Digital Mammography Update: Design and Characteristics of Current Systems

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Educational Objectives

- Understand the physics of digital detector technology
- Recognize that vendors use varying detector technology in FFDM systems
- Appreciate the advantages and disadvantages of digital mammography systems
- Understand briefly the image quality metrics such as DQE and MTF
Resources

- Doug Pfeiffer, MS, DABR
- Digital Mammography: An overview – Dr. Mahesh (Radiographics 2004;24:1747-1760)
- Fundamentals of Digital Mammography Primer – Dr. Smith (Hologic Inc)
- Digital Mammography – Pisano and Yaffe (Radiology 2005; 234:353-262)
- Bloomquist and Yaffe – Med Phys 33 (3), 2006

Introduction
**Full-Field Digital Mammography (FFDM)**

**Mammography - Screen-Film**

- X-Ray → X-Ray → Light → Phosphor → Film → Analog Image

**Mammography – Full Field Digital Detector**

- X-Ray → X-Ray → Detector → Digital Image


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**Full-Field Digital Mammography (FFDM)**

- Wide dynamic range (1000:1) compared with SFM (40:1)
- Dynamic image manipulation
- Ability to post-process
- Soft-copy read accompanied by computer-aided-diagnosis (CAD)
- 3D imaging

Radiographics 2004:24,1749
Full-Field Digital Mammography (FFDM)

- Advantage
  - Each component of the mammographic process can be optimized with digital mammography

SFM vs. FFDM

SFM: Half mAs, Automatic exposure control, Double mAs

FFDM: Same technique factors as SFM, W/L adjusted
### SFM vs. FFDM

![SFM vs. FFDM Images](image)

### FDA and Digital Mammography

**FDA Office of Device Evaluation**
- Clears FFDM for sale in US
- GE Senographe 2000D, DS, Essential
- Fischer SenoScan
- Lorad Selenia Amorphous Selenium
- Siemens Mammat Novation DR
- Fuji FCRm
- Approves monitors and printers for sale in US

**FDA Office of Communication, Education and Radiation Programs**
- Writes and enforces MQSA regulations
- Issues MQSA certificates

MQSA Scorecard

- Certification statistics, as of July 1, 2009
- Total certified facilities / Total accredited units
  - 8,714 / 12,875
- Certified facilities with FFDM units / Accredited FFDM units
  - 4,659 / 6,964
- 53% certified facilities with FFDM units
- 54% accredited FFDM units (38% last year)


Technologies for FFDM
Technologies for FFDM

**Indirect Capture**

- A scintillator such as cesium iodide (CsI) absorbs x-rays and generates a light scintillation
- Detected by an array of photodiodes or charge-coupled devices (CCDs)
- Resolution degradation

**Direct Capture**

- X-ray photons are directly captured by a photoconductor such as amorphous selenium (a-Se), which converts the absorbed x-rays directly to a digital signal
- Spatial resolution limited to pixel size
Various Approaches in development of FFDM systems

- **Indirect**
  - A single flat-panel scintillator and an amorphous silicon (a-Si) diode array – GE
  - Slot scanning with scintillators and CCD arrays – *Fischer Imaging, now Hologic*
  - Photostimulable phosphor plates - *Fuji*

- **Direct**
  - A flat-panel amorphous selenium (a-Se) array – *Hologic, Siemens*
  - Tiled scintillators with fiberoptic tapers and mosaic CCD arrays – *Hologic Stereotactic*

Technologies for FFDM – Indirect Capture GE

- **GE Senographe 2000D Full Field Digital Mammography System** on 01/28/00
- **GE Senographe DS Full Field Digital Mammography (FFDM) System** - 02/19/04
- **GE Senographe Essential Full Field Digital Mammography (FFDM) System** - 04/11/06 (larger detector)
Technologies for FFDM – Indirect Capture

GE

- In this system, the digital detector array is constructed from an a-Si thin-film transistor (TFT) matrix deposited on a glass substrate.
- The CsI scintillator is deposited on the a-Si detector.
- Each light-sensitive diode element is connected by TFTs to a control and a data line so that charge produced in the diode is read out in response to light emission from the scintillator.

