Nuclear medicine: scintigraphy, SPECT and PET

Outline

Nuclear medicine

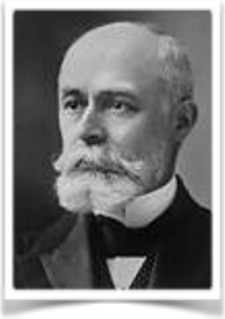
- Radioactivity
- How to use radioactivity for diagnosis
- Interaction of γ-rays with body
- Clinical applications: oncology, cardiology
- Similarities/differences with radiography

Imaging modalities

- Planar scintigraphy
- Single Photon Emission Computed Tomography (SPECT)
- Positron Emission Tomography (PET)

The discovery of radioactivity

- 1896: **Henri Becquerel** provided evidence of radioactivity
  - He was studying x-rays (discovered in 1895) with fluorescent minerals (*potassium uranyl sulfate*)
  - *Exposed uranium to sunlight* and placed it on photographic plates, believing it absorbs the sun's energy and then emits it as x-rays



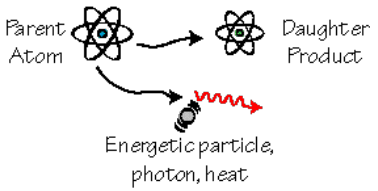
  - *By chance*, he developed the films also on a *cloudy day*…and images were bright!
  - He discovered that *uranium emitted radiation* without an external source of energy

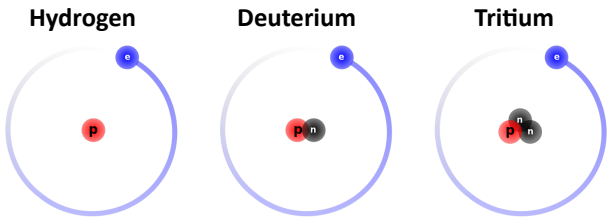
- *1898*: **Pierre & Marie Curie** develop the theory of radioactivity
  - Scientific community little interested by Becquerel's discovery, but the Curies were very inspired by this "*radiation phenomena*"
  - Discovered two new chemical elements – *radium* and *polonium*

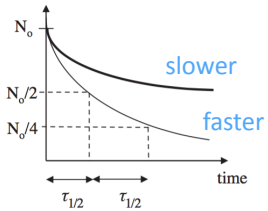
- *1903*: jointly awarded for **Nobel Prize in Physics**

What is radioactivity? (1/2)

- Radioactive decay (a.k.a. radioactivity) is the process by which **an unstable atomic nucleus loses energy** by emitting radiation
  - **Isotope** = variant of a chemical element that differ in neutron number (same element, different atomic mass)
  - This makes the **nucleus unstable**, leading to spontaneous **changes in its composition**
  - Results in **emission of radiation**
  - Usually measured by **half-life time**





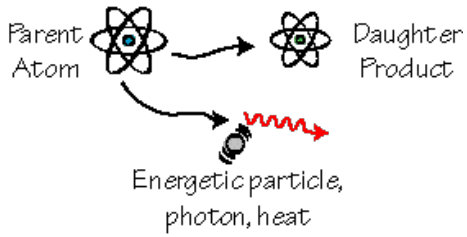


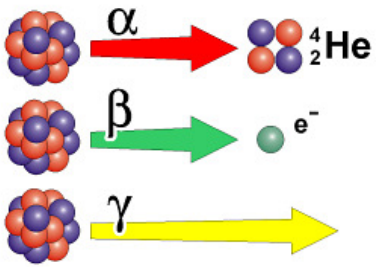
- **Common radioactive isotopes** used in nuclear medicine

Radiotracer	Half-life (hours)	γ-ray energy (keV)	Clinical application
^{99m}Tc	6.0	140	various
^{67}Ga	76.8	93, 185, 300, 394	tumour detection
^{201}Tl	72	167, 68–82 (X-rays)	myocardial viability
^{133}Xe	127.2	81	lung ventilation
^{111}In	67.2	171, 245	inflammation

What is radioactivity? (2/2)

