New Generation of Detectors and Patient Doses in Digital Radiology

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Introduction

- Digital imaging systems entered in the radiology departments >15 years ago using:
  - photostimulable phosphors (PSP) (CR technology)
  - CCD (Charge Coupled Device)
  - photoconduction detectors (Thoravision)
- PSP have been developed >25 years and represent the most diffused technology

- 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, cone beam CT, etc.)

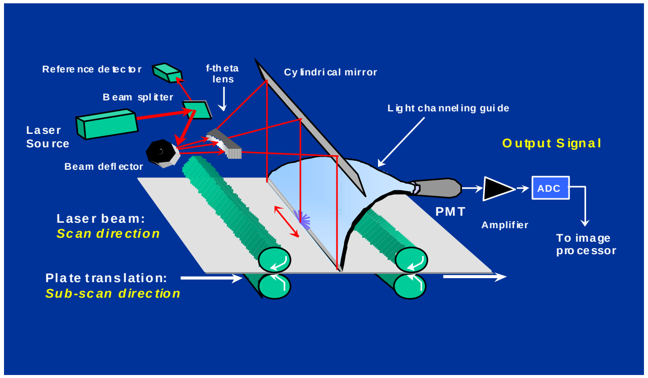
Technologies for digital radiography imaging

- Computed Radiography (CR)
  - X-ray detector (Photostimulable Phosphor Plates (PSP)) → Laser scanning → Optics → PM
- CCD
  - Xray detector (Scintillator) → Optics / Fiber Optics → CCD
- AMFPI (a-Silicon)
  - X-ray detectors (Selenium, CsI(Tl)) → 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:
    - in last years:
      - Mammography
      - Line scan
      - Double side reading



  - **but not for image or dose performances !**

Success of CR technology

- New features:
  - Dual-sided image readout
  - Channelled storage phosphor

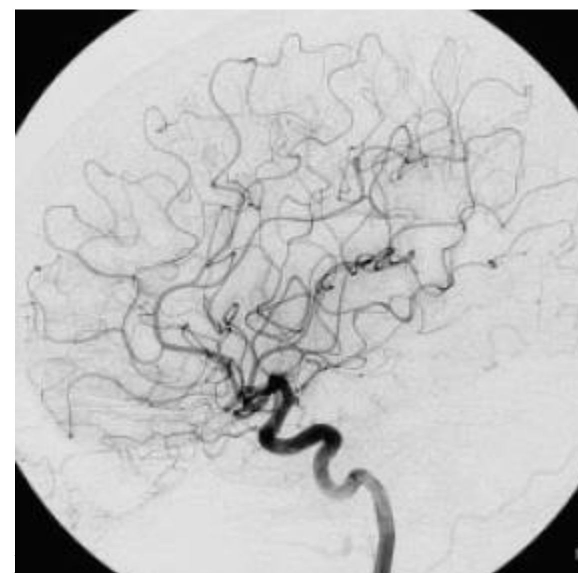
- These technologies have improved detective quantum efficiency (DQE) by approximately 50 and 100% compared with standard CR
- New CR affords greater scope for reducing patient dose, and is competing with the new solid-state, flat-panel, digital radiography detectors

Cowen AR, Davies AG, Kengyelics SMAdvances in computed radiography systems and their physical imaging characteristics.

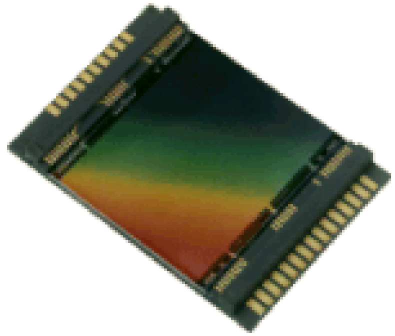
Clin Radiol. 2007 Dec;62(12):1132-41.

CCD imaging detector

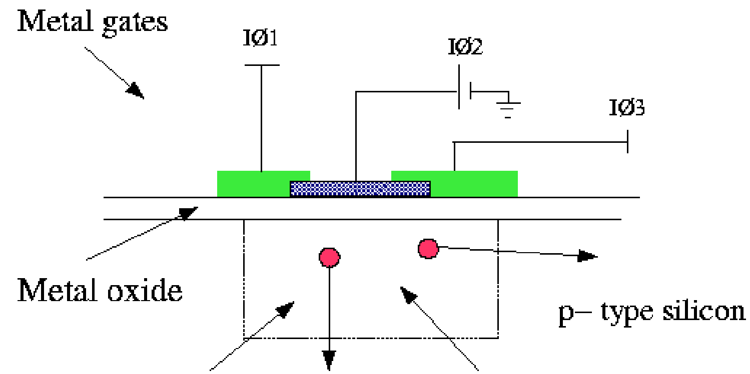
- Used today in all image intensifier fluoroscopy/angiography systems
- CCDs offer many advantages
  - high sensitivity
  - linear response
  - fast response
  - no lag (recover rapidly from overload situations)
  - inherently stable (no drift or degradation)
  - smaller than a conventional camera tube

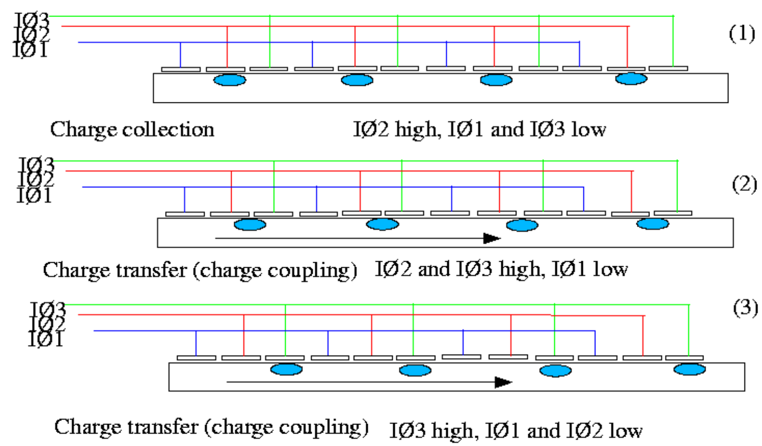


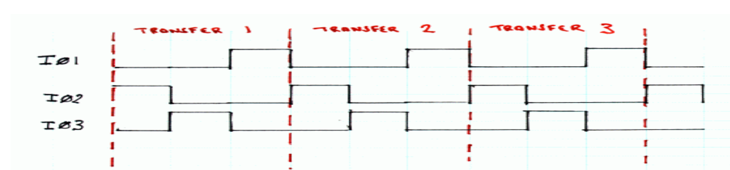
CCD



- A Charge Coupled Device (CCD) is a highly sensitive photon detector:
  - The CCD is divided up into a large number of light-sensitive small areas (known as pixels)
  - A photon of light which falls within a pixel will be converted into one (or more) electrons
  - The number of electrons are directly proportional to the light intensity at each pixel.
  - When the CCD is clocked out, the number of electrons in each pixel are measured and the image can be reconstructed.







CCD imaging detector (dental)

- Adopted in many x-ray imaging systems:
  - Dental panoramic
  - For special high resolution images

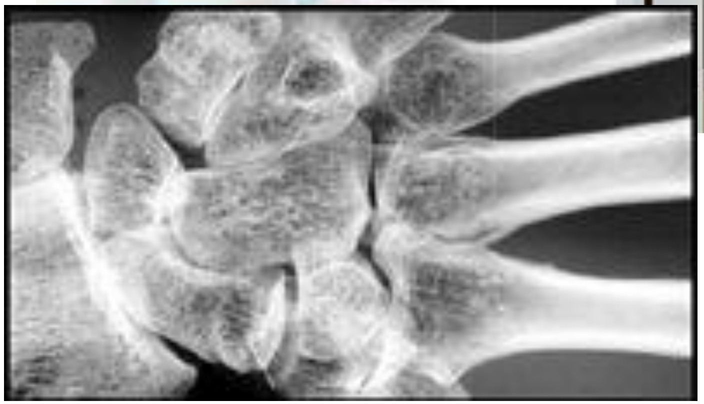
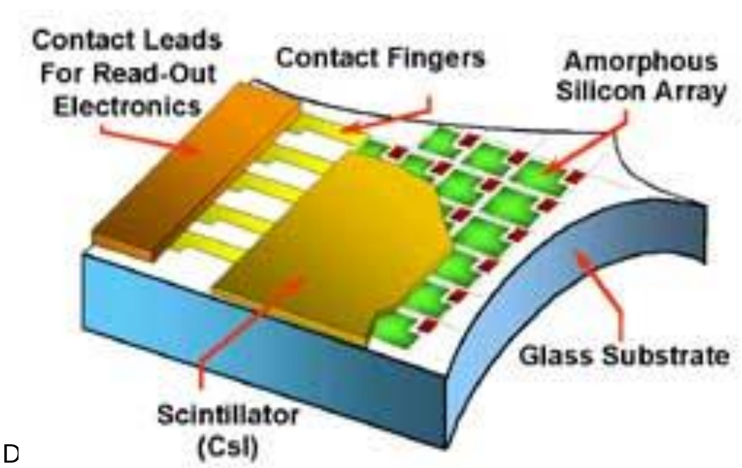
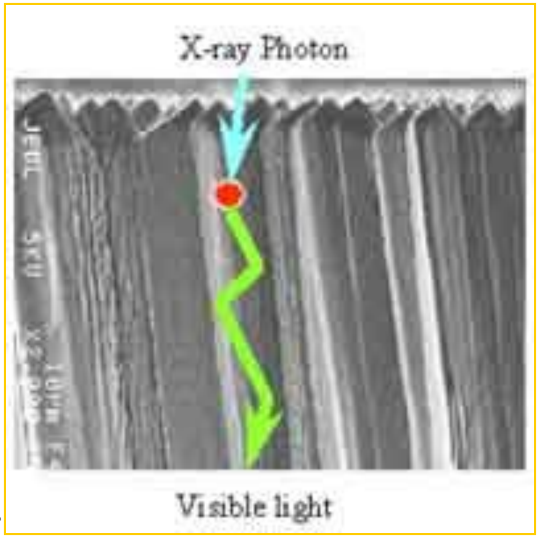


Image of a hand phantom obtained using 175 micron thick microcolumnar CsI:Tl coupled to a 5 x 9 cm^2 area CCD developed at RMD. The X-ray settings were 40 kVp, 8 mAs

Direct Radiography (DR)

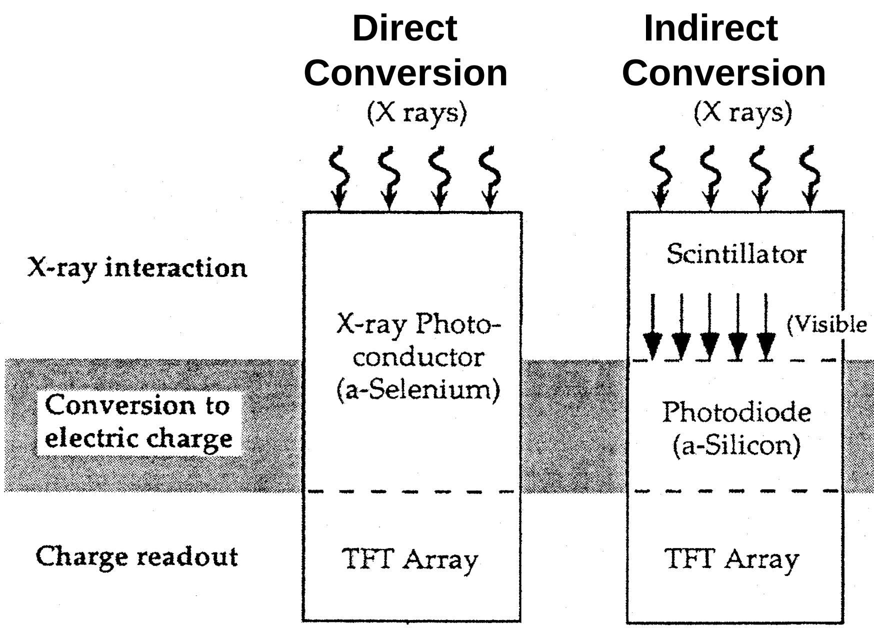
- DR (indirect conversion technology) started using the knowledge and the technology on phosphors gained for CR
- The most important scintillator for DR is the CsI(Tl) that can be produced in needle-structure (1-10 μm) for a better geometric resolution