<table>
<thead>
<tr>
<th></th>
<th>2000D</th>
<th>DS</th>
<th>Essential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector size</td>
<td>19.2 x 23.0</td>
<td>19.2 x 23.0</td>
<td>24.0 x 30.7</td>
</tr>
<tr>
<td>Pixel size</td>
<td>100 µm</td>
<td>100 µm</td>
<td>100 µm</td>
</tr>
<tr>
<td>Limiting Spatial Resolution</td>
<td>5 lp/cm</td>
<td>5 lp/cm</td>
<td>5 lp/cm</td>
</tr>
<tr>
<td>Image size</td>
<td>1914 x 2294 pixels (9 MB)</td>
<td>1914 x 2294 pixels (9 MB)</td>
<td>2394 x 3062 pixels (14 MB)</td>
</tr>
<tr>
<td>Bit Depth</td>
<td>14</td>
<td>14</td>
<td>14</td>
</tr>
</tbody>
</table>
Technologies for FFDM – Indirect Capture

GE – Advantages and Disadvantages

- Close bonding between CsI and a-Si ensures minimal light loss
- Strong signal from the Si diode array yields higher detective quantum efficiency
- Detector is linear over a wide range \((10^5)\) of exposures

- Limiting factor is the large pixel size \((100 \mu m)\)
- Smaller pixel sizes improve spatial resolution but at the cost of increased image noise and decreased SNR for the same breast dose
- Possibility of ghosting in images

Radiographics 2004;24:1753

Technologies for FFDM – Indirect Capture

Computed Radiography – Fuji (7/10/2006)

Technology introduced in 1981

- PSP (Barium fluorobromide)
- Base support
- Plate exposure: create latent image
Technologies for FFDM – Indirect Capture
Computed Radiography – Fuji

Technology introduced in 1981

- Laser beam scan
- Plate readout: extract latent image
- Light erasure
- Plate erasure: remove residual signal

Technologies for FFDM – Indirect Capture
Computed Radiography – Fuji

- Fuji FCRm, Dual-side reader

<table>
<thead>
<tr>
<th>Feature</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector size</td>
<td>18 x 24&lt;br&gt;24 x 30</td>
</tr>
<tr>
<td>Pixel size</td>
<td>50 μm</td>
</tr>
<tr>
<td>Image size</td>
<td>3328 x 4096 pixels (24 MB)</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>10 lp/mm</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>14 bits</td>
</tr>
</tbody>
</table>

http://www.fujimed.com/
Technologies for FFDM – Indirect Capture

Fuji – Advantages and Disadvantages

- Advantage of the CR mammo system is that film-screen cassettes can be replaced by CR cassettes without replacing the entire system
- Both small and large cassettes can be accommodated by the reader
- Dual side reader, 50 μm pixel size

- Disadvantage - Effective pixel size influenced by phosphor thickness, light diffusion within phosphor, laser light scatter & diameter of laser beam
- Technologist time on processing of images
- Noise associated with the low collection efficiency of emitted light
Technologies for FFDM – Indirect Capture
SenoScan; Fischer Imaging – 9/25/01

- A narrow slot-detector and a narrow fan beam of x-rays are scanned synchronously across the full field of view to cover the entire breast
- System consists of phosphor (thallium-activated CsI) with a fiberoptic coupling to a CCD

