TOF PET technology today, and Siemens Biograph Vision PET/CT scanner

Maurizio Conti, Acireale September 3,2019

Table of contents

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TOF PET technology and advantages

Time-of-Flight PET (TOF)

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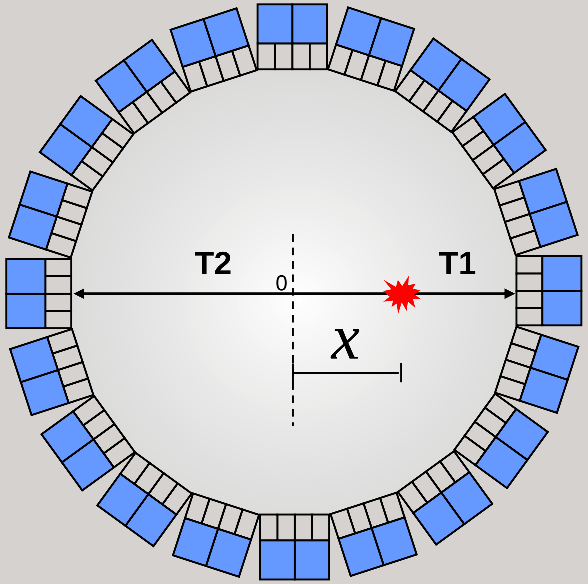
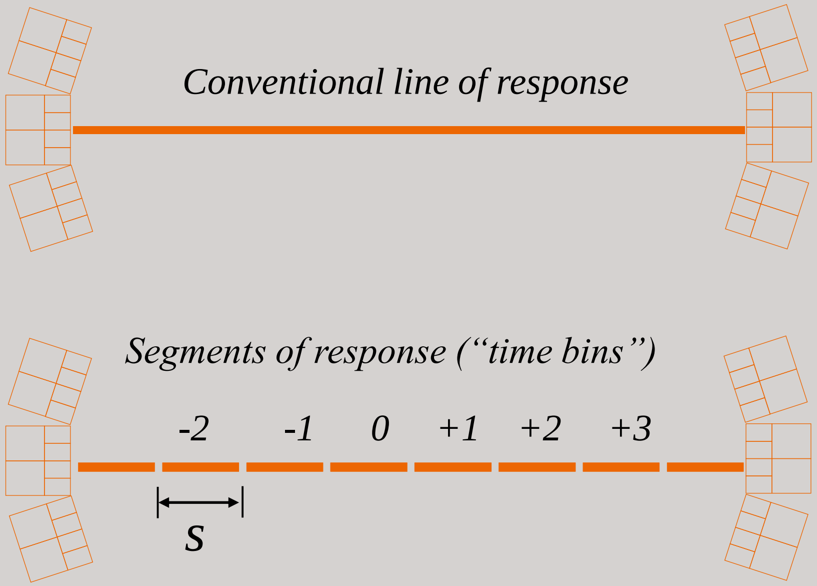
Time of Flight (TOF) systems measure the time between each coincidence photon to determine the event location along the line of response. The event location accuracy can be measured proportionally to the system's time resolution.



$$x = \frac{(T2 - T1) \times c}{2}$$

c = speed of light

TOF systems are able to record segments of response instead of lines of response. The time resolution defines the size of the segment of response ("time bin").



s *=> directly proportional to the system's time resolution*

Time-of-Flight PET (TOF)

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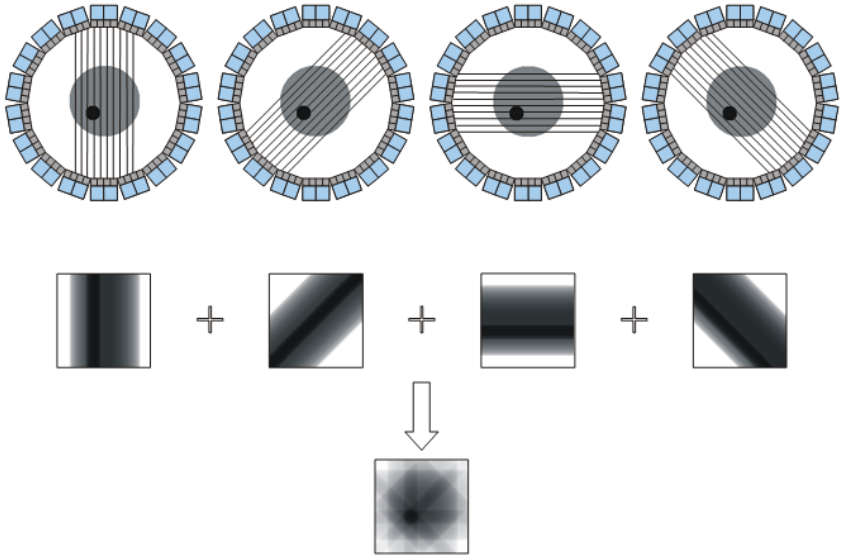
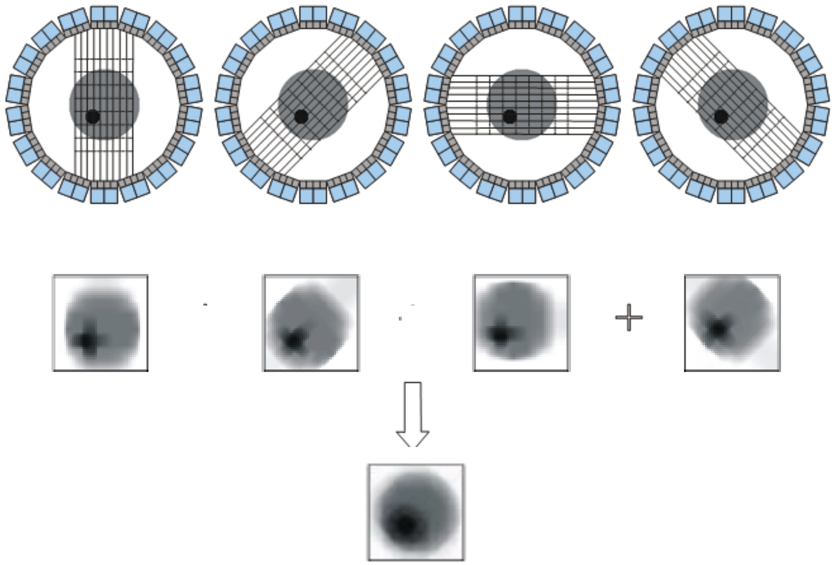
Conventional



- LOR projections are summed together
- The resulting image is a rough approximation of the real image with noticeable blurring

ToF



- Projections are organized in time bins along each LOR
- The result is better estimation of the actual image with much less blurring (noise)

Time-of-Flight PET (advantage)

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TOF reconstruction = sensitivity amplification or noise reduction

$$G_{NEC} \approx \frac{D}{\Delta t}$$

$$G_{SNR} \approx \sqrt{\frac{D}{\Delta t}}$$

Δt (ps)	Δx (cm)	G_{NEC} (D=40cm)	G_{SNR} (D=40cm)
300	4.5	8.9	3.0
400	6	6.7	2.6
500	7.5	5.3	2.3
600	9	4.4	2.1

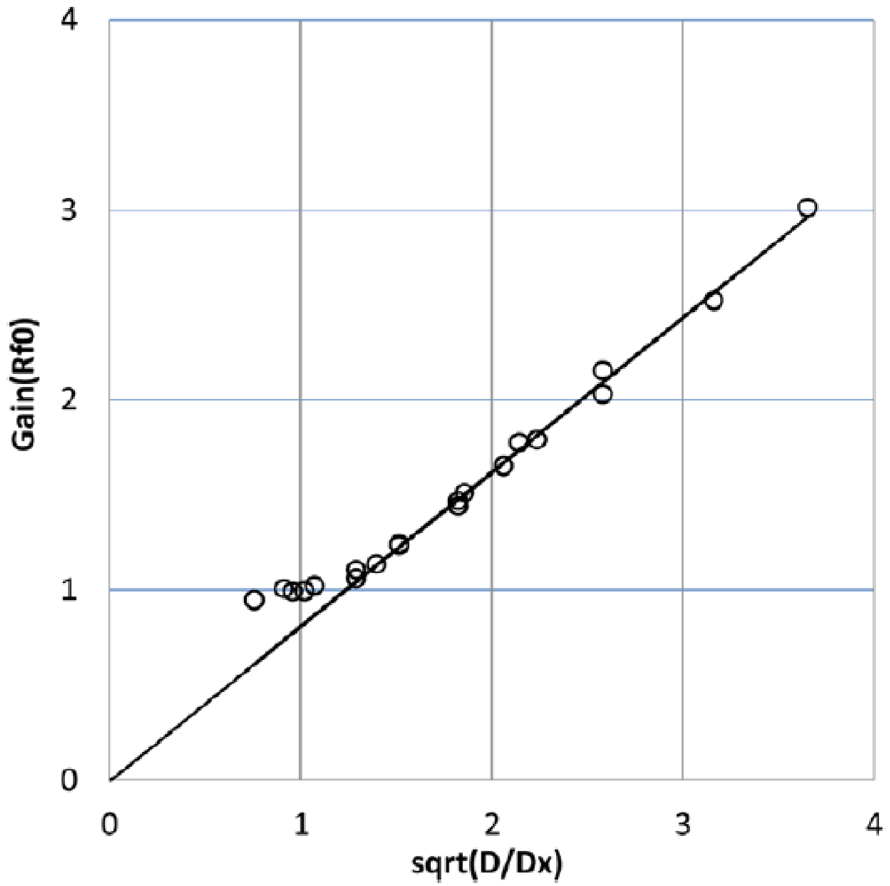
D is patient “diameter”, Δt is time resolution of TOF PET scanner
*estimate based on uniform cylindrical object and analytical reconstruction:

- T.F. Budinger, “Time-of-flight positron emission tomography: status relative to conventional PET”, *J. Nucl. Medicine*, vol. 24, pp. 73-78, 1983.
- M. Conti, "State of the Art and Challenges of Time-of-Flight PET", *Physica Medica*, no. 25, pp. 1-11, 2009.