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

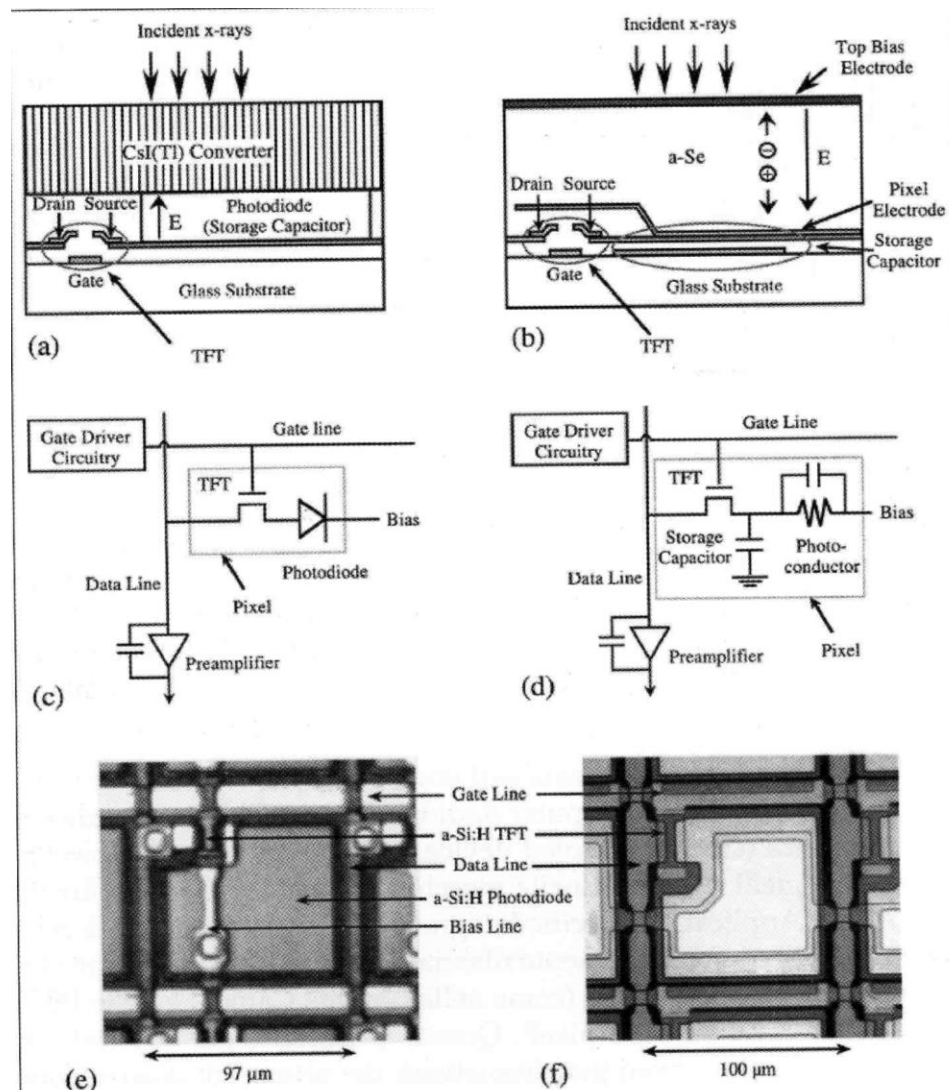


- Two type of x-ray detectors are today mainly used:
  - Selenium (photoconductor)
  - CsI(Tl) (scintillator)

AMFDI imaging detectors

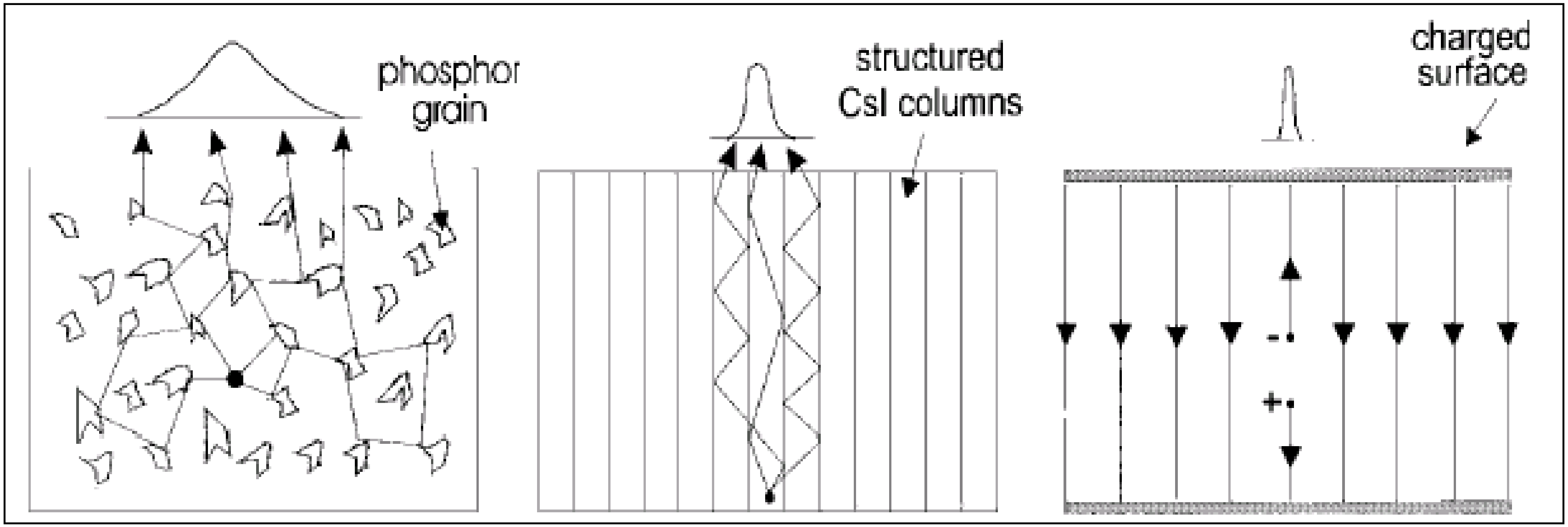
- Indirect conversion:
  - Light produced by the interaction of x-ray in the scintillator are converted to charge by the a-Si
- Direct conversion:
  - Electrons produced by the interaction of x-ray in Se are collected in the storage capacitor of each pixel

