Advances in detector technology in nuclear medicine & hybrid imaging

27 September 2018 Thursday (Day 1) 1430 – 1500 Hrs

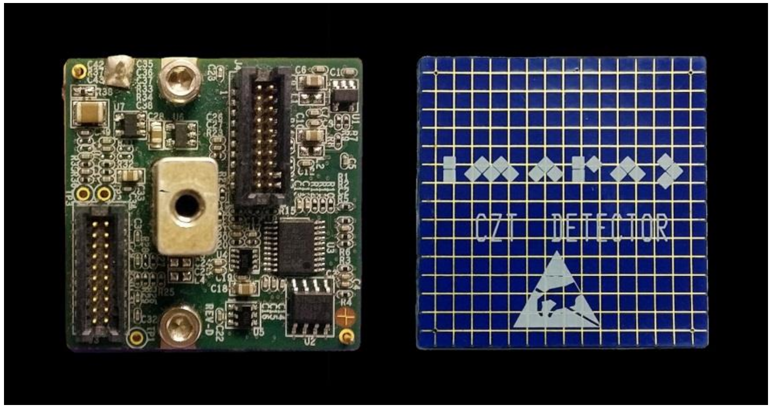
S . Somanesan
Senior Principal Medical Physicist,
Dept. of Nuclear Medicine & Molecular Imaging,
Singapore General Hospital.

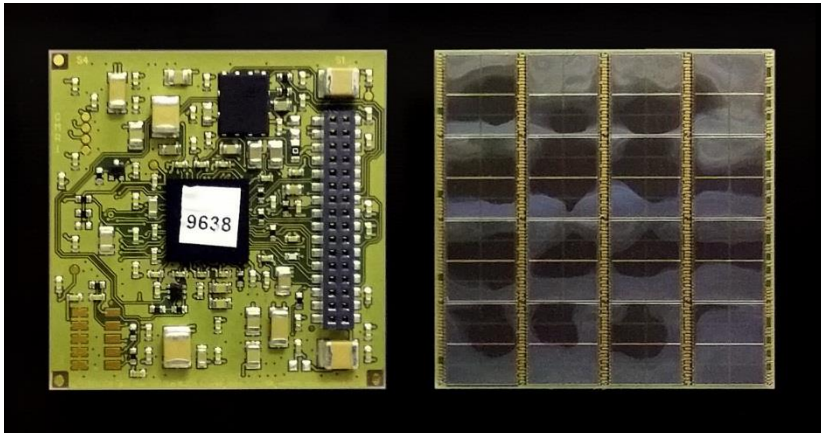
Hospital Radiation Safety Officer,
Chief, Radiation Response Team.
Operational & QA Manager, PET/CT Facility,

Advances of detector technology in nuclear medicine - *Scope*

- Introduction to Nuclear Medicine and PET detectors,
- Development and current trends in SPECT Detection Instrumentation:
  - Scintillators,
  - Photon Transducers
  - Semiconductors Detectors
- Summary: What the future holds for detector technology,

