Design and Performance Characteristics of Flat-panel Acquisition Technologies

John Yorkston Ph.D.
Eastman Kodak Company, Rochester NY

DR: "Digital" Radiography

DR: 1 step acquisition with electrical "area scanning"

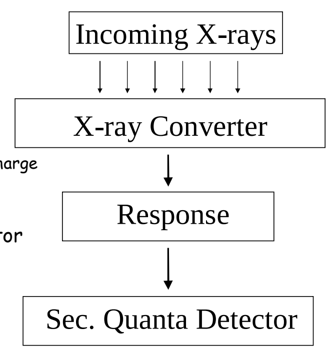
"Flat panel" and CCD based technology (introduced ~1995)

(Courtesy Imaging Dynamics Corp.)

- Will not cover
  - Linear scanning CCD or CR systems

DR Detector Components

- X-Ray Converter
  - Phosphor creates light
  - Photoconductor creates charge
- Secondary quanta detector
  - Flat panel array
    - Photodiodes
    - Capacitors
  - CCD
    - Photodiodes



Outline

- Review most common X-ray Converters
- Review Secondary Quanta Detectors
  - a-Si:H flat panel based approaches
    - a-Si:H technology
    - Pixel design, detector operation & system config.
- Image Corrections
  - Gain and Offset corrections
- Image Artifacts
- Advanced Clinical Applications
- Future Directions

X-Ray Converters

DR X-Ray Converters

- Two types of x-ray converter distinguished by *secondary quanta*

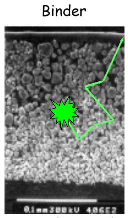
- Phosphors: Produce light ("Indirect")
  - Gd_2O_2S used in traditional screen/film systems
  - CsI(Tl) used in image intensifiers

- Photoconductors: Produce e-h pairs "*Directly*"
  - a-Se historically used in xero-mammo/radiography
    recently used in Thoravision system (Philips)

- Challenge:
  - Increase thickness to increase x-ray absorption
  - Maintain spatial resolution
  - Control variability in production/escape efficiency of 2nd quanta
    - Known as Swank noise or excess noise

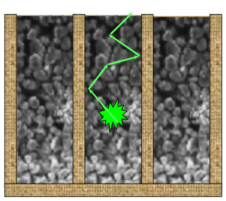
Containment of Spatial Spreading

Particle in Binder



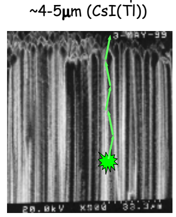
Spatial Spread ~ Thickness (~150μm)

Phosphor Packed Reflective "Cells"



Variable Escape Effic. Increases Swank noise

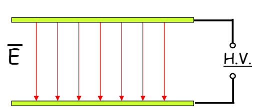
Structured Phosphor ~4-5μm (CsI(Tl))



With n~1.8 TIR ~<50%

Photoconductor (a-Se)

- Electric field confines image charge
- Resolution virtually independent of thickness



Secondary Quanta Detectors

a-Si:H Flat-Panel Based Systems

Flat-Panel (a-Si:H) Technology

- Technology behind AMLCD displays
- Mature technology using high tech equipment
- Multi billion $ industry (>$40 billion 2004)
- Fabrication done by PECVD & Photolithography
- Allows VERY large area coverage
  - Gen. 8 Fab. line 2.4x2.4 meters

(Source: Samsung)

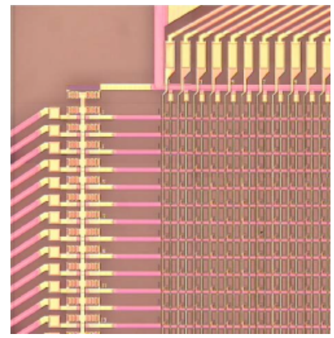
(Source: AUO)

(Courtesy: Corning Glass.)