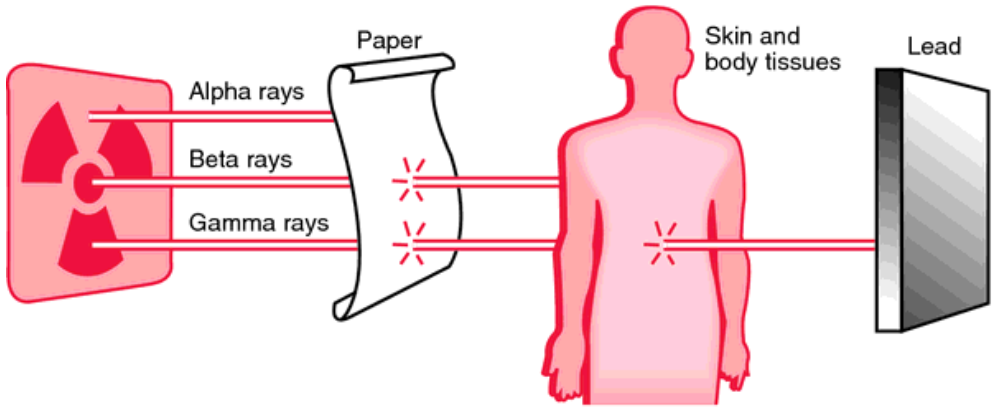
Three **major decay processes**





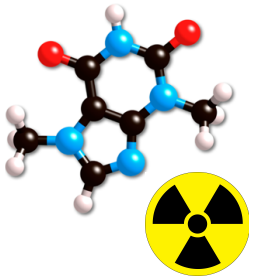
- **alpha** : nucleus ejects an helium particle
- **beta** : nucleus emits an electron or positron + a neutrino
- **gamma** : emission of γ-rays = *high energy photons*

Only γ-rays useful for **diagnostic imaging**

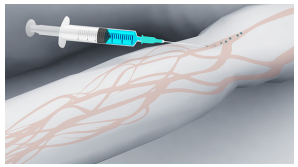


Basic principle (1/2)

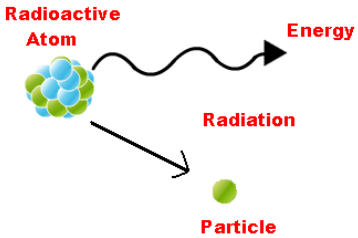
- Use of **radioactivity** for the **diagnosis of disease**



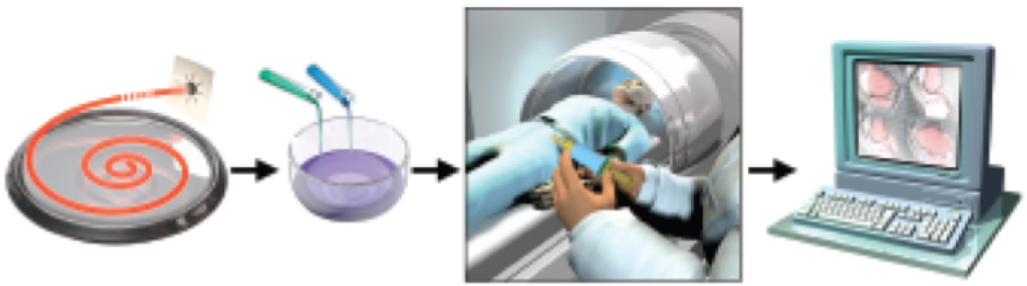
1. A radioactive isotope is "**attached to a molecule**" which has a *specific biological effect/function* in the body (**radiotracer**) (usually *glucose*)



2. Very small amount of this radiotracer is **injected into patient** (usually *nanogrammes*)
3. Radiotracer **accumulates** in specific organs

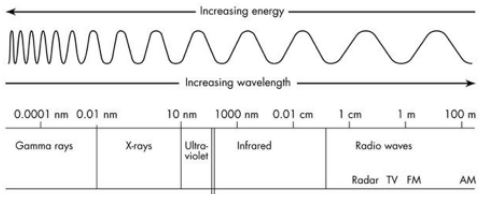


4. Decay of the radiotracer **produces γ-rays** (high energy *photons*)
5. These γ-rays **pass through (and exit) the body** and can be collected by **detectors around the body**
6. **Reconstruction** gives the position of these *accumulation sites*