CZT





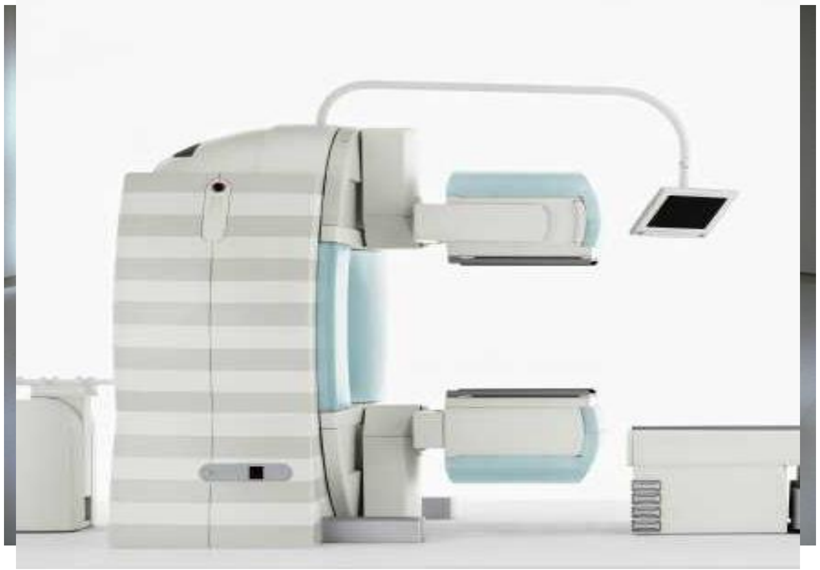
SiPM photo detector

Singapore General Hospital

Historical perspective - Developments in Instrumentation

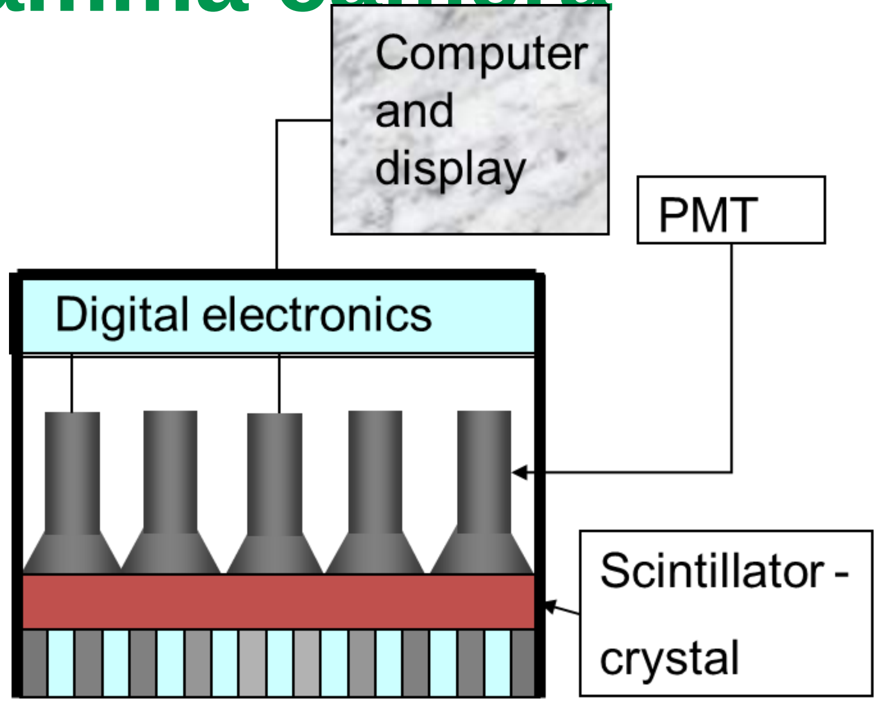
- In the early days of nuclear medicine (1927), scans were performed by manually positioning a simple GM counter above the organ of interest.
- A major breakthrough followed with the invention of the Anger scintillation camera (early 1950's).
- The basic design of a large-area NaI(Tl) scintillation crystal, an array of photomultiplier tubes (PMTs), in combination with an absorptive collimator has been referred to as the 'Anger Camera'.

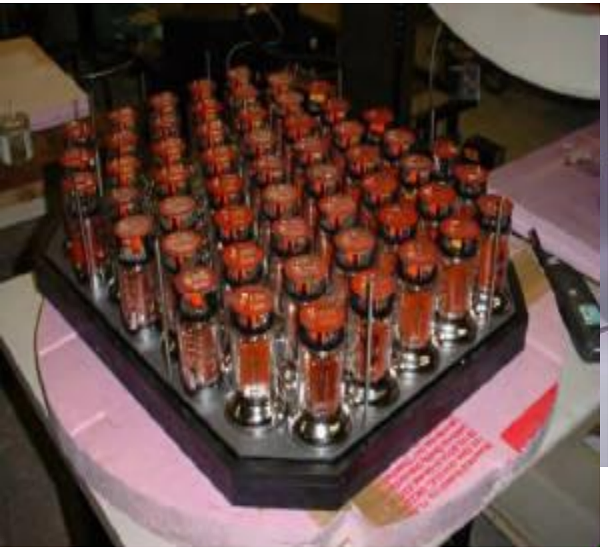
Types of gamma camera

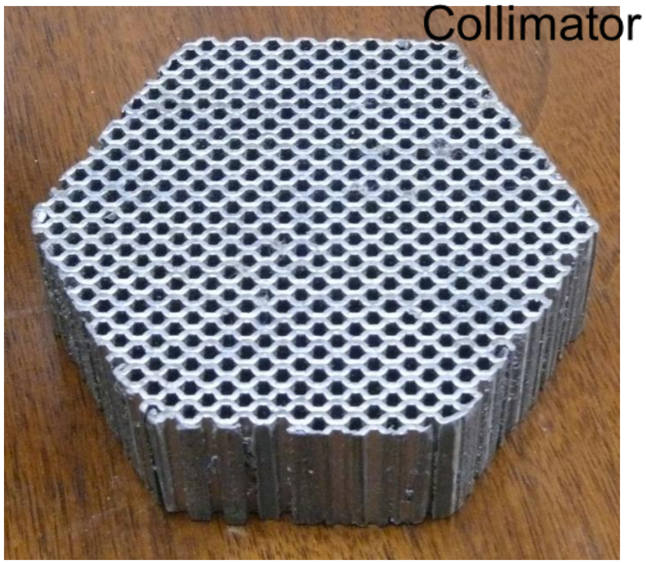


Components of a gamma camera

- Collimator
- Sodium Iodide (NaI) crystal
- Photomultiplier tube (PMT)
- PHA circuit, discriminator & analyser circuits
- Computers for data processing & display





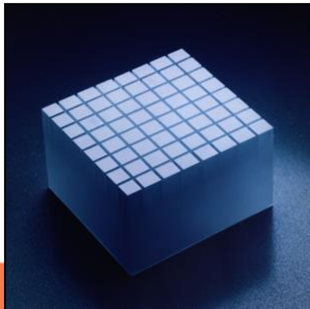


Development in SPECT Detection
1. Scintillators

- The advances in SPECT are directly tied to:
  - improving the quality and accuracy of the acquired projections either through:
    - better instrumentation or better correction algorithms.
- CsI(Tl), CsI(Na)[1] & $LaBr_3$ [2] are used in comparison with NaI(Tl).

