Design and Performance Characteristics of Computed Radiographic Acquisition Technologies

Ralph Schaetzing, Ph.D.
Agfa Corporation
Greenville, SC, USA
Digital Radiography: Acquisition Technologies in General

- Aerial X-ray Image (Image-in-Space)
- Latent Image
- Digital Image

CONVERT

INTERACT
Digital Radiography: Acquisition Technologies in Context

Operational

Clinical

PATIENT

OUTCOME

Referral

Exam

Acquire

Store

Distribute

Process

Reproduce

Aerial X-ray Image (Image-in-Space)

INTERACT

CONVERT

Latent Image

Digital Image

Treatment

Diagnosis

Exam

Diagnosis

Referral

Treatment

Clinical

Technical

Operational

Socio-Economic
Digital Radiography: A Taxonomy

• Many dimensions along which to classify DR technologies
  • Direct vs. Indirect x-ray-to-signal conversion
  • Scanned (e.g., point, line) vs. Full-field
  • Beam geometry/Detector geometry
  • Detector type/material
  • Dynamic vs. Static
  • …
Digital Radiography: A Taxonomy
(x-ray interaction/detector*, signal extraction)

* Other detectors (e.g., pressurized gas, Si/metal strips) have also been used
Historical Context

Full-field (incl. x-ray) imaging with PSL intermediates (1842 - 1936)

R&D on SP scanning systems

Installed Base: 1
Price: $1,200,000
Size: ~ 10 m²
Speed: 40 plates/hr

Full-field night-vision "cameras" (IR/heat stim. SP)

Installed Base: ~20,000+
Price: ~ 10x lower
Size: ~ 10x smaller
Speed: ~ 2-4x faster

"Commercial Era"

CR: the most widespread form of DR!
Learning Objectives

• Describe the form and function of today’s computed radiography (CR) systems
• Identify the main factors that influence the image quality of CR systems
• Compare modern CR systems to other acquisition technologies
• Describe the latest and future developments in CR
Computed Radiography Technologies

- Basics
- System Design
  - Screens
  - Scanners
- Imaging Performance
  - Input/Output Relationship
  - Spatial Resolution
  - Noise
- New CR Developments
Basics
CR Characteristics

- Detector is SP screen (PSL screen, Imaging Plate, IP, ...)
- Screen can absorb, and store (partially) as a latent image, incoming high-energy electromagnetic radiation
- Exposure to low-energy stimulating radiation ($\lambda_s$) causes screen to emit the previously stored energy at a (shorter) wavelength ($\lambda_e$) in the visible – $\lambda_s$, $\lambda_e$ must be sufficiently different, or no CR possible
Basics:
CR: Digital Alternative to Screen/Film

- BOTH systems
  - use phosphor screens as x-ray absorbers
  - use screens with similar structures (small phosphor particles dispersed in a binder)
  - emit light promptly on x-ray exposure (x-ray luminescence)
  - use screens that can be exposed thousands of times

- ONLY storage phosphors
  - can retain a portion of the absorbed x-ray energy (as a latent image of trapped electrons, e⁻)
  - can be read out at a later time, (destructively, i.e., latent image is erased as it is read)
Basics:
CR vs. Screen/Film - Advantages of CR

- Extended Exposure Latitude (10000:1 vs. ~40:1)
  - High exposure flexibility with 1 detector (retakes )
- Reusable Detector
  - Reduction in consumables (film, chemistry) costs (but, full impact only with softcopy interpretation)
- Compatibility/Scalability/Workflow/Productivity
  - No major changes to equipment/rooms/technique
  - Flexible reader placement (centralized and/or distributed architectures)
- Digital Data
  - Gateway for projection radiography into PACS
Computed Radiography Technologies

- Basics
- System Design
  - Screens
  - Scanners
  \} A System!
- Imaging Performance
  - Input/Output Relationship
  - Spatial Resolution
  - Noise
- New CR Developments
Design: Storage Phosphor Screens

