Emerging Solid-State Detector Technologies

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EMERGING AND SOLID STATE

“Emerging”:
- under development
- being tested on the lab bench
- in clinical trials or in prototypes
- and expected to be clinically useful in nuclear medicine

“Solid State”:
- Not a gas
- Not a vacuum tube (PMT)
- Direct conversion of radiation into signal
- Direct conversion of scintillation light into signal w/o PMTs
After 50 years of failure, why do we continue to do it?

• What are the drivers advancing the technologies?
  – Micro-machining, micro-electronics, materials, packaging
  – Computers, algorithms, corrections, statistical optimization
  – Competition – CT, MRI, Ultrasound – tremendous progress
  – Pre-clinical imaging – proving ground for new technologies

• Why do we do it?
  – We want to invent the camera for the next 50 years! (that is, we have Anger issues....)
  – “We don’t do it because it’s easy, we do it because it’s hard!” President JF Kennedy
OUTLINE

• Review State-of-the-Art
• PET
• CT Counting mode
• SPECT
• Concluding Remarks
STATE-OF-THE-ART RADIATION DETECTORS FOR CLINICAL IMAGING

• PET
  – Fast Scintillators & PMTs
  – Fast Electronics & Time-of-flight
  – Fast Signal Processing and Depth-of-interaction
  – MR-compatibility with Silicon-based Photosensors

• CT
  – Multiple x-ray tubes
  – Wide, multi-slice scintillator/photodiode detectors
  – 1/3 second Acquisition

• SPECT
  – SPECT + CT
  – Dedicated Anger cameras for nuclear cardiology
  – CZT in new nuclear cardiology products
  – Dedicated breast imagers
STATE-OF-THE-ART
RADIATION DETECTORS FOR PRE-CLINICAL IMAGING
PROVING GROUND FOR NEW IMAGERS!

• PET
  – Many prototypes being built world-wide
  – Clever depth-of-interaction schemes
  – “Zoom lens” magnification schemes
  – New crystal and photodetector materials
  – Gas and Semiconductor detectors

• CT
  – High resolution (< 20 microns)
  – “High” speed (< 30-60 seconds) (not high by clinical standards!)

• SPECT
  – Anger cameras
  – Annulus-shaped crystals
  – Panel-detectors of CZT
  – Rings of CZT
  – Pinholes, multiple pinholes, slits, slats, coded apertures.
“SOLID STATE” PET APPROACH WITH APDS COUPLED ONE-TO-ONE

Conventional coding scheme
Mapping of Crystals to PMT

Often with light guide
And software maps

One-to-one coupling
Of crystal with APD

Long-time research project
Many publications

LabPET™
Courtesy GM-I)
LabPET™ Architecture

Design Parameters
- 16.2 cm diameter ring
- FOV: 10 cm diameter × 3.75, 7.5 or 11 cm axial
- 2×2×10 mm³ LYSO/LGSO scintillators
- 8-pixel, quad-APD detector modules
- Individual readout, parallel signal processing

http://www.advanced-mi.com/
LabPET™ Sub-system

Specifications and Highlights

- Intrinsic Spatial Resolution
  ~ 1.2 mm at center of FOV
  ~ 1.35 mm reconstructed

- FWTM ~ 2.2 mm

- Sensitivity up to 6 %

- Peak NEC > 2500 kcps

- 1536/3072/4608 APD detectors

- Parallel signal processing

- High count rate

- Negligible dead time
LabPET™ Sub-system

Spatial Resolution is high, because no coding is done

\[ FWHM = a \sqrt{\left(\frac{d}{2}\right)^2} + b^2 + (0.0022D)^2 + r^2 \]
LabPET™ Sub-system

*Spatial Resolution is high, because no coding is done*

\[ FWHM = a \sqrt{\left(\frac{d}{2}\right)^2} + b^2 + \left(0.0022D\right)^2 + r^2 \]
Intrinsic resolution Measurement

Coincidence response functions

- Radial
  - Counts vs Source Position (mm)
  - LGSO: 1.22 mm, <1.13-1.31>
  - LYSO: 2.28 mm

- Axial
  - Counts vs Source Position (mm)
  - LGSO: 1.16 mm, <1.10-1.24>
  - LYSO-LGSO: 2.40 mm

- Nearly triangular shape
- Intrinsic resolution ~1.2 mm
- FWTM ~ 2 x FWHM

Intrinsic radial resolution vs Position

- FWTM
- FWHM

Check marks:
- Nearly triangular shape
- Intrinsic resolution ~1.2 mm
- FWTM ~ 2 x FWHM
WHAT IS ON THE HORIZON FOR PET?