Scintillator	Atomic number Z effective	Density p (g/cm3)	Decay time (ns)	Wavelength (nm)	Relative light output (% of NaI(Tl))	Remarks
NaI (Tl)	50	3.67	200	415	**100**	
CsI (Tl)	54	4.5	1,000	550	45 (118*)	Long wavelength; Cardius.
CsI (Na)	54	4.51	630	420	85	Used in LinoView, s animal
LaBr3:Ce	47	5.3	25	360	160	Used in s animal SPECT

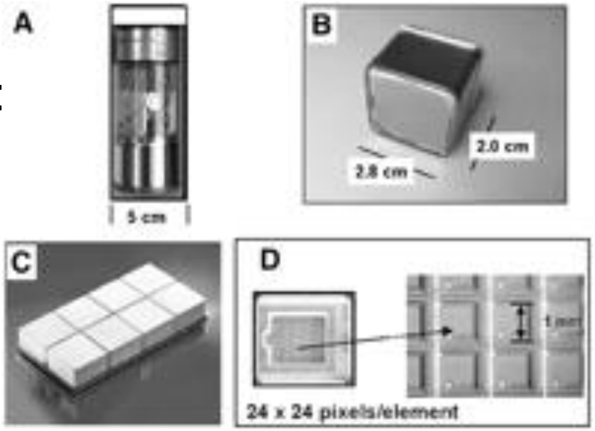
  - Comparable effective atomic #'s & densities ⇒ similar photopeak efficiency,
  - Advantage: less dead edges ⇒ better spatial resolution.



1. Walrand S, Jamar F, de Jong M, Pauwels S. Evaluation of novel whole-body high-resolution rodent SPECT (Linoview) based on direct acquisition of linogram projections. J Nucl Med. 2005;46:1872–1880.
2. Moses WW, Shah KS. Potential for RbGd2Br7:Ce, LaBr3:Ce, LaBr3:Ce, and LuI3:Ce in nuclear medical imaging. Nucl Instrum Methods Phys Res A. 2005; 537:317–320.

Development in SPECT Detection
2. Photon Transducers

- PMTs have been in use for 40 years:
  - PMTs have very large electronic gains (10^6) with relatively low noise,
  - conversion efficiency is low (20%), that affects both energy resolution & intrinsic spatial resolution,
  - are affected by environmental changes such as temperature, humidity and magnetic fields and their age,
  - they are bulky as well as expensive.
- Improved replacements for conventional PMTs, [1,2]:
  - B the position sensitive PMT(PSPMT),
  - C avalanche photodiode (APD),
  - D silicon PMT [3]



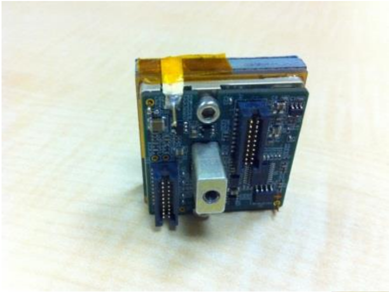
Adapted from [1]

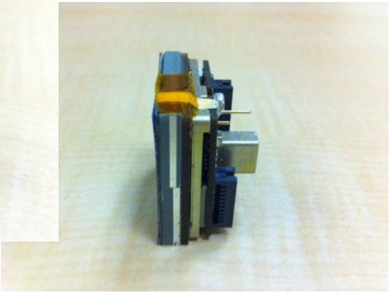
- These have been recently introduced and are being incorporated into SPECT & PET detectors.

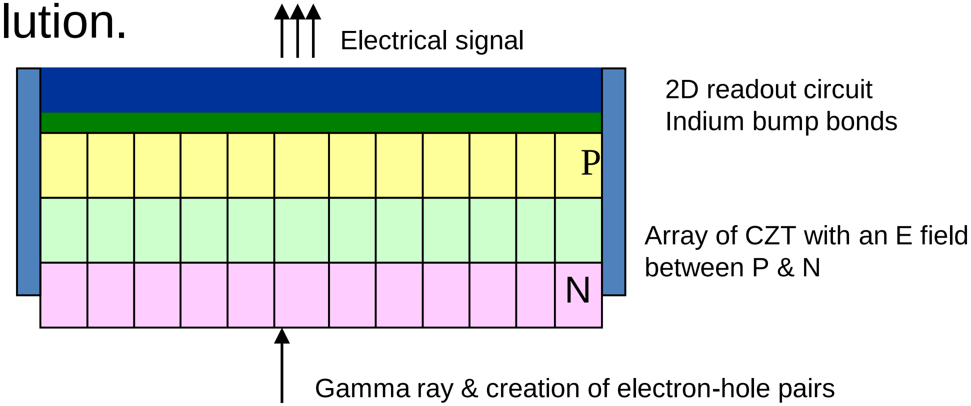
1. Pichler BJ, Ziegler SI. Photodetectors. In: Wernick MN, Aarsvold JN, eds.Emission Tomography: The Fundamentals of SPECT and PET. 1st ed. San Diego, CA: Elsevier; 2004:255–269.
2. Bernd J. Pichler et al, Latest Advances in Molecular Imaging Instrumentation, ,JNM, Vol. 49 No. 6 (Suppl) June 2008
3. Moehrs S, Del Guerra A, Herbert DJ, Mandelkern MA. A detector head design for small-animal PET with silicon photomultipliers (SiPM). Phys Med Biol. 2006;51:1113–1127.

Development in SPECT Detection
3. Semiconductor Detector

- Solid-state devices (CZT) that provide direct conversion of absorbed γ-ray energy into an electronic signal [1].
- Are compact & operate at low voltages as no need for a PMT like high-gain amplification,
- The absorbed energy from a γ -ray interaction liberates charge carriers (electrons and holes) within the semiconductor.
- The induced charge on the terminals generates an electronic pulse with an amplitude proportional to the absorbed energy.
- The precision of the γ signal detection is better as no need for *light-electrical signal* conversion,
  - $\Rightarrow$ improved energy resolution.



