TG117 Workshop

Radiological Protection in PET and PET/CT

Chapter 2: Principles of PET and PET/CT

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Chapter 2: Principles of PET and PET/CT

- 2.1. PET, principles and technology
- 2.2. CT technology
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In total: 14 pages, 55 paragraphs (35-89 in current version)

The PET (coincidence) principle

Two 511 keV photons:

”Almost” on a straight line that ”nearly” contains the point of decay

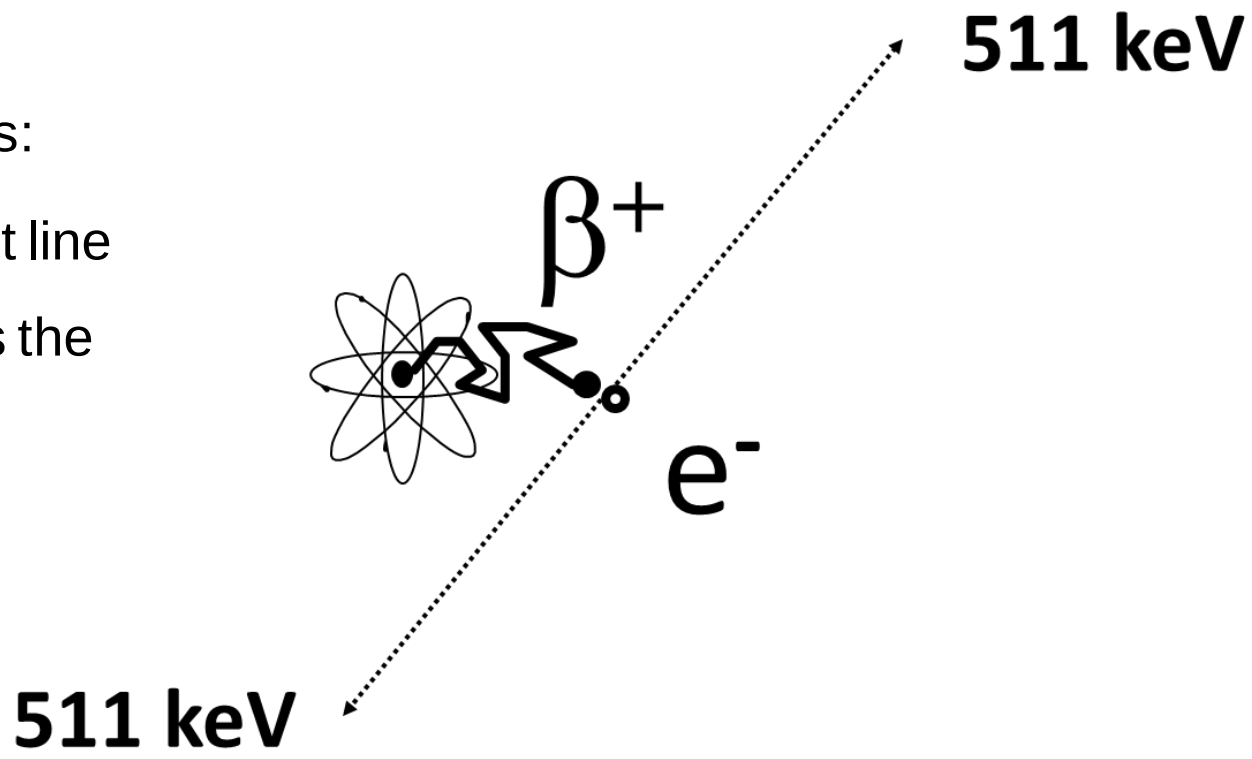
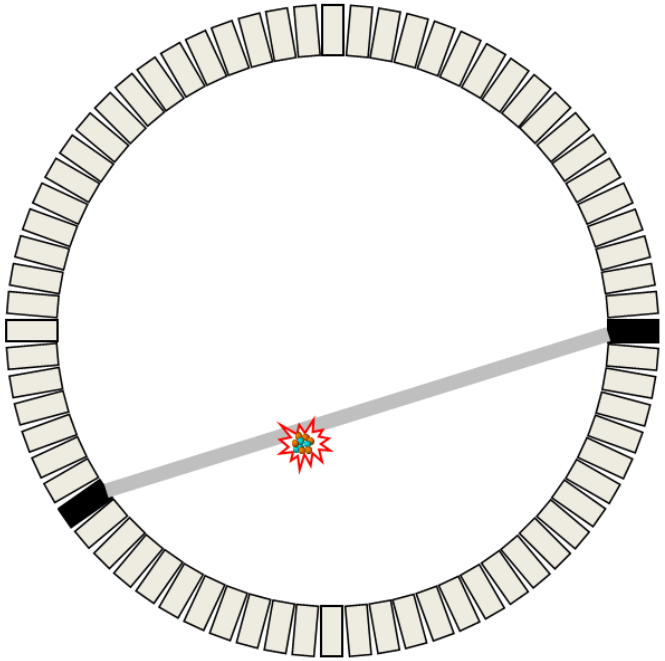