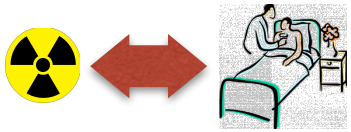
Basic principle (2/2)

Notes

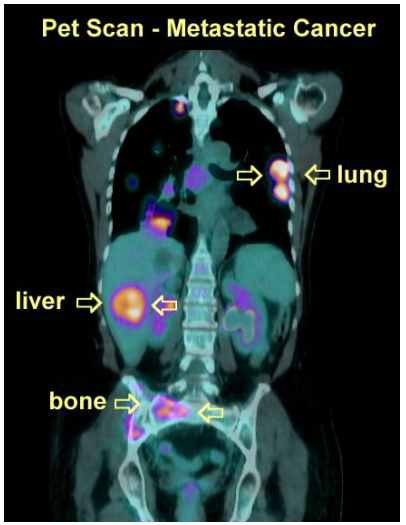


- **Ionizing radiation**
  (like x-rays but more energetic)
- Provides functional information about the body, so it represents an **important complement to other modalities** (CT, MRI etc)
- Extremely high **sensitivity**
  (able to detect nanograms of radiotracer)
- Extremely high **specificity**
  (no natural sources of radioactivity in the body)

How can this help patients?



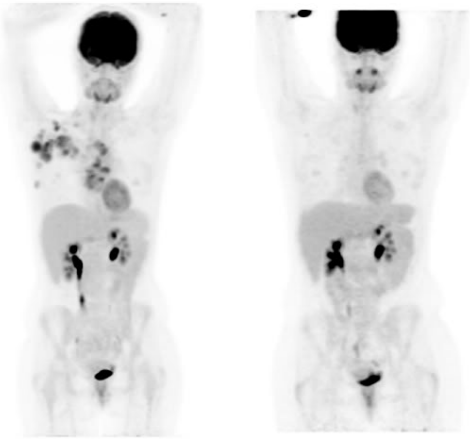
- Determine *extent or severity of the disease*
  (including whether it has spread elsewhere in the body)
- Determine the patient's *response to specific drugs*
- Monitor *disease progression* and adapt treatment
- …



Clinical applications

Oncology

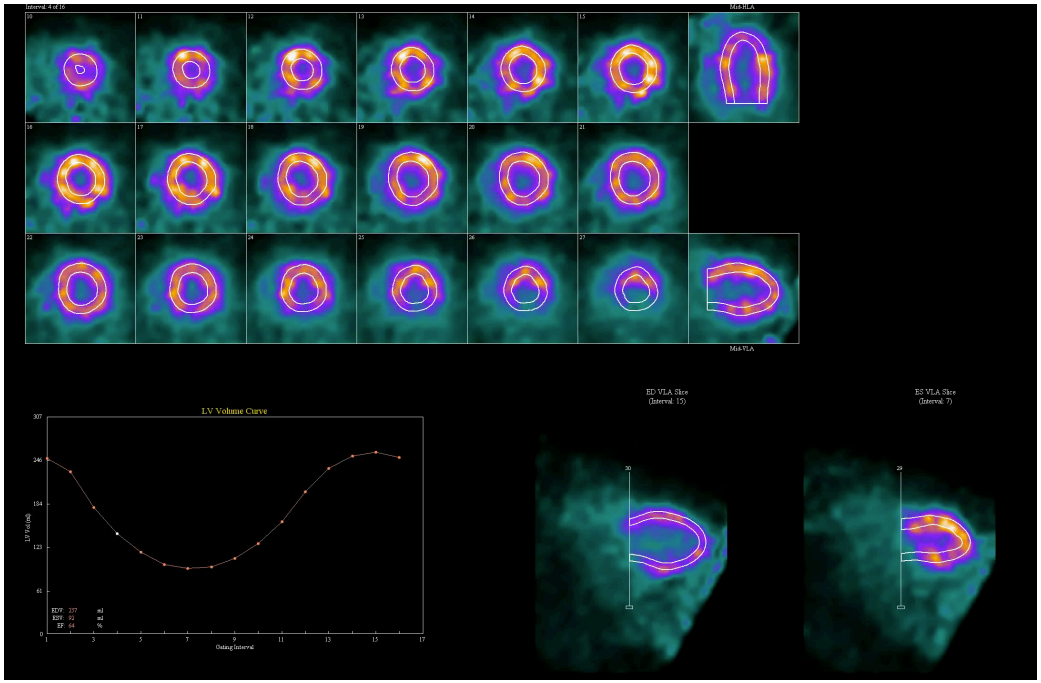
- Radiotracer is attached to **glucose**
- **Cancer cells are highly metabolic** and rapidly synthesize the radioactive glucose
- **Abnormal locations** with high radioactivity may represent the presence of such cancer cells



