

Image Acquisition

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Learning objectives

After the the lecture the student should know the basic PET concepts of

- **Data acquisition**
 - **line-of-response (LOR)**
 - **coincidence detection**
 - **2D and 3D acquisition**
 - **time-of-flight (TOF)**
- **Data representation**
 - **list-mode data**
 - **sinograms**
 - **micelogram**

Note: Presentation is adapted from lecture notes by J. Teuho



Definitions

- **LOR = Line of response connecting two detectors**
- **TOF = Time of flight**
- **List-mode data = PET raw data**
- **Sinogram = Histogrammed list-mode data**
- **Michelogram = Illustration of 3D acquisition**



Further information

Contact people at Turku PET Centre

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STIR/SIRF (Reconstruction)

- <http://stir.sourceforge.net/>
- <https://www.ccppetmr.ac.uk/node/1>

NiftyRec (Reconstruction)

- <http://niftyrec.scienceontheweb.net/wordpress/>

ASIM/SIMSET (Simulation)

- http://depts.washington.edu/simset/html/user_guide/user_guide_index.html
- <https://depts.washington.edu/asimuw/>

GATE/GEANT (Simulation)

- <http://www.opengatecollaboration.org/>

Handbook of Nuclear Medicine Imaging:

- <https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1617web-1294055.pdf>



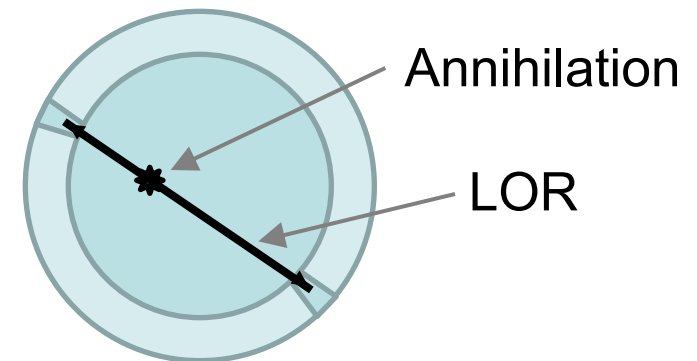
PET Data Acquisition

- Line-of-response
- Coincidence detection
- 2D vs 3D acquisition
- Non-TOF system vs. TOF system



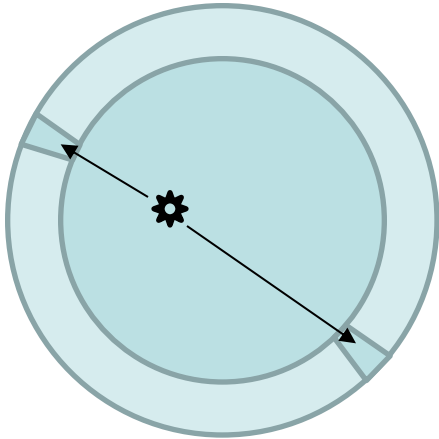
Line of Response

- ❑ A straight line which connects the centers of two detectors X and Y is called a line of response (**LOR**).
- ❑ The two 511 keV photons are detected in coincidence across a LOR, in the absence of an absorptive collimator.
- ❑ This technique is called **electronic collimation**.
- ❑ All coincident events recorded are collectively called as prompt events, containing:
 - True events
 - Random events
 - Scattered
 - Multicoincidence

