PET Basics

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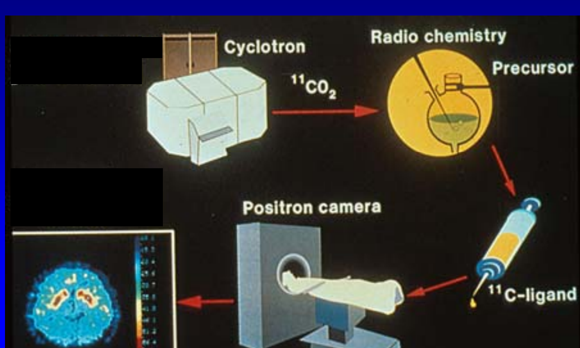
Outline

- Positron Emission
- Basics of PET Scanner Design
- Data Acquisition
- Review of Scintillation Materials
- PET/CT
- Time-of-Flight (TOF) PET
- Special PET devices

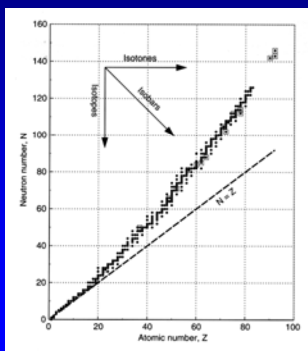
PET Overview Slide



Radionuclides Used in Nuclear Medicine

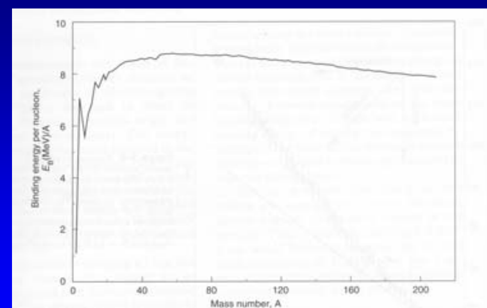
Single Photon			Positron		
Isotope	**T1/2**	**Examples**	**Isotope**	**T1/2**	**Examples**
^{99m}Tc	6 hrs	MDP, HMPAO, MAA, DTPA	^{15}O	2 min	H_2O, CO, O_2, CO_2
^{201}Tl	72 hrs	Chloride	^{13}N	10 min	NH3
^{131}I	192 hrs	Thyroid (Tx, Dx)	^{18}F	109.8 min	FDG
			^{11}C	20.4 min	methionine
			^{82}Rb	1.3 min	cardiac
			^{64}Cu	12.7 hrs	MoAB

Positron Decay



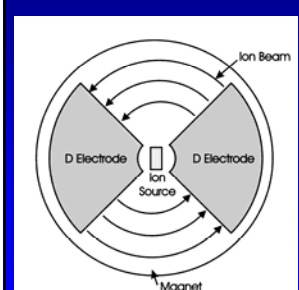
- Have an excess number of protons
- Lie below the line of stability
- Require accelerator for production

Positron Decay



Note: It takes about 8 MeV for a particle to overcome the nuclear binding energy

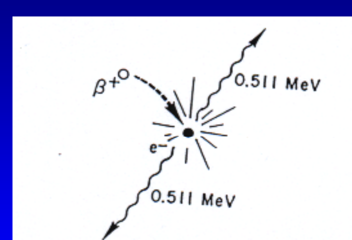
Cyclotron



- Provides energetic charged particles (p, d, α)
- 10 – 20 MeV
- For example,

^{18}O (p,n) ^{18}F

Annihilation Reaction



Two 511 keV annihilation photons are emitted 180° ± sd

Annihilation Reaction

Conversion of mass to energy (Einstein)

$E(erg) = mc^2$

$= 9.1091e\text{-}28g \times (2.997e10cm/sec)^2$

$= 8.18e\text{-}10\ gcm^2/cm^2$

$= 8.18e\text{-}10$ erg

$E(MeV) = 8.18e\text{-}10\ gcm^2/cm^2 \times (1\ Mev/1.6e\text{-}06\ erg)$

$= 0.511$ MeV

Electron Capture

For lower transition energies, electron capture is an alternative decay mode for proton-rich isotopes.

$${}^{A}_{Z}X_{N} + e^{-} \longrightarrow {}^{A}_{Z-1}Y_{N+1}$$

$$p + e^{-} \longrightarrow n + \gamma$$

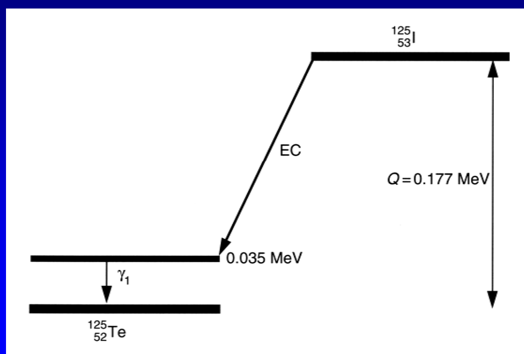
Positron Decay

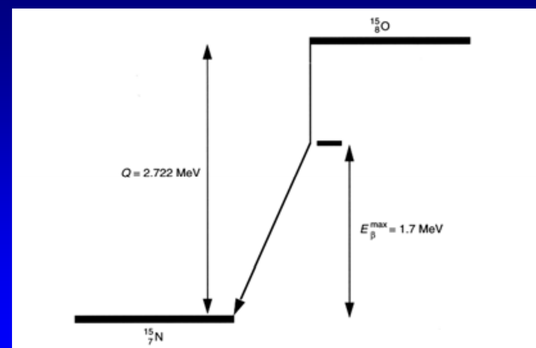
"Particles, particles, particles."

