Photodetectors for Nuclear Medical Imaging

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Outline:

• Overview of Nuclear Medicine
• Current SPECT & PET Instrumentation
• Potential for New Photodetectors

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Needs & Technologies

PET
SPECT
MRI Compatible
Stability
Small Animal
Time-of-Flight
Cost
Depth-of-Interaction

High QE PMTs
APDs
PSAPDs
HPDs
SiPMs

Linkage is Complex…
Photodetector Technologies

High Quantum Efficiency PMTs
Gain $\sim 10^6$, 35%–50% QE (instead of 25%).

APDs
Si device, gain $\sim 10^2$, small pixels, QE > 90%.

Hybrid Photodiodes (HPDs)
Gain $10^4$–$10^6$, 25% QE, very uniform gain, good single p.e. resolution, can be pixellated.

Silicon Photomultipliers (SiPMs)
Si devices, gain $\sim 10^6$, small pixels, good single p.e. resolution, QE up to $\sim 40%$. 
Nuclear Medicine

- Patient injected with *small* amount of radioactive drug.
- Drug localizes in patient according to metabolic properties of that drug.
- Radioactivity decays, emitting gamma rays.
- Gamma rays that exit the patient are imaged.

*Well Established Clinical Technique*
*10 Million Studies Annually*
Single Photon Emission Computed Tomography (SPECT)

- One, two, or three imaging heads (cost / performance tradeoff)
- Direction of gamma defined by mechanical (parallel hole) collimators.
- Multiple views obtained by rotating the imaging heads around the patient.

Images 140 keV Photons
• Radionuclide decays by emitting a positron ($\beta^+$).
• $\beta^+$ annihilates with $e^-$ from tissue, forming back-to-back 511 keV photon pair.
• 511 keV photon pairs detected via time coincidence.
• Positron lies on line defined by detector pair.

- Detects Pairs of Back-to-Back 511 keV Photons
- No Collimator Needed $\implies$ Much Higher Efficiency
Desires

Research
High Spatial Resolution (small animal)
MRI Compatible
Depth-of-Interaction
Time-of-Flight (PET only)

Commercial
Stability
Cost / Unit Area
⇒ Cover ~0.5 m² @ $2 / cm² (SPECT)
$16 / cm² (PET)

How Can New Photodetectors Satisfy These Desires?
Starting Point for SPECT Detector: “Anger Camera”

Position Measured by PMT Analog Signal Ratio

Typical “Intrinsic” Resolution:
- 3.5 mm fwhm spatial
- 10% fwhm energy

3" PMT 3" PMT 3" PMT

Nal:TI

3/8" — 1/2"
SPECT Collimator Tradeoffs

Resolution = \(2 \frac{w}{L} \left( d + \frac{L}{2} \right)\)

Efficiency \(\propto \left( \frac{w}{L} \right)^2\)

Typical Values:
- \(w = 2\) mm
- \(L = 30\) mm
- \(t = 0.25\) mm

Resol. (@5 cm) = 6 mm
Efficiency = 0.02%
SPECT Detector Requirements

Based on Existing “Anger Cameras”

- High Efficiency (>85%)
- Good Energy Resol. (<15 keV fwhm)
- High Spatial Resol. (<4 mm)
- Low Cost (<$15/cm²)
- “Short” Dead Time (<2000 μs cm²)

At 140 keV:

- Scintillator Crystal (NaI:Tl, 50 cm square x 1 cm thick)
- Photomultiplier Tubes (~50 / head)

*Image courtesy of L. Shao, Philips Medical Systems
How Can Photodetectors Improve SPECT?

- **Spatial Resolution?**
  No — limited by collimator

- **Efficiency?**
  No — limited by collimator

- **Dead Time?**
  No — limited by collimator

- **Energy Resolution?**
  No — limited by scintillator

- **Cost?**
  Possibly — high QE PMTs

- **Stability?**
  Possibly — HPDs

**Not Many Possibilities…**
High Quantum Efficiency PMTs

- High Quantum Efficiency (>50% reported)
- Just Like Conventional PMTs, but Higher QE
  - Higher Dark Count Rate
  - Cost
How Can SPECT Cost Be Reduced?

• Higher QE PMT ⇒ More Photons Detected
• Intrinsic Resolution $\propto$ Pixel Size / $\sqrt{\# \text{ Photons}}$
• PMT Cost $\sim$ Independent of PMT Diameter

Get Same Spatial Resolution with Fewer High QE PMTs
Hybrid Photomultiplier Tubes (HPDs)

Hamamatsu Photonics

R9792U-40

Photocathode

PIN or APD Array

10 kV

3.6 eV per e/h
\[ \Rightarrow \text{Gain} \approx 3000 \times \text{PIN/APD Gain} \]

+ Pixellated, Gain is Very Stable
+ Single Photon Counting, Very Narrow Single PE Peak
- Large Dead Area, Lower Gain than PMT
Can Stability Be Improved?

