Computed Radiography Technology 2004

AAPM 2004 Summer School
Specifications, Performance Evaluation And QA
of Radiographic and Fluoroscopic Systems in the Digital Era
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Outline

- Digital radiography system overview
- CR system function
- Image data acquisition
- Image pre- and post-processing
- Physicist role with CR implementation
- Exposure indicators
- CR Image quality: resolution, SNR, DQE

Introduction

Computed Radiography…..

Photostimulable Storage Phosphor (PSP) detector

- two decades of clinical use
- primary modality for *digital* radiography in an electronic imaging environment
- closely emulates the screen-film paradigm

Logical step for first transitioning from screen - film

Continuing technological advances

Ten years ago……..

- Computed Radiography the only clinically relevant digital projection radiography modality
- First generation PACS just getting started, with radiology centric implementation
- DICOM and HL-7 compliance issues were nearly intractable

Now, in 2004

- Digital projection radiography has many players, from CR to CCD to flat panel systems, all with innovative updates
- Second generation PACS is rapidly moving forward to thin-client capability and leveraging the Internet for enterprise distribution
- DICOM is now experienced; *WORKFLOW* optimization from scheduling to image archive is the major issue, with Integrating the Healthcare Enterprise (IHE) a key mandate

Digital System Technologies
Projection Radiography

- Computed Radiography (CR)
- CCD cameras
- CMOS detectors
- TFT Flat Panel arrays

(CCD cameras, CMOS detectors, TFT Flat Panel arrays:) "Direct" Radiography (DR)

Computed Radiography (CR)

- Currently *the* major technology available for large field-of-view digital imaging
- Based upon the principles of photostimulated luminescence
- Operation emulates the screen-film paradigm in use and handling.. (flexible but labor intensive)
- Manufacturing trends:
  - Smaller, faster, less expensive

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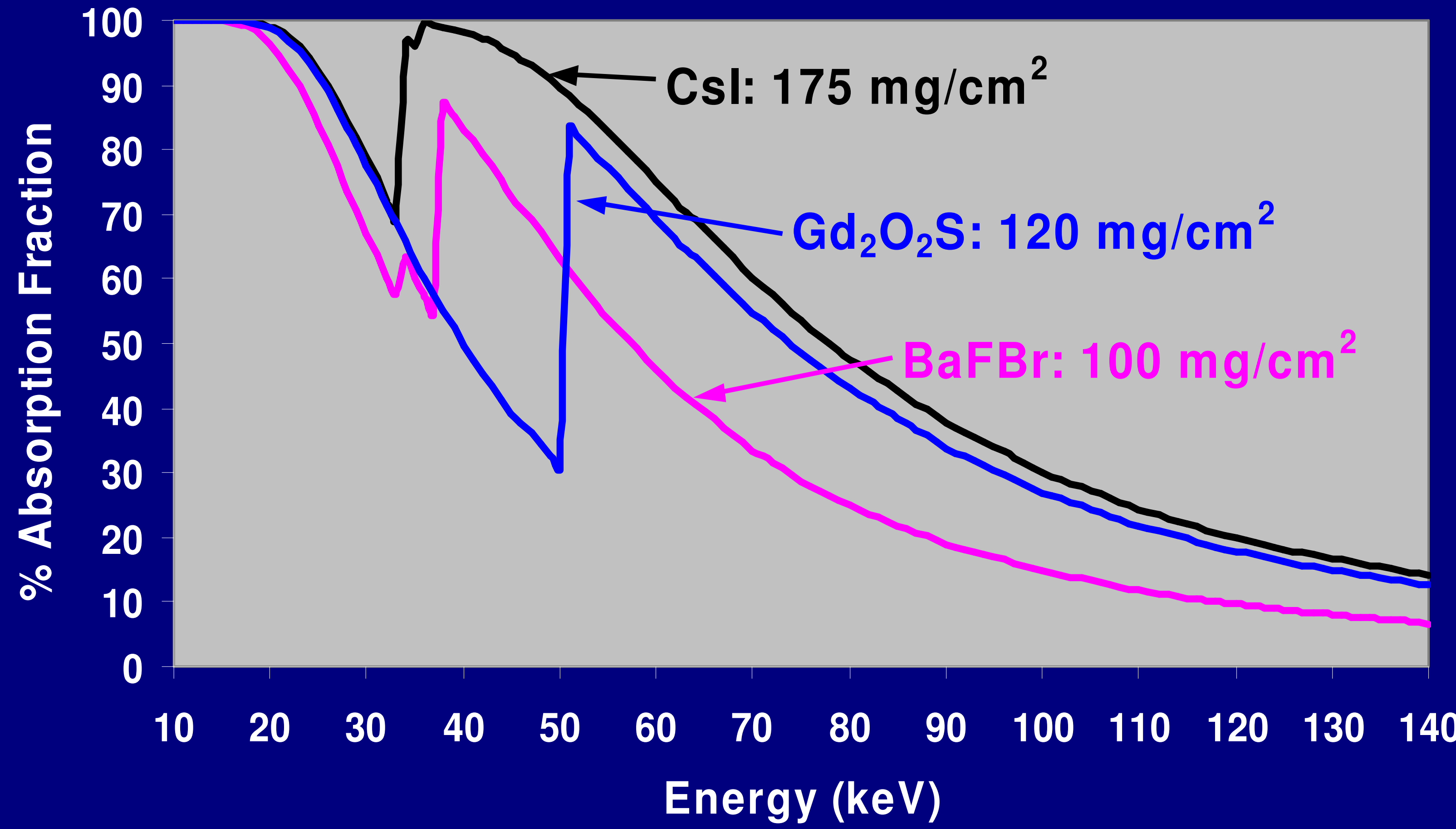
CR Detector