- Charge amplification and line collection are the same in the 2 technologies

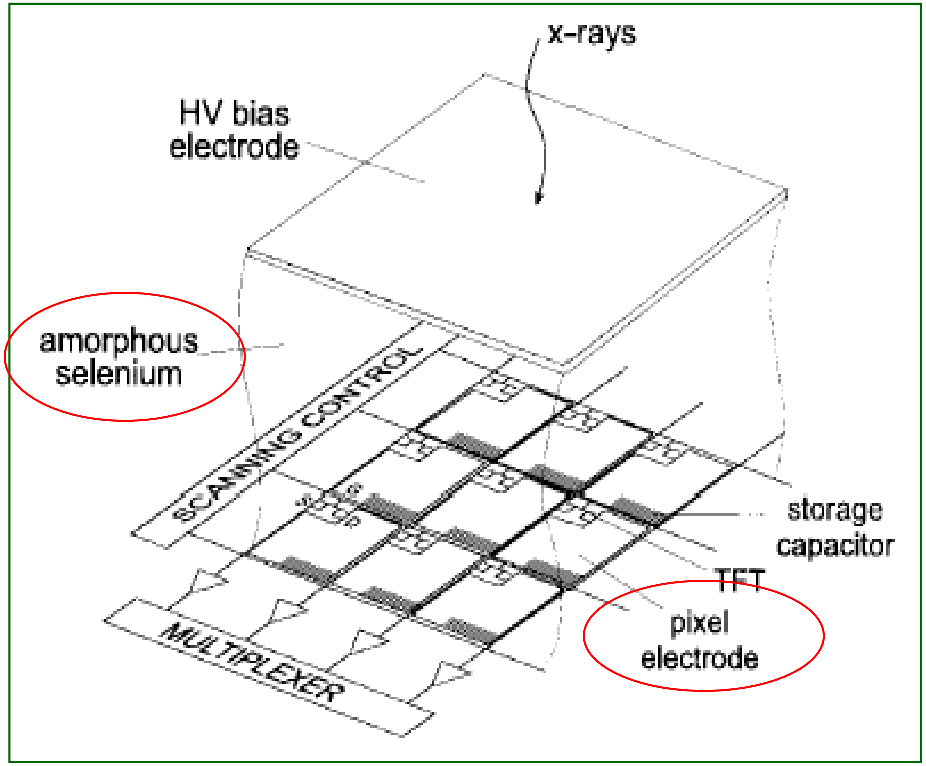


AMFDI imaging detectors

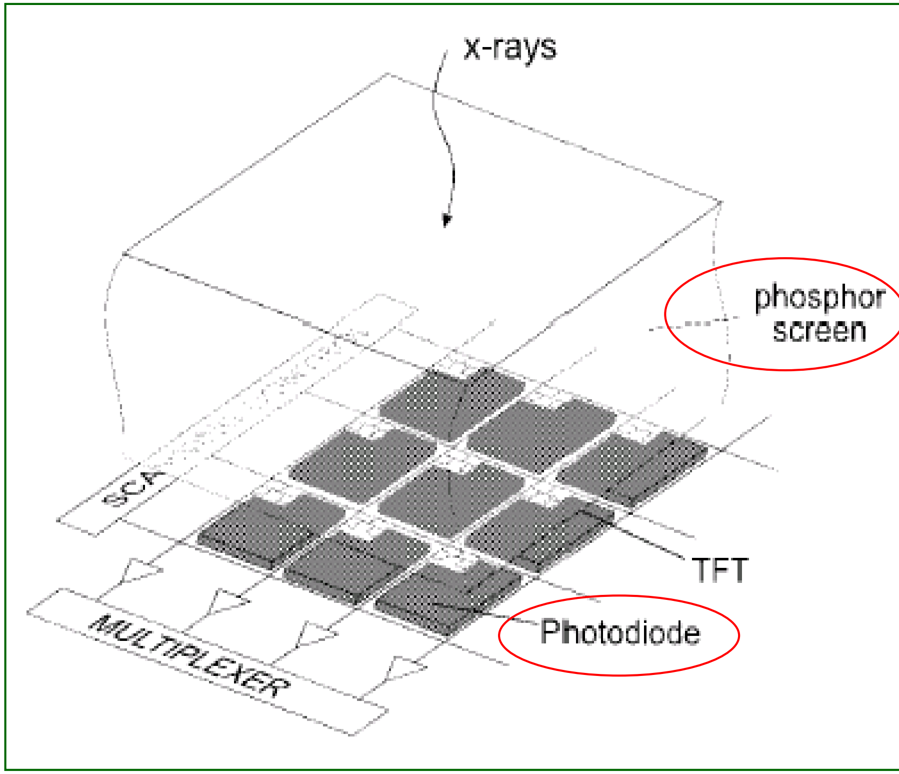
Resolution properties



Flat panel technology: assembly

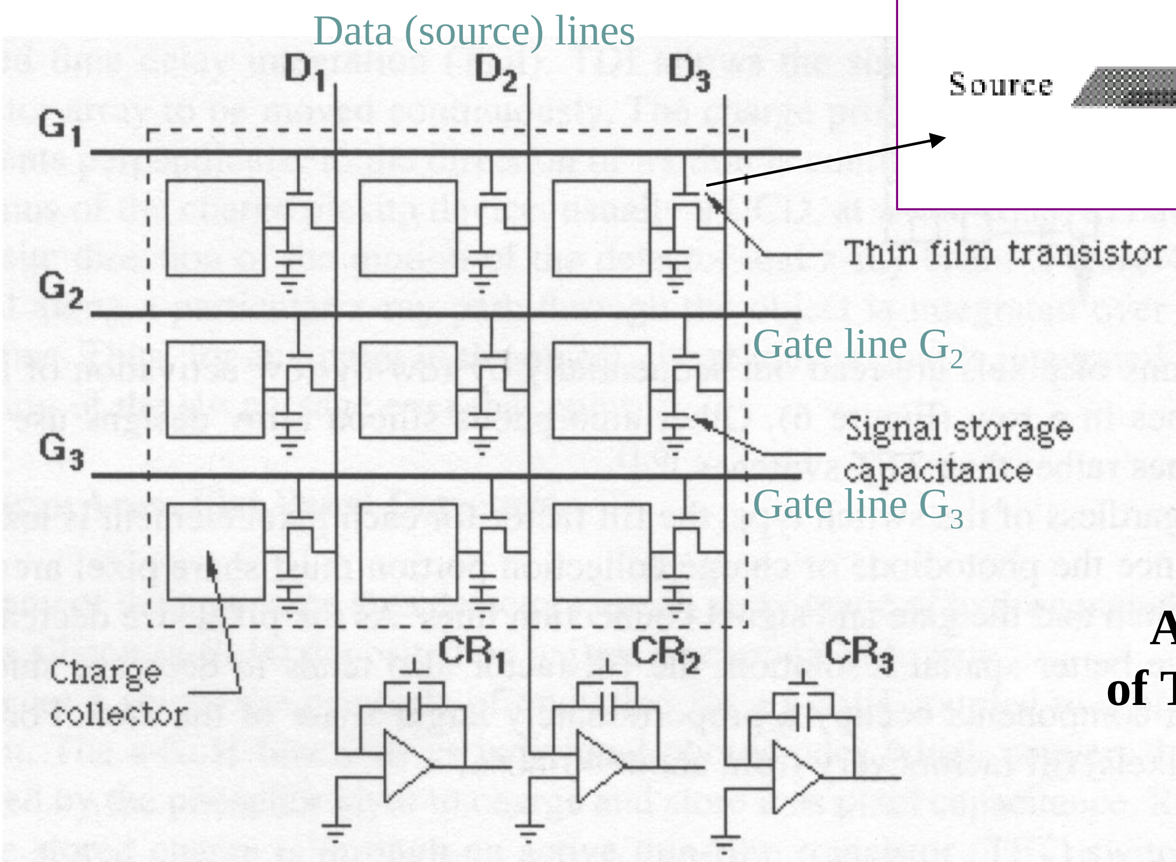


(a) Direct conversion



(b) Indirect conversion

TFT layer



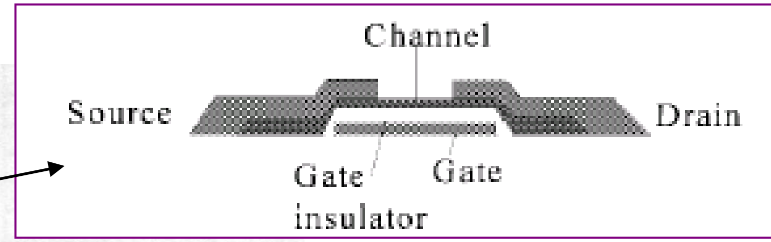


Figure 6. Readout electronics for a TFT active matrix array (by permission from L.S. Jeromin).[12]

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

IMAGE DETECTOR PERFORMANCES

X-ray detector performances

	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			

Signal to Noise Ratio: CR vs. DR

- 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

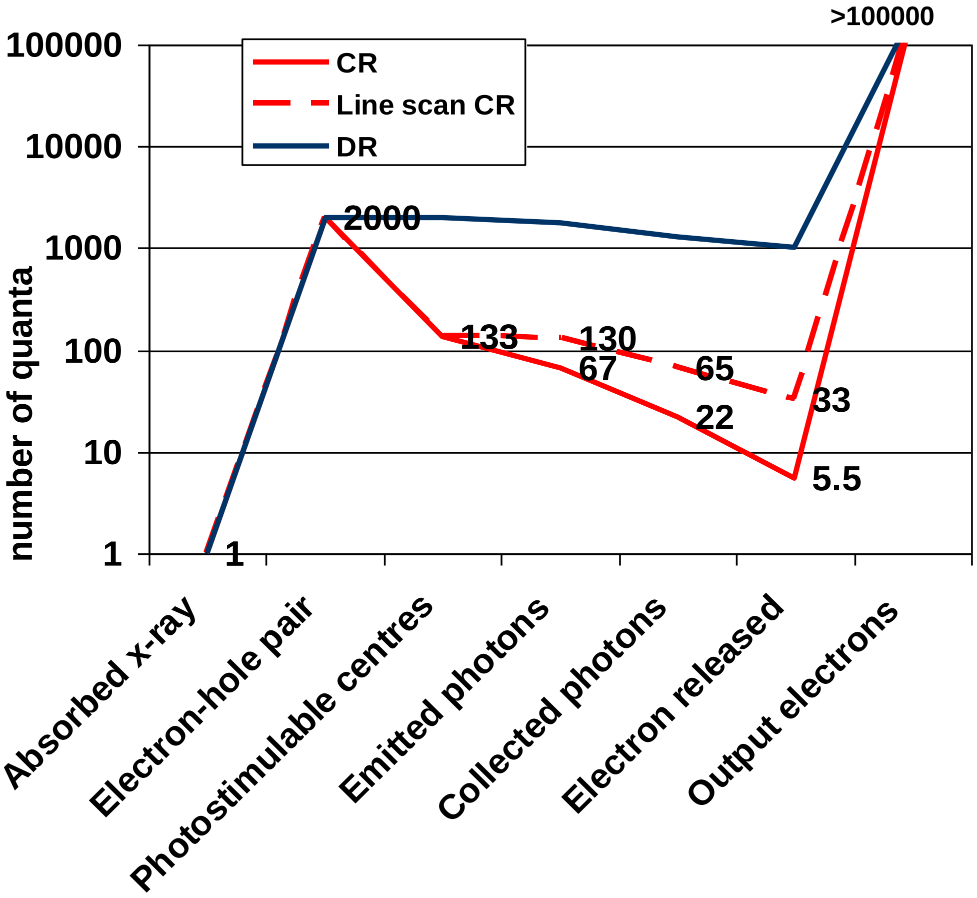


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Image detector performances

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

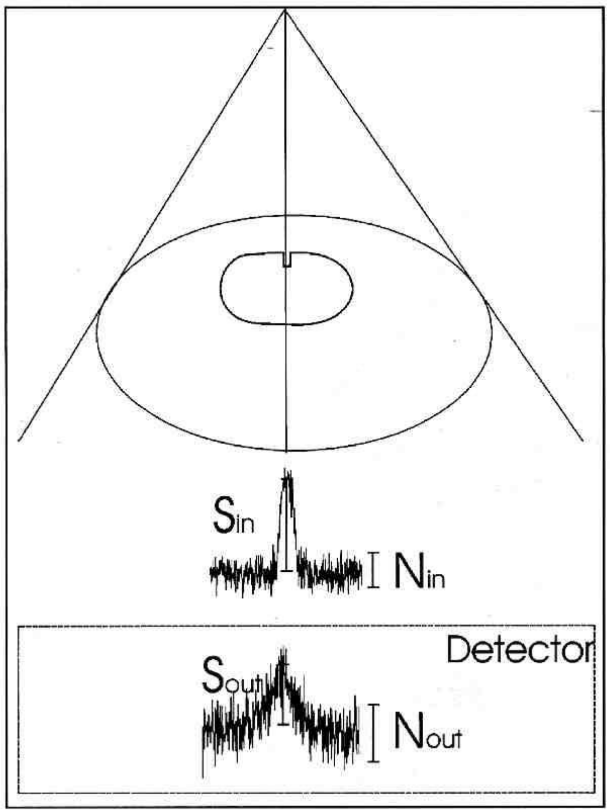
  this quantity is related to the detective quantum efficiency (DQE).

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

→ DQE is the most important <u>object-independent</u> 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:

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

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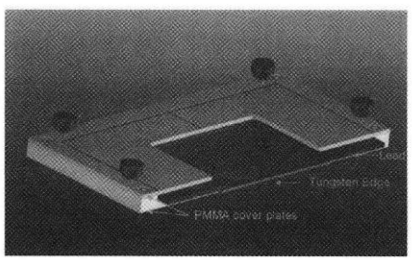
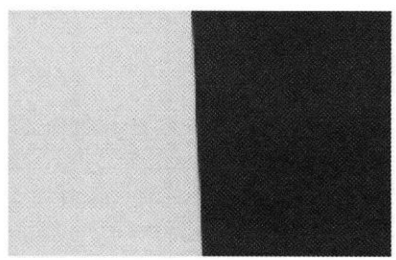
Modulation Transfer Function

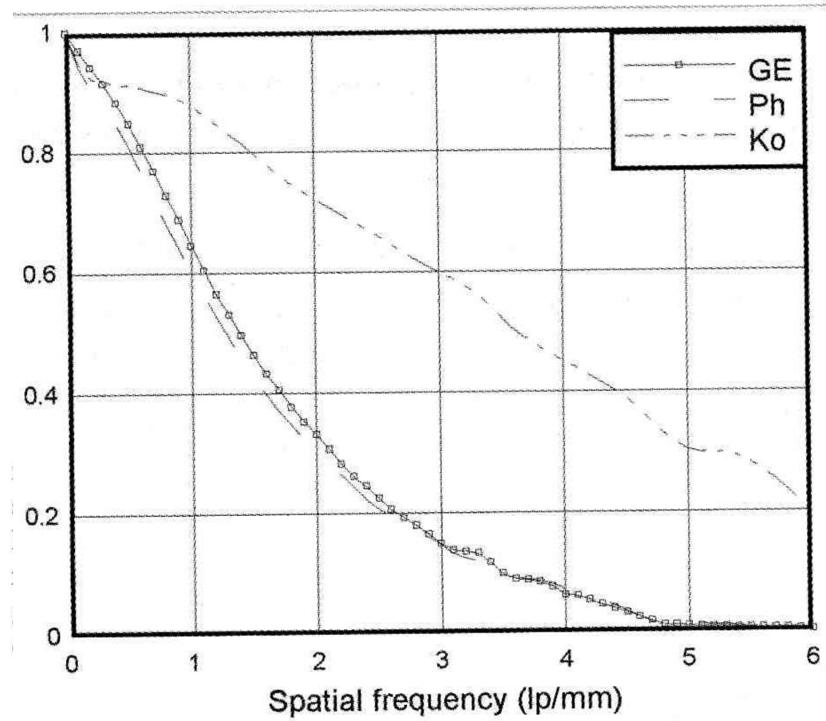
Evaluation methodology

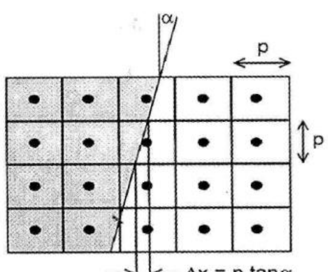
Comparison of MTF of 3 flat panel detectors