Before treatment **After** treatment

Cardiology

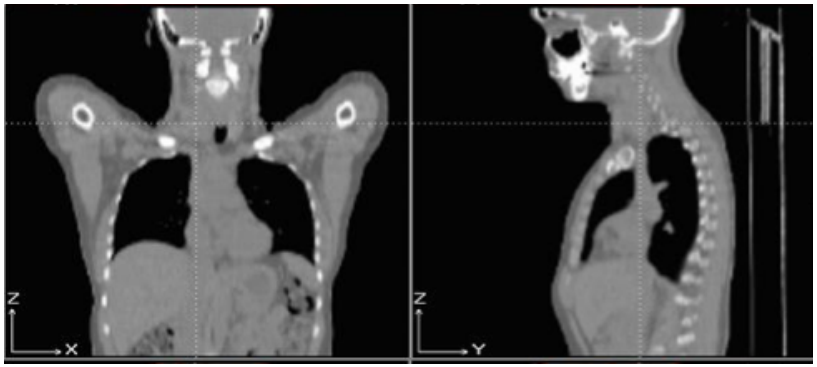
- Study **perfusion**, i.e. *blood passage* in the circulatory system, to diagnose *Coronary Artery Disease* (CAD)
- Characterize the **damage to the heart muscle** after an heart attack
  - a specific radiotracer accumulates in the *mitochondria* present in the heart muscle
  - possible to evaluate volumes etc



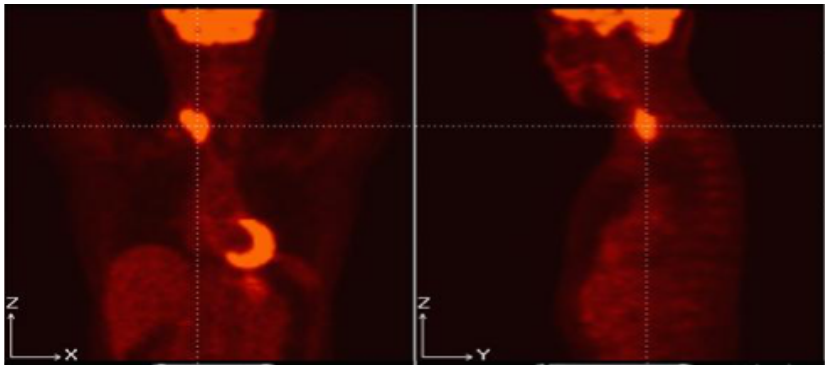
Similarities/differences with radiography (x-ray/CT)

Functional vs structural

- Images represent the **physiology/metabolism** (functions) of the organs



radiography = **morphology**



nuclear medicine = **physiology**

Location of radiation source

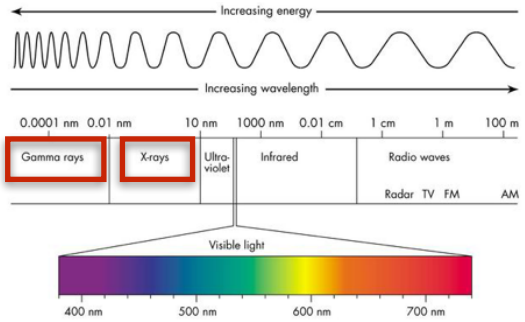
- **Radiography** : x-rays transmitted from **outside** the body
- **Nuclear medicine** : γ-rays propagate from **inside** the body

Other than that

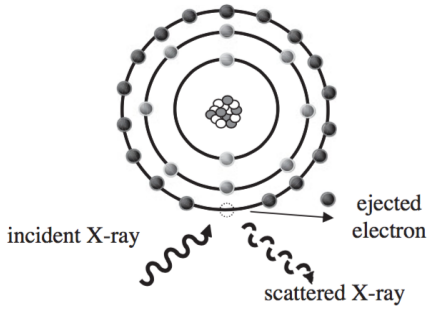
- Image formation/reconstruction are **very similar**, so…
- …most of what we've seen before can be re-applied here!