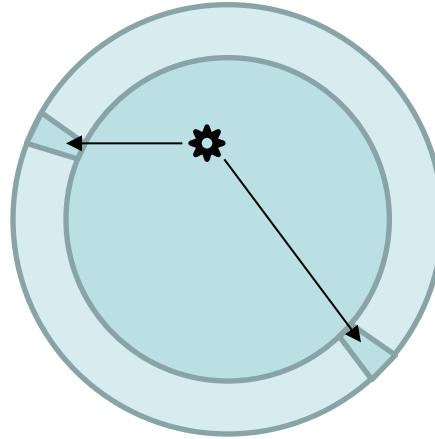


Types of events

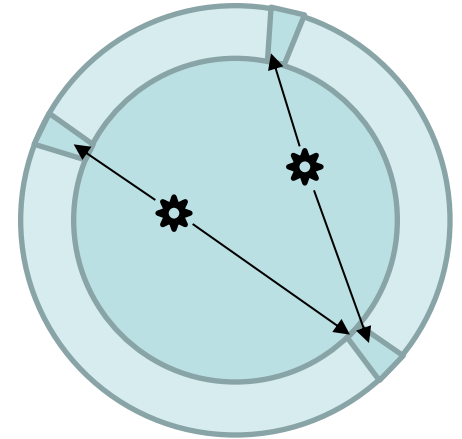
True event



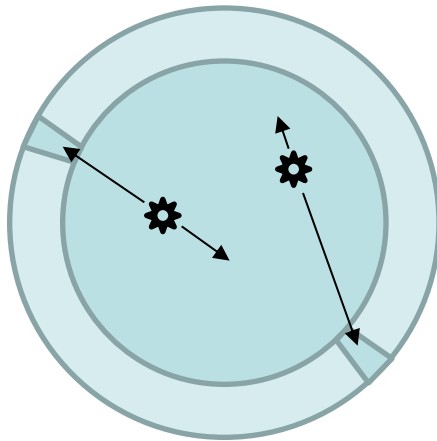
Scattered event



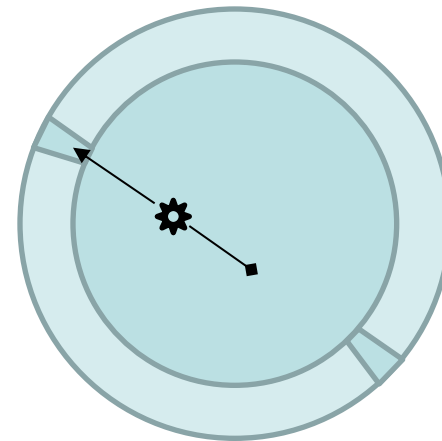
Multicoincidence



Random event



Attenuated event



Coincidence Detection

- ❑ Creation of two electronic pulses (at detectors X and Y) at the same time (“in coincidence”) signifies a point of annihilation *somewhere* in the LOR connecting the associated detectors X and Y.
- ❑ During the scan, coincidence counts are recorded for each LOR and stored in a raw data format (list-mode or sinogram).

List-mode data

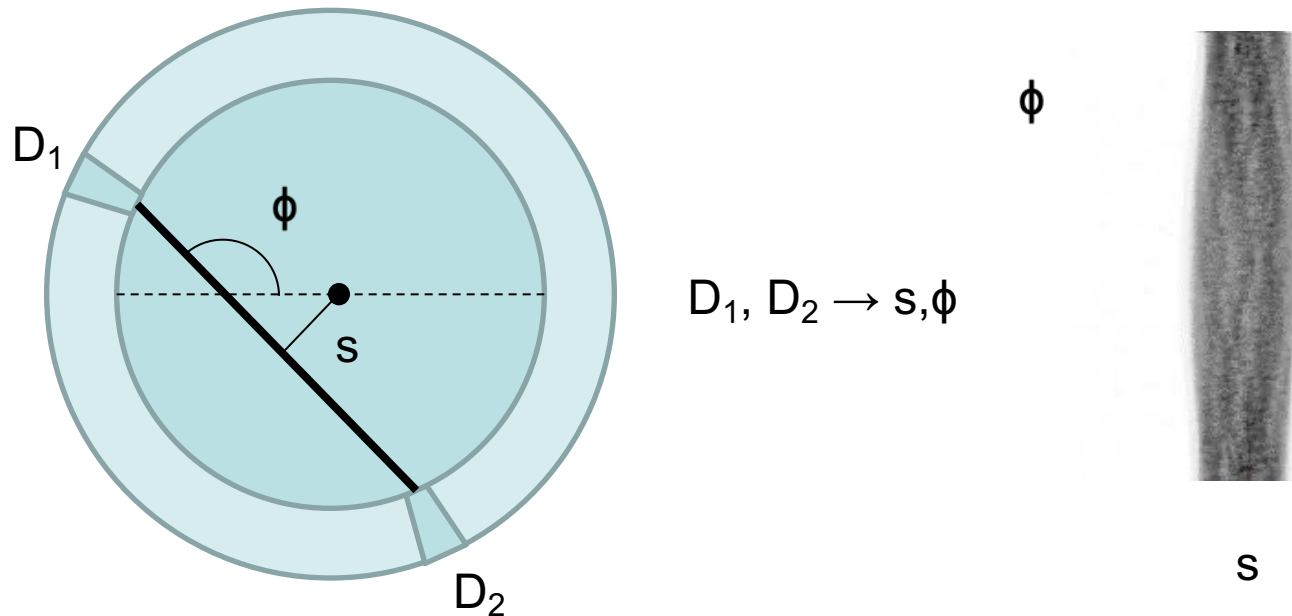
Time	1 ms	1 ms	1 ms	1 ms	2 ms	...
D ₁	2	72	102	36	97	...
D ₂	56	86	32	45	63	...

- ❑ The number of coincidence counts obtained on a particular LOR indicates amount of radioactivity (“counts”) present along that line during the scan.



