Nuclear medicine

1. Introduction
2. General details
3. Instrumentation
4. SPECT
5. PET
6. Dosimetry

1. Introduction

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medical speciality in which radioactive substances are used

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diagnosis

intimately linked to medical image

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- radiology “inside ⟶ outside” or ”endoradiology"
  radiation emitted from within the body is recorded
- scans emphasize on functions rather than anatomy

1. Introduction

Nuclear medicine: some historical facts

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- Nobel prize in chemistry in 1943
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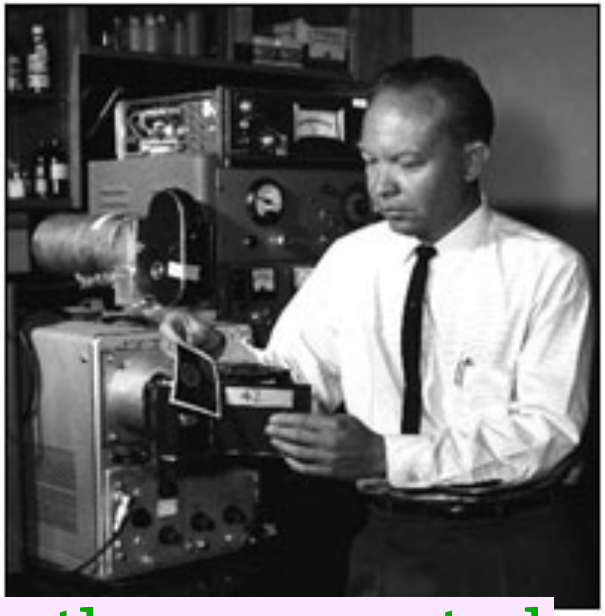
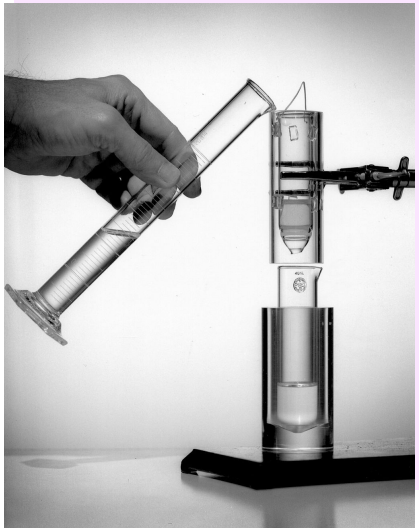


1960: P. Richards proposed the use of ^{99m}Tc as a medical tracer



- W. Tucker and M. Greene had developed the first generator of ^{99m}Tc in 1958
- P.V. Harper, G. Andros and K. Lathrop reported the first application to humans in 1962

1. Introduction

Nuclear medicine → medical image

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- **radiopharmaceuticals**
  - -pharmaceuticals are marked with radioisotopes
  - -they are administered to patients (e.g., intravenously, orally)
  - -radiopharmaceuticals distribute through body according their biokinetical properties
  - -they deposit in different organs/tissues depending on the physiological functions and their status (e.g., healthy or not)

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- **detectors**
  - -emitted radiation is detected
  - -radioactivity distribution is determined
  - -*in-vivo* study of the degree of assimilation of the radiopharmaceuticals in organs/tissues
  - -information about the way how they are operating

2. General details

medical images

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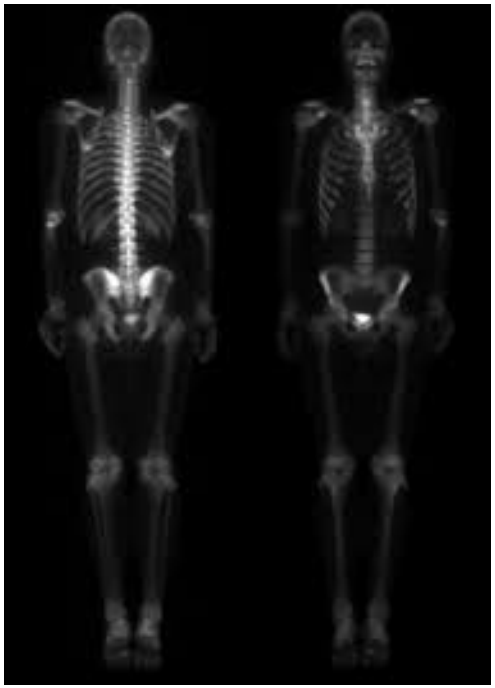
medical images

- conventional
  - -2D images of the radioactivity distribution
  - -projection onto the detection plane



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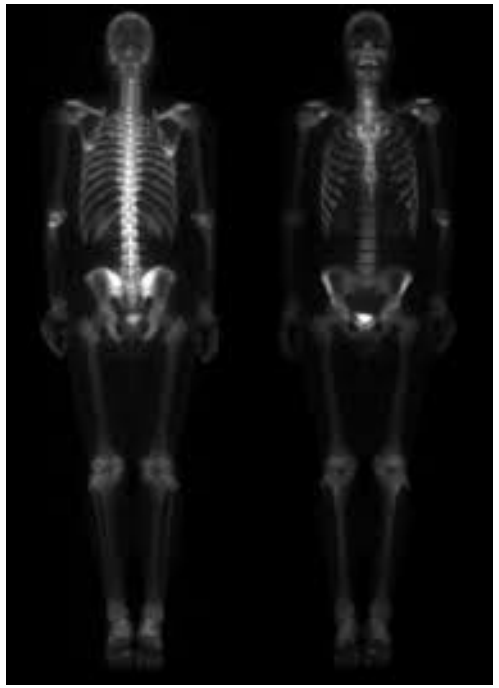
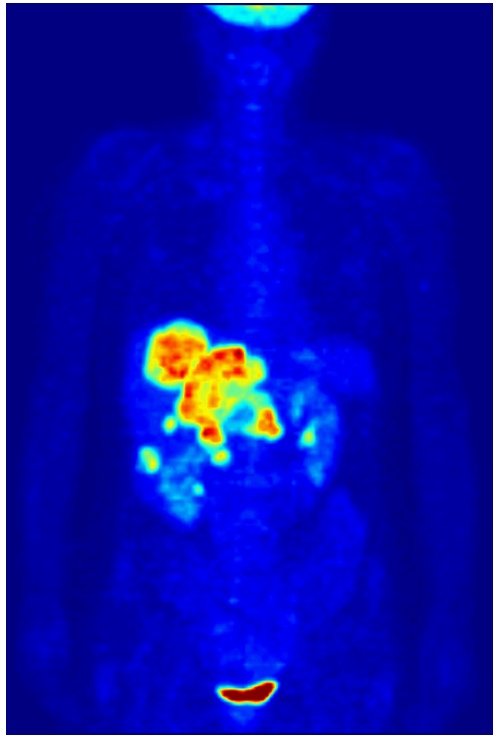


- **computed tomography**
  - -3D radioactivity distribution
  - -*SPECT* and *PET*



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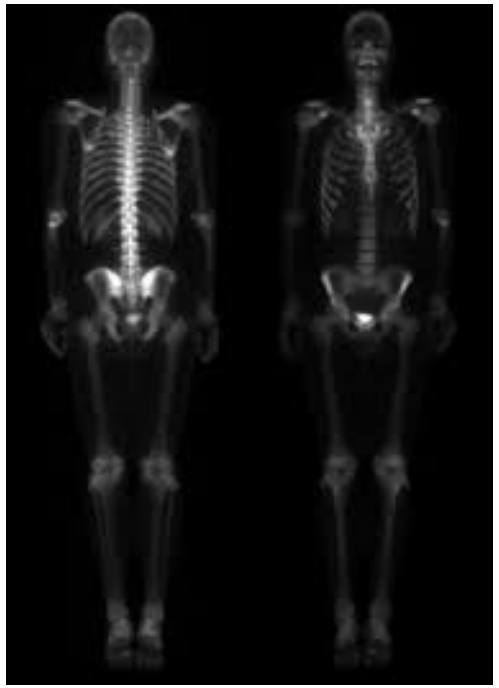

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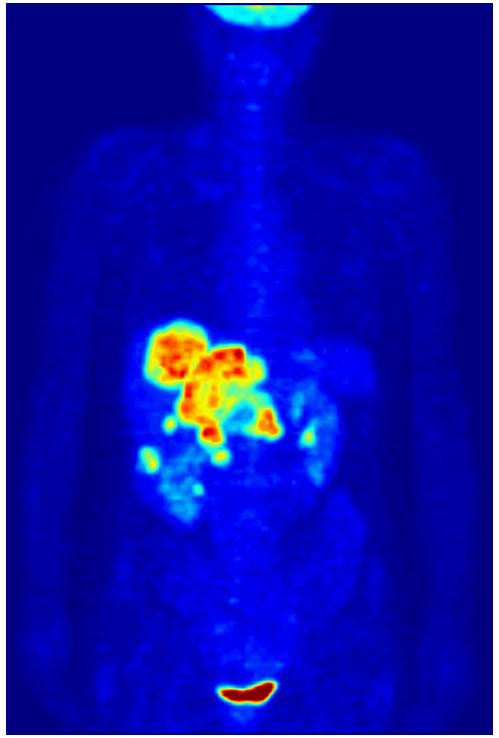

- **images**
  - -determination of the status of the organs or tissues in order to differentiate between normal and ill behaviors
  - -diagnosis of the illness causes
  - -both functional and physiological information

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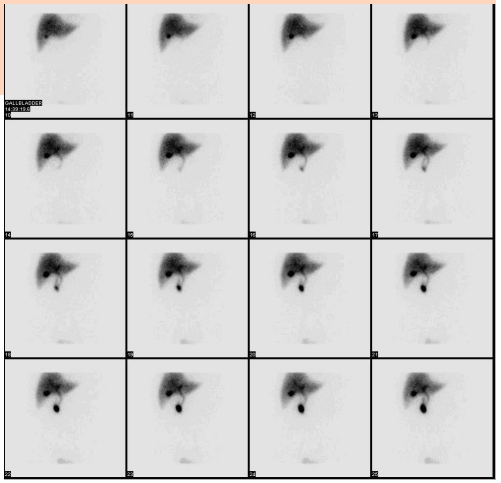
- **pharmaceuticals are marked with radioisotopes**
  - -sulfur coloids marked with ^{99m}Tc ($t_{1/2}$~6 h; E_{photon}=140 keV)
    fix in healthy (and not in cancerous) liver



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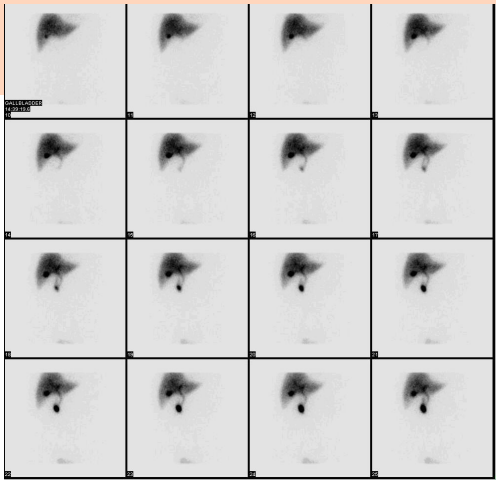
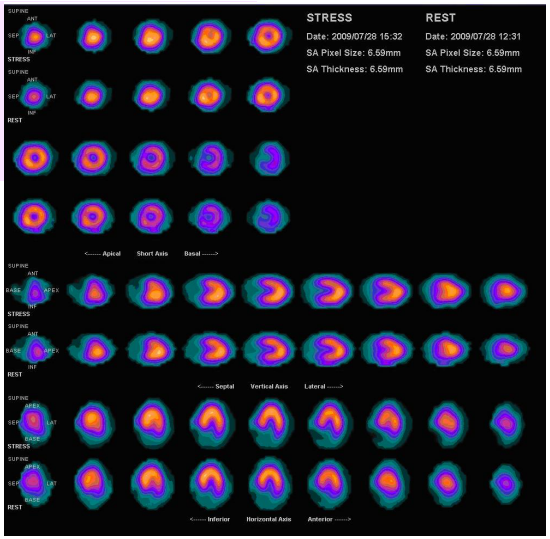


  - ^{201}Tl: analogous to potassium used to study heart behaviors



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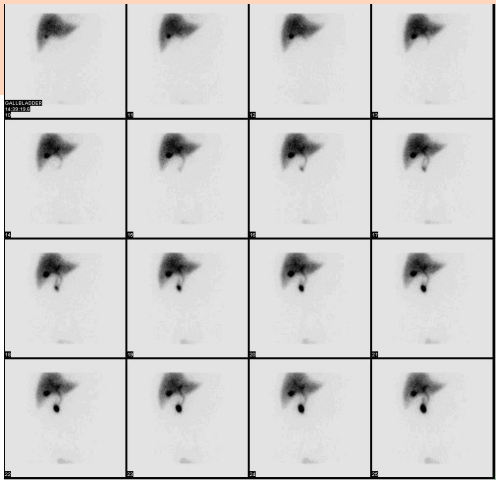

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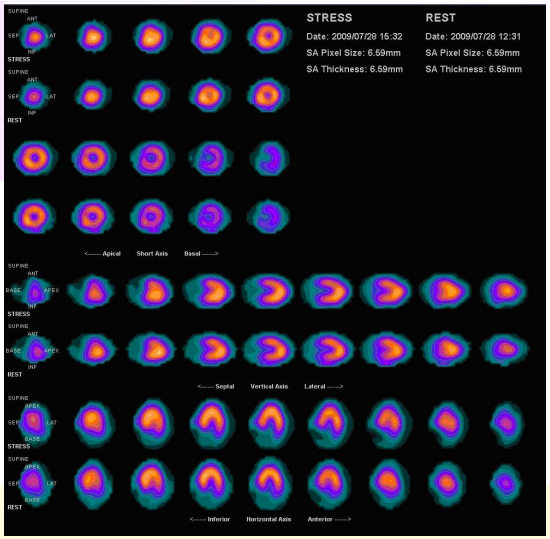

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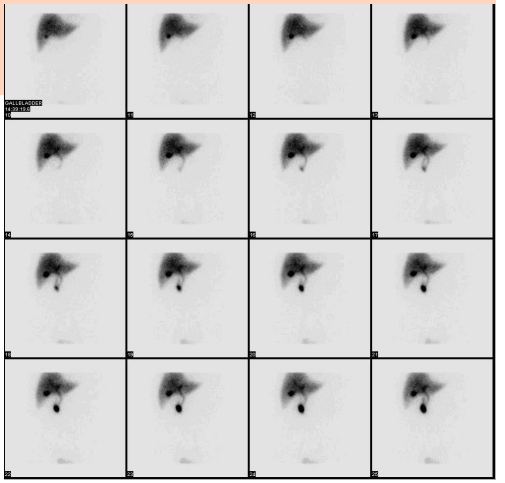

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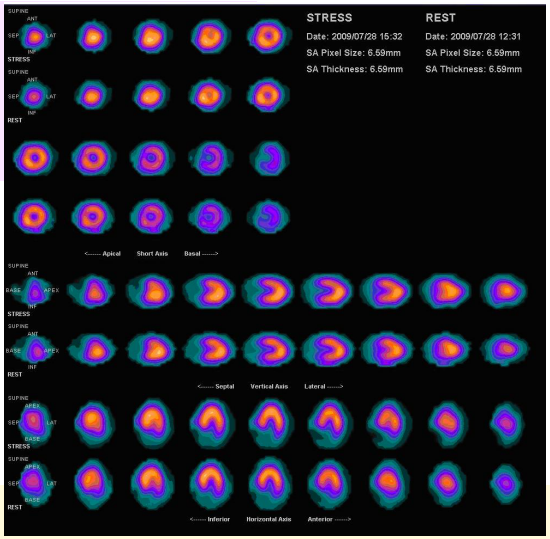

