

Nuclear radiation in the clinical practice

07-12-2020
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Steps of diagnostic procedure

- Radioactive material introduced into the patient
- Distribution and alteration of activity is detected
- Monitoring of physiological pathways and/or identification and localization of pathological changes

Information from various medical imaging techniques

Structure	X-ray	<i>differences according to the different physical parameters / properties of tissues</i>
	Ultrasound	
	MRI	
Function	Isotope diagnostics	<i>dynamic physiological / metabolic processes of different body organs can be followed</i>
	MRI	



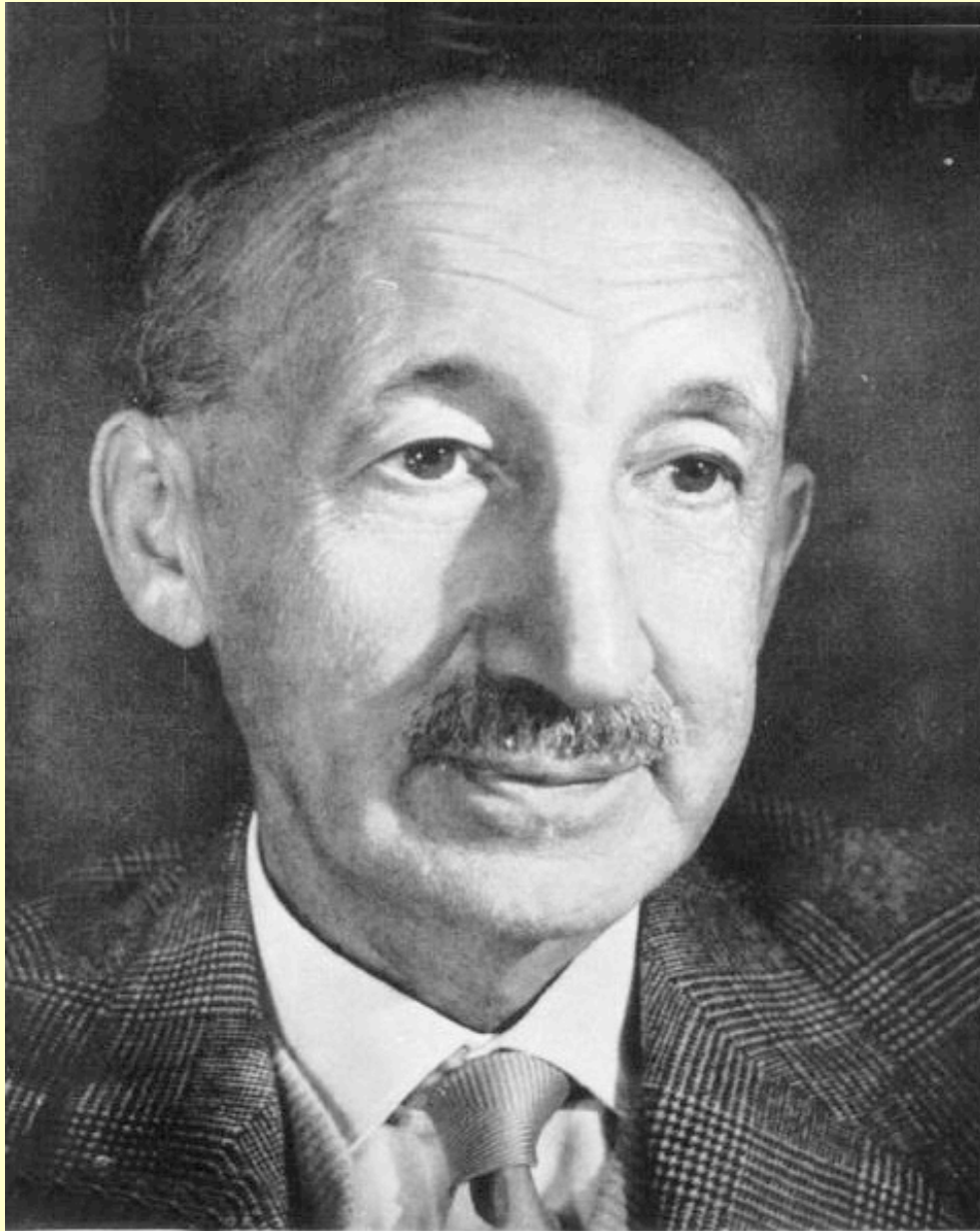
X-ray

Shows the structure



Isotope diagnostics

*Reports the
metabolic activity*



Georg de Hevesy

Father of Nuclear Medicine

Georg Charles de Hevesy
(1885 - 1966)

Nobel Prize in Chemistry
1943

**for his work on the use of
isotopes as tracers in the
study of chemical
processes**

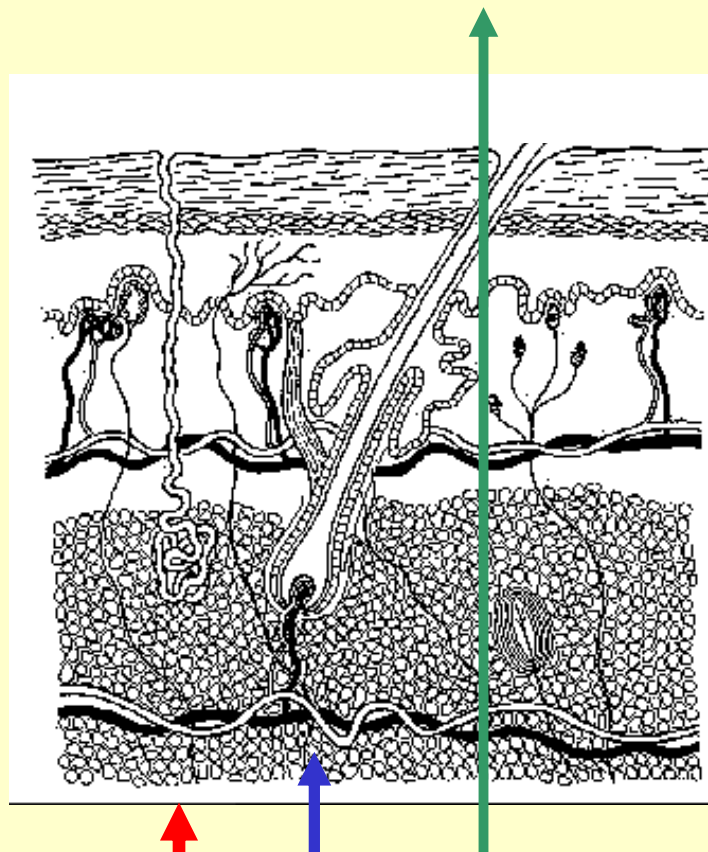
The choice of the appropriate radioisotope for nuclear imaging

Maximize the information — Minimize the risk

For that find the optimal

- type of radiation
- photon energy
- half-life
- radiopharmakon

Type of radiation



α β γ

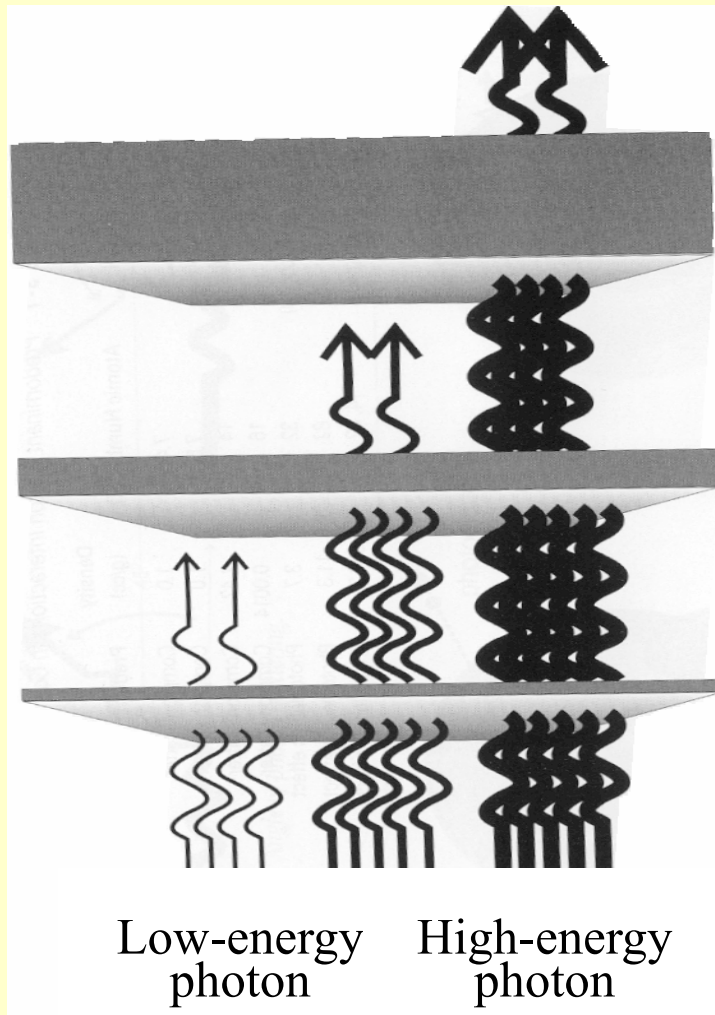
decay via photon emission
to minimize absorption
effects in body tissue

only **γ -radiation** has
sufficient penetration
depth

purely gamma-emitting isotope is preferable

photon energy

$$hf > 50 \text{ keV}$$



Photon must have sufficient energy to penetrate body tissue with minimal attenuation

BUT!

Photon must have sufficiently low energy to be registered efficiently in detector and to allow the efficient use of lead collimator systems (must be absorbed in lead)

a suitable physical half-life

$$\Lambda = \lambda N = \frac{0,693}{T} N$$

smaller is better
but

the value is limited by the
sensitivity of the detector

smaller is better

dose considerations for
patients

shorter is better

but

it has to be long enough for monitoring the
physiological organ functions to be studied

radiopharmaceutical – is a substance that contain one or more radioactive atoms and are used for diagnosis or treatment of disease. It is typically made of two components, the radionuclide and the chemical compound to which it is bound.

Basic requirements:

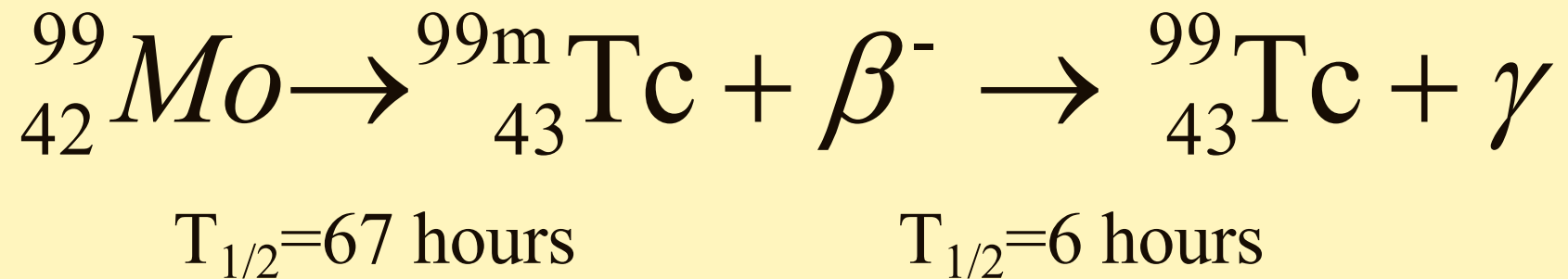
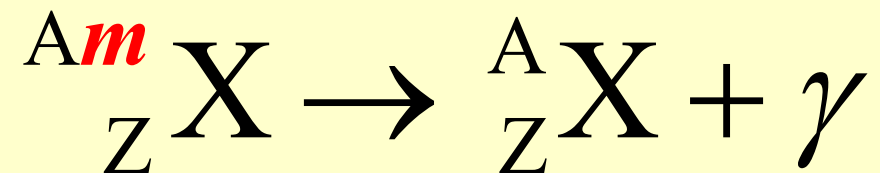
- specific localizing properties
- high *target / non-target* ratio
- have no pharmacological or toxicological effects which may interfere with the organ function under study.