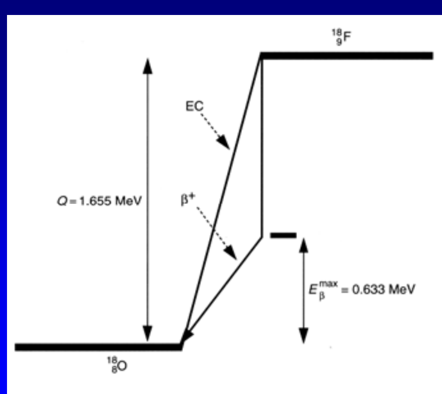
Positron Decay

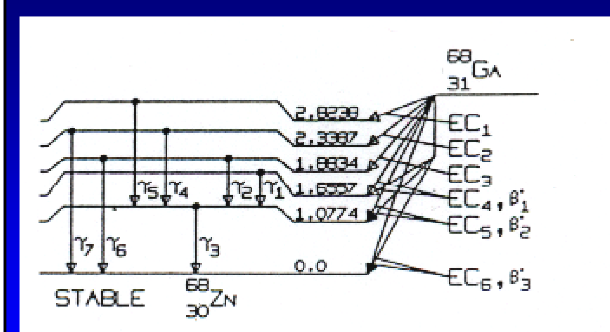
- Requires 1.022 MeV transition energy (creation of β+ and difference in number of orbital electrons). Electron capture results if the transition energy is below 1.022 MeV.
- Transformations with transition energies of greater than 1.022 MeV can decay via electron capture or positron decay.
- The greater the energy over the required 1.022 MeV the more likely positron decay will occur (rather than electron capture) and higher the kinetic energy of the emitted β+.

Examples


125
53 I
EC
Q = 0.177 MeV
0.035 MeV
γ1
125
52 Te


15
8 O
Q = 2.722 MeV
E β max = 1.7 MeV
15
7 N


18
9 F
EC
Q = 1.655 MeV
β+
E β max = 0.633 MeV
18
8 O

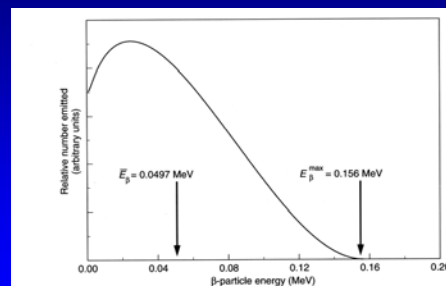

68
31 GA
2.8238
2.3387
1.8834
1.6557
1.0774
0.0
EC1
EC2
EC3
EC4, β+1
EC5, β+2
EC6, β+3
γ5 γ4
γ2 γ1
γ7 γ6
γ3
STABLE
68
30 ZN

Energy of the Positron (β^+)

- Transition energy that is used during the annihilation process is shared by the β+ and the neutrino (ν).
- If the β^+ were to receive all of the energy it would have the maximum energy

  $E_T - 1.022 \text{ MeV} = E_{\beta max}$
- Positron shares excess energy with neutrino.

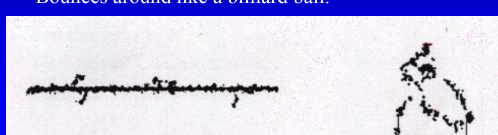
Energy of the Positron (β^+)



Average energy of β+ is 1/3 $E_{\beta max}$

Range of the Positron (β^+)

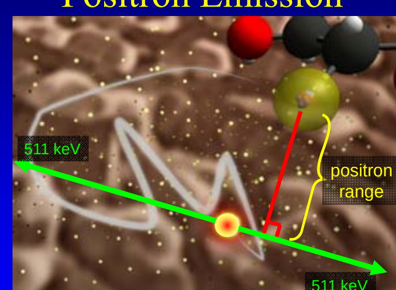
- The range of the positron is determined empirically.
- Unlike larger/heavier charged particles the positron does not travel is a straight path.
- Bounces around like a billiard ball.



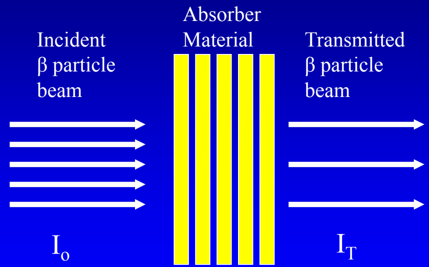
alpha **beta**

In water

Positron Emission

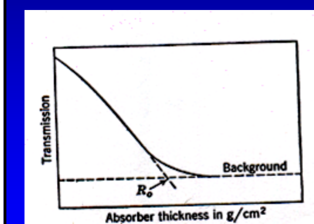


Range of the Positron (β^+)

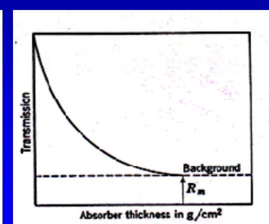


Transmission = I_T/I_o

Absorber Method for Determining Range of Positrons



Monoenergetic



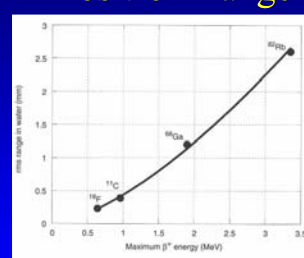
Continuous spectrum

Range of the Positron (e^+)

Isotope	E_{max} (MeV)	R_{max} (mm)
Ga-68	1.9	8.2
O-15	1.7	7.3
N-13	1.2	5.1
C-11	0.97	4.1
F-18	0.64	2.4

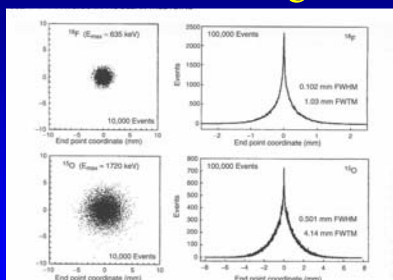
Note: Average range is about 1/3 the maximum.

Positron Range



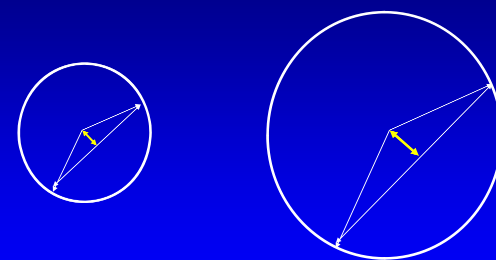
The rms range is proportional to positron energy.

Positron Range



The distribution of rms range is exponential and not well characterized by FWHM.

Non-Colinearity



The same level of non-colinearity leads to a bigger uncertainty with a larger ring diameter.