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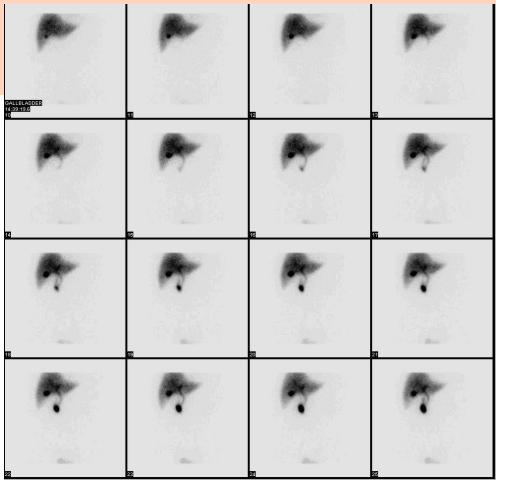

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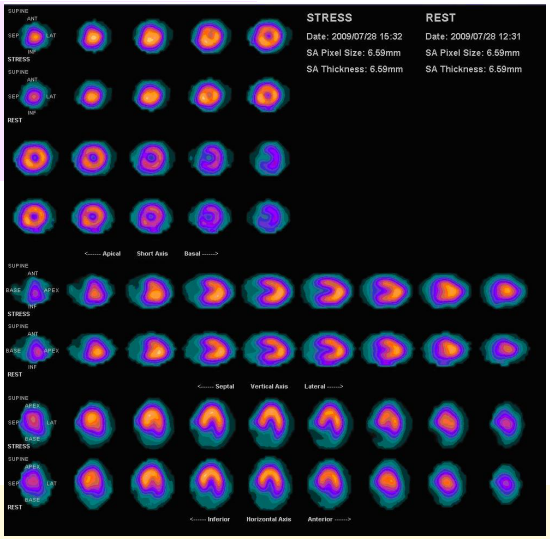

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- emitted photons are detected with "position sensitive detectors"

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- but, images are degraded because of:
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  -biokinetics of the radiopharmaceuticals

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- research:
  -improvement in the instrumentation
  -developement of better methodologies for processing and reconstructing the images
  -investigation in biokinetics of radiopharmaceuticals

3. Instrumentation

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-position sensitive detectors

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-collimators

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-computer
(for image reconstruction)

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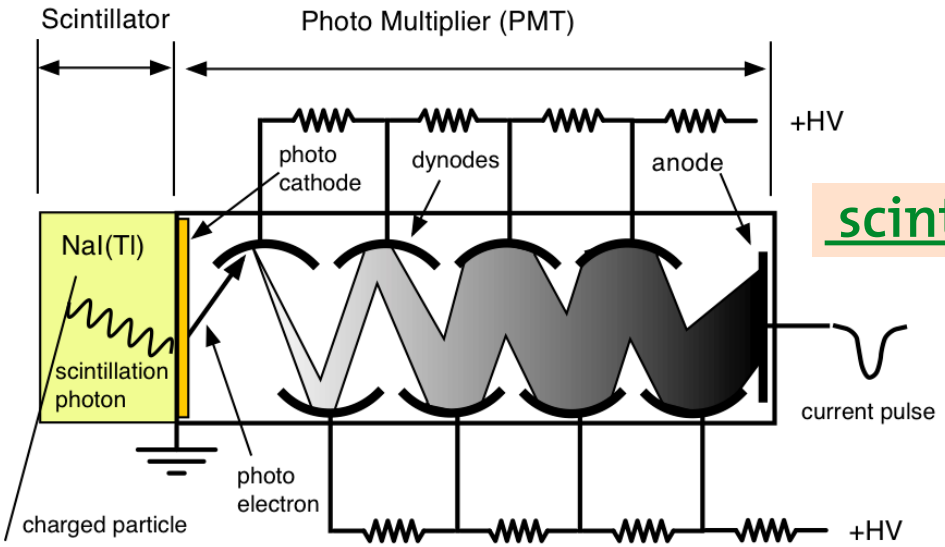

scintillation detector

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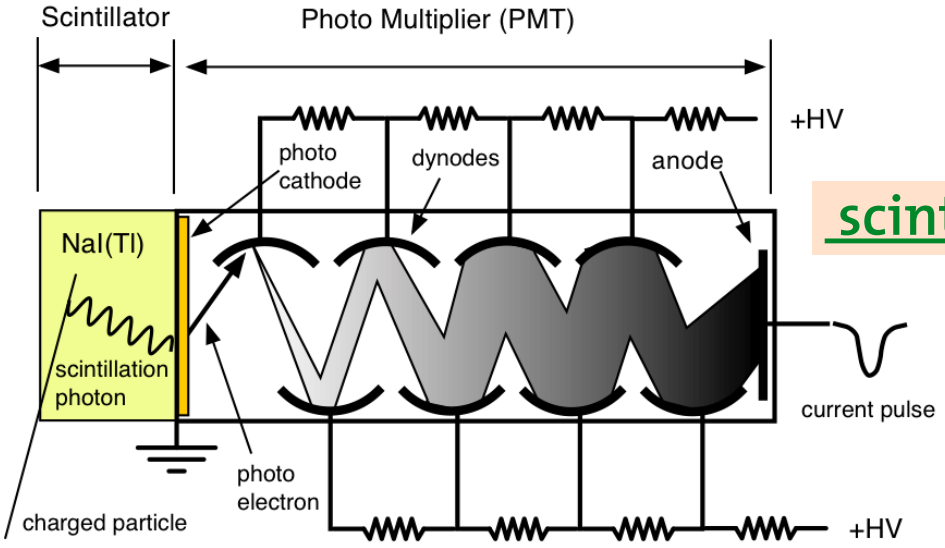

scintillation detector

- how to obtain the information about the position?
  -moving the detector at various points in the area under study, collecting a certain number of photons or measuring a given time in each one
  -too long procedures

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gammacamera

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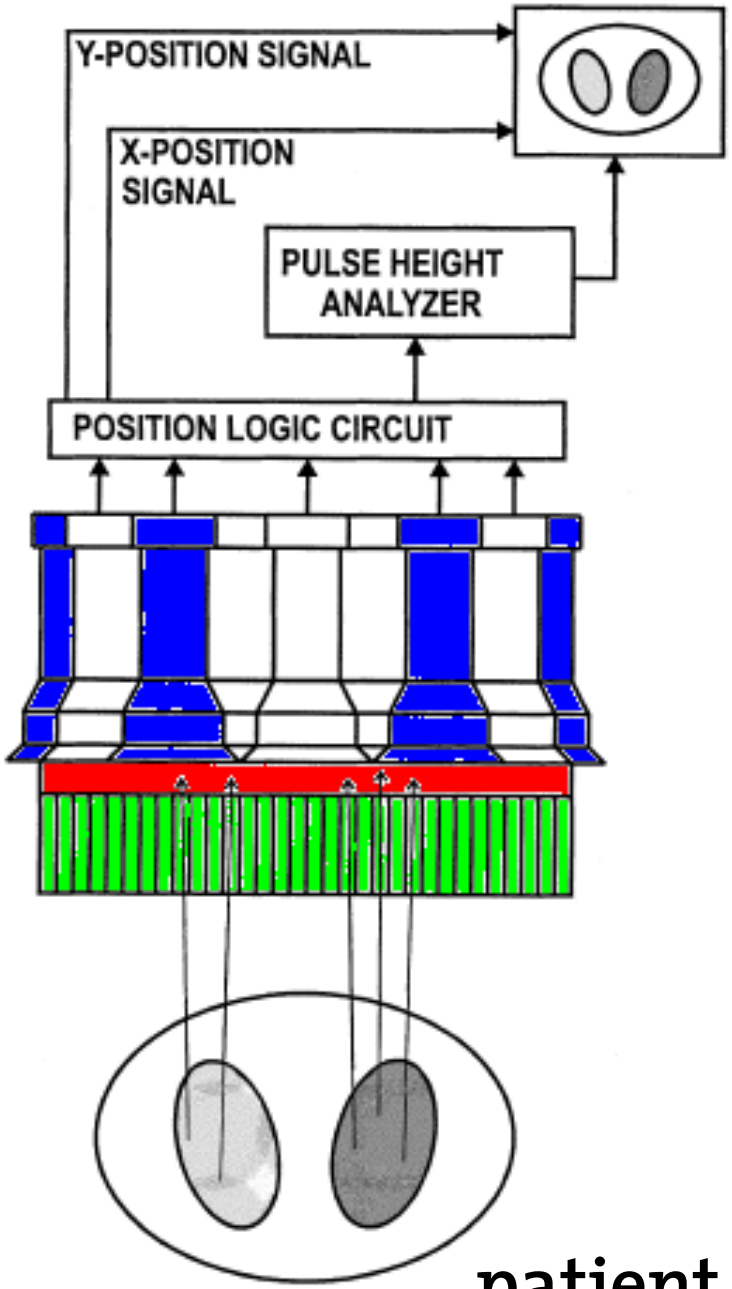

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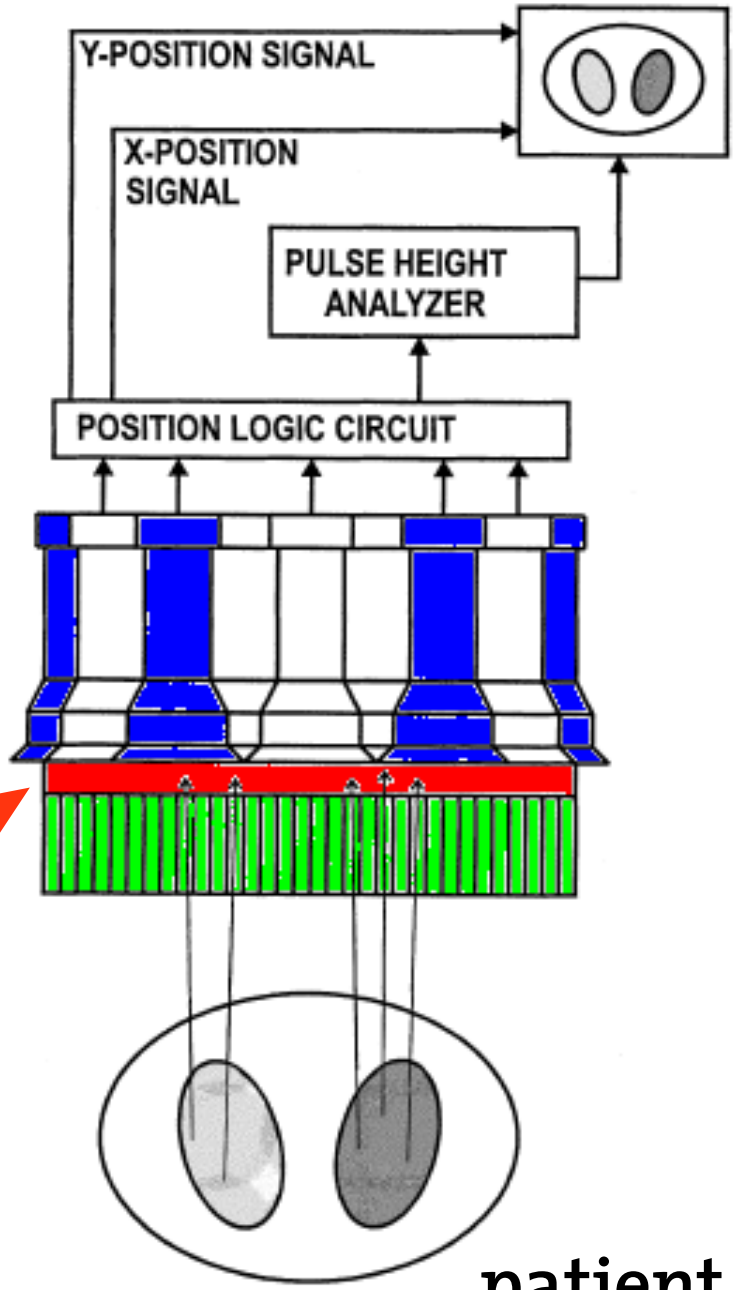

scintillator cristal

-circular (~40 cm O) or

-rectangular (~40 cm x 50 cm)

-thickness: <1 cm (low energy photons)

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photomultiplier tubes

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-usually work with an energy window and have ~10% energy resolution

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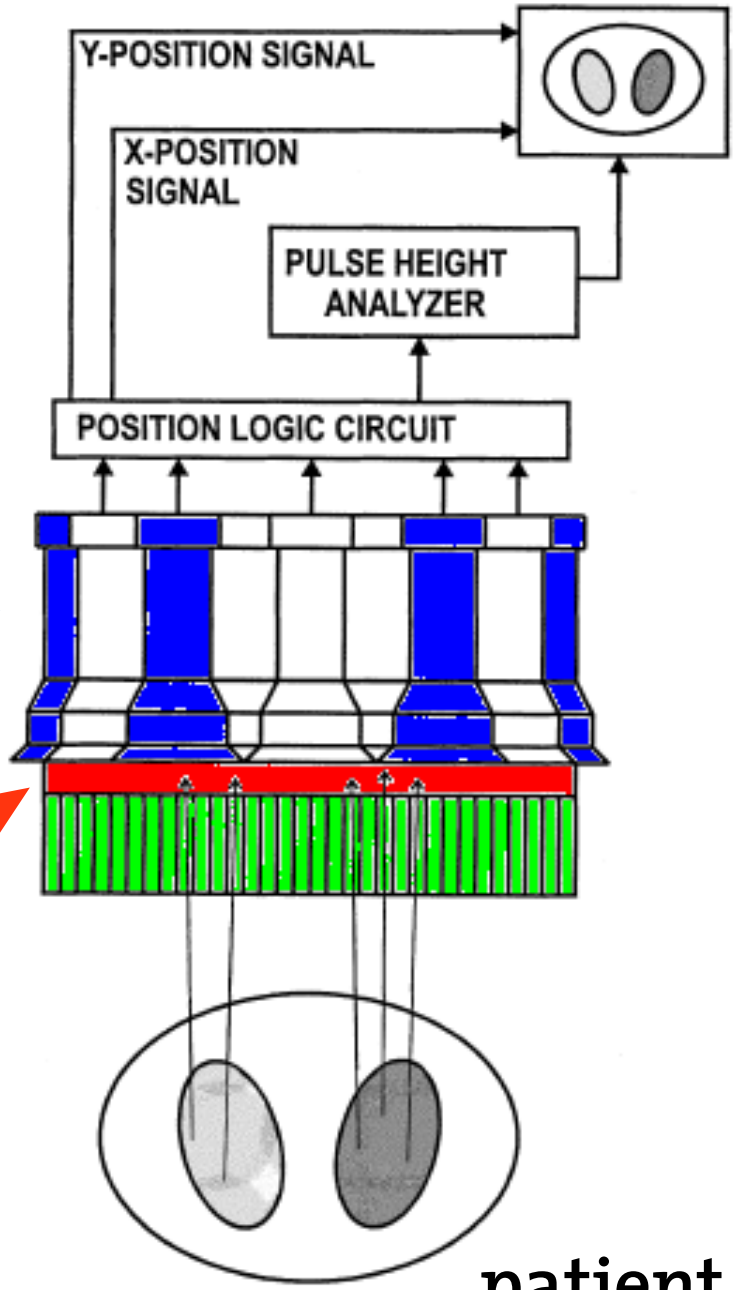