SNR TOF gain validation: experimental and simulation

SNR_{gain} (or TOF gain) vs. Sqrt(D/Dx) at zero random fraction.

Graph is summary of all experimental and simulated data acquired in this work, plus data from reference



L. Eriksson and M. Conti, “Randoms and TOF Gain revisited”, *Phys. Med. Biol.* 60 1613-1623 (2015).

Time-of-Flight PET (advantages): noise reduction or improved contract recovery

same time,
better image

3 minute/bed

non-TOF

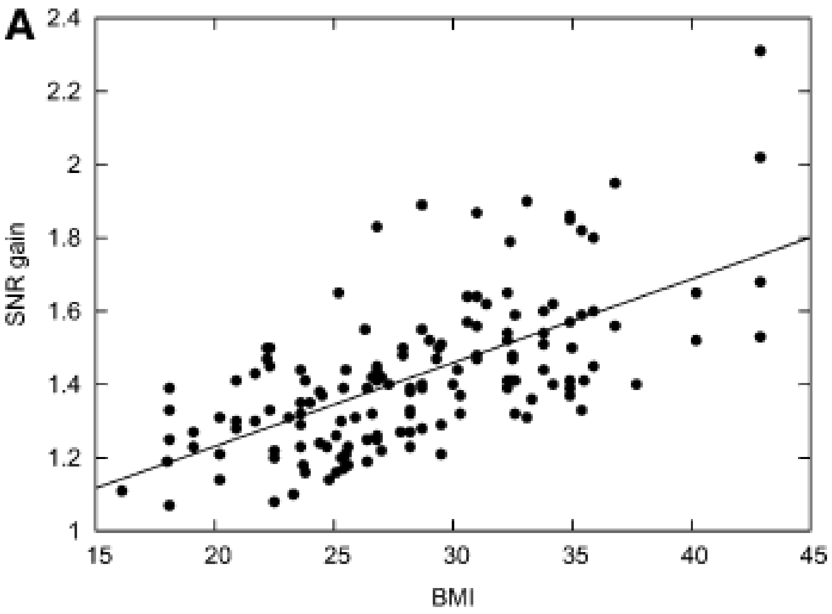
TOF

Time-of-Flight PET (advantages): noise reduction and patient size

Journal of Nuclear Medicine, published on January 15, 2010 as doi:10.2967/jnumed.109.068098

An Assessment of the Impact of Incorporating Time-of-Flight Information into Clinical PET/CT Imaging

Cristina Lois[1,2], Bjoern W. Jakoby[1,3,4], Misty J. Long[1], Karl F. Hubner[1], David W. Barker[1], Michael E. Casey[3], Maurizio Conti[3], Vladimir Y. Panin[3], Dan J. Kadrmas[5], and David W. Townsend[1]



- Multiple lesions (<2cm) analyzed in 30 patients
- Body Mass Index used as a measure of the size

$$G_{SNR} = \frac{SNR_{TOF}}{SNR_{nonTOF}} \propto \sqrt{\frac{D}{\Delta t}}$$

Time-of-Flight PET (advantages): more robust with inconsistent data

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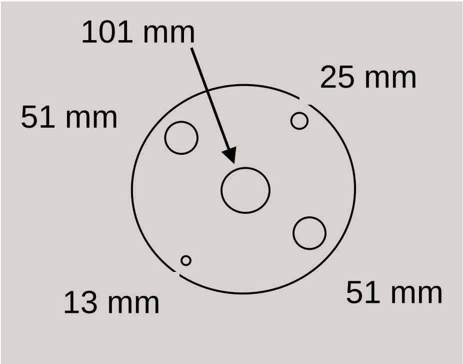
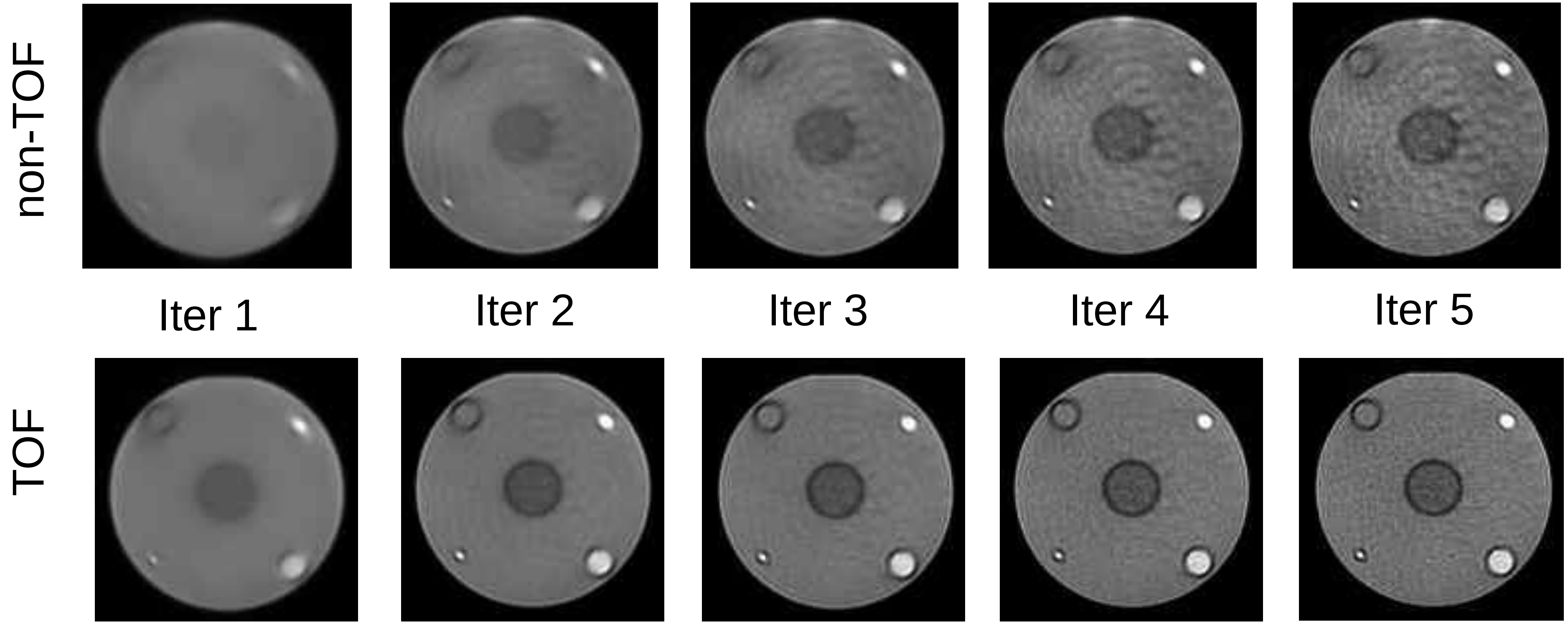
Inaccurate μ-map and normalization