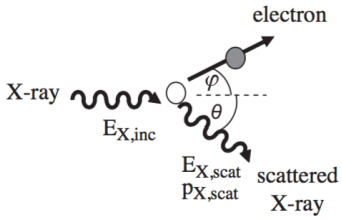
Interaction of γ-rays with body

- Both *γ-rays* and *x-rays* are **high-energy photons**
  - Difference in the way they are *produced*
  - Difference in *wavelength/energy*

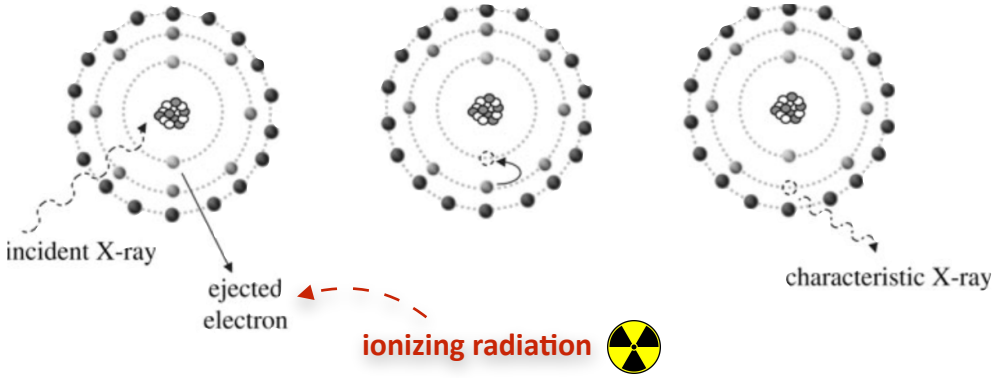


- Same interaction as x-rays
  - Compton scattering





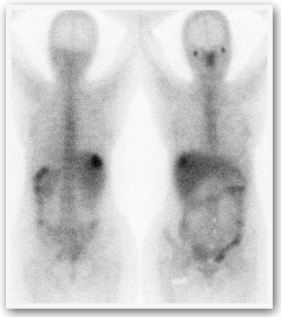
  - Photoelectric effect

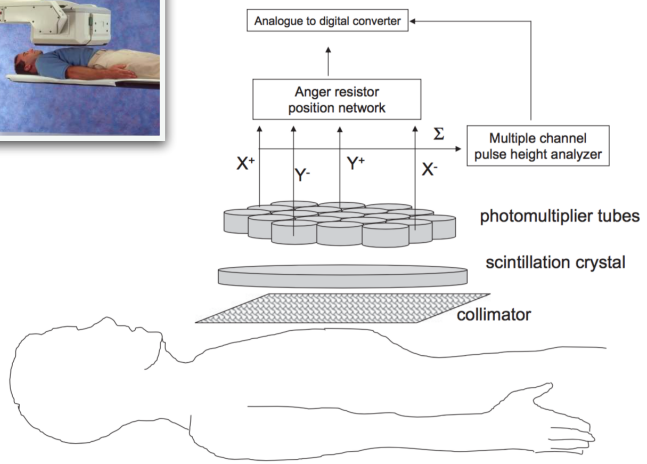


Imaging modalities (1/3)

Planar **scintigraphy**

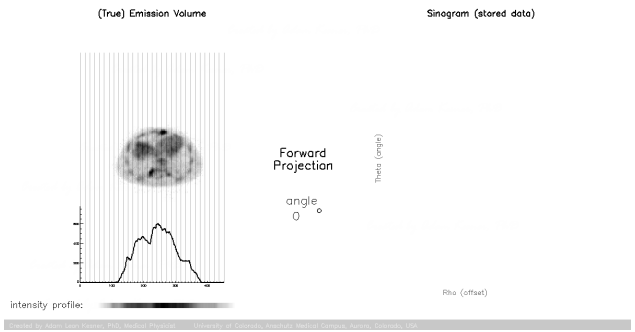
- Equivalent to *planar radiography* (x-rays)
- Detectors (*gamma camera*) count number of γ-rays emitted
- Images are *2D*

