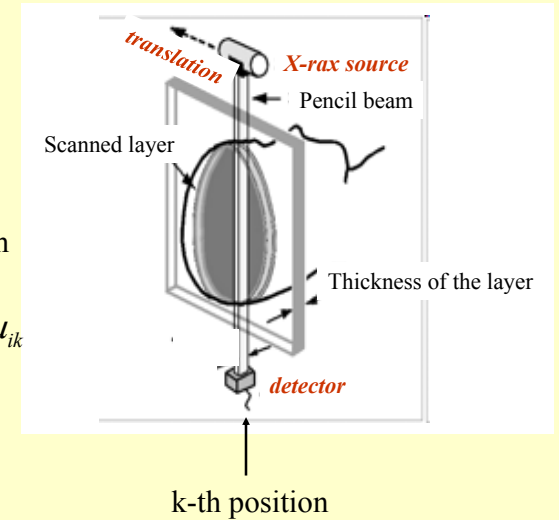
Computed tomography (CT) techniques allows sectional imaging .

## Innovation of CT

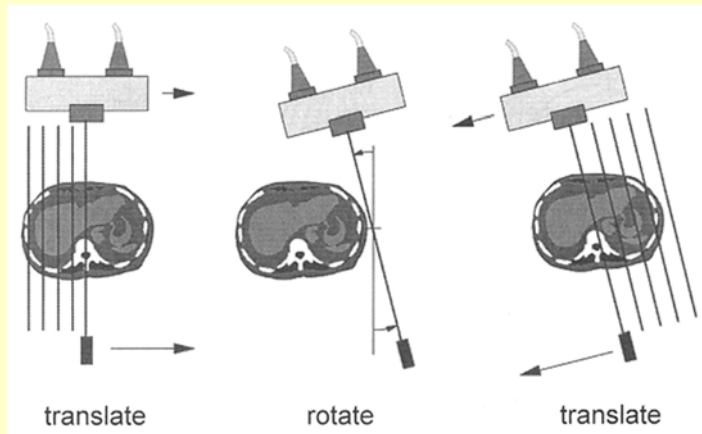
$$J_k = J_0 e^{-(\sum \mu_{ik}) \Delta x}$$

$\mu_i$ : attenuation coefficient of volume element along the beam

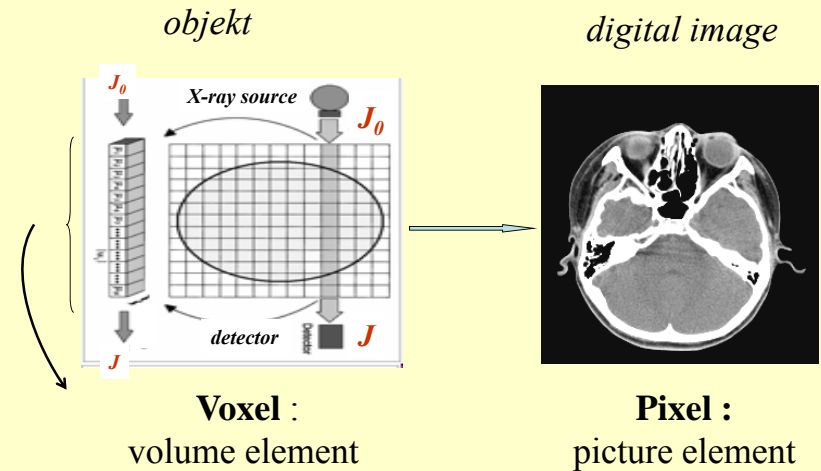
$$\lg \frac{J_0}{J} = \lg e \Delta x \sum_{i=1}^n \mu_{ik}$$



## First generation CT



To store the multitude of images and process the data requires computer.



Each *pixel* on the CT image displays the average x-ray attenuation properties of the tissue in the corresponding *voxel*.