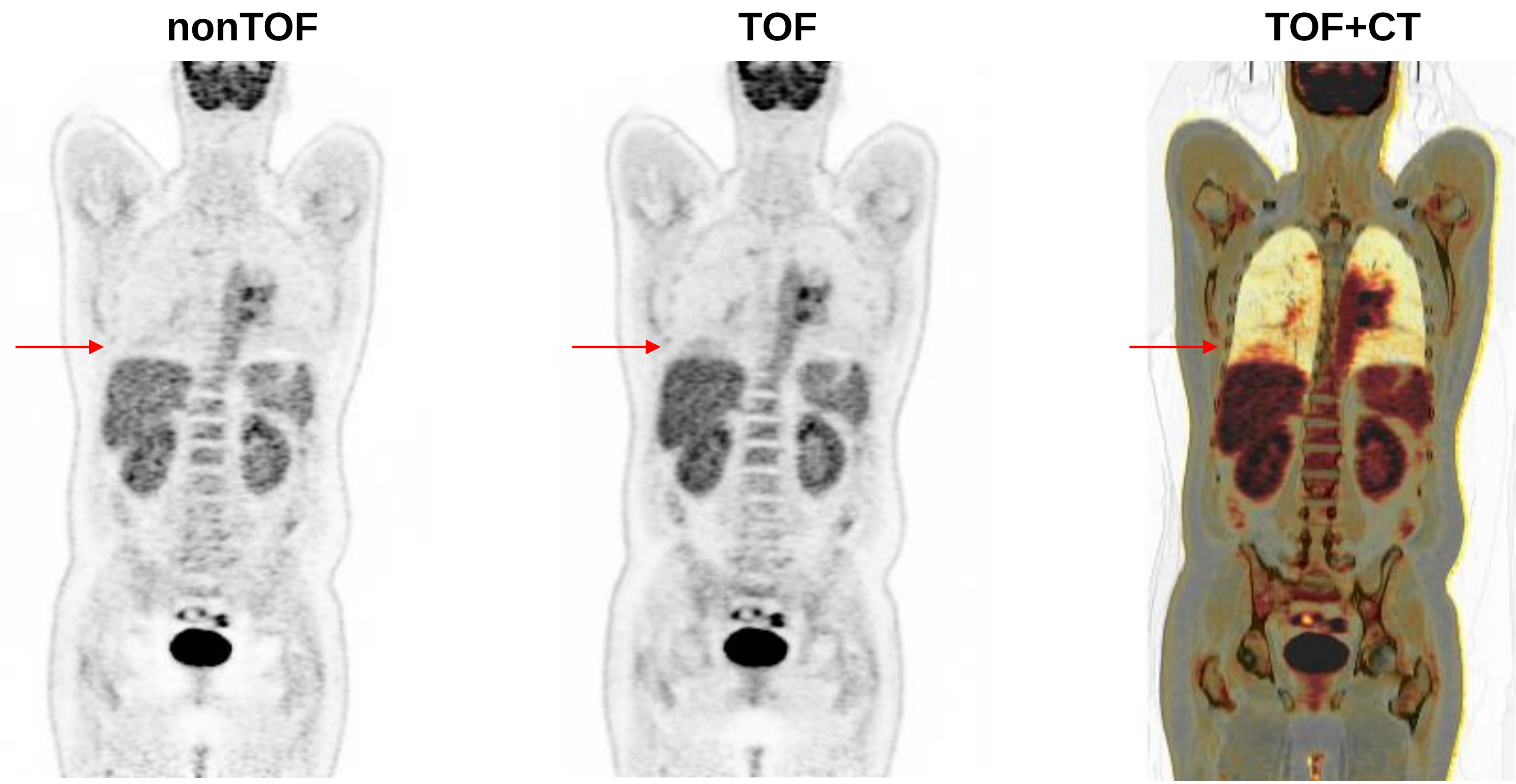
50 cm diameter water cylinder with cylindrical inserts.
Variable contrast to background.
μ-map was assumed uniform, and normalization was incorrect.





Time-of-Flight PET (advantages): more robust with inconsistent data

Respiratory artifacts: a mismatch between attenuation and emission data



mCT patient: CT during breath hold, PET in shallow breathing

Biograph Vision performance

Biograph Vision – system overview

Biograph Vision

- SiPM-based LSO detector with 3.2 x 3.2 x 20 mm crystals
- 82 cm transaxial diameter and 26 cm axial length
- 19 detector module assemblies with 16 detectors per assembly
- 60,800 total crystals. 760 per ring and 80 rings
- Water-cooled gantry with 3 zones of cooling
- Large 78 cm bore
- 64 or 128-slice CT
- FlowMotion continuous bed motion

Biograph Vision performance (IEEE MIC 2018)

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M-11-03

Performance Evaluation of the SiPM based Siemens Biograph Vision PET/CT system

J.S. Reddin[1], J.S. Scheuermann[1], D. Bharkhada[2], A.M. Smith[2], M. E. Casey[2], M. Conti[2], J.S. Karp[1]

[1]University of Pennsylvania, Philadelphia, PA

[2]Siemens Medical Solutions USA, Inc., Knoxville, TN

Physics & Instrumentation Group

Department of Radiology, University of Pennsylvania

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Biograph Vision performance

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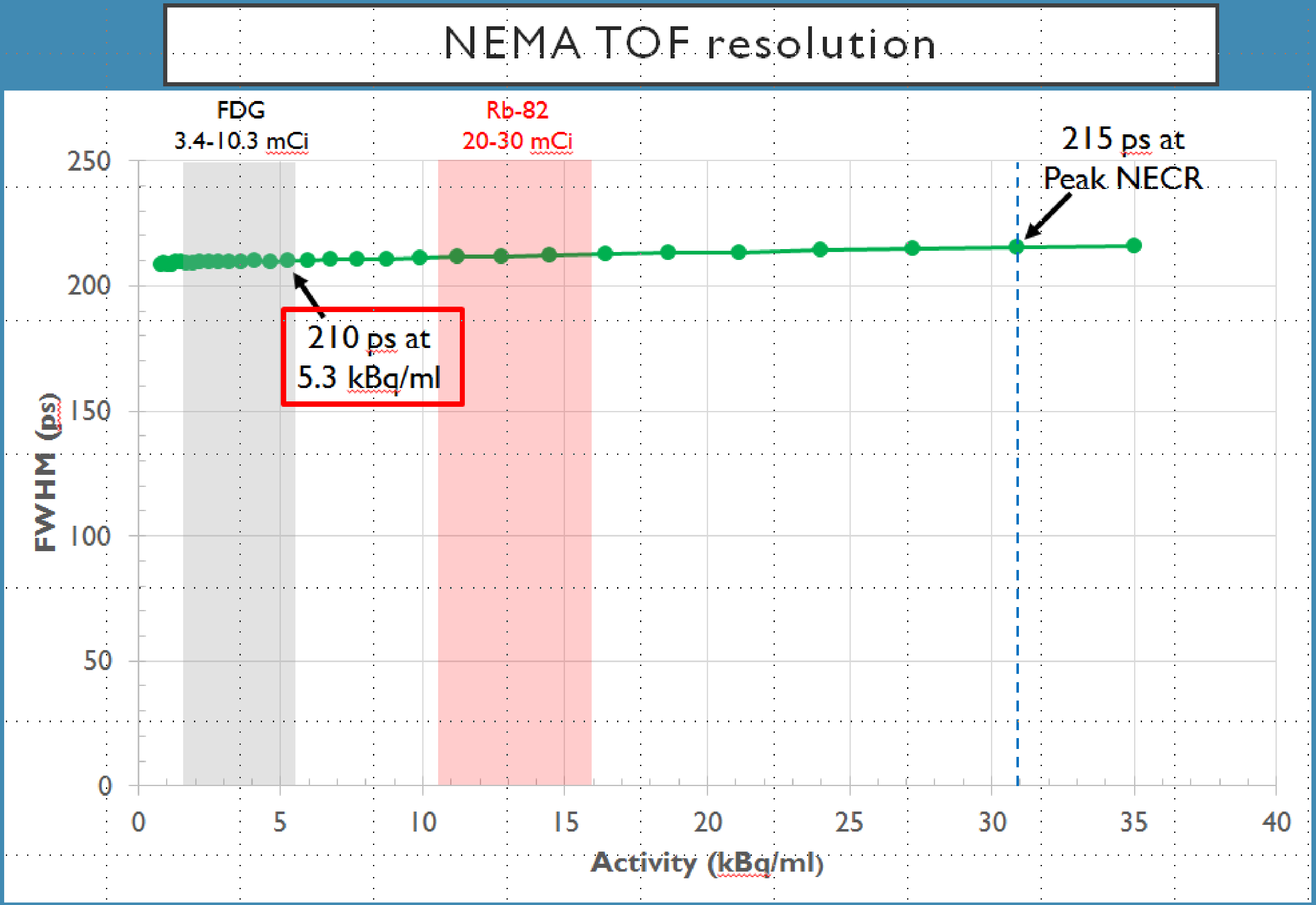

- New to NEMA NU 2-2018
- Analysis of the spread of line source in TOF dimension
- Timing error: difference between measured TOF data for each coincidence event and expected TOF offset based on the point of closest approach of line source to the LOR

Biograph Vision performance

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Summary of Measurements and Conclusions

	Siemens Biograph Vision (2018)	Siemens Biograph 4-ring mCT (2011)
Energy Resolution	9.04%	11.3%
Spatial Resolution (axial)	3.6 mm at 1 cm; 4.3 mm at 10 cm	4.2 mm at 1 cm; 5.6 mm at 10 cm
Sensitivity	15.6 kcps/MBq at 10 cm	10.0 kcps/MBq at 10 cm
Peak Trues	> 1,323 kcps at 58.0 kBq/ml	609 kcps at 37.4 kBq/ml
Peak NECR	296 kcps at 30.9 kBq/ml	181 kcps at 25.2 kBq/ml
Scatter Fraction	39% at peak NECR	36% at peak NECR
TOF Resolution	215 ps FWHM at peak NECR	538 ps FWHM

- Our Siemens Biograph128 Vision 600 Edge has excellent sensitivity and timing resolution.
- System is now in routine clinical use, scanning 11 to 15 patients per day.
- Acquisition times reduced for all scan types, and dose for Rb-82 studies reduced from 30 to 20 mCi.
- Will continue to investigate how best to use the enhanced performance characteristics of this scanner to improve clinical metrics.