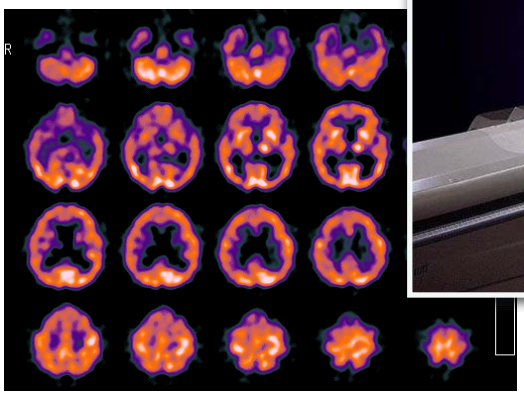


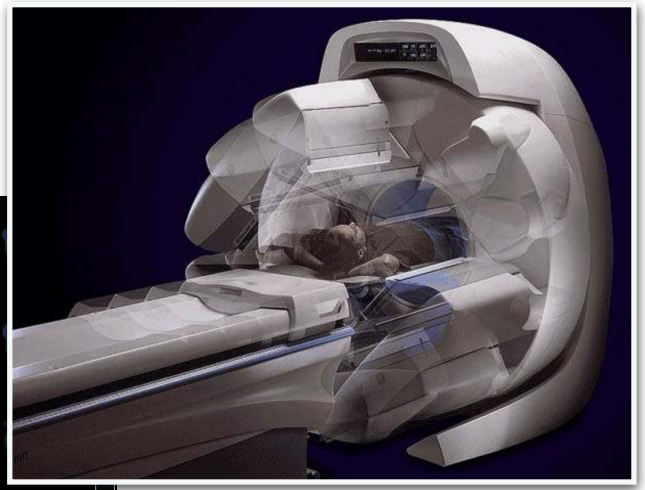


Single Photon Emission Computed Tomography (**SPECT**)

- Equivalent to *computed tomography* (CT)
- Produces 3D images (slice by slice)
- Same **reconstruction** procedure



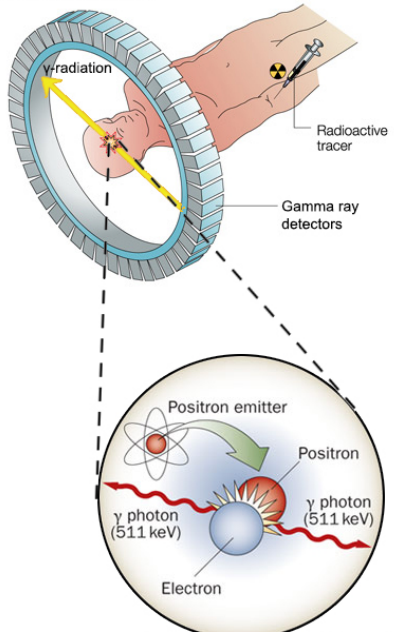




Imaging modalities (2/3)

Positron Emission Tomography (**PET**)

- PET radiotracers decay emitting a **positron**
- These positrons **annihilate on contact with electrons** in the body after traveling a short distance (≈1 *mm*)
- Annihilation forms **two γ-rays** with **opposite trajectories** (180° apart) with very high energy (511 *keV*)
- γ-rays are collected by **ring of detectors**



Comparison with SPECT

- PET has **higher SNR** (100-1000x)
  - 511 *keV* photons of PET *penetrate more* than 140 *keV* of SPECT
  - No need for collimators
- PET has **better contrast** and **spatial resolution** (2-3 *mm* vs 7-8 *mm*)
- PET radiotracers have **much shorter half-life time** than SPECT
  - Access to a local cyclotron essential
- PET equipment is much more **expensive**

SPECT

Radiotracer	Half-life (hours)
^{99m}Tc	6.0
^{67}Ga	76.8
^{201}Tl	72
^{133}Xe	127.2
^{111}In	67.2

