AAPM2018 CE: New and Emerging PET Instrumentation and Technologies

Tuesday July 31st at 11:00-12:15

Solid State Digital Photon Counting PET/CT Instrumentation and Technology

Jun Zhang, PhD, DABR
Assistant Professor

Wright Center of Innovation in Biomedical Imaging
Department of Radiology
The Ohio State University Wexner Medical Center

Disclosure

None

Let's start with a brief History of PET

- 1928: Existence of positron first postulated
- 1932: gave the positron its name - positron
- 1950: introduced the concept of positron emission
- 1970: first synthesis of FDG
- 1975: first commercial PET scanner
- 1980s: 1st generation TOF PET scanners
- 2000s: 2nd generation TOF PET scanners
- 2013 -: 1st solid state clinical PET/CT, 3rd generation TOF

Neurology. 2013 Mar 5; 80(10): 952–956.

PMT TOF PET/CT Systems

Philips Ingenuity TF (495ps)

Siemens Biograph 64 / mCT (525ps)

GE Discovery 690 (544ps)

Toshiba Celesteion (410ps)

United Imaging uMI510 (475ps)

SinoUnion PoleStar m660 (434ps)

Vereos DPC TF 64

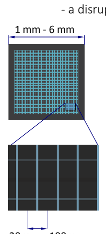
- 764mm PET ring
- 3.86x3.86x19mm LYSO
- 18 detector modules
- 310 ps timing

Vereos at The Ohio State University Wexner Medical Center
Wright Center of Innovation (*PI: Michael V Knopp, MD, PhD*)

Solid State DPC PET

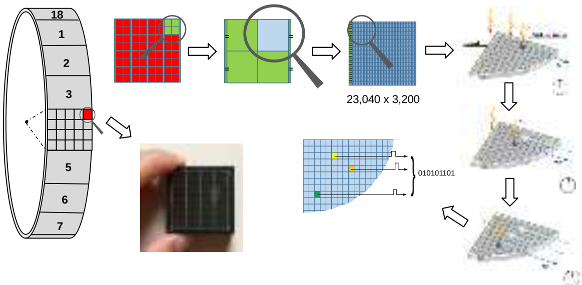
silicon photomultiplier (SiPM)

- a disruptive photosensor technology

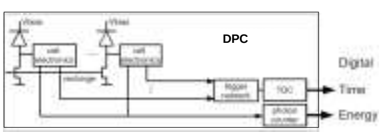


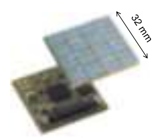
- Array of many self-quenched Single-photon avalanche diodes (SPADs) connected in parallel
- The combined output of all the microcells is “proportional” to the incident photon flux.
- Increasingly interesting as replacement for PMTs:
  - high gain (~10^6)
  - high PDE
  - compact and rugged
  - transparent to γ-photons
  - fast response (ns)
  - insensitive to magnetic fields

Vereos PET Detector Geometry



Digital Photon Counter



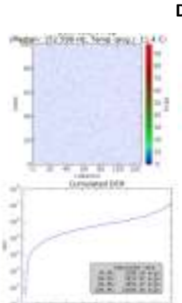


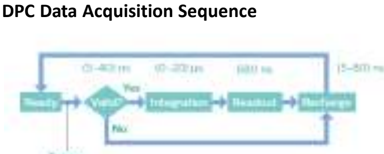
- Cell -> active circuitry -> quenches discharge when single phone detected -> output -> sum # of cells
- Cell -> balanced trigger network -> ultra low trigger level to set 1st photon for timestamp -> small single-photon time jitter
- negligible noise at single photon level -> switch off noisiest

16 Si dies (4 x 4)
Each Si die:
→ 1 timestamp
→ 4 pixels values (no. of counts)

D. R. Schaart et al "Advances in Digital SiPMs ...," NIM A 809, 31-52, 2016

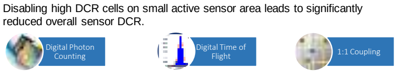
DPC Data Acquisition Sequence





Biggest contribution to the overall sensor DCR is caused by only a small percentage of the cells such as ~10 % cells responsible for 70-80% DCR.

