AN OVERVIEW OF PET IMAGING

Junyu Chen
jchen245@jhmi.edu
Johns Hopkins University

July 22, 2021

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1 Positron Decay and Annihilation

In the case that an atom is unstable by having too many protons, this atom may undergo positron decay (another choice would be electron capture). In positron decay, a proton is converted into a neutron and a positron, which is an electron with a positive charge.

As a positron comes to rest, it is absorbed by a free or loosely bound atomic electron (comparing to the positron energy, e.g., 635 keV, all electrons are loosely bound), in a process known as annihilation, in which the two particles mutually self-destruct. Their rest mass is then converted into two photons each possessing an energy of 511 keV (equivalent to the rest mass of an electron or a positron). To conserve momentum these two photons are emitted in two opposite directions (i.e., 180° apart).

2 Fundamentals of PET imaging system

Similar to a SPECT imaging system, PET system consists of a detector unit, a set of photomultiplier tubes (PMTs), and pulse-height analyzers. Because PET imaging system relies on detecting coincident events, collimator used in a SPECT system is not required in PET. However, time discriminators and coincidence circuits are needed in order to detect and process the coincident events.

2.1 Detector unit (Crystal)

Initially, Thallium-doped sodium iodide (NaI(Tl)) was used for PET systems. However, due to its relatively low density and small atomic number, it is less effective at stopping the 511 KeV photons. Crystals with higher densities and atomic numbers have been developed for use with 511 keV imaging. Instead of using a single large crystal like in SPECT, PET uses crystal blocks watched by a few PMTs. There are slits on and between crystal blocks, where the scintillation photons can be deflected and focused on the PMT. Thus, creating a smaller light distribution that improves resolution.

2.2 Photomultiplier tubes

PMTs used in PET are identical, in terms of function, to the ones used in SPECT. However, the actual size of the PMTs in PET maybe smaller.

2.3 Pulse-height analyzer

Pulse-height analyzer determines whether the signal has the correct amplitude (i.e., 511 keV photon) to have come from a 511 keV photon interaction within the crystal.

2.4 Coincidence circuits

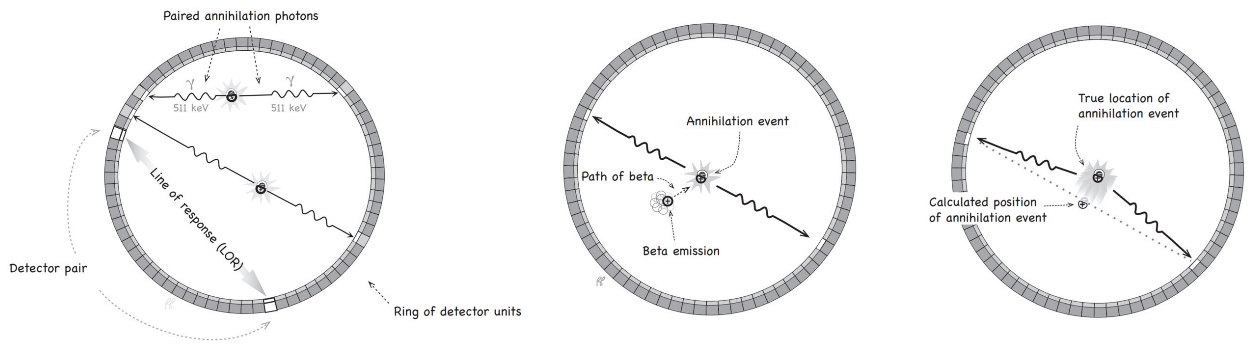
When the pulse-height analyzer confirms the photon is the primary photon (i.e., 511 keV photon), the next step is to determine if there is coincidence photon on the opposite direction of interaction. The timing discriminator first records the time the 511 keV signal was detected. The coincidence circuit then examines signals of adequate amplitude coming from opposing detectors and determines whether the timing of the signals occurred within the coincidence time window. Typically, this coincidence time window is set to 5-15 nano-second.

2.5 Septa between crystal rings

Septal rings can be used to improve resolution by reducing the amount of scatter from photons outside the plane of one ring of crystals. The sensitivity is reduced because a significant fraction of true coincidence events are rejected. Scans with septa in place are called 2-dimensional scans; without septa, the scans are called three-dimensional scans.