$R_{180} \approx 0.002 \times D_R$

Limit on PET Spatial Resolution

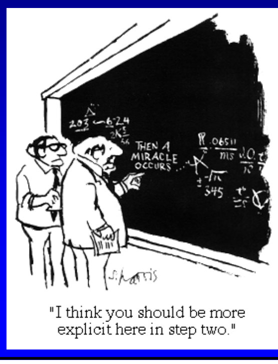
(in mm, regardless of detector size)

Scanner	β+ Range	Non-Colin	Total
Whole Body (100 cm)			
^{18}F	0.2	2.0	~2.2
^{82}Rb	2.6	2.0	~4.6
Animal (20 cm)			
^{18}F	0.2	0.4	~0.6
^{82}Rb	2.6	0.4	~3.0

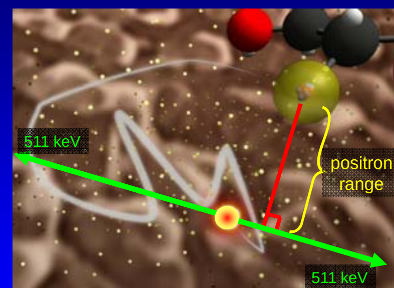
Summary

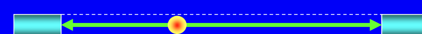
- PET images the annihilation photons that result from β^+ decay.
- The annihilation photons are collinear ± sd.
- The transition energy must be at least 1.022 MeV.
- Excess energy of the β^+ must be used before annihilation can occur
- PET spatial resolution is ultimately limited by the positron range and the non-colinearity of the annihilation

Annihilation Coincidence Detection

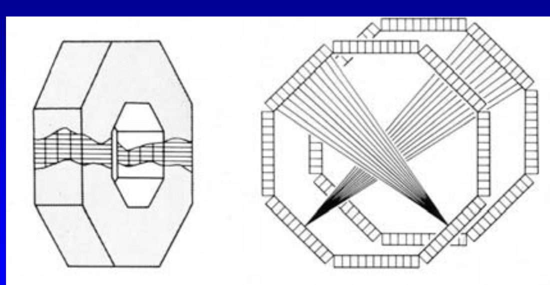


Positron Emission

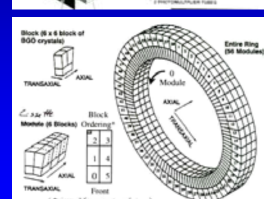


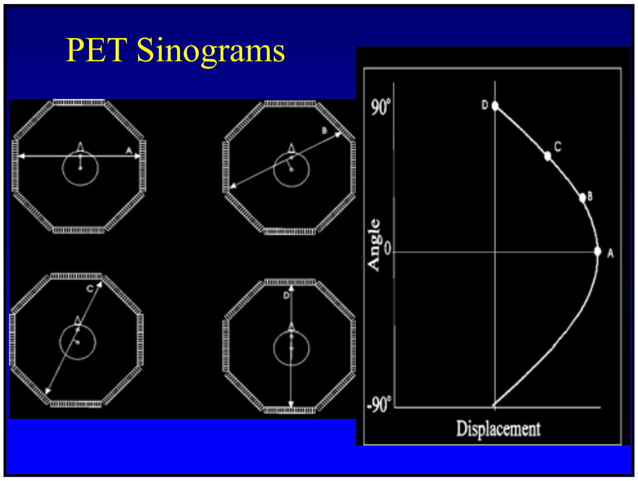


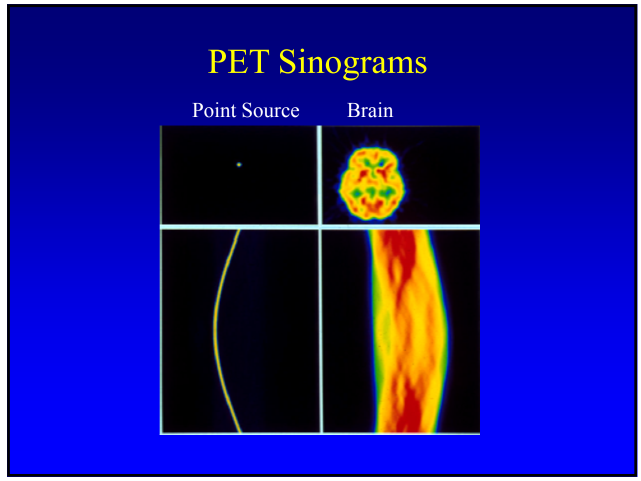
Detector Ring

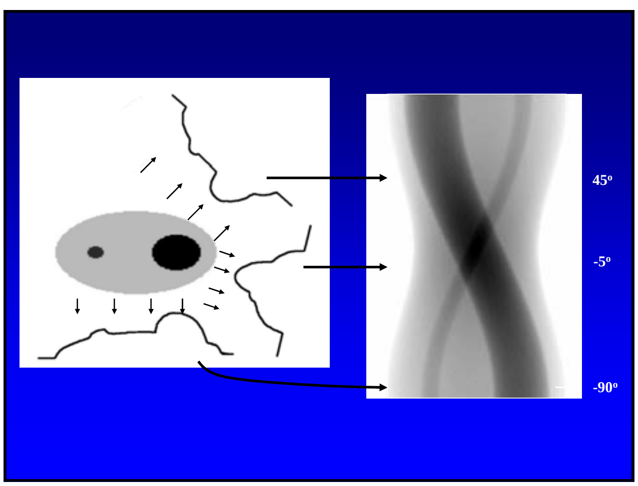


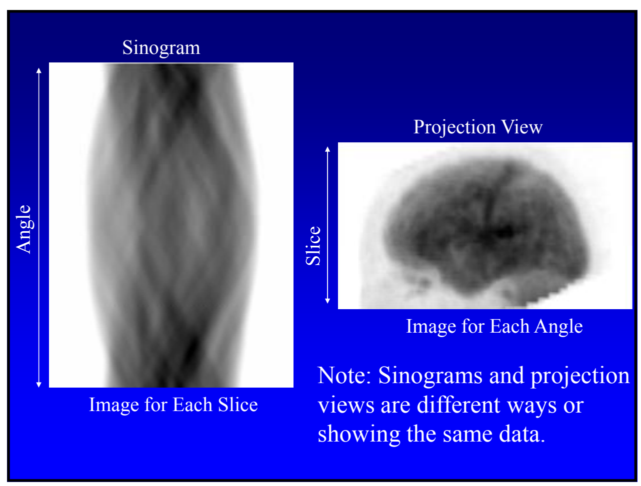
Detector Blocks (GE Advance NXi)