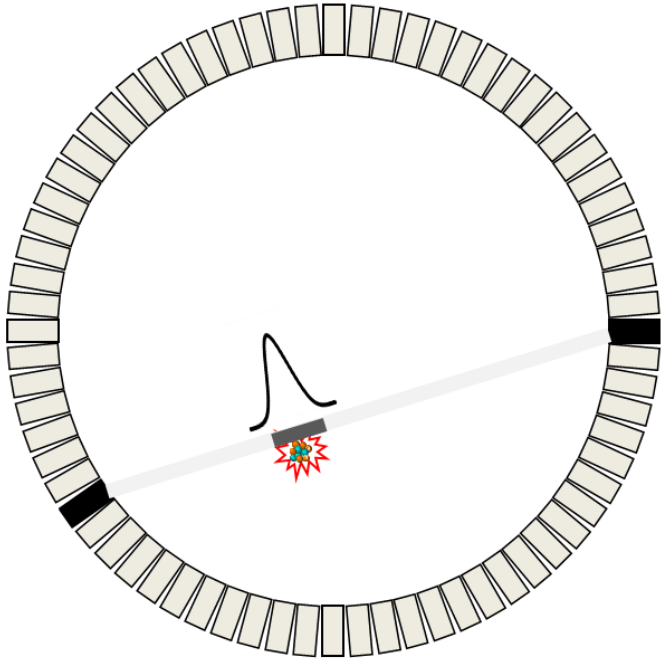
Fig. 2.1. The annihilation of the positron with its anti-particle, an electron, results in the emission of two photons of 511 keV each, almost on a straight line.

Non-TOF



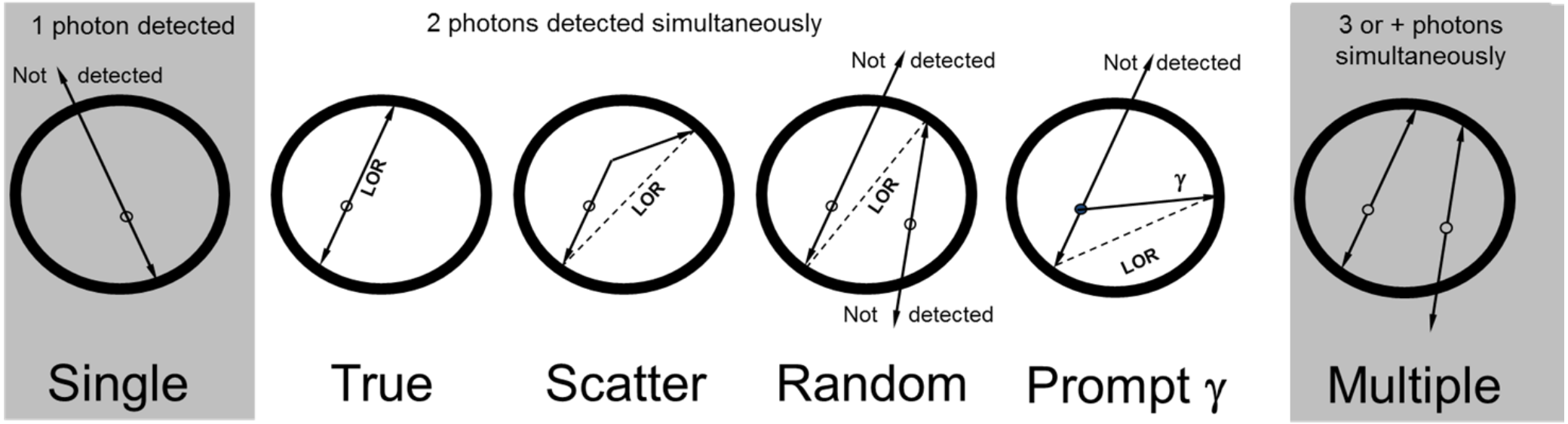
A detection within the coincidence timing window is assigned to the LOR, with uniform probability

TOF



In TOF, a position is calculated along the LOR, and the probability of the event is assigned only to a small segment of the LOR

Types of events



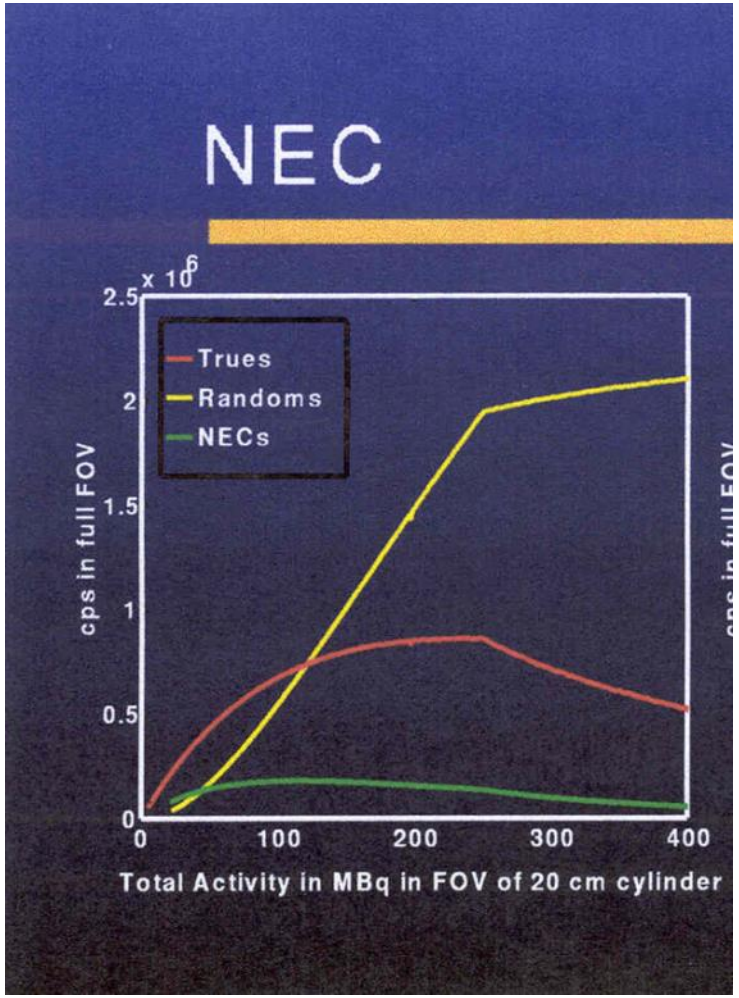
Corrections for scatter, random (and prompt gamma) adds noise to the data