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Clear visualization of the 2.4 mm cylinders of the Mini-Derenzo Phantom with Biograph Vision

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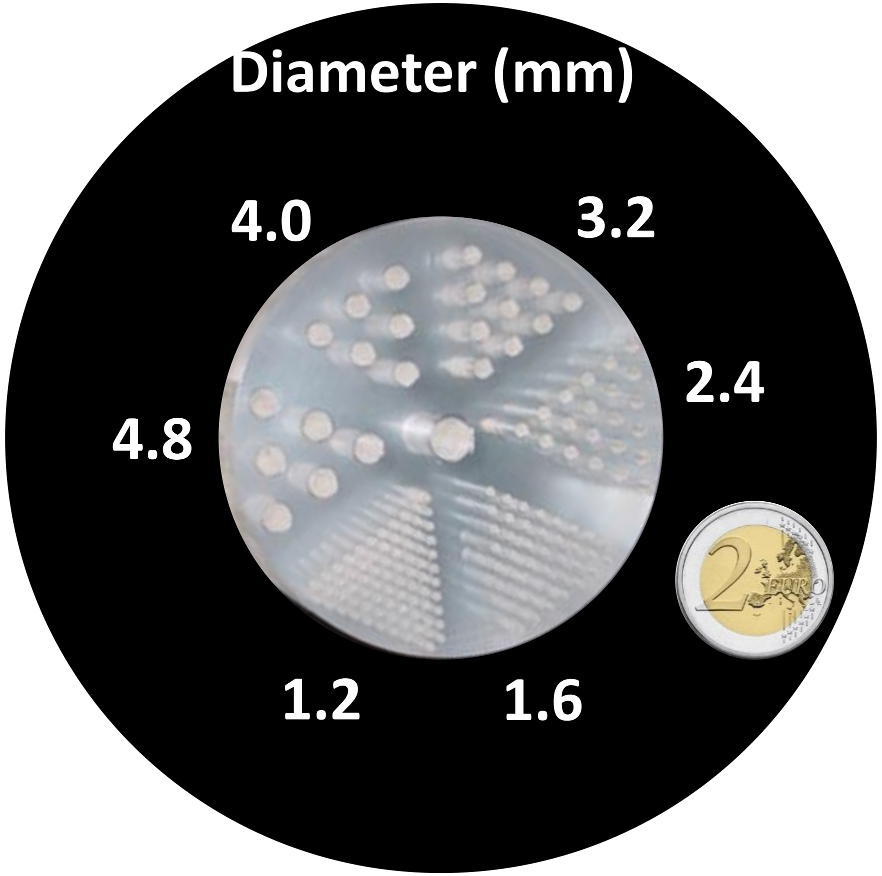
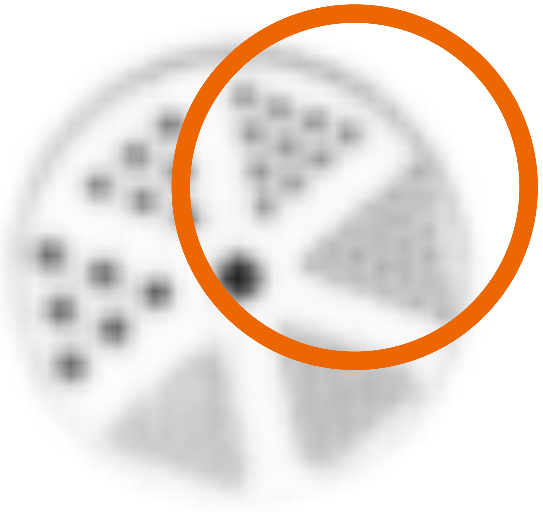
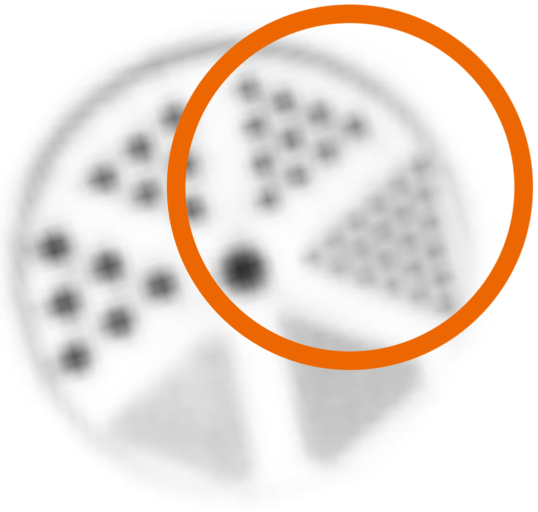


Biograph mCT

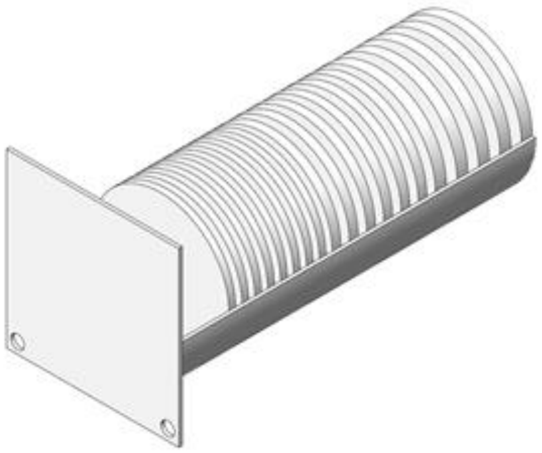


Biograph Vision



All planes of a modified Defrise phantom are clearly visible with biograph vision, even off-center