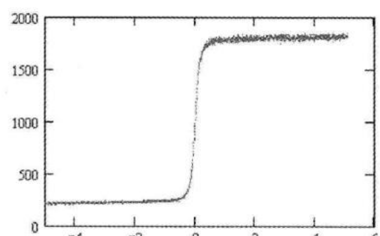
- Direct conversion FP exibits highest MFT at high spatial frequencies

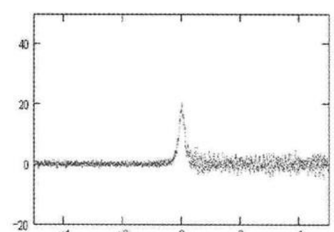












G. Borasi et. Al; On site evaluation of three flat panel detectors for digital radiography; Med.Phys. 30 (7), July 2003

Modulation Transfer Function

- MTF comparison of CR and DR systems

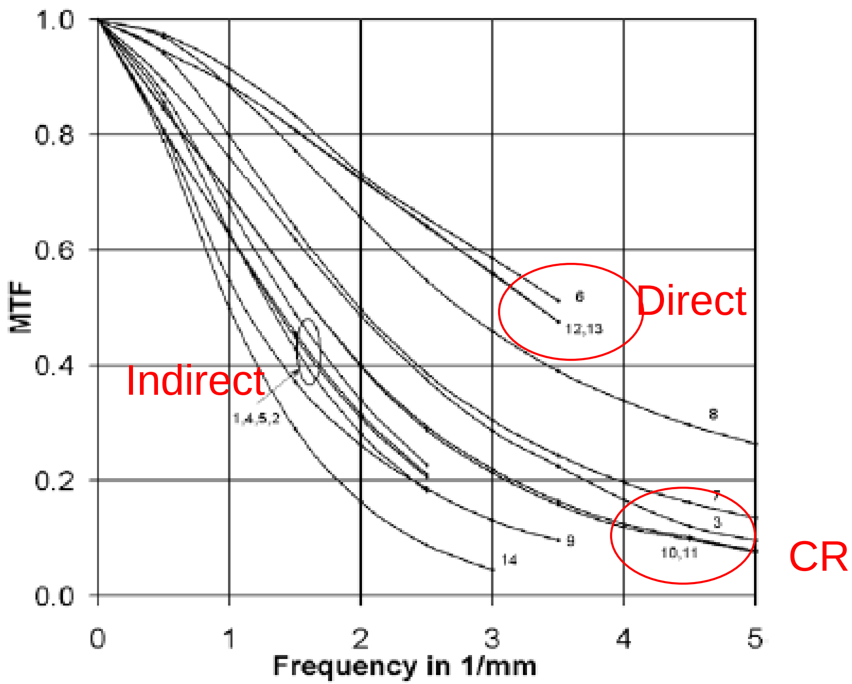


Figure 1. Mean MTF for the 14 edge images averaged over all individual MTF results using the different algorithms.

Table 1. Characteristics of detectors, x-ray beam qualities, edge signal mean within the image. Image nos 1 and 2 represent two s

Image no	Detector			
	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

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

Noise Power Spectrum

- NPS:
  - NPS is function of entrance air kerma to the detector
  - Important differences between detectors:
    - 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 entrance dose)

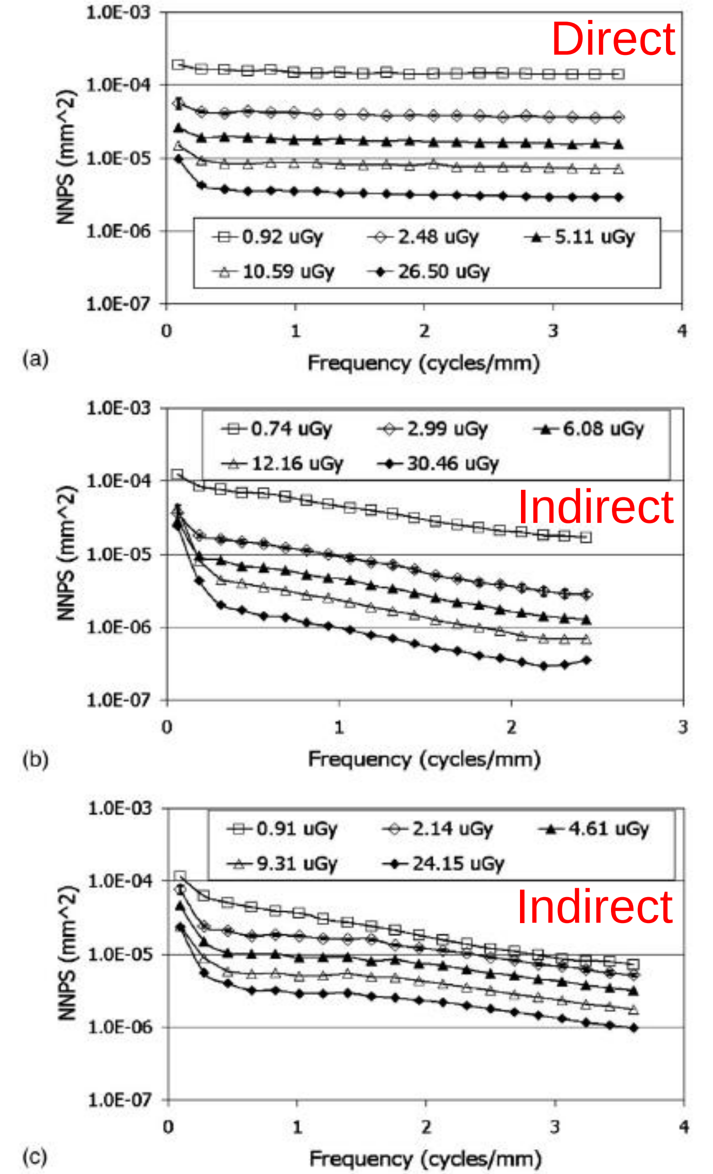


FIG. 10. Normalized noise power spectrum at 70 kV + 0.5 mm Cu: (a) system A; (b) system B; (c) system C.

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

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

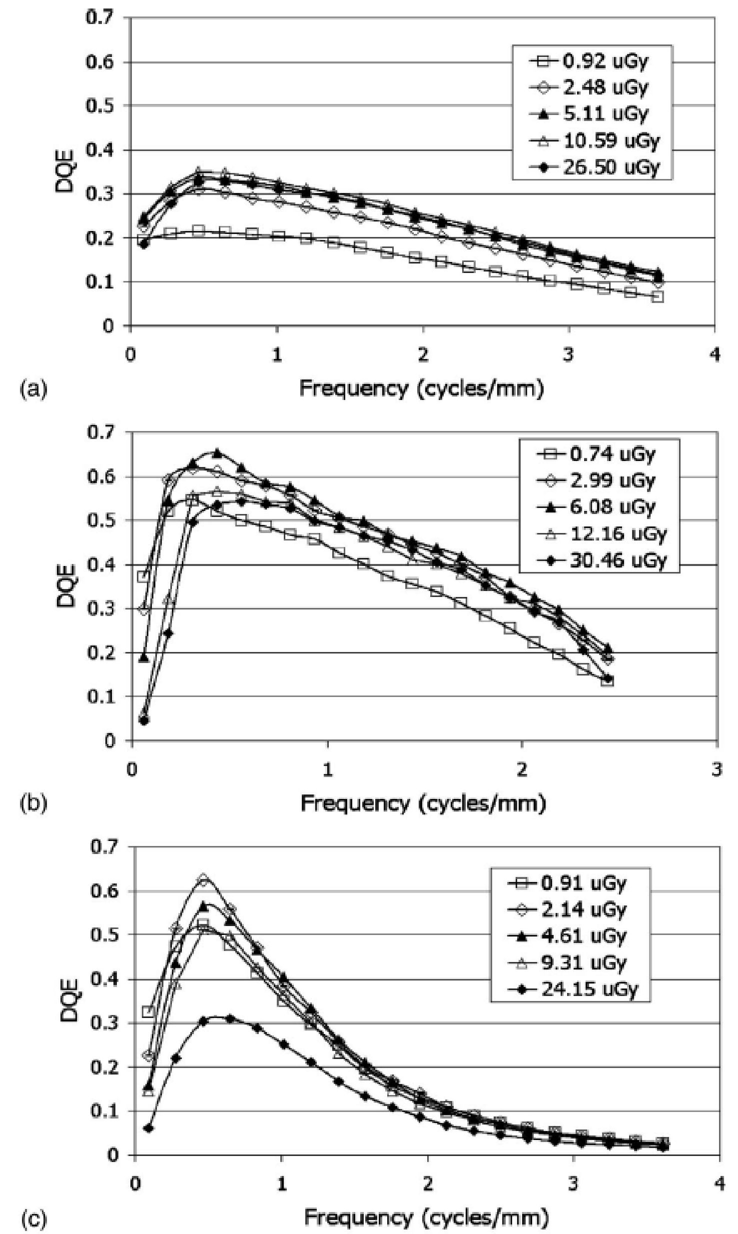
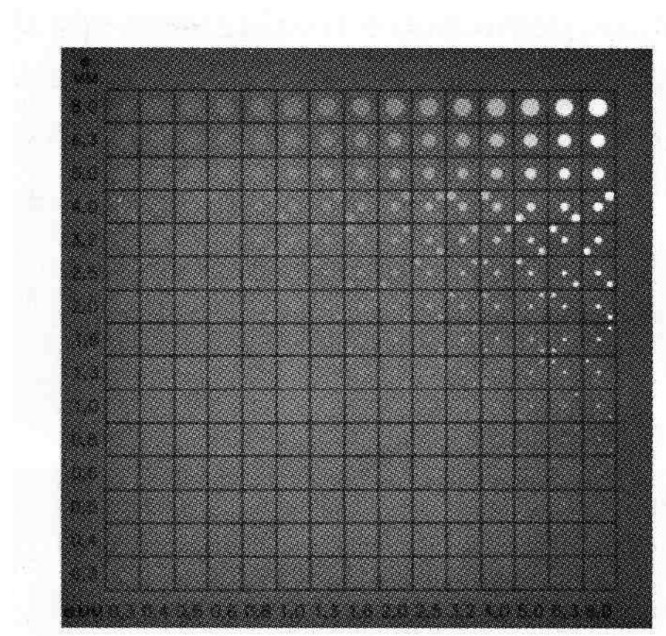


FIG. 12. Detective quantum efficiency at 70 kV + 0.5 mm Cu (a) system A; (b) system B; (c) system C.