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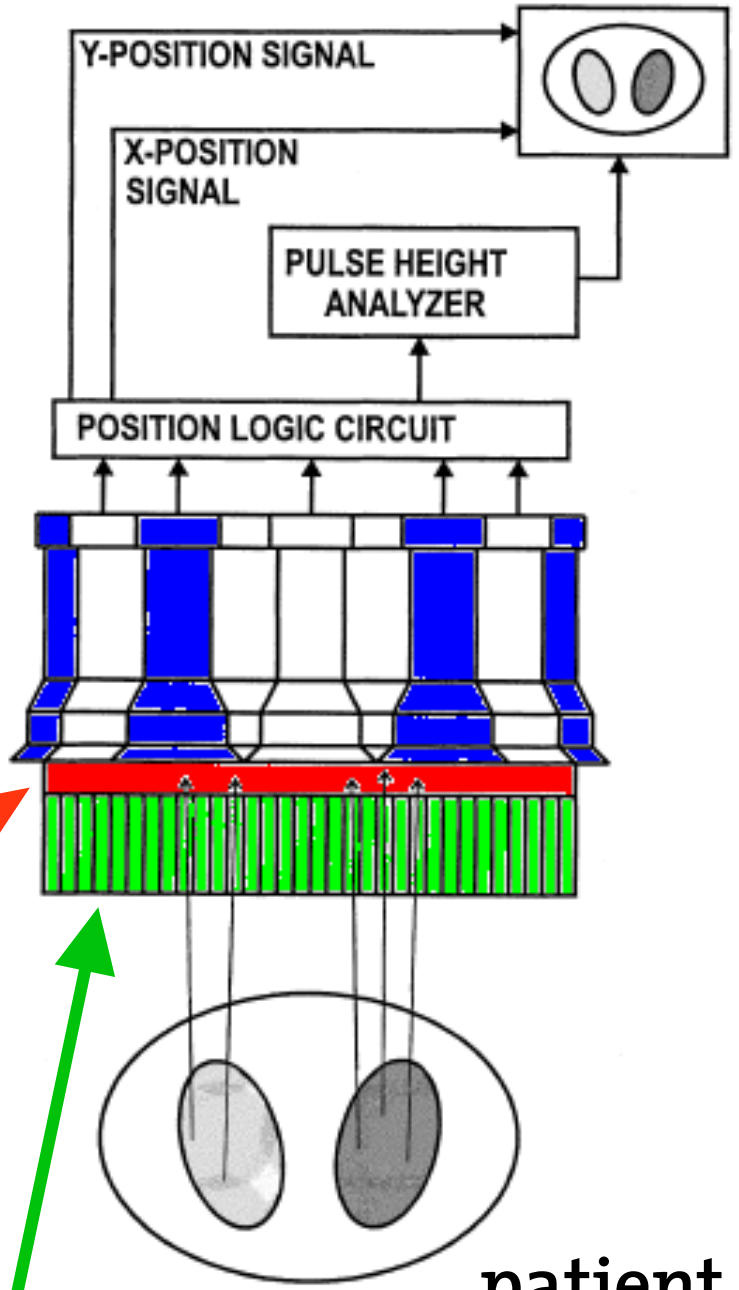

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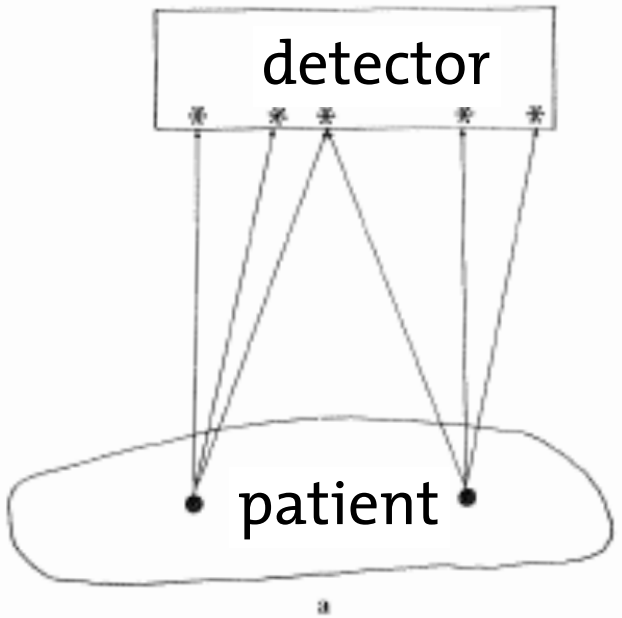

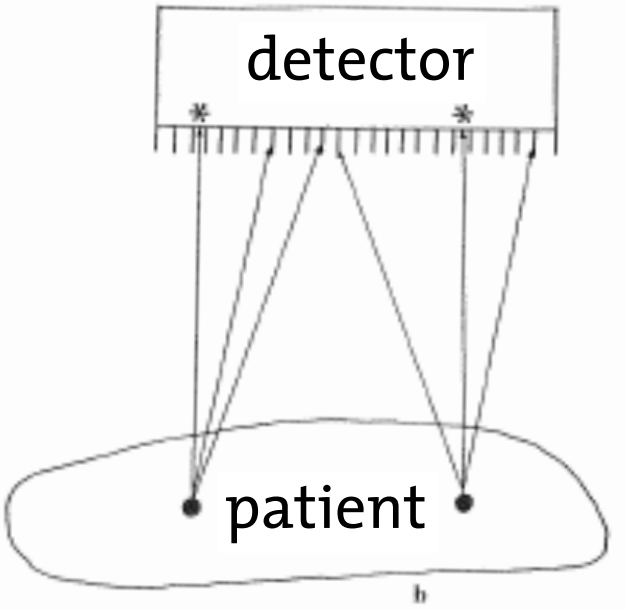

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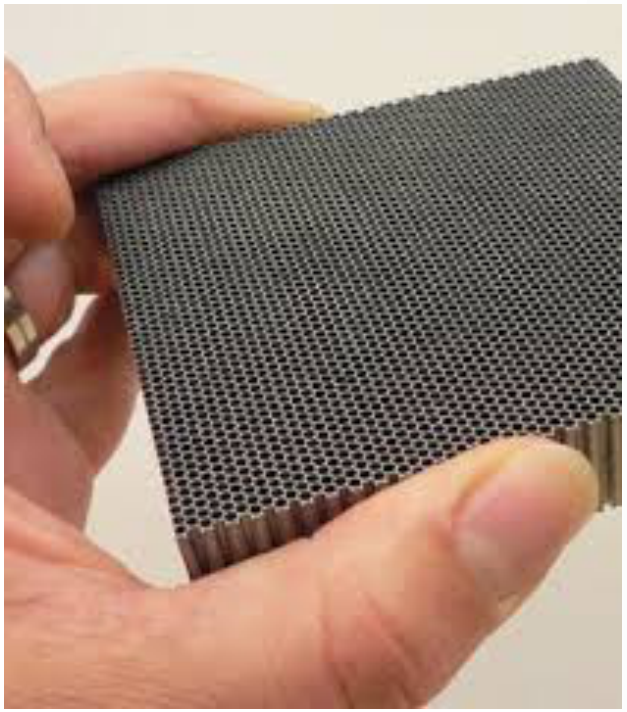
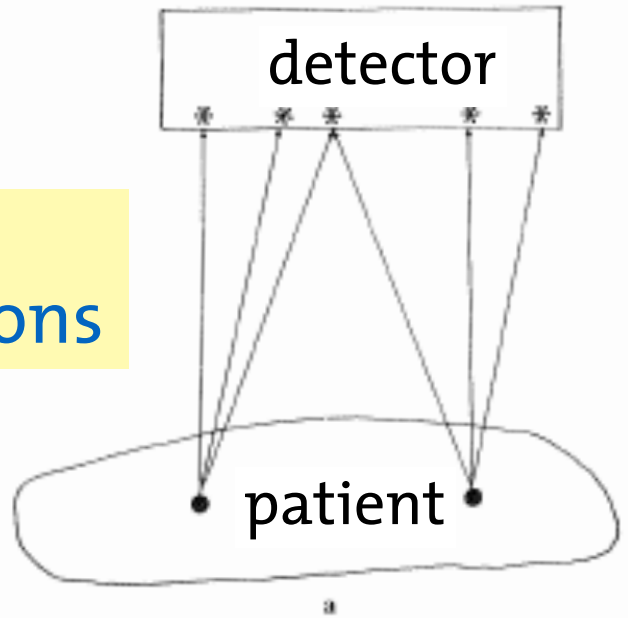
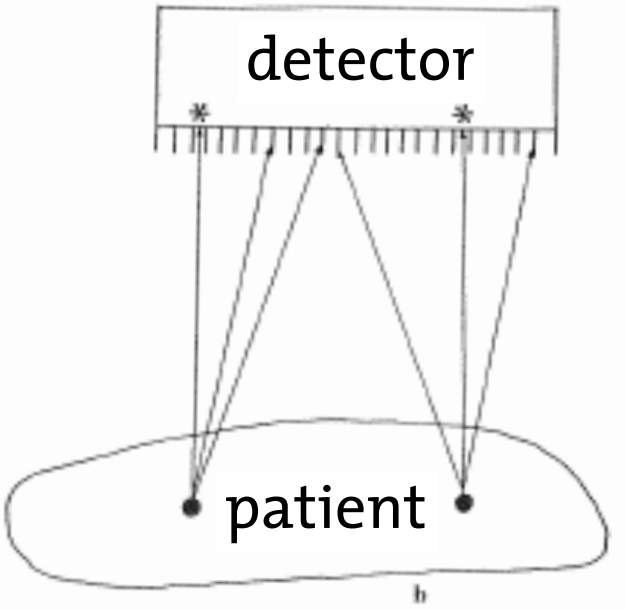
3. Instrumentation

why the collimator is fundamental?

-lead plate with small holes
-restrict the direction of the detected photons







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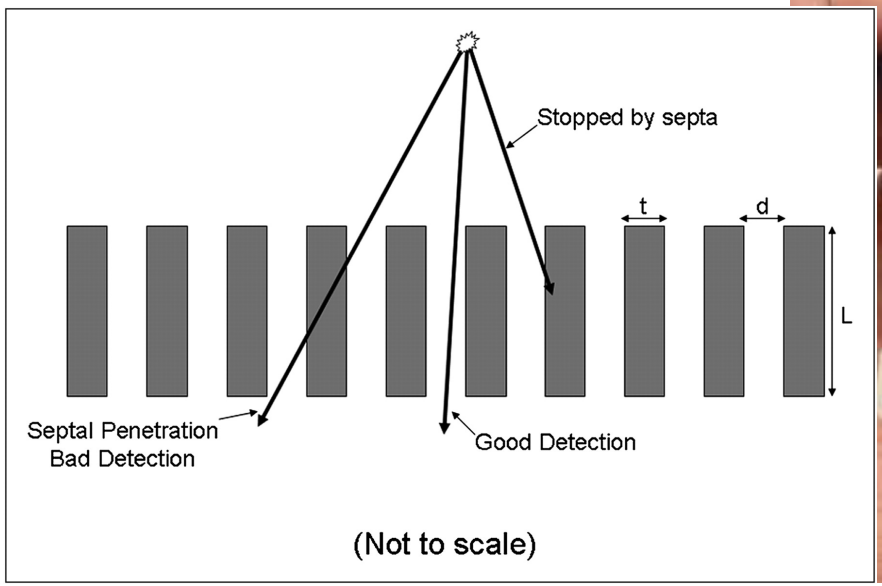

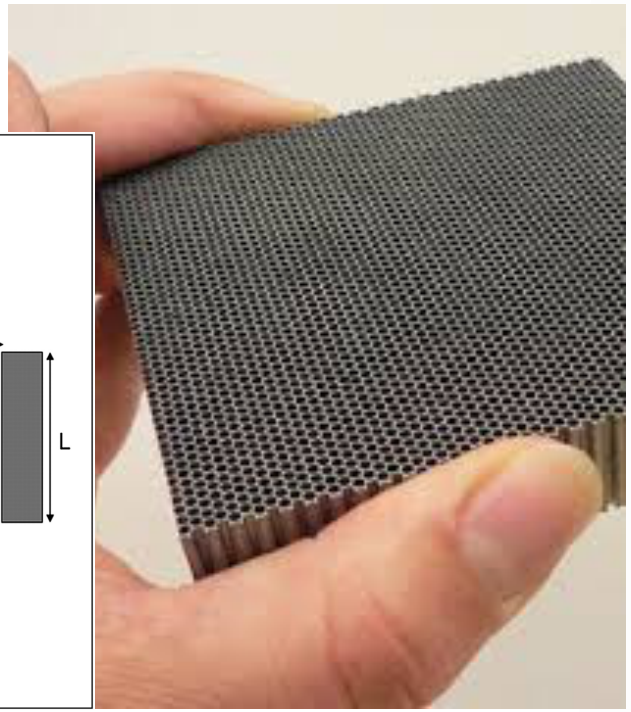

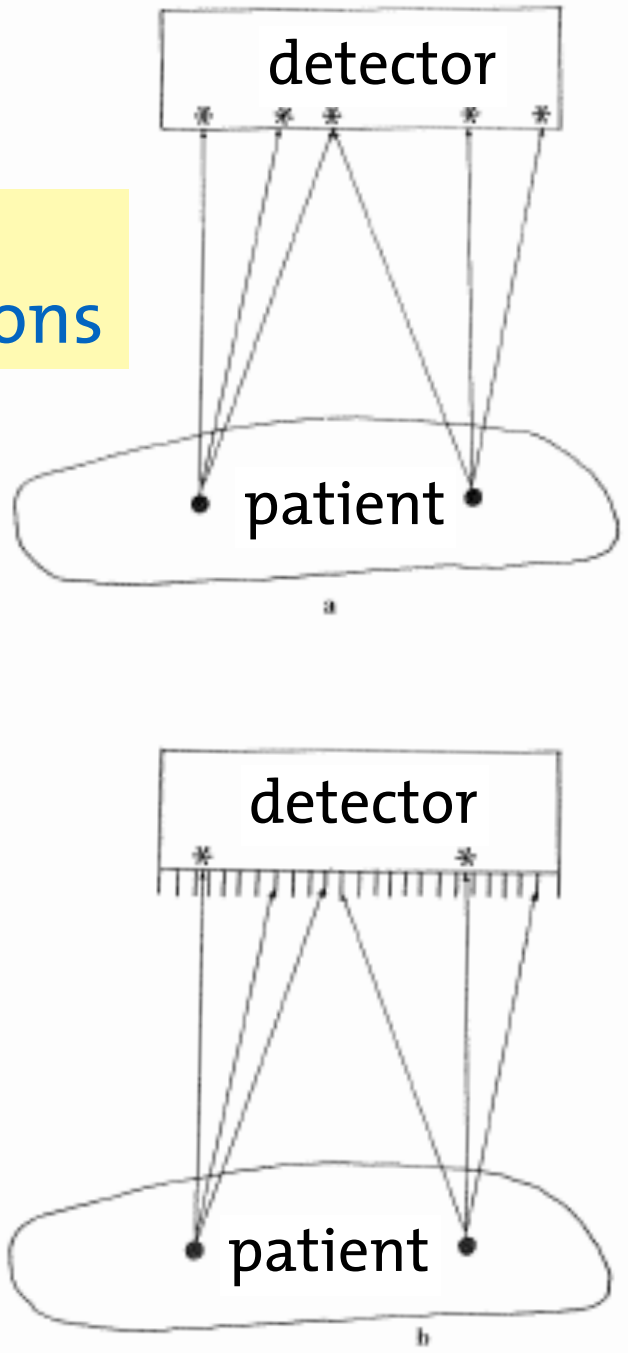

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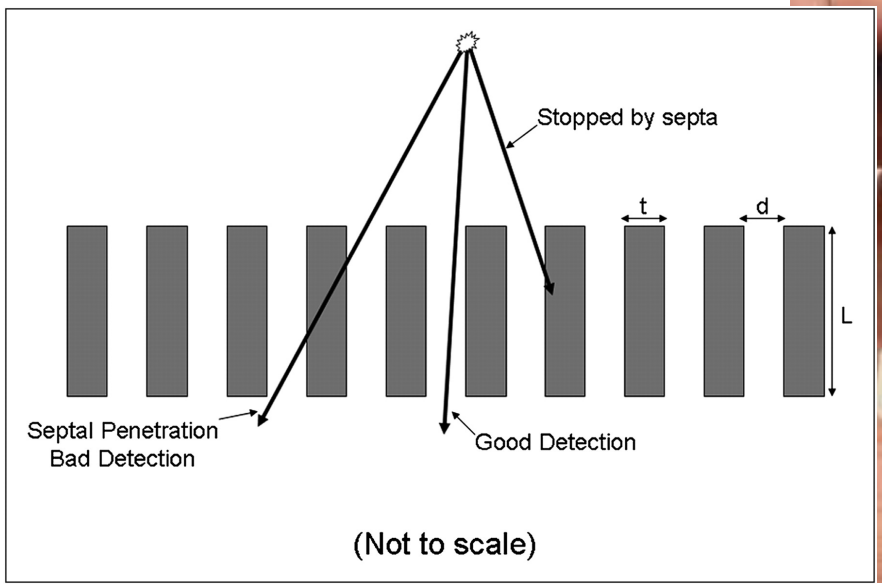