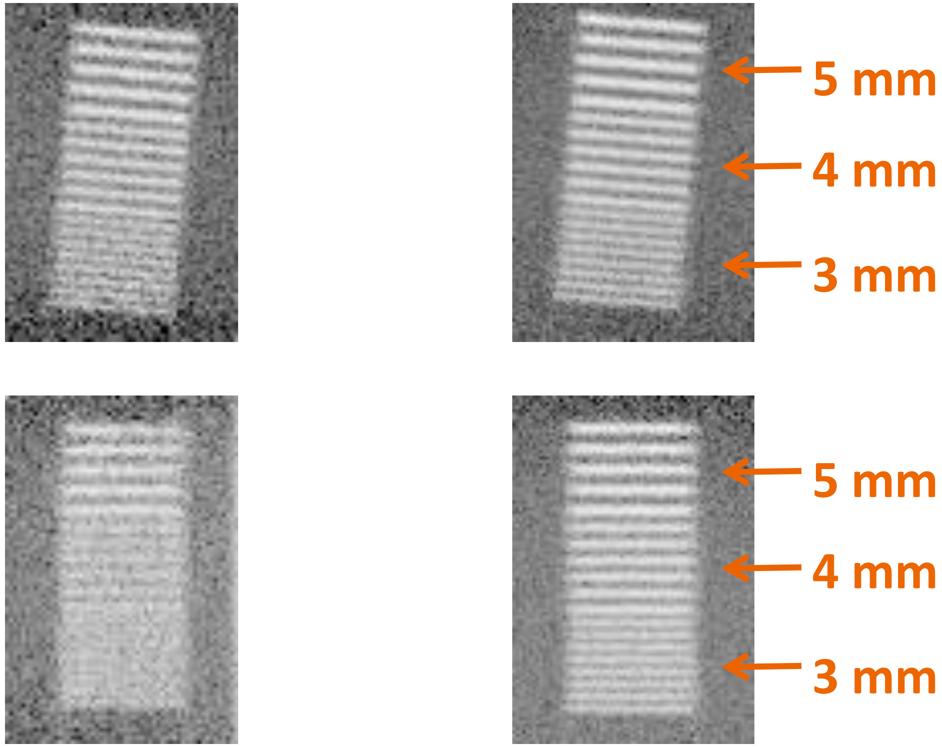
Axial Resolution Phantom



Biograph mCT | Biograph Vision

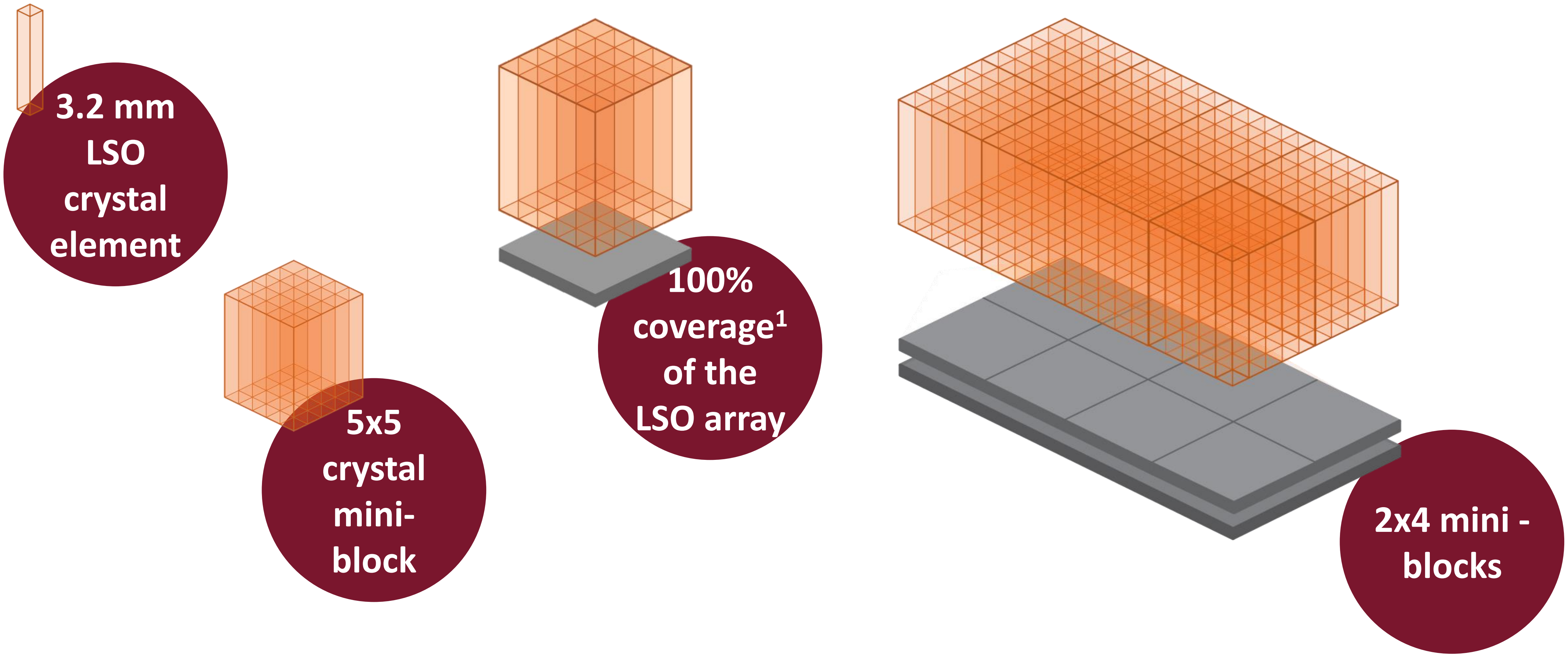
center

off center



Vision detector technology

A new approach to detector design with Biograph Vision™

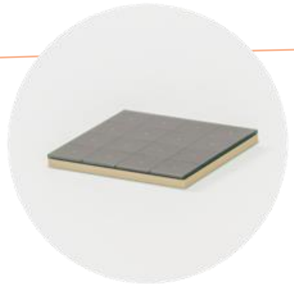


Description of the Detector

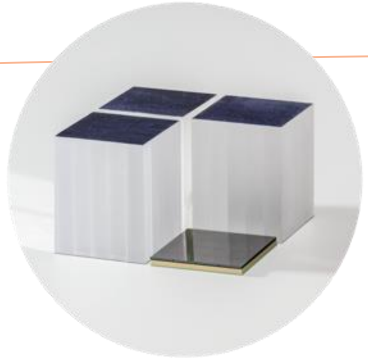
SiPM-based LSO detector

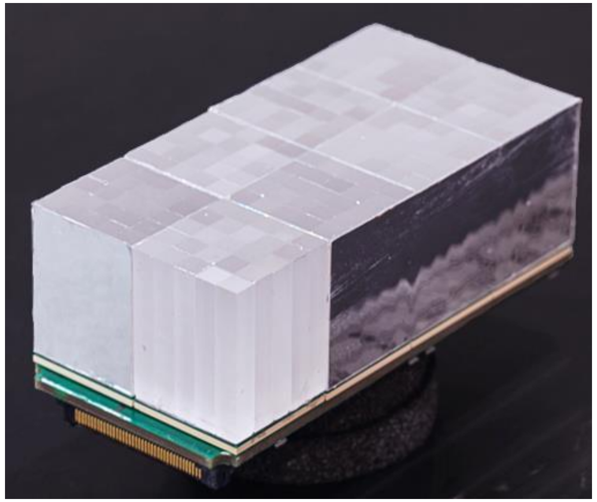
- A mini-block consists of a 5 x 5 array of 3.2 x 3.2 x 20 mm^3 LSO crystals.
- Coupled to a 4x4 array of 4.0 x 4.0 mm SiPMs.
- 2x4 mini-blocks in a block detector
- 2x8 detectors axially =26.3 cm axial FOV
- 19 detector modules in the detector ring
- Operates at room temperature

Mini-block

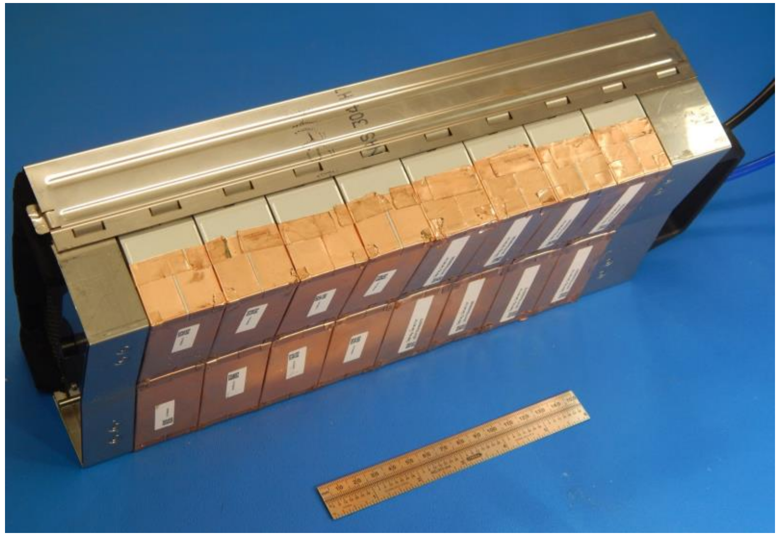


SiPM





2 readout channels are packaged into a detector



2 detectors transaxially and 8 axially are packaged into a detector module

Biograph Vision detector (IEEE MIC 2017)

Sanghee Cho, 10/26/2017

Silicon-photomultiplier TOF-PET Detector

Sanghee Cho, Robert A. Mintzer, Johannes Breuer, Mehmet Aykac,
Michael Loope, John Valenta, James L. Corbeil,
James C. Arnott, David Binkley, Melika Roknsharifi, Song Yuan

Molecular Imaging, Siemens Medical Solutions USA, Inc.

Detector Design : SiPM Readout Architecture

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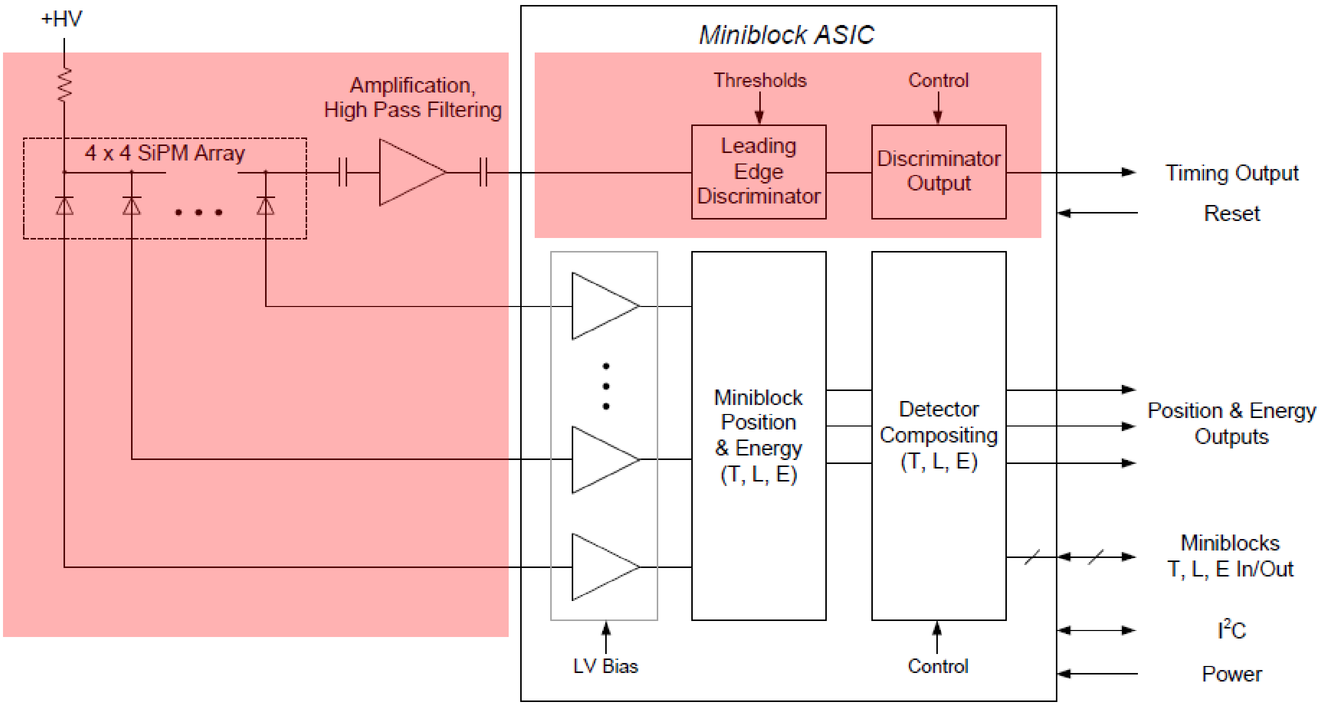
❑ Common cathode readout for timing signal generation



- Good option for a light-sharing miniblock, triggering on multiple photon level for optimum timing without summing electronics
- Requires only one high speed low noise channel, targeting power usage for highest timing performance
- Optimized high pass filtering to ensure minimal performance degradation due to SiPM dark noise
- High pass filtered timing signal fed to high performance leading edge discriminator
- Provides very uniform timing performance within the miniblock array

