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Community Research

TRAINING COURSE
DIGITAL PROJECTION RADIOGRAPHY
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Basic Principle of Flat Panel Imaging Detectors

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SENTINEL

Introduction

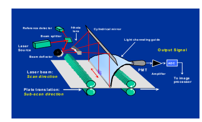
- Digital imaging systems entered in the radiology departments >15 years ago using:
  - photostimulable phosphors (PSP) (CR technology)
  - CCD (Charge Coupled Device)
  - photoconduction (Thoravision)
- PSP plates have been developed >25 years and represent the most diffused technology
- Recent introduction of AMFPI (Active Matrix Flat Panel Imager) has opened new possibilities for:
  - image quality improvement,
  - patient dose reduction
  - and, new imaging technique (tomosyntesis, dual energy imaging, etc.)

Technologies for digital radiography imaging

- CR
  - PSP → laser scanning → Optics → PM
- CCD
  - Scintillator → Optics / Fiber Optics → CCD
- AMFPI (a-Silicon)
  - X-ray detectors (Selenium, CsI) → AMA (flat panel)
- (work in progress)
  ASIC (Application Specific Integrated Circuits)
  - detectors: CdTe, c-Si, …
  - electronic on-board

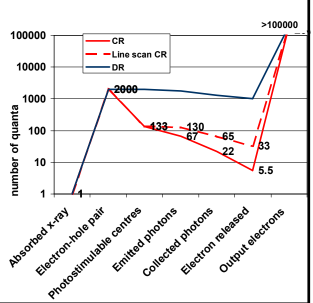
Success of CR technology

- Success of CR:
  - high dynamic range (> 10^4)
  - digital nature
  - easy to introduce
  - relative low cost
  - improvements for more than 25 years
  - **but not for image or dose performances !**



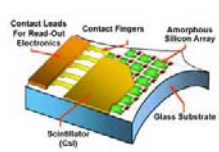
Signal to Noise Ratio

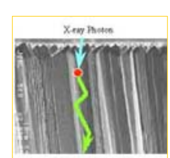
- Quantum accounting for CR and DR:
  - It is important that the detector maintains a large number of quanta representing each x-ray if **quantum noise** is to be minimised
  - This allows to increase the **signal to noise ratio (SNR)**
- Advantages of DR:
  - High quantum conversion efficiency compared to CR technology



Direct Radiography (DR)

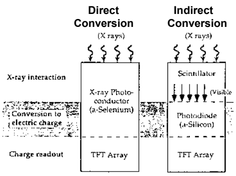
- DR (indirect conversion technology) started using the knowledge and the technology on phosphors gained for CR
- The most important scintillator for DR is the CsI(Tl) that can be produced in needle-structure (1-10 μm) for a better geometric resolution





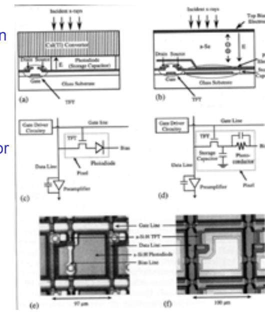
Structure of a AMFPI

- AMFPI (Active Matrix Flat Panel Imager) is composed of:
  - a x-ray detection layer
  - an AMA (Active Matrix Array) of TFT (Thin Film Transistors) layer
- Two type of x-ray detectors are today mainly used:
  - Selenium (photoconductor)
  - CsI(Tl) (scintillator)



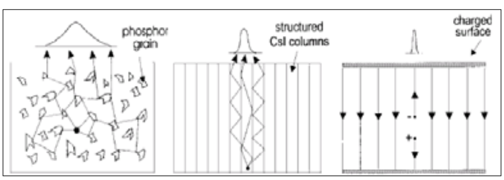
AMFDI imaging detectors

- Indirect conversion:
  - Light produced by the interaction of x-ray in the scintillator are converted to charge by the a-Si
- Direct conversion:
  - Electrons produced by the interaction of x-ray in Se are collected in the storage capacitor of each pixel
  - Charge amplification and line collection are the same in the 2 technologies