Noise Equivalent Count (rate)

The NEC curve peaks at a much lower activity (concentration) than the trues rate.

Knowledge of this curve may be useful. Sometimes the value of an increase in dose is limited, or reverse: a large dose reduction may be possible with only a minor loss in ”good” counts.

In fact a compromise between throughput and doses (not only to patients, but also staff etc.)

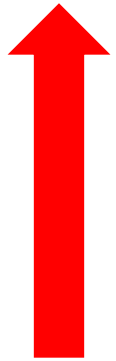


The SPECT compromise

* Figure not in publication

Smaller / longer collimator holes

SPECT with collimator



Better Resolution

(lower FWHM)

Higher image noise

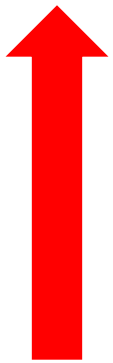
(Less counts)

The SPECT compromise

* Figure not in publication

Wider / shorter collimator holes

SPECT with collimator



Worse Resolution

(higher FWHM)

Less image noise

(more counts)

Independent improvements

* Figure not in publication

PET with
”electronic collimation”

Smaller crystals

Better Resolution

(lower FWHM)

Larger solid angle

Less image noise

(more counts)

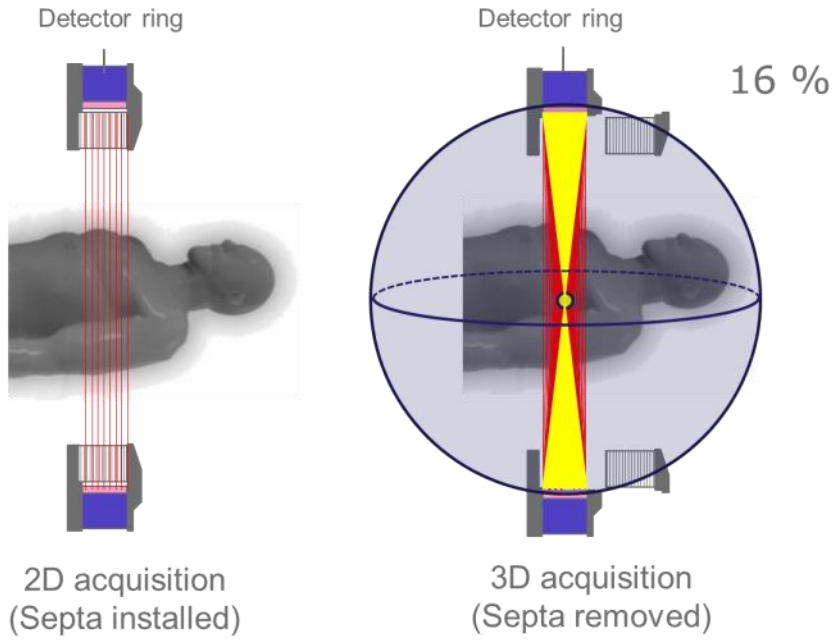
(text in publication)

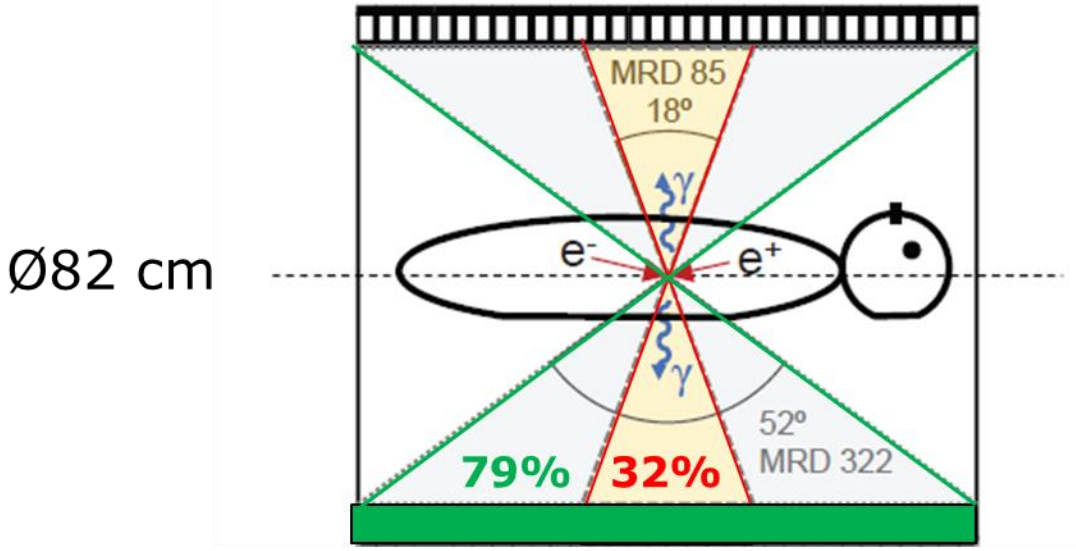
- (38) One major advantage of the coincidence principle is that sampling takes place in all directions (angles) simultaneously without the need for rotating parts or collimators. This allows for a **high detection efficiency** (sensitivity) well suited for dynamic studies, and it also means that **spatial resolution can be improved** (e.g. by smaller detection elements) **without compromising the sensitivity**. In nuclear medicine imaging outside PET, where only 'single photons' are available, imaging requires a collimator with narrow holes to define the direction of origin, and only a very limited fraction of the emitted photons can contribute to the image. Under these circumstances, any attempt to improve resolution necessarily further reduces the number of events that can reach the detector and this trade-off represents a serious limitation for dose reductions. For typical low energy collimators the detection fraction may be around **0.01%**. The similar value for PET early reached **1%** and is still increasing (see below).
- (39) Another fundamental advantage of PET is, that biologically important elements like carbon, nitrogen, and oxygen all have isotopes with positron decay (^{11}C, ^{13}N, ^{15}O), but no gamma-emitting isotopes suited for single photon detection. Due to practical limitations of half-life, labelling with ^{18}F ($T_{½}$ = 110 min) is however preferred, when possible.