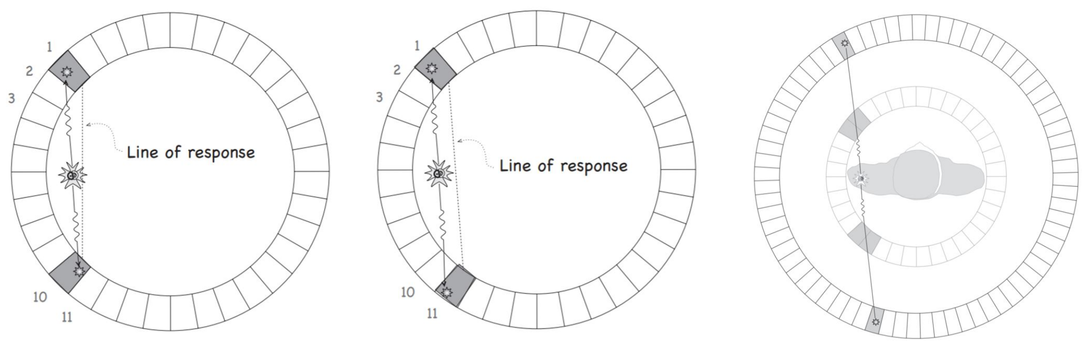
2.6 Time of flight

Positron annihilation can be localized along the line of flight of the coincident photons by measuring the time of arrival if each of the photons at the opposing crystals. Unless the event occurs in the exact center of the detection ring, one of the photons will arrive later than another. This information can be used to calculate the position of the event along the line connecting the detectors. However, due to the limitations of the electronics, the calculated position is not



Annihilation photon detection of a PET system   Positron range   Acollinearity

Figure 1: Factors limit PET resolution.



Parallax error

Figure 2: Parallax error.

precise. However, the approximated location still helps constrain the reconstruction algorithm to improve the quality of the image.

3 PET system resolution

3.1 Line of response

Line of response (LOR) refers to the imaginary line between the detection of annihilation photons.

3.2 Positron range

Positrons travel a short distance in tissue before it undergoes annihilation with an electron (as shown in Fig. 1). Therefore, the camera cannot precisely determine the true location of where the positron is originated. For low energy emitters like ^{18}F, this range is relatively small (1.2mm in water). Therefore, the resolution of PET imaging is limited to the average range of the positrons in the tissue.

3.3 Acollinearity

The 511 keV photons do not always travel by an exactly 180° apart (as shown in Fig. 1). This is because the positron-electron combination will often be in motion during the process of annihilation. Both momentum and energy must be conserved in the annihilation event between the positron and the atomically bound electron. Instead there is a small deviation from the ideal 180 degree emission angle. This small angular deviation is referred to as the acollinearity angle. This angular uncertainty causes a Gaussian blurring to the resulting PET image.

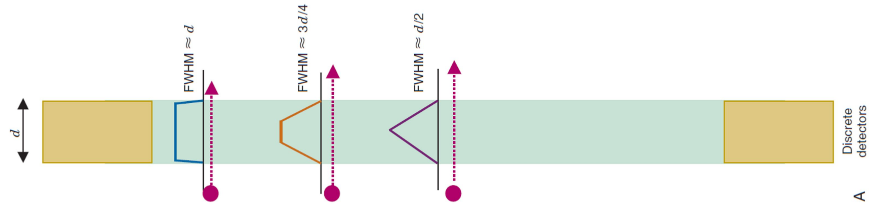


Figure 3: Parallax error.

3.4 Parallax error

Resolution of a PET system decreases toward the periphery of a ring of PET detectors. This is because some photons travel to the detector rings at an oblique angle and the photons can pass through several detectors before it interacts with the crystal. This effect is sometimes referred to as the parallax error or depth-of-interaction effect (as shown in Fig. 2). The larger the size of the detector ring, the less the parallax effect, because the annihilation events will be more centrally located and photons will cross the detector at a loss oblique angle.

3.5 Detector size

The spatial resolution of annihilation coincidence detection is primarily determined by the size of the individual detectors. If the annihilation event is at the midpoint between two detectors, the detector resolution has a FWHM of $d/2$ (as shown in Fig. 3). Moving the event closer to a detector, then the FWHM becomes trapezoidal, eventually becoming a box of width d at the face of either detector.

4 PET sensitivity

In a SPECT system, a collimator reduces a camera's sensitivity because the collimator blocks a lot of incident gamma photons. PET system does not require a collimator, it is thus more sensitive (by at least a factor of 100) than a SPECT camera. However, the septas between detector blocks (i.e., the 2D PET) reduces the sensitivity.

References