Historical development of CR/DR and new detector technologies

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Learning Objectives

• Explain technology of available and future digital radiography technology

• Understand underlying system operation and characteristics

• Compare CR – DR - Novel image acquisition advantages and disadvantages
DIGITAL IMAGING IN RADIOLOGY

• Digital imaging is an essential component of Electronic Imaging, Telemedicine and Remote Diagnosis

• Steps for digital imaging
  – Acquisition
  – Display
  – Diagnosis
  – Distribution
  – Archive
The “Big” Picture

- “Digital” Radiology
- PACS
- Digital Radiography
- MRI
- Interventional Angio
- CT
- Nuclear Medicine
- Ultrasound
Imaging Volume

Projection imaging: 60% - 70% of medical imaging
But First...... CR & DR

- An intrinsic part of the PACS
- Historically, the last electronically integrated
- Lots of changes in the past decade.....
Digital x-ray detector

1. Acquisition

- Transmitted x-rays through patient
- X-ray converter: x-rays → electrons
- Charge collection device

2. Display

- Digital Pixel Matrix
- Digital to Analog Conversion

3. Archiving

- Digital processing
- Digital Pixel Matrix
Analog versus Digital

Exposure Latitude

Signal output

Log relative exposure

Film

Digital

100:1

10000:1
Digital sampling

Spatial Resolution

Fourier transform of Rect (Dx) = sinc(Dx)
Cutoff frequency $f_C = (Dx)^{-1}$
With sampling pitch = sampling aperture, Dx
Nyquist Frequency $f_N = (2 \times Dx)^{-1}$
• Separation of Acquisition, Display, and Archive

• Wide dynamic range
  – ~0.01 to 100 mR (~0.1 to 1000 mGy) incident exposure

• Variable detector exposure operation
  – 20 to 2000 “speed class”

• Appropriate SNR & image processing are crucial for image optimization
Categorization of digital radiography detectors

- Detector form factor
  - Cassette versus cassette-less

- Passive versus active x-ray detection
Categorization of digital radiography detectors

- Image acquisition geometry
  - Large FOV (milliseconds)
    - Reduced patient motion
    - Real-time operation possibilities
    - Anti-scatter grid necessary
  - Slot-scan (seconds)
    - Reduced scatter
    - Lower patient dose
    - Possible motion problems
Available digital radiography technology 2013

- **CR**: Photostimulable Storage Phosphor (PSP)
  - Cassette-based detectors/readers
  - Flying spot mechanical changers
  - Line scan integrated detectors

- **CCD**: Charge-Coupled Device
  - 2-D lens coupled systems
  - 1-D slot-scan systems

- **Thin-Film-Transistor (TFT) flat panel**
  - Indirect detection (scintillator)
  - Direct detection (semi-conductor)
  - Portable wireless implementations

- **Photon Counting slot-scan systems**
“In-progress” technologies

- X-ray energy sensitive counters: gas or silicon strip detectors
- Complementary Metal Oxide Semiconductor (CMOS)
- Hybrid direct / indirect flat panel TFT with variable gain
- X-ray “light valve” Liquid Crystal / scanner detector system
Starting point: Analog film digitization

- Video of trans-illuminated radiographs
  - “Camera on a stick”
  - Low cost, low quality

- Film digitizers
  - LASER
    - Better quality
    - Not reliable
  - CCD Array
    - Limited dynamic range
    - Very reliable
Computed Radiography (CR)

• *The* first clinically useful technology available for large field-of-view digital imaging

• Based upon the principles of photostimulated luminescence; 30+ years of experience

• Operation emulates the screen-film paradigm in use and handling. (flexible, but labor intensive)

• Manufacturing trends:
  – Smaller, faster, less expensive
PSP Detector

- Photostimulable Storage Phosphor (PSP)