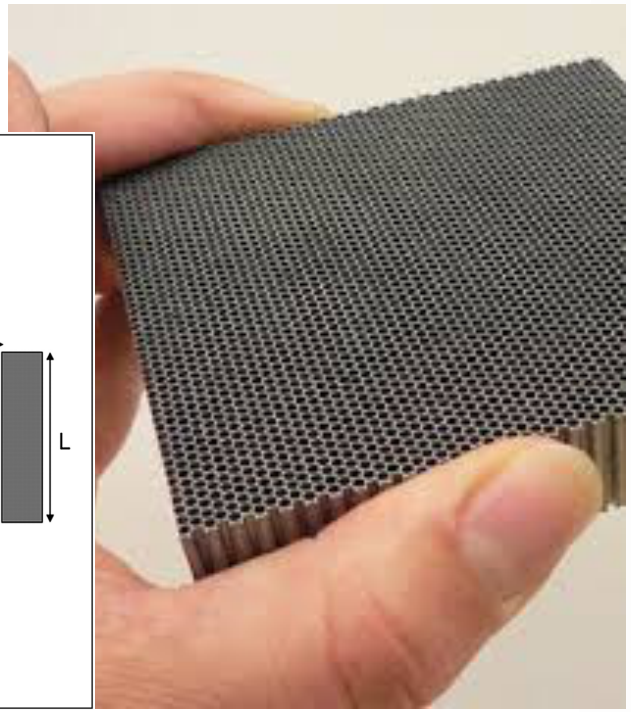

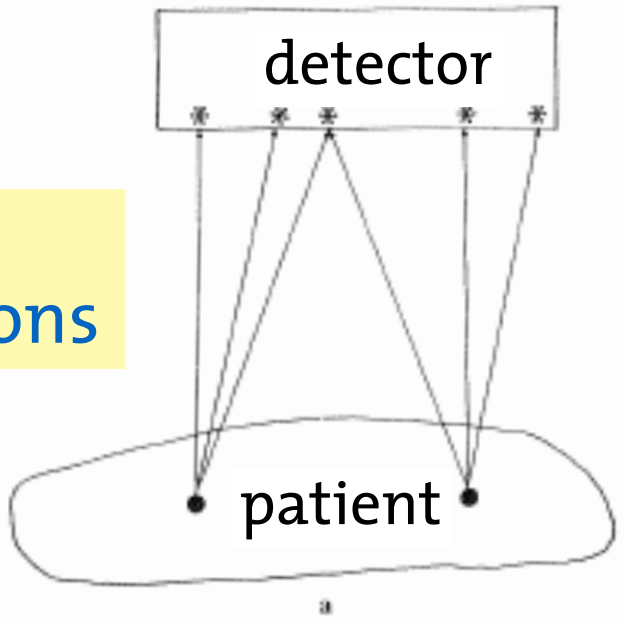

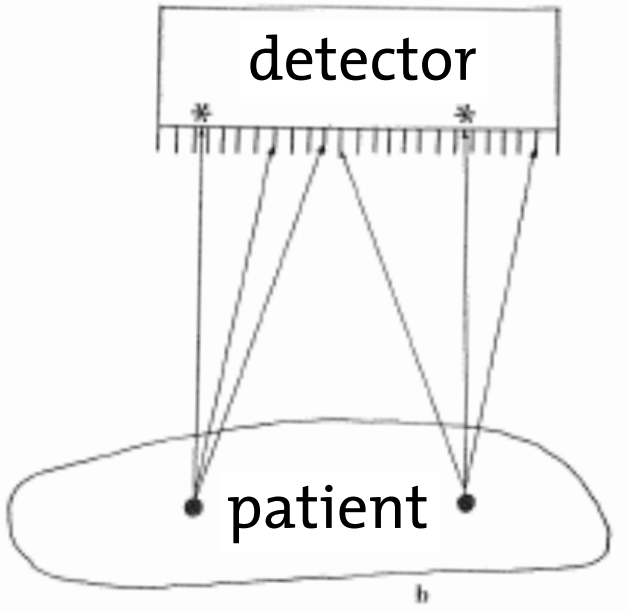

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t should be large to avoid septa penetration, but this reduces efficiency (fraction of gamma rays passing through the collimator per gamma ray emitted by the source)

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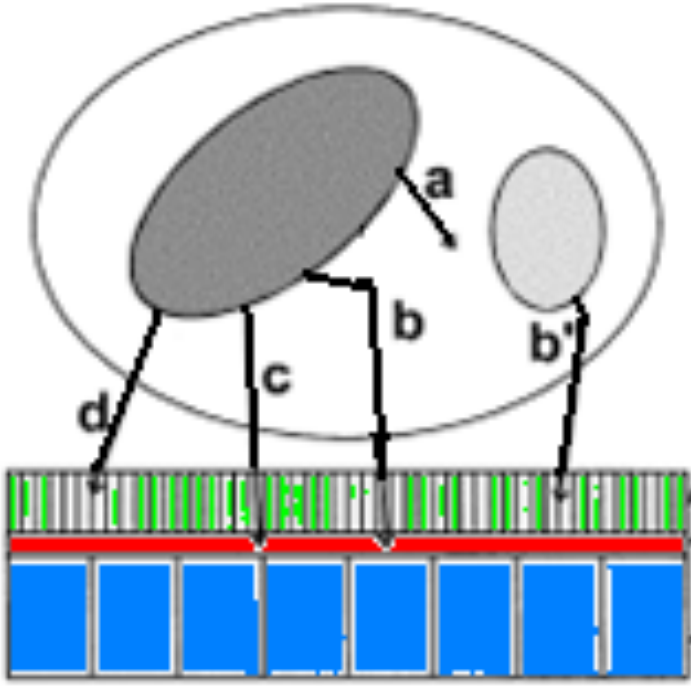

energy window !!

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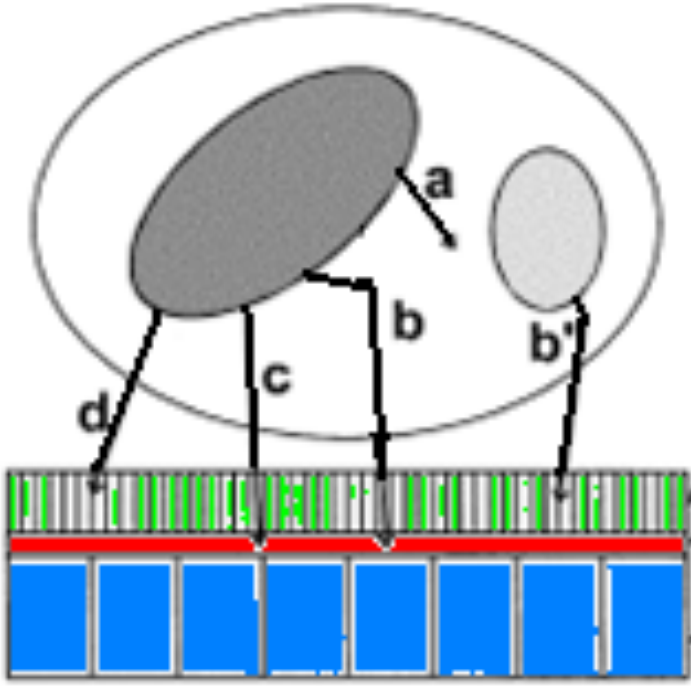
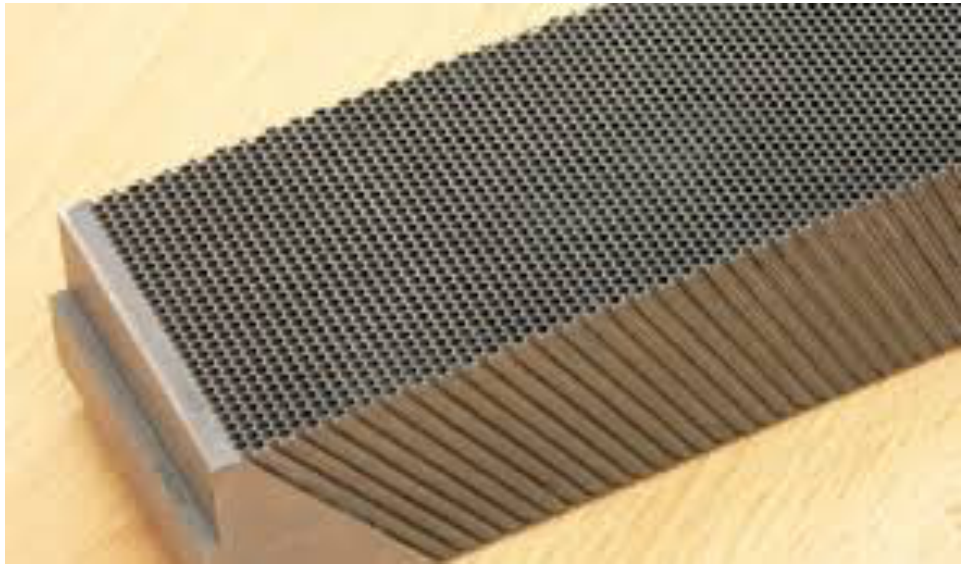
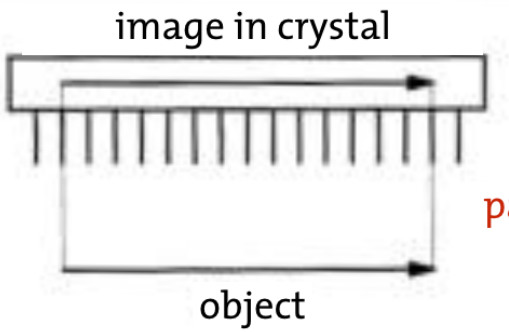
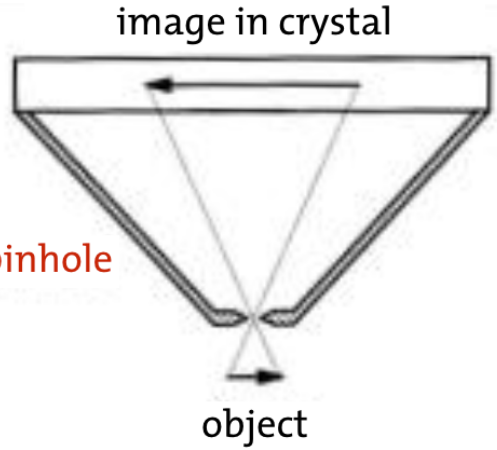


energy window !!



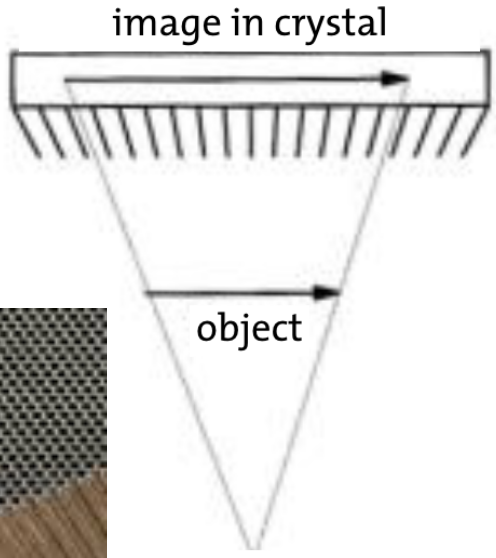


parallel hole

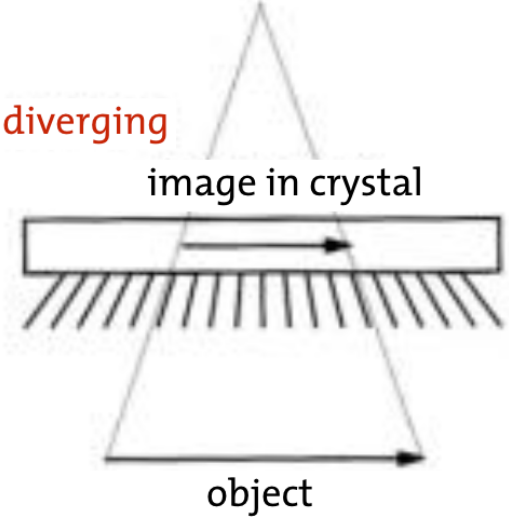


pinhole

converging



diverging

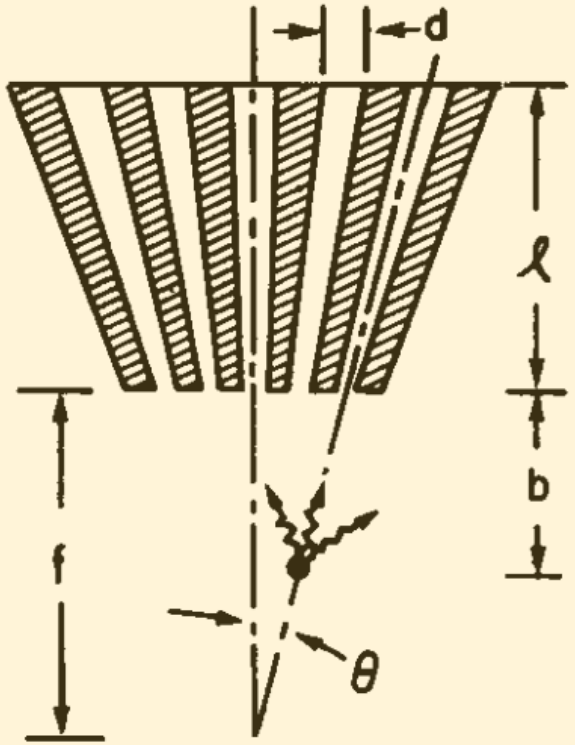


3. Instrumentation

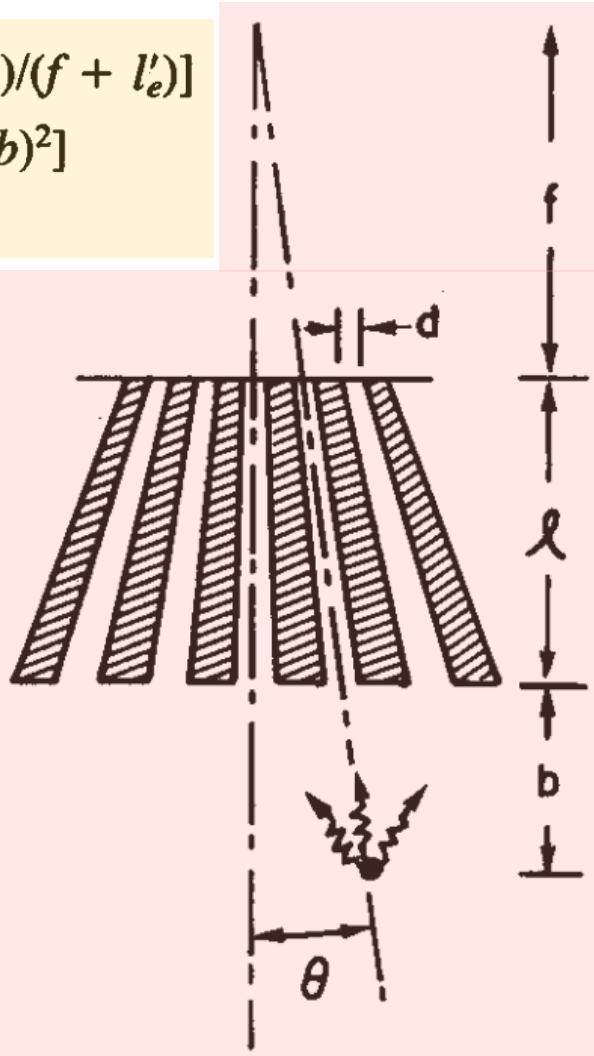
collimator resolution, R_c, and efficiency, g