<table>
<thead>
<tr>
<th>Technologies for FFDM – Indirect Capture</th>
<th>Fischer SenoScan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector material and design</td>
<td>Caesium iodide with 4 CCDs</td>
</tr>
<tr>
<td>Detector area (cm)</td>
<td>21 x 1 *</td>
</tr>
<tr>
<td>Maximum field size (cm)</td>
<td>21 x 29</td>
</tr>
<tr>
<td>Image acquisition time (time to display image on workstation) (s)</td>
<td>12 to 15</td>
</tr>
<tr>
<td>Image matrix (pixels)</td>
<td>4096 x 5625</td>
</tr>
<tr>
<td>Pixel pitch (μm)</td>
<td>25 or 50</td>
</tr>
<tr>
<td>High contrast limiting resolution (lp mm⁻¹)</td>
<td>13 (at 25 μm)</td>
</tr>
<tr>
<td></td>
<td>10 (at 50 μm)</td>
</tr>
</tbody>
</table>
Technologies for FFDM – Indirect Capture (SenoScan; Fischer Imaging (now Hologic))

Advantages and Disadvantages

- Compact detector that is less expensive compared to others
- Excellent scatter rejection due to small volume of breast exposed at any time
- No grid needed therefore less dose
- Longer compression since scan times are longer (approx. 6 sec)
- Powerful tubes, elaborate signal readout and image reconstruction required

Comparison – Indirect Capture

<table>
<thead>
<tr>
<th></th>
<th>Fischer SenoScan</th>
<th>GE Senographe DS</th>
<th>Fuji FCRm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector material and design</td>
<td>Caesium iodide with 4 CCDs</td>
<td>Caesium iodide / TFT array</td>
<td></td>
</tr>
<tr>
<td>Detector area (cm)</td>
<td>21 x 1 *</td>
<td>19 x 23</td>
<td>18 x 24</td>
</tr>
<tr>
<td>Maximum field size (cm)</td>
<td>21 x 29</td>
<td>19 x 23</td>
<td>24 x 30</td>
</tr>
<tr>
<td>Image acquisition time (time to display image on workstation) (s)</td>
<td>12 to 15</td>
<td>&lt; 15</td>
<td></td>
</tr>
<tr>
<td>Image matrix (pixels)</td>
<td>4096 x 5625</td>
<td>1914 x 2294</td>
<td>3328 x 4096 pixels (24 MB)</td>
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<td>50 µm</td>
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<tr>
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<td>10 (at 50 µm)</td>
<td>10 lp/mm</td>
</tr>
</tbody>
</table>
Technologies for FFDM – Direct Capture

a-Se Array (Selenium, Hologic) – 10/2/01

- a-Se, a good photoconductor is deposited directly onto the a-Si TFT substrate enabling direct capture
- The a-Se detector directly converts x-rays to electron-hole pairs
- The a-Si TFT converts the electron-hole pairs to electronic signal

http://www.hologic.com/wh/digisel.htm

Technologies for FFDM – Direct Capture

Flat-Panel a-Se Array (Selenium, Hologic)

<table>
<thead>
<tr>
<th>Detector size</th>
<th>24.0 x 29.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel size</td>
<td>70 µm</td>
</tr>
<tr>
<td>Image size</td>
<td>3328 x 4096 pixels (24 MB)</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>&gt; 7 lp/cm</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>14 bits</td>
</tr>
</tbody>
</table>

http://www.hologic.com/wh/digisel.htm
Technologies for FFDM – Direct Capture

Flat-Panel a-Se Array (Selenia, Hologic)

Advantages and Disadvantages

- Advantage is that the detector response function maintains its sharpness even with increasing thickness
- High MTF and DQE can be achieved

- Potential weaknesses are the need for high biasing voltage, drifting of the dark signal and cost of detector
- Inherent sharpness of detector may also increase the severity of aliasing artifacts associated with undersampling on any digital detector

Technologies for FFDM – Direct Capture

a-Se Array (Mammomat Novation, Siemens – 8/20/04)

