Bringing Photon Counting Detectors to the Interventional Room

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Siemens Medical Solutions

Introduction: Clinical Example of Image-Guided Intervention

62 y.o. diagnosed with acute ischemic stroke

Pre-treatment

Post-treatment
Baseline non-contrast MDCT

Post-treatment FPD-CBCT

Lesions: Isotope? Hemorrhage? Calcium?

Technical limitations of the existing scintillator-based energy-integrating FPDs:
- Poor low-contrast detectability
- Lack of material quantification capability
Poor Quantum Absorption Efficiency of Scintillator-Based Flat Panel Detectors

Absorption efficiency @ 80 keV

- 2 mm CdTe
- 0.6 mm CsI

Why not making CsI in PPD thicker?

Figure 1. Spatial resolutions in terms of the MTF (O of various thicknesses. (Miller et al., Proc. SPIE, Vol. 5923, pp. 59230F (2005))

Other Limitations of Scintillator-Based Flat Panel Detectors

- Swank noise [1]
- Lubberts noise [2][3]
- Long transmission distance of analog signals [4]
- Highly suboptimal photon weighting [5]

[1] Swank, JAP 44, 4199 (1973)
[2] Lubberts, JOSA 58, 1475 (1968)

What is photon counting detector?

- In EIDs, X-rays are first converted into visible lights in a scintillator and then to electrical signal. In PCDs, X-rays are directly converted to electric signal.
- In PCDs, a bias voltage is applied to a photoconductor.
- PCDs resolve the energy of X-rays.
- PCD-CT is a radically new technology.
**Fundamental Difference between PCDs and EIDs:**

- **PCDs: pulse detection mode**
  - Electric pulses induced by each input quanta are counted to
  - Estimate the number of input quanta
  - and the energy of each input quanta if multiple comparators are used

- **EIDs: current/charge integration mode**

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**The First CT IS a Photon Counting Detector CT**

The first experimental CT system developed by Allan Cormack in 1963 used a photon counting detector (Geiger counter).

A. Cormack, Applied Physics 34, 2722 (1963)

A. Cormack, Nobel Lecture (1979)

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**Detection of Individual X-Ray Pulses using a Silicon Photomultiplier (SiPM)**

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**Photon Counting Detectors**

- Gas based (direct conversion)
  - G-M counter
  - Proportional counter
  - Pulse-mode ion chamber

- Scintillator based (indirect)
  - Scintillator + PMT
  - Scintillator + SiPM
  - Scintillator + EMCCD

- Semiconductor based (direct conversion)
  - CdTe/CZT
  - Si
  - a-Se

**Semiconductor-based Photon Counting Detectors**

- Single-photon avalanche photodiode (SPAD) in Si photomultiplier (SiPM)
- Pulse-mode direct-conversion detector

**Larger Number of Information Carriers/Input Energy**

Glenn Knoll*

* “One of the major limitations of scintillation counters is that the energy required to produce an information carrier (a photoelectron) is of the order of 100 eV or more.”

* “...the use of semiconductor materials as radiation detectors can result in a much larger number of carriers for a given incident radiation event than is possible with any other common detector type.”

<table>
<thead>
<tr>
<th>Material</th>
<th>Number of secondary quanta generated</th>
<th>Average # of secondary quanta per 100 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>33.97</td>
<td>2,900</td>
</tr>
<tr>
<td>CsI(Tl)</td>
<td>17</td>
<td>5,900</td>
</tr>
<tr>
<td>Si</td>
<td>3.6</td>
<td>28,000</td>
</tr>
<tr>
<td>CdTe</td>
<td>4.4</td>
<td>23,000</td>
</tr>
</tbody>
</table>

To maximize CNR, the optimal weighting scheme is

\[
N_{\text{out}} = \sum_{\text{E}} w(E) N_{\text{in}}(E)
\]

If \( n_1(E) - n_2(E) \) = constant as in white and gray matters, then equal weighting is the optimal, and that is exactly what PCDs do!