Coincidence Detection

- A parallel set of LORs through the imaged object $f(x,y)$ can be collected as a set of projections $p(s,\phi)$ of the radioactivity distribution. The collection of all these projections is called a sinogram.



From Coincidence to Raw Data

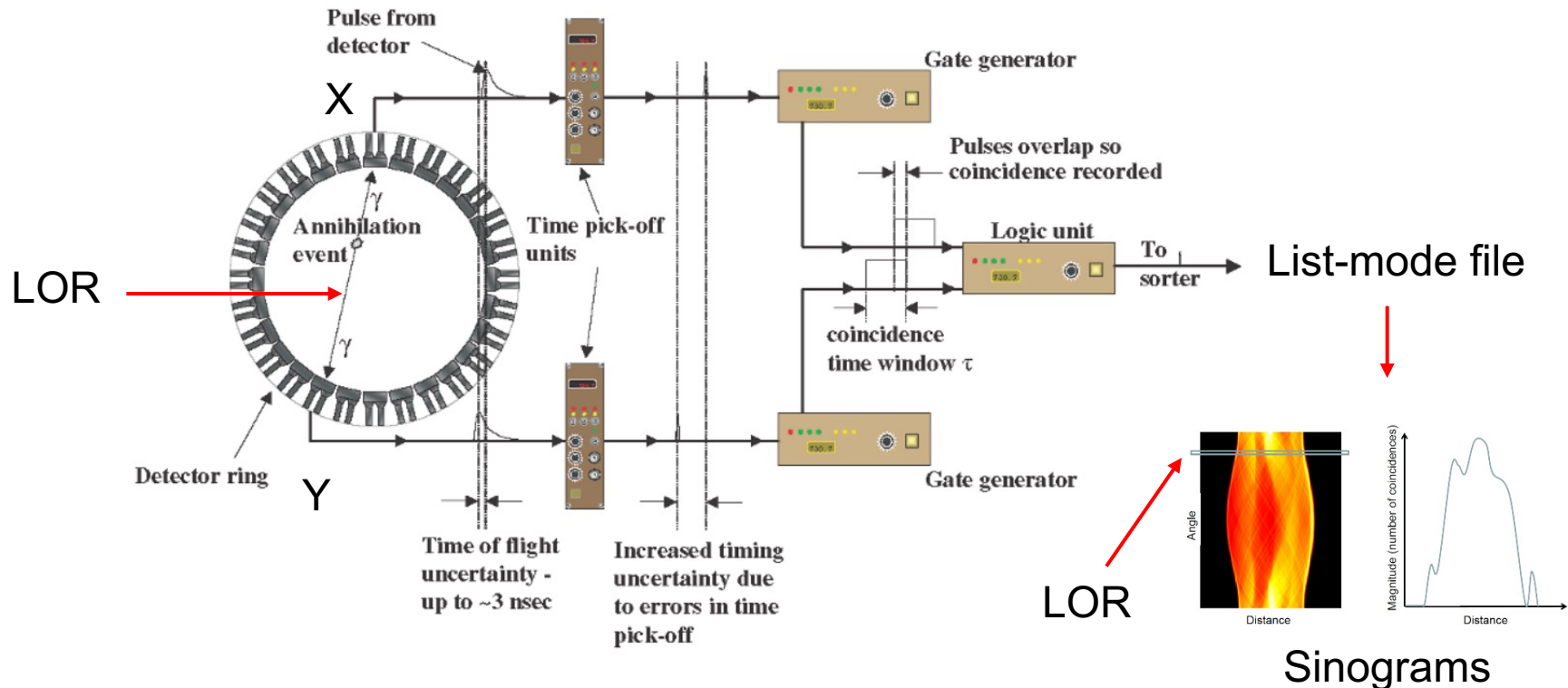


Figure 5.2. Figure 5.2 Example coincidence circuitry. Each detector generates a pulse when a photon deposits energy in it; this pulse passes to a time pick-off unit. Timing signals from the pick-off unit are passed to a gate generator which generates a gate of width τ . The logic unit generates a signal if there is a voltage on both inputs simultaneously. This signal then passes to the sorting circuitry.