Timing performance

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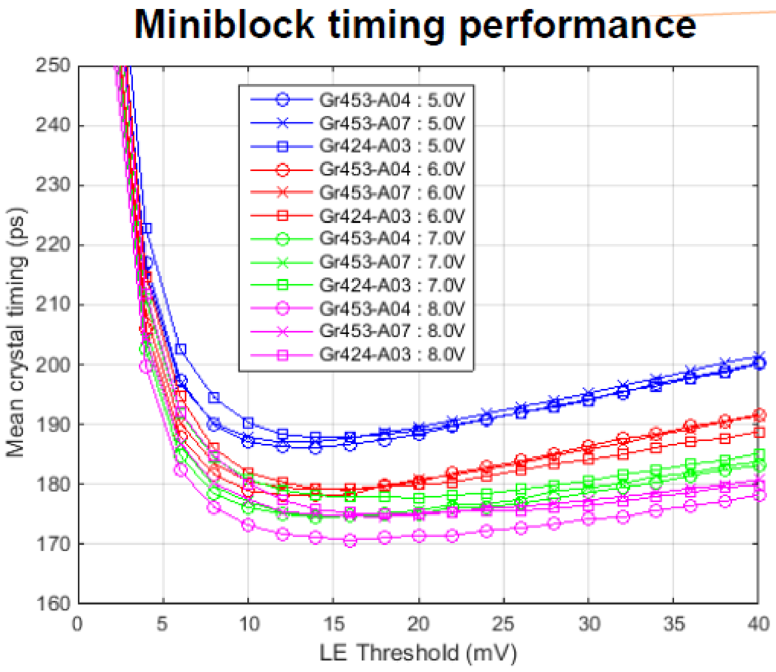

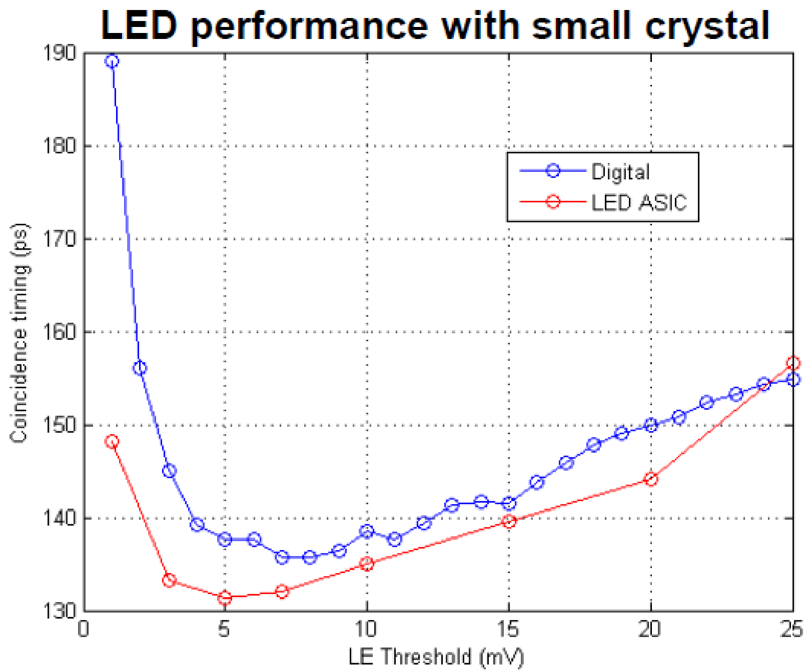

- Best performance for single miniblock mean crystal timing of 170 ps FWHM CTR

- 4x4x5 mm^3 LSO crystal was used with common cathode readout of entire 16 mm SiPM array to test limits of leading edge discriminator performance
- Impressive result of 132 ps FWHM CTR was measured with prototype ASIC discriminator

Energy and time resolution

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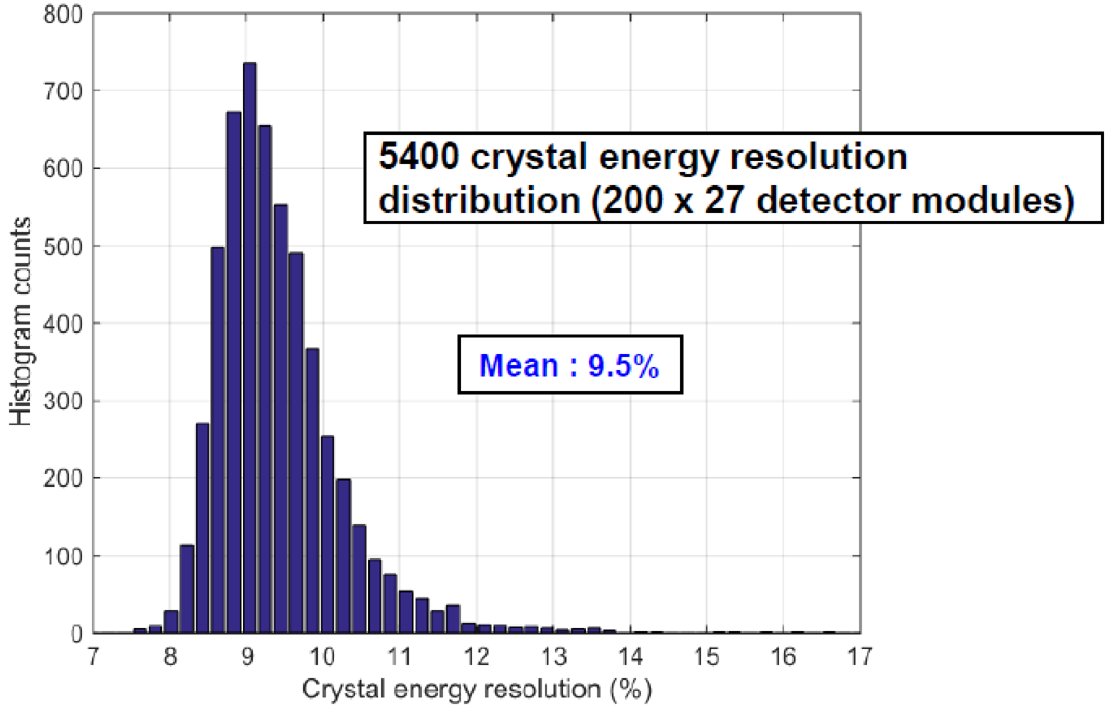
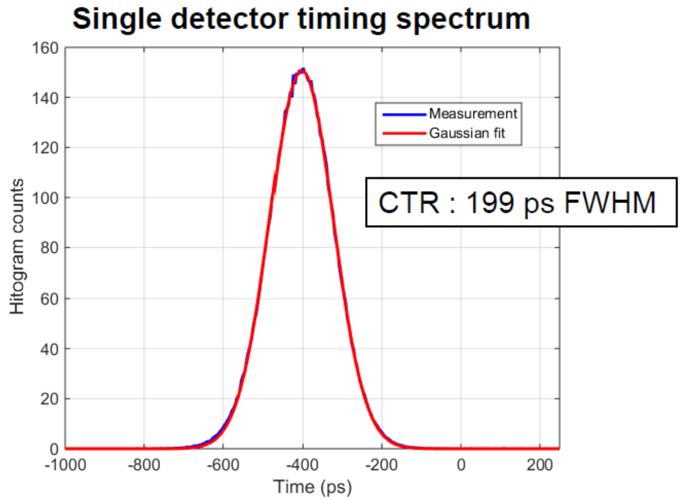
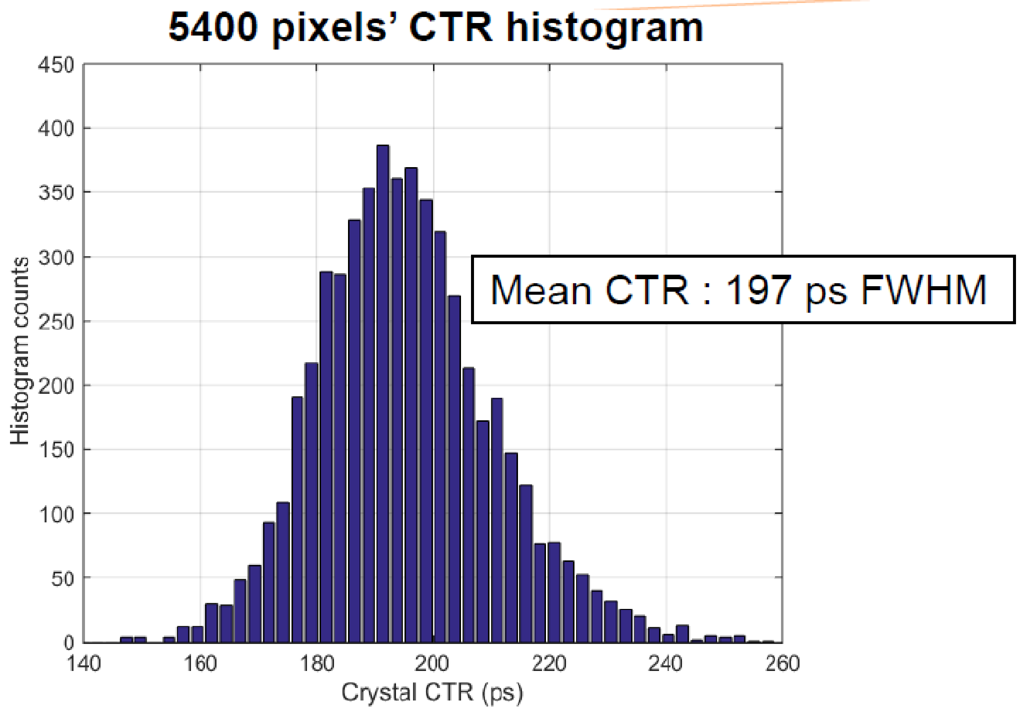
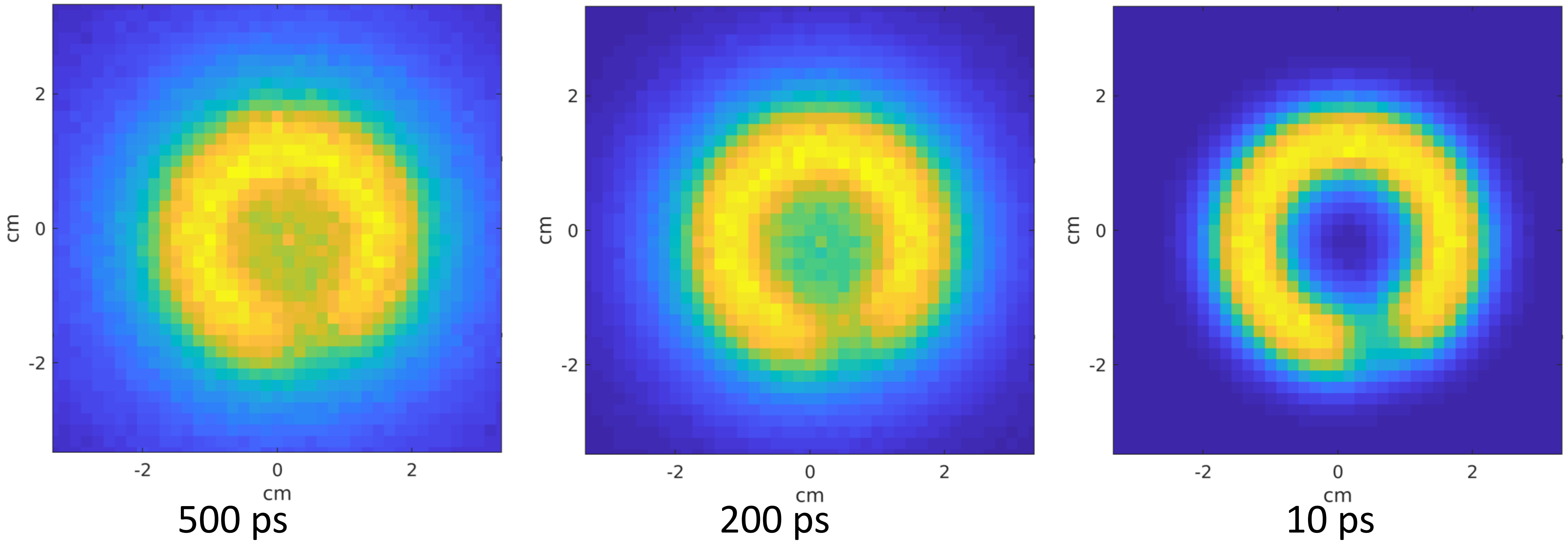