- Anger Decoding (Positioning) Depends Strongly on Photodetector Gain
- Conventional PMTs are Notorious for Gain Drift
- Frequent Calibrations Required (~Weekly)

- HPD Stability VERY Attractive
- HPD Cost & Dead Area Are Potential Problems
Hybrid Photodetectors

Potential Applications

• Improve Stability for Clinical SPECT (calibrate once at the factory)
• Improve Stability for Clinical PET (calibrate once at the factory)

Possible Drawbacks

• Cost per Unit Area Unlikely To Be Competitive
• Large Dead Area

Drawbacks Will Be Difficult to Overcome...
Starting Point for PET Detector:
“Block Detector Module”

- Saw cuts direct light toward PMTs.
- Depth of cut determines light spread at PMTs.
- Crystal of interaction found with Anger logic (i.e. PMT light ratio).

4 PMTs (25 mm square)

Scintillator Crystal Block
(BGO ⇒ 8x8 array, 6 mm square xtal
LSO ⇒ 13x13 array, 4 mm square xtal)

Good Performance, Inexpensive, Easy to Pack
Crystal Identification with Anger Logic

- Uniformly illuminate block.
- For each event, compute X-Ratio and Y-Ratio, then plot 2-D position.
- Individual crystals show up as dark regions.
- Profile shows overlap (i.e. identification not perfect).

Can Decode 64 Crystals with BGO, 169 with LSO
Conventional PET Detector Requirements

- High Efficiency (>85%)
- High Spatial Resolution (<5 mm)
- Low Cost (<$100/cm²)
- Short Dead Time (<1 µs cm²)
- Good Timing Resolution (<5 ns fwhm)
- Good Energy Resolution (<100 keV fwhm)

Based on BGO or LSO “Block Detector”

*Image courtesy of M. Casey, CPS Innovations
Small Animal PET

microPET II

- 17,640 LSO crystals (0.95x0.95x12.5 mm)
- 15 cm ring diameter
- 8 cm transverse FOV
- 4.9 cm axial FOV
- ~1.2 mm resolution
- ~2.5% sensitivity
Detector Module for Small Animal Camera

- 4 PMTs ➔ Multi-Anode PMT
- Current Division Mimics Anger Logic
- Dead Area ➔ Light Guides Couple PMT to Crystals

Scintillator Crystals (1–2 mm square)

Flood Map

14x14 Crystals
1 mm square x 12.5 mm
How Can Photodetectors Improve PET?

- **Spatial Resolution?**
  - Yes — high QE PMTs, APDs, SiPMs

- **Efficiency?**
  - Possibly — APDs, SiPMs

- **Timing Resolution?**
  - Yes — high QE PMTs, SiPMs

- **Energy Resolution?**
  - No — limited by scintillator

- **Cost?**
  - Possibly — high QE PMTs

- **Stability?**
  - Possibly — HPDs

Many Possibilities…
High Quantum Efficiency PMTs

16x16 LSO Crystals

- Decode More Crystals ⇒ Improve Spatial Resolution
- Larger PMT ⇒ Reduce Cost?
Time-of-Flight in PET

- Can localize source along line of flight.
- Time of flight information reduces noise in images.
- Time of flight cameras built in the 80’s with BaF$_2$ and CsF.
- These scintillators forced compromises that prevented TOF from flourishing.
- New scintillators (LSO & LaBr$_3$) have resurrected TOF PET.

\[ c = 30 \text{ cm/ns} \]

500 ps timing resolution \( \Rightarrow \) 7.5 cm localization

\[ \Delta t \]

- Variance Reduction Given by \( 2D/c\Delta t \)
- 600 ps Timing Resolution \( \Rightarrow \) 4x Reduction in Variance!
High Quantum Efficiency PMTs

- Increased QE $\Rightarrow$ Better Timing Resolution
- Valuable for Time-of-Flight PET

$I(t) = I_0 \exp(-t/\tau)$

Timing Resolution $\propto 1/\sqrt{I_0}$
High Quantum Efficiency PMTs

Potential Applications

• Reduce Cost in Clinical SPECT & PET (get same spatial resolution w/ fewer PMTs)
• Improve Timing Resolution for TOF PET (higher initial photoelectron rate)

Possible Drawbacks

• Cost per Unit Area May Not Be Competitive

It All Depends on the Cost / Area…
Avalanche Photodiode Arrays

- High Quantum Efficiency (90% Possible)
- Small Pixels (Individually Couple to Crystals)
- Compact, Insensitive to Magnetic Fields
  - Large Dead Area
  - Lower Gain than PMT
- Poor Signal to Noise Ratio, Noise Scales w/ Area
- Reliability & Cost, # of Electronics Channels
Simultaneous PET/MRI

- Combine Anatomic Information from MRI w/ Functional Information from PET
- Need Phototdetectors that are Insensitive to B Fields
- Desired for Both Human and Small Animal

Several Prototype PET/MRI Cameras Built Using APDs
Simultaneous PET/MRI

Human Brain / Animal PET/MRI Camera Using APDs
Radial Elongation

- Penetration of 511 keV photons into crystal ring blurs measured position.
- Blurring worsens as detector’s attenuation length increases.
- Also known as Parallax Error or Radial Astigmatism.
- Can be removed (in theory) by measuring depth of interaction.
Depth-Encoding PET Detector Module

- PMT Provides Timing Pulse
- PD Array Identifies Crystal of Interaction
- PD+PMT Provides Energy Discrimination
- PD / (PD+PMT) Measures Depth of Interaction

Key Photodetector Feature is Compactness
Typical APD Module Readout

Advantages:
- Channels Are Independent
- High Rate
- Minimum Noise (Low C, Low I)
- Complex Readout (thresholding, nearest neighbors, multi-hit rejection, etc.)