Disabling high DCR cells on small active sensor area leads to significantly reduced overall sensor DCR.



1. Philips Vereos PET/CT Whitepaper
2. Haemisch Y, et al. Physics Procedia. 2012;37:1546–1560

NEMA NU 2-2012 Spatial Resolution

- a point source of ~4 MBq ^{18}F
- capillary tube, ≤1 mm inner D, 100 mm length
- center of axial FOV and 3/8 off axial FOV
- (x,y) = (0, 1), (0, 10), (10, 0), (0, 20) and (20, 0) cm
- Listmode, 3D Fourier re-projection
- Standard NEMA analysis in FWHM and FWTM
- Results were combined and averaged for the two axial positions

Philips fixtures:
for axial measurements, rotated the capillary with 90 degrees -> perpendicular to the long axis of the system -> axial extent of the source ≤1 mm

NEMA NU 2 2012 Spatial Resolution

	Axial		Transverse (Radial)		Transverse	
(in mm)	FWHM	FWTM	FWHM	FWTM	FWHM	FWTM
Center	**3.88**	8.36	**4.13**	8.27	**4.13**	8.27
at 10cm	4.22	8.47	4.47	8.8	4.36	8.78
at 20cm	4.62	9.16	5.75	10.31	4.92	10.26

Key factors determining PET system SR:
- crystal width
- positron range
- Noncollinearity
- localization decoding error (anger logic)
- reconstruction

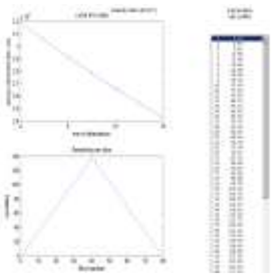
- NOT the smallest detectable lesion size of a PET system

1. WW Moses. Nucl Instrum Methods Phys Res A. 2011; 648 (Supplement 1): S236–S240
2. Jun Zhang, Michael V Knopp. J Nucl Med 2017; 58 (supplement 1): 1322

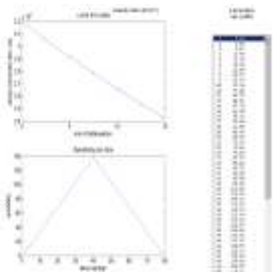
NEMA NU 2-2012 Sensitivity

NEMA PET Sensitivity Phantom *(Data Spectrum Corporation, Hillsborough, NC)*

- five concentric aluminum sleeves (70 cm)
- stacked one inside the other
- 70 cm plastic tubing with ~6MBq ^{18}F
- Successive measurements
- Decay corrected count rate was summed for all slices to give the total count rate for each sleeve and then extrapolated to an attenuation free measurement.



Average at center: 5.5 kcps/MBq

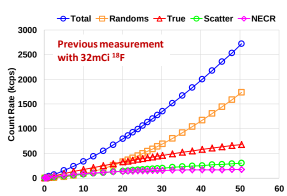


Average at 10 cm off center: 5.5 kcps/MBq

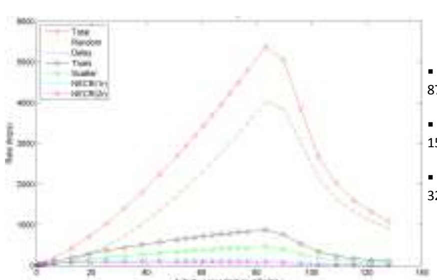
Diff caused by gaps between detector elements -> LOR ends at gap -> caused reduction less at 0cm -> geometry leads to 1% diff

NEMA NU 2-2012 Scatter fraction, Count loss and Randoms

NEMA PET Scatter phantom
Tubing Activity: 3181MBq / 86mCi ^{18}F
Filled length: 700mm



NEMA NU 2-2012 Scatter fraction, Count loss and Randoms



- **peak true count rate:** 878 kcps @ 83 kBq/mL
- **peak NECR:** 153 kcps @ 54 kBq/mL
- **scatter fraction:** 32.2 %

NECR, SNR and Background

$$NECR = \frac{T^2}{P}$$

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

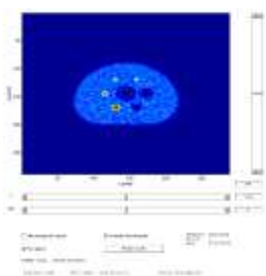
$$SNR \approx \frac{T}{P + |^{0}_{R}|}$$

More background → more statistical image noise.