- Photostimulable Storage Phosphor (PSP)

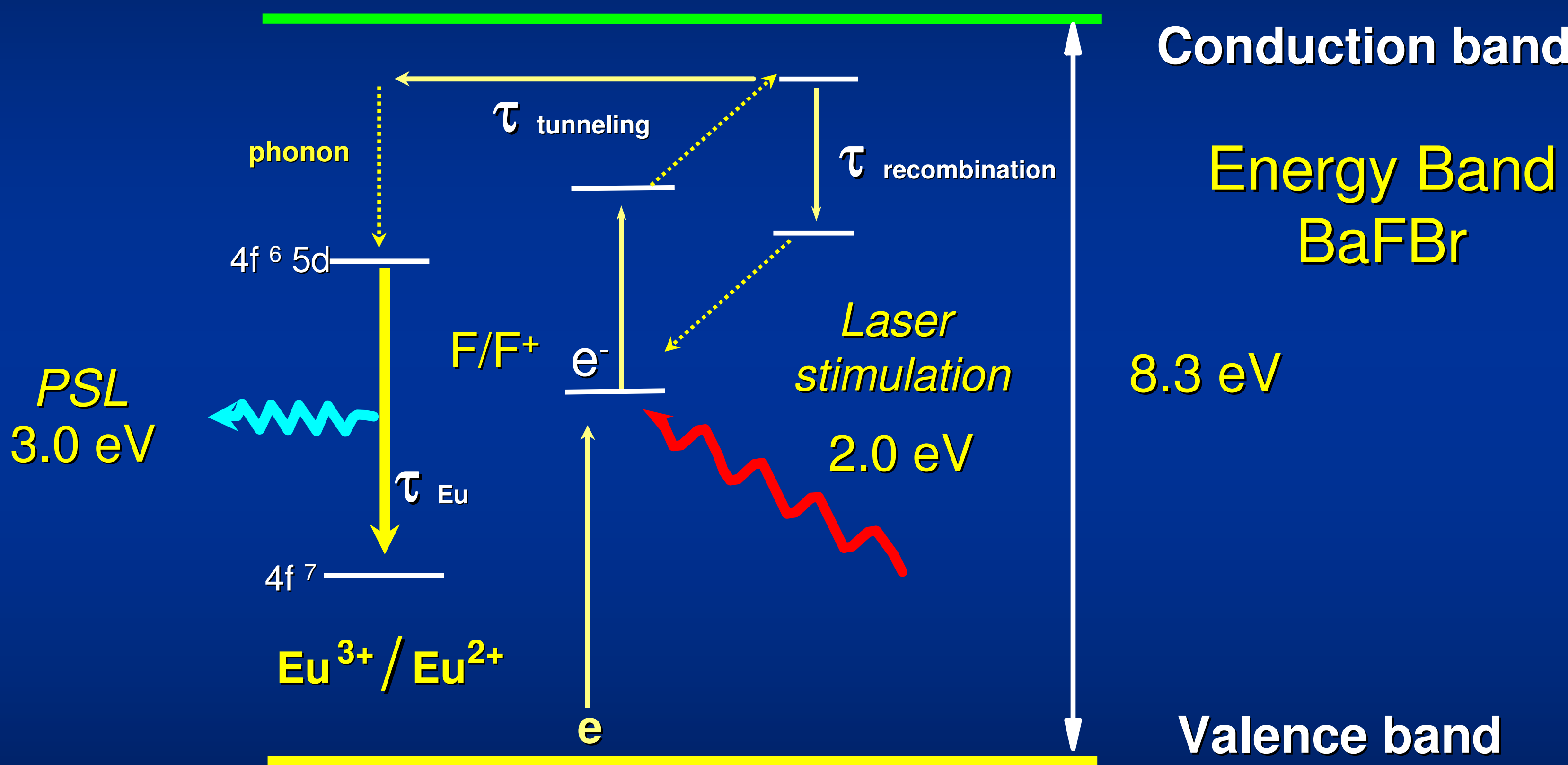
X-ray absorption Efficiency: CsI, BaFBr, Gd_2O_2S