$g \sim R_c^2$

$$R_c \approx [d(l'_e + b)/l'_e][1/\cos\theta][1 - (l'_e/2)/(f + l'_e)]$$
$$g \approx K^2(d/l'_e)^2[d^2/(d+t)^2][f^2/(f-b)^2]$$
$$l'_e \approx (l - 2\mu^{-1})/\cos\theta$$

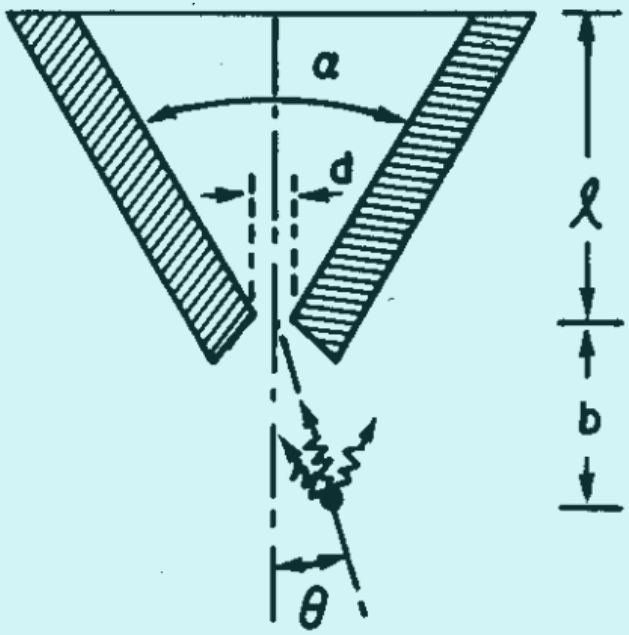


CONVERGING



DIVERGING

$$R_c \approx d_e(l + b)/l$$
$$g \approx d_e \cos^3\theta/16b^2$$
$$d_e = \sqrt{d[d + 2\mu^{-1}\tan(\alpha/2)]}$$



PINHOLE

$$R_c \approx d(l_e + b)/l_e$$
$$g \approx K^2(d/l_e)^2[d^2/(d+t)^2]$$
$$l_e = l - 2\mu^{-1}$$

parallel

$$R_c \approx [d(l'_e + b)/l'_e][1/\cos\theta][1 + (l'_e/2f)]$$
$$g \approx K^2(d/l'e)^2[d^2/(d+t)^2][f + l)/(f + l + b)]$$

4. SPECT

4. SPECT

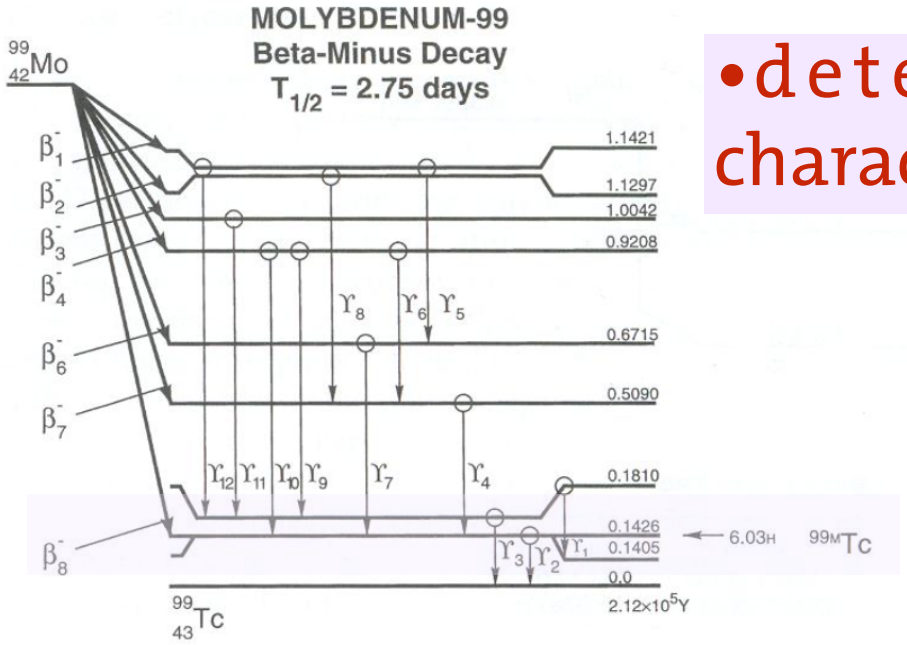
Single-Photon Emission Computed Tomography

4. SPECT

Single-Photon Emission Computed Tomography

- detection of a unique photon characteristic of a given disintegration

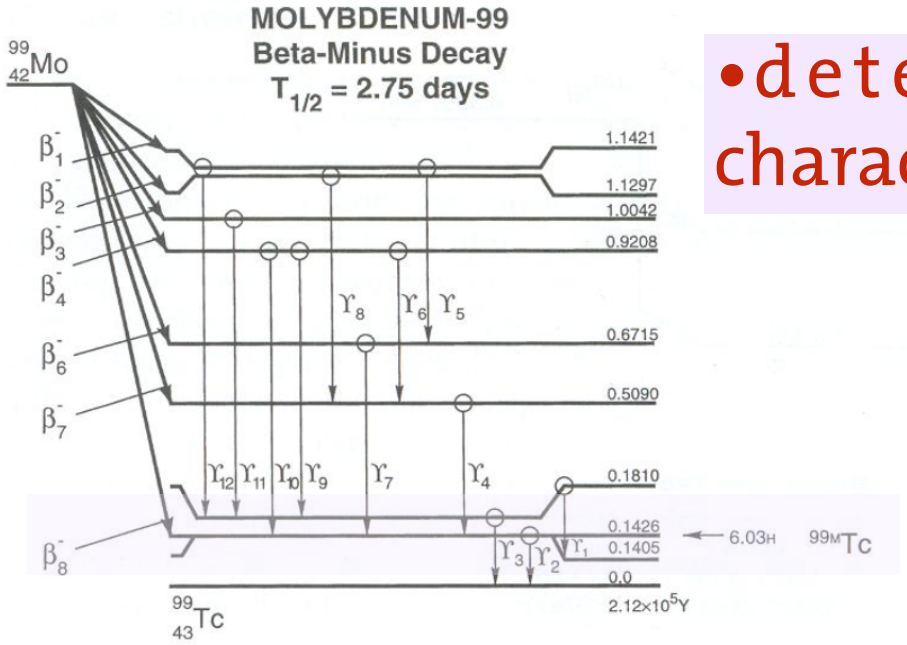
Single-Photon Emission Computed Tomography



- detection of a unique photon characteristic of a given disintegration

Radiation		Mean Number per Disintegration	Mean Energy per Particle (MeV)	Radiation		Mean Number per Disintegration	Mean Energy per Particle (MeV)
Beta Minus	1	0.0012	0.0658	Gamma	4	0.0143	0.3664
Beta Minus	3	0.0014	0.1112	Gamma	5	0.0001	0.3807
Beta Minus	4	0.1850	0.1401	Gamma	6	0.0002	0.4115
Beta Minus	6	0.0004	0.2541	Gamma	7	0.0005	0.5289
Beta Minus	7	0.0143	0.2981	Gamma	8	0.0002	0.6207
Beta Minus	8	0.7970	0.4519	Gamma	9	0.1367	0.7397
Gamma	1	0.0130	0.0405	K Int Con Elect		0.0002	0.7186
K Int Con Elect		0.0428	0.0195	Gamma	10	0.0479	0.7782
L Int Con Elect		0.0053	0.0377	K Int Con Elect		0.0000	0.7571
M Int Con Elect		0.0017	0.0401	Gamma	11	0.0014	0.8231
Gamma	2	0.0564	0.1405	Gamma	12	0.0011	0.9610
K Int Con Elect		0.0058	0.1194	K Alpha-1 X-Ray		0.0253	0.0183
L Int Con Elect		0.0007	0.1377	K Alpha-2 X-Ray		0.0127	0.0182
Gamma	3	0.0657	0.1810	K Beta-1 X-Ray		0.0060	0.0206
K Int Con Elect		0.0085	0.1600	KLL Auger Elect		0.0087	0.0154
L Int Con Elect		0.0012	0.1782	KLX Auger Elect		0.0032	0.0178
M Int Con Elect		0.0004	0.1806	LMM Auger Elect		0.0615	0.0019
				MXY Auger Elect		0.1403	0.0004

Single-Photon Emission Computed Tomography



- detection of a unique photon characteristic of a given disintegration

- 3D images are obtained by situating a gammacamera around the patient
- improvements:
  - -multicamera systems
  - -combined SPECT/CT

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4. SPECT

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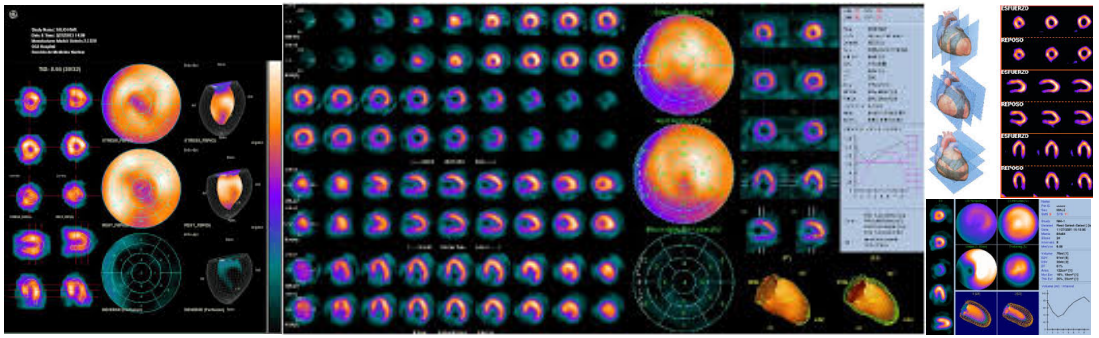
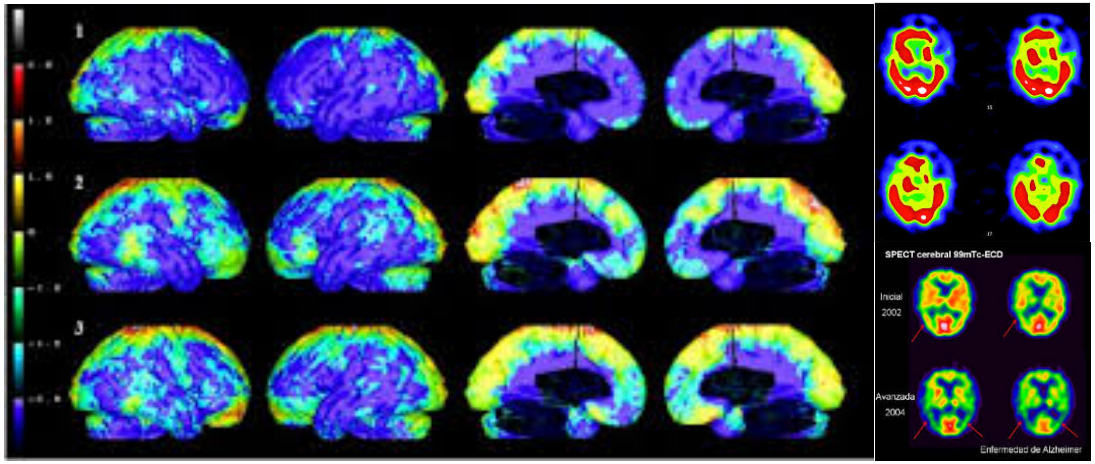
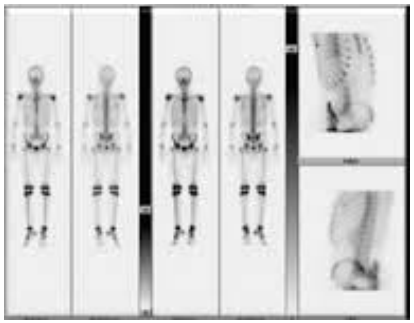
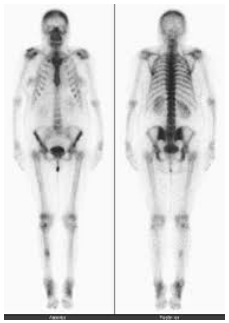
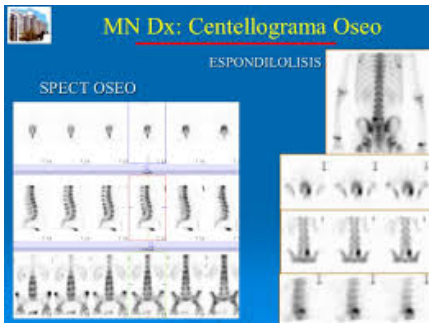