Factors responsible for the ultimate distribution of the radioisotope

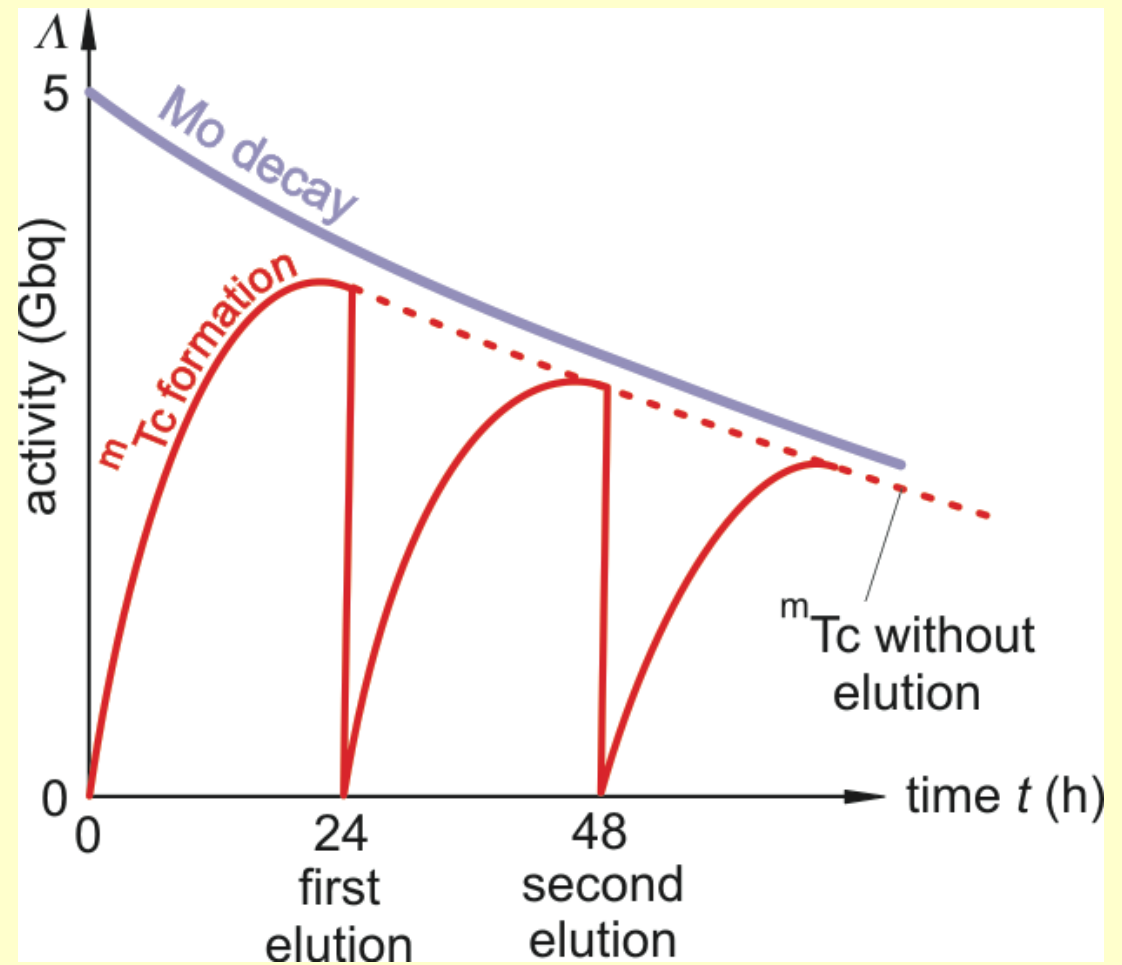
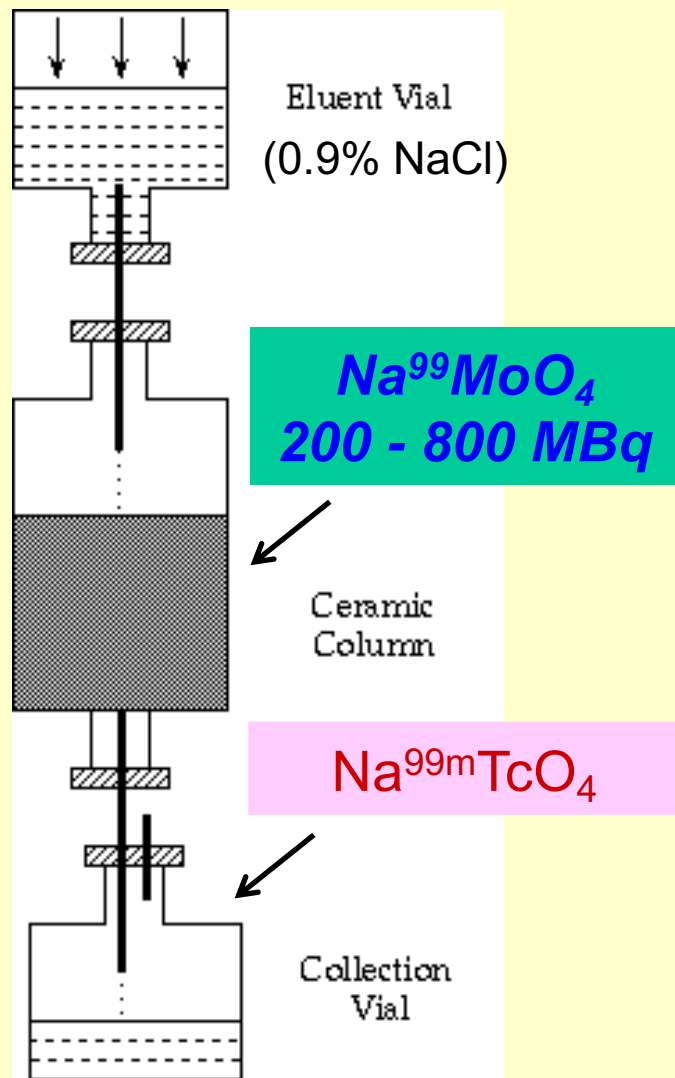
- blood flow (percent cardiac input/output of a specific organ)
- availability of compound to tissue, or the proportion of the tracer that is bound to proteins in the blood
- basic shape, size, and solubility of molecule which controls its diffusion capabilities through body membranes

Gamma-emitting isotopes

Isomeric transition: some excited states may have half-lives ranging from hours up to more than 600 years



Technetium-99m generator



examples

pharmaceutical	radioisotope	activity (MBq)	target organ
Pertechnetate	^{99m}Tc	550 - 1200	brain
Pirophosphate	^{99m}Tc	400 - 600	heart
Diethylene Triamine Penta Acetic Acid (DTPA)	^{99m}Tc	20 - 40	lung
Mercaptoacetyltriglycine (MAG3)	^{99m}Tc	50 - 400	kidney
Methylene Diphosphonate (MDP)	^{99m}Tc	350 - 750	bones

Optimal activity for diagnostic procedure

Maximize the information

Minimize the risk

$$\Lambda \sim 100 \text{ MBq}$$

Types of images

Static image – spatial distribution of isotope / activity
at a certain time

Dynamic image – variation of the amount of isotope /
activity in time

Static and dynamic image – series of static recordings

Emission CT

SPECT (Single Photon Emission Computed Tomography)

PET (Positron Emission Tomography)

Types of images

Static – spatial distribution of isotope / activity at a certain time



thyroid glands

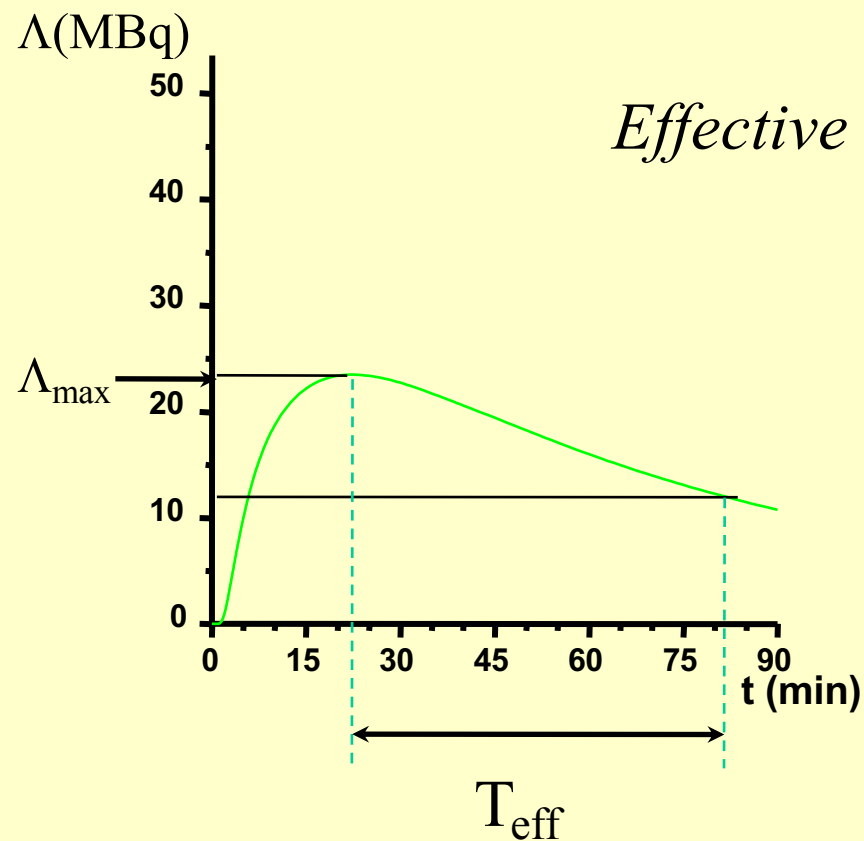


kidneys

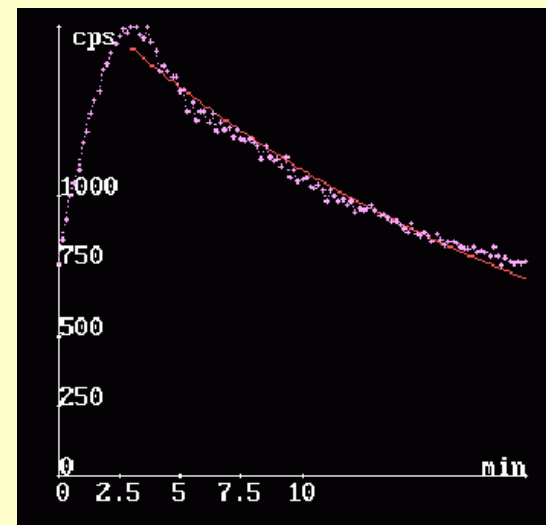
Isotope accumulation in

Types of images

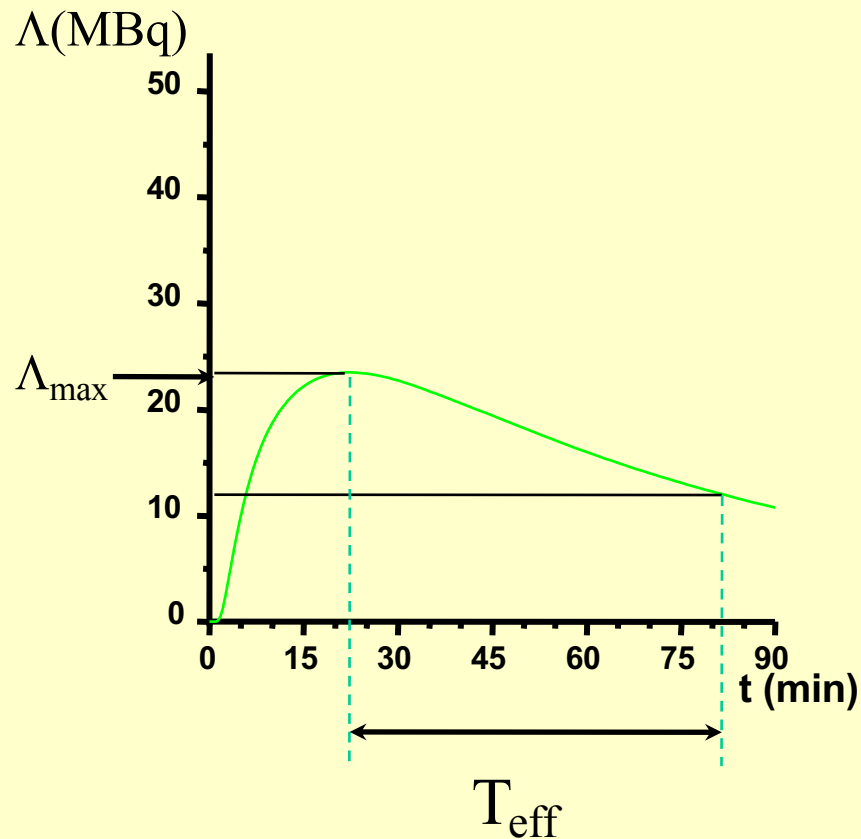
Dynamic image – variation of the amount of isotope / activity in time