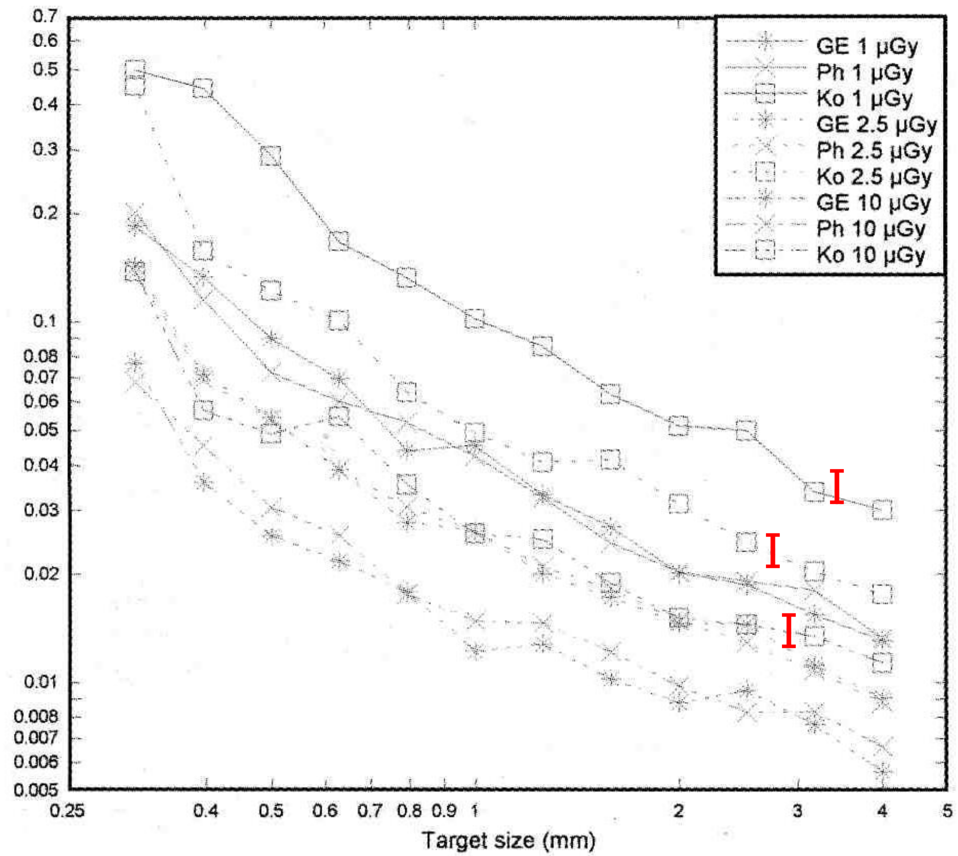
Imaging performance

- Contrast-detail analysis
  - Several phantoms are available for this test (TO16, CDRAD, ..)
  - Operator judges the contrast for which the disk perceptibility is vanishing
  - Digital images can be automatically evaluated by a software routine



Imaging performance

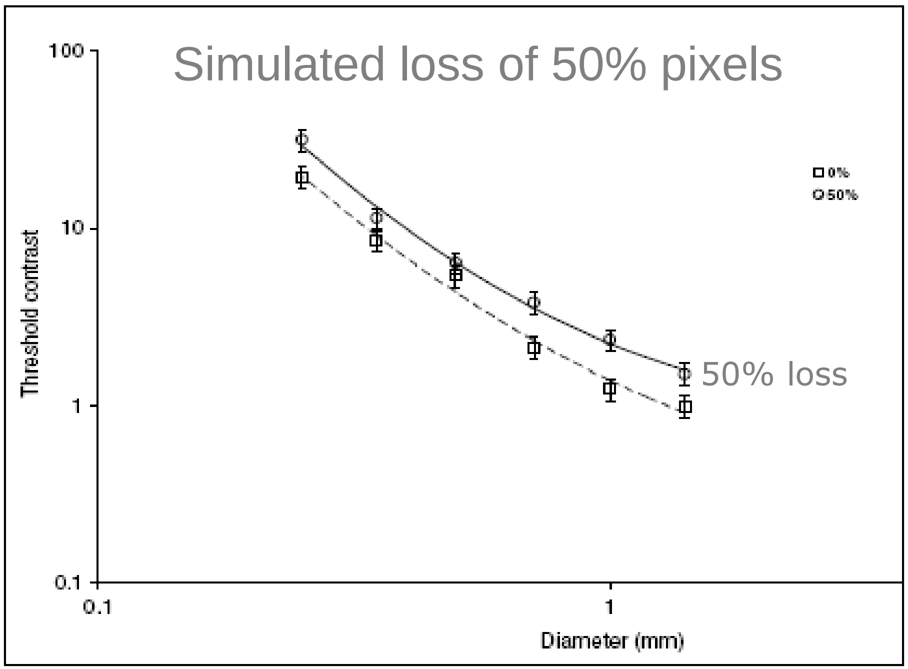
- Contrast-detail analysis
  - This test has provided the same evaluation of the 3 DR systems:
    - DR with lowest DQE has lower contrast-detail performance
  - Good relationship between DQE and CD

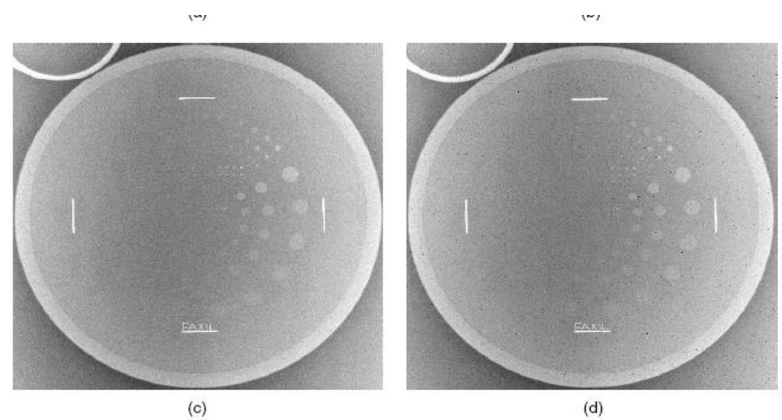


G. Borasi et. Al; On site evaluation of three flat panel detectors for digital radiography; Med.Phys. 30 (7), July 2003

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





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

Dynamic flat panels

Dynamic Flat Panel technology

- From 20x20 cm^2 for cardiac application up to 40x40 cm^2 for peripheral angiography
- Fluoroscopy/angiography equipment:
  - Less mechanically complex, compared to II
  - More compact → new design of angiography units
- No geometric distortion, good uniformity and constant resolution across its area
- Advanced applications:
  - rotational angiography
  - 3D reconstructions (cone beam CT)

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 the **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

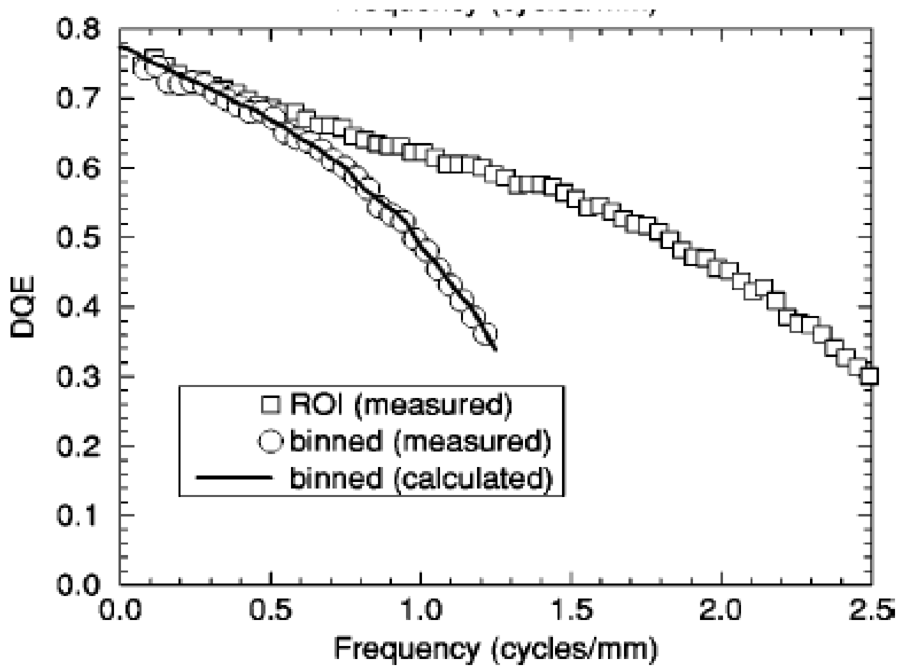
Dynamic Flat Panel technology

- Acquisition modality can be more complex than conventional radiographic systems

- Example of acquiring modalities of a large area dynamic detector. It can be read out:
  1. at **full resolution and full field of view** (**FR-FFOV mode**) to produce 2048x2048 pixel images.
     - In this mode, similar to that of radiographic detectors, can acquire images up to 5-10 frames per second.
  2. in the region-of-interest or **ROI mode**, the central 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

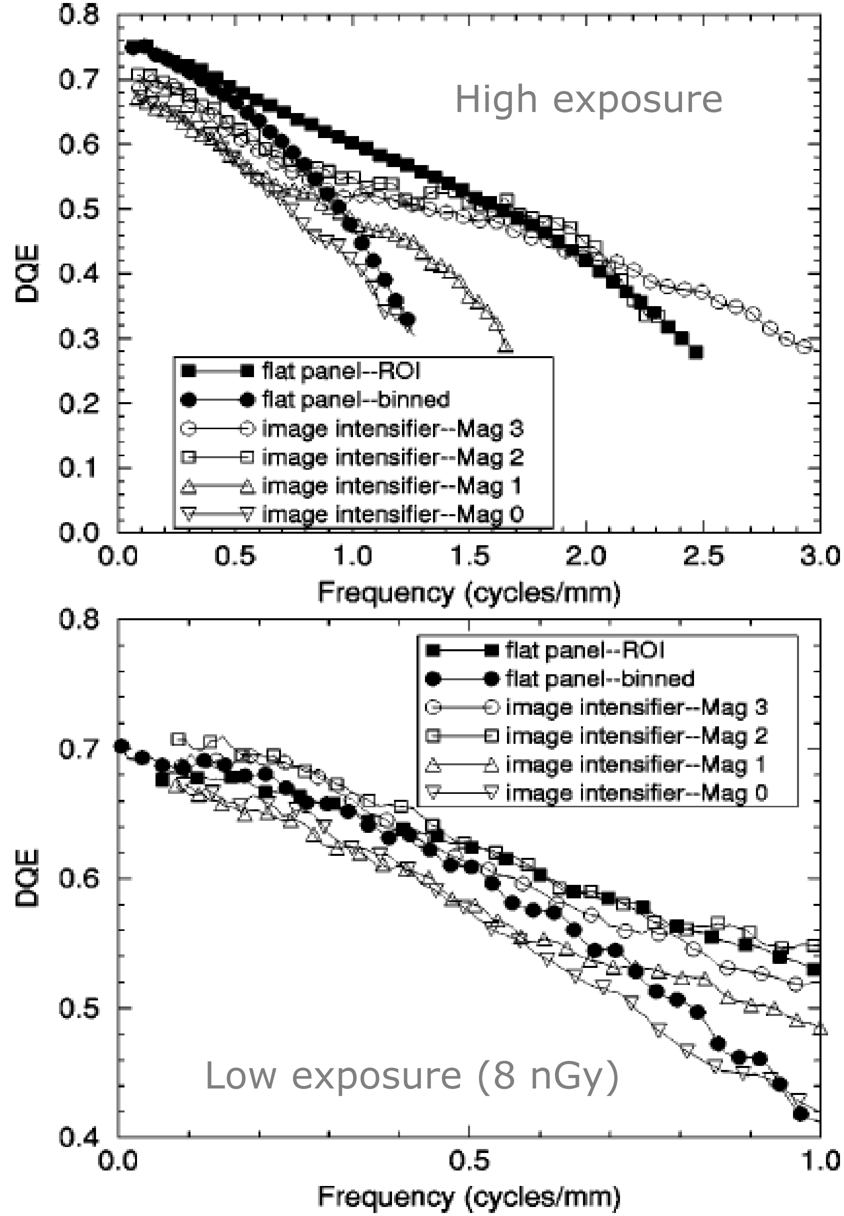
- Different acquisition modes give different imaging performances: DQE for ROI and binned modes



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

FP
vs. Image Intensifie

- At high doserates, typical of angiography acquisition FP has higher DQE than II
- At low doserates, typical of fluoroscopy mode, II and FP show similar DQE



New technologies and applications

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 paediatric patients (400-800 speed).