SPECT cerebral 99mTc-ECD
Inicial
2002
Avanzada
2004
Enfermedad de Alzheimer






MN Dx: Centellograma Oseo
ESPONDILOLISIS
SPECT OSEO

5. PET

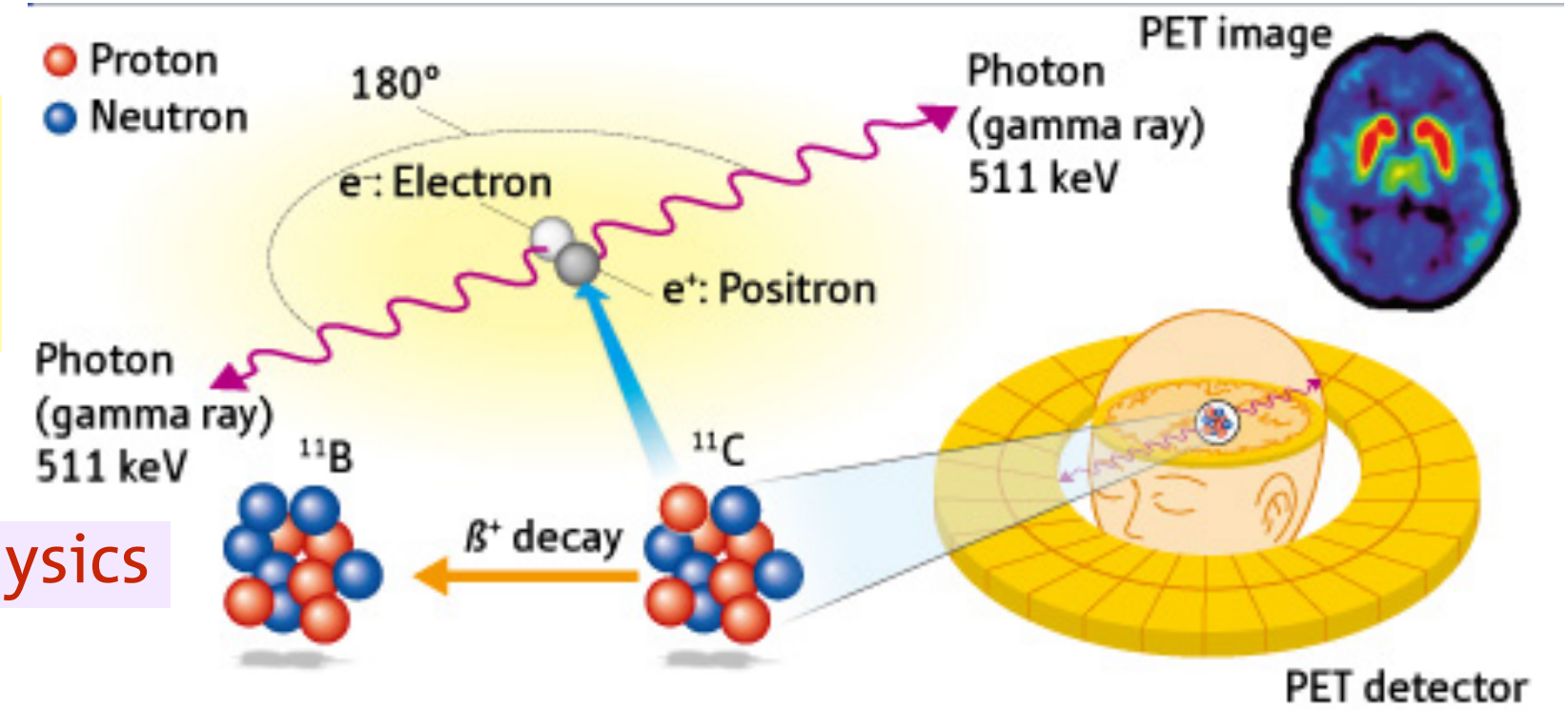
5. PET

Positron Emission Tomography

5. PET

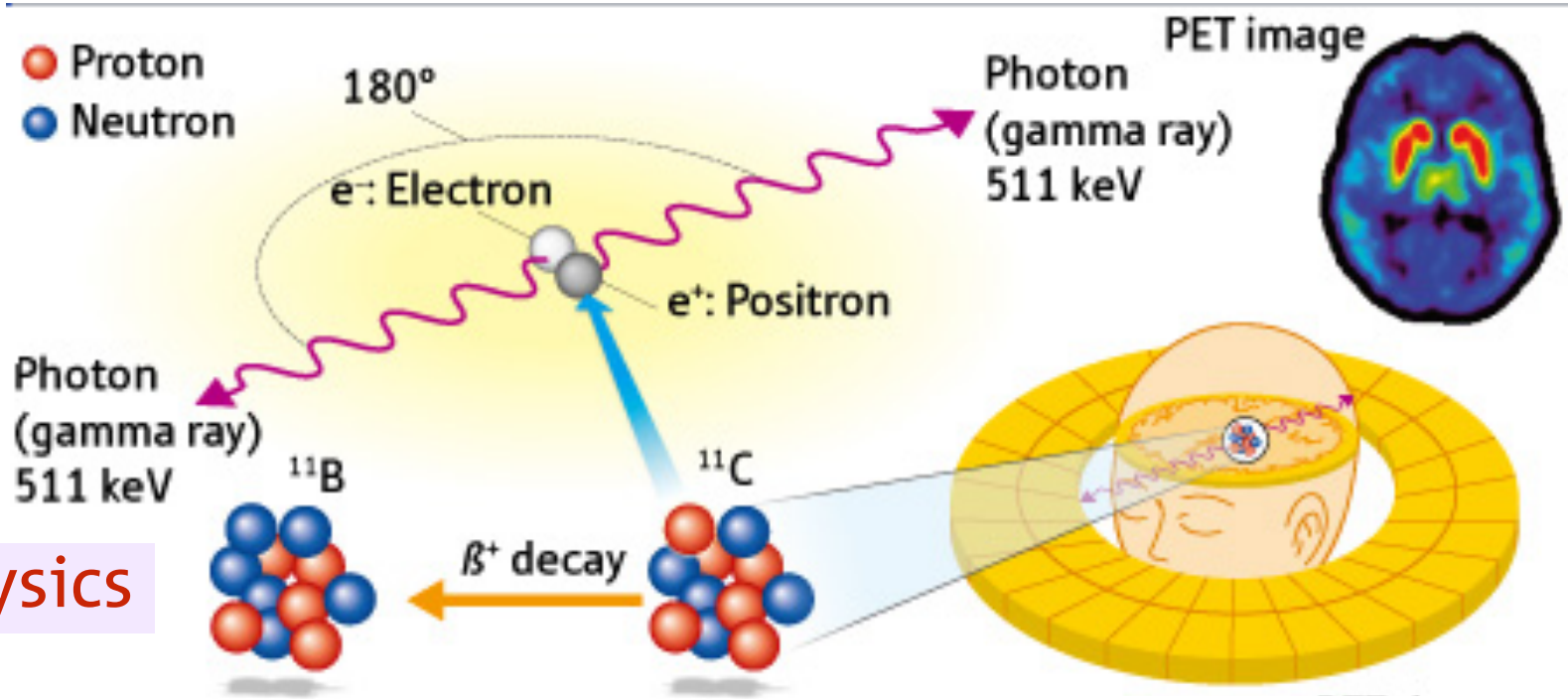
Positron Emission Tomography

- basic physics



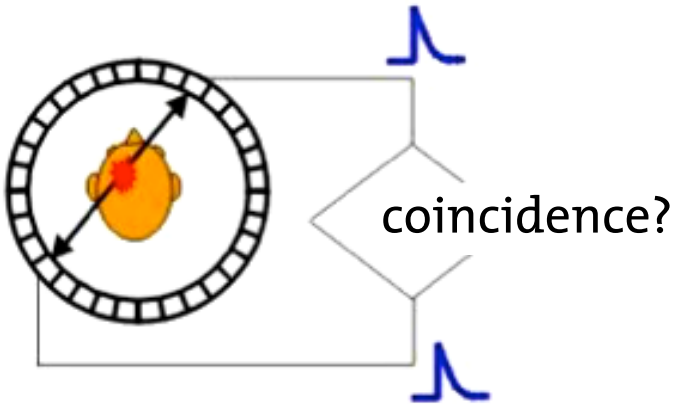
5. PET

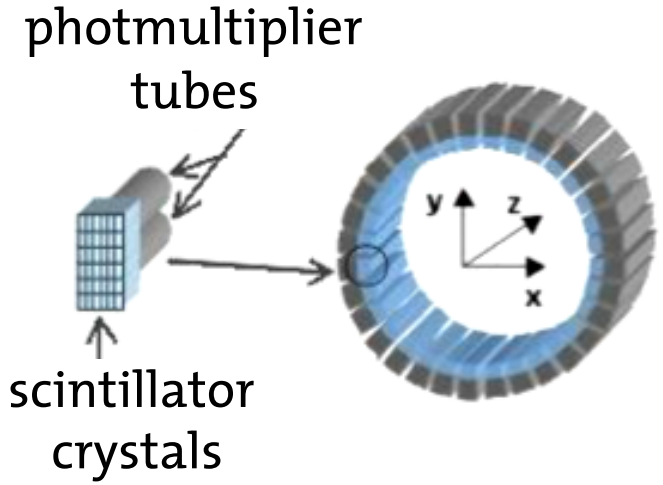
Positron Emission Tomography

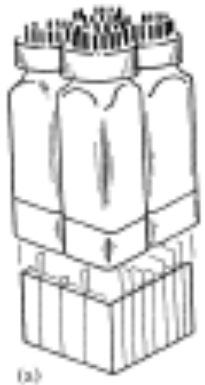


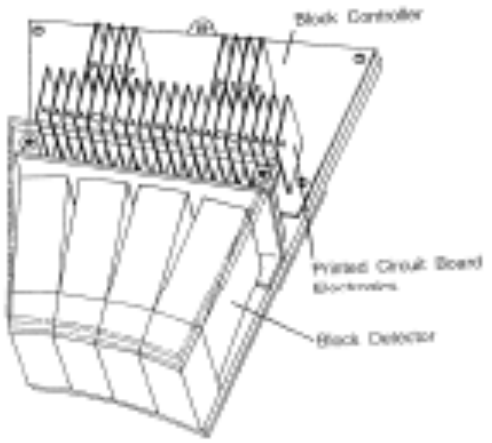
- basic physics

- annihilation photons are detected in coincidence









scintillator materials

- INa(Tl):
  - -requires thick crystals to stop 511 keV photons
- BGO:
  - -high stopping power for 511 keV photons
  - -high light recollection time
- new options:
  - -Lu / Gd orthosilicates (LSO, GSO)

most significant parameters of the usual scintillator crystals

	INa(Tl)	BGO	LSO	GSO
density (g cm^{-3})	3,67	7,13	7,40	6,71
effective atomic number	50	74	66	59
light decay time (ns)	230	300	40	60
light production (%INa)	100	15	75	16

radioisotopes

- to mark pharmaceuticals physiologically actives involved in biomechanical or metabolic procedures
- most used: ^{18}F
  - largest half-life
  - smaller average energy
  - smaller range

emitter	$T_{1/2}$ (min)	E_{max} (MeV)	range (mm)	production reaction	production device
^{11}C	20.3	0.97	2.06	$^{14}N(p, \alpha)^{11}C$	ciclotrón
^{13}N	9.96	1.19	3.0	$^{16}O(p, \alpha)^{13}N$ $^{13}C(p, n)^{13}N$	ciclotrón
^{15}O	2.07	1.7	4.5	$^{14}N(d, n)^{15}O$ $^{15}N(p, n)^{15}O$ $^{16}O(p, pn)^{15}O$	ciclotrón
^{18}F	109.8	0.635	1.4	$^{18}O(p, n)^{18}F$ $^{20}Ne(d, \alpha)^{18}F$	ciclotrón
^{82}Rb	1.27	3.15	13.8	$^{82}Sr \rightarrow {}^{82}Rb$	generador
^{68}Ga	68.3	1.88	5.4	$^{68}Ge \rightarrow {}^{68}Ga$	generador

5. PET

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- no physical collimators are needed: better efficiency!

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- actual collimation through the “line of response” (LOR)

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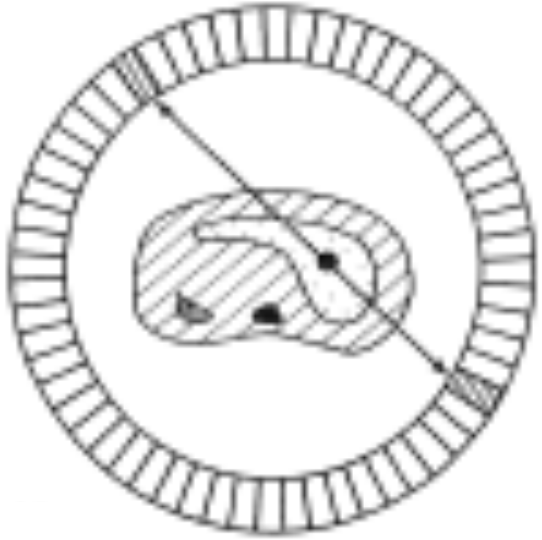
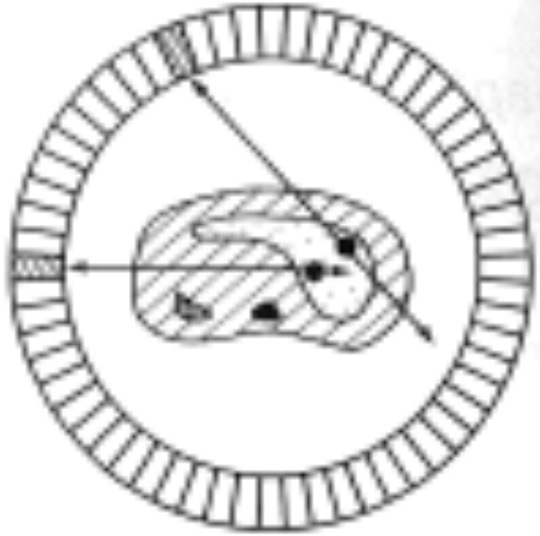
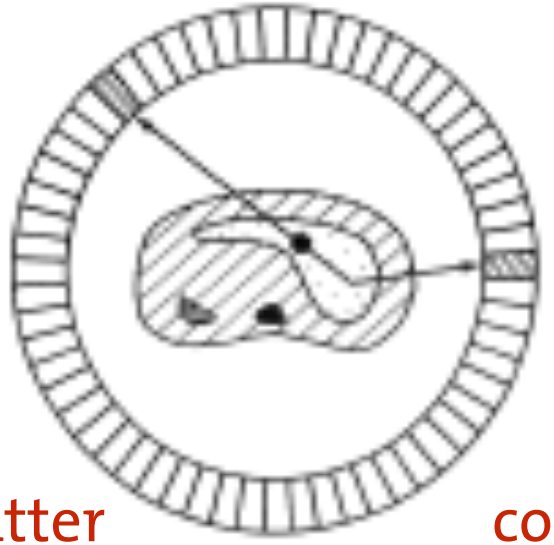
true coincidence

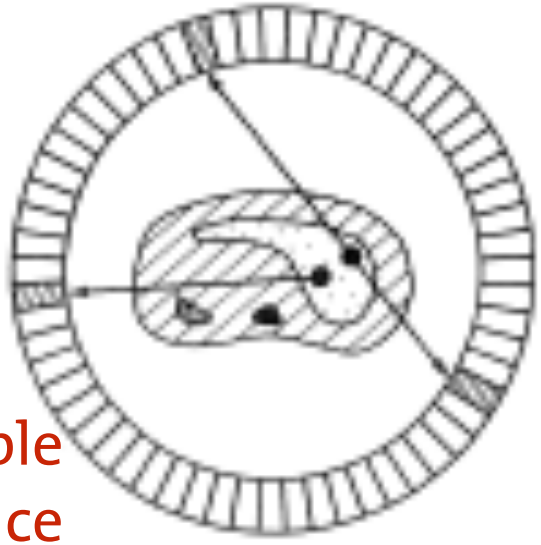


accidental coincidence





scatter

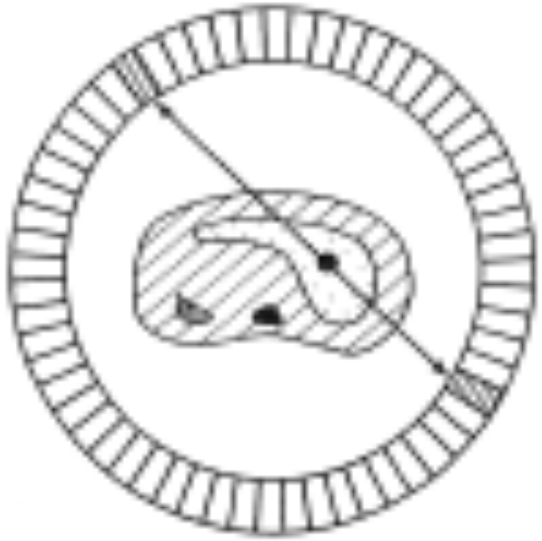


multiple coincidence

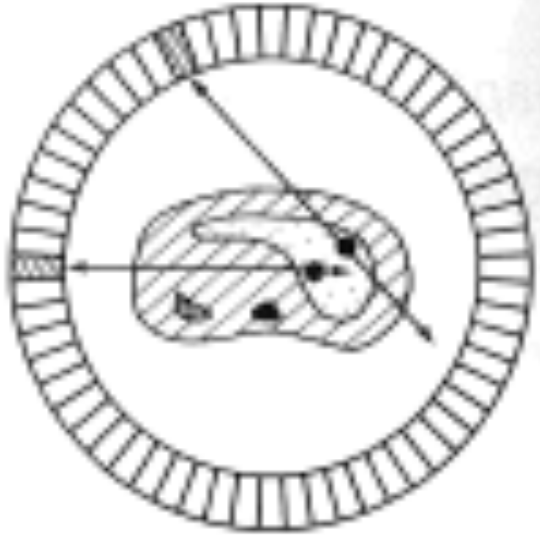
- no physical collimators are needed: better efficiency!
- actual collimation through the "line of response" (LOR)