Flat-panel Array Construction

(Image courtesy R. Kane, dpiX LLC)

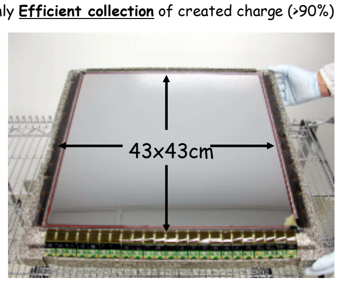
Large Area Substrate



Corner of Substrate

a-Si:H Technology Advantage

- Very Large Surface Area (as large as 43 x 43 cm)
  - No need for image reduction via lenses or fiber optics
  - Allows highly **Efficient collection** of emitted light (>50%)
  - or highly **Efficient collection** of created charge (>90%)

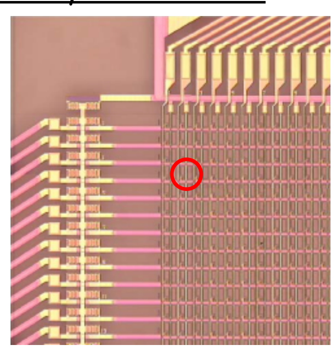


(Image courtesy Dr. B. Polischuk, Anrad Corp.)

Flat-panel Array Construction

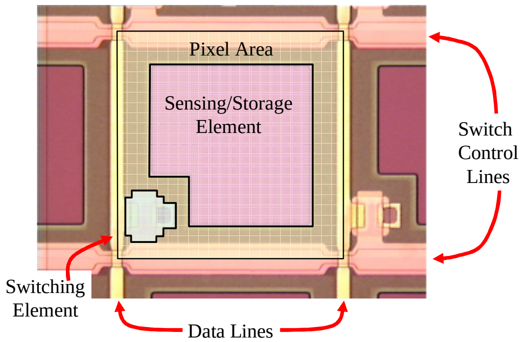
(Image courtesy R. Kane, dpiX LLC)

Large Area Substrate

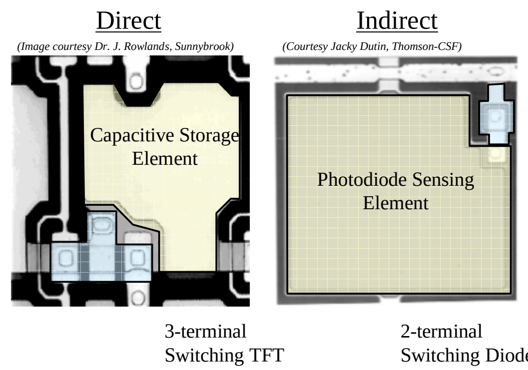


Corner of Substrate

Pixel Construction



Other Pixel Designs



Flat-panel Detector Construction

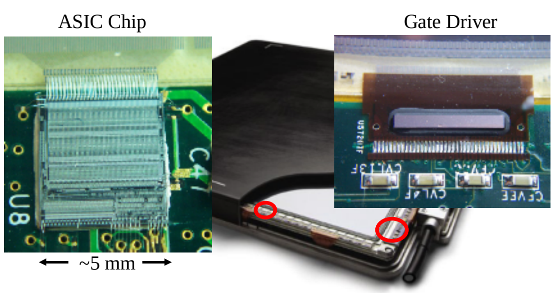
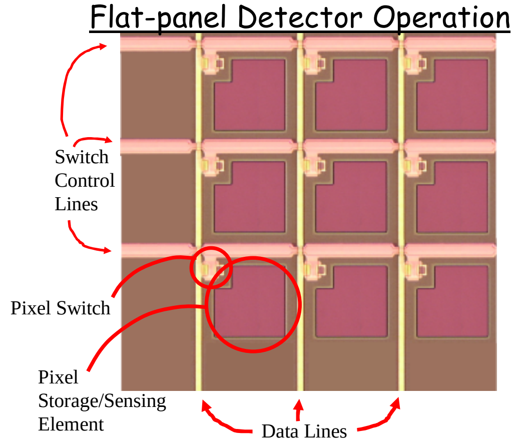
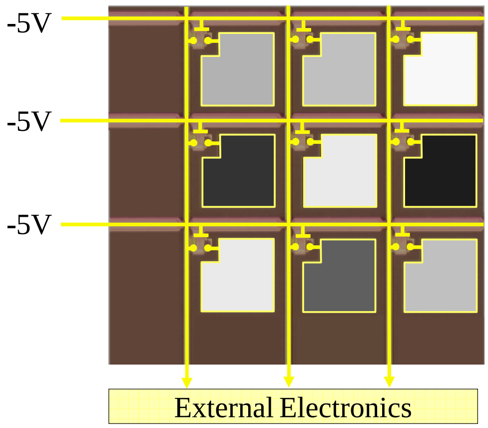
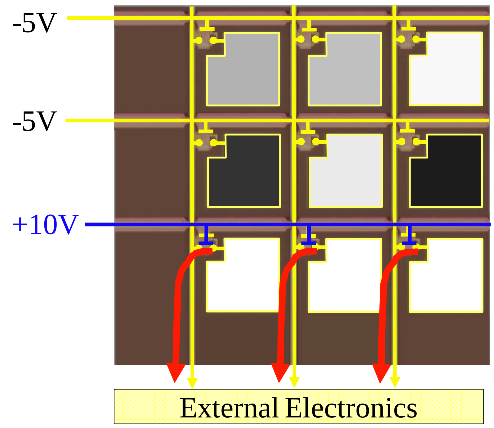