Modified from : Quantitative Techniques in PET
 Steven R Meikle and Ramsey D Badawi



Line-of-Response in TOF and non-TOF

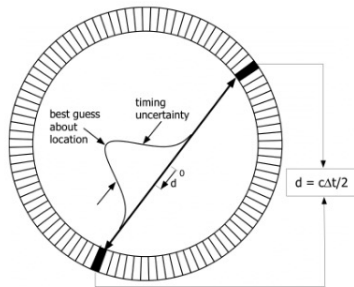
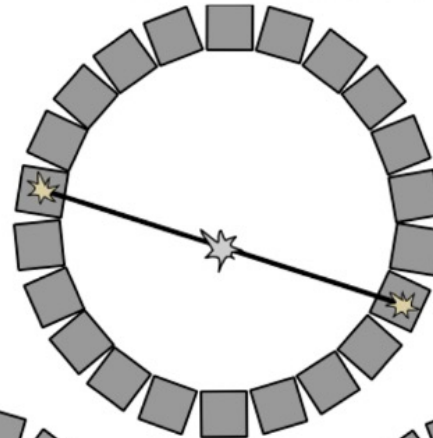
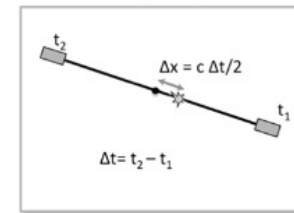


Fig. 4b. Coincidence processing in time-of-flight (TOF) PET data acquisition.

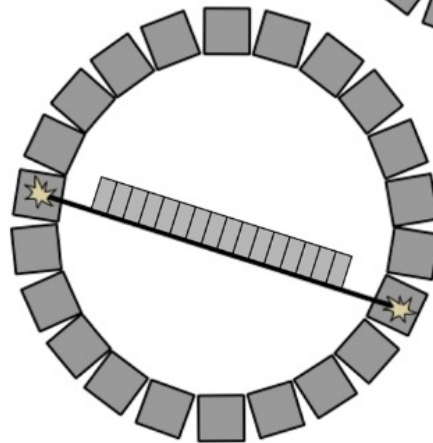
Real annihilation event



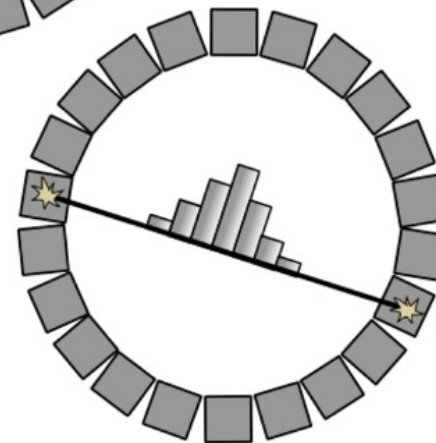
TOF principle



Non-TOF PET, the probability of detection is assumed uniform across the LOR



Conventional PET



Time-Of-Flight PET

In TOF PET the arrival-time difference of the two detected photons is measured.

Time difference is used to determine the most likely location (d) of the annihilation event.



Data Representation

- List-mode data
- Sinogram
- Michelogram



List-mode data

- ❑ In list-mode acquisition, digitized X- and Y- signals are coded with “time marks” as they are received in sequence.
- ❑ Signals are stored as individual events as they occur.
- ❑ After the acquisition is completed, data can be histogrammed to individual sinograms.
 - Other terms: data sorting, unlisting, sometimes re-binning
- ❑ This way of storing the data allows flexibility, since the data can be sorted to sinograms as:
 - Static (whole scan time e.g. 15 minutes)
 - Dynamic (by time to shorter frames e.g. 3x180 s, 5x300 s, etc.)
 - Gated (respiratory or cardiac time marks e.g. by respiratory or cardiac phase)
- ❑ Practical hurdles:
 - Size and storage requirements (1,5 GB for non-TOF and 4 GB+ for TOF)
 - Increased activity / sensitivity => disk writing speed + memory/storage requirements



Sinogram

- ❑ It is typical to store and display the raw data in a sinogram.
- ❑ The imaged object $f(x,y)$ is now collected as a set of projections $p(s,\phi)$ of the radioactivity distribution.
- ❑ In essence, by performing image reconstruction we want to recover the original imaged object $f(x,y)$ from this set of projections $p(s,\phi)$.
- ❑ The line-integral transform of $f(x,y)$ to $p(s,\phi)$ is called the X-ray transform, or the **Radon transform** in 2D. During image reconstruction process, this is usually referred as *forward projection* operation while *backprojection* is the adjoint operation of forward projection (**inverse Radon transform**).