- PMTs have been targeted for replacement for decades!
- Finally technology is here to replace them:
  - AVALANCHE PHOTODIODES (APDs)
  - SMALL, FAST, MR-compatible
- Next Generation is Anticipated; Timeline Unknown
  - Silicon Photomultipliers – in the APD family
  - Carbon-based (organic) photodetectors

For the foreseeable future, we look to

AVALANCHE PHOTODIODES
CT Detectors:
Direct Conversion versus Scintillators

• For more than a decade Direct Conversion semiconductor detectors have been researched for use in CT
  • CdTe, CZT, HgI$_2$ are the best candidates
  • Fast (1/3 second) CT rotation/readout precluded CZT
• BUT
  – PRE-CLINICAL CT IMAGING CAN USE SLOWER READOUT, SINCE SCANS TAKE >30 seconds!
  – AGAIN, PRE-CLINICAL IMAGING WILL BE PROVING GROUND FOR A NEW TECHNOLOGY
Mercuric Iodide Panel
3200 x 3200 pixels

Advantages:

- Fast readout (compared to CCD)
- Selected readout (sections)
- Higher resolution (30 micron)
- Higher DQE
- Higher contrast
- Lower dose
Counting mode “color” CT

- Current commercial CT technology
  - Silicon (p-n junction) photodiode/scintillator arrays
  - Current-integrating mode operation
  - **Direct conversion on the horizon in pre-clinical**

- Next generation technology
  - Single photon counting (SPC) and “Color” i.e. energy discrimination or spectroscopy
  - Measures and counts each x-ray individually
  - Bins the individual x-rays according to energy
  - Advantages:
    - Increased dynamic range (2-3 orders) on the low photon side
    - Additional information in the data (energy spectrum)
  - Results
    - >4-10 x lower dose or higher speed for same quality image
    - Tissue composition analysis; better soft-tissue contrast
PET Module for X-ray CT Photon Counting

Close to 1 mm res
5 MCT/pix/s
Energy discrimination

Philippe Bérard, Joel Riendeau, Catherine M. Pepin, Daniel Rouleau, Jules Cadorette, Réjean Fontaine, and Roger Lecomte.

Photon-counting CT performance assessment of the LabPET™ detector and electronics for molecular imaging applications. IEEE 2006 (San Diego, Oct 06) abstract #M14-93.
FIRST GENERATION COUNTING MODE CT

2 CdTe crystals

4x384 CdTe counting detector arm

5 energy bins

Frey E, et al SPIE (Jan 07, in press)
Revolutionize CT

• COUNTING CT OFFERS
  – ENERGY BINNING
  – ENERGY MANIPULATION TECHNIQUES
    • researched for more than 30 years
    • filtering, dual-detector, single shot
    • double shot (different kVp)
  – MATERIAL DEPOSITION THROUGH SPECTRAL ANALYSIS
  – SOFT TISSUE CONTRAST ENHANCEMENT
  – LOWER DOSE
CZT (CdTe) Modules

- Zanio (1977)
- Entine (1979 IEEE TNS 26(1): 552-3)
- Arizona (1993)
- Digirad (1997)
- Gamma Medica-Ideas (beginning 2001)

MAIN DEVELOPMENT GOAL: A multi-channel (at least 256), pixellated module that can be plugged in to and removed from a SPECT imaging system.
HIGH DENSITY LOW POWER ASIC ELECTRONICS

Sub-micron CMOS
128-channel Asics
16x16 array (2 Asics)
256 individual spectrometers operating simultaneously
Room for improvement: sub-pixel resolution with more signal processing
CZT DETECTOR HEADS

Isorad/Nucam 1998
Digirad 1998
GE/Mayo 2001

Siemens 2002
Gamma Medica-Ideas 2004

Gamma Medica-Ideas 2007
DETECTOR PARAMETERS

ANGER (50 years)
- Uniformity
- Linearity
- Useful FOV
- PMT Drift
- Hygroscopic
- Brittle and large
- Daily floods
- Monthly maps

CZT (5 years)
- Channel variability
- Pixellated
- Dead pixels
- Temp-dependence
- Surface prep
- Brittle and small
- On-the-fly testing
- Perhaps > monthly (WIP)
CZT STABILITY DEFINED
6400 pixels, 2 time points
4 month separation

Peak position values in ADC units for the 80x80 small animal imaging head under test in the laboratory of GM-I. This plot depicts 6400 pixels measured at two time points separated by 4 months.