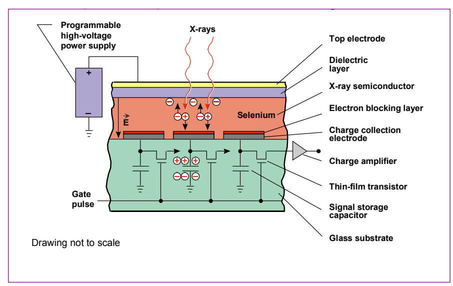


AMFDI imaging detectors

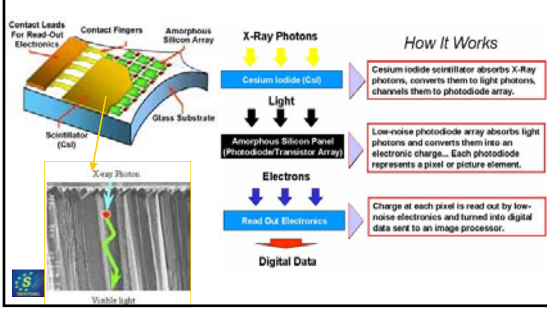
Resolution properties



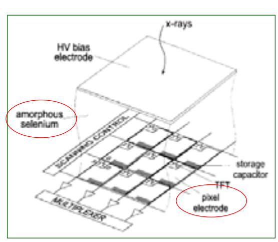
Flat panel technology: direct conversion



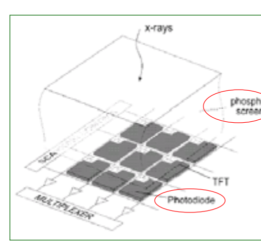
Flat panel technology: indirect conversion



Flat panel technology: assembly

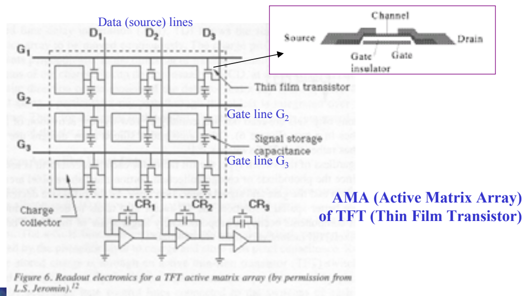


(a) Direct conversion



(b) Indirect conversion

TFT layer



AMA (Active Matrix Array) of TFT (Thin Film Transistor)

Detector performances: x-ray detectors

	CR	Indirect	Direct Conversion	new detectors	
	Gd_2O_2S:Tb	CsI:Tl	a-Se amorphous	CdTe Sing. cryst.	PbI_2 polycryst.
Atomic number	64	55,53	34	48,52	82,53
Density	7.5	4.5	4.3	6	6.2
K edges (keV)	50.2	33.1, 36	12.7	26.7, 31.8	88, 33.1
Average abs. coeff. (cm^{-1})	52	48	16	48	57
RQA5 (70 kVp, 21 mm Al)					
Bandgap (eV)			1.7-1.9	1.5	2.4
$\mu\tau$ electrons (cm^2/V)			3×10^{-7}	2×10^{-3}	10^{-5}
$\mu\tau$ holes (cm^2/V)			4×10^{-6}	4×10^{-4}	2.10^{-6}
Conversion efficiency	~ 60 $h\nu$/keV	~ 60 $h\nu$/keV	20 el/keV	~ 220 el/keV	~ 240 el/keV
Refractive index	> 2	1.78			2.7
Emission spectrum (nm)	540	500-600			

Detector perfomances

- The best objective measure of detector performance is the Contrast to Noise ratio (CNR)

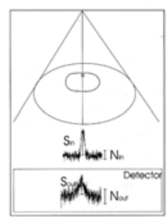
  this quantity is related to the detective quantum efficiency (DQE).