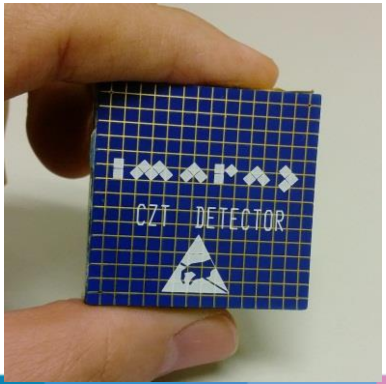




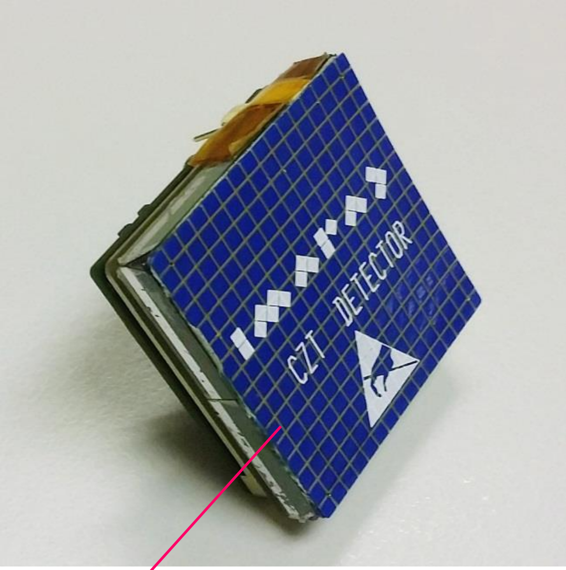
1. Darambara DG, Todd-Pokropek A. Solid state detectors in nuclear medicine. Q J Nucl Med. 2002;46:3–7.

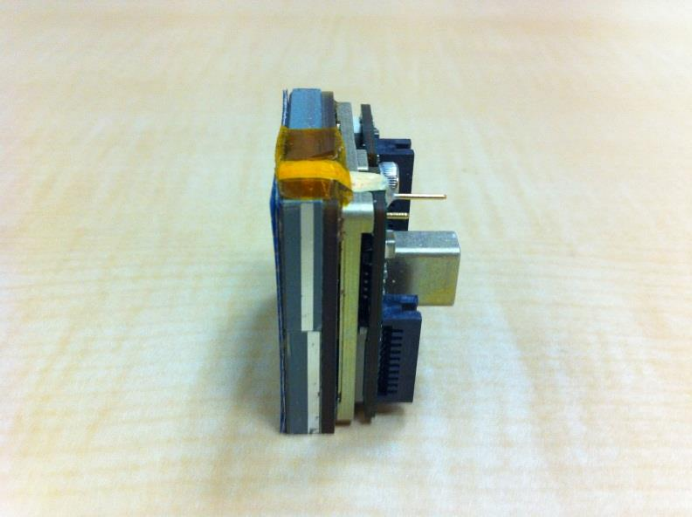
Advances in semiconductor detectors

- The most popular alternative for *Crystal/ PMT* is the semiconductor.
- By avoiding the need for bulky PMTs, the imaging systems can be more compact.
- The precision of the γ signal is better as no need for light-electrical signal conversion, $\Rightarrow$ improved energy resolution.
- The most widely used semiconductors for nuclear medicine are CdTe and CdZnTe (CZT)
- The cost differential has been coming down over the decades.