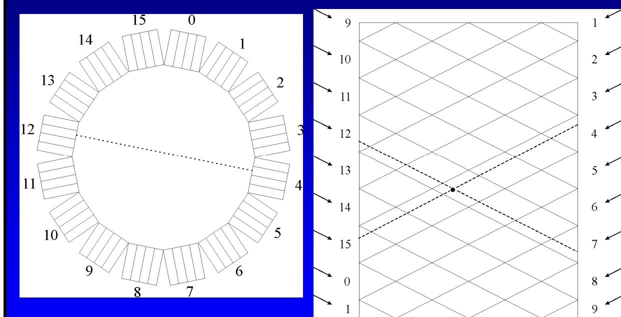



PET Sinograms
90°
Angle
0
-90°
Displacement
A
B
C
D


PET Sinograms
Point Source
Brain


45º
-5º
-90º

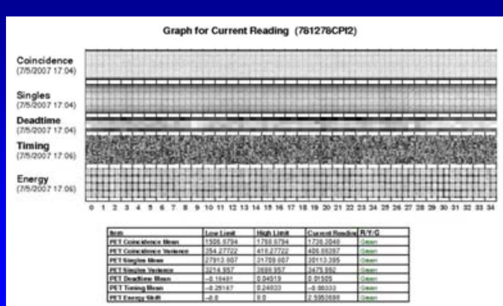

Sinogram
Angle
Image for Each Slice
Projection View
Slice
Image for Each Angle
Note: Sinograms and projection views are different ways or showing the same data.



Blank Scan Sinograms

Raw Normalized Detector Out

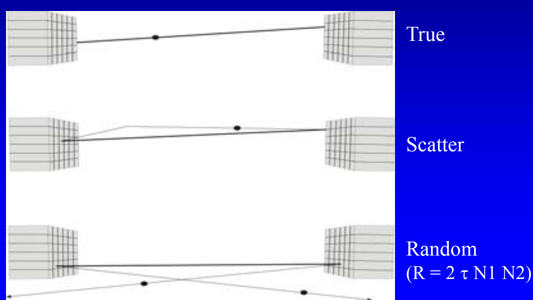
Daily PET QC



PET Sinograms

- Point in transverse slice maps to sine wave
- Displacement (x) vs Angle (y)
- Each row is a projection through the object at the corresponding angle
- Each detector is mapped along a diagonal
- Each pixel in the sinogram corresponds to a particular "line of response" (LOR) i.e. detector pair

True, Scatter and Random Coincidence Detections

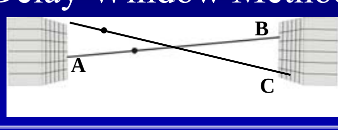


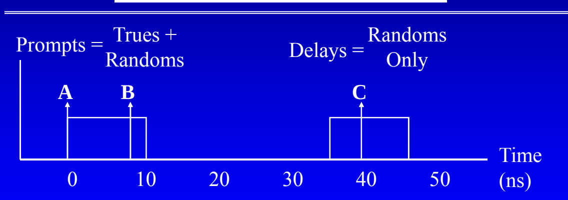
Randoms Estimation

- Background Subtraction
- Singles Rate Calculation

  $R = 2\,\tau\,N_1\,N_2$
- Delay Window Method

Delay Window Method





Estimated Trues = Prompts - Delays

Noise Equivalent Counts (NEC)

- Not all coincidences are created equal. We must correct for random and scatter coincidences.
- The "Noise Equivalent Count" is the number of counts from a Poisson distribution (SD estimated by SQRT{N}) that will yield the same noise level as in the data at hand.
- This allows one to compare counts acquired on different machines or using different acquisition schemes.

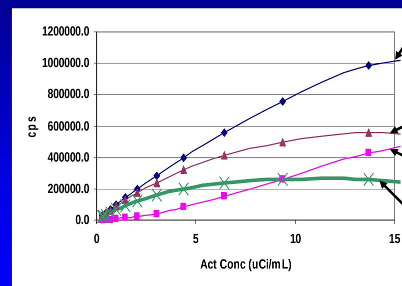
Noise Equivalent Counts (NEC)

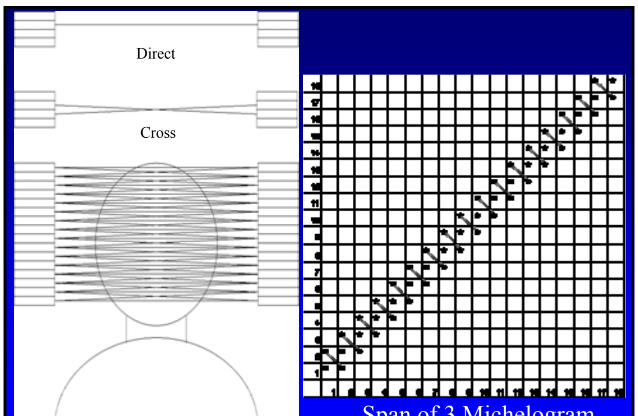
$$NEC = \frac{T}{1 + k\,R/T + S/T}$$

Where T is True counts
R is Random counts
S is Scattered counts

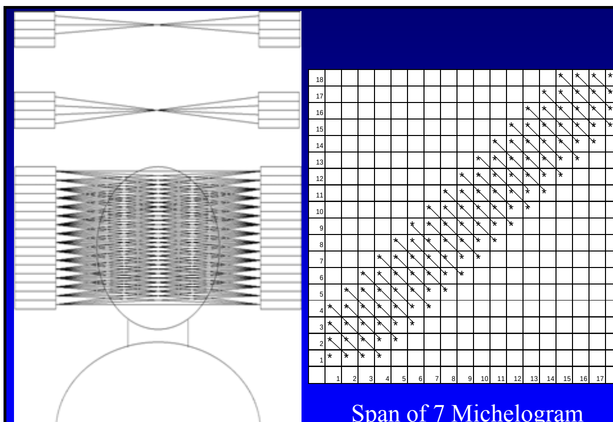
k = 1 if singles rates calculation and
2 if delayed subtraction method