Increasing sensitivity by solid angle

* Figure not in publication

Figure based on Prenosil et al. JNM 2021





LAFOV = Long Axial Field of View (system)

Sensitivity is a most important feature

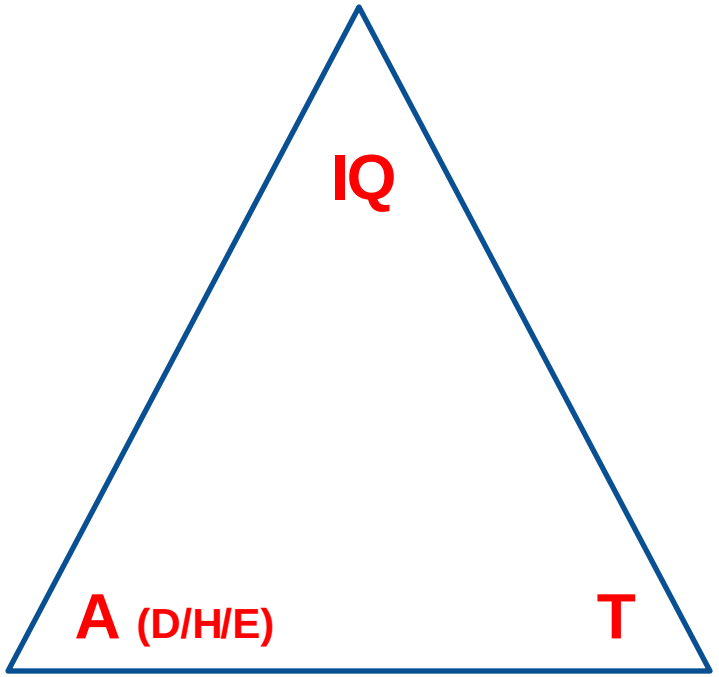
(text in publication)

(57) From a radiological protection perspective, **the most important technical improvements are those increasing sensitivity**. While higher resolution actually will require more photons to maintain a certain noise level, and better count rate performance might allow the patient throughput to be raised by increasing patient activity, the advent of '3D' and increased axial field of view also makes it possible to decrease the injected activity (patient dose) while still maintaining image quality. TOF-PET may also reduce noise by using the added position information in reconstruction, a feature sometimes (with a slightly unfortunately term) marketed by vendors as increased 'effective sensitivity'.

With higher sensitivity, you can

* Figure not in publication

Improve image quality



Reduce activity and dose

Reduce scan time

(e.g., avoid general anesthesia in small children)

(text in publication)

(62) In early CT systems, the x-ray tube heat capacity and cooling rate was a limitation for scanning extended body regions. This has been solved in some modern tube designs that allow the rotating anode to be cooled by direct heat transfer, rather than through a radiative process out of the tube containment. An important correlate to this is that there is no longer a simple inherent technical limitation to the dose that might be given to a patient during a scanning session and that other guards must be in place to secure against unintended high exposure.

(65) Modern systems have automated algorithms that can assist in dose reduction, using the information from the pre-scan and/or adjusting to data obtained during a scan (McCollough, 2006; Singh, 2011; ICRP, year TG108-2). All major vendors have proprietary programs (under different names) that can modulate the tube current, either longitudinally only (reducing, e.g. exposure over the lung region compared to abdomen) or during rotation, observing that the anterior-posterior attenuation in general is much lower than the lateral. The setting of the algorithm will require the user to enter an allowed mAs interval, an 'image quality index' or other information to describe the wanted outcome. It must be noted that, in setting up the scan, a number of pitfalls exist. If the patient is placed off-centre, the prescan may assume the patient to be larger (or smaller) than what is actually the case and adjust the current accordingly, and if dose limiting shielding (or metal implants) are in the field, the current might be increased beyond the intended if not limited by the user.