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

Advanced technologies

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

CMOS, which requires a fraction of the power of CCD, and has a simple, more durable design:

- 30 μm pixel size
- 20x30 mm^2

Advanced technologies: for fluoroscopy

- The DQE(*f*) of FP compares favourably 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:
  - For direct FP:
    - photoconductors of higher Z and x-ray/charge conversion gain
    - lead iodide (PbI_2) and mercuric iodide (HgI_2) have 7 times higher conversion gain 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 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: 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

Patient doses with digital detectors

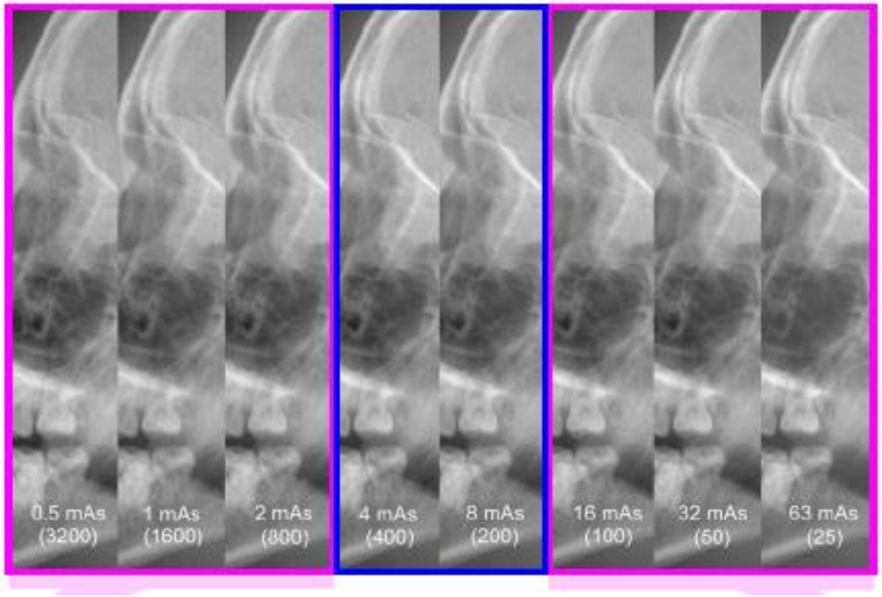
Advantages of digital radiology

- Digital imaging has practical technical advantages compared with film techniques:
  - wide contrast dynamic range,
  - post-processing functionality,
  - multiple image viewing options,
  - electronic transfer,
  - electronic archiving possibilities.

Comparison of conventional film-screen and digital imaging when increasing dose

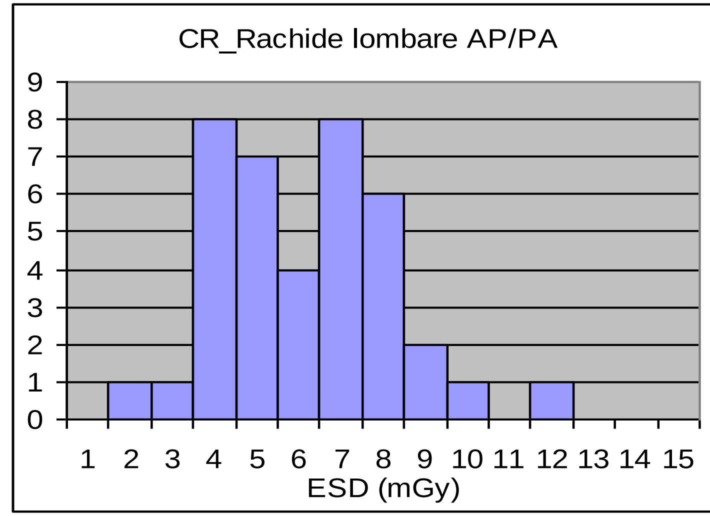
- With screen film systems, if dose is too high, the film is too black and radiographers realize that they are using excessive dose.

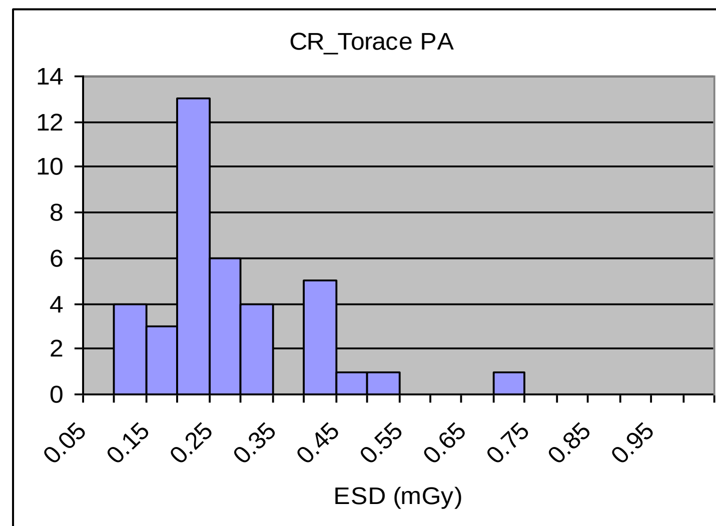
- With digital radiology, the dynamic range of the imaging detector is wider and higher doses can be used without any detrimental effect on the image.



Patient doses
(survey of 2003 in Italy)

- Large differences between hospitals with CR

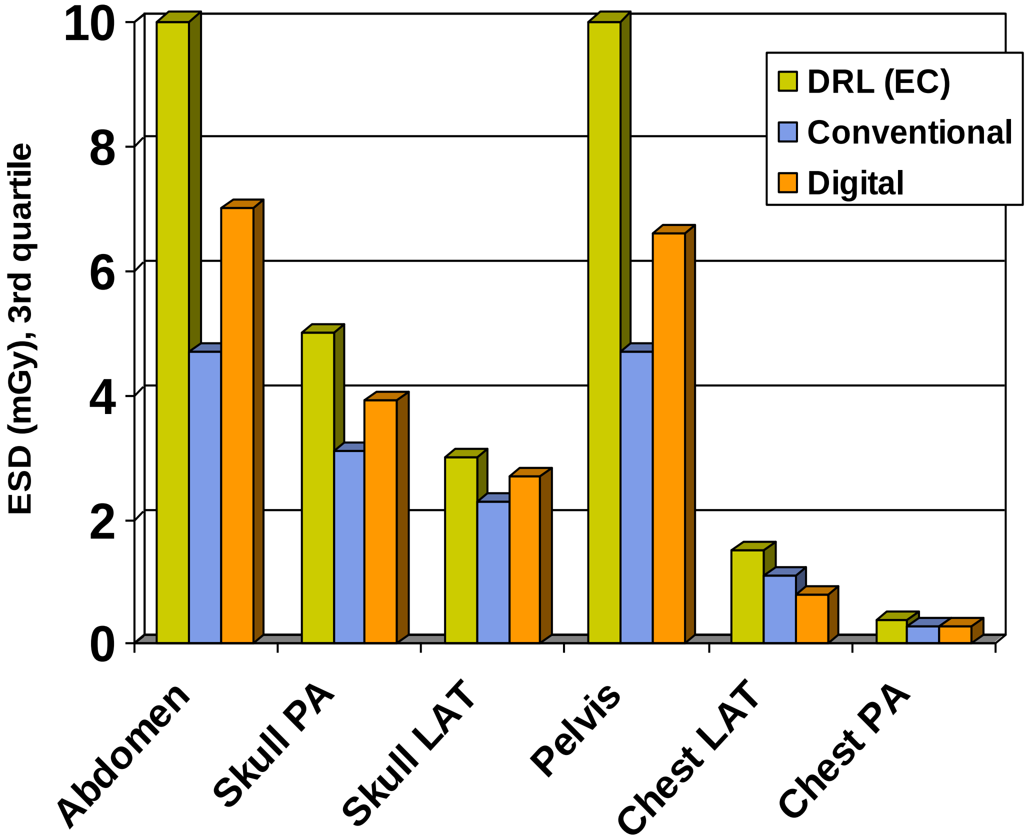




Patient dose comparison
(survey of 2003 in Italy)

Introduction of digital technology do not automatically brings to lower doses

Italian survey identifies <u>higher doses</u> for hospital using digital technologies compared to FSS.



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Some key points (ICRP 93)

- In digital radiology, higher patient dose per image usually means improved image quality.
- However, there is a tendency with digital systems to use higher patient doses than necessary.
- This increase should be avoided.

- <u>Different medical imaging tasks require different levels of image quality</u>.
  - Quality criteria should be established for all medical imaging tasks.
  - The objective is to avoid unnecessary patient doses; doses which have no additional benefit for the clinical purpose intended.

Different medical imaging tasks require different level of image quality (ICRP 93)