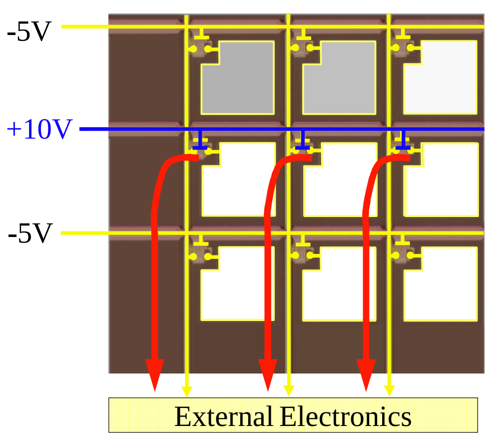
Image courtesy Mr. K. Schwarz, Direct Radiography Corp.

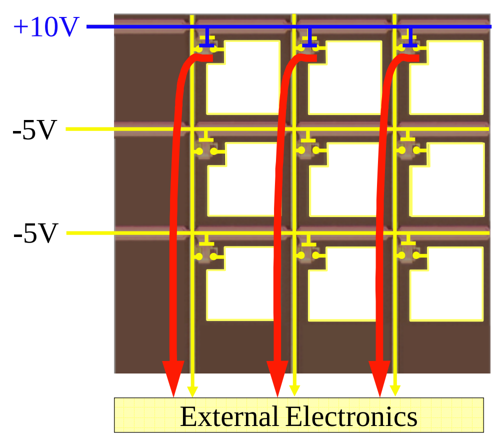
Flat-panel Detector Operation

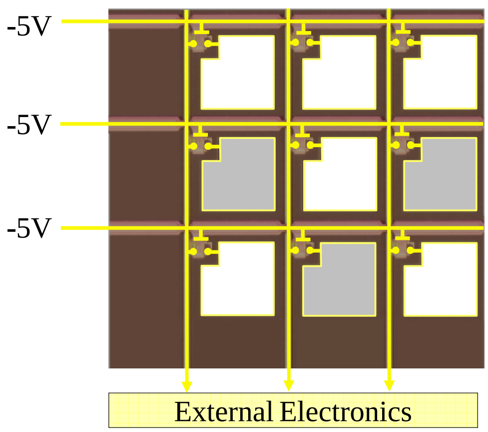



-5V
-5V
-5V
External Electronics


-5V
-5V
+10V
External Electronics


-5V
+10V
-5V
External Electronics

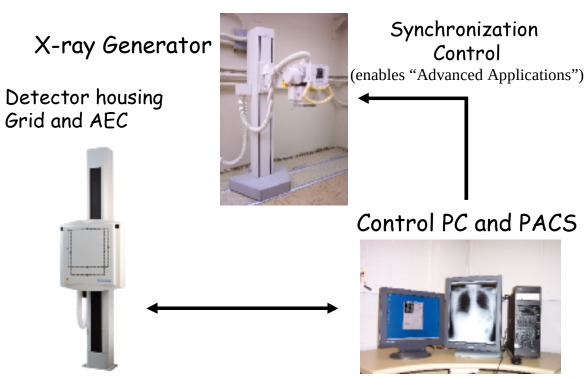

+10V
-5V
-5V
External Electronics



Re-Initialization

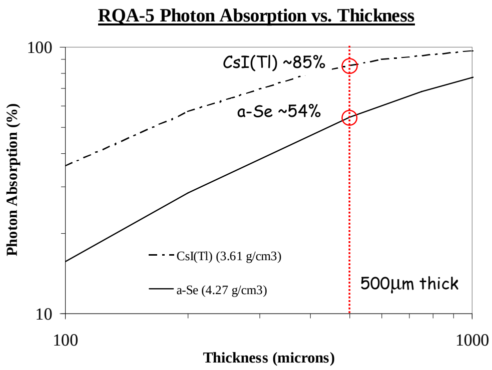
- Required to address issues with x-ray detection media
  - Phosphor – sensitivity increase (bright burn)
  - Photoconductor – sensitivity decrease
- Required to address issues with a-Si:H array
  - Incomplete charge readout from pixel
  - Charge retention in a-Si:H switching element
  - Charge retention in a-Si:H photodiode
  - Charge redistribution due to HV protection schemes
- Can involve complex, time consuming manipulation of :
  - Magnitude and polarity of applied bias voltages
  - Intensity and duration of applied reset light field
  - Injection of signal offset charges
- Determines array suitability for real-time imaging