P	T	S	R	NECR
100	50	50	0	25
100	50	20	30	25
100	50	45	5	25
100	**100**	**0**	**0**	**100**
200	100	100	0	50
200	100	50	50	50
400	**200**	**200**	**0**	**100**
1600	**400**	**800**	**400**	**100**

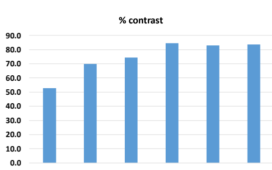
Maximize NECR by maximizing sensitivity (Trues/s/activity) while minimizing background (S/T and R/T)

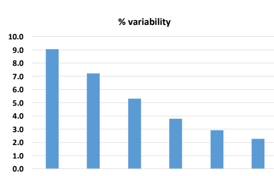
NEMA NU 2-2012 Image Quality



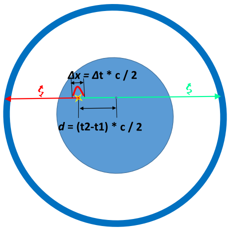
$$Q_H = 100 \times \frac{C_{M,S}/C_{M,B} - 1}{C_{T,S}/C_{T,B} - 1}$$

NEMA NU 2-2012 Image Quality



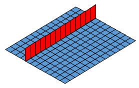


Time of Flight

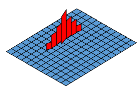


$$G_{TOF} = \frac{D}{\Delta x} = \frac{2D}{c\Delta t}$$

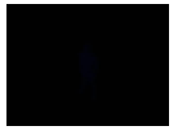
$$G_{SNR} = \sqrt{\frac{D}{\Delta x}}$$



non-TOF: Detected event projected to *all* voxels between detector pairs; Many Iterations to Converge; noises contributed from all voxels used



Time-of-Flight: Detected event projected *only* to voxels within the annihilation localization uncertainty; less iterations to Converge; less noise; improved SNR

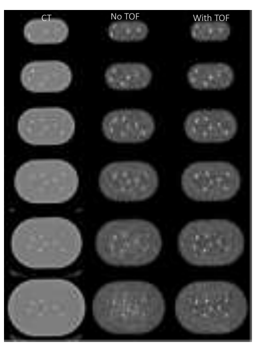


Δt (ps)	Δx (cm)
600	9
550	8.3
310	4.6
200	3
100	1.5
70	~1

Surti, Karp. Phys Med, 2016; 32(1)

Fillable, Tapering Phantom with 1 cm lesions

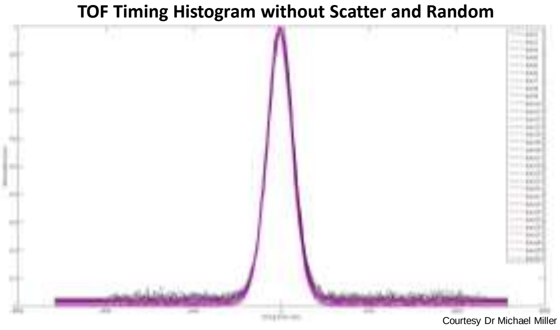
Josh Wilson, PhD



Courtesy Dr Tim Turkington

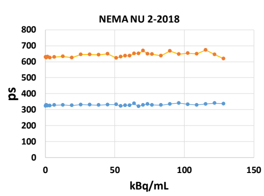
NEMA NU 2-2018 vs NEMA NU 2-2012

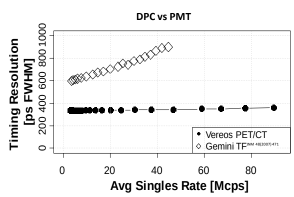
TOF Timing Histogram without Scatter and Random