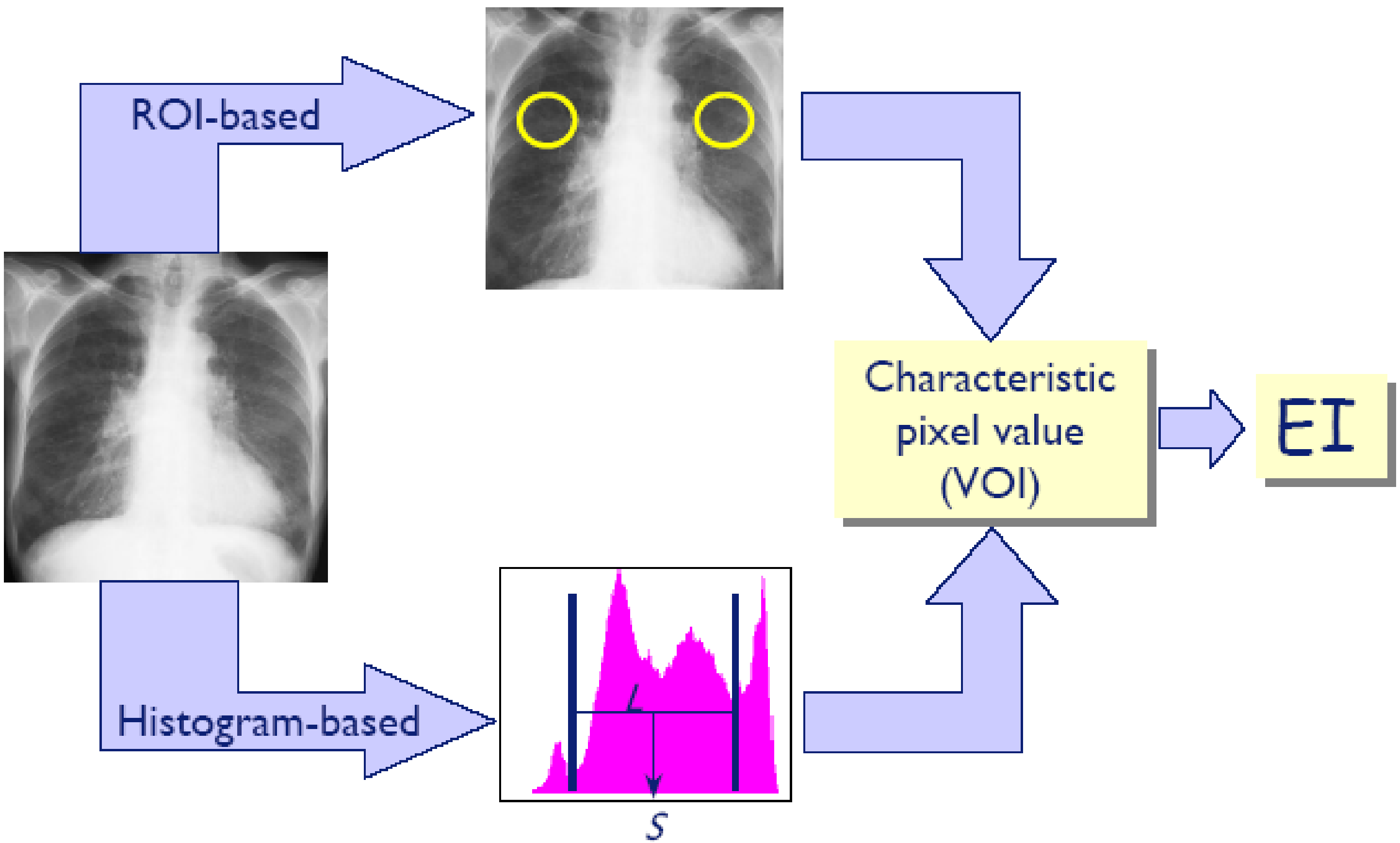
- A <u>three-level classification of image quality</u> (i.e. high, medium, and low) has been developed in the European DIMOND project for image quality and patient dose management in digital radiology.
- Relative dose values equivalent to speed classes:
  - 400 → high quality
  - 800 → medium
  - 1600 → low quality

  are assigned to levels of image quality for the specific imaging method

Dose information in digital systems

- The exposure index EI (or dose level) is usually used in relation to the absorbed dose to the imaging plate.
- EI reflects the dose to the imaging plate.
- After reading the image, the signal histogram is computed, and the dose level or exposure index is determined from the pixel values.
- It prevents systematic errors like overexposure or underexposure.

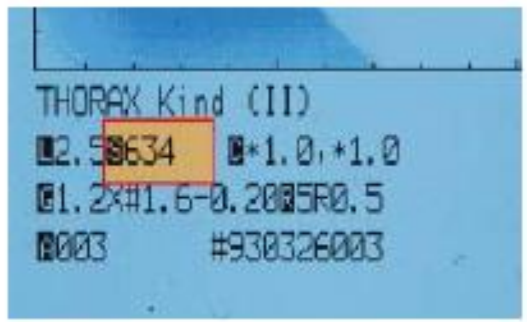
Determination of Exposure Index



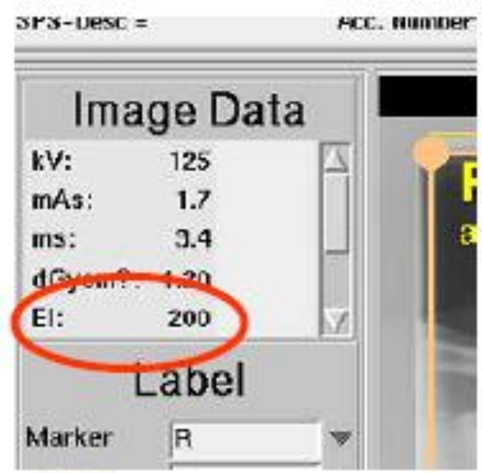
Exposure Index today

…. like European currencies before the EURO

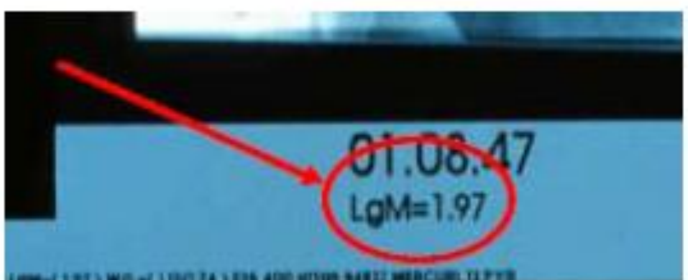
Kodak



Fuji



Philips



Agfa

???

Exposure Index today

	Name	Symbol	Range (typ.)	Value @2.5 μGy
Agfa (CR)	Logarithmic median	LgM	1.6 – 2.2	Depends on selected speed
Canon (DR)	Reached Exposure	REX	?	Depends on processing
Fuji (CR)	Sensitivity	S	200 – 800	200
Kodak (CR)	Exposure Index	EI	1300 – 1800	1500
Philips (DR)	Exposure Index	EI	200 – 800	400
Siemens (DR)	Exposure Index	EXI	200 – 800	380(?)

Exposure Index today

	linear			logarithmic		
	EI (Philips)	S (Fuji)	EXI (Siemens)	EI (Kodak)	lgM (Agfa) SC= 200	lgM (Agfa) SC= 400
1.25 µGy	800	1600	190	1100	1.3	1.6
2.5 µGy	400	800	380	1400	1.6	1.9
5 µGy	200	400	760	1700	1.9	2.2
10 µGy	100	200	1520	2000	2.2	2.5

Standardised EI (AAPM & IEC WIP)

- Shall reflect detector exposure
- Derived from pixel value (VOI)
- Lin scale proportional to detector signal / dose
- Still open:
  - radiation quality for calibration
  - scale
    - AAPM: directly in µGy
    - DIN: proportional, but not directly µGy
  - scale resolution / precision

EI stored in DICOM header

Tag	Attribute Name	Description
~~0018,1152~~	~~Exposure~~	~~Tube current-time product in mAs~~
~~0018,115E~~	~~Image Area Dose Product~~	~~Kerma area product in dGy · cm²~~
~~0018,1404~~	~~Exposures on plate~~	~~Number of exposures on plate~~
0018,1405	Relative X-ray Exposure	Relative exposure on plate
0018,6000	Sensitivity	Detector sensitivity
~~0040,0302~~	~~Entrance Dose~~	~~Entrance dose on the patient [dGy]~~

DICOM HEADER

(contains a lot of useful information to audit patient dose and goodness of the procedure)

(Courtesy of E. Vano)

Relevant DICOM tags GE Chest flat panel
(0008,0020) : Study Date : 27/01/03
(0008,0030) : Study Time : 10:31:12
(0008,0033) : Image Time : 10:32:43
(0010,0020) : Patient ID : 795607
(0010,0040) : Patient's Sex : F
(0010,1010) : Patient's Age : 085Y
(0018,0015) : Body Part Examined :
(0018,0060) : KVP : 125
(0018,1150) : Exposure Time : 5
(0018,1151) : X-ray Tube Current : 250
(0018,115E) : Image Area Dose Product : 0.83557
(0018,1190) : Focal Spot(s) : 0.6
(0018,1405) : Relative X-ray Exposure : 61
(0018,7060) : Exposure Control Mode : AUTOMATIC
(0018,7062) : Exposure Control Mode Descript: AEC_left_and_right_cells
(0028,0010) : Rows : 2022
(0028,0011) : Columns : 2022
(0028,0100) : Bits Allocated : 16
(0028,0101) : Bits Stored : 14

DICOM Radiation Dose Report

- DICOM Supplement 94 (Nov 2005)
- “Diagnostic X-ray radiation dose reporting (Dose SR)“
- DICOM Structured Report object
- Provides mechanism for extensive dose reporting
- Can be independent of PACS or RIS

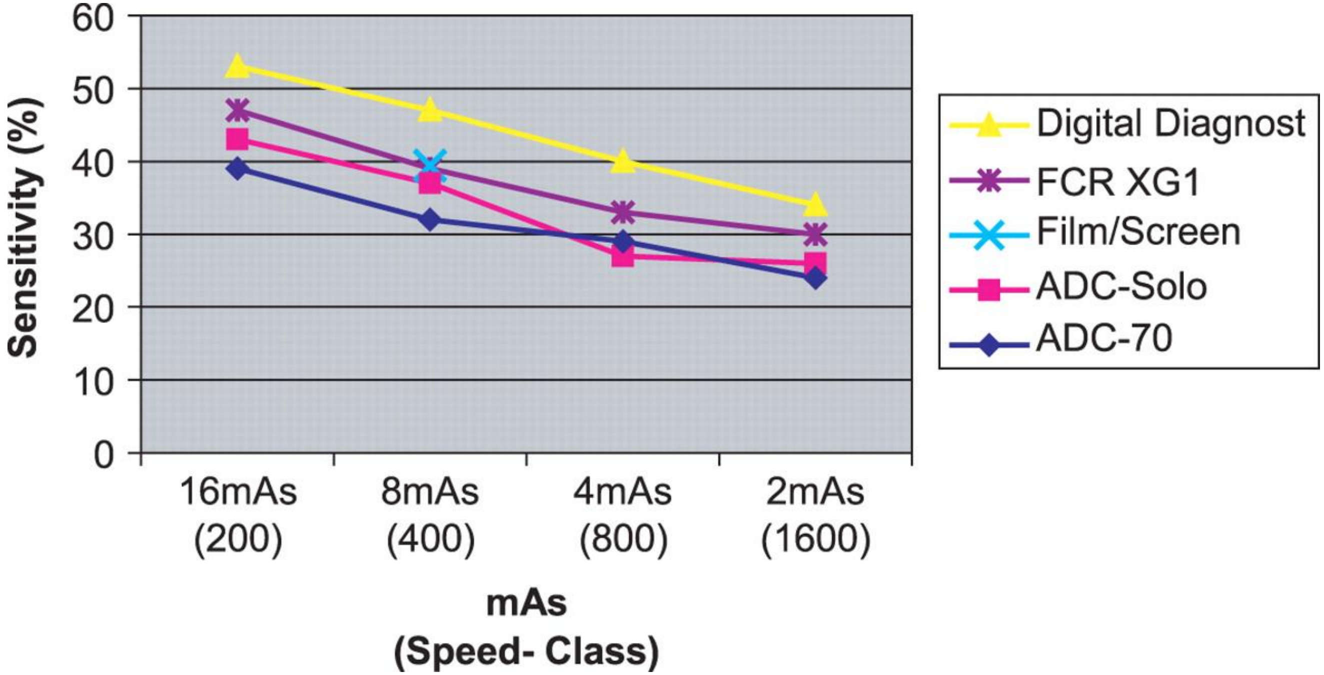
Dose monitoring

- Options:
  - Dose data are stored in DICOM header
  - Dose data are transmitted with MPPS protocol (DICOM MPPS) to PACS/RIS
  - Data are included in the “DICOM Structured report”

- Period data mining of digital archives is a new and easier methodology to monitor patient exposure.