Scatter Fraction, Count Rate and Randoms Measurement

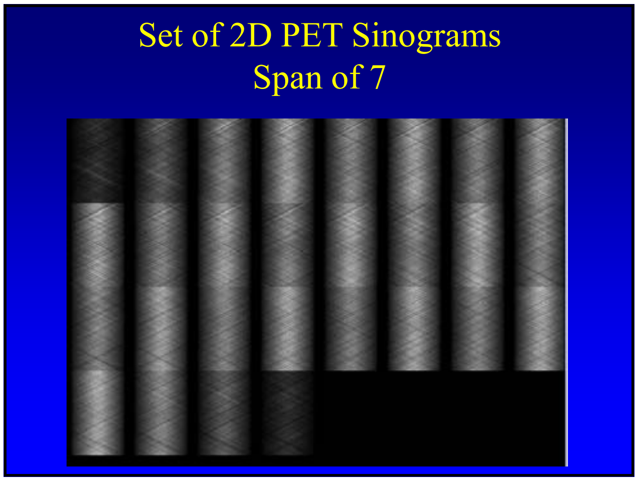


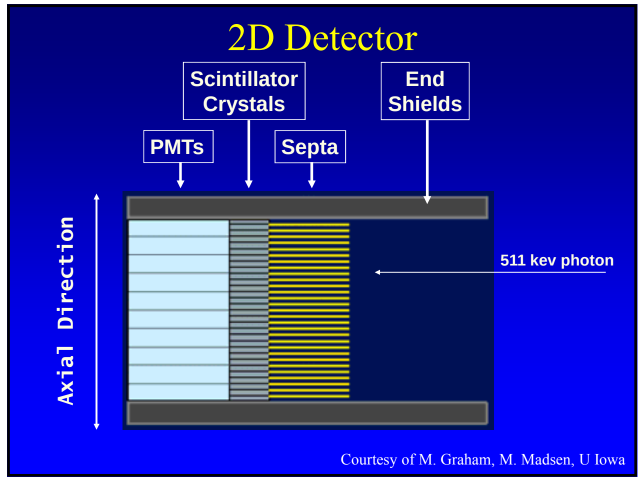


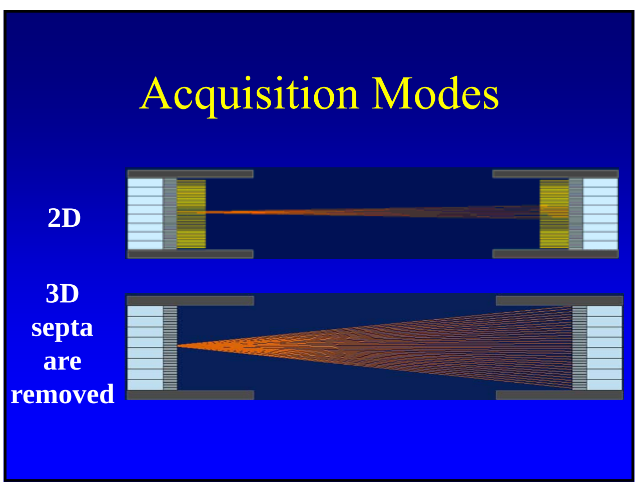
Span of 3 Michelogram

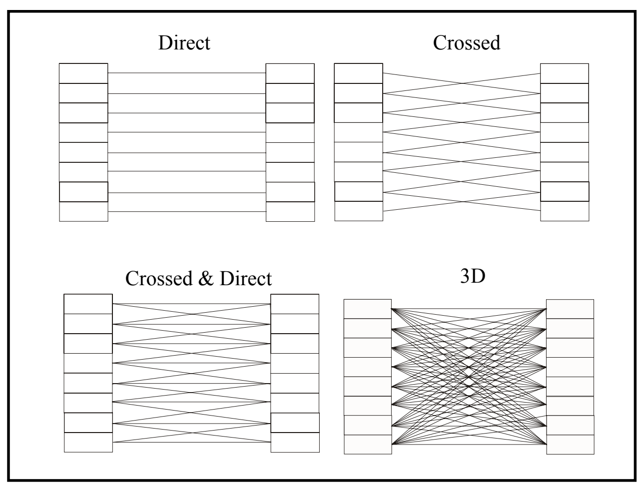


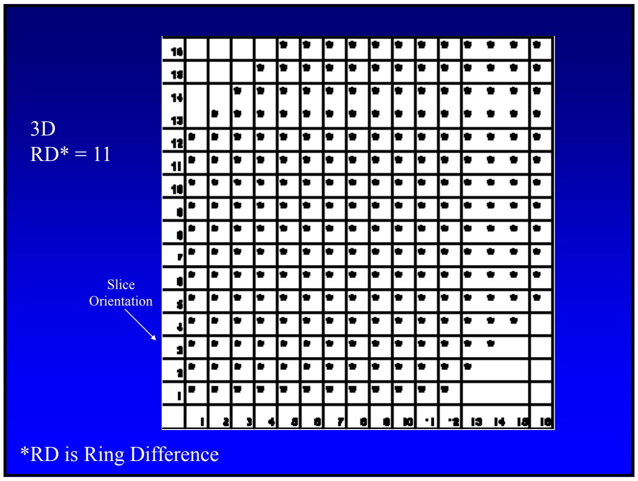
Span of 7 Michelogram

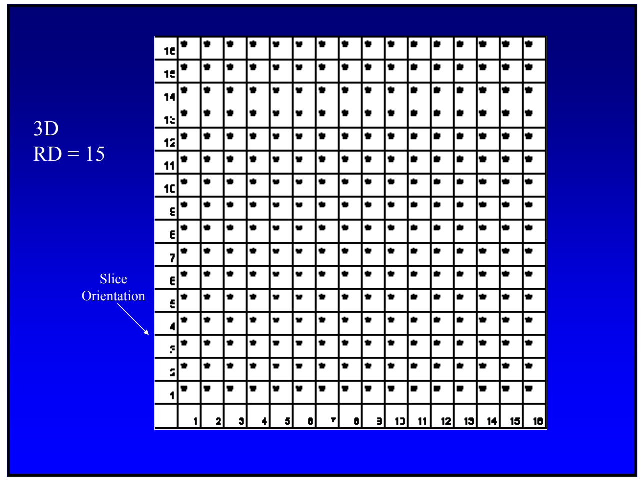

Set of 2D PET Sinograms
Span of 7

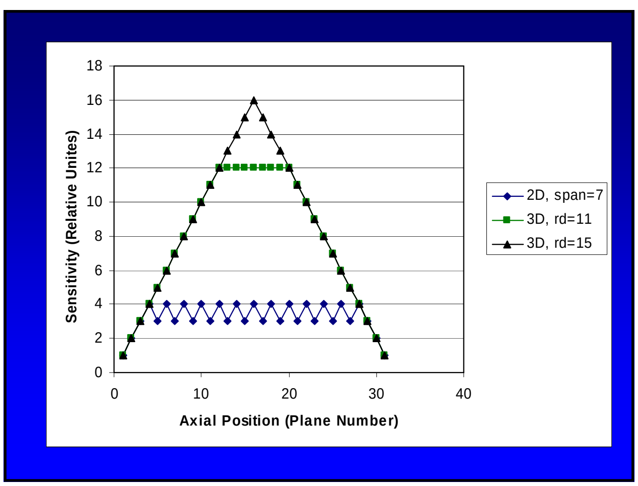

2D Detector
Scintillator Crystals
End Shields
PMTs
Septa
511 kev photon
Axial Direction
Courtesy of M. Graham, M. Madsen, U Iowa

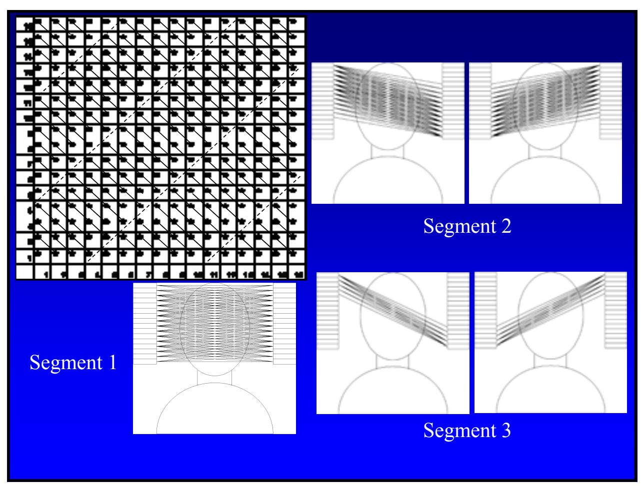

Acquisition Modes
2D
3D septa are removed


Direct
Crossed
Crossed & Direct
3D

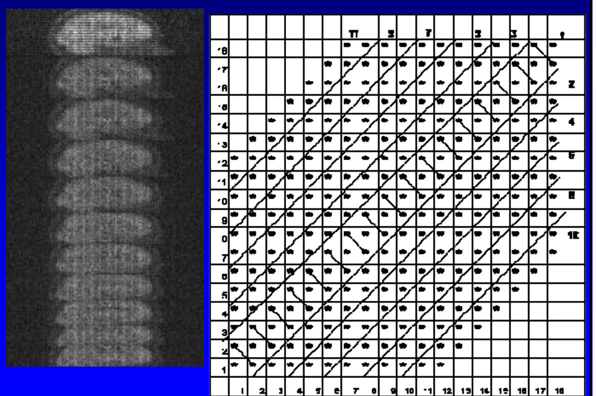

3D
RD* = 11
Slice Orientation
*RD is Ring Difference


3D
RD = 15
Slice Orientation

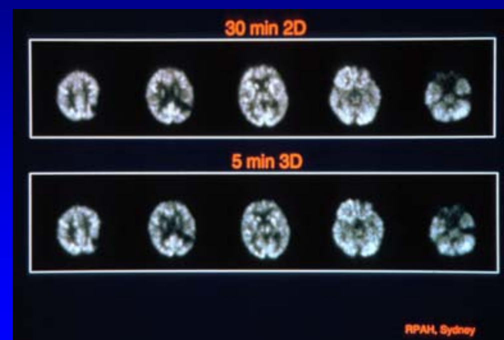

Sensitivity (Relative Unites)
Axial Position (Plane Number)
2D, span=7
3D, rd=11
3D, rd=15
0
2
4
6
8
10
12
14
16
18
0
10
20
30
40


Segment 2
Segment 1
Segment 3

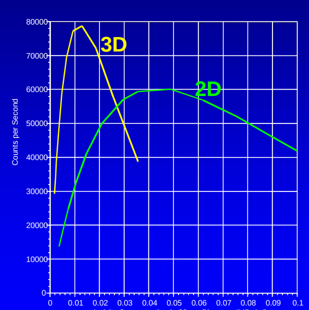