Effective half-life – activity decreases by half in the target organ



Effective half-life – activity decreases by half in the target organ



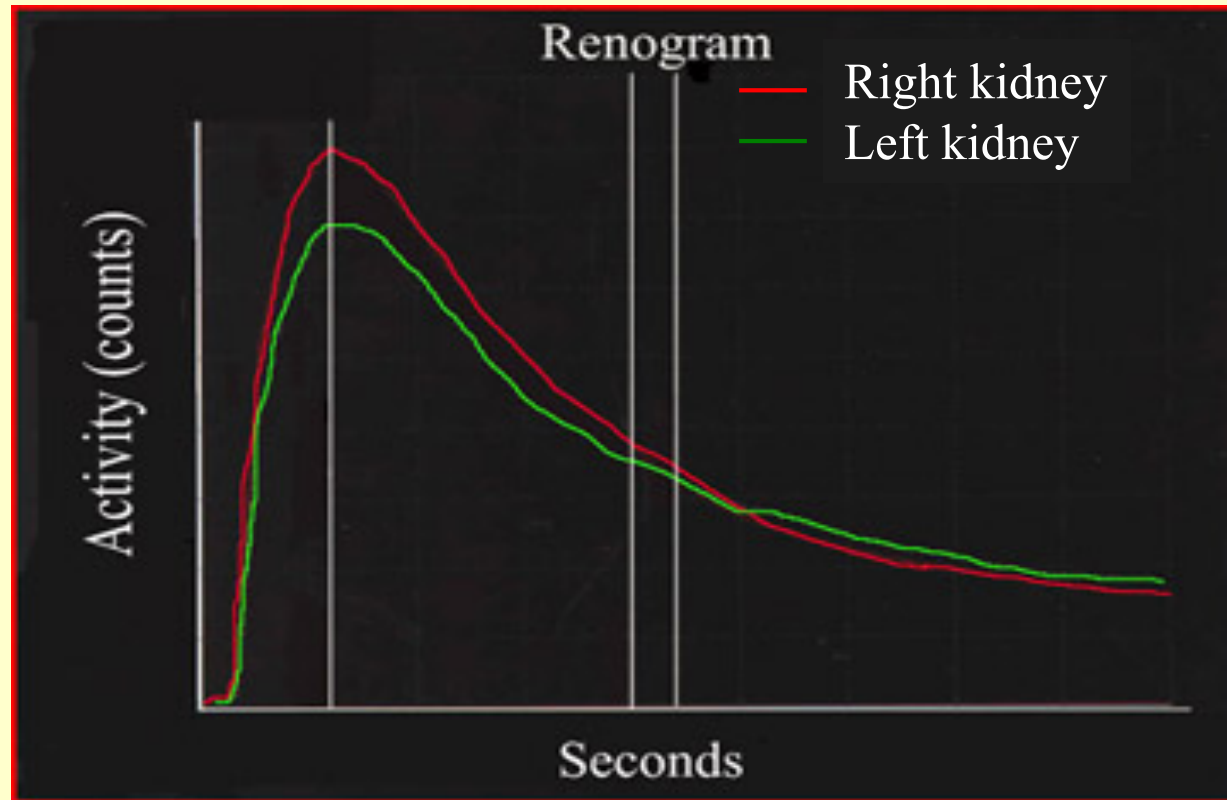
$$\Lambda = \Lambda_0 e^{-(\lambda_{\text{phys}} + \lambda_{\text{biol}})t}$$

$$\lambda_{\text{effective}} = \lambda_{\text{phys}} + \lambda_{\text{biol}}$$

$$\frac{1}{T_{\text{eff}}} = \frac{1}{T_{\text{phys}}} + \frac{1}{T_{\text{biol}}}$$

The final fate of the radiotracer depends on how the addressed organ deals with the molecule, whether it is absorbed, broken down by intracellular chemical processes or whether it exits from the cells and is removed by kidney or liver processes. These processes determine the **biological half-life** T_{biol} of the radiopharmaceutical.