PET/CT = PET + CT

CT is used for:

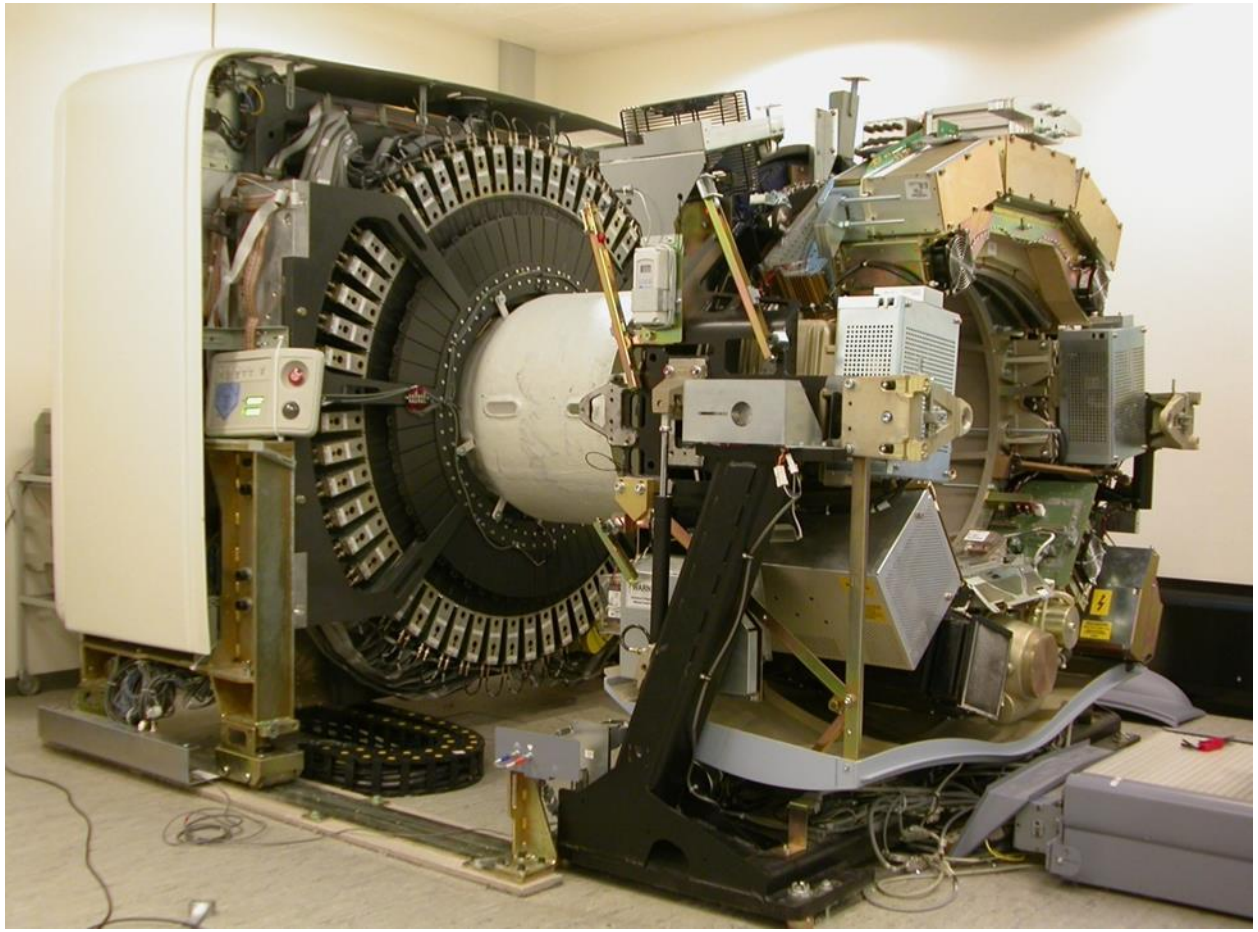
Attenuation **correction** of PET data

Anatomical **localisation** of tracer

A full **diagnostic** examination

In PET/CT, doses from CT may well exceed the PET doses.

Justification of scan type mandatory



One of the first commercially available PET/CT systems (2001)

The PET/CT session

(text in publication)