GE 3D Projection view and Michelogram



3D vs 2D in Brain PET



NEC Rate: 2D vs 3D



3D PET

- Sensitivity drops off towards edges
- 4-5X increased sensitivity overall
- Increased scatter (15% to 40%)
- Increased randoms from out-of-field activity
- Rebinning algorithms to apply 2D reconstruction
- Some devices can acquire in 2D or 3D whereas some can only acquire in 3D
- 3D in Brain, 2D (or 3D) in Whole Body

3D Data – How much?

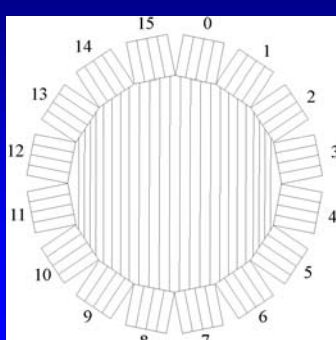
(values in parentheses are for GE Advance NXi)

- N_d is # of detectors in a ring (672)
- N_r is # of detector rings (18)
- Assume FOV is ½ the ring diameter
- Max ring difference
- $N_s = (N_r)^2 (N_d/2) (N_d/2) = \frac{1}{4} N_r^2 N_d^2$
- For GE NXi,
  - 3.66×10^7 samples
  - 73 MB per bed position (for 2 bytes/pixel)

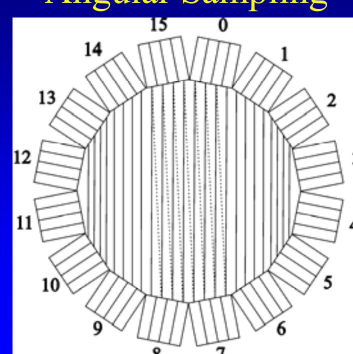
3D Data Reduction

- Combine angular samples or "mashing"
  - Samples reduced by 2^{-m} where m is the "mashing factor"
- Combine axial samples (span of 7)
- Limit ring difference (11 vs 15)