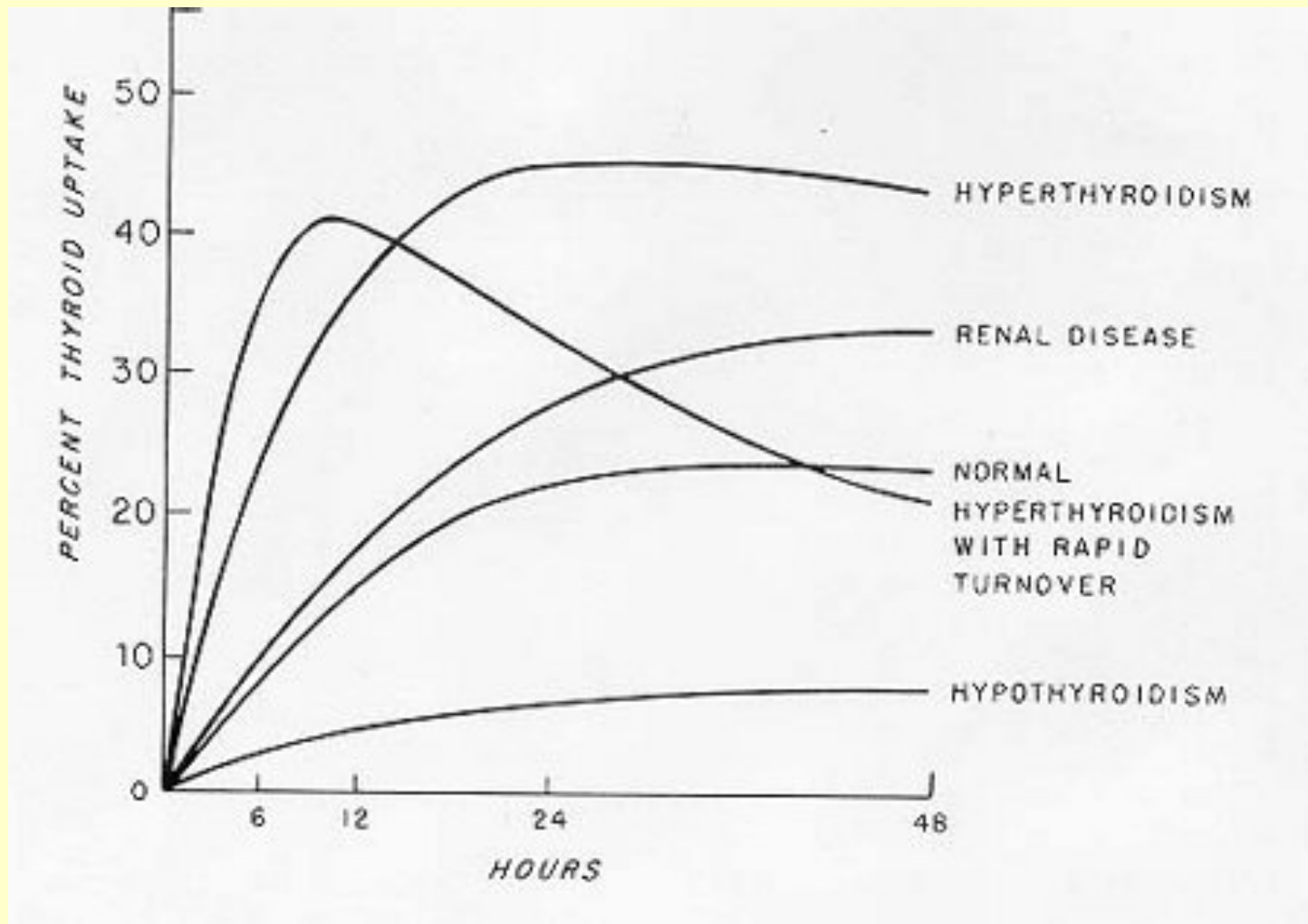
example



kidney

Isotope accumulation traces

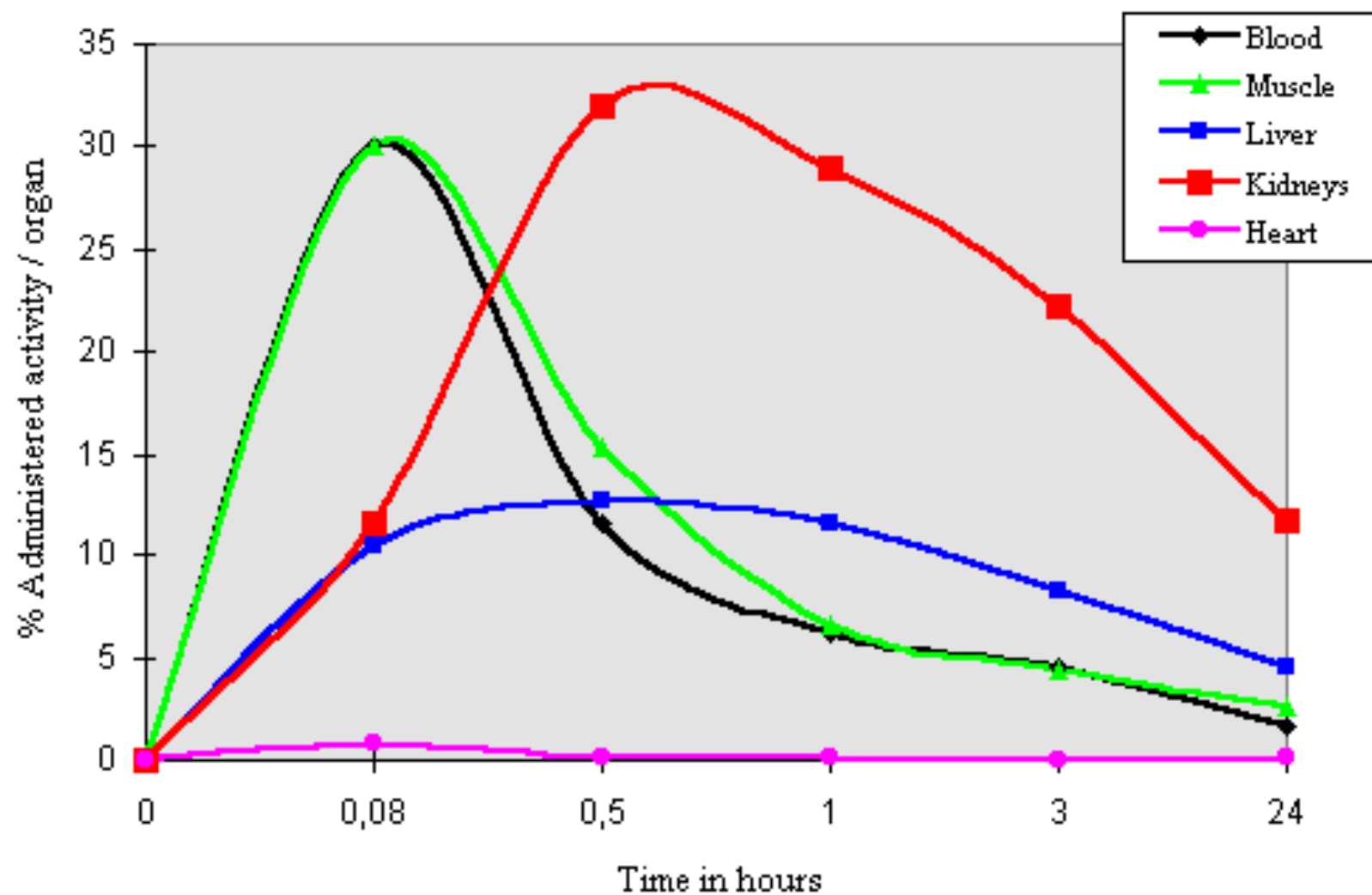
example



Thyroid glands

Isotope accumulation traces

Time-activity curve of Tc-99m scorpion venom in rats

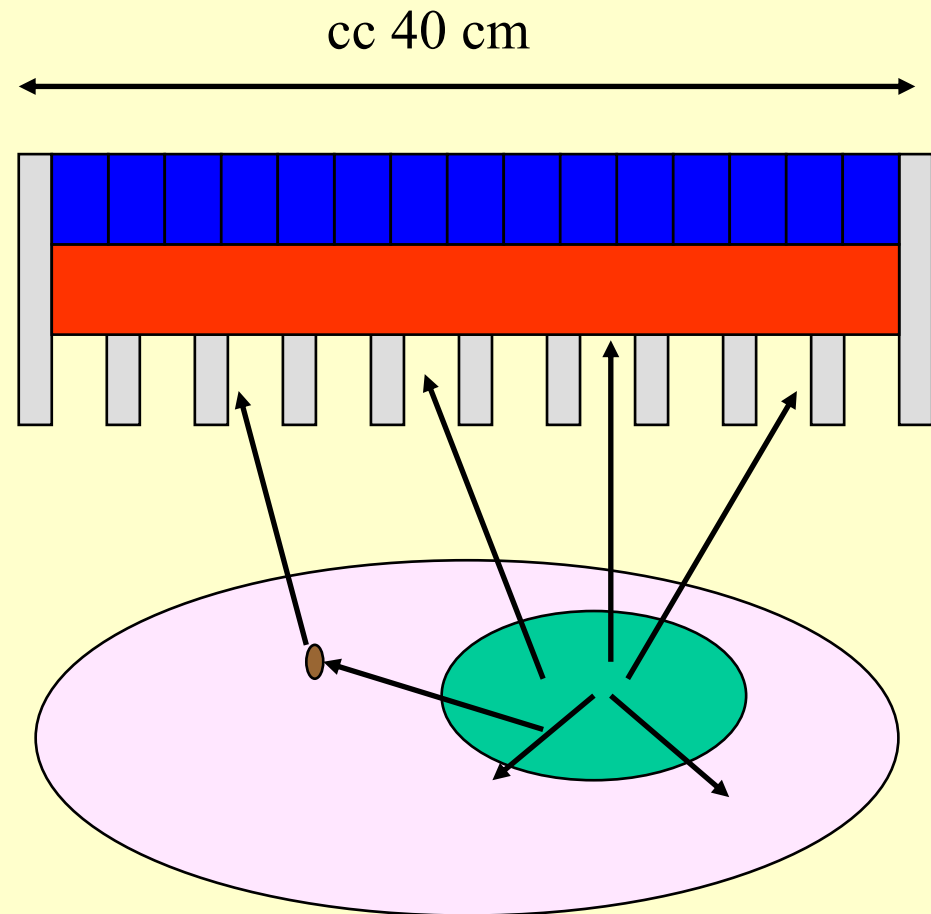




Hal Anger
1920-2005

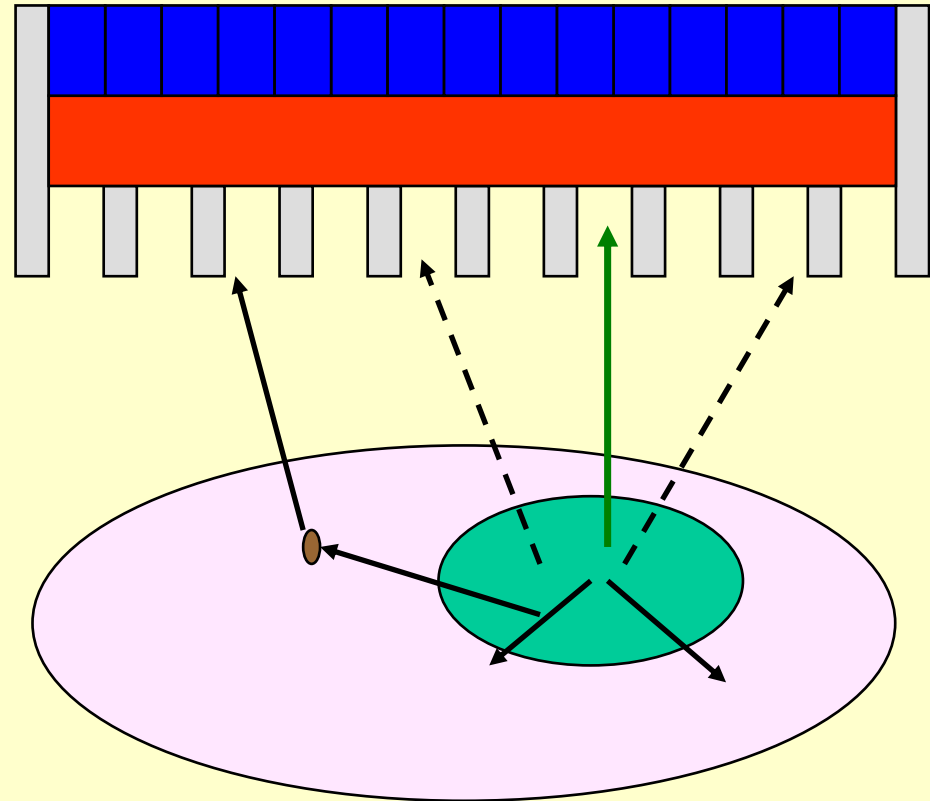
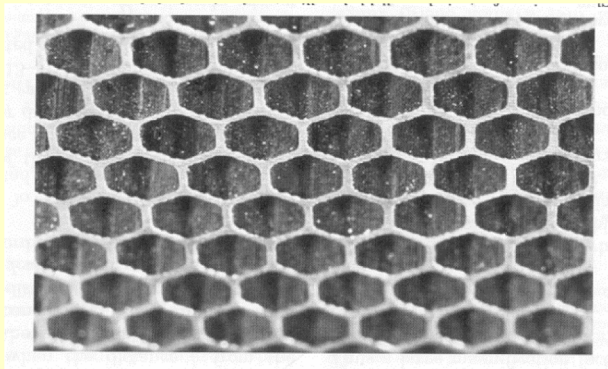
Gamma camera

Photomultiplier tubes →
Scintillation crystal →
Collimator →



A radioactive source emits gamma photons in all directions.

collimator

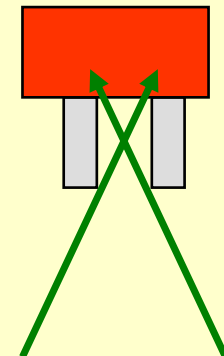


Collimators are composed of thousands of precisely aligned channels made of lead.

The collimator conveys only those photons traveling along the long axis of each hole.

Photons emitted in other directions are absorbed by the septa between the holes.

Size and geometry of holes determine resolution.



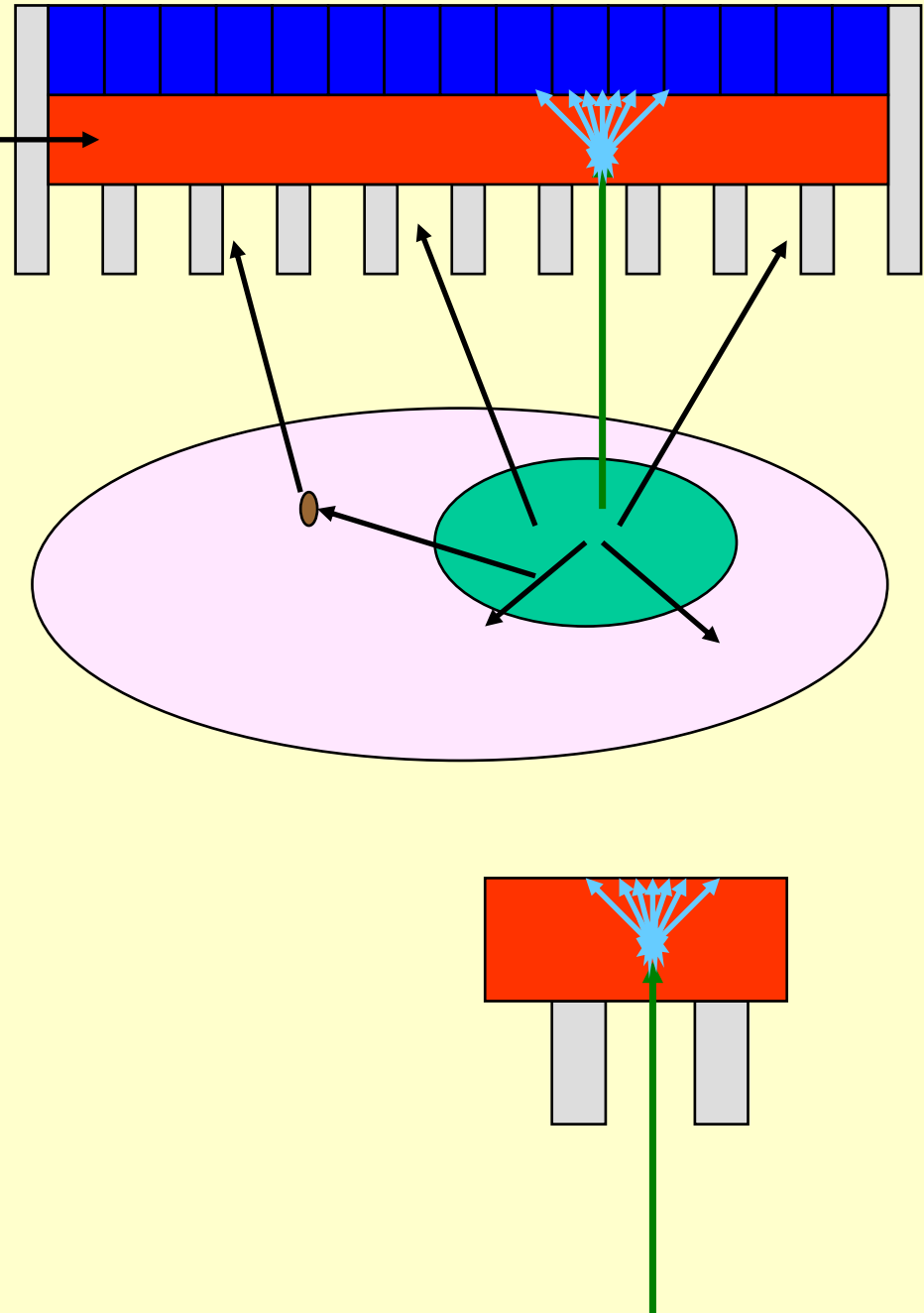
Scintillation crystal

NaI(Tl)

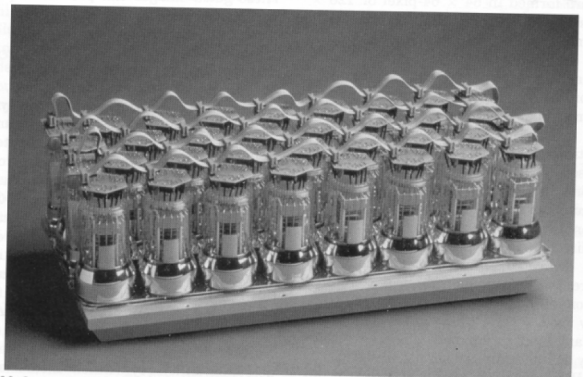
Sufficient detection efficiency
photons of 150 keV, $\mu \sim 2.2$ 1/cm
10 mm thickness $\sim 90\%$ attenuation

Proper wavelength – 415 nm – for
PM photocathode

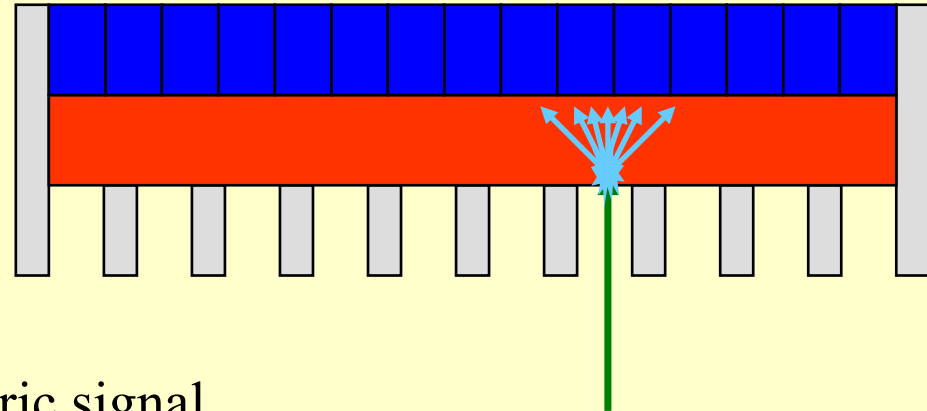
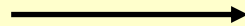
Problems with NaI:
fragile
temperature sensitive
hygroscopic



Photomultiplier tubes



13-3. A rectangular gamma camera detector with the cover removed showing the photomultiplier tubes (PMTs).