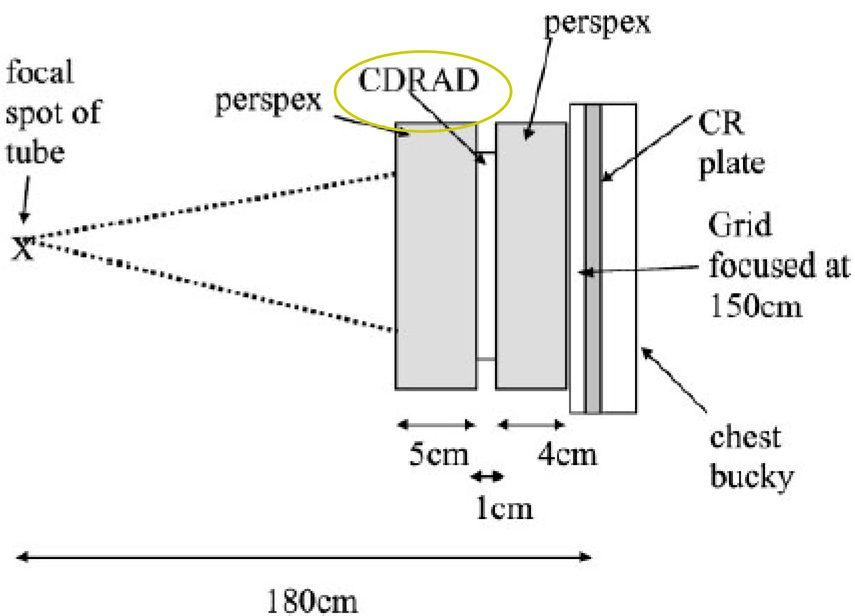
Optimisation: Image quality vs dose

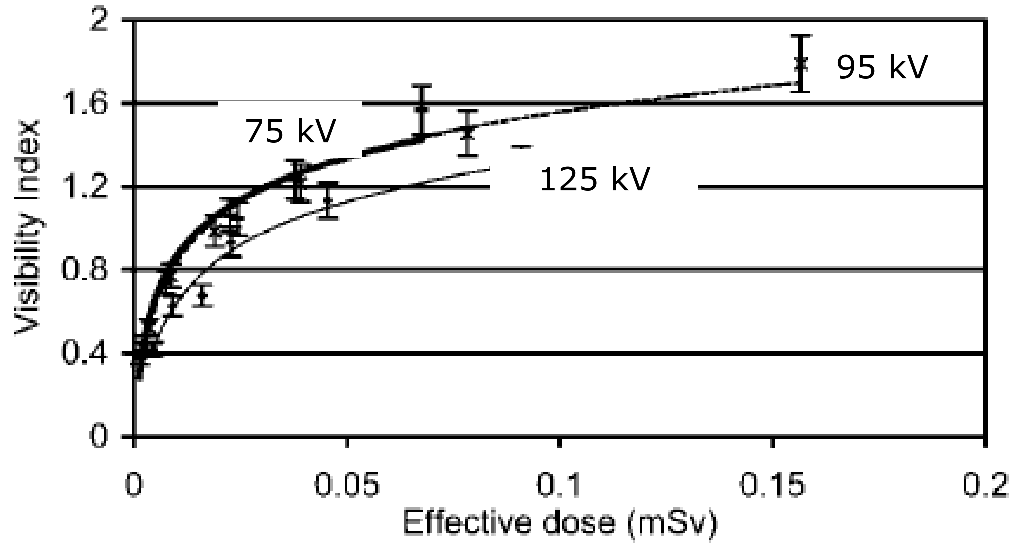
- Comparison of the sensitivity by the CDRAD phantom for different digital imaging methods and different dose values. DR: Digital Diagnostic (Philips); CR: FCR XG1 (Fuji), ADC-Solo (Agfa) and ADCV70 (Agfa).



H. P. Busch1 and K. Faulkner, Image quality and dose management in digital radiography: a new paradigm for optimisation , Radiation Protection Dosimetry Advance Access originally published online on February 3, 2006

Optimisation: Image quality vs dose





Chest radiography:

- The study indicates 75-95 kV is the optimal range to optimise image quality with CR

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I D HONEY, MSc, A MACKENZIE, MSc and D S EVANS, MSc The Investigation of optimum energies for chest imaging using film–screen and computed radiography British Journal of Radiology, 78 (2005), 422–427

Role of Diagnostic Reference Levels

- **For digital, DRL should not be higher that those defined for film-screen systems**
- **Can they be lower for DR?**

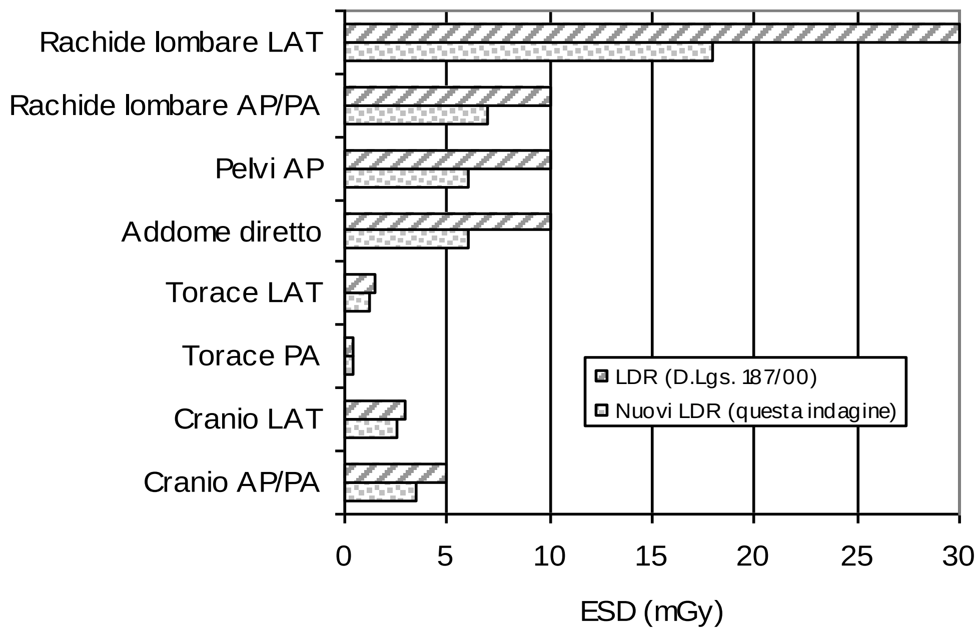
- Use of DRL to manage patient doses:
  - UK experience has shown substantial reduction of patient doses applying DRLs since 90s

DRL in UK & Italy compared to EC DRL

Recommended national reference doses for individual radiographs on adult patients (NRPB,2000)

Radiograph	*ESD per radiograph (mGy)*
Skull AP/PA	3
Skull LAT	1.5
Chest PA	0.2
Chest LAT	1.0
Thoracic spine AP	3.5
Thoracic spine LAT	10
Lumbar spine AP	6
Lumbar spine LAT	14
Lumbar spine LSJ	26
Abdomen AP	6
Pelvis AP	4

Comparison of new DRL with EC DRL (Italy, 2004)



DRL in paediatric radiology

- NRPB 2000 report

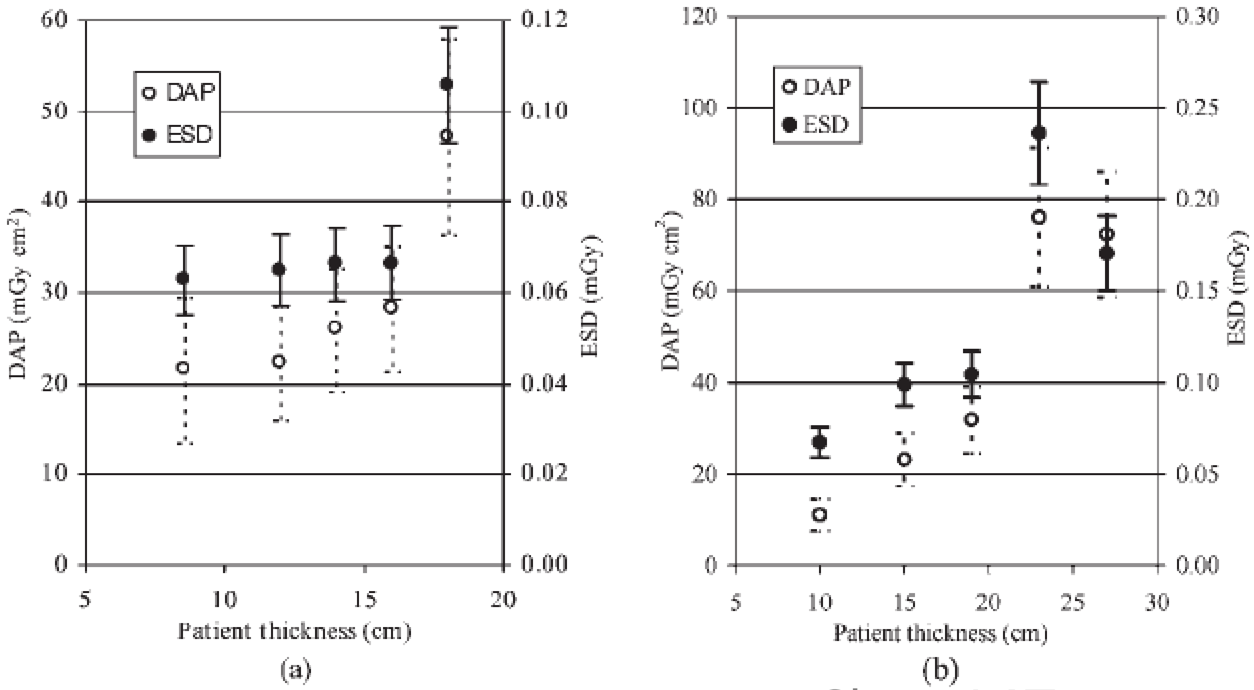
Table 2. The third quartile patient dose values of standard sized patients

Standard thickness (*s*)	Corresponding age (years)	With grid ESD (µGy)	With grid DAP (mGy cm^2)	Without grid ESD (µGy)	Without grid DAP (mGy cm^2)	All patients ESD (µGy)	All patients DAP (mGy cm^2)
Thorax AP/PA projection							
8.5	0	9	38	4	5	6	22
12	1	9	35	4	9	6	22
14	5	9	39	5	13	7	26
16	10	9	45	4	12	7	28
18	15	11	47			11	47
Thorax LAT projection							
10	0	9	17	4	6	7	11
15	1	13	32	7	15	10	23
19	5	12	39	9	25	10	32
23	10	24	76			24	76
27	15	17	72			17	72

Doses are calculated by the NRPB method for patients with and without the anti-scatter grid and, in the last column, all patients are summed together. The patient data consisted of 380 patients including new measurements in two hospitals.
DAP, dose–area product; ESD, entrance surface dose.

DRL in paediatric radiology

DRLs for chest PA & LAT have been assessed as the 3rd of the dose distributions for each size group (STUK, Finland 2006)



Chest PA

Chest LAT

Conclusions

- Patient dose management with digital technology
  - There is a need of a new set of DRLs at the European level
  - The assessment of DRLs has to be performed more frequently, because technology and practice is changing rapidly
  - Hospital must also assess local references and periodically monitor patient exposure (every 2 years?)
  - Evaluation of image quality and repetition rate should be part of a QA programme
  - Mainly for CR, it is mandatory to make proper adjustment of AEC set-up to expose the plates at selected EI
  - It should be mandatory for radiographers to use the AEC
- Finally, the introduction of digital radiography requires proper training of radiographers, radiologists and medical physicists