**Coating thickness:**
- Standard resolution: ~100 mm BaFBr
- High resolution: ~50-70 mm BaFBr

**Enhancements:** Dual-side read; structured phosphor – CsBr
Computed Radiography “reader”

Various capabilities, sizes, throughput
Photostimulated Luminescence

Incident Laser Beam

Light guide

Exposed Imaging Plate

Light Scattering

Photostimulated Luminescence

Laser Light Spread

"Effective" readout diameter

Exposed Imaging Plate

Protective Layer

Phosphor Layer

Base Support

PSL Signal

PMT
CR Point-scan readout

Reference detector

Laser Source

Polygonal Mirror

f-θ lens

Cylindrical mirror

Light channeling guide

Output Signal

PMT

ADC

x = 1279
y = 1333
z = 500

Plate translation: Sub-scan direction

Laser beam: Scan direction

Plate translation: Sub-scan direction

ERASURE → Reuse
Typical CR resolution:
- 35 x 43 cm -- 2.5 lp/mm (200 μm)
- 24 x 30 cm -- 3.3 lp/mm (150 μm)
- 18 x 24 cm -- 5.0 lp/mm (100 μm)

Screen/film resolution:
- 7-10 lp/mm (80 μm - 25 μm)
Phosphor Plate Cycle

- **PSP**
- **Base support**

**Reuse**

- **x-ray exposure**
  - Plate exposure: create latent image

- **laser beam scan**
  - Plate readout: extract latent image

- **light erasure**
  - Plate erasure: remove residual signal
Dual-side CR readout with transparent substrate

- CR cassette
- Reference detector
- Laser Source
- f-θ lens
- Mirror
- Cylindrical mirror
- Light channeling guide
- PMT
- Output Signal
- ADC
- To image processor
- Erasure Stage Transport
- Light Erasure
- To image processor
- Dual-side CR readout with transparent substrate
Parallel excitation *line-scan* PSP readout
“Direct” Radiography (DR)

....refers to the acquisition and capture of the x-ray image *without user intervention* (automatic electronic processing and display)

- “Indirect” detector: a conversion of x-rays into light by a scintillator, *and* light into electrons for signal capture
- “Direct” detector: a conversion of x-rays to electron-hole pairs with direct signal capture
X-ray scintillator conversion
(Gd$_2$O$_2$S, CsI compounds)

Unstructured (turbid) phosphor

**Thick Screen:**
- Good Absorption
- Poor Resolution

**Thin Screen:**
- Poor Absorption
- Good Resolution

Structured phosphor

**Thick Screen:**
- Good Absorption
- Good Resolution

Light Pipe
(Optical Fiber)
Direct *semi-conductor* conversion

10 kV

X-rays

Top electrode

Blocking contacts

Readout plane

TFT substrate

**FUTURE:**

- PbI$_2$
- PbO
- HgI$_2$
- CdZnTe

Little or no horizontal spread of signal

*LSF* Spread is ~ independent of detector thickness
CCD-based DR systems

- Area Scintillator / lens coupling
  - Scintillating Screen (Gd$_2$O$_2$S, CsI)

- Slot scintillator / fiberoptical coupling
  - Fiber Optical Coupling
CCD area detector

- High fill factor ~ 100%
- Good light conversion efficiency (~85%)
- 4 to 16 megapixels
- Optical de-magnification
- Lens efficiency?
- Secondary Quantum Sink
Light emission & Optical coupling

Scintillator -> Light

Large loss of light!!!
Optical coupling inefficiency

X-rays

Lens

Demagnification >10:1

CCD Detector
Optically coupled CCD systems

- Technology improvements have overcome quantum sink issues (lens / CsI phosphor)
- Relatively low cost (for integrated DR unit)
- Capable, OK image quality, higher dose
CCD slot-scan imaging

- “One dimensional” scanning acquisition
- Efficient scatter rejection
- Best dose efficiency
- Time-Delay-Integrate (TDI mode)
- “Effective DQE” in absence of scatter is comparable to CsI area detectors
Slot Scan CCD systems
No grid; Reduced scatter; Low dose

- Exposure time
- Patient motion
- Tube loading
- DQE
Flat Panel Detector:

TFT *active matrix* array

(Amorphous Silicon)

**Gate**

**Switches**

**Thin-Film Transistor**

**Storage Capacitor**

**Charge Collector Electrode**

**Charge Amplifiers**

**Analog to Digital Converters**

**Fill Factor** = Active area ÷ (Active area + Dead Zone)

Large pixels: ~ 70% 120 – 200 mm
Small pixels: ~ 30% 70 - 100 mm
TFT *active matrix* array