<table>
<thead>
<tr>
<th>Detector size</th>
<th>24.0 x 29.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel size</td>
<td>70 µm</td>
</tr>
<tr>
<td>Image size</td>
<td>3328 x 4096 pixels (24 MB)</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>&gt; 7 lp/mm</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>14 bits</td>
</tr>
</tbody>
</table>

http://www.medical.siemens.com
Comparison – Direct Capture

<table>
<thead>
<tr>
<th></th>
<th>Selenia</th>
<th>Siemens Mamnomat NovationDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector material and</td>
<td>Amorphous selenium /</td>
<td>Amorphous selenium /</td>
</tr>
<tr>
<td>design</td>
<td>TFT array</td>
<td>TFT array</td>
</tr>
<tr>
<td>Detector area (cm)</td>
<td>24 x 29</td>
<td>24 x 29</td>
</tr>
<tr>
<td>Maximum field size (cm)</td>
<td>24 x 29</td>
<td>18 x 23 (small format),</td>
</tr>
<tr>
<td></td>
<td></td>
<td>23 x 29 (large format)</td>
</tr>
<tr>
<td>Image acquisition time</td>
<td>10 to 15</td>
<td>40 to 60</td>
</tr>
<tr>
<td>(time to display image</td>
<td></td>
<td></td>
</tr>
<tr>
<td>on workstation) (s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Image matrix (pixels)</td>
<td>3328 x 4096 (24x30)</td>
<td>3328 x 4096</td>
</tr>
<tr>
<td></td>
<td>2560 x 3328 (18x24)</td>
<td></td>
</tr>
<tr>
<td>Pixel pitch (μm)</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>High contrast limiting</td>
<td>&gt; 7</td>
<td>&gt; 7</td>
</tr>
<tr>
<td>resolution (lp mm⁻¹)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Technologies for FFDM

The Evolution of Digital Radiography Detectors

| Screen-Film System     | Fuji/Kodak/Agfa/Philips |
| Computed Radiography   | Fischer (Hologic)       |
| CCD Detector with     | GE                      |
| Scintillator Screen    | Hologic (Hologic)       |
| Direct Imaging         | Siemens                 |

MTF, DQE, DOSE

MTF is a measure of signal transfer over a range of frequencies and quantifies spatial resolution.

Yaffe - Radiology 2005:234,353

**MTF**

- Bloomquist et al - DMIST trial

![MTF Diagram](image_url)

**DQE**

- Detective Quantum Efficiency (DQE) measures SNR transfer through the system as a function of spatial frequency and is a good measure of dose efficiency.

![DQE Diagram](image_url)
FFDM – Radiation Dose

- Bloomquist et al - DMIST trial

<table>
<thead>
<tr>
<th>System</th>
<th>N</th>
<th>μC/kg</th>
<th>mR</th>
<th>Range</th>
<th>MGD mGy</th>
<th>Range mGy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fischer</td>
<td>26</td>
<td>144</td>
<td>560</td>
<td>400–750</td>
<td>1.31</td>
<td>0.81–1.79</td>
</tr>
<tr>
<td>Fuji</td>
<td>25</td>
<td>278</td>
<td>1080</td>
<td>270–1660</td>
<td>1.87</td>
<td>0.79–2.69</td>
</tr>
<tr>
<td>GE</td>
<td>46</td>
<td>196</td>
<td>760</td>
<td>410–1410</td>
<td>1.49</td>
<td>0.84–2.53</td>
</tr>
<tr>
<td>Lorad DBI</td>
<td>11</td>
<td>254</td>
<td>1140</td>
<td>540–1610</td>
<td>1.98</td>
<td>1.10–2.70</td>
</tr>
<tr>
<td>Lorad Selec</td>
<td>12</td>
<td>273</td>
<td>1060</td>
<td>620–1830</td>
<td>1.85</td>
<td>1.00–2.98</td>
</tr>
<tr>
<td>All</td>
<td>121</td>
<td>219</td>
<td>850</td>
<td>270–1830</td>
<td>1.62</td>
<td>0.79–2.98</td>
</tr>
<tr>
<td>Screen-film</td>
<td>140</td>
<td>304</td>
<td>1178</td>
<td>708–1810</td>
<td>1.90</td>
<td>1.24–2.75</td>
</tr>
</tbody>
</table>