- Support (flexible, rigid) coated with tiny (3-10 µm) SP particles dispersed in binder
  - Screen is turbid (white)
- Many materials tested, only a few successful
  - SrS:Ce, Sm
  - RbBr:Tl
  - BaFX: Eu\(^{2+}\) (where X=Br, I)
  - CsBr: Eu\(^{2+}\) (new)
- SP mechanisms/processes at micro (quantum) level still subject of active research!
Design: Storage Phosphor Screens

- Manufacturer-specific layers to optimize mechanical, optical, electrical performance, e.g.,
  - Wear, handling layer
  - Electrostatic discharge layer
  - Optical coupling layer
    - reflective backing
      - direct more emitted light to surface/photodetector
    - absorbing backing, dyes, filters
      - reduce spread/transmission of stimulating light (sharpness)
  - X-ray backscatter control layer (lead)
Design: Three-step Imaging Cycle

Exposure (INTERACT)
(Create Latent Image)

Prompt Emission of Light ($\lambda_e$) $\sim$50%

Stored Signal (trapped e-)

Remnant Signal

Read Out (CONVERT Latent Image)

"Fresh" Screen

Erase (Reset/Reinitialize)
(Remove Residual Latent Image)
Design: The Flying-Spot CR Scanner

- **Components**
  - IP transport stage
  - Beam deflector
  - Laser + intensity control
  - Beam shaping/control
  - Collection optics
  - Optical filter
  - Photodetector
  - Analog electronics
  - A/D Converter
  - Image buffer
  - Control computer
  - (Erase station)

- **Mech.**
  - IP transport stage
  - Beam deflector

- **Opt.**
  - Laser + intensity control
  - Beam shaping/control
  - Collection optics
  - Optical filter
  - Photodetector
  - Analog electronics
  - A/D Converter
  - Image buffer
  - Control computer
  - (Erase station)

- **Comp.**
  - Analog Electronics (signal conditioning)
  - Analog-to Digital Conversion (Sampling+Quantization)
  - Control Computer
  - Image Buffer
Design: The Flying-Spot CR Scanner

Laser Source + Intensity Control

- Efficient, rapid, accurate read-out of latent image
  - Power: high-power light source = laser (gas, solid-state)
    compact, efficient, reliable, tens of mW over \(\sim 100 \text{ µm} \ Ø\)
  - Wavelength, \(\lambda_s\): choice depends on energy needed to stimulate latent image electrons out of traps (typically reddish), and emission spectral range (\(\lambda_e\), typically bluish)
  - Constancy: laser power must be constant during scan to avoid artifacts/noise (fluctuation tolerance as low as \(\sim 0.1\%\) - active control with feedback loops)
Design: The Flying-Spot CR Scanner

Beam Shaping Optics

- Problem: laser point source and beam deflector cause size, shape, and speed of beam at IP surface to change with beam angle (similar to flashlight beam moving along wall)
  - Signal output and resolution depend on beam position - BAD
- Special scanning optics keep beam size/shape/speed largely independent of beam position
Design: The Flying-Spot CR Scanner

Beam Deflector

- Scans beam in one direction across IP surface (transport stage handles orthogonal direction)
  - Desired scan speed/throughput determines deflector type
    - rotating drum (slow)
    - galvanometer/mirror (shown)
    - rotating mirrored polygon (fast)
  - Beam placement accuracy is critical to avoid artifacts (edge jitter, waviness)
    - error tolerance: fractions of the pixel dimension
Design: The Flying-Spot CR Scanner Transport Stage

- Moves IP at constant velocity in one direction (Beam deflector handles orthogonal direction)
  - Desired scan speed/throughput determines transport type
    - rotating drum
    - flat bed/table
  - Small velocity fluctuations can lead to artifacts (visible banding)
    - error tolerance: few tenths of 1%
Design: The Flying-Spot CR Scanner Light Collection Optics

- Problem: stimulated light within phosphor layer is emitted and scattered diffusely in all directions
- Collect/channel as much as emitted light as possible to photodetector (numerical aperture: distance between IP surface and collector)
  - Mirrors
  - Integrating cavities
  - Fiber optic bundles
  - Light pipes
Design: The Flying-Spot CR Scanner