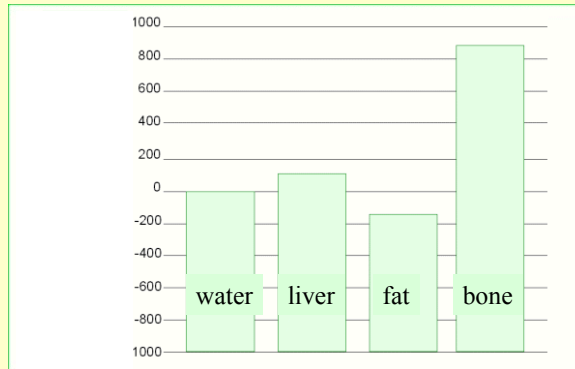
## Reconstruction of the image

Density matrix

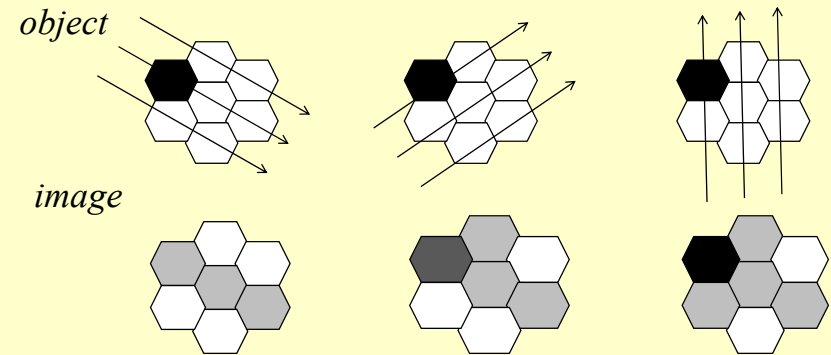
Hounsfield units

$$H_{CT} = 1000 \frac{\mu - \mu_{\text{water}}}{\mu_{\text{water}}}$$

Hounsfield scale

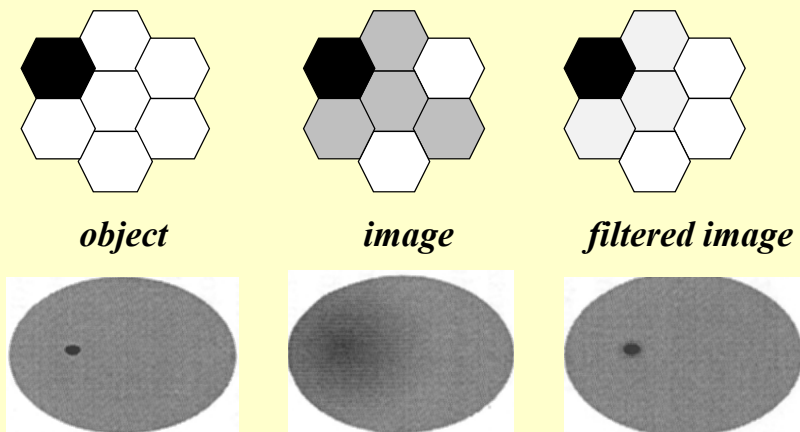


## Tomographic reconstruction



As data from a large number of rays are backprojected onto the image matrix, areas of high attenuation tend to reinforce one another, as do areas of low attenuation, building up the image.

## Tomographic reconstruction



## GOALS OF CT

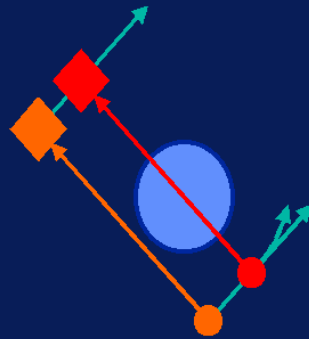
- Minimal superimposition
- Image contrast improvement
- Small tissue difference recording



180 DEG ROTATION

### First Generation

---

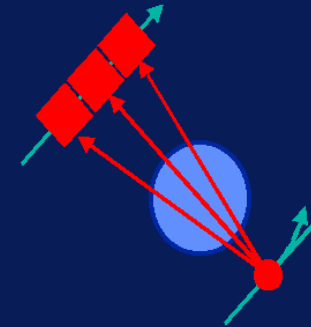


One detector  
Translation-rotation  
Parallel-beam

180 DEG ROTATION

### Second Generation

---

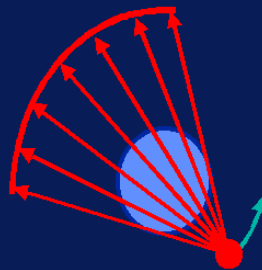


Multiple detectors  
Translation-rotation  
Small fan-beam

360 DEG ROTATION

### Third Generation

---

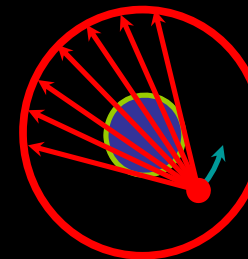


Multiple detectors  
Rotation  
Large fan-beam

360 DEG ROTATION

### Fourth Generation

---



Rotatable X-ray source.  
Stationary ring of detectors  
Fanned X-ray beam.