Sinogram Formation, Forward Projection

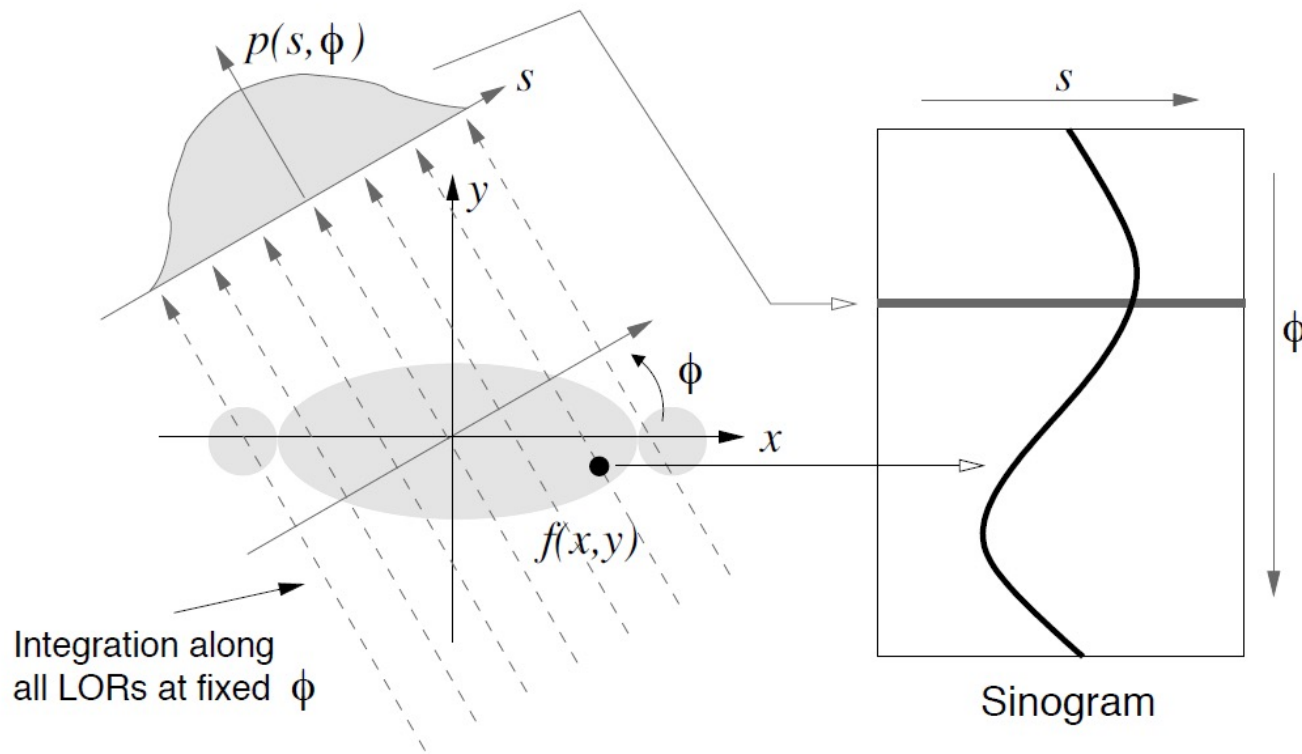


Figure 2. A projection, $p(s, \phi)$, is formed from integration along all parallel LORs at an angle ϕ . The projections are organized into a sinogram such that each complete projection fills a single row of ϕ in the sinogram. In this format, a single point in $f(x,y)$ traces a sinusoid in the sinogram.



PET Image Reconstruction
Adam Alessio and Paul Kinahan

Backprojection

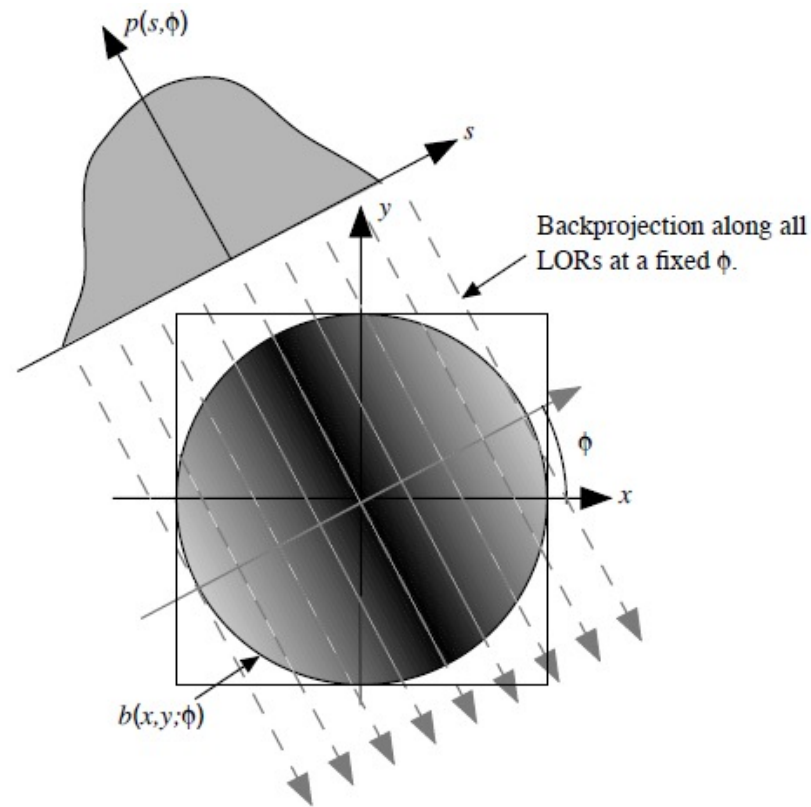


Figure 6. Backprojection, $b(x, y; \phi)$, into an image reconstruction array of all values of $p(s, \phi)$ for a fixed value