System Configuration

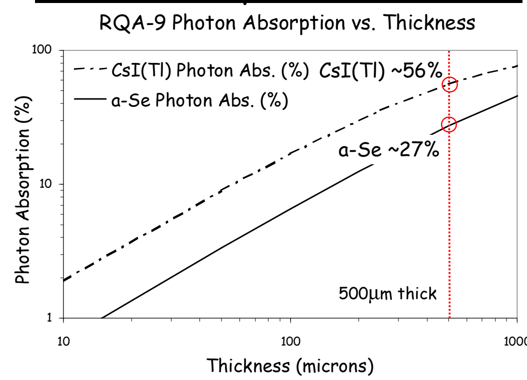


Flat Panel Detector Performance

Photon Absorption vs Thickness

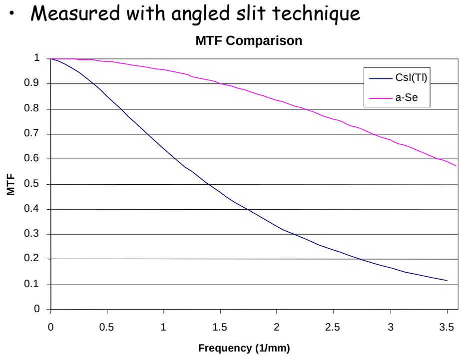


Photon Absorption vs Thickness

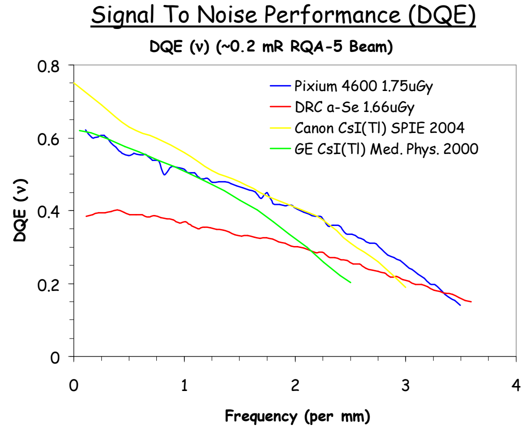


RQA-5 MTF Comparison

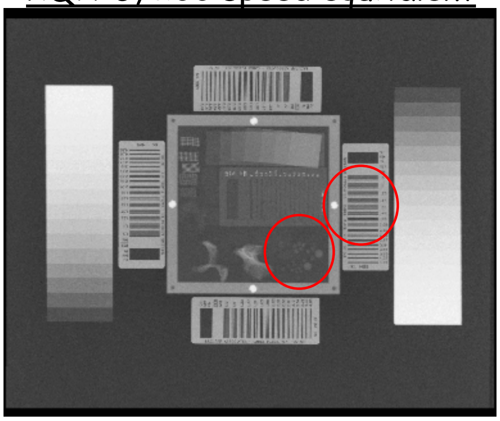
- Measured with angled slit technique



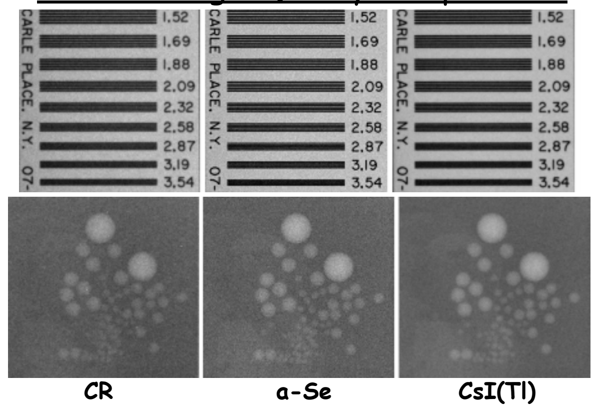
Signal To Noise Performance (DQE)



RQA-5, 200 speed equivalent



Native Image Quality Comparisons



Limitations of DQE

- DQE doesn't typically include scatter
- DQE doesn't include line correlated noise
  - Zero frequency axes ignored
- Detector DQE doesn't include grid or housing
- Doesn't usually include imaging task
- Doesn't include anatomical noise
  - This can be by far (x10) largest noise source
- "Digital" DQE not completely accepted as valid
- Connection between DQE and clinical efficacy unproven

Clinical Image Comparisons: Lateral Chest (120kVp)

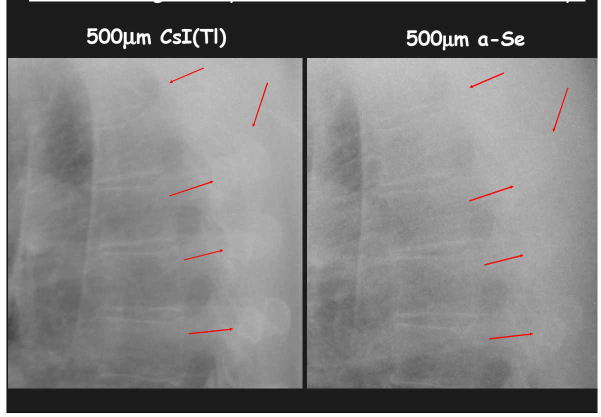