Courtesy Dr Michael Miller

TOF Timing Resolution





1. Wang GC, Li X, Niu X, Du H, Balakrishnan K, Ye H, et al. PET Timing Performance Measurement Method Using NEMA NEC Phantom. IEEE Transactions on Nuclear Science. 2016; 63(3): 1335-1342

2. Mao Y, Miller M, Bai C, et al. Evaluation of a TOF resolution measurement method using standard NEMA NEC phantom. J Nucl Med. 2017; 58 (supplement 1): 436

Surti S, Kuhn A, Werner ME, Perkins AE, Kolthammer J, Karp JS. Performance of Philips Gemini TF PET/CT scanner with special consideration for its time-of-flight imaging capabilities. J Nucl Med. 2007; 48(3): 471-80

NEMA Results Summary

Index	MeasurementS	Improved?	downgraded?	Equal?
1	NEMA NU 2 scatter fraction			X
2	NEMA NU 2 maximum relative count rate error	X		
3	NEMA NU 2 hot sphere contrast , 10 mm (Qh)		X	
4	NEMA NU 2 hot sphere contrast , 13 mm (Qh)		X	
5	NEMA NU 2 hot sphere contrast , 17 mm (Qh)		X	
6	NEMA NU 2 hot sphere contrast , 22 mm (Qh)			X
7	NEMA NU 2 hot sphere contrast , 28 mm (Qh)			X
8	NEMA NU 2 hot sphere contrast , 37 mm (Qh)			X
9	NEMA NU 2 background variability, 10 mm (BGVar)	X		
10	NEMA NU 2 background variability, 13 mm (BGVar)	X		
11	NEMA NU 2 background variability, 17 mm (BGVar)	X		
12	NEMA NU 2 background variability, 22 mm (BGVar)	X		
13	NEMA NU 2 background variability, 28 mm (BGVar)	X		
14	NEMA NU 2 background variability, 37 mm (BGVar)	X		
15	NEMA NU 2 transverse spatial resolution at 1 cm (mm in FWHM)			X
16	NEMA NU 2 transverse radial spatial resolution at 10 cm (mm in FWHM)			X
17	NEMA NU 2 transverse tangential spatial resolution at 10 cm (mm in FWHM)			X
18	NEMA NU 2 axial spatial resolution at 1 cm (mm in FWHM)	X		
19	NEMA NU 2 axial spatial resolution at 10 cm (mm in FWHM)	X		
20	Activity concentration at location of the NEMA NU 2 peak NECR (kBq/mL)	N/A	N/A	N/A
21	NEMA NU 2 peak NECR (kcps)		X	
22	NEMA NU 2 peak true count rate (kcps)	N/A	N/A	N/A
23	NEMA NU 2 system sensitivity at center of FOV (cps/MBq)			X
24	NEMA NU 2 system sensitivity 10 cm from center of FOV (cps/MBq)			X
25	Time-of-flight resolution (ps in FWHM)	X		

PET Design Goals

1. Maximize NECR by maximizing sensitivity (Trues/s/activity) while minimizing background (S/T and R/T)
2. Good spatial resolution (not compromising much sensitivity)
3. Better TOF capability
4. Optimized recon