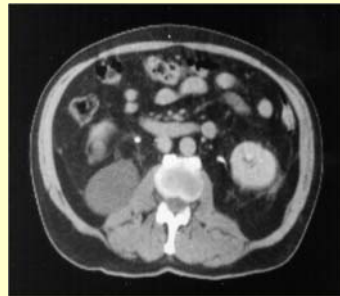
## Early days vs Today

Second generation



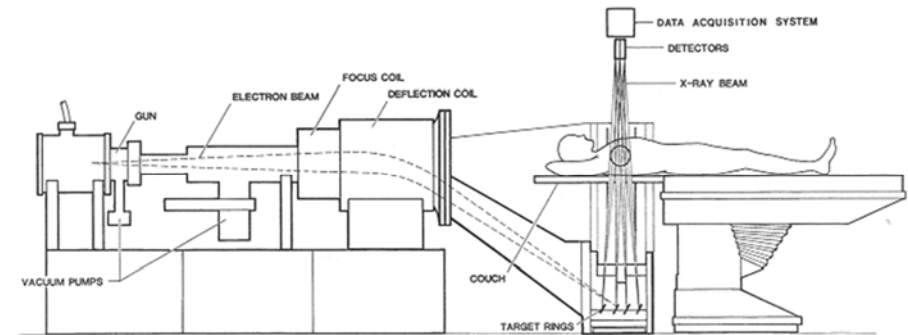
*5 minutes*

Fourth generation



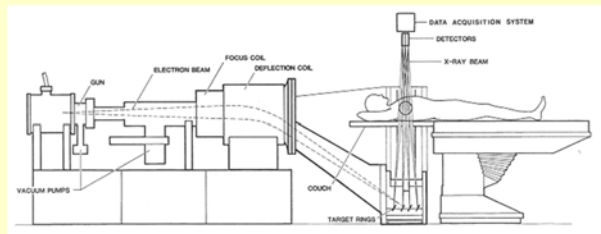
*2 seconds*

## 5<sup>th</sup> generation: stationary/stationary



No conventional x-ray tube. Large arc of tungsten encircles patient and lies directly opposite to the detector ring.  
Electron beam steered around the patient to strike the annular tungsten target.

### • 5<sup>th</sup> generation: stationary/stationary



- Developed specifically for cardiac tomographic imaging
- No conventional x-ray tube; large arc of tungsten encircles patient and lies directly opposite to the detector ring
- Electron beam steered around the patient to strike the annular tungsten target
- Capable of 50-msec scan times; can produce fast-frame-rate CT movies of the beating heart

## AXIAL SCAN

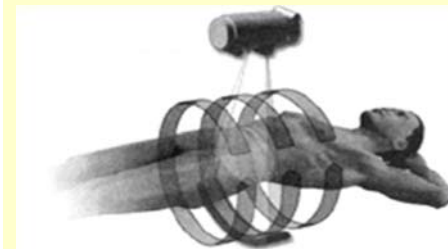


Table stops at the scanning position and the tube rotates around a patient.

Patient continuously moves in the Z-axis direction while the tube rotates around.

## Detectors for X-ray diagnostics

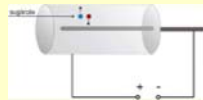
radiation  
sensitive film



scintillators



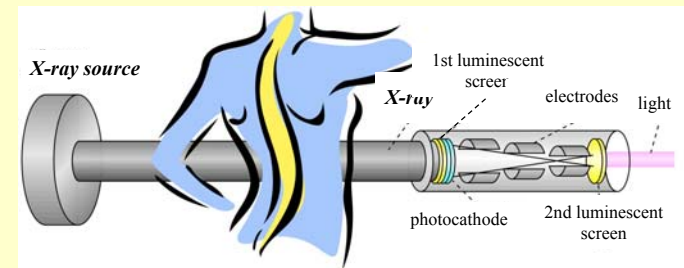
gas ionisation chamber



semiconductor  
detectors



## X-ray image intensifier



Possibility of image digitization

Smaller patient exposure

Manipulation under X-ray control

*Damjanovich, Fidy, Szöllősi: Medical Biophysics*

VIII. 3.1

3.1.1

3.1.2

VIII.4.3