Developments in Imaging Receptors and Applications in Projection X-ray Imaging:

J. Yorkston Carestream Health
Rochester NY
Disclosure:

- John Yorkston works for Carestream Health that manufactures and sells CR and DR systems for medical applications
Digital Acquisition: Introduction

• “CR” technology introduced in 1980’s
  – Originally referred to “storage” phosphor based systems
  – Cassette based imaging with separate readout scanner
  – Similar workflow as screen-film cassettes

• “DR” technology introduced in mid 1990’s
  – Originally referred to a-Si:H (and CCD) based systems
  – Integrated with x-ray system
  – Fully “electronic” readout with no moving parts

• Since then a number of novel hybrid systems:
  – “Avalanche” of new terms and nomenclature that confuse and confound
  – Much of this originates in the “marketing” departments of companies
Educational Goals:

• Identify features that define the underlying technology

• Decipher confusing terminology present in marketplace
  – Know what questions to ask

• Appreciate differences between competing approaches
  – All systems have their pros and cons...
  – Important to know which suits your application and budget

• Understand recent/future developments
  – New detector design and system configurations
  – New types of “future” detectors and their capabilities
Digital Image Formation:

- X-rays modulated by object
- X-Ray Converter/Absorber
- Secondary quanta response
- Secondary quanta detector

Diagram:

1. Incoming X-rays
2. X-ray “Converter”
3. Response
4. Detector
Outline:

• Discuss x-ray absorption material selection

• Review secondary quantum detection options

• Review current status of projection x-ray technology
  – Highlight new developments in designs and their rationale

• Review future detector developments
  – New configurations (e.g. flexible substrates, “smart pixels”)
  – New capabilities (e.g. photon counting and energy resolution)
X-Ray Absorption Materials:

• Advantageous properties for an x-ray absorber include:
  – Absorb as many x-rays as possible
  – Provide accurate measure of how many x-rays interacted
  – Maintain information on spatial location of point of interaction
  – Manufacturable over suitably large physical areas

• Two different types of materials used:
  – Phosphor materials that generate light
  – Photoconductor materials that generate electrical charge
X-Ray Phosphors:

- Two categories of x-ray phosphor materials
  - Prompt emission materials (e.g. $\text{Gd}_2\text{O}_2\text{S}(\text{Tb})$ also known as GOS)
    » Emit light “instantaneously” on absorption of x-ray
    » Formed basis for “modern” screen-film systems
  - Photo-stimulated emission materials (e.g. $\text{BaFBr(I)}$)
    » Fraction of x-ray energy stored in long lived “latent” sites
    » Require readout with stimulating radiation (typically laser)
    » Also known as “storage” phosphors
    » Formed basis for Computed Radiography (CR) systems
    » Actually emit ~50% of energy as “prompt” light
    » Require erasure step to remove remaining signal

- Traditionally created as particle-in-binder (PIB) layers
  » Also known as phosphor-in-binder or POWDERED Phosphor
X-Ray Phosphors:

- PIB configured from small phosphor grains in plastic
  - Relatively “easy” to manufacture (after decades of development)
  - Very physically robust

- Issue with creating thick layers to increase absorption
  - Light scatters within material
  - As thickness increases so does light spreading
    » Reduces resolution and increases noise (Lubberts effect)
  - Escape efficiency of light from screen varies through screen depth
    » Also results in increased noise (Swank noise)

![Scanning Electron Micrograph](image.png)

- phosphor
- Air gaps
- binder

Approximately 100-150 µm
X-Ray Phosphors:

- More recently “structured” phosphors have been used
  - Prompt emission type: CsI(Tl)
  - Stimulated emission type: CsBr(Eu)
  - Reduces effect of thickness on spatial resolution: allows thicker layers
  - Improves light escape efficiency so reduces Swank noise
  - Allows higher “packing fraction” than PIB so higher effective absorption

~200 µm Mammo.
~500-600 µm Gen. Rad.
X-Ray Photoconductors:

- Somewhat different issues than phosphors:
  - Require applied voltage to “energize” layer and allow charge collection
  - Internal field constrains lateral drift of released charges
  - Near perfect spatial resolution almost independent of thickness
  - High collection efficiency so low Swank noise
  - Most mature material is amorphous selenium (Z=34)
    » Low Z value limits x-ray absorption at diagnostic energies (>60kVp)
    » Difficult to manufacture thick layers (~1000\(\mu\)m) over large area
    » More suited to mammographic applications (<30kVp)
  - Other materials include c-Si, CdTe, CdZnTe, HgI, PbI, PbO, Xenon.
Mammo. Photon Absorption vs. Thickness

(28kVp Mo/Mo 5cm PMMA)

- a-Se Photon Abs. (%)
  - ~97%

- CsI(Tl) Photon Abs. (%)
  - ~84%
RQA-9 Photon Absorption vs. Thickness

- CsI(Tl) Photon Abs. (%)
- a-Se Photon Abs. (%)

CsI(Tl) ~56%
a-Se ~27%
Clinical Image Comparisons: Lateral Chest (120kVp)

500μm CsI(Tl)  

500μm α-Se
X-Ray Absorption Materials Summary:

• Can be divided into 3 main types:
  – Prompt emitting phosphors \( \text{Gd}_2\text{O}_2\text{S}(\text{Tb}), \text{CsI}(\text{Tl}) \)
  – Stimulated emission phosphors \( \text{BaFBr(I)}, \text{CsBr(Eu)} \)
  – Photoconductors (a-Se)

• Phosphors can be sub-divided into:
  – Powdered or Particle-in-binder layers
  – Structured/Needle/Focused Phosphors

• All have sufficiently good properties to be “useful”

• Which is “best” depends on specifics of application
Secondary Quanta Detection:

• Issues are similar for phosphors and photoconductors
  – Need accurate measure of generated signal over large areas
  – Maintain image “quality” produced by x-ray absorption layer

• Possible approaches include
  – Point by point scanning
  – Line scanning
  – Full area readout
Point by Point Scanning:

- Storage Phosphors/CR lend themselves to this approach
  - Image information “stored” in phosphor till scanned
  - Allow time to scan whole area with small laser spot
  - Spot ~100\(\mu\)m in size, 10mW power,
  - Dwell time ~few \(\mu\)secs/pixel
  - ~30 or so seconds for full readout
Point by Point Scanning:

- Optics and mechanical motion require “large” system
- Issue with collection efficiency of stimulated light
  - Secondary quantum sink at collection stage
- One solution: read out signal from both sides of phosphor

Image courtesy R. Uzenoff Fuji Medical
Point by Point Scanning:

- NovaRay’s ScanCath™ inverse geometry system (SBDX)
- Uses large area source and small area detector
  - Pixellated CdZnTe photon counting detector
  - Transmission anode target with collimator
  - Excellent scatter rejection
  - Targetted to cardiac imaging at 30 fps.
  - Automatically collects tomosynthesis data
Line/Slot Scanning:

- To improve scan speed read out a line at a time.
- With storage phosphor can readout lines after area exposure
  - Incorporate line laser and solid state collector in compact single unit
  - Significantly reduces space requirements for beam path optics
  - Still requires mechanical motion
  - Also possible with photoconductor (e.g. Thoravision)

![Diagram of line/slot scanning components: Laser Source + Intensity Control, Beam Shaping, Light Collection Optics, Optical Filter, Photodetector, Image Plate.]