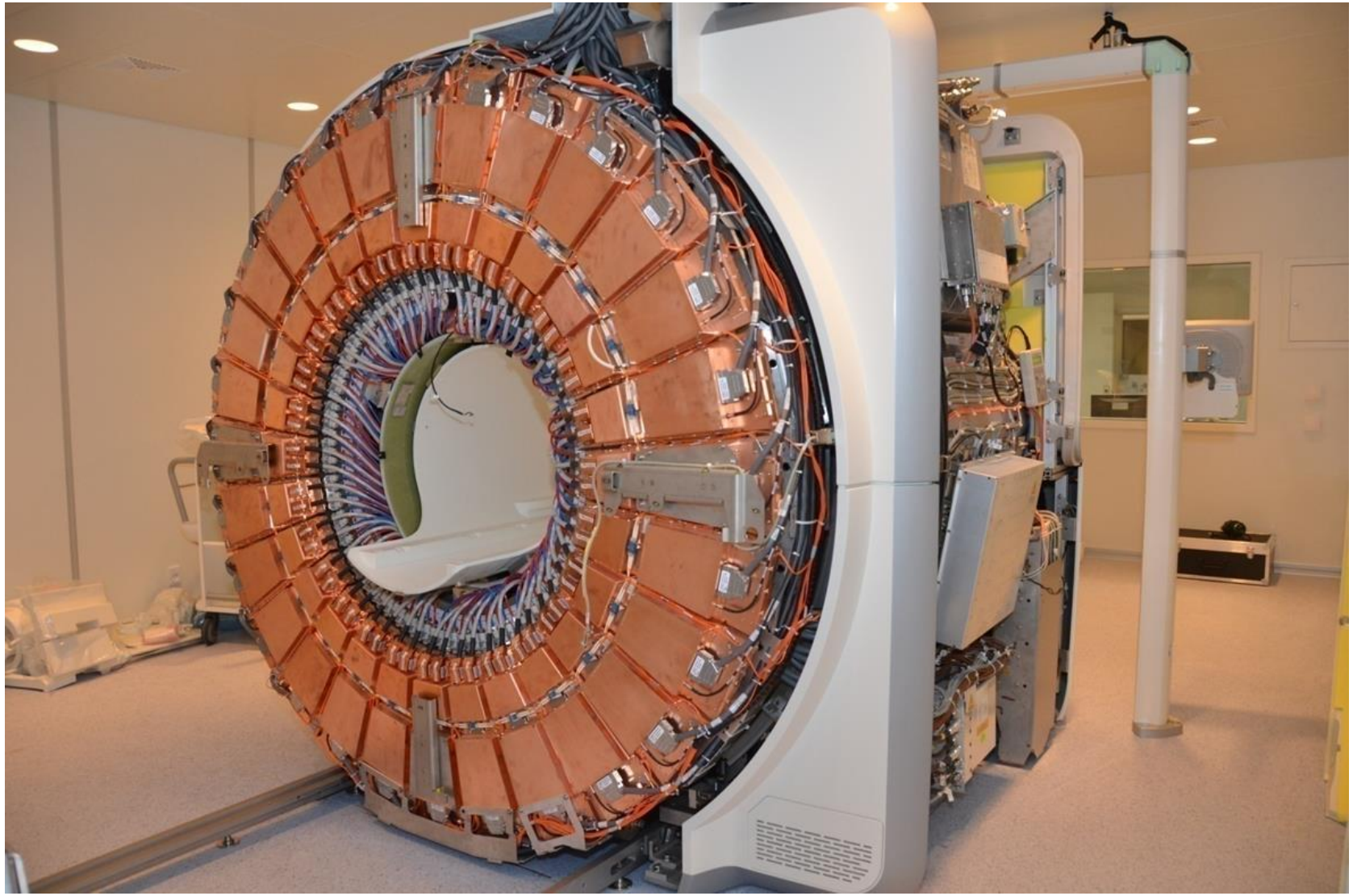
(70) A typical PET/CT session will consist of 1) a pre-scan providing a simple x-ray projection image, 2) a CT scan, and 3) a PET scan. From a protection perspective it is important to stress the significance of the justification for the type of CT scan applied. It is possible to perform either a full diagnostic scan (potentially with intravenous and/or oral contrast agents), making a low dose CT scan, mainly for orientation (and AC), or an 'ultralow dose' CT for AC only. In general, a diagnostic CT with contrast may also be used for AC although with the potential of (recognisable) local artefacts as well as a minor deviation in the quantitative values of PET (Berthelsen et al., 2005). Therefore, if high accuracy is needed, a low dose scan for AC is performed before the PET, and the contrast enhanced CT after the PET acquisition.

(71) It should be noted here that the photon flux during a (diagnostic) CT scan can be 4–5 orders of magnitude higher than the emission rate from a patient injected with a typical activity for the PET scan, delivering the same absorbed dose to the exposed tissue in a second as the injected tracer will provide over the lifetime of the activity. The high flux ratio explains why it is not feasible to perform simultaneous measurement of PET and CT because the scatter from CT would disturb the PET detectors.