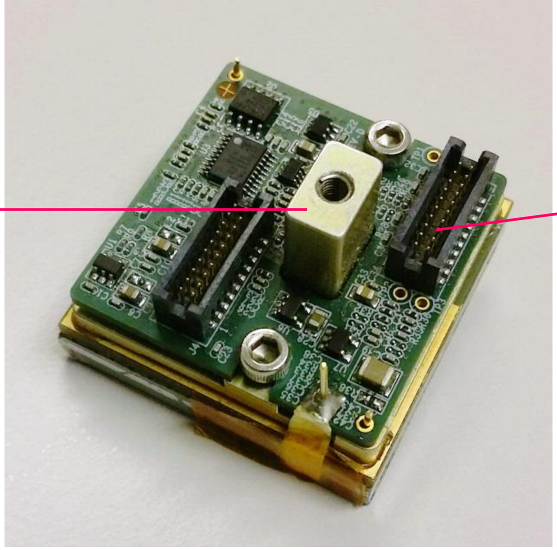


Semiconductors Detectors - CdZnTe





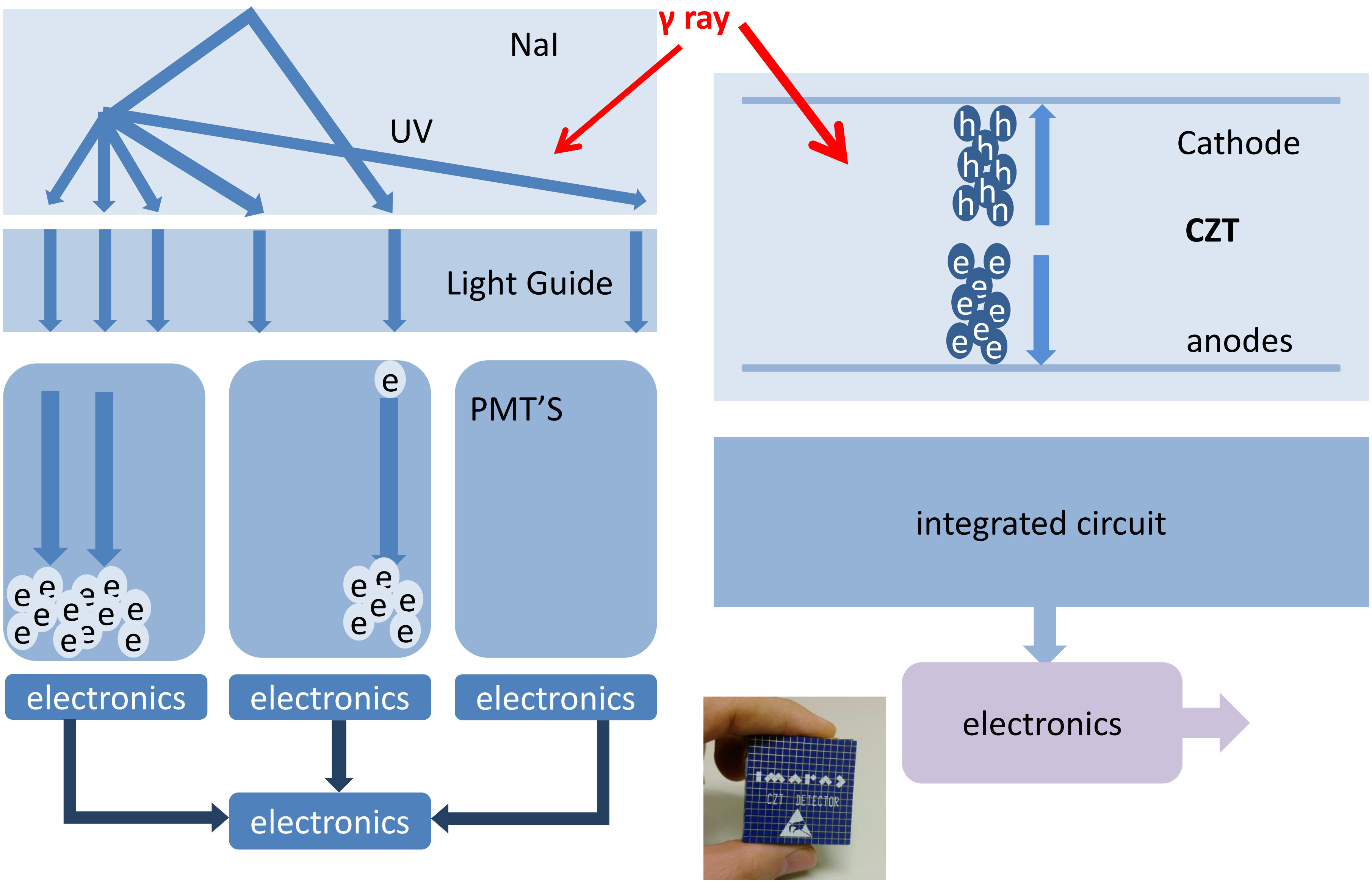
Detector face



To cooling fin

Electronics

Gamma detection with scintillation v.s. semiconductor detectors



Scintillation Detector

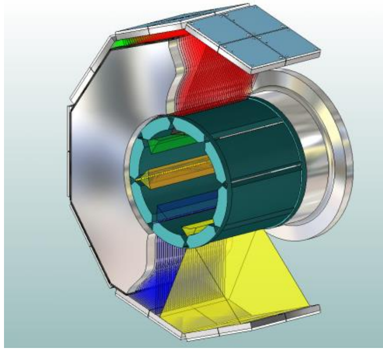
Semiconductor Detector

New Approaches in SPECT

- A number of imaging systems have been introduced, that were designed specifically for cardiac imaging applications
  - With improved sensitivity in order to reduce scan times (@ 5 mins MPI).
  - Better patient comfort (imaging in an upright or reclining position)
  - By eliminating positioning the patient's arms above the head
  - Limiting claustrophobic effects (with open & smaller gantries)
  - overall sizes reduced (minimal floor space requirement).
- **Cardius XCT**™, manufactured by Digirad, Inc. Poway, CA
- **D-SPECT**™, Manufactured by Spectrum Dynamics, Haifa, Israel.

Approaches in SPECT – Alcyone™

- Manufactured by GE Healthcare using Alcyone detector
- The detectors are composed of arrays of pixilated CZT modules arranged in 180º geometry and utilising focused collimation to optimise data acquisition from the myocardium.
- Alcyone technology allows for data acquisition without detector motion.
- Spatial resolutions of 5 mm are obtainable with acquisition times of 3 to 5 minutes in typical clinical imaging situations.



PET-CT

Time Magazine's Medical Invention of the Year 2000

TIME ***magazine December, 2000***

http://www.prnewswire.com/news-releases/time-magazine-selects.html

Singapore General Hospital

Brief Introduction of PET

- All PET systems utilize coincidence detection of the annihilation photons with 511 keV from positron decay.

- Since the paired gamma rays are anti-parallel, the detection of the gamma rays determines a line of response (LOR) along which the annihilation took place.