Optical Filter

- Intensity of emitted light ($\lambda_e$) is $\sim10^8$ lower than that of stimulating light ($\lambda_s$)
- Optical design must find “needle in a haystack”
- Importance of wavelength difference between $\lambda_e$, $\lambda_s$
  - High-quality optical filter can pass emitted light ($\lambda_e$) spectrum to photodetector and block stimulating light ($\lambda_s$)

![Diagram showing the optical filter, light collection optics, and emission spectrum with HeNe gas laser and solid-state laser wavelengths](image)
Design: The Flying-Spot CR Scanner

Photodetector

- Weak signal: need high conversion efficiency (light photons $\rightarrow$ electrons), high gain, low noise
  - Photomultiplier Tube
    - dynamic range $\approx$ SP ($>10^3$)
    - Quant. Eff. @ $\lambda_e \approx 25\%$
  - Charge-Coupled Device
    - Efficiency $\approx 2x$ PMT (@ $\lambda_e$)
    - But, also sensitive @ $\lambda_s$
      (need low-noise electronics, better optical filter)
Design: The Flying-Spot CR Scanner
Analog Electronics

- Condition/amplify analog, time-varying electrical current from photodetector before A/D conversion
  - Scale/compress large dynamic range of photodetector output to reduce performance requirements, distortion, cost in electronic chain
    - linear (compress after A/D)
    - logarithmic compression
    - square-root compression
  - Remove higher frequencies (> Nyquist) that will cause digitization/aliasing artifacts (fast-scan)
Design: The Flying-Spot CR Scanner Analog-to-Digital Conversion

• Analog signal must be sampled (made discrete in space/time) and quantized (made discrete in value)
  • Sampling rate determines spatial resolution (e.g., making a 2000 x 2500 image in 20 s requires sampling rate of $5,000,000/20 = 250$ kpixels/s)
  • Quantizer resolution must be high enough to maintain small, clinically relevant signal differences over full exposure range
    • 12-16 bits/pixel for linear data
    • 8-12 bits/pixel for nonlinear data (e.g., log, sqrt)
Design: The Flying-Spot CR Scanner

Image Buffer

- Until/unless digital images can be transferred to a more permanent storage location (such as a long-term archive), they need to be buffered (stored) locally (e.g., local hard disk, workstation).
- Buffer capacity depends on local storage needs, image throughput, network load, remote storage availability, system redundancy concept, etc.
Design: The Flying-Spot CR Scanner Erasure

• Remnant signal on screen must be reduced to a level much lower than lowest expected signal from next exposure (otherwise, ghost images)
  • Can become issue in RT applications
• Different designs (screen/scanner-dependent):
  • High-power halogen/incandescent lamps
  • LEDs (recent development)
• Spectrum is important (screen-dependent)
Computed Radiography Technologies

- Basics
- System Design
  - Screens
  - Scanners
- Imaging Performance
  - Input/Output Relationship
  - Spatial Resolution
  - Noise
- New CR Developments
Imaging Performance: Input/Output (I/O) Relationship

- CR screen is linear detector over >4 decades in exposure (CR scanner may lower this: flare, photodetector response)
- Latitude ≠ Dose Reduction
  - CR is NOT inherently lower dose than S/F: modern CR needs comparable dose to get same image quality
  - However, need many S/F systems to cover the same exposure range covered by one IP and one CR scanner

![Graph showing X-ray Sensitometry - Screen/Film and CR](image)
Imaging Performance: Spatial Resolution

- Spread/scatter of light within phosphor layer is the primary cause of unsharpness
  - S/F: emitted light spread
  - CR: stimulating light spread
- Amount depends largely on layer thickness, d: resolutions of S/F, CR are comparable
- Other factors: dyes, absorbing or reflecting backing, x-ray absorption depth, penetration depth (light), reflect./transm. readout geometry

**X-ray absorption and resolution are coupled**
Imaging Performance: Spatial Resolution - Other Factors

• Afterglow (flying-spot speed limit)
  • Luminescence decay time - screen continues to emit light after beam has passed (material-dependent)
  • If beam "dwell time" on each pixel too short, light from previous pixels collected with that of current pixel (1-dimensional smear/blur)

• Laser power
  • High power: +signal, -sharpness
  • Low power: +sharpness, -signal

• Analog electronics (filter effects)