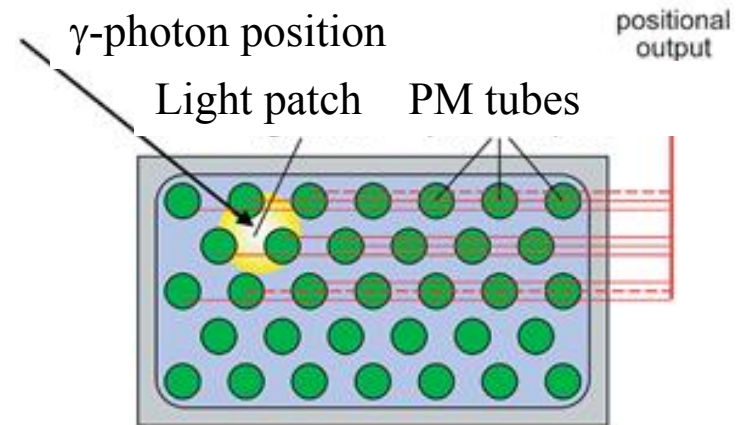


Transformation of light pulses to electric signal.

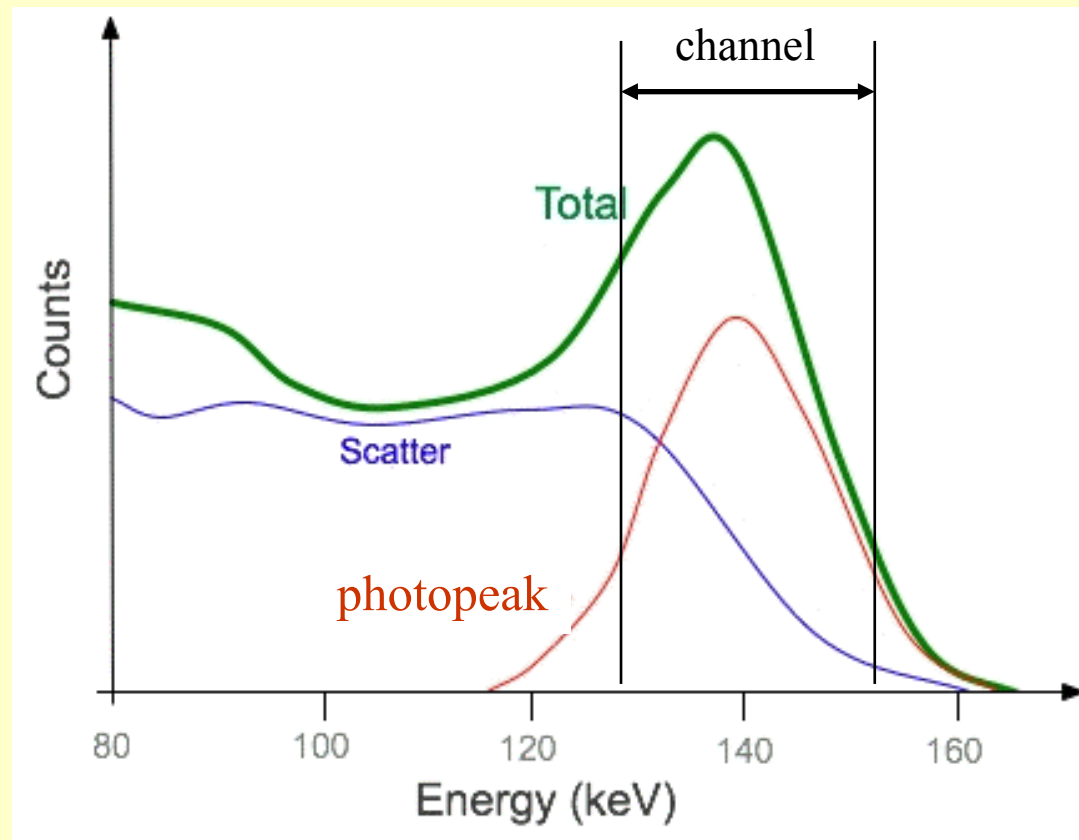
Typically 37-91 tubes, 5.1-7.6 cm diameter each

Amplitude of electric pulses varies in a wide range, because

- absorption of one γ -photon induces electric signals in more than one tubes,
- attenuation mechanism can be photoeffect and Compton-scattering.

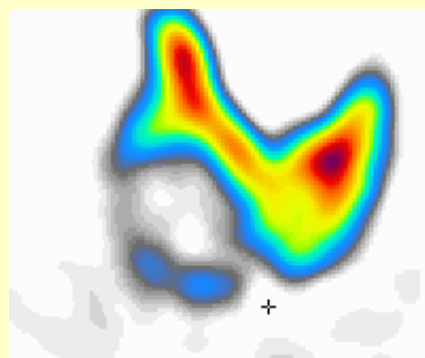
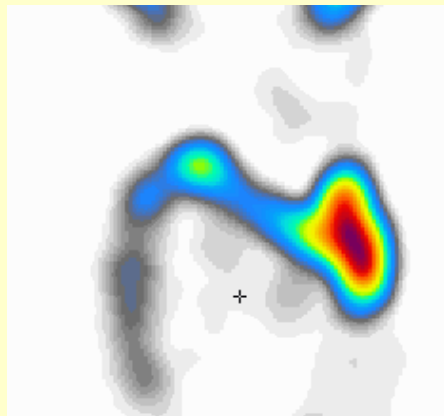
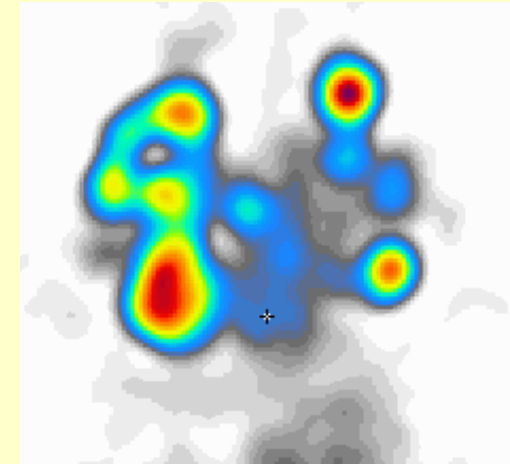
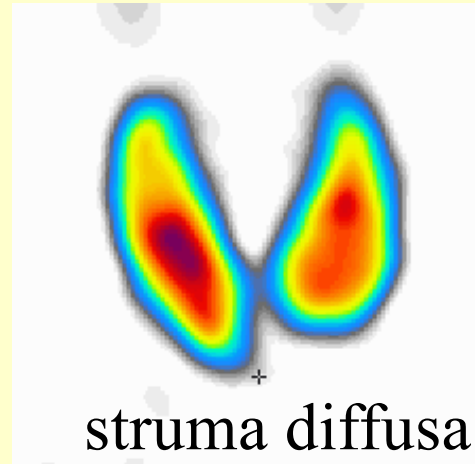
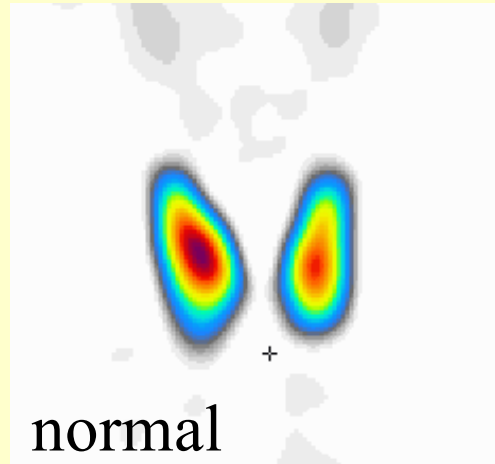


Pulse amplitude spectrum – Amplitude of an electric pulse generated by a γ -photon absorption in photoeffect is proportion to the photon energy.



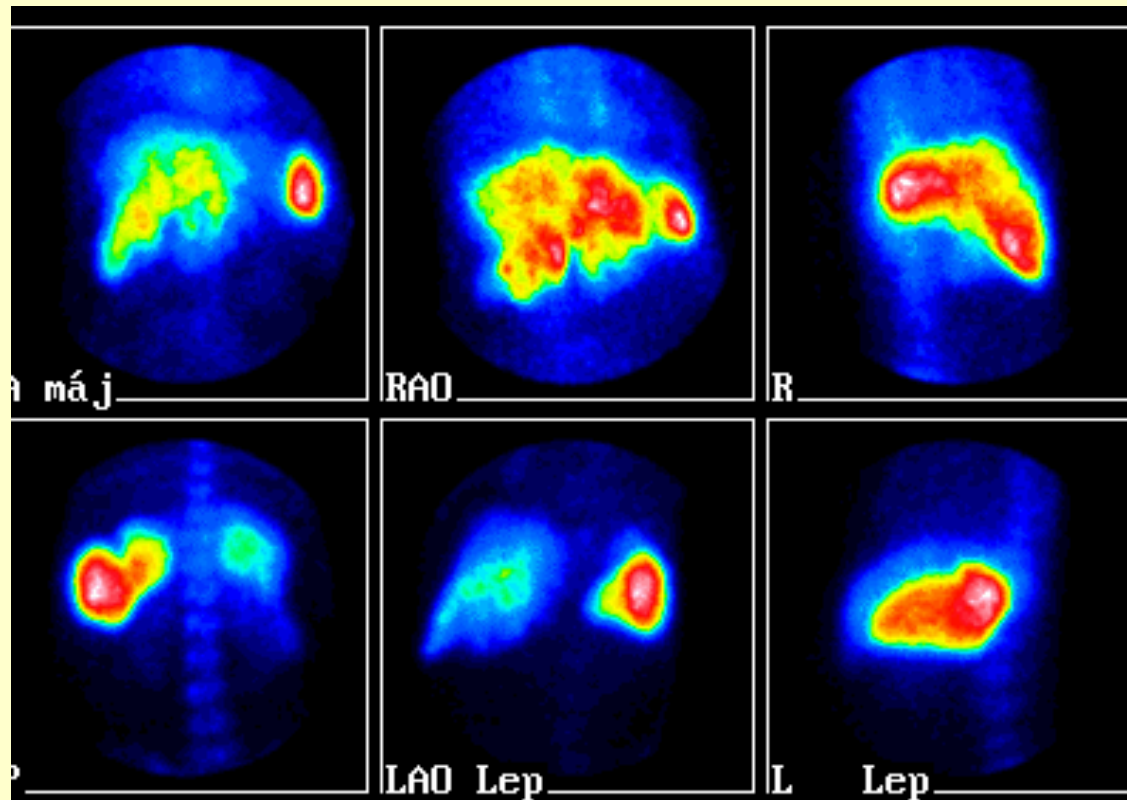
These electric pulses can be distinguished by discrimination (DD).