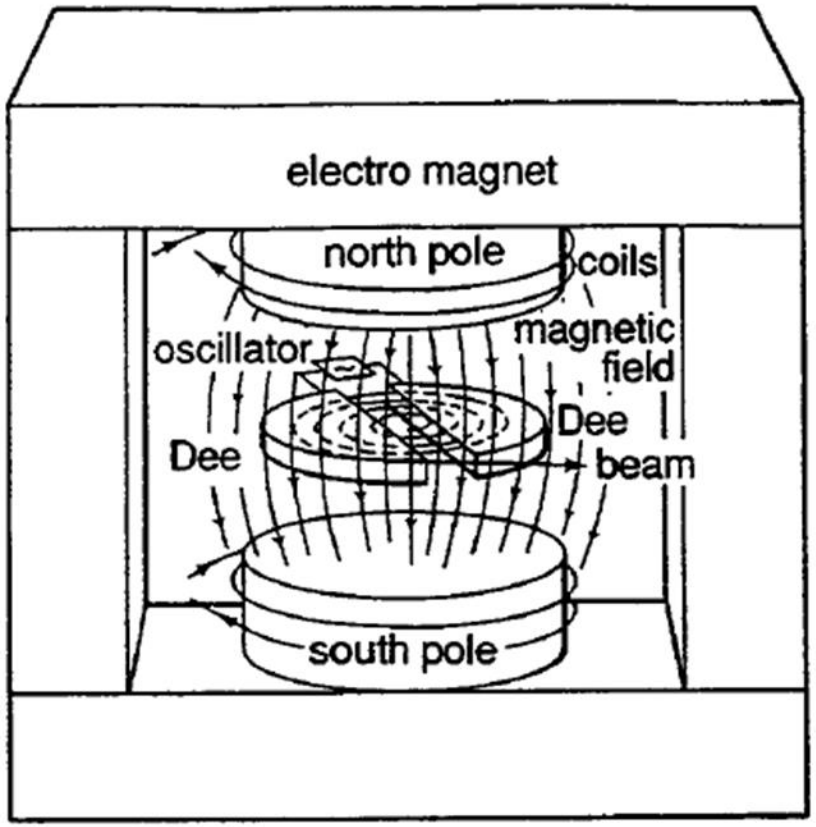
PET/MR

* Figure not in publication

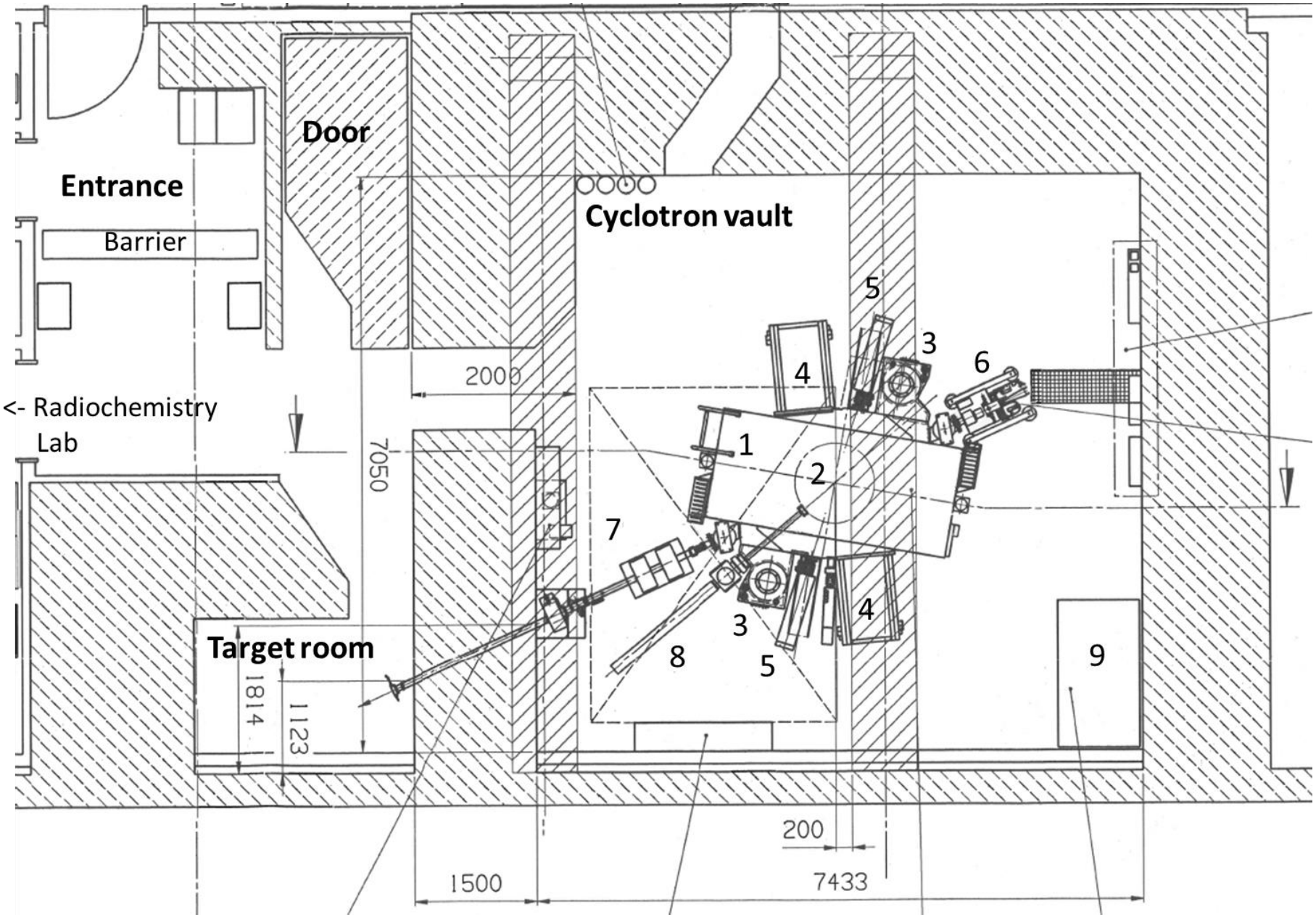
PET/MR



Cyclotron principle



(from a brochure published by the Lawrence Berkeley laboratories).