PET Image Reconstruction
Adam Alessio and Paul Kinahan

Sinogram in 2D Acquisition and Reconstruction

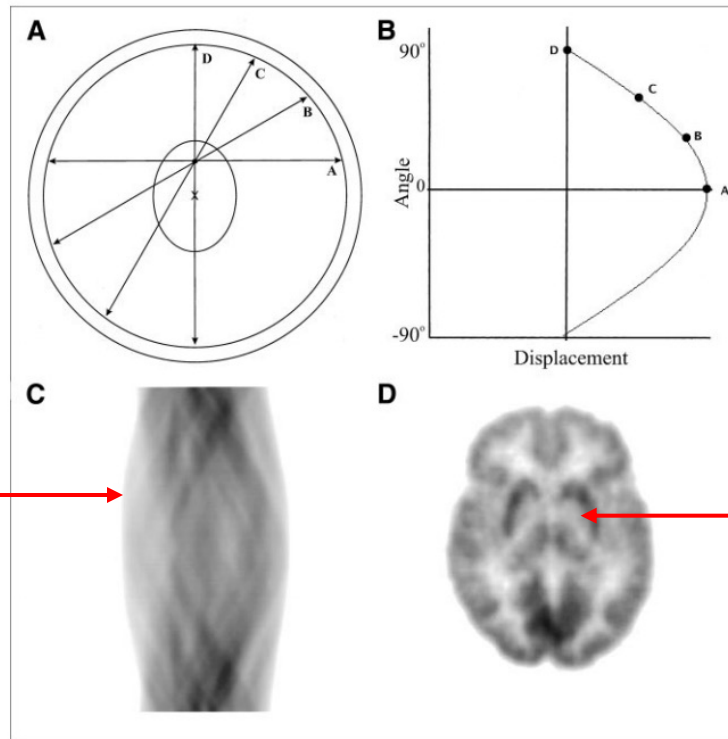
- ❑ In projection space, the imaging volume is described as $p(s, \phi, z, \theta)$
- ❑ In the 2D case all data are sampled (or assumed to be sampled) with polar angle $\theta = 0^\circ$, where projections $p(s, \phi, z)$ are formed only for a single transverse slice at a time of the volumetric object $f(x, y, z)$.
- ❑ The volumetric object $f(x, y, z)$ is recovered by reconstruction of each 2D sinogram $p(s, \phi, z)$ corresponding to an individual slice z , leading to an 3D image. Stack of sinograms \Rightarrow individual slices \Rightarrow imaged 3D object.
- ❑ The image reconstruction process starts with collected & uncorrected raw data (typically sinograms), performs essential data corrections and tries to recover the cross-sectional images that represent radioactivity distribution inside the imaged object.



Practical Example

One 2D Sinogram

Each sinogram represents the data acquired for a slice across all angles



The sinogram is a two-dimensional histogram of the LORs in distance and angle coordinates

After data corrections and image reconstruction, the image is a pixel-by-pixel representation of the radiotracer concentration at scan time.

FIGURE 1. Sinogram formation. Coincidence events in PET scanner are categorized by plotting each LOR as function of its angular orientation versus its displacement from center of gantry. (A) Center of gantry is noted by cross (X), and locus of interest (e.g., tumor) is noted by ellipse. Four LORs passing through locus of interest are labeled A, B, C, and D. (B) These 4 LORs are plotted on this sinogram where angular orientation is on y-axis and displacement from center of gantry is on x-axis. If all possible LORs that pass through this point are plotted, it maps out half of sine wave turned on its side as shown here. (C) Sinograms of more complicated objects, such as sinogram of brain scan shown, are composed of many overlapping sine waves. (D) Reconstructed brain image corresponding to sinogram in (C) is shown.