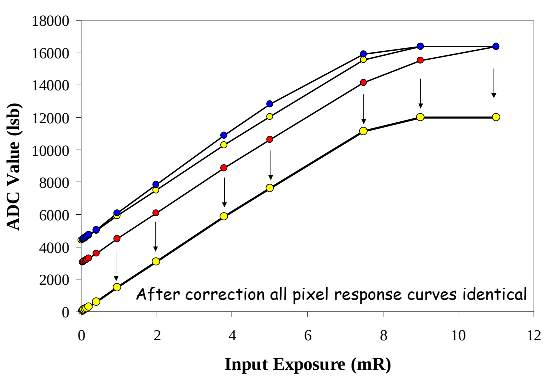
Image Corrections

Gain/Offset Corrections

Image Correction/Processing

- Offset/Gain corrections needed to account for:
  - Variation in phosphor/photoconductor sensitivity
  - Variation in pixel sensitivity and dark/offset signal
  - Variations in external electronics gain & offset
  - Achieved through flat field correction and offset subtraction
- Image corrected for bad pixels and lines
  - 2 stage process, identification and correction
  - ID typically done through Flat Field analysis
  - Correction typically achieved through mean/median filtering
- Corrected image log converted and optimized for display

Individual Pixel Responses



Offset/Gain Corrections

- Goal: To have identical pixel response curves
  - Typically done with 2 point linear fit
  - Only effective within linear region of response
  - Essential that flat-field exposure is in linear range
  - As signal approaches saturation, corrections begin to fail