** Low-Contrast Detectability Supremacy of PCDs **

- PCD-CT
- FPD-CBCT
- MDCT

Display window: 60 HU
Display window: 120 HU

** Better Spatial Resolution **

Pre-sampling MTFs with Matched Detector Pixel Pitch

- PCD: AntiC On; Threshold=15 keV
- PCD: AntiC Off; Threshold=15 keV
- FPD (4030CB)
- Xcounter PCD (2x2 binned)

** Matched Detector Pixel Pitch **

<table>
<thead>
<tr>
<th>Detector</th>
<th>Pixel size (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Varex 4030CB</td>
<td>194</td>
</tr>
<tr>
<td>Xcounter PCD</td>
<td>200 (2x2 binned)</td>
</tr>
</tbody>
</table>
Better Spatial Resolution

- C-arm PCD-CT: 21 lp/cm
- FPD-CBCT: 12 lp/cm

Excellent Temporal Resolution (which also benefits LCD!)

- 1000 fps
- 100 fps
- 50 fps

True Velocity of the Object: 0.5 m/s

Bringing PCD to Intervention Room: Prior Art

References:
### PCD - CT

- Full axial FOV low-contrast / spectral PCD-CT
- PCD can be surrounded by EID modules to form single piece for full-FOV imaging
- PCD output can be combined with output from the rest of the flat-panel EID to form a single projection image

### Dagger (†)-shaped Hybrid Detector Design

- I module
- Full axial FOV low-contrast / spectral PCD-CT
- □ module
- 3D VOI and 2D ROI high-res / spectral imaging

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**References**

[2] Treb et al., SPIE Medical Imaging, 2021

**US patent pending**
PCD Nonuniformity Correction

- w/o correction
- With correction

Change of PCD transvers offset

- w/o correction
- With correction
- Nonuniformity correction
- Geometric correction

Ji et al., IEEE TMI 40, 3674 (2021)

Geometric Distortion in C-arm PCD-CT

- Change of magnification factor
- Change of PCD transvers offset

Results: Head Phantom

- w/o correction
- With nonuniformity correction
- With both nonuniformity and geometric correction

Ji et al., IEEE TMI 40, 3674 (2021)
Potential Applications of C-arm PCD-CT in Image-guided Interventions

Grey-White Matter Differentiation

Detection of Intraparenchymal Hemorrhage
Detection of Subarachnoid Hemorrhage

Photon counting CT  
State-of-the-art commercial CT  
State-of-the-art commercial CT

Ji et al., RSNA Annual Meeting (2017)

Intracranial Calcification/Iodine Discrimination

PCD-CT  
Dual-Energy MDCT

Human Cadaver Heads  

Ji et al., IEEE TMI, 2021

Material Quantification

Phantom illustration  

Low energy bin PCD-CT  
High energy bin PCD-CT

Radon transform  

Virtual non-iodine contrast  

I-2 differentiation

Iodine basis  
Effective atomic number
High-Speed Angiography and Flow Imaging

- Presentations from the University at Buffalo:
  - TH-C-201-4: Vanderbilt et al., "BEST IN PHYSICS (IMAGING): Implementation of 1000 Fps CdTe Photon-Counting Detectors (PCD's) for Simultaneous Biplane High-Speed Angiography (HSA)."
  - TH-C-201-1: Wu et al., "1000 Fps High Speed Angiography (HSA) of Contrast Injections in An In-Vitro Model with Pulsatile Flow Using Simulated Cardiac Gating Techniques"
  - TH-B-207-1: Shields et al., "Evaluation of Shear Forces Within Stenotic Vessel Models Using 1000 Fps X-Ray Particle Image Velocimetry (X-PIV)."

Summary

- The fundamental difference between PCDs and energy-integrating FPDs in existing C-system systems:
  - Pulse mode vs. current integration mode
- Semiconductor-based direct-conversion PCD is a sub-type of the PCD family
- Advantages of semiconductor-based direct-conversion PCD
  - Low-contrast detectability supremacy
  - Single-shot dual-energy imaging
  - Superior spatial and temporal resolution
Summary

- With proper calibration and correction, high-quality C-arm PCD-CBCT images can be generated.

Potential applications of PCD-CBCT in interventional imaging:
- Spectral imaging for material quantitation and differentiation without compromising dose efficiency and speed of non-spectral imaging.
- Non-spectral imaging applications should not be overlooked:
  - Improved gray-white matter delineation (for ASPECTS and hemorrhagic transform risk evaluation).
  - Improved detection of intraoperative hemorrhage.
  - Improved detection of small blood vessels and devices.
  - High frame rate angiography and flow imaging.

Thank You!

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