Data Acquisition in PET Imaging, Frederic H. Fahey

Sinogram in 3D Acquisition and Reconstruction

- ❑ In the 3D case, the sinograms $p(s, \phi, z, \theta)$ are extended to measuring projections at polar angles $\theta > 0^\circ$ (oblique or tilt angles).
- ❑ In 3D data, the acquired LORs are represented in terms of four parameters, s , ϕ , z and θ , which denote:
 - the radial distance s
 - rotation angle ϕ
 - shift in the axial direction z
 - oblique or tilting angle θ
- ❑ A 2D reconstruction algorithm can also be applied to 3D data by rebinning the data to individual 2D sinograms:
 - Single-slice rebinning (SSRB), fourier rebinning (FORE, e.g. FORE-FBP, FORE-OSEM)
- ❑ Naturally, a fully 3D reconstruction algorithm can be applied (iterative or analytical). There are specific considerations when using analytical algorithms for 3D data, as some of the projections are truncated.
 - The interested reader is referred to e.g.: Image Reconstruction Algorithms in PET, Michel Defrise, Paul E Kinahan and Christian J Michel



Michelogram

- ❑ A graphical representation was introduced by the Belgian scientist Christian Michel to illustrate the plane definitions used in a large multi-ring PET system - known as “**Michelogram**” representations.
- ❑ A michelogram illustrates how different planes can be combined to optimize storage space and data-handling requirements.
- ❑ In 3D-PET sinograms from direct and crossing planes can be merged to additionally reduce the data volume, effectively resulting in an axial compression (span). Axial and angular compression is performed by the scanner hardware during the data acquisition process.
- ❑ The interested reader is referred to:
 - Image Reconstruction Algorithms in PET, Michel Defrise, Paul E Kinahan and Christian J Michel
 - Data Acquisition in PET Imaging, Frederic H. Fahey
 - Data Acquisition and Performance Characterization in PET, Dale L Bailey



Michelogram Example

2D PET, span 7

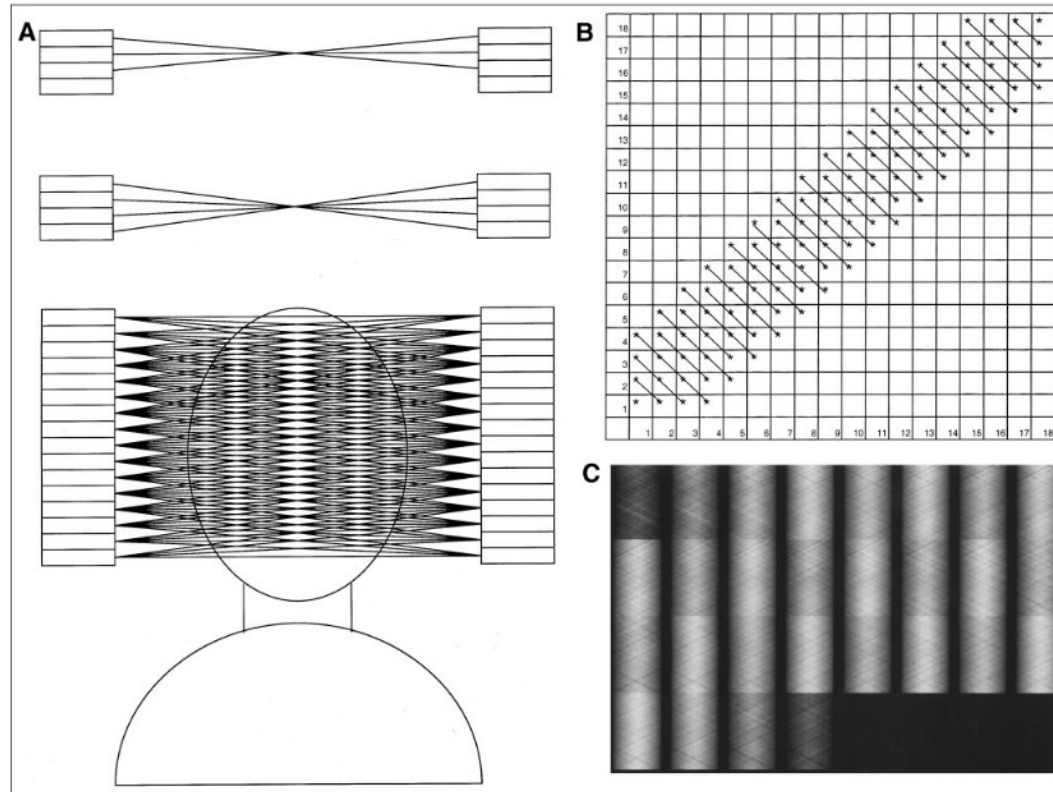


FIGURE 7. 2D PET with span of 7. (A) Top of figure shows configuration for odd-numbered slices. Not only is direct LOR used but also 2 cross LORs on either side of it. For example, Ring 2 in coincidence with Ring 2, Ring 3 with Ring 1 and Ring 1 with Ring 3. For even-numbered slices, 2 sets of cross LORs are used (e.g., Ring 2 to Ring 3, Ring 3 to Ring 2, as well as Ring 1 to Ring 4, and Ring 4 to Ring 1). Since odd-numbered planes contain 3 LORs and even ones contain 4, this is referred to as span of 7. (B) Michelogram for 16-ring scanner using span of 7. (C) Set of sinograms corresponding to Michelogram in (B) that have not been corrected for detector sensitivity or plane