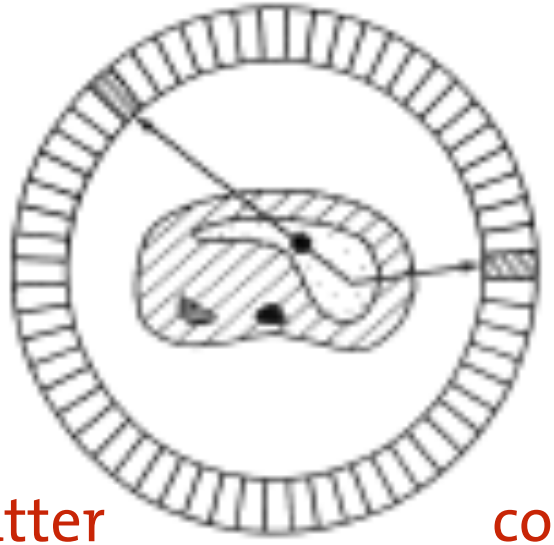
- deconvolution of the distribution of annihilation points

true coincidence

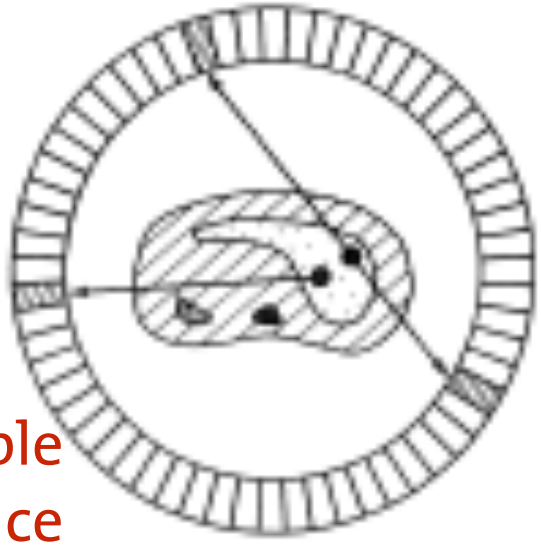


accidental coincidence





scatter

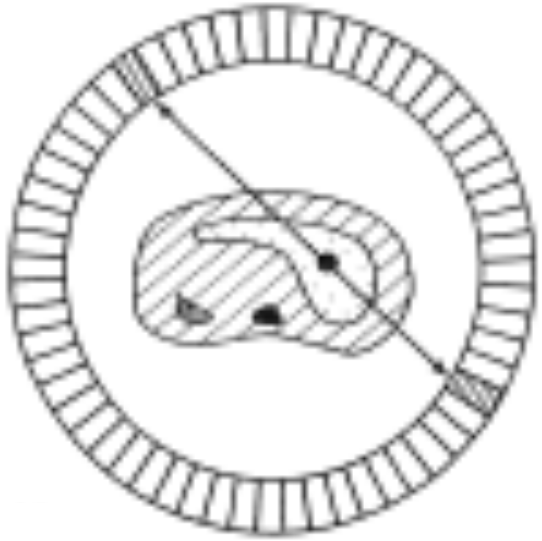


multiple coincidence

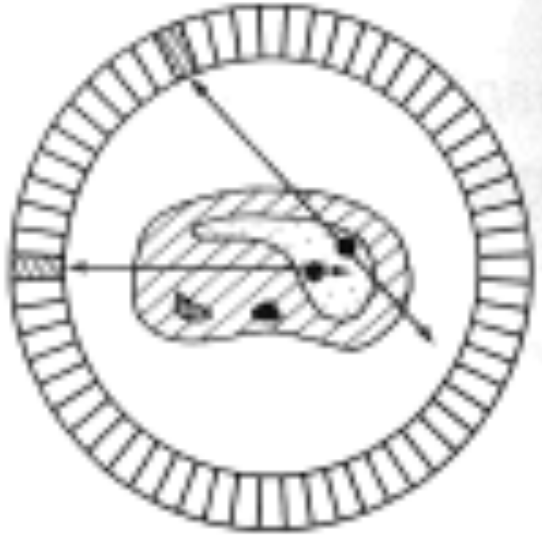
- no physical collimators are needed: better efficiency!
- actual collimation through the "line of response" (LOR)

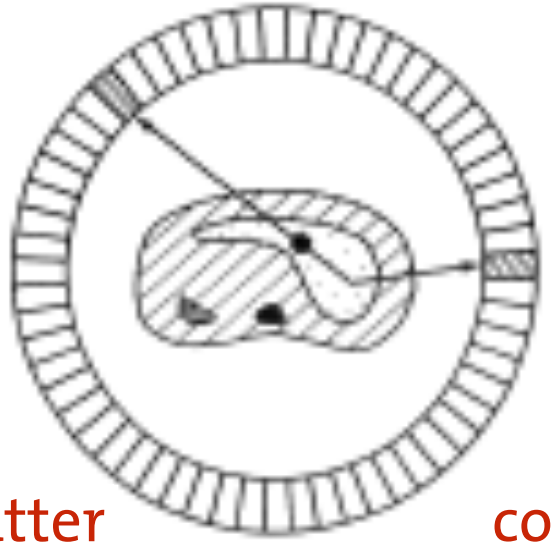
- deconvolution of the distribution of annihilation points
- evaluated (via, e.g. Monte Carlo) and included in the image reconstruction algorithms

true coincidence

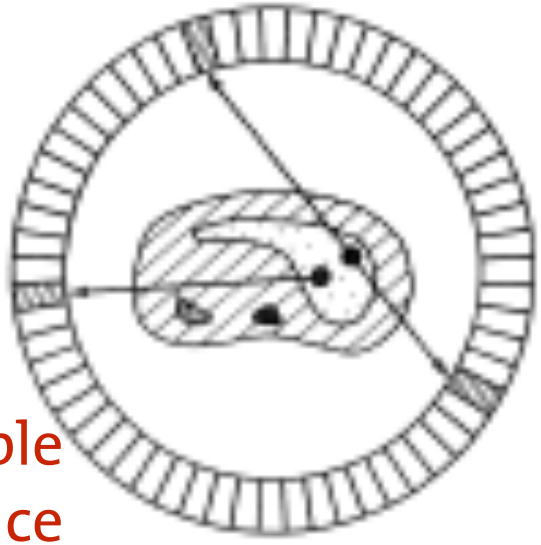


accidental coincidence



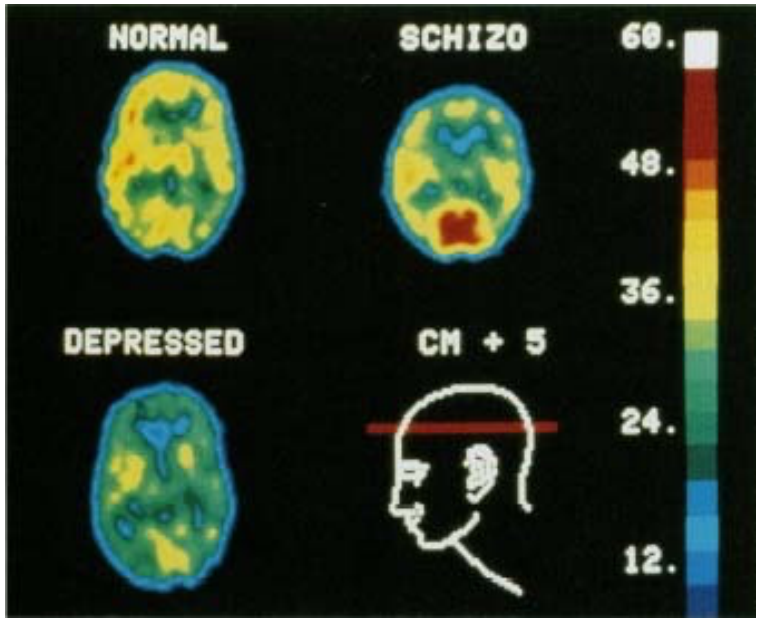


scatter



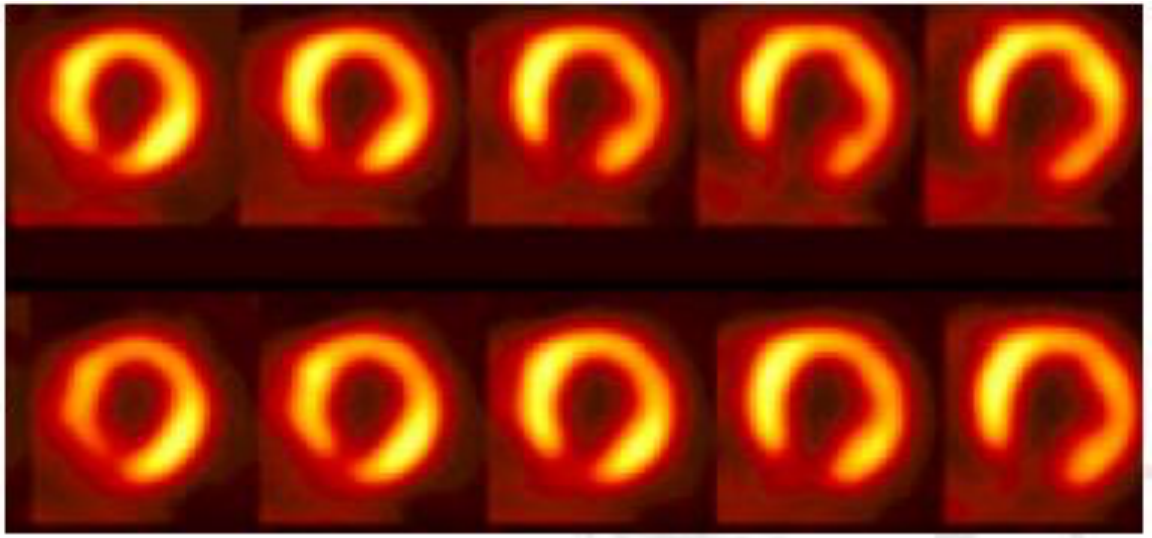
multiple coincidence

5. PET

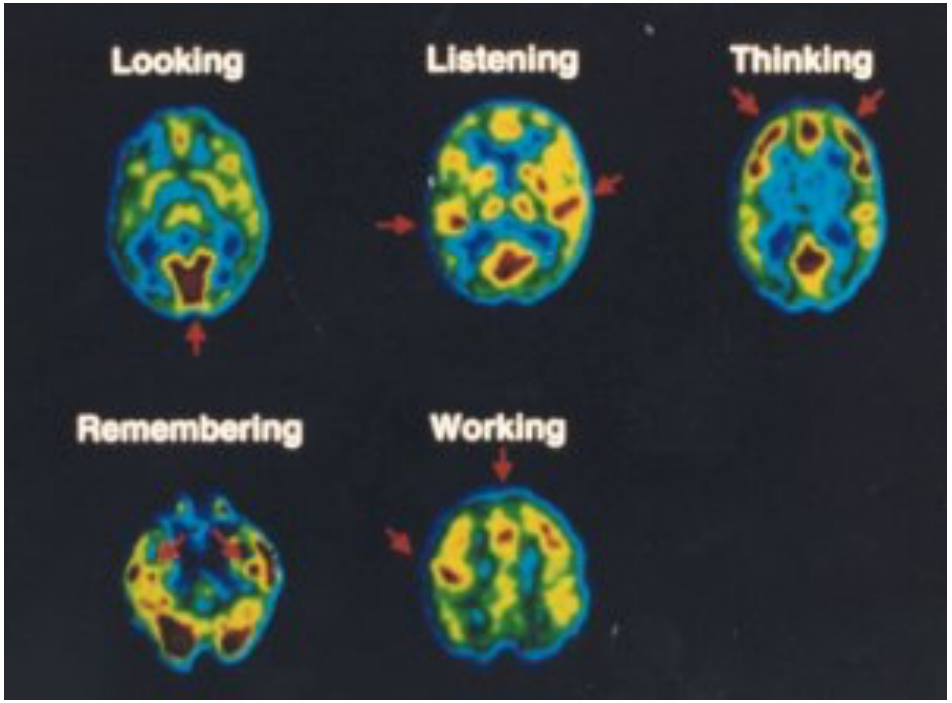


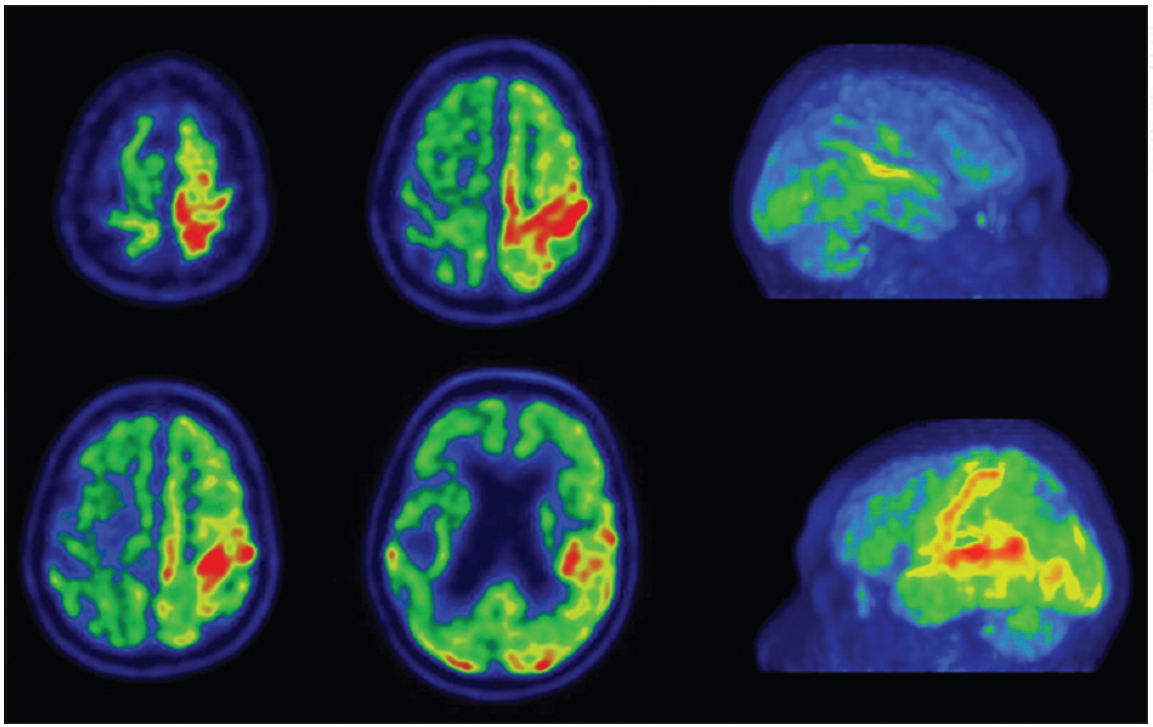
stress

at rest



necrosis of myocardium





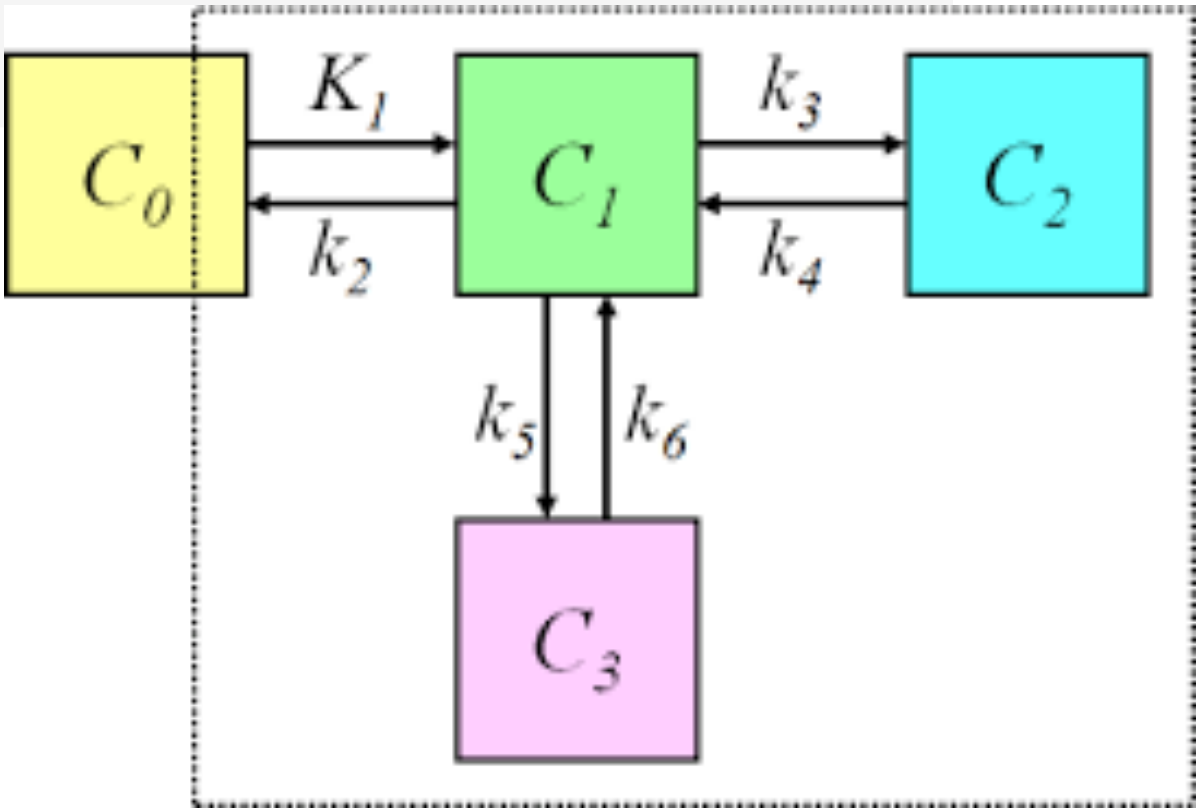
severe asymmetrical right hemisphere hypometabolism