Arc Correction

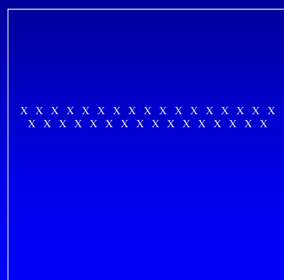


Angular Sampling



Angular Sampling

- Interleaved rows combined into one row
- Doubles transverse sampling
- Halves angular sampling
- Slight angular error

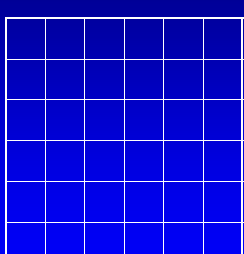


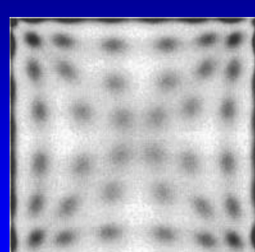
Interleaved Sinogram

Criteria for Scintillation Material

- Detection Efficiency (Stopping Power)
  - High Effective Z
  - High Density
- Light Output
  - Good energy resolution
  - Good crystal identification
- Decay Time
  - Reduction of random coincidences
  - Time-of-Flight PET

Crystal Identification

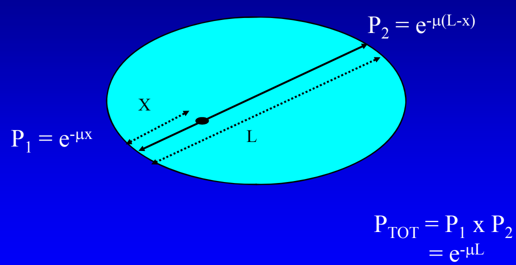




New Detector Materials

SCINTILLATOR	NaI(Tl)	BGO	LSO	GSO
Rel. Light Output	100	15-20	75	20-25
Peak Wavelength (nm)	410	480	420	440
Decay Constant (ns)	230	300	12,42	30-60
Density (g/mL)	3.67	7.13	7.40	6.71
Effective Z	51	75	66	59
Index of Refraction	1.85	2.15	1.82	1.85
Hygroscopic ?	Yes	No	No	No

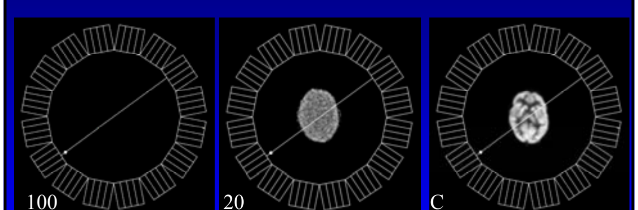
PET Attenuation Correction



PET Attenuation Correction Methods

- Calculated
  - No noise but possibly inaccurate
- Measured
  - Accurate but noisy
- Segmented, Measured
  - Less noise => less time
- Singles
- CT-Based

Measured Attenuation Correction

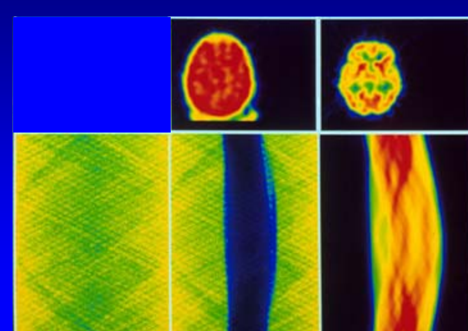


Blank Transmission Emission

Corrected Emission = (Blank/Transmission) * Emission

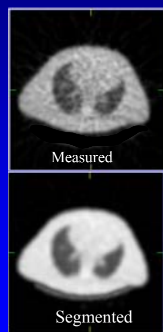
= (100/20) * C

Measured Attenuation Correction

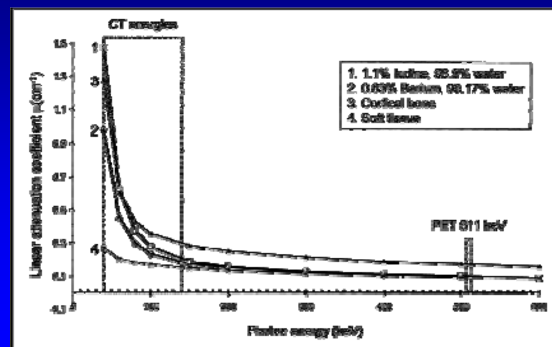


Segmented, Measured Attenuation Correction

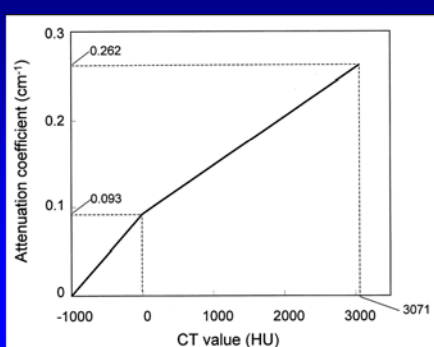
- Noise added from measured attenuation correction
- Rel err in unif phantom (10 min EM)
  - 9% with calc atten
  - 16% with 10 min TR
  - 18% with 5 min TR
- Segmentation classifies by tissue type
- Smoothes lung areas
- Substantial reduction in noise added



PET-CT Attenuation Correction



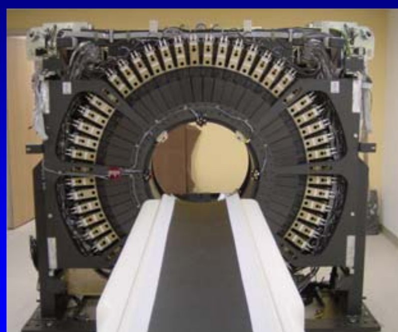
PET-CT Attenuation Correction



PET-CT Attenuation Correction

- Acquire CT Scan and reconstruct
- Apply energy transformation
- Reproject to generate correction matrix
- Smooth to resolution of PET
- Apply during reconstruction