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Michelogram Example, 2D and 3D PET

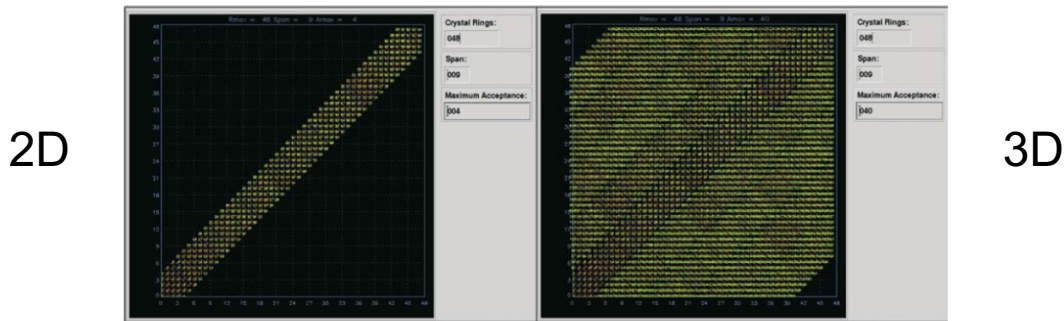


Figure 3.8. Michelograms representing the plane combinations for a 48-ring scanner are shown for the 2D case (left) and the 3D case (right). The x and y axes represent ring numbers on opposing sides of the scanner. Each point on the graph defines a unique plane of response (e.g., all lines-of-response in ring 1 in combination with ring 2). The diagonal lines joining individual dots indicate that the planes of response are combined (added together) thus losing information about each individual point's polar acquisition angle. This form of combination of data from different planes represents a "lossy" compression scheme.

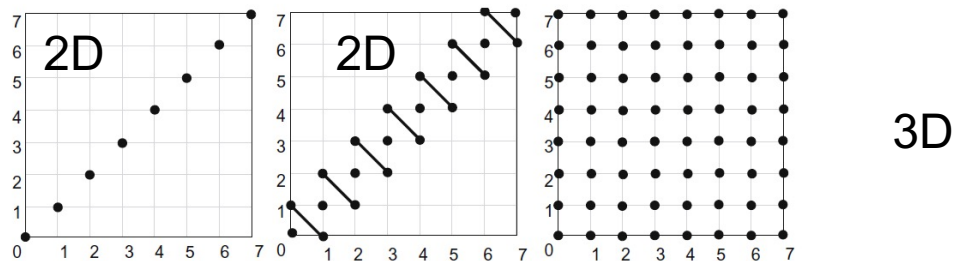


Figure 3.7. The graphical Michelogram is shown for three different acquisition modes on a simple eight-ring tomograph. Each point in the graph represents a plane of response defined between two sets of opposed detectors (a sinogram). In the graph on the left (a simple 2D acquisition with no "inter-planes"), the first plane defined is ring 0 in coincidence with the opposing detectors in the same ring, 0; ring 1 in coincidence with ring 1; etc., for all rings, resulting in a total of eight sinograms. In the middle graph, the same planes are acquired with the addition of a set of "inter-planes" formed between the rings with a ring difference of ± 1 ring (ring 0 with ring 1, ring 1 with ring 0, etc). These planes are added together to form a single plane, indicated by the line joining them. This would lead to approximately twice the count rate in this plane compared with the adjacent plane which contains data from one ring only. Physically, this plane is positioned half way between detector rings 0 and 1. While the data come from adjacent rings they are assumed to be acquired with a polar angle of 0° for the purposes of reconstruction. This pattern is repeated for the rest of the rings. This results in 15 (i.e., $2N - 1$) sinograms. This is a conventional 2D acquisition mode, resulting in almost twice the number of planes as the previous mode, improving axial sampling, and contributing over 2.5 times as many acquired events. In the graph on the right, a fully 3D acquisition is shown with each plane of data being stored separately (64 in total). The 3D mode would require a fully 3D reconstruction or some treatment of the data, such as a rebinning algorithm, to form 2D projections prior to reconstruction (see Ch. 4).



Data Acquisition and Performance Characterization in PET, Dale L Bailey

Thank You!



Turku PET Centre



Turun yliopisto
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