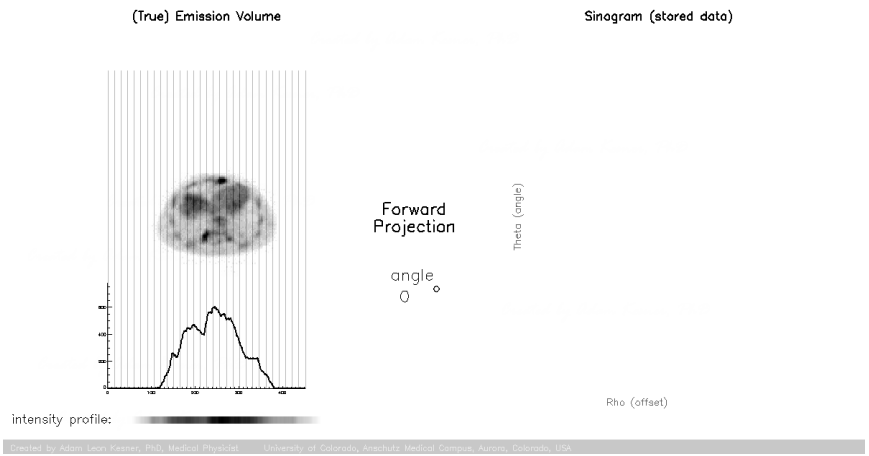
PET

Half-life (minutes)	Radiotracer
109.7	^{18}FDG
20.4	^{11}C-palmitate
2.07	$H_2{}^{15}O$
9.96	$^{13}NH_3$
1.27	$^{82}RbCl_2$

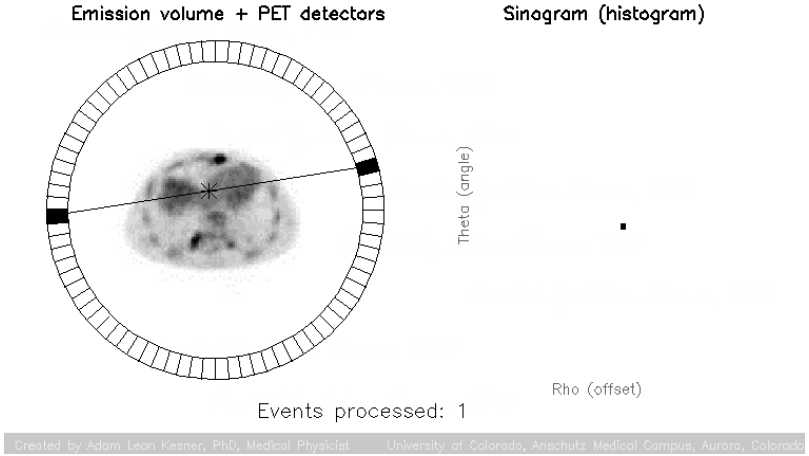
Imaging modalities (3/3)