Storage and Economics
Storage of Digital Images

Table 2
Typical Image Sizes and Storage Requirements for FFDM Systems

<table>
<thead>
<tr>
<th>Manufacturer and Model</th>
<th>Image Matrix (pixels)</th>
<th>Image Size (megapixels)</th>
<th>Storage Requirement (MB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE Senographe 2000D</td>
<td>1,020 × 2,304</td>
<td>4.4</td>
<td>8.8</td>
</tr>
<tr>
<td>Fischer SenoScan</td>
<td>4,096 × 5,625</td>
<td>23.0</td>
<td>46.1</td>
</tr>
<tr>
<td>Hologic Selenia</td>
<td>3,328 × 4,096</td>
<td>13.6</td>
<td>27.2</td>
</tr>
<tr>
<td>Fuji CR®</td>
<td>1,770 × 2,370</td>
<td>4.2</td>
<td>8.4</td>
</tr>
<tr>
<td>Hologic CCD array®</td>
<td>2,364 × 2,964</td>
<td>7.0</td>
<td>14.0</td>
</tr>
<tr>
<td></td>
<td>4,500 × 6,000</td>
<td>27.0</td>
<td>54.0</td>
</tr>
</tbody>
</table>

*For a typical four-image screening examination.

†No longer commercially available.

Display of Digital Images

Radiographics 2004;24,1755

41

Radiographics 2004;24,1757

42
Advantages and Disadvantages

- **Advantages**
  - Optimize post-processing of images
  - Permit computer-aided detection to improve the detection of lesions
  - Storage of images easier

- **Disadvantages**
  - Image display and system cost
  - Limiting spatial resolution is inferior to film, 5-13 lp/mm vs. 20 lp/mm

Economics of FFDM

- SFM systems cost well under $100,000
- FFDM systems cost in the range of $300,000 - $450,000
- Reimbursement rates approved by Medicare are decreasing every year

- **Plain Film Screening**
  - 2008 - $83.03, 2009 - $81.51

- **Digital Screening**
  - 2008 - $133.69, 2009 - $129.84

- **Diagnosis**
  - 2008 - $151.21, 2009 - $152.56

- **CAD**
  - 2008 - $14.86, 2009 - $12.26
Benefits

Expected Benefits of FFDM

- The costs of FFDM systems should be compared along with the inherent benefits of the digital technology prior to the purchase:
  - Reduced recall rates
  - Increased patient throughput
  - Increased early detection of breast cancer
  - Decreased false-negative biopsy results
  - Decreasing film and processing costs
  - Increasing the caseload of each mammography room
Clinical Trials and Phantom Studies

- Large screening study screened 49,500 women
- *Digital Mammographic Imaging Screening Trial* (DMIST), funded by NCI and conducted by ACRIN (http://www.acrin.org/6652_protocol.html)

**CONCLUSIONS**

The overall diagnostic accuracy of digital and film mammography as a means of screening for breast cancer is similar, but digital mammography is more accurate in women under the age of 50 years, women with radiographically dense breasts, and premenopausal or perimenopausal women. (ClinicalTrials.gov number, NCT0008346.)

Future Developments
Future Developments

- Dual energy
- CAD integration
- Telemammography
- Tomosynthesis
- Contrast enhanced digital mammography

**Future Developments**
**Contrast Enhanced Digital Mammography**

![Image of mammogram](image)


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**TAKE HOME POINTS**

- Different technologies exist for digital systems – indirect and direct
- Commercially available FFDM systems vary in technology
- Many advantages exist for FFDM in comparison to FSM
- MTF and DQE are typically used to characterize FFDM systems
- Dose is lower with FFDM compared to FSM
- Advanced applications of FFDM include tomosynthesis, contrast enhanced mammography etc
THANK YOU