• Destructive read-out physics (complex!)
Imaging Performance: Noise

- Random variation of an output signal around the mean value predicted by its I/O Relationship

**Exposure-related**
- Quantum noise
- Equipment noise
- Incident x-ray quanta

**Screen-related**
- X-ray quanta absorbed
- X-ray quanta scattered
- e⁻ per x-ray quantum
- Latent image decay
- Phosphor layer structure
- Overcoat/backing layer structure
- Phosphor particle size distribution

**Scanning-related**
- Deflector/transport velocity
- Laser source/intensity control
- Spread/scatter of stimulating beam
- Light photons emitted in screen
- Light photons escaping screen
- Light photons collected
- e⁻ created in photodetector
- Analog electronics
- Sampling and quantization
Imaging Performance:
Detective Quantum Efficiency*

<table>
<thead>
<tr>
<th></th>
<th>Direct</th>
<th>Indirect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screen/Film</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Photoconductor + TFT (gen. rad.)</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Needle scint. + TFT</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>Needle IP-CR</td>
<td>0.7</td>
<td>0.8</td>
</tr>
<tr>
<td>Powder scint. + TFT</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>Powder scint. + CCD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Powder IP-CR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Powder IP-CR (dual-sided)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ideal Detector

*Caution: mostly literature reports; not all measurements done according to IEC 62220-1
Computed Radiography Technologies

- Basics
- System Design
  - Screens
  - Scanners
- Imaging Performance
  - Input/Output Relationship
  - Spatial Resolution
  - Noise
- New CR Developments
New CR Developments: Dual-sided Read-out*

- Use transparent support
- Detect emitted light from both sides of screen
  - More signal in same time
  - Phosphor layer can be thicker (x-ray absorption ↑)
  - Reduce noise by combining front/back signals
  - Sharpness comes from front signal (relatively unchanged), so need frequency-weighted combination of front/back)
  - DQE improvement (at lower frequencies) relative to single-sided readout

New CR Developments: Needle Detectors*

- Some SP materials (e.g., RbBr:Tl, CsBr:Eu$^{2+}$) grow in needles (like CsI in image intensifiers and indirect flat-panel DR)
- Image quality better than powder IP
  - I/O Relationship ➔
    - No binder: higher x-ray absorption
    - Increase layer thickness without degrading resolution (decouple sharpness and absorption)
    - Better conversion efficiency and read-out depth (CsBr)
  - Spatial Resolution ➔
    - Needles act as light pipes to reduce spread/scatter
  - Noise ➔
    - More uniform layer structure

---

New CR Developments: Line Scanning*

- Discrete components of current, point-at-a-time CR scanners lead to
  - low packing density
  - limits to throughput
- New integrated, line-at-a-time scanners
  - reduce scanner size
  - increase system throughput

New CR Developments:
Other

- Energy Subtraction
  (multiple IPs in single cassette, x-ray filter)
  - More image processing than acquisition
  - Automated IP/filter handling, image registration
  - Qualitative (Diagnostic) and Quantitative (Bone Mineral Densitometry, Absorptiometry) Imaging

- CR for mammography
  - Special IPs, cassettes
  - High-resolution scanning modes
  - Custom image processing (incl. CAD)
New CR Developments: Other

• "Flat-Panel CR"
  • fixed (needle) detector + movable line scanner in integrated package

• Radiation Therapy
  • Special screens and scanner protocols
  • Simulation, localization, verification
  • Dosimetry
Learning Objectives Revisited

• Describe the form and function of today’s computed radiography (CR) systems
• Identify the main factors that influence the image quality of CR systems
• Compare modern CR systems to other acquisition technologies
• Describe the latest and future developments in CR
CR Acquisition Technologies

Summary

- CR technology is mature (but not outdated!):
  - 30+ years of intensive R&D
  - Multiple generations and manufacturers
  - Diagnostically accepted and still expanding (hundreds of man-years of diagnostic experience)

- Performance/image quality now exceeds that of S/F with greater placement flexibility (distributed/centralized)

- New CR developments have
  - Raised image quality and system throughput
  - Decreased size
  - Lowered cost

CR will remain a valuable DR technology in the future
Thank You for Your Attention!

e-mail: ralph.schaetzing@agfa.com