TOF PET update

Direct TOF back projection from listmode, simulation



“cardiac “simulation: 4-cm diameter ring, 1-cm thick , with on 1-cm defect

Direct TOF back projection from listmode, simulation

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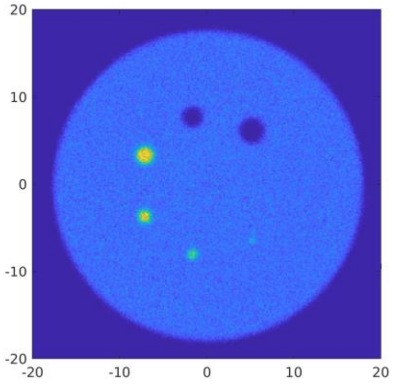
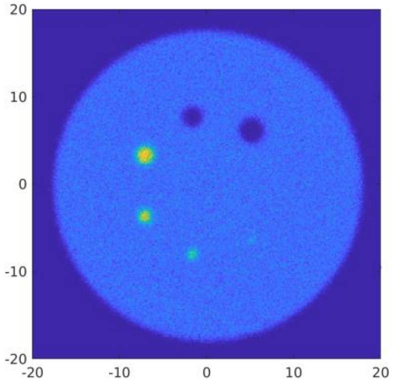
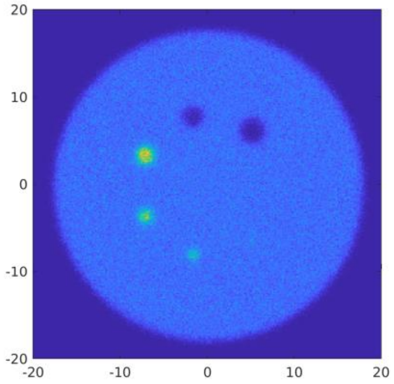


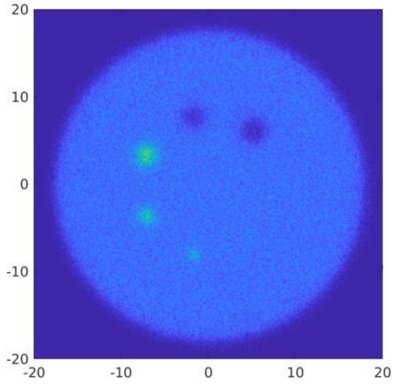
CTR 10ps



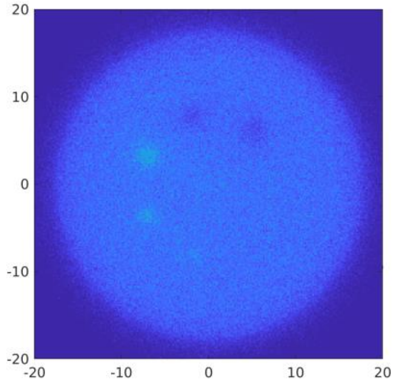
CTR 50ps



CTR 100ps



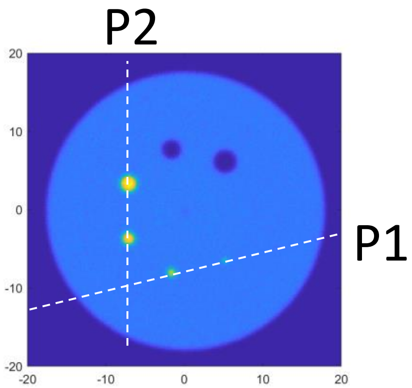
CTR 200ps

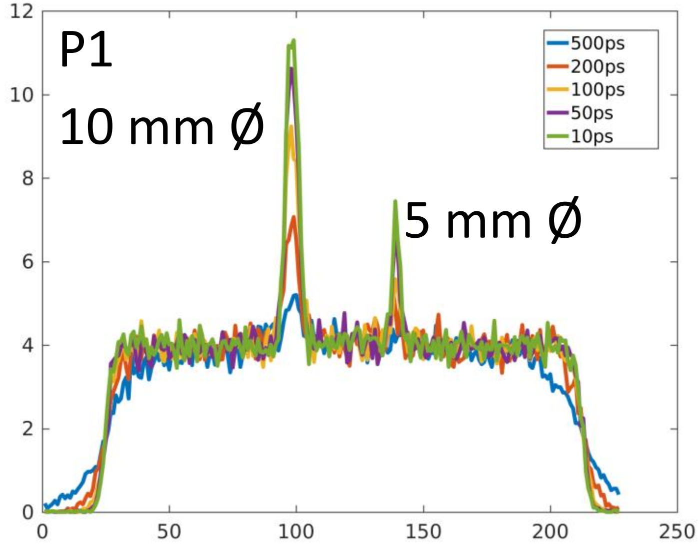


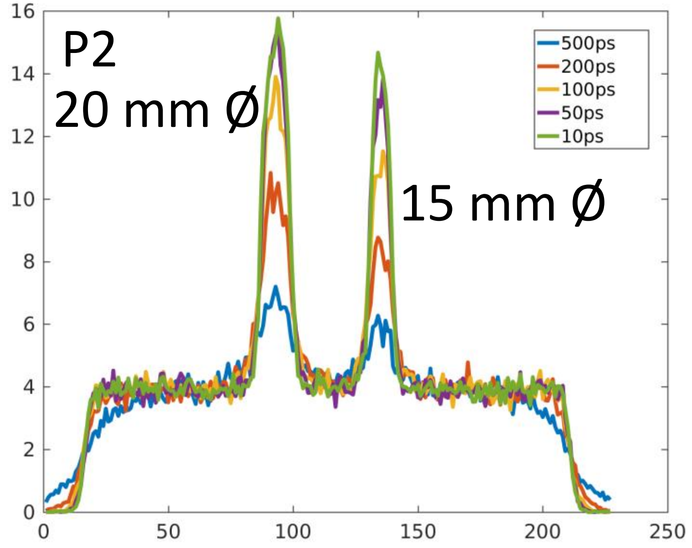
CTR 500ps

Background (17.5 cm Ø): 4.1 kBq/mL
Hot: 2.0/5.0/10.0/15.0/20.0 mm Ø
Cold: 25.0/30.0 mm Ø
No attenuating media (no AC/SC)
3.0×10^{7} coincidences