Kinetic compartmental models

$$\frac{dC_1(t)}{dt} = K_1 C_0(t) - (k_2 + k_3 + k_5) C_1(t) + k_4 C_2(t) + k_6 C_3(t)$$

$$\frac{dC_2(t)}{dt} = k_3 C_1(t) - k_4 C_2(t)$$

$$\frac{dC_3(t)}{dt} = k_5 C_1(t) - k_6 C_3(t)$$



Kinetic compartmental models

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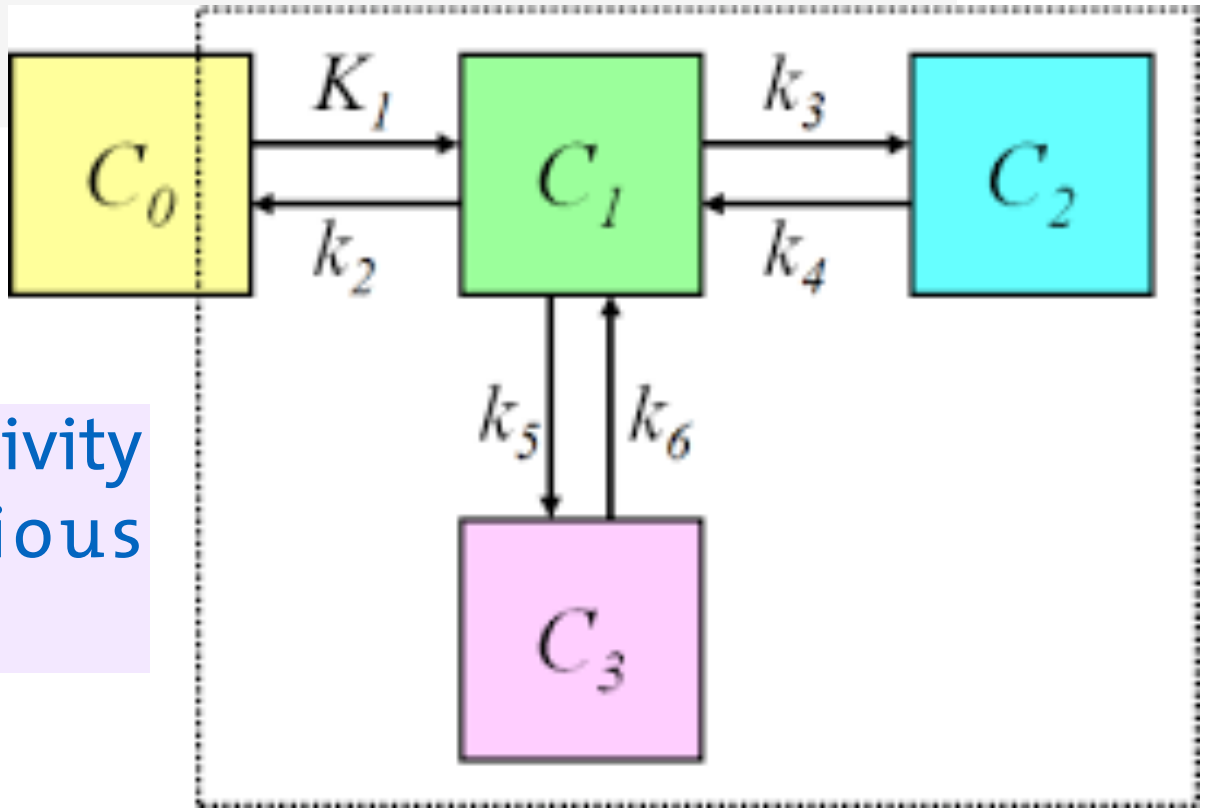
$$\frac{dC_2(t)}{dt} = k_3 C_1(t) - k_4 C_2(t)$$

$$\frac{dC_3(t)}{dt} = k_5 C_1(t) - k_6 C_3(t)$$



- determination of the activity deposited in the various organs

6. Dosimetry

- specific absorbed fraction

$$\Phi(\mathrm{T} \leftarrow \mathrm{S}) = \frac{\phi(\mathrm{T} \leftarrow \mathrm{S})}{m_\mathrm{T}} = \frac{E_\mathrm{T}/E_\mathrm{S}}{m_\mathrm{T}}$$

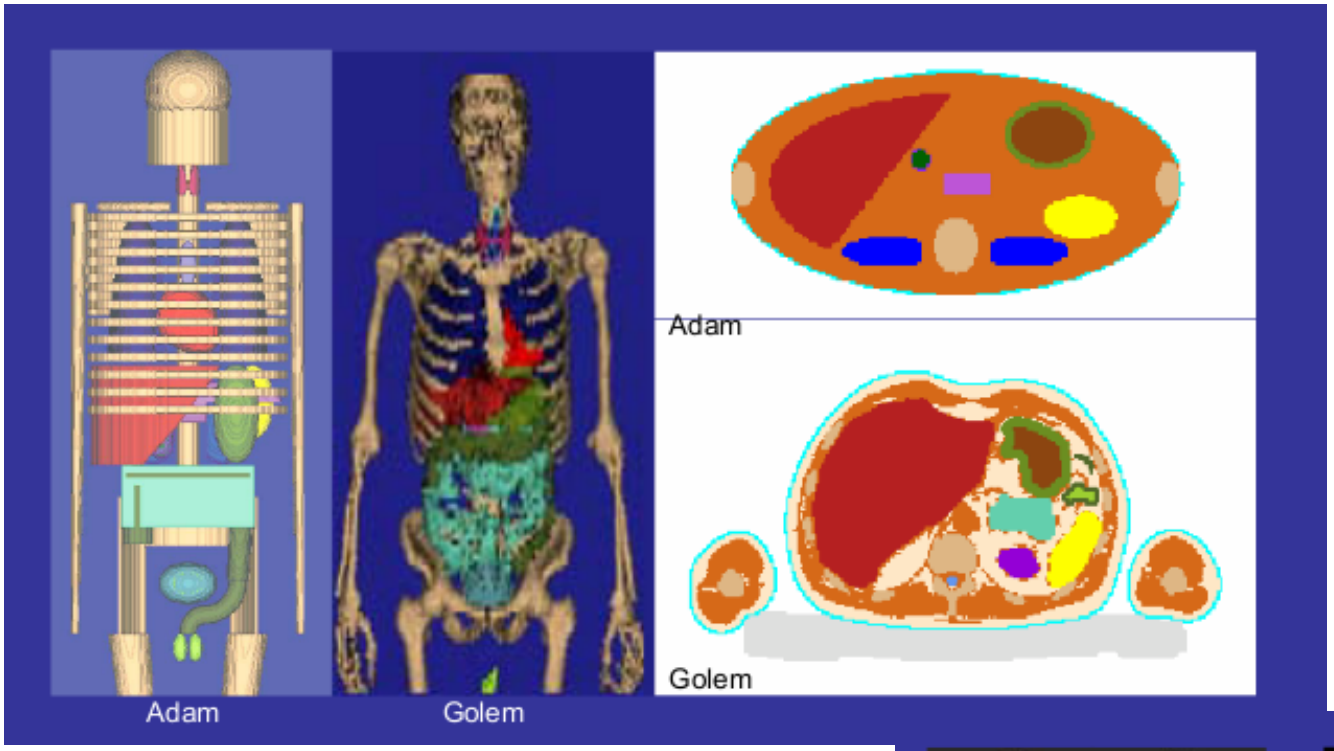
TABLE 24-8. Tc-99m S FACTORS FOR SOME SOURCE/TARGET ORGAN COMBINATIONS

	Source organs (r_h)									
			Intestinal Tract							
Target organs (r_k)	Adrenals	Bladder contents	Stomach contents	SI contents	ULI contents	LLI contents	Kidneys	Liver	Lungs	Other tissue (muscle)
Adrenals	3.1E-03	1.5E-07	2.7E-06	1.0E-06	9.1E-07	3.6E-07	1.1E-05	4.5E-06	2.7E-06	1.4E-06
Bladder wall	1.3E-07	1.6E-04	2.7E-07	2.6E-06	2.2E-06	6.9E-06	2.8E-07	1.6E-07	3.6E-08	1.8E-06
Bone (total)	2.0E-06	9.2E-07	9.0E-07	1.3E-06	1.1E-06	1.6E-06	1.4E-06	1.1E-06	1.5E-06	9.8E-07
GI (stomach wall)	2.9E-06	2.7E-07	1.3E-04	3.7E-06	3.8E-06	1.8E-06	3.6E-06	1.9E-06	1.8E-06	1.3E-06
GI (SI)	8.3E-07	3.0E-06	2.7E-06	7.8E-05	1.7E-05	9.4E-06	2.9E-06	1.6E-06	1.9E-07	1.5E-06
GI (ULI Wall)	9.3E-07	2.2E-06	3.5E-06	2.4E-05	1.3E-04	4.2E-06	2.9E-06	2.5E-06	2.2E-07	1.6E-06
GI (LLI Wall)	2.2E-07	7.4E-06	1.2E-06	7.3E-06	3.2E-06	1.9E-04	7.2E-07	2.3E-07	7.1E-08	1.7E-06
Kidneys	1.1E-05	2.6E-07	3.5E-06	3.2E-06	2.8E-06	8.6E-07	1.9E-04	3.9E-05	8.4E-07	1.3E-06
Liver	4.9E-06	1.7E-07	2.0E-06	1.8E-06	2.6E-06	2.5E-07	3.9E-06	***4.6E-05***	2.5E-06	1.1E-06
Lungs	2.4E-06	2.8E-08	1.7E-06	2.2E-07	2.6E-07	7.9E-08	8.5E-07	2.5E-06	5.2E-05	1.3E-06
Marrow (red)	3.6E-06	2.2E-06	1.6E-06	4.3E-06	3.7E-06	5.1E-06	3.8E-06	***1.6E-06***	1.9E-06	2.0E-06
OTH TISS (muscle)	1.4E-06	1.8E-06	1.4E-06	1.5E-06	1.5E-06	1.7E-06	1.3E-06	1.1E-06	1.3E-06	2.7E-06
Ovaries	6.1E-07	7.3E-06	5.0E-07	1.1E-05	1.2E-05	1.8E-05	1.1E-06	4.5E-07	9.4E-08	2.0E-06
Pancreas	9.0E-06	2.3E-07	1.8E-05	2.1E-06	2.3E-06	7.4E-07	6.6E-06	4.2E-06	2.6E-06	1.8E-06
Skin	5.1E-07	5.5E-07	4.4E-07	4.1E-07	4.1E-07	4.8E-07	5.3E-07	4.9E-07	5.3E-07	7.2E-07
Spleen	6.3E-06	6.6E-07	1.0E-05	1.5E-06	1.4E-06	8.0E-07	8.6E-07	9.2E-07	2.3E-06	1.4E-06
Testes	3.2E-08	4.7E-06	5.1E-08	3.1E-07	2.7E-07	1.8E-06	8.8E-08	***6.2E-08***	7.9E-09	1.1E-06
Thyroid	1.3E-07	2.1E-09	8.7E-08	1.5E-08	1.6E-08	5.4E-09	4.8E-08	1.5E-07	9.2E-07	1.3E-06
Uterus (nongravid)	1.1E-06	1.6E-05	7.7E-07	4.6E-06	5.4E-06	7.1E-06	9.4E-07	3.9E-07	8.2E-08	2.3E-06
Total body	2.2E-06	1.9E-06	1.9E-06	2.4E-06	2.2E-06	2.3E-06	2.2E-06	***2.2E-06***	2.0E-06	1.9E-06

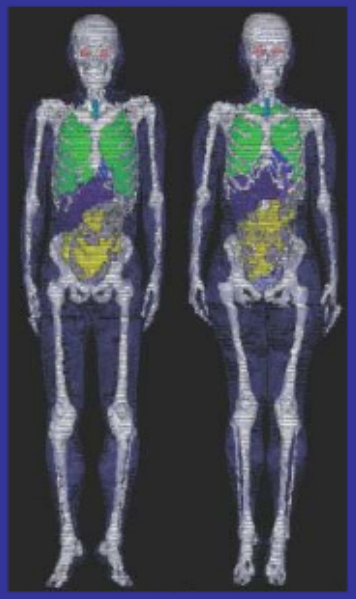
Note: GI, gastrointestinal; SI, small intestine; ULI, upper large intestine; LLI, lower large intestine; OTH TISS, other tissue. Bold italized correspond to values in MIRD example problem.
Source: Medical Internal Radiation Dosimetry (MIRD) Committee of the Society of Nuclear Medicine.

- calculated with Monte Carlo using human phantoms

6. Dosimetry



phantoms



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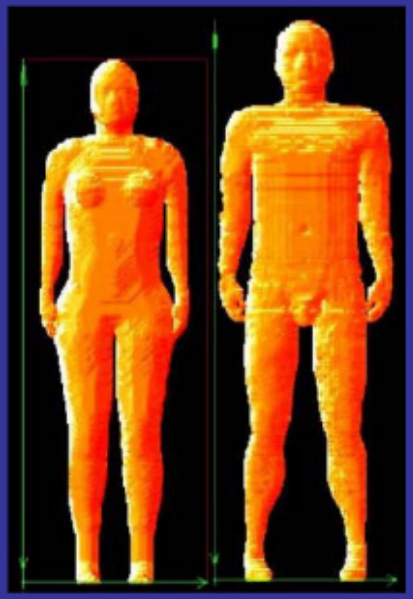
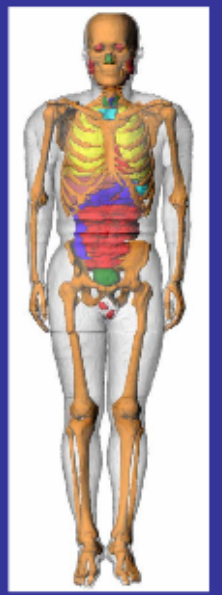


FAX06 and MAX06
(Kramer *et al.* 2006 Phys. Med. Biol. **51**, 3331-3346)



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