Pertechnetate (intravenous 80 MBq) distribution in thyroid glands



Cold nodules

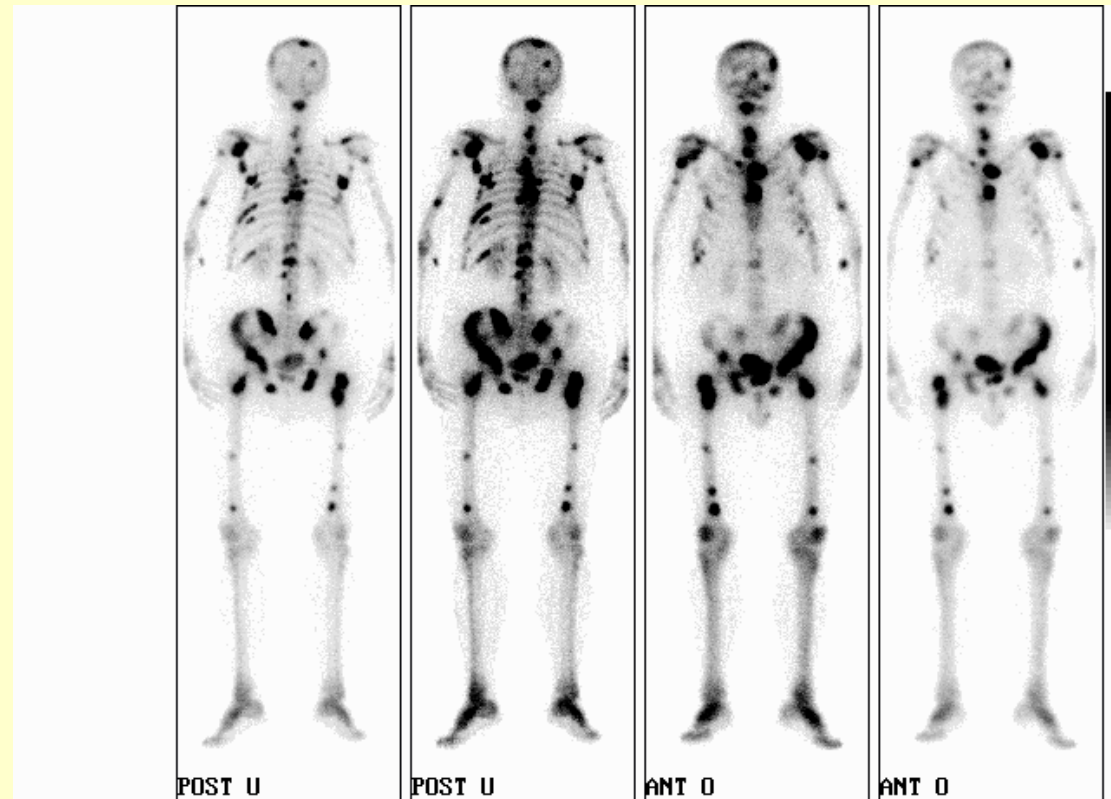
Liver lesion nodules



^{99m}Tc - fytion

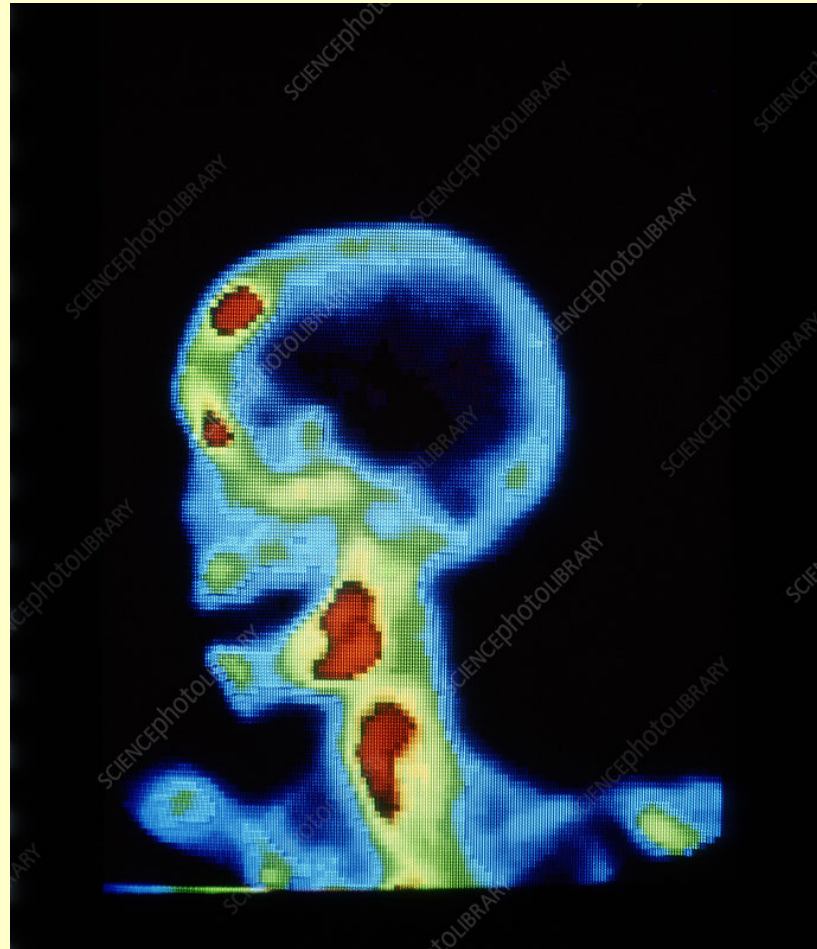
Bone scintigraphy

^{99m}Tc -MDP: 600 MBq



imaging bone metastases

Gamma camera image: summation image



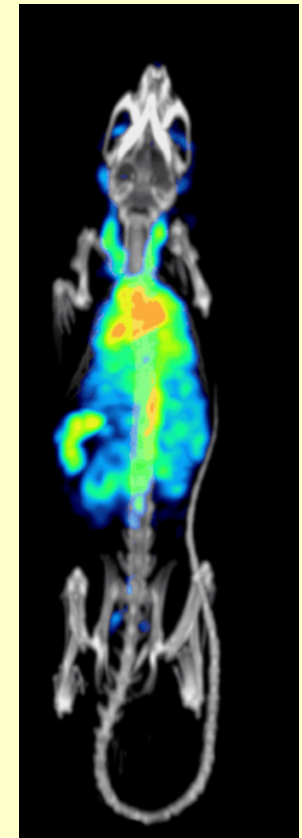
For depth / 3D resolution: tomographic device is necessary

SPECT – Single Photon Emission Computed Tomography

Tomographic application of γ -cameras – data collection in 360°

Measurement of a series of projections.

3D image can be reconstructed from projections.