Functional Illustration

Exposure to x-rays

Store the charge

*Active* Readout
Activate gates
Amplify charge
Convert to Digital
X-ray Indirect Detection

_Csl phosphor / a-Si TFT_

Scintillator:
- X-rays to light

Photodiode:
- Light to electronic signal

Amplifiers – Signal out

TFT array: Storage and readout
X-ray Direct Detection

*a-Se layer / a-Si TFT array*

**Semiconductor:**
X-rays to charge

**Charge collection electrode**

**Incident x-rays**

**Amplifiers – Signal out**

**TFT array:** Storage and readout

**Amorphous Selenium**

**Charge collection electrode (del size)**

**Thin-Film-Transistor Storage capacitor**

**Glass substrate**

**Alternate materials:** PbI$_2$, Hg$_2$
DR flat panel systems

Indirect

Direct
Flat panel portability

- Initial products introduced by Canon
  - Tethered, thick profile
- Wireless products now on the market
  - Trixell, Carestream, Canon, Source one ...
CR and DR mobile radiography

Tethered cassette

CR reader / processor
Wireless DR cassette

- Integrated
- Battery powered
- On-board computer and processing
Point of service direct imaging

- 14x17inch cassette...
Point of service direct imaging

- Preview image in 2-3 s
Point of service direct imaging

- For Processing image.... 15 s
- QC
- Annotation
- Send
DR replacement trends

- Passive for active detector technology
Spatial Resolution – MTF

- a-Selenium: 0.13 mm
- Screen-film
- CR: 0.05 mm
- CsI-TFT: 0.20 mm
- CR: 0.10 mm

Modulation vs. Frequency (lp/mm)
Detective Quantum Efficiency (DQE)

$$DQE(f) = \frac{SNR_{out}^2}{SNR_{in}^2} = \frac{MTF(f)^2}{NPS_N(f^*) \times q}$$

- A measure of the *information transfer efficiency* of a detector system

- Dependent on:
  - Absorption & conversion efficiency
  - Spatial resolution (MTF)
  - Conversion noise & electronic noise
  - Detector non-uniformities / pattern noise
  - **Not necessarily indicative of clinical performance**
Detective Quantum Efficiency
Radiography

DQE($f$)

<table>
<thead>
<tr>
<th>Spatial Frequency (cycles/mm)</th>
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<tbody>
<tr>
<td>0.0</td>
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<tr>
<td>0.5</td>
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<tr>
<td>1.0</td>
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<td>1.5</td>
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<tr>
<td>2.0</td>
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<tr>
<th>DetecCve</th>
<th>Quantum Efficiency</th>
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<tbody>
<tr>
<td>Radiography</td>
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<tr>
<td>CsI - TFT</td>
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<td>$\alpha$-Se - TFT</td>
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<tr>
<td>Screen-film</td>
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<tr>
<td>CR “dual-side”</td>
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<tr>
<td>CR Conventional</td>
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High DQE does not “guarantee” good image quality

- There is no substitute for appropriate radiographic technique
- Optimization of acquisition technique
  - kV, mAs, SID, filtration, anti-scatter grid
- For similar acquisition techniques and grid use, similar SNR requires dose proportional to DQE^{-1}
- “Effective DQE” concept takes into account clinical situations (magnification, grid)
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<thead>
<tr>
<th>Attribute</th>
<th>CR</th>
<th>DR</th>
<th>CCD</th>
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<tr>
<td>Positioning flexibility</td>
<td>****</td>
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<tr>
<td>Replacement for screen/film</td>
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<tr>
<td>DQE / dose efficiency</td>
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<td>Patient throughput</td>
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<td>X-ray system integration</td>
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<td>Access to advanced technology applications</td>
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<td>Cost for comparable image throughput</td>
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<tr>
<td>Radiographer ease of use (manufacturer dependent)</td>
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SUMMARY

Enterprise distribution of images is crucial for implementation and application of technology

- *Cassetteless, active detector* radiography devices are becoming the detectors of choice

- Proliferation of web-based PACS and unified patient database (instead of Radiology centric orientation) is coming

- New opportunities
  - Image acquisition and image processing tools
  - Imaging technology innovation for diagnosis and intervention