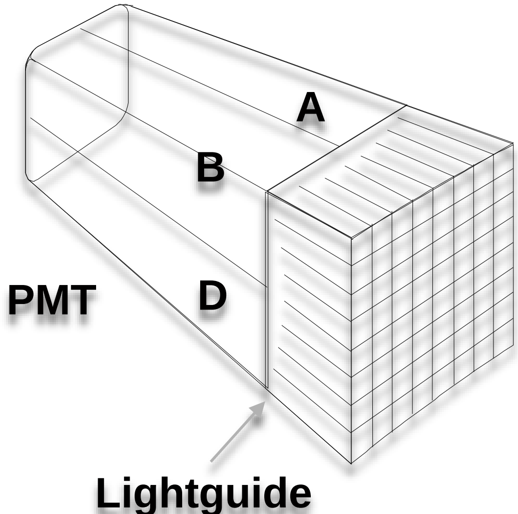
- The coincidence is determined by imposing an acceptance time window on the difference in time between detection of the two events.

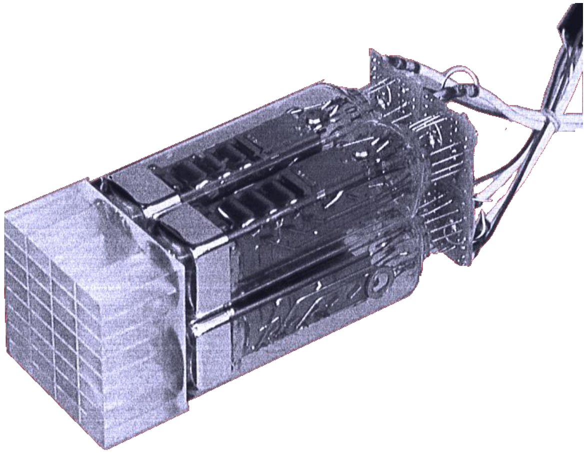
- If the system has very high timing resolution(<1ns), ►a time-of-flight (TOF) resolution ► provide higher signal-to-noise ratio (SNR).

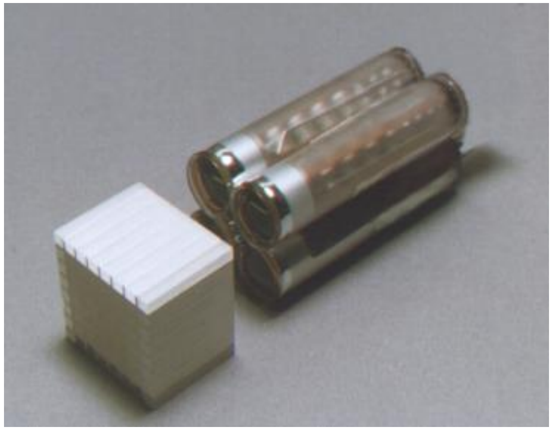
Singapore General Hospital

PET detectors

- A crystal/PMT 'block detector' uses 4 PMTs to decode an array of crystals with various combinations of reflectors and surface treatments between the crystals.
- LSO provided designers with a series of fast, bright, dense scintillators.
  - The increased light output to decode more crystals per PMT and
  - allow the use of arrays of smaller crystals, increasing resolution.
- With improved electronics and better performing PMTs, TOF PET appeared as a commercial product around 10 years back.







Singapore General Hospital

Advances in photodetectors - APD

- The "workhorse" for a scintillation detectors has been PMT. They are very high gain (typically ~ x 10^6), low noise, fast response and relatively moderate cost.
- The desire to further reduce the volume and to have detectors that can operate within magnetic fields has led to solid-state photodetectors.
- One of the most popular choice is the avalanche photodiode (APD).
  - It has low gain (~10^2 - 10^3)
  - timing, suited for non-TOF PET applications
  - with a temperature sensitive gain (@1 or 2° celsius change)
  - SNR of current photodiode devices is a potential limitation

Advances in photodetectors - SiPM

- Silicon photomultipliers, (SiPM) are proving to be promising.
- Series of APD micro-cells.
- Gains range from 10^5 to 10^7 and have achieved 250-400 ps timing resolution with high light output, fast scintillators.
- Like most semiconductor devices, SiPMs are susceptible to **thermal noise** but noise is negligible due to high gain.
- Limitation: difficulty in scaling up to large detection areas.
- The devices can be used in magnetic fields and samples have been tested in fields up to 15 Tesla without showing any degradation.
- Can be used in TOF PET-CT and PET-MR scanners.

S. Dolinsky, et al., Nuclear Instruments & Methods in Physics Research : Timing resolution performance comparison of different SiPM devices .

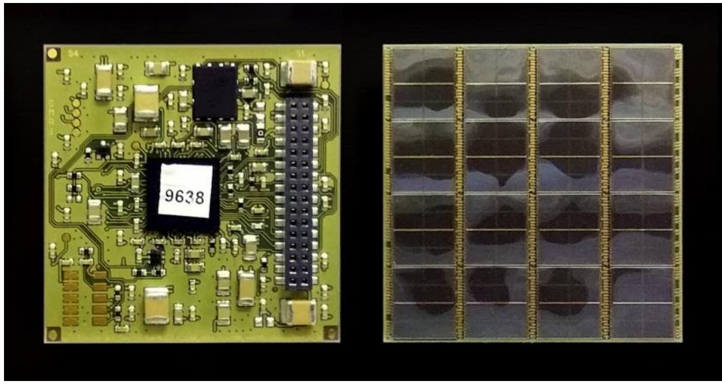
Comparing PMT, APD and SiPM

- The table below compares the main features of PMT, APD and SiPM.