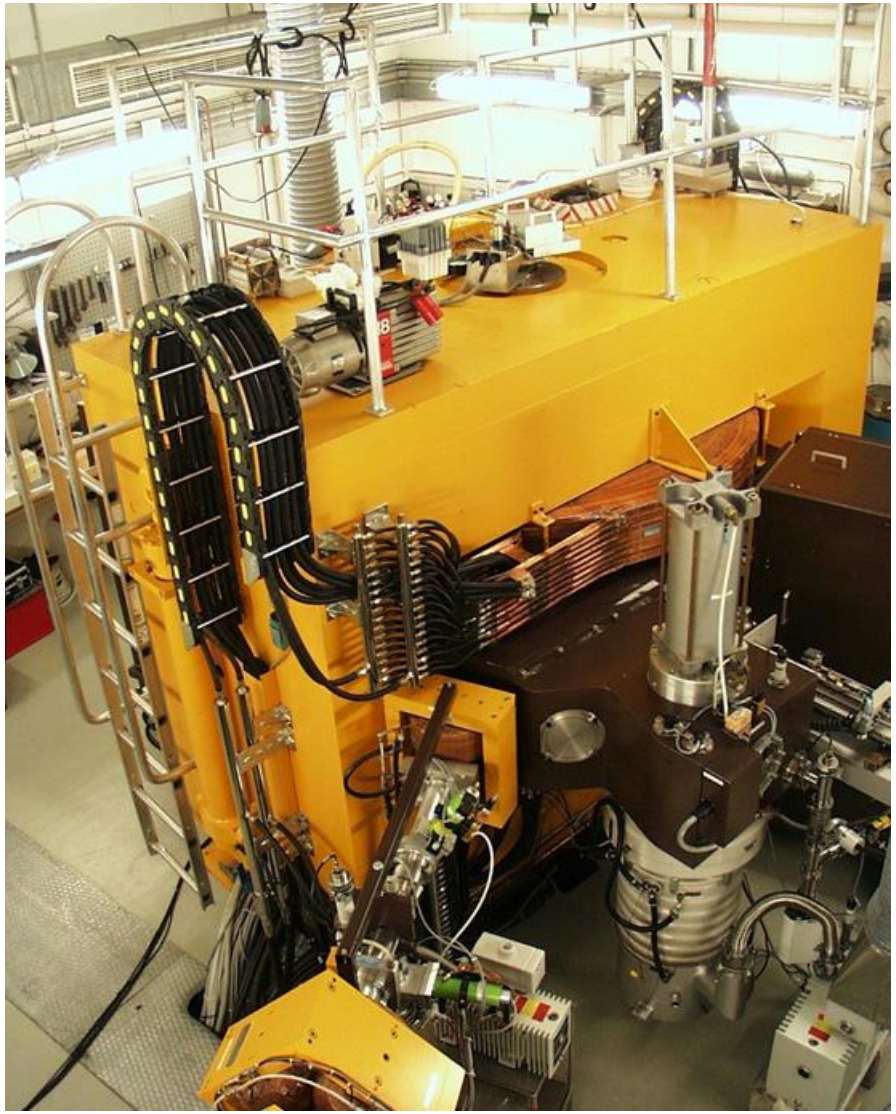


Example of a cyclotron vault and surroundings for an ”unshielded” 32 MeV device (installed 1991)

Cyclotrons

* Figures not in publication

”Self-shielded” 11 MeV Cyclotron



”Un-shielded” 32 MeV Cyclotron

The ”classical four” nuclides for PET

- Table 2.1. The 'classical four' cyclotron produced radionuclides for PET.

Nuclide	Half-life	Production route(s)
^{11}C	20.4 min	$^{14}N(p,\alpha)^{11}C$
^{13}N	9.97 min	$^{16}O(p,\alpha)^{13}N$
^{15}O	2.04 min	$^{15}N(p,n)^{15}O$ or $^{14}N(d,n)^{15}O$
^{18}F	109.8 min	$^{18}O(p,n)^{18}F$ (F^-) or $^{20}Ne(d,\alpha)^{18}F$ (F_2)

2.6. Clinical applications and radiopharmaceuticals examples

- **Neurology**
  - For neurodegenerative disorders particularly 2-[^{18}F]FDG and radiotracers for the detection of amyloid accumulation in suspected Alzheimer's disease are in clinical use.
  - In Parkinson's disease a number of tracers are gradually being introduced: 6-[^{18}F]FDOPA, [^{18}F]FE-PE2I.
  - In brain tumours radiolabelled amino-acids are used for glioma, ^{11}C labelled methionine, 6-[^{18}F]FDOPA and [^{18}F]FET. [^{68}Ga]Ga-DOTA-conjugated peptides are binding to the SSTR2 receptor in meningiomas.
  - Finally [^{15}O]H_2O is (still) used to estimate the cerebral hemodynamic reserve capacity in chronic cerebrovascular disease.
- **Cardiology**
  - quantitative determination of myocardial perfusion with
    ^{15}O labelled water [^{15}O]H_2O, ^{13}N labelled ammonia [^{13}N]NH_3 and [^{82}Rb]$RbCl_2$.
- **Oncology**
  - 2-[^{18}F]FDG WB-scans are used for diagnosis, staging, radiotherapy planning, response to therapy
  - ^{68}Ga or ^{64}Cu labelled somatostatin receptor ligands (DOTATOC/DOTATATE) for neuroendocrine tumours
  - ^{68}Ga labelled peptides to prostate specific membrane antigen (PSMA) imaging in prostate cancer (metastases).

Summary – key points

- PET uses a detection principle based on the annihilation photon radiation that follows a positron decay.
- The PET detection principle has the advantage that high resolution can be obtained without compromising sensitivity.
- Biologically important elements like carbon, nitrogen, and oxygen have positron emitting isotopes with short half-lives.
- PET is a quantitative technique when all the relevant corrections are applied
- Originally a complex research tool with limited accessibility, PET has evolved into an important and widespread clinical modality.
- The combination of PET with CT into one system has been a driving force for the clinical applications.
- PET and PET/CT have important applications within oncology, neurology, and cardiology.
- The short half-life of PET-nuclides requires either an on-site cyclotron, a fast distribution system, and/or the use of generator systems.

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