Spheres: 16.4 kBq/mL







Direct TOF back projection from listmode, Biograph mCT

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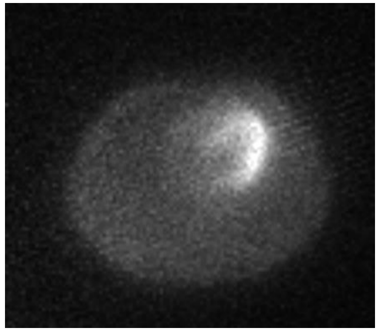
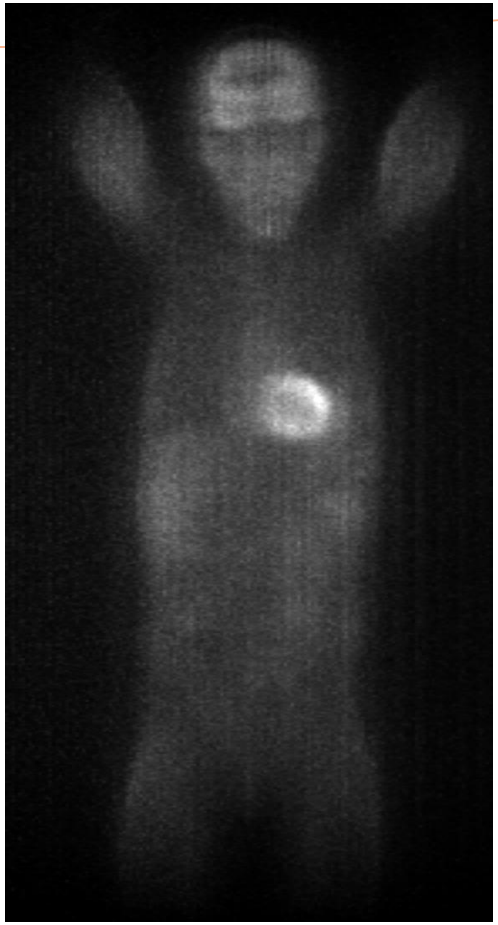
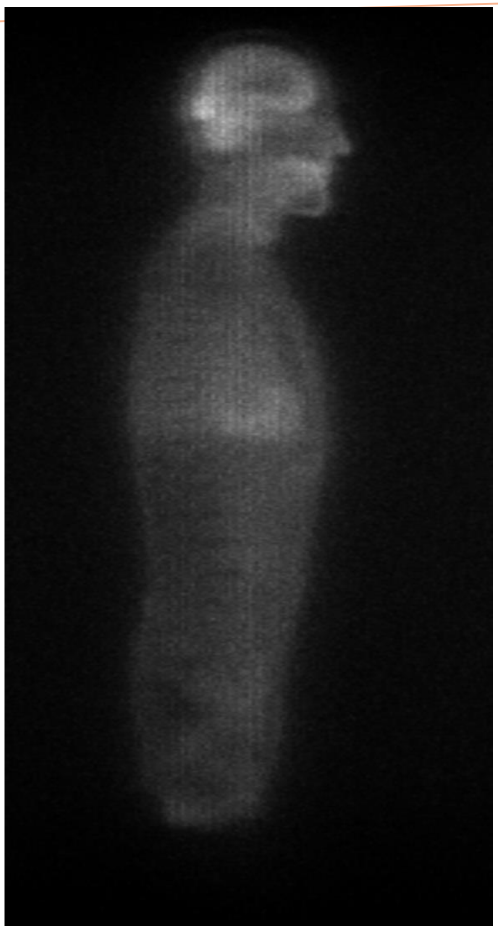


Transaxial



Coronal



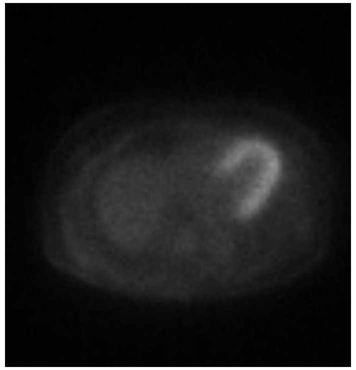
Sagittal

MIP

No normalization, attenuation, scatter correction – 550 ps time resolution

Data Courtesy of University of Tennessee

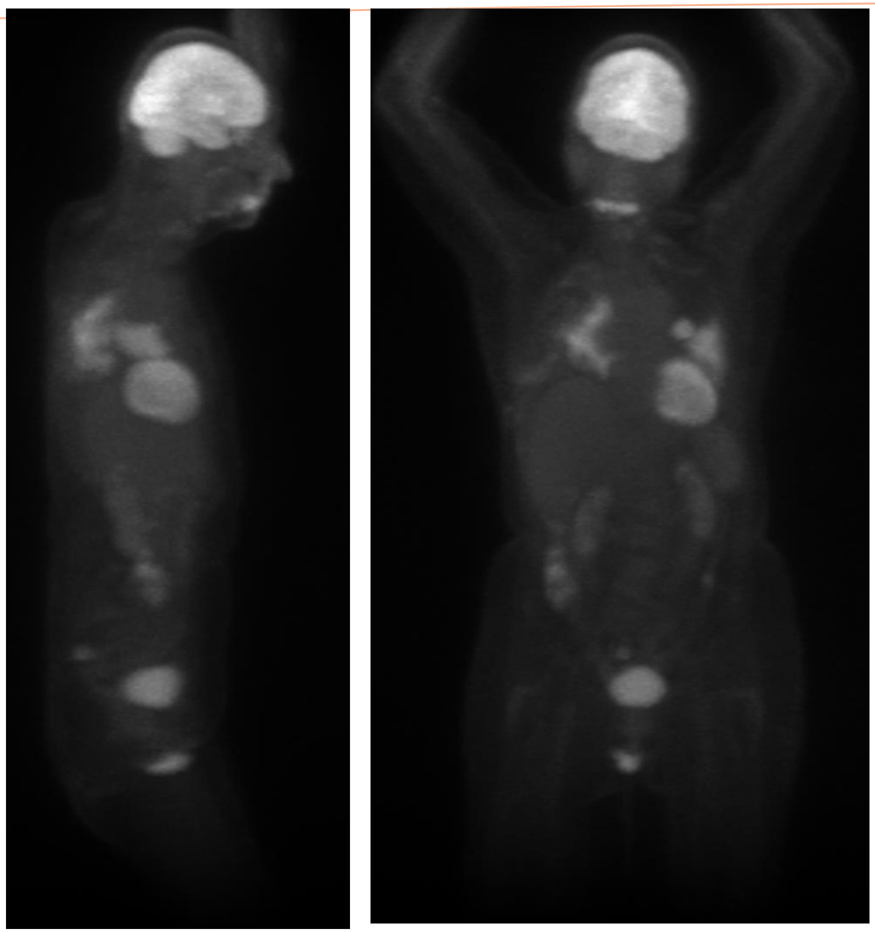
Direct TOF back projection from listmode, Biograph Vision



Transaxial

Coronal

Sagittal

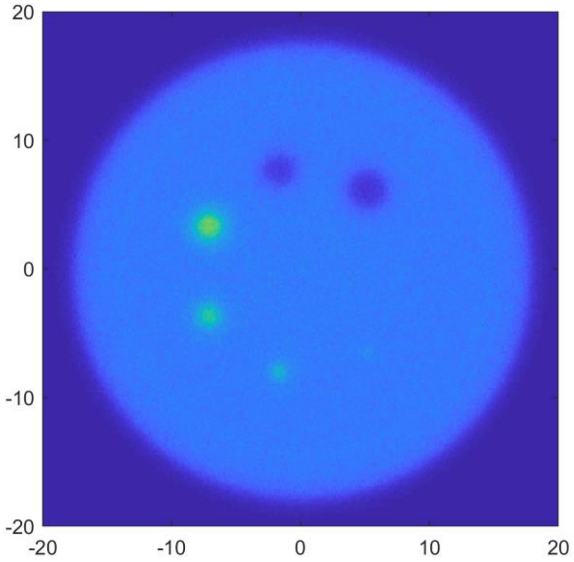


MIP

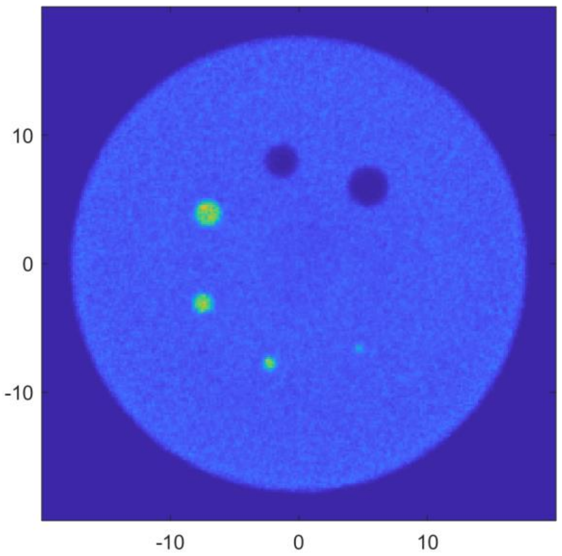
No normalization, attenuation, scatter correction – 210 ps time resolution

Data Courtesy of Hospitalier Universitaire Vaudois, Lausanne, Switzerland

Do we still need reconstruction physicists?



TOF BP (200ps)



OSEM TOF (200 ps, 4i5s) reconstruction

Probably yes…

Consistency of space-time information is enforced by iterative reconstruction

conclusions

- In the Biograph Vision, the excellent time resolution and improved reconstruction software allows for unique image quality, in terms of noise reduction and detectability, which can be exploited in new clinical applications
- The dramatic jump in time resolution in Biograph Vision allows to consider alternative reconstruction approaches, unrealistic for the previous generation of PET scanners
- With the Biograph Vision, the LSO-block technology has (almost) reached the physical limits of achievable time resolution: “something different” will be needed to match the 10 ps challenge!

Thanks to:

SIEMENS Healthineers

- John Prior and Silvano Gnesin (CHUV, Lausanne)
- Joel Karp and Janet Reddin (Univ. Pennsylvania)
- Jorge Cabello, Sanghee Cho, Inki Hong, Vladimir Panin, Paul Schleyer, Matthias Schmand (Siemens Molecular Imaging)

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