Different way of **filling the sinogram**

SPECT

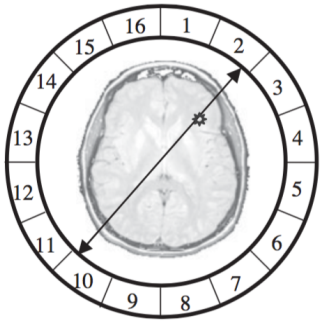


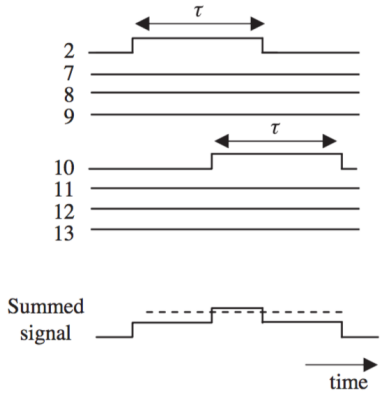
PET



Annihilation **coincidence detection**

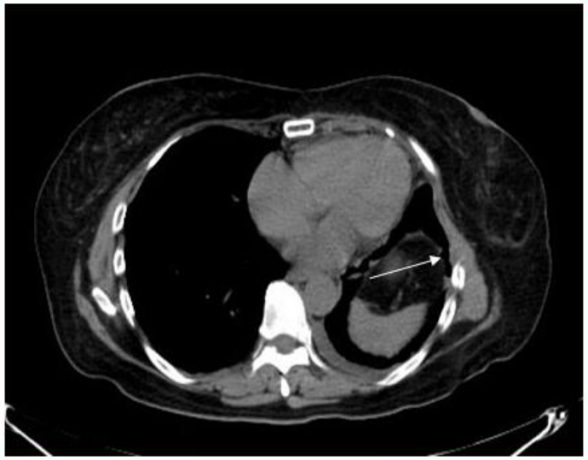
- The *two γ-rays* hit detectors at *different times*
- An *Annihilation Coincidence Detector* (ADC) register the hit time of all *γ-rays*, *i.e. time stamp*
- Two *γ-rays* **belong to the same annihilation** if:
  - fall within given "*coincidence resolving window*", e.g. 6 *nanoseconds*
  - are *compatible,* e.g. detectors 2+5 would fall outside the brain



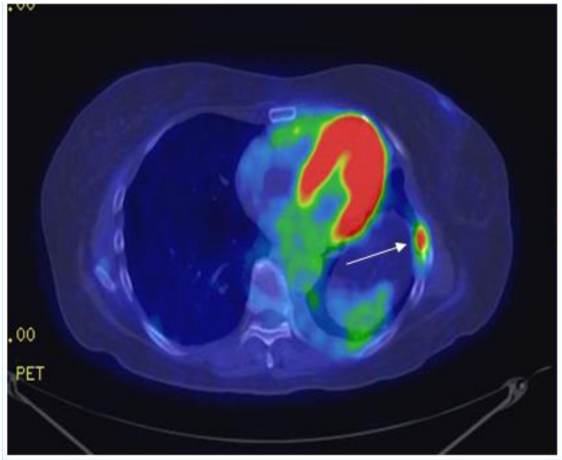


PET/CT scanners

- Get the **best from both worlds!**
  - Combines *functional information* from PET…
  - …with *anatomical location* provided by CT



CT only



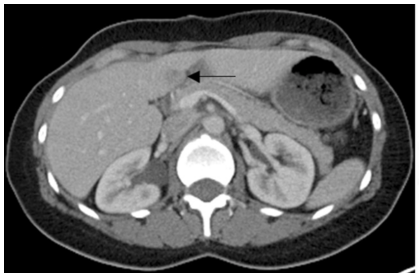
PET-CT

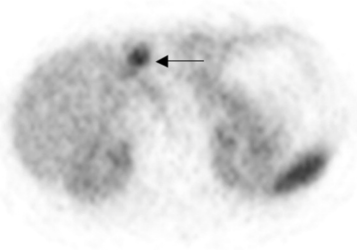
- Greater detail with a **higher level of accuracy**
  - Patient does not change position between scans ➜ no need for *registration*
  - No time between scans ➜ both images represent the *same temporal situation*

Image quality

- **Spatial resolution** is low

CT



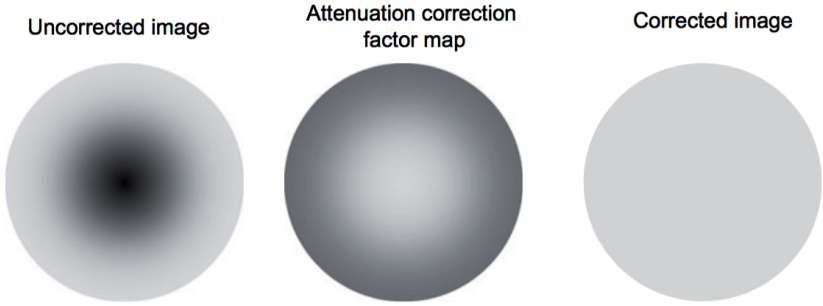


SPECT

- **SNR** is low
  - *SNR* ∝ number of detected γ-rays
  - Typically, only *0.01-0.5%* of the generated γ-ray are detected

- **CNR** is high
  - Extremely high **sensitivity** and **specificity**

- **Intensity correction** is necessary to relate *image values* to *radiotracer concentration* for "quantitative analyses"
  - **Example**
    - γ-rays located in the center of the body have to *pass through more tissue*
    - they are attenuated more than those close to e.g. the skin



Summary

Pros

- Images represent the **physiology/metabolism** of the organs
- Very high **sensitivity** and **specificity**

Cons

- **Ionizing** radiation 
- Low **spatial resolution**
- Rather **expensive**

Applications

- Oncology
- Cardiology