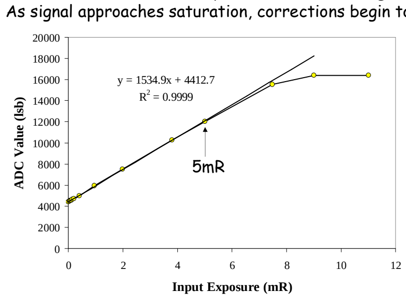
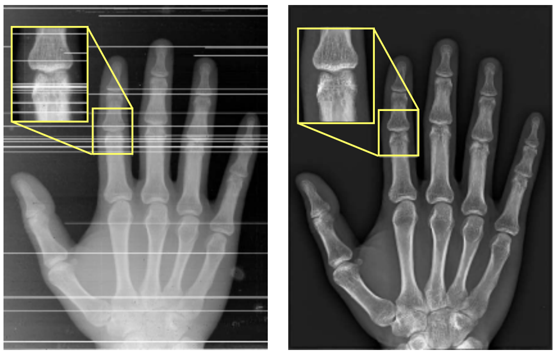


Image Correction/Presentation

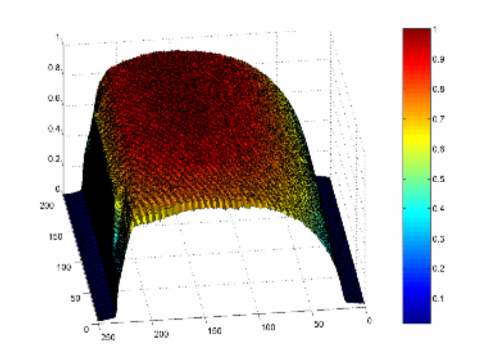


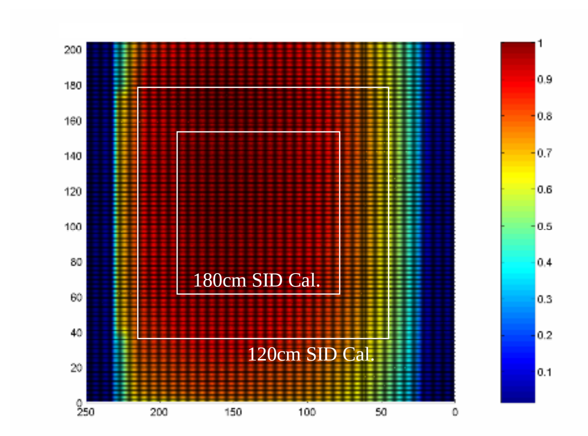
Other Practical Gain Correction Issues

- Gain/offset corrections are only fully effective at calibration configuration
  - kVp, filtration, scatter conditions, external components, SID
  - Changing conditions affects quality of calibration and can cause image artifacts (e.g. grid, AEC)
- Gain/offset correction has inherent noise
  - Take multiple flood fields to reduce stochastic noise
  - Analogous to "structure noise" in CR
- Gain calibration required periodically
- Offset determination required frequently
  - Exposure history and temperature dependant

- Gain correction removes fixed pattern noise
- Gain correction cannot remove stochastic noise variations

X-Ray Tube Output Distribution (Heel Effect)





Effect of Varying SID

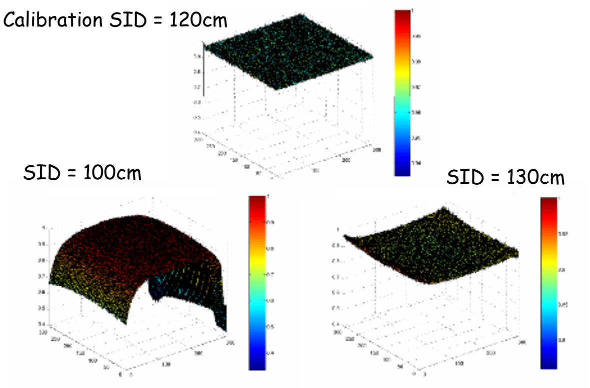
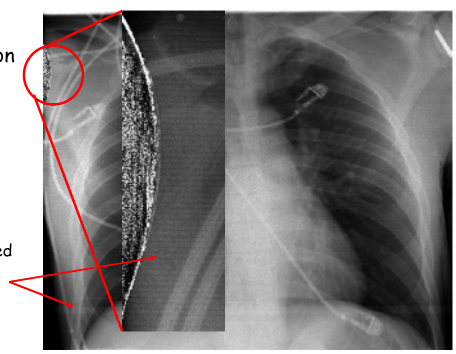