- But:
  - object constrast is a function of material imaged and x-ray spectra
  - DQE is a function of exposure, spatial frequency and x-ray spectrum

  → DQE is the most important object-independent parameter for characterizing the performance of a imaging detector

DQE evaluation

- Detective Quantum Efficiency



$$DQE = \frac{NEQ_{out}}{q_{in}} = \frac{\left(\frac{S_{out}}{N_{out}}\right)^2}{\left(\frac{S_{in}}{N_{in}}\right)^2}$$

$$DQE(u) = \frac{1}{q_{in}} \cdot \left[K \cdot \frac{MTF(u)^2}{NPS(u)}\right]$$

Per i rivelatori digitali:

$$DQE^d(u) = \frac{1}{q_{in}} \cdot \left[K \cdot \frac{MTF_{pre}(u)^2}{NPS^d(u)}\right]$$

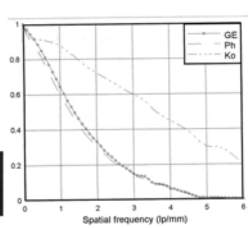
Fig. 7. Il concetto di Detective Quantum Efficiency e la sua relazione con la Modulation Transfer Function (MTF), lo spettro del rumore (Noise Power Spectrum – NPS) e la curva di risposta del sistema (qui riassunta nel solo parametro della sua pendenza K, al livello di dose prescelto)

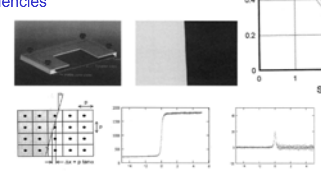
Modulation Transfer Function

Evaluation methodology

Comparison of MTF of 3 flat panel detectors:

- Results:
  - •Direct conversion FP exibits highest MFT at high spatial frequencies





G. Borasi et. Al; On site evaluation of three flat panel detectors for digital radiography; Med.Phys. 30 (7), July 2003

Another comparison of imaging performance of digital detctors

- MTF comparison of CR and DR systems

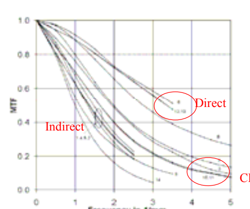


Figure 1. Mean MTF for the 14 edge images averaged over all individual MTF results using the different algorithms.

Table 1. Characteristics of detectors, x-ray beam qualities, edg[e] ... signal mean within the image. Image nos 1 and 2 represent two ...

Image no	Detector type	Detector material	Thickness (mm)	Pixel pitch (mm)
1	Indirect	CsI	~0.5	0.2
2	Indirect	CsI	~0.5	0.2
3	CR	BaFBr	~0.1	0.1
4	Indirect	CsI	~0.5	0.2
5	Indirect	CsI	~0.5	0.2
6	Direct	a-Se	0.5	0.139
7	Simulated	–	–	0.1
8	Simulated	–	–	0.1
9	Indirect	CsI	0.5	0.143
10	CR	BaFBr	0.16	0.05
11	CR	BaFBr	0.16	0.05
12	Direct	n.a.	n.a.	0.139
13	Direct	n.a.	n.a.	0.139
14	CR	BaFBr	0.5	0.168

Comparison of edge analysis techniques for the determination of the MTF of digital radiographic systems
Ehsan Samei, Egbert Buhr, Paul Granfors, Dirk Vandenbroucke and Xiaohui Wang
Phys. Med. Biol. **50** (2005) 3613–3625

Noise Power Spectrum

- NPS:
  - Important differences between detectors
  - NPS is function of entrance air kerma to the detector
  - Highest noise values for Direct conversion systems

(at 2 cycles/mm the same level of noise is obtained with the DC system with 4-5 times the entance dose)

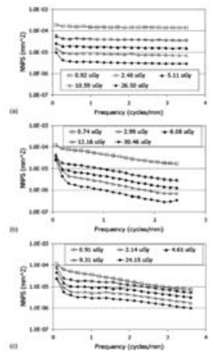


FIG. 10. Normalized noise power spectra at 70 kV + 0.5 mm Cu: (a) system A; (b) system B; (c) system C.

G. Borasi et. Al; On site evaluation of three flat panel detectors for digital radiography; Med.Phys. 30 (7), July 2003

Detective Quantum Efficiency

- DQE:
  - Important differences between detectors
  - DQE is influenced by the entrance air kerma to the detector
  - Lowest DQE for Direct conversion systems

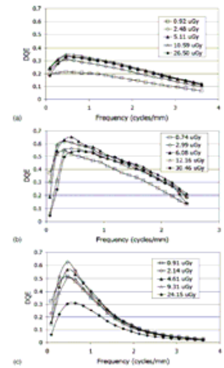
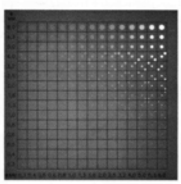


FIG. 12. Detective quantum efficiency at 70 kV + 0.5 mm Cu (a) system A, (b) system B, (c) system C.