GE Advance NXi



GE Discovery ST

GE Discovery ST

PET-CT Scanners

	GE Discovery STE	GE Discovery ST	Philips Gemini
Detector Dimension (mm)	4.7 x 6.3 x 30	6.2 x 6.2 x 30	4 x 6 x 20
# of PET Detectors	13,440	10,080	17,864
PET Detector Material	BGO	BGO	GSO
Spatial Resolution	5.0	6.1	4.9
2D/3D	2D/3D	2D/3D	3D
Atten Corr	CT	CT	CT&Cs-137

	Siemens Biograph LSO	Siemens Hi-Rez LSO
Detector Dimension (mm)	6.5 x 6.5 x 25	4 x 4 x 20
# of PET Detectors	9,216	23,336
PET Detector Material	LSO	LSO
Spatial Resolution	6.3	4.6
2D/3D	3D	3D
Atten Corr	CT	CT

Time-of-Flight PET

Speed of Light $c = 3 \times 10^{10}$ cm/s

Time (ns)	0.1	0.5	1.0	5.0
Distance (cm)	3	15	30	150

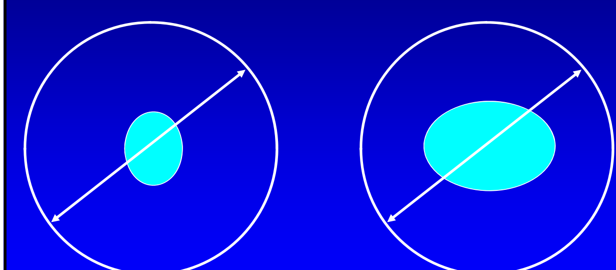
Time-of-Flight PET

$\Delta x = c\,\Delta t/2$

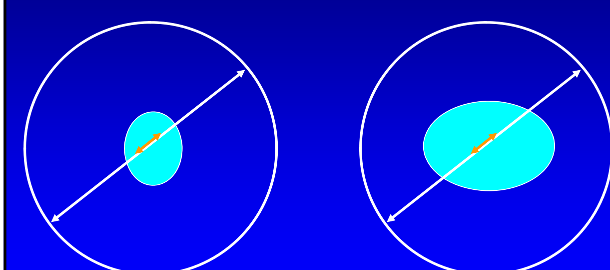
Where Δx is the time-of-flight spatial uncertainty and Δt is the timing resolution.

Δt (ns)	0.1	0.3	0.5	1.0
Δx (cm)	1.5	4.5	7.5	15.0

Time-of-Flight PET



Time-of-Flight PET



Assume Δt of 0.5 ns => Δx of 7.5 cm

Time-of-Flight PET

SNR Gain from Time-of-Flight PET

$$D/1.6\,\Delta x \approx 2\,D/\,1.6\,c\,\Delta t$$

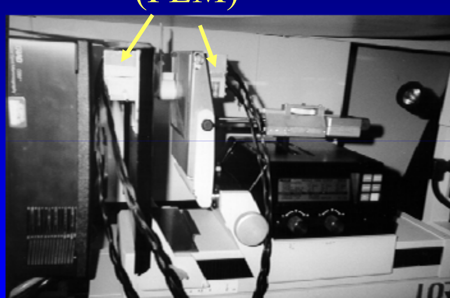
where D is the diameter of the object

D (cm)	20	30	40
SNR Gain	1.6	2.5	3.3

Special Devices

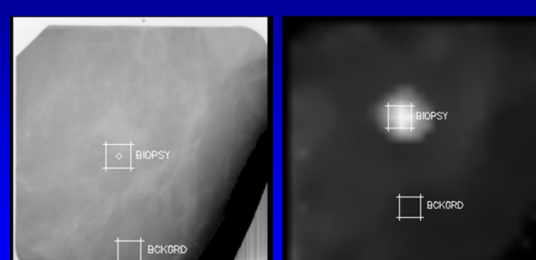
- Positron Emission Mammography
- MicroPET
- PET/MR

Positron Emission Mammography (PEM)



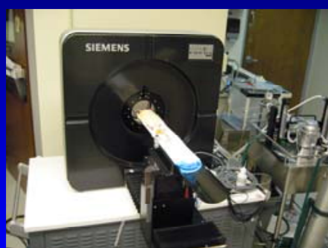
Courtesy of Wake Forest University and PEM Technologies

Positron Emission Mammography (PEM)



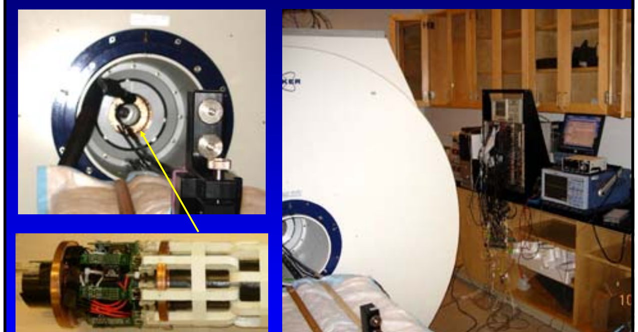
Courtesy of Wake Forest University

CHB MicroPET Scanner



1.4 mm resolution
7% sensitivity

PET-MRI



Courtesy of Simon Cherry, PhD

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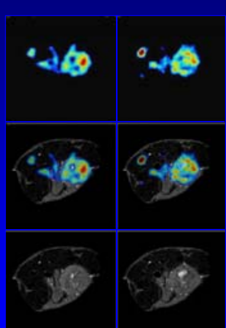
In Vivo Simultaneous PET/MRI



Mouse
FDG Tumor Imaging

PET
- ~200 µCi ^{18}F-FDG
- Voxel size: 0.35x0.35x1.5 mm^3

MRI
- RARE sequence
- Whole body imaging RF coil
- FOV=4x4 cm^2
- Matrix size 256x256

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Summary

- Modern scanners designed for oncologic imaging
- All PET sales are now PET/CT scanners
- New scintillation crystals combine excellent detection efficiency with short decay times
- Shorter decay times leads to possibility of time-of-flight PET.
- MicroPET scanners can provide very high spatial resolution with high sensitivity in a small foot print and easy access to the research animals.


FAR SIDE
Unbeknownst to most historians, Einstein started down the road of professional basketball before an ankle injury diverted him into science.