Image Artifacts

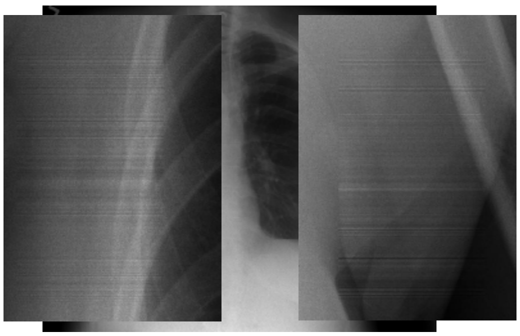
Image Artifacts

- Caused by:
  - Failed/unstable pixels and lines
  - Signal retention between consecutive images (ghosting/lag)
  - Non-linear pixel response
  - Chemical interactions between array and x-ray converter
  - Degradation of x-ray converter due to moisture
  - External electronics failure
  - Mechanical vibrations/microphonics (e.g. Cooling fans)
  - Differential temperature changes
  - 1000's other unknown reasons

a-Se Delamination



Microphonics Interactions



AEC Chamber Visibility

(Courtesy: Brent Colby, MeritCare)

Artifact Creation

- Image Artifacts can be generated by:
  - Detector malfunction
  - Interaction with other system components
  - Limitations with calibration procedures
- They can be of diagnostic relevance or of cosmetic concern only.
- Important to view artifacts with appropriate display contrast (γ ~2-4 depending on application)

Advanced Clinical Applications

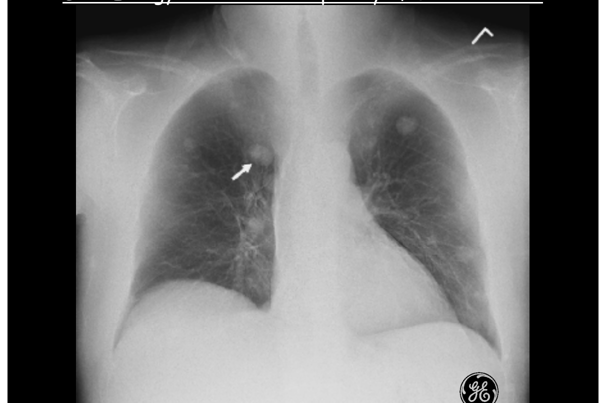
Clinical Challenge

3-Dim 2-Dim

- 3 dim. structure projected into 2 dim.
  - Overlapping structures obscure clinical details
  - Anatomical structure noise > x10 detector noise
  - Particularly problematic in chest and mammo.

(Source: A. Pommert et.al. Univ. Hosp. Eppendorf, Hamburg www.nim.nih.gov/research/visible/vhpconf2000)

Dual-Energy Increases Conspicuity of Subtle lesions

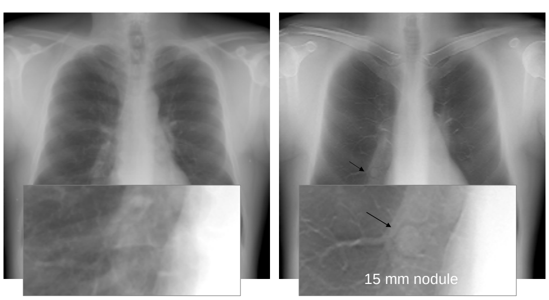


(Courtesy: JM Sabol, GE Healthcare and RC Gilkeson, Dept. Radiology Case Western Univ.)