The stability of this CZT camera’s performance over time is perhaps the best ever recorded.
ENERGY RESOLUTION OF CZT

$^{111}\text{In} + ^{99m}\text{Tc}$ lab spectrum
– best CZT pixel performance

![Graph showing energy resolution of CZT](image)

- 23-26 keV
- 140 keV
- 171 keV
- 245 keV

- FWHM 2.7%
- FWHM 2.6%
- FWHM 2.7%
- FWHM 2.0%

CZT detector
Tc-99m + In-111
ENERGY RESOLUTION OF CZT COMPARED WITH PIXELLED NAI (TI)

[Graphs showing energy resolution for different isotopes with CZT and NaI(Tl) compared]
Technetium-Thallium dual-isotope with CZT
Recommend Tungsten
### MODALITY ONE
- Vessels/flow
- Bone uptake
- Organ function (e.g., kidney, thyroid)
- Organ function under stress (cardiac)
- Perfusion
- Metabolism
- Targeted uptake, e.g. antibody
- Biological process #1: e.g. Angiogenesis
- Biological process #2: e.g. Apoptosis
- Inflammation

### MODALITY TWO
- Vessels/flow
- Bone uptake
- Organ function (e.g., kidney, thyroid)
- Organ function under stress (cardiac)
- Perfusion
- Metabolism
- Targeted uptake, e.g. antibody
- Biological process #1: e.g. Angiogenesis
- Biological process #2: e.g. Apoptosis
- Inflammation

### MODALITY THREE?
TRI-ISOTOPE SPECT WITH CT

Orange Tc99m bone
Blue I-123 thyroid
Green TI-201 heart
CZT In the Clinic...

CardiARC

Spectrum Dynamics

Dual-isotope Cardiac Scatter rejection
Breast Imaging with CZT

LumaGem (courtesy of Gamma Medica-Ideas)
ADVANTAGE OF TWO CZT HEADS
We want many “mini-gamma cameras to view the tissue simultaneously for dynamic, stationary SPECT: HIGHER RESOLUTION AND SENSITIVITY
Space-Bandwidth Product

- DETECTOR AREA / INTRINSIC RESOLUTION

- Scintillator slivers, PSPMTs, silicon photosensors
- 0.320 mm intrinsic resolution achievable with CZT and GMI-ASICs and clever (induced) signal processing
- What to do with 0.320 mm intrinsic resolution?

- MINI-GAMMA CAMERAS
- MULTIPLE GAMMA CAMERA-ON-A-CHIPs
- EACH WITH A PINHOLE VIEW AND PROJECTION
- DYNAMIC SPECT; MOTION-FREE SPECT
SURROUND THE TARGET
WITH MINI-CZT GAMMA CAMERAS –
1st GENERATION

5 “mini” cameras per head (4 heads, 5 pinholes per head)
Room for larger detectors for more mini-cameras

4th generation multi-modality pre-clinical imager

Less industrial, more clinical
2nd Generation – RING OF CZT Mini-Cameras

Stationary SPECT
24 simultaneous views
Smallest SPECT camera
CZT modules
MR-compatible (tested up to 7.0 T)

Gamma Medica-Ideas
NIH SBIR Grant #1R43HL080819
MRI-CZT SPECT FIELD TESTS

For mouse imaging – 12 cm outer dia.!
MINIFICATION IS THE KEY

2.5 mm  1.6 mm  0.8 mm  0.4 mm
CONCLUDING REMARKS

• PET – APDs allow one-to-one coupling of crystals
• PET – APDs allow MR-compatibility
• SPECT – space*bandwidth product drives CZT
  – Pinhole minification
  – Off-plane projections of Rugulski (1993)
  – Simultaneous Dynamic SPECT
  – High sens and high res at cost of S-B product
• CT – counting mode
  – Lower dose
  – Higher soft tissue contrast
• GM-I  Research is involved in all these efforts
  – Happy to discuss collaborations, prototype testing, etc.