G. Borasi et. Al; On site evaluation of three flat panel detectors for digital radiography; Med.Phys. 30 (7), July 2003

Imaging perfomance

- Contrast-detail analysis
  - Several phantoms are available for this test (TO16, CDRAD, ..)
  - Operator judges the constrast for which the disk perceptibility is vanishing



Imaging perfomance

- Contrast-detail analysis
  - This test has provided the same evaluation of the 3 DR systems: DR with lowest DQE has lower constrast-detail performance
  - Good relationship between DQE and CD

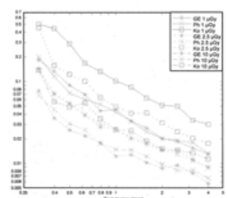


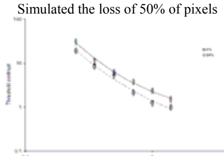
Fig. 20. Curve Contrasto Dettaglio ai tre livelli di dose, per i sistemi considerati. I colori ed i simboli contraddistinguono i diversi produttori. Il tratteggio il livello di dose. Il sistema a rivelazioni diretta a 2.5 μGy, presenta delle prestazioni inferiori a quelle dei sistemi a rivelazione indiretta a 1 μGy.Le curve di percettibilità del sistema a rivelazione indiretta a 10 μGy, sono equivalenti a quelle die sistemi a rivelazione indiretta a 2.5 μGy

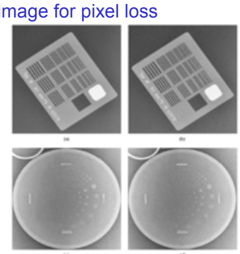
G. Borasi et. Al; On site evaluation of three flat panel detectors for digital radiography; Med.Phys. 30 (7), July 2003

Effects of pixel loss on image quality

- Effects on contrast-detail curve for a loss of 50% of pixels
- No important deterioration of image for pixel loss

Simulated the loss of 50% of pixels





Assessment of the effects of pixel loss on image quality in direct digital radiography
R Padgett and C J Kotre
Phys.Med. Biol. 49 (2004) 977–986

Stability of FP performances

- FP used for portal imaging in radiotherapy and evaluation on dosimetry performance stability:
  - Dark signal is a function of detector temperature
  - The reproducibility of the *a*-Si EPIDs at the central pixel region was excellent: 0.5% SD over a period of up to 23 months.
  - This result proves that the gain of the tested *a*-Si EPIDs does not depend on radiation history or temperature fluctuations.

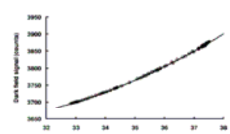


FIG. 3. The dark-field signal of images B_i during several temperature cycles, plotted as a function of the EPID surface temperature. The solid line represents a fit obtained with the factors presented in Table III.

The long-term stability of amorphous silicon flat panel imaging devices for dosimetry purposes
R. J. W. Louwe, L. N. McDermott, J.-J. Sonke, R. Tielenburg, M. Wendling, M. B. van Herk, and B. J. Mijnheera
Med. Phys. 31 (11), November 2004

New technologies and applications

Dynamic Flat Panel technology

- From 20x20 cm^2 for cardiac application up to 40x40 cm^2 for peripheral angiography
- No geometric distorsion, good uniformity and constant resolution across its area
- Less mechanically complex, compared to II
- More compact → new design of angiography units
- Advanced applications: rotational acquisition, 3D reconstruction (volumetric images)

Dynamic Flat Panel technology

Limits of FP for fluoroscopy applications:

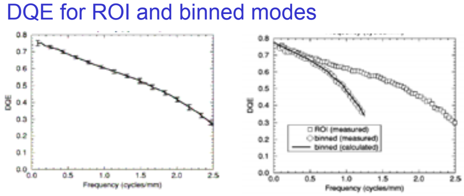
- A digital radiographic detector images at relatively low rates and at relatively large exposure levels
- A detector designed for angiography and R&F applications must be able to image:
  - at **higher rates**
  - and at **lower exposure levels** required for fluoroscopy.
- To enable fluoroscopic imaging, the detector should be designed to produce:
  - a large signal per exposure
  - and very low additive electronic noise

Dynamic Flat Panel technology

- Acquisition modality can be more complex than conentional radiographic systems
- Example of acquiring modalities of a large area dynamic detector can be read out:
  1. at **full resolution and full field of view** (**FR-FFOV mode**) to produce 2048x2048 pixel images.
     - This mode, similar to that of radiographic detectors, can acquire images up to 5-10 frames per second.
     - A control circuitry enables two 1024x1024 imaging modes, capable of image rates as high as 30 frames per second.
  2. In the region-of-interest or **ROI mode**, the center 1024x1024 pixels of the detector are read out.
  3. In the **binned mode**, the full 41x41 cm^2 is read out in blocks of 2x2 adjacent pixels. This mode is achieved by reading out pairs of gate lines simultaneously and summing the signals from pairs of data lines.

Dynamic Flat Panel performance

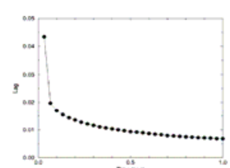
- Different acquisition modes give different imaging performances
- DQE for ROI and binned modes



Performance of a 41x41 cm2 amorphous silicon flat panel x-ray detector designed for angiography and R&F imaging applications
P. Granfors et al.
Med. Phys. 30 (10), October 2003

Dynamic Flat Panel performance

- Lag or retention of signal from frame to frame
  - Lag characteristics:



Performance of a 41x41 cm2 amorphous silicon flat panel x-ray detector designed for angiography and R&F imaging applications P. Granfors et al Med. Phys. 30 (10), October 2003

FP vs II performance

- At high doserates, typical of angio acqisition FP is better than II
- At low doserates, typical of fluoroscopy mode, II and FP show similar DQE

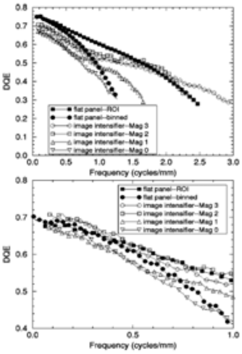


FIG. 13. Comparison of DQE between flat panel detector and image intensifier system (a) at high exposure limit and (b) at 8 nGy air kerma. Note that image intensifier data have not been corrected for lag. This correction would lower the image intensifier DQE curves.

Performance of a 41x41 cm2 amorphous silicon flat panel x-ray detector designed for angiography and R&F imaging applications P. Granfors et al Med. Phys. 30 (10), October 2003

Advanced technology: Portable FP

- In the detection of catheters, nodules, and almost all interstitial lung disease **portable flat-panel detector** was superior than storage phosphor radiography at equivalent and reduced speeds.
- Results suggest that the **portable flat-panel detector** could be used with reduced exposure dose in pediatric patients (400-800 speed).

Experimental Evaluation of a Portable Indirect Flat-Panel Detector for the Pediatric Chest: Comparison with Storage Phosphor Radiography at Different Exposures by Using a Chest Phantom

U.Rapp-Bernhardt, et al.
Radiology. 2005;237:485-491

Advanced technologies: new detectors and applications

- New applications:
  - Other scintillator materials used (scintillators of conventional screens)
  - 400 and 200 μm pixels
  - Different FP sizes: 9" and 16"
  - Applications (medical & industrial):
    - portable FP
    - NDT (non destructive testing)
    - Pipeline inspections
    - Portal imaging
    - Bone densitometry
    - Veterinary imaging

Advanced technologies

- New flat panels:
  - CMOS detector
  - Faster readout (up to 60 fr/s
  - Lower cost (standard semiconductor production processes
  - Higher integration (on-chip ADC, …)