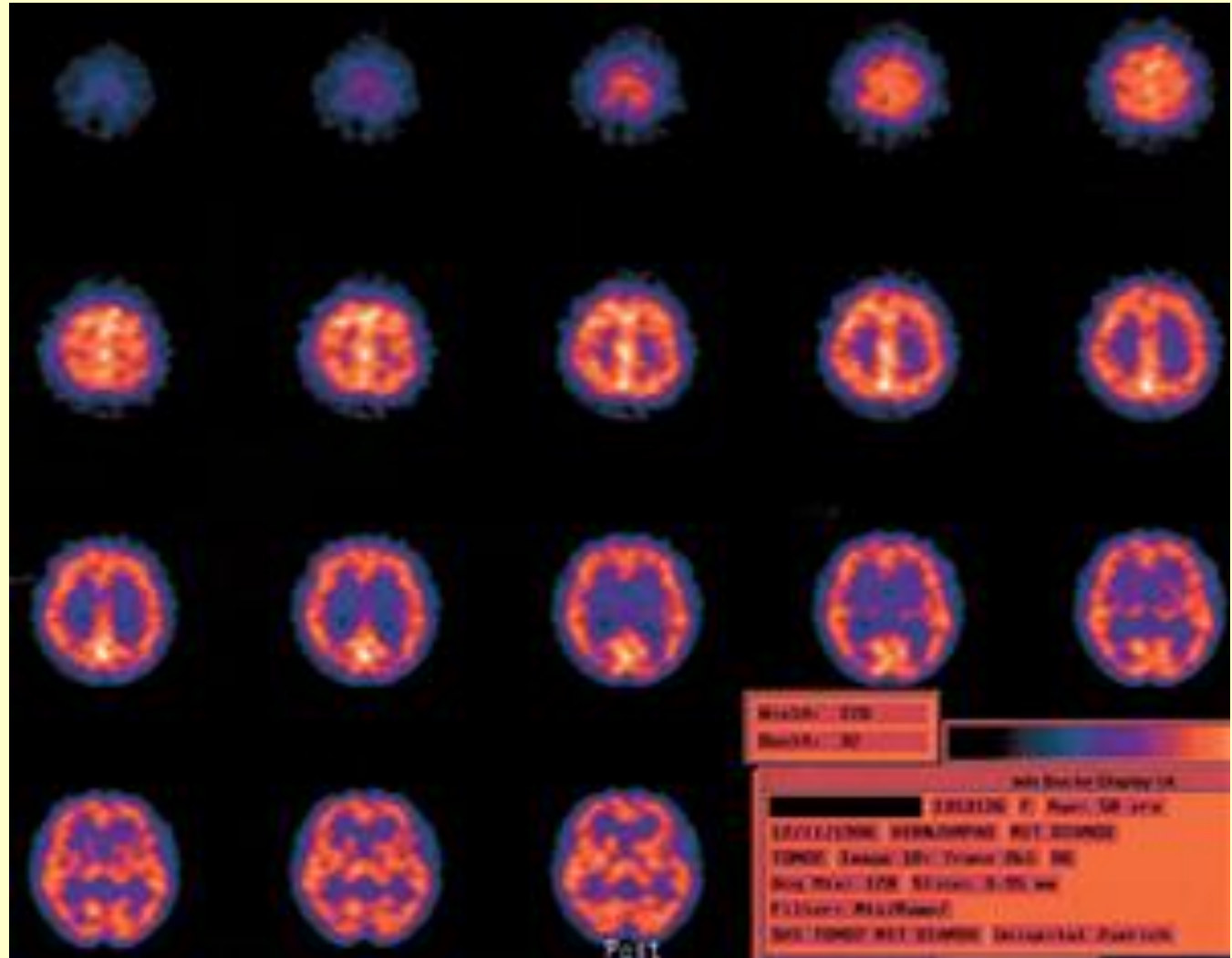
Various camera arrangements

SPECT

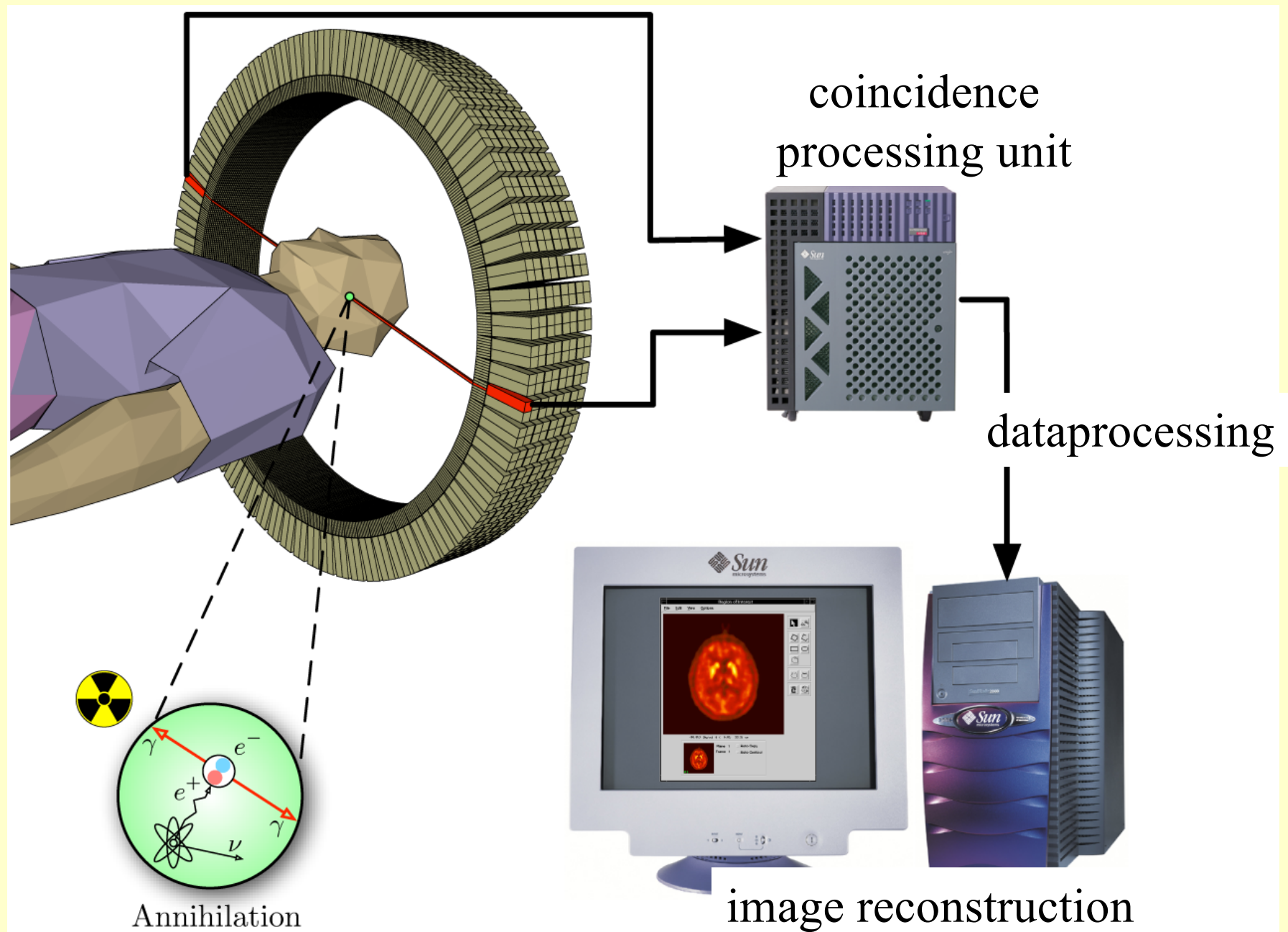


SPECT – images of scalp

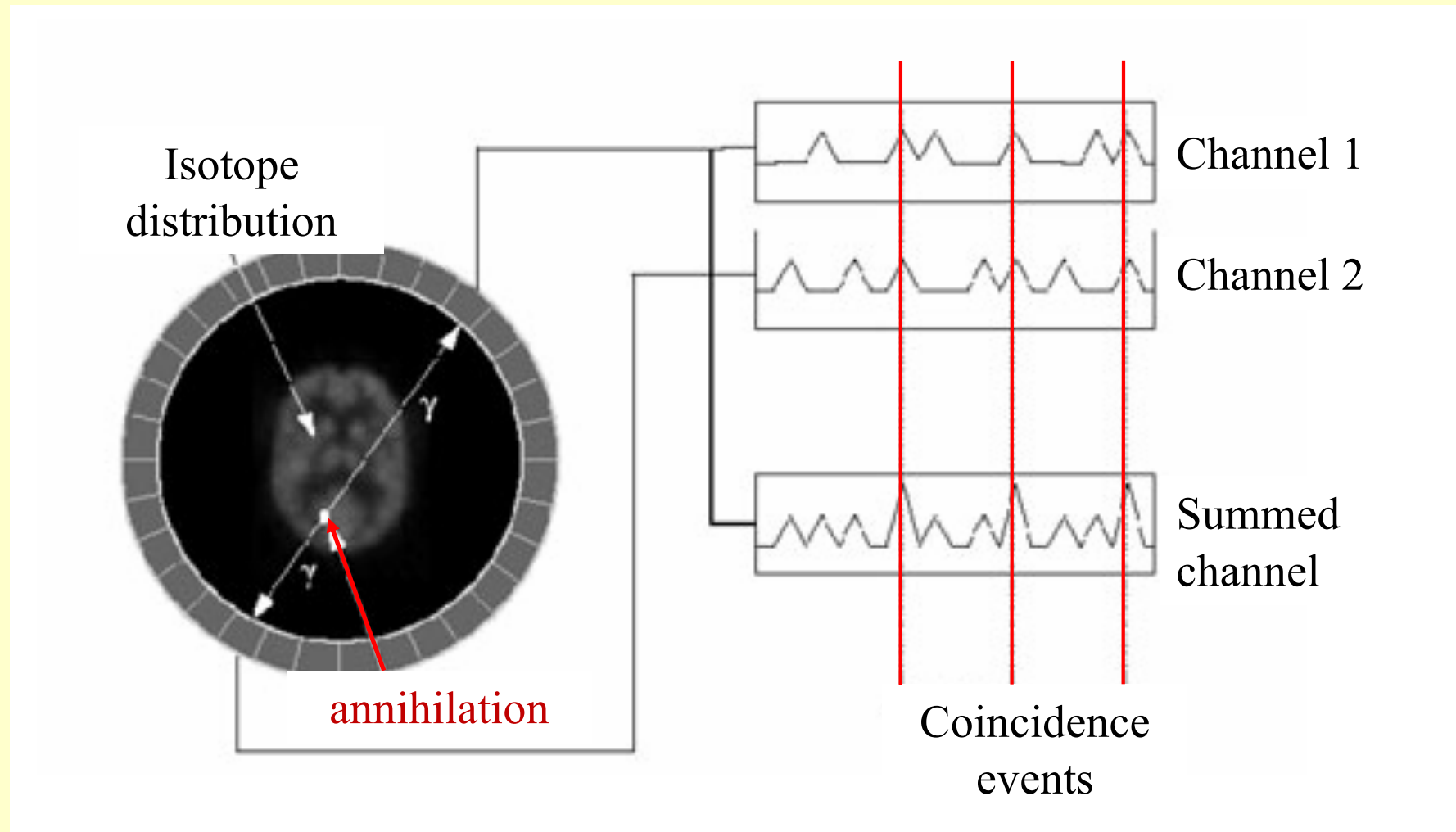
^{99m}Tc - HMPAO



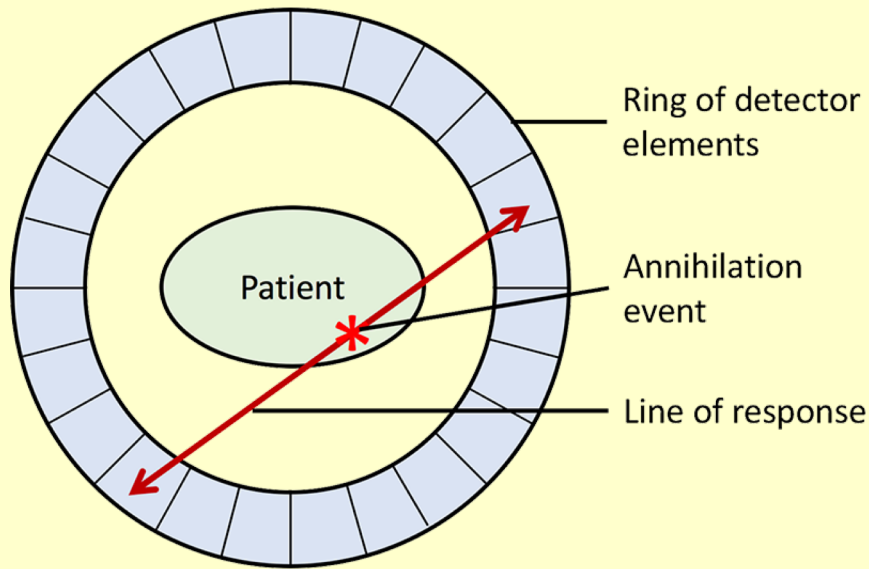
Positron Emission Tomography PET



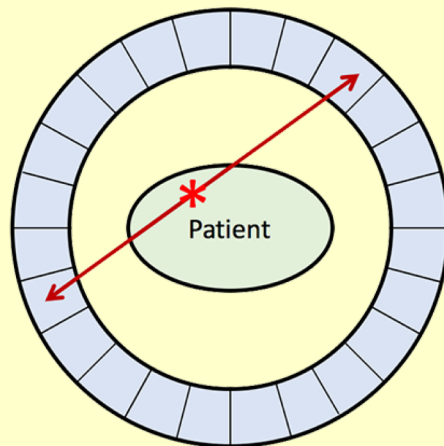
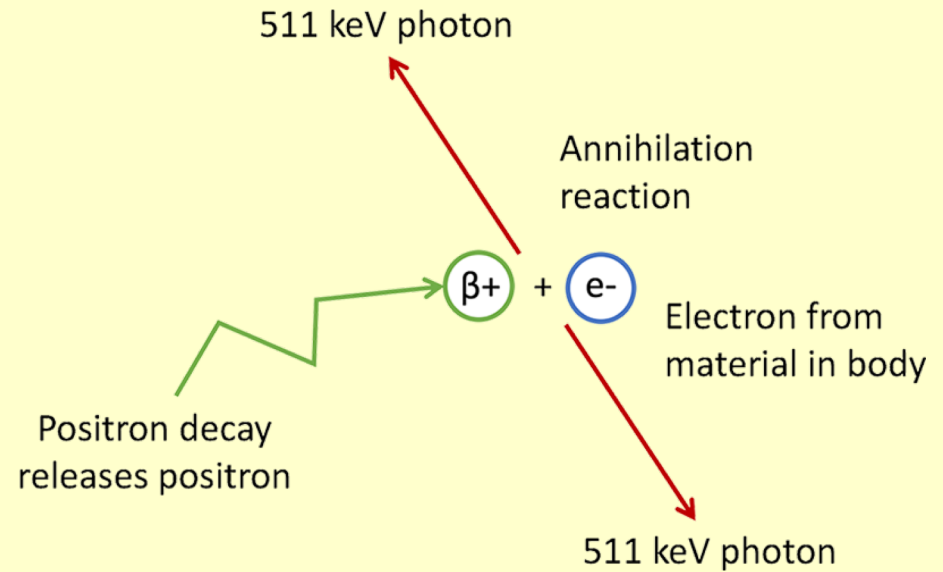
Coincidence detection



Coincidence detection

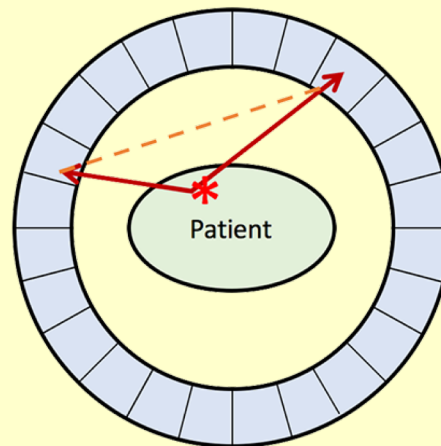


↔ Annihilation path
 - - - - - Calculated line of response



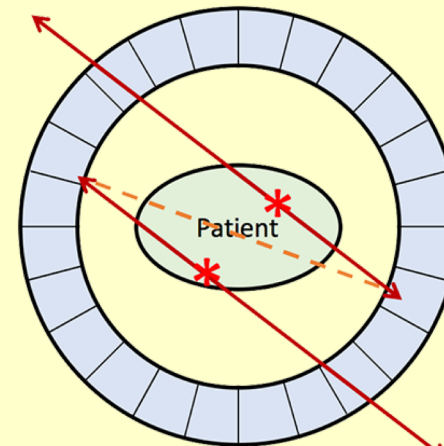
True coincidence

- One annihilation
- Straight path photons in opposite directions



Scatter coincidence

- One annihilation
- Photons scatter
- Measured line of response places annihilation reaction along artefactual projection

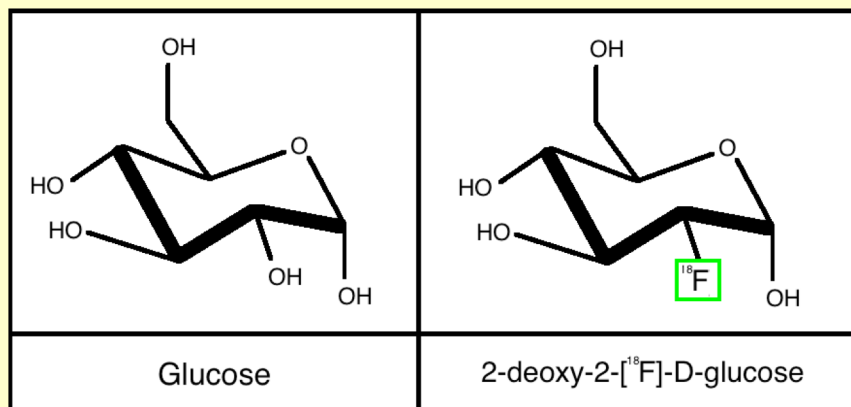


Random coincidence

- More than one annihilation
- Photons from different annihilations are detected simultaneously
- Artefactual line of response calculated

The most frequently used radionuclides in PET are radioisotopes of common elements in organic molecules.