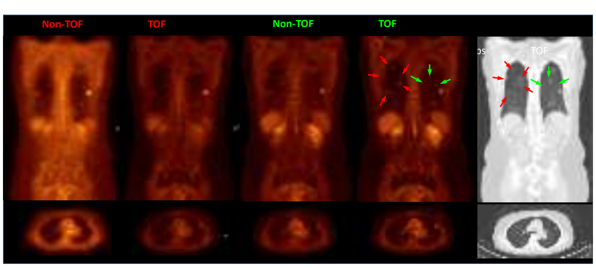
Lesion Detectability

Gemini

Vereos

Courtesy Dr. Michael V Knopp

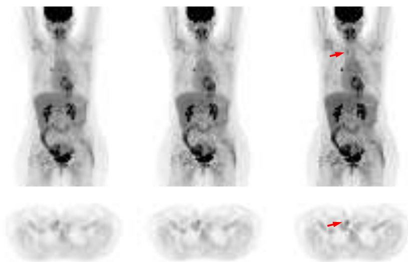
TOF: PMT PET vs DPC PET



Gemini 4mm PET

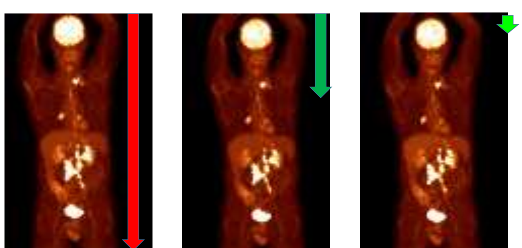
Vereos 4mm PET

PVE by adjusting voxel size



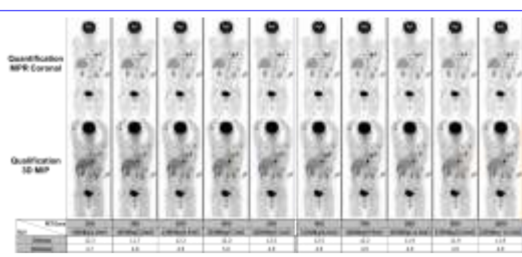
4x4x4 mm³   2x2x2 mm³   1x1x1 mm³

Speed

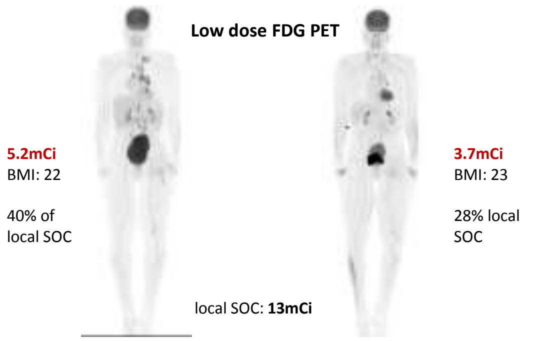


90s/bed 15min   30s/bed 5min   9s/bed 1.5min

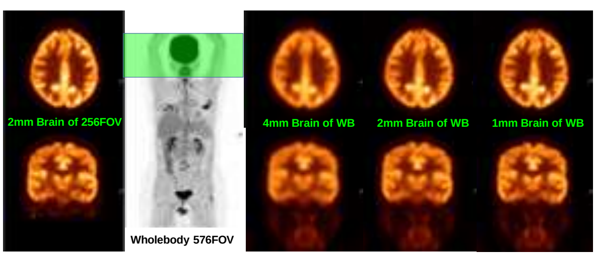
Low Dose FDG PET



NIH R01 PIs: *Knopp, Zhang*

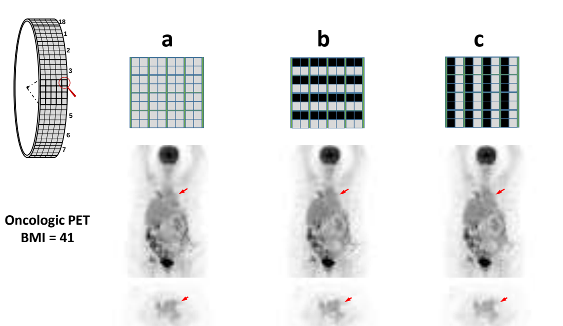


Speed, Convenience, Dose, IQ

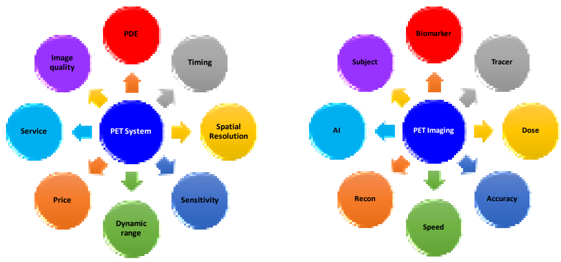


10min FDG

90s/bed FDG



Future: Direction vs Balance



Acknowledgement

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- Research support: Ohio Third Frontier OSDA TECH 09-028 (*Knopp),* NCI R01CA195513 (*Knopp, Zhang*)
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