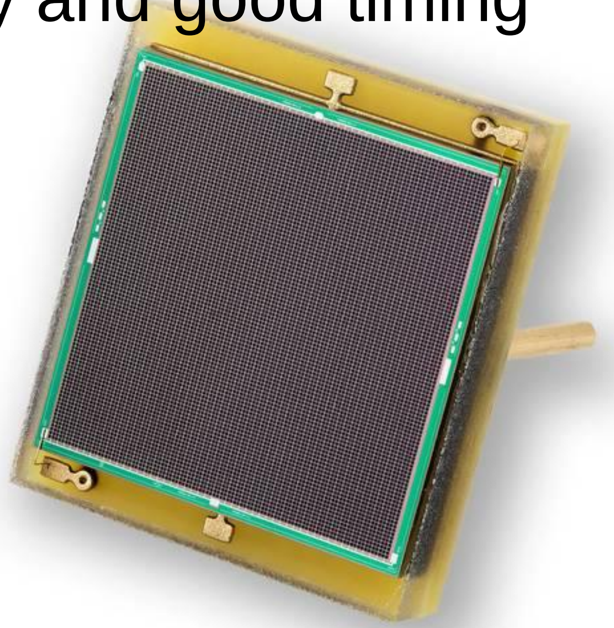
	PMT Photomultiplier Tube	APD Avalanche Photodiode	SiPM Silicon Photomultiplier
Quantum Efficiency	25% … 40%	… 80%	… 80%
Compactness	Bulky	Compact	Compact
Operation Voltage	1000 – 3000 V	100 - 500 V	20 - 80 V
Gain	10^4 - 10^9	30 - 300	10^5 - 10^7
Insensitivity to Magnetic Field	No	•	•
Timing Resolution	550ps	~2000ps	<400ps
Production Costs	Medium	Low	Low

[1] D. Renker, Nuclear Instruments & Methods A 567 (2006) 48. [2] J.S. Karp, et al., Journal of Nuclear Medicine 49 (3) (2008) 462. [3] M. Moszynski, et al., IEEE Transactions on Nuclear Science NS53 (5) (2006) 2484; [4] A Iltis, et al., Nuclear Instruments & Methods A 563 (2006) 359. [5] C.L. Melcher, Journal of Nuclear Medicine 41 (6) (2000) 1051.

Advantages of the Silicon Photomultiplier



- Single photon resolution
- High photon detection efficiency
- High gain and high signal to noise ratio
- Very fast device with short recovery and good timing
- Low bias voltage
- Insensitive to magnetic fields
- Very low nuclear counting effects
- Very compact devices
- Simple calibration and monitoring
- Not damaged by day light
- Low costs

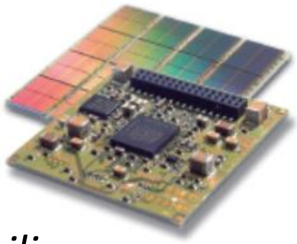


[1] D. Renker, Nuclear Instruments & Methods A 567 (2006) 48. [2] J.S. Karp, et al., Journal of Nuclear Medicine 49 (3) (2008) 462. [3] M. Moszynski, et al., IEEE Transactions on Nuclear Science NS53 (5) (2006) 2484; [4] A Iltis, et al., Nuclear Instruments & Methods A 563 (2006) 359. [5] C.L. Melcher, Journal of Nuclear Medicine 41 (6) (2000) 1051.

So What in the Market now for hybrid PET-MR & PET-CT scanners

Philips™ Vereos™ PET/CT

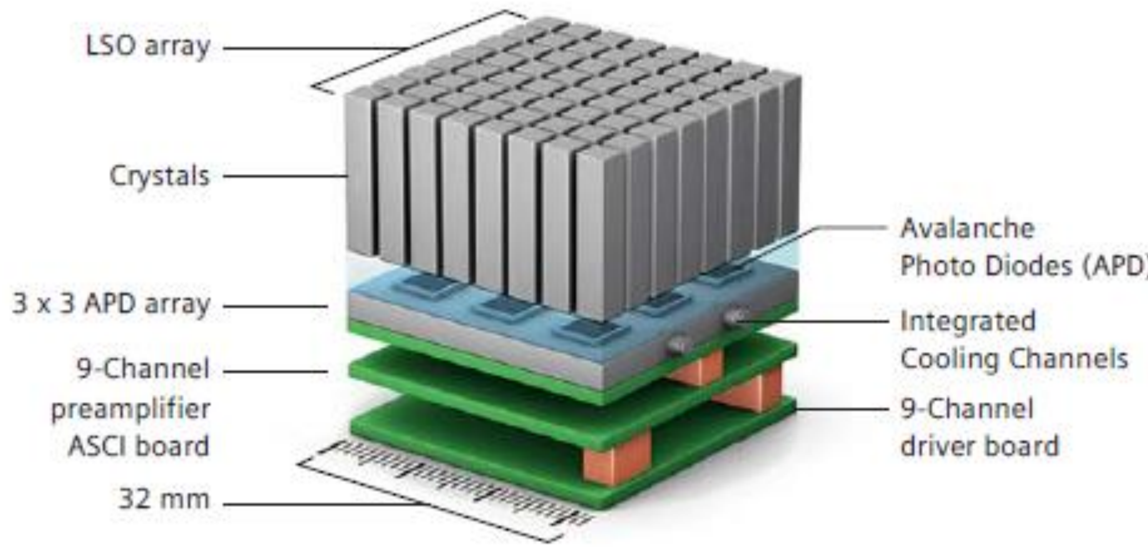
- Using Digital Photon Counting (DPC) technology so every scintillator crystal is directly coupled to a single SiPM detector.
- Each detector light sensor contains microcells that are capable of detecting a single photon converting the photon signal directly to an electrical output.
- The system contain more than 400,000 cells.
- Fast timing resolution of 345ps so the TOF localization accuracy is 5.2cm.