Disadvantages:
- High # Channels ($\propto$ linear_dim$^2$)
- High Connection Density
- High Power Consumption
- Complex Readout

- Individual Amplifiers for Each Pixel
- Necessary to Minimize Noise
- Can Do Current Division After Amplifiers
Position-Sensitive APD (PSAPD)

- 28 mm LSO Array

Flood Map, 
–20° C

- 15% fwhm Energy Resolution
- 3 ns fwhm Timing Resolution

- Similar to APD Array Read Out with Current Division
- Cooling Often Needed to Reduce Noise

*Data and image courtesy of K. Shah, RMD, Inc.*
APDs & PSAPDs

Potential Applications

• Simultaneous PET/MRI (insensitive to magnetic fields)
• Depth of Interaction for Clinical PET (measure light ratio on both ends of crystal)
• Depth of Interaction for Animal or Breast PET (measure light ratio on both ends of crystal)

• Possible Drawbacks

• Cost per Unit Area May Not Be Competitive
• Tradeoff Between Number of Electronics Channels and Signal-to-Noise Ratio
• Worse Timing Resolution than PMT

• Already Incorporated in Some Cameras
• May Be Replaced By Other Technologies?
Silicon Photomultipliers (SiPMs)

+ High Quantum Efficiency (~40% Possible)
+ Small Pixels (Individually Couple to Crystals)
  + Insensitive to Magnetic Fields
  + Good Stability?
  – Large Dead Area
– Reliability & Cost, # of Electronics Channels
  – Scale-Up to Large Areas Difficult

Bias

20% fwhm Energy Resolution

\[ \chi^2 / \text{ndf} = 24.38 / 33 \]

Constant: 664 ± 7.0
Mean: 1.248 ± 0.001
Sigma: 1.007 ± 0.001

Energy Resolution
Scale Up In Area

Issues:
• Dark Count Rate High, Proportional to Area
• Capacitance High, Proportional to Area
⇒ 1x1 mm Common, 3x3 mm Rare, None >4x4 mm
• Very Few Monolithic Arrays

If PET Only Required a Single Pixel, SiPMs Would Be Commonly Used Today…
Readout Electronics For SiPMs

Individual Pixel Readout?
- ~50k Scintillator Pixels / Camera
- 100 mW / ADC $\Rightarrow 5$ kW / Camera
- Lots of Connections / Packaging Issues

Current Division Readout?
- Large C & Division Resistors Degrades Timing
- Use On-Device Electronics to Buffer?

Not Impossible, But Needs Serious Thought!
Improve PET Efficiency

+ Continuous Xtal Reduces Dead Volume & Handling
  + 1–2 mm Resolution w/ 5–10 mm Thick Slab
+ With High QE Photodetector, Increase to 25 mm thick?
+ Width of Light Distribution Measures DOI

*Images courtesy of S. Tavernier, Vrije Univ.*
What SiPM Advances Are Necessary Before They Are Used for PET? (In Order of Decreasing Importance)

**Scale Up Area**

- Whole-Body PET Camera has 50k crystals, each 4x4 mm ⇒ 800k 1 mm² pixels
- Minimum Package Size 2.5 cm x 2.5 cm (monolithic or hybrid)
- Minimum Pixel Size 3 mm x 3 mm (4 mm x 4 mm preferable)

**Practical Readout Electronics**

- “Anger Logic” without severe performance drawbacks
- Low power individual channel (implies ASIC + packaging)
- On-sensor CMOS
What SiPM Advances Are Necessary Before They Are Used for PET II? (In Order of Decreasing Importance)

Stabilize Output

- Cannot have photopeak drift with time
  ⇒ Product of PDE and Gain is constant
- Inherent Stability
- Calibration (temperature sensor w/ data correction)
- Active Feedback (temperature sensor w/ bias V adjust)

Reduce Cost

- $?? / cm² APD Array
- $150 / cm² Multi-Anode PMT
- $15 / cm² Conventional PMT
What SiPM Advances Are Necessary Before They Are Used for PET III?  
(In Order of Decreasing Importance)

Increase Photon Detection Efficiency

• SNR meets present specifications w/ ~10% PDE
• Imagine what you can do with 90% QE!!!

Dark Count Rate (Not Really Important)

• Adequate SNR at 1 MHz / cm² — little gain from reduction

Saturation

• “True” 511 keV photopeak position & width unimportant
• Scatter rejected with window placed on either side of photopeak
Conclusion

High QE PMTs
- Several Potential Benefits
- Limiting Factor Will Be Cost

SiPMs
- MANY Potential Uses
- Significant Technical Challenges Must Be Overcome First
- Challenges Are Not Fundamental — CAN Be Solved