Philips Thoravision a-Se Chest System (Agfa)
Line/Slot Scanning:

- With prompt emitting phosphors need to collimate x-rays
- Numerous versions of line/slot scanned systems
- Most use some form of linear CCD as detector
  - c-Si photon counting mammo system recently approved by FDA
  - Gas wire chamber based systems have also been reported
- Good coupling between phosphor and CCD, good DQE
- Excellent scatter rejection
- Still require mechanical motion and collimation alignment
- Scan times of multiple seconds

Commercial examples that used CsI(Tl) coupled & linear CCD’s include:
  - Thorascan (Oldelft) chest system
  - Senoscan (Fischer) mammo system
Line/Slot Scanning:

- **Lodox Statscan**
  - Full body scan 13 secs
  - Linear CCD with CsI(Tl)
Line/Slot Scanning:

- Biospace EOS
  - Full body scan 20 secs
  - Perpendicular wire/gas chambers
**Line/Slot Scanning:**

- **Crystalline Si low x-ray absorption efficiency (Z=12)**
  - Si chip fabrication uses thin layer of processed materials (~100's μm)
  - Not thick enough for direct x-ray absorption
  - Increase effective thickness by rotating thin layer of c-Si
  - Used in commercial scanning “photon counting” mammo system
  - Takes multiple seconds for scan

*Philips MicroDose*
Full Area “Electronic” Readout:

- Earliest approaches used CCD detectors
Area Readout: Single CCD Configuration

- Lens or F.O. Demag. ~x10-12
- Photon Collection Efficiency ~0.1%
  - 2nd quanta shot noise dominant
    (Secondary quantum sink)

CsI(Tl) → X-rays → CCD

Mirror → High Quality Lens or Fibre Optic Reducer

(Courtesy Imaging Dynamics Corp.)
Area Readout: Multiple CCD Configuration

- SwissRay and Apelem
- reduces de-mag.

(Source: SwissRay Corp.)
Area Readout: Multiple CCD/CMOS Config.

- CaresBuilt and Naomi
- Tiling of image an issue
Area Readout: a-Si:H Flat Panel Readout

- Fabricated using large area a-Si:H deposition facilities
  - 14x17” or larger readily available with pixels down to <100μm
  - Can use prompt emitting phosphor or photoconductor
  - Directly coupled to x-ray absorption layer (high transfer effi.)
  - “Electronic” readout can operated in static or fluoroscopic modes

Sharp Gen. 10 Glass Substrate 9x10’
Area Readout: a-Si:H Flat Panel Readout

(Click to view full image)

(Image courtesy Dr. B. Polischuk)
Area Readout: a-Si:H Flat Panel Readout

• Advantages of a-Si:H readout arrays
  – Large area fabrication (>40cm dimensions) allowing non-tiled detector
  – “Mature” fabrication infrastructure (based on display industry)
    – Many peripheral components now available “off-the-shelf”
  – Excellent image quality due to high 2nd quanta collection efficiency
  – True “electronic” readout (no mechanical moving parts)
  – Advanced application capable (i.e. supports “real-time” readout speeds)
  – Very tolerant of radiation damage (due to amorphous structure)

• Challenges for a-Si:H readout arrays
  – Relatively high “additive” electronic noise
    – Compromises low exposure performance
  – Fabricated on “fragile” glass substrates (0.5mm thick or less)
  – Inherent materials properties affect “image quality”
    – Low carrier mobility limits “smart” pixel capabilities
    – Large feature sizes may limit “fill factor” of small pixels
Recent Developments: α-Si:H Portable Systems

• Recently, portable 14x17” & 17x17” detectors introduced
  • Initially rather heavy/bulky/thick with tether
  • More recently wireless, battery powered with cassette form factor
  • Smaller sized detectors (10x12”) now being introduced
Recent Developments: Beam Triggered Readout

- Synchronization between detector & x-ray delivery essential
  - Unlike screen/film and CR which are always “active”
- Traditional flat panel detectors integrated with generator
- New approaches have no hardwired “electrical” interface
  - Makes retrofitting of older systems easier

Konica Aero Sync™

[Diagram showing X-ray auto detection process]
• Concept previously used in film/screen mammography
• Most advantageous when:
  • Energy deposition weighted towards entry side of screen (e.g. mammo)
  • Have low x-ray absorption substrate
  • Can reduce Swank noise and Lubberts Effect hence improving IQ