Courtesy of Philips

Siemens™ Biograph™ mMR

- First fully integrated PET/MR in the world.
- Currently uses LSO crystal with APDs for the PET/MR system.
- Time of flight is not available due to the limitation of APDs.



Images Courtesy of Siemens Medical Systems

Singapore General Hospital

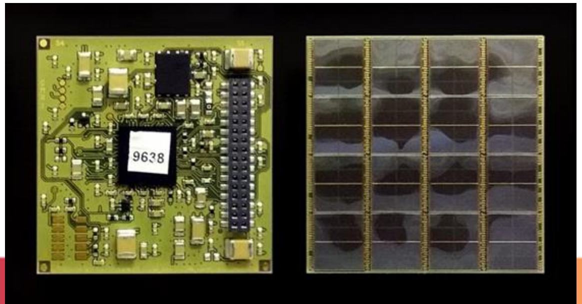
GE™ SIGNA™ PET/MR

- Simultaneous time of flight (TOF) PETMR
- Currently uses LySO crystal with Silicon Photomultiplier (SiPM)

Images Courtesy of GE Healthcare

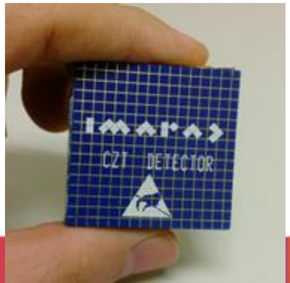
Summary: Future of photodetectors

- SiPMs have shown good energy and timing resolution, and an ability to decode arrays of scintillator elements,
- SiPM's have confirmed their potential as possible replacements for PMTs in PET detectors.
- Key questions that will determine whether PET scanners of the future will continue to be based on SiPMs:
  - Can SiPMs arrays be made with larger sensitive areas of at least 20 x 20 mm^2 without any degradation;
  - Can performance and cost per unit area be significantly less than PMT's?
  - If the answers are '*Yes*', then it would be hard to imagine that we will not see widespread adoption of SiPM technology in PET in the future



Summary: Future of solid state detectors

- This technology was approved by the FDA since 1997.
- The high cost and sporadic availability of CZT crystals have limited the adoption by the majority of companies & use in large FOV scanners.
  - Currently a vendor has a whole body dual detector CZT scanner for general SPECT and whole body imaging.
- One strong driver for solid-state technology could be its ability to be coupled with other imaging modalities, such as MRI,
- In addition, solid-state detectors have good low-energy resolution.
- **While the ideal detector has yet to be realized, the capabilities of modern scanners have continued to advance.**



Reference:

- *Tom K Lewellen, Recent developments in PET detector technology, Phys Med Biol. 200 8 Sep 7; 53(17): R287-R317.*
- *Ron Jaszczak et al. The early years of single photon emission computed tomography: an anthology of selected reminiscences.Phys.Med.Biol.51(2006) R99-R115*
- *Tom K Lewellen. Recent developments in PET detector technology.Phys Med Biol. 2008 september 7;53(17):R287-R317*
- *J Huizenga et al.A fast preamplifier concept for SiPM-based time-of-flight PET detectors.Nuclear Instruments and Methods in Physcis Research A 695 (2012)379-384*
- *Mark T.Madsen. Recent advances in SPECT Imaging.J Nucl Med 2007,48:661-673*
- *Todd E Peterson et al. SPECT detectors: the Anger Camera and beyond.Phys. Med. Biol 56(2011) R145-R182*
- *Emilie Roncali & Simon R. Cherry; Annals of Biomedical Engineering, Vol. 39, No. 4, April 2011 (2011) pp. 1358–1377*
- *D. Renker, Nuclear Instruments & Methods A 567 (2006) 48.*
- *J.S. Karp, et al., Journal of Nuclear Medicine 49 (3) (2008) 462.*
- *M. Moszynski, et al., IEEE Transactions on Nuclear Science NS53 (5) (2006) 2484;*
- *A Iltis, et al., Nuclear Instruments & Methods A 563 (2006) 359.*
- *C.L. Melcher, Journal of Nuclear Medicine 41 (6) (2000) 1051.*
- *Walrand S, Jamar F, de Jong M, Pauwels S. Evaluation of novel whole-body high-resolution rodent SPECT (Linoview) based on direct acquisition of linogram projections. J Nucl Med. 2005;46:1872–1880.*
- *Moses WW, Shah KS. Potential for RbGd2Br7:Ce, LaBr3:Ce, LaBr3:Ce, and LuI3:Ce in nuclear medical imaging.*
- *Nucl Instrum Methods Phys Res A. 2005; 537:317–320.*


Q&A