Chest Tomosynthesis Clinical Example

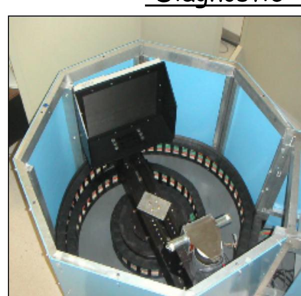
15 mm hilar nodule not visible on PA

16-degree tube angle, 61 projection images, 5 mm slice spacing
Total tomo exposure ≈ Lateral image exposure (screen film)



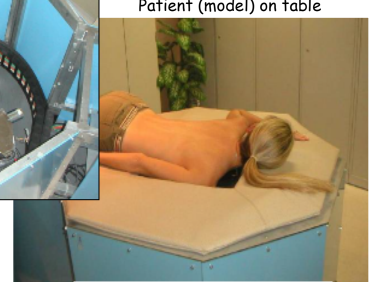
(Courtesy: James Dobbins, PhD, Duke University Medical Center)

"Diagnostic" CBCT Application



Dedicated Breast CBCT scanner at UC Davis

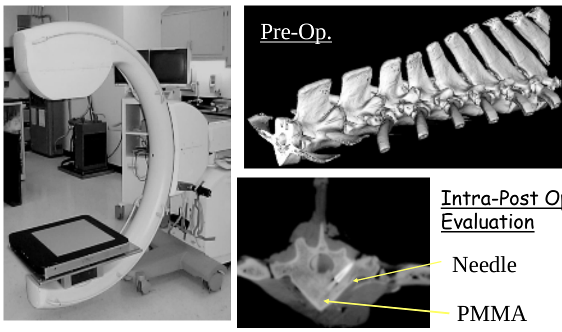
Patient (model) on table



The Breast Tomography Project
University of California, Davis

(Courtesy Dr. J.Boone UC Davis)

“Image Guidance” CBCT Application



(D. A. Jaffray and J. H. Siewerdsen, Princess Margaret Hospital , University of Toronto)

Future Directions

Flat-panel Detector Limitations

- High cost
- Heavy and relatively fragile
  - Limits use for portable exams
  - “Tethered” systems non-optimal
- Realtime systems have poorer low exposure performance than II tube
  - Relatively high electronic noise levels

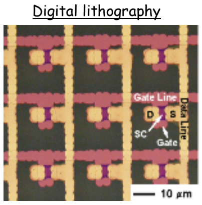
Future Developments: X-Ray Converters

- Most activity with PHOTOCONDUCTORS (mainly for fluoroscopy)
- Desire to:
  - Increase x-ray absorption using higher Z materials ($\mu \sim Z^3$)
    - PbI_2, PbO, HgI_2
  - Increase signal by:
    - Incorporating avalanche multiplication region into a-Se layer
    - Using materials with lower W (energy per e-h pair)
      - a-Se W_{eff}~50eV/e-h (dependant on applied field strength)
      - PbI_2 and HgI_2 W_{th} ~ 5eV/e-h
- Main issues with:
  - Dark current magnitude and stability
  - Trapped charge and temporal response
  - Uniformity of sensitivity
  - Environmental/chemical stability

Future Developments: Array Fabrication

- Array innovation driven by flat panel display market
- Desire to reduce array **cost** and improve **robustness**
- Desire to reduce external connections

Digital lithography



Jet-printed polymer TFT array (polythiophene)
(Courtesy Dr. R. Street, Xerox Parc)

Flexible Substrate

(Courtesy Dr. T.Jackson PennState)

On-glass Shift Register

1 mm

Historical Perspective

- Early 1900's
  - Radiography performed on glass plates
  - Expensive, fragile and heavy
  - WWI stopped supply of specialized Belgian glass
  - 1918 George Eastman introduced sensitized film
  - Credited with accelerating the spread of radiology

- Early 2000's
  - Digital Radiography performed on glass plates
  - Expensive, fragile and heavy
  - Will flexible, robust and cheap detectors do the same for digital radiography ?

(Source: Litrex Corp.)

(Source: Schott Glass.)

Conclusions

- Flat-panel and CCD based detectors are clinical reality across many different specialties
  - Projection and real time imaging (static to 30+fps)
  - Mammography (~20kVp) to Megavoltage imaging (~20MeV)
- Flat-panel large area drives improved image quality
- Optimal detector choice dependant on application
- Care should be taken on deciding calibration config.
- Integration of detector with x-ray generator facilitating advanced applications
  - Tissue and depth discrimination
  - CBCT and image guidance
- Developments in display manufacturing will enhance detector capabilities ("electronic film")
  - Reducing cost and improving robustness

- Most interesting developments still to come !!

Acknowledgements

Sincere thanks to all my colleagues who supplied the images used in this presentation…….

Thank You…..