**Recent Developments: Back Screen Config.**

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Phosphor</th>
<th>Pixels</th>
<th>Signal Spread</th>
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<tbody>
<tr>
<td>Front Screen Config.</td>
<td><img src="image" alt="Front Screen Diagram" /></td>
<td><img src="image" alt="Signal Spread" /></td>
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</table>
Recent Developments: Smart Pixels

• Numerous research groups reported on pixel level circuitry
  • Main goal to amplify signal level to reduce effect of addt. noise
  • Issue with size of a-Si:H TFT’s which can reduce fill factor
• First large area demonstration of multiple TFT a-Si:H pixels
  • 17x17” CsI detector, 150um pixels
  • 1x1 or 2x2 binning at pixel level
  • Improves noise performance
    • Adds signals before digitization

Recent Developments: New Materials

- New substrate materials
  - Flexible substrates e.g. plastic, metal & glass (~0.1mm thick!)
    - These would allow conformable, large area, very robust detectors
    - Available 30cmx300m for roll-to-roll proc.

- New fabrication materials
  - Low temperature poly-Si
    - Has improved carrier mobilities
  - IGZO
    - Compatible with large area deposition
    - Has better carrier mobility hence smaller feature sizes
    - Allows more complex circuitry at pixel level

- New X-ray converters for lower dose applications
  - Mostly photoconductors that generate more signal per x-ray
    (e.g. PbI, HgI, CdTe, CdZTe, PbO)
  - Still mainly academic and commercial research activities
Recent Developments: Flexible Substrates

• Worlds first com. available curved screen TV from LG (~$10,000 !)
  • Uses a flexible substrate and IGZO instead of a-Si:H
  • 4.3mm thick !!
Area Readout: CMOS Technology

• Fabricated with “standard” silicon IC chip technology
  • Typically use standard 8” Si wafer fab. capability
  • Limits physical dimensions of sensor
  • Small feature size (<10nm) allows complex pixels
    • e.g. Pixel level amplification, and dose sensing
  • Larger sensor tiles can reduce yield and increase cost
Area Readout: CMOS Technology

- Recent development is “large” 3 side buttable CMOS tiles
  - Very low “additive” readout noise (100’s el. c.f. 1000’s for a-Si:H)
  - High speed readout (~30+ f.p.s)
  - Integrated electronics (e.g. ADC’s and pixel level circuitry)
  - Directly coupled to x-ray absorption layer (high transfer effic.)
  - High fill factor even with small pixels (<75um)
CMOS allows energy integrating or photon counting

- Energy integrating typically utilizes CsI or GOS bonded to chip
- Photon counting typically uses photoconductor (CdTe or CdZnTe)
  - Use of CdTe and CdZnTe currently limits size of sensor to < ~2-5 cm
  - Energy selective imaging is possible
  - Photons can be weighted according to image information “content”

Energy resolved photon counting allows multi-spectral imaging
Summary:

- Knowing the basic components allows for informed choices.
- Storage phosphor systems: Faster, smaller and cheaper
  - Slow readout speeds prevent “real time” use
- a-Si:H Flat Panels: Form factor and functionality (and price!)
  - New materials continue to be investigated
  - Watch for developments in display manufacturing (e.g. use of IGZO)
- CMOS: Increasing commercial visibility and viability
  - Confined to smaller area applications at present (tiled arrays)
    - Dental intra-oral, mammography, small field fluoro, CBCT
  - Excellent image quality and energy selective imaging capabilities
### Performance Summary:

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<th>Full Area Readout</th>
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<tr>
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<td>Prompt Emission Phosphor</td>
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<tr>
<td></td>
<td>BaFBr(I)</td>
<td>CsBr(Eu)</td>
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<tr>
<td><strong>Speed of Readout</strong></td>
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<td><strong>Image Quality</strong></td>
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<td>++</td>
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<tr>
<td><strong>Robustness</strong></td>
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<td><strong>Size</strong></td>
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<tr>
<td><strong>Cost</strong></td>
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<td><strong>Adv. Apps.</strong> (tomo&amp; DE)</td>
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