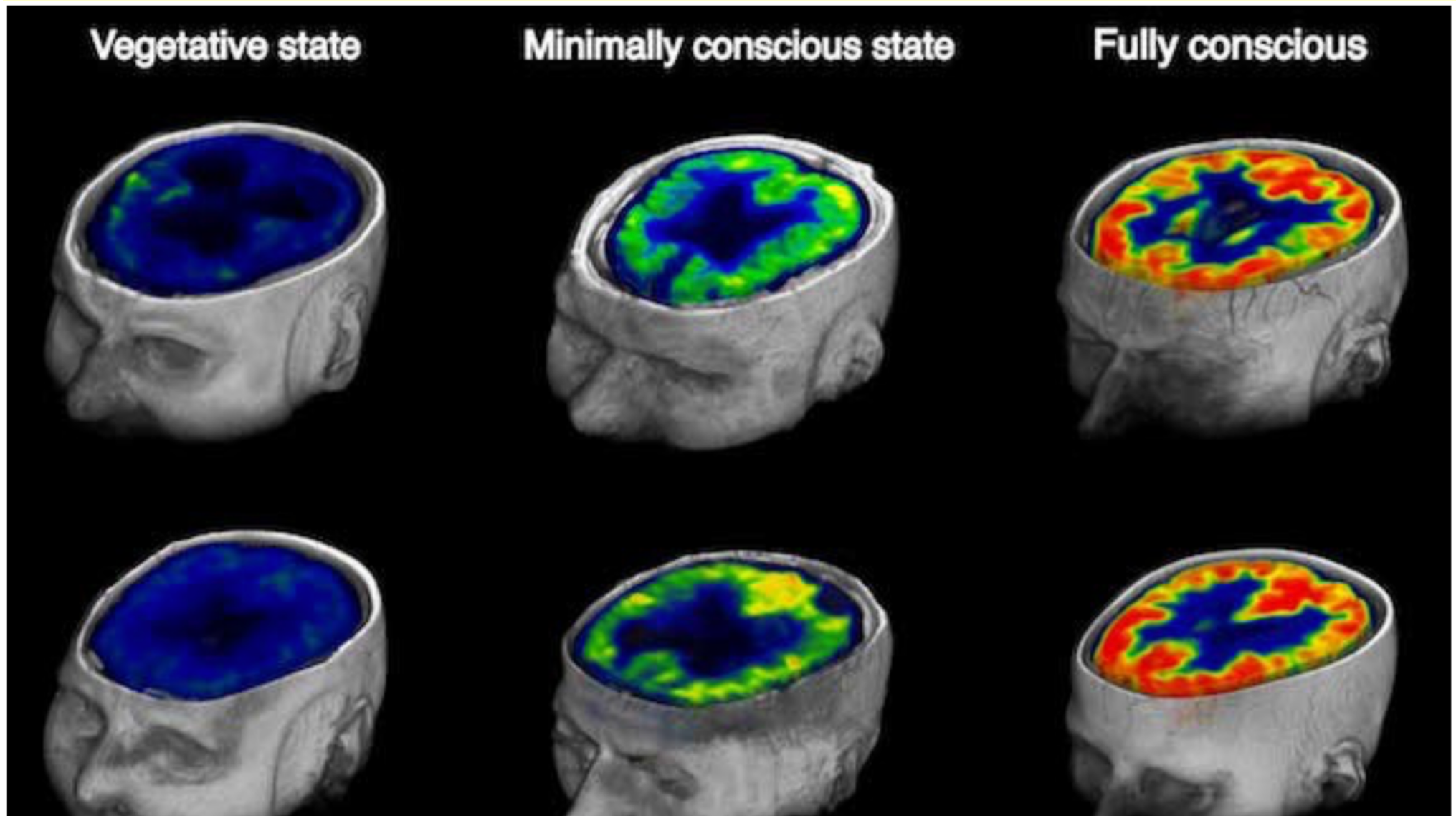
Isotope	β^+ energy (MeV)	β^+ range (mm)	1/2-life	Applications
^{11}C	0.96	1.1	20.3 min	receptor studies
^{15}O	1.70	1.5	2.03 min	stroke/activation
^{18}F	0.64	1.0	109.8 min	oncology/neurology
^{124}I	2.1350/1.5323	1.7/1.4	4.5 days	oncology



Isotope manufacturing must be nearby the site of application (see half-lives).

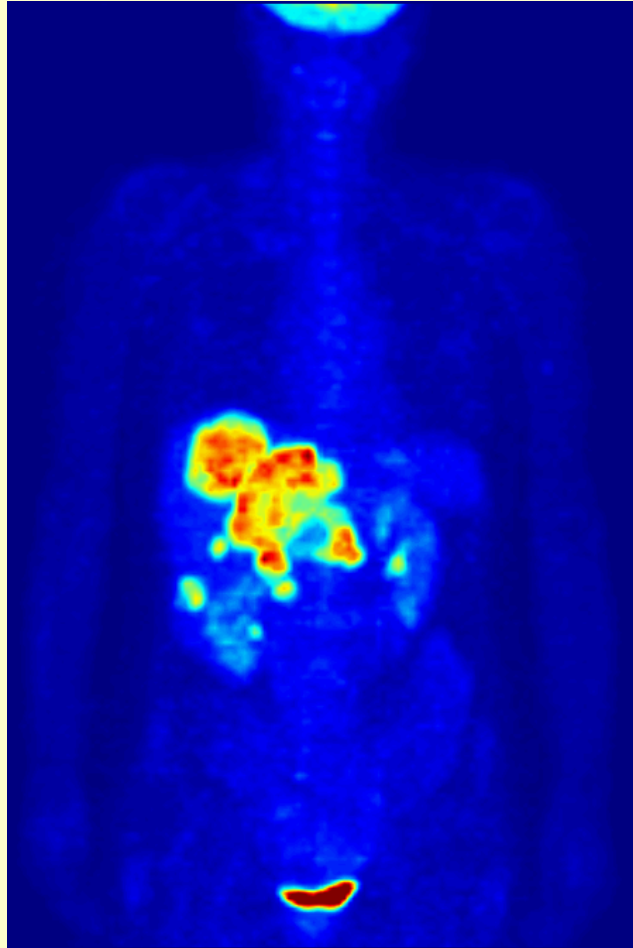


$[^{18}\text{F}]$ -fluorodeoxyglucose (FDG) – showing glucose metabolism



Global cerebral metabolic rate of glucose as an indicator of consciousness. 42% of normal cortical activity represents the minimal energetic requirement for the presence of conscious awareness (middle).

[^{18}F]-fluorodeoxyglucose (FDG) – showing glucose metabolism



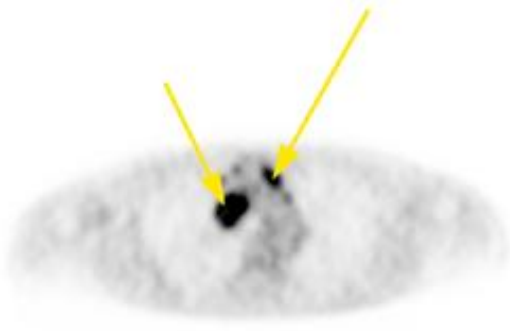
3D reconstruction of tissue metabolic activity from a [^{18}F]-FDG PET scan. Notably, we see increased activity along the chest walls, indicating carcinoma, as well as the supraclavicular fossa.

Information like this cannot be obtained from a regular CT scan, and is thus invaluable to many specialties, particularly oncology and neurology

PET/CT

Combination of structural and functional imaging

A.



B.



C.



Radiotherapy

Which radiation is the best?

What is the optimal dose of radiation?

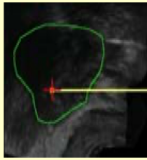
What is the best technique for generating radiation?

Irradiation selectivity – protection of healthy structures?



Radiotherapy

α



Internally deposited radioactivity

β^-

Linear ion density:

e^-

the amount of ion pairs in a line generated in a unit distance (n/l)

γ

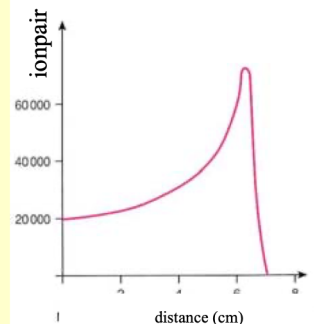
LET (Linear Energy Transfer : the energy transferred to the material surrounding the particle track, by means of secondary electrons. ($nE_{ionpair}/l$)

Rtg,

p

n

In the air: $E_{ionpair} = 34 \text{ eV}$



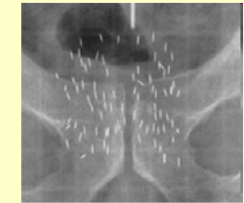
α

Particle energy is not optimal

β^-

continuous energy spectrum

typical energy: few MeV



Internally seeded radioactivity

e^-

accelerated electron - 10-20 MeV

γ

production: linear accelerator

Rtg,

Efficient distance! $\approx 1 \text{ cm}/3 \text{ MeV}$

p

In the practice 6-21 MeV \Rightarrow 2-7 cm

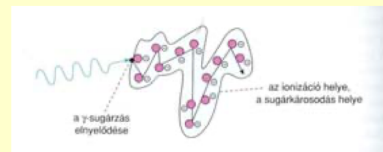
n

treatment of superficial tumours

γ : external radiation source

Site of absorption \neq sites of ionization = site of radiation damages

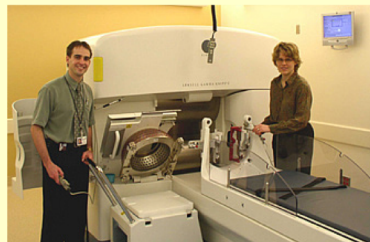
Penetration distance
is energy dependent



γ -knife: focused dose of radiation

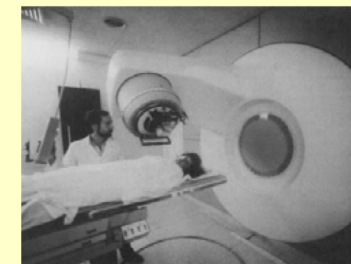
about 200 portals in a specifically
designed helmet

e.g., ^{60}Co $E_\gamma \approx \text{MeV}$,
about TBq activity



Treat tumours and lesions in the brain

X/ray:



The X-rays are generated by a linear accelerator .

Few MeV photon energy.

Radiotherapy



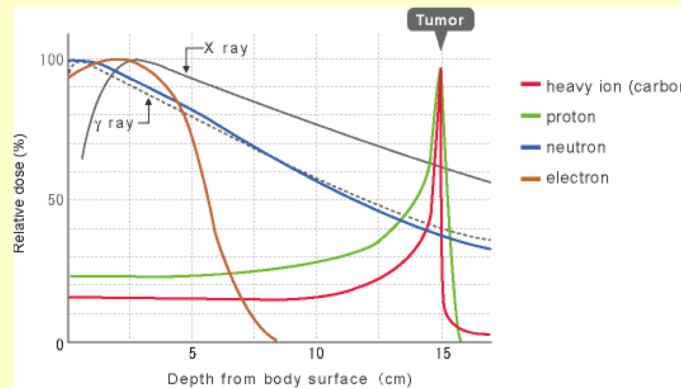
Would be ideal, but very expensive!

γ ,

Rtg,

p :

n



LET	Radiation	Energy(MeV):	LET(keV/ μ m):
high	α – particles	5.0	90
	fast neutrons	6.2	21
	protons	2.0	17
low	X-rays	0.2	2.5
	60-Co γ -radiation	1.25	0.3
	β – particles	2.0	0.3
	accelerated electrons	10.0	

Cheklist

Selection rules of radioactive markers

- physical parameters
- biological and pharmacological characteristics

Information provided by isotope diagnostics

Types of isotope diagnostic images

- static pictures
- dynamic pictures

Gamma-camera, SPECT

Physical concept of PET

PET scanners – coincidence detectors

Radiotherapy, gamma-knife, LET

Damjanovich, Fidy, Szöllősi: Medical biophysics

II. 3.2.3

3.2.4

3.2.5

VIII. 3.2

VIII. 4.4

IX.3