Advanced technologies for fluoroscopy: new materials

- The DQE(*f*) of FP compares favorably to II except at the lowest exposure encountered in fluoroscopy (< 5 nGy), where the electronic noise of FP degrades the DQE.
- To improve the DQE at low dose many recent developments for direct and indirect FP are available.
  - For direct FP:
    - photoconductors of higher z and x-ray to charge conversion gain, e.g. lead iodide (PbI_2) and mercuric iodide (HgI_2)
    - The x-ray to charge conversion gain for these new photoconductors is seven times higher than that of a-Se.
  - For indirect FP:
    - a thin layer of a-Se avalanche photoconductor is being investigated as a replacement for a-Si photodiodes.
    - Under electric field of > 80 V/micron, avalanche multiplication occurs in a-Se, which can amplify the signal in low dose applications.

Flat Panels Vs. IIs: A Critical Comparison
W Zhao*, SUNY Stony Brook, Stony Brook, NY; AAPM 2005

Development of Direct Detection Active Matrix Flat-Panel Imagers Employing Mercuric Iodide for Diagnostic Imaging
Y El-Mohri*, LE Antonuk, Q Zhao, Z Su, J Yamamoto, H Du, A Sawant, Y Li, Y Wang, University of Michigan, Ann Arbor, MI

Advanced technologies: detector structure

- The detector is made by optically coupling a structured scintillator (CsI) to a uniform layer of avalanche amorphous selenium (a-Se) photoconductor called HARP (High Avalanche Rushing amorphous Photoconductor):
  - The HARP layer absorbs the visible photons emitted from the scintillator and generates electron-hole pairs.
  - These carriers undergo avalanche multiplication under a sufficiently high electric field and form an amplified charge image.
- The proposed detector is called SAPHIRE (Scintillator Avalanche Photoconductor with High Resolution Emitter readout).

A New Concept of Indirect Flat-Panel Detector with Avalanche Gain: SAPHIRE (Scitillator Avalanche Photoconductor with High Resolution Emitter Readout)
D Li*1, W Zhao1, K Tanioka2, G Pang3, JA Rowlands3, (1) State University of New York at Stony Brook, Stony Brook, NY, (2) Japan Broadcasting Corporation, Tokyo, Japan, (3) Sunnybrook & Women's College Health Sciences Center, Toronto, Ontario, Canada

Advanced technologies: pixel structure

- Sophisticated pixel structures incorporating more than three TFTs at each pixel has been designed
- It provides higher signal amplification at each pixel reducing the electronic noise

Conclusion

- Distinctions between CR and DR are less obvious:
  - some storage phosphor (CR) devices are automated with direct image display
  - some direct flat-panel devices (DR) are used like a portable cassette.
- Digital detector technologies now available include
  - PSP line-scan systems in a cassetteless enclosure,
  - optically coupled CCD-camera systems,
  - fiber-optically coupled slot-scan
  - CCD array detectors,
  - indirect x-ray conversion scintillators and thin-film-transistor (TFT) photodiode arrays and direct x-ray conversion semiconductors layered on TFT detector arrays

Overview of Digital Detector Technology
J Seibert*, UC Davis; Medical Center, Sacramento, CA; AAPM 2005

Conclusion

- Today FP: it has become apparent that current devices suffer from a number of intrinsic limitations that affect their cost, performance and robustness.
- Technologies, emerging from advances in displays, offer the potential of enabling the creation of fundamentally different forms of active matrix x-ray imagers:
  - imagers would incorporate innovations as flexible, plastic substrates or sophisticated in-pixel circuitry
- Potential impact of such radically different forms of imagers can be important (more rapid diffusion of DR in developed and developing coutries)

Active Matrix, Flat-Panel Imagers: From Rigid and Simple to Flexible and Smart
L.E. Antonuk*, University of Michigan Medical Center, Ann Arbor, MI; AAPM 2005

Conclusions

- Compared to SFS, digital radiography is still in its infancy.
- CR is a mature technology and constant technological progresses are mantaining the large prevalence of CR compared to DR
- The lower cost of CR indicates that this technology can be introduced in developing countries providing great improvement in image quality
- Advantages of digital images for post-processing, new digital modalities (dual energy, digital subtraction), support to the diagnosys (CAD- Computer Aided Diagnosys - technology) and teleradiology will impose new technologies to the SFS