Less absorption efficiency compared to Gd_2O_2 S and CsI;
In general, higher dose required relative to 400 speed screen film

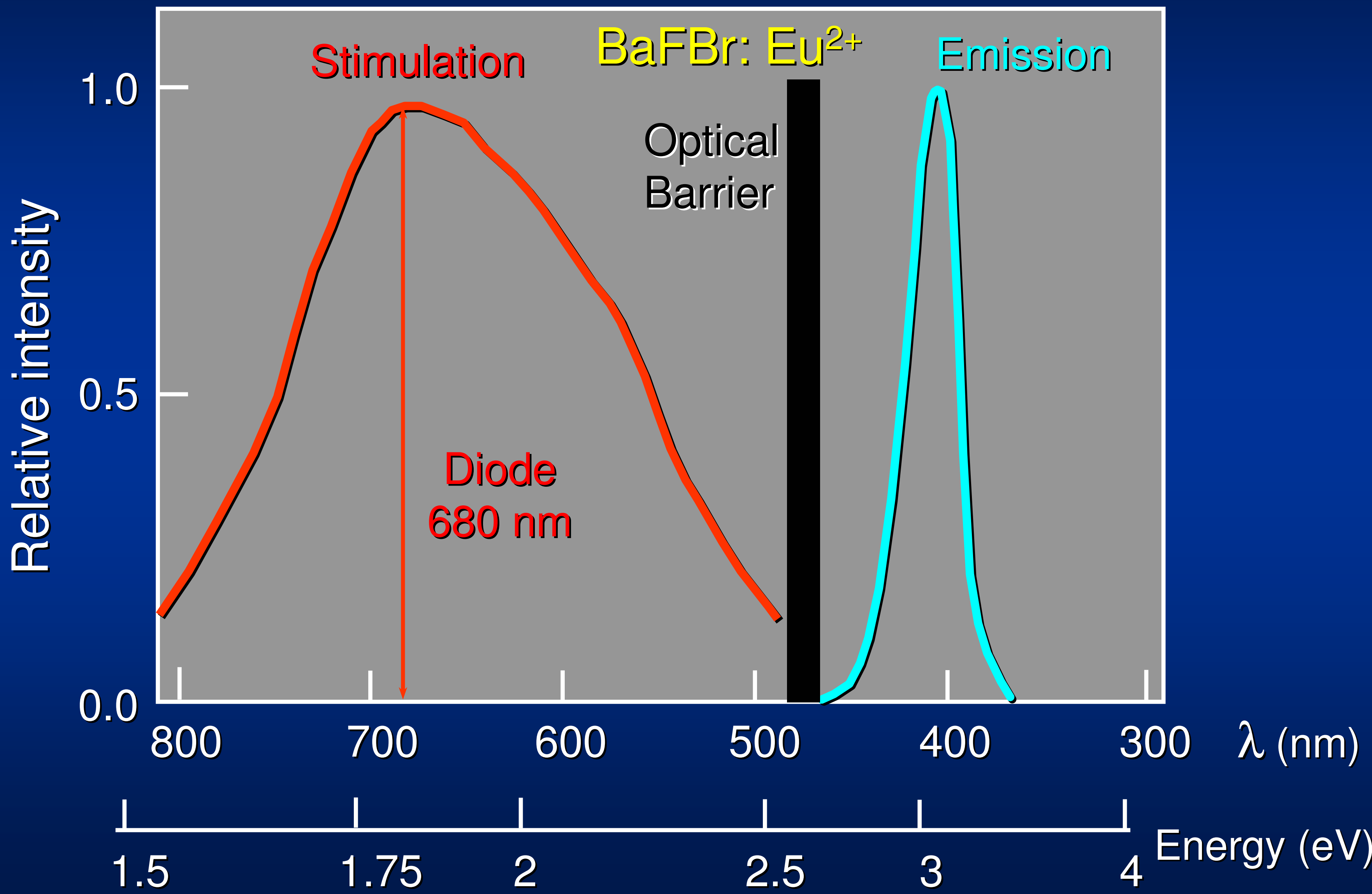
CR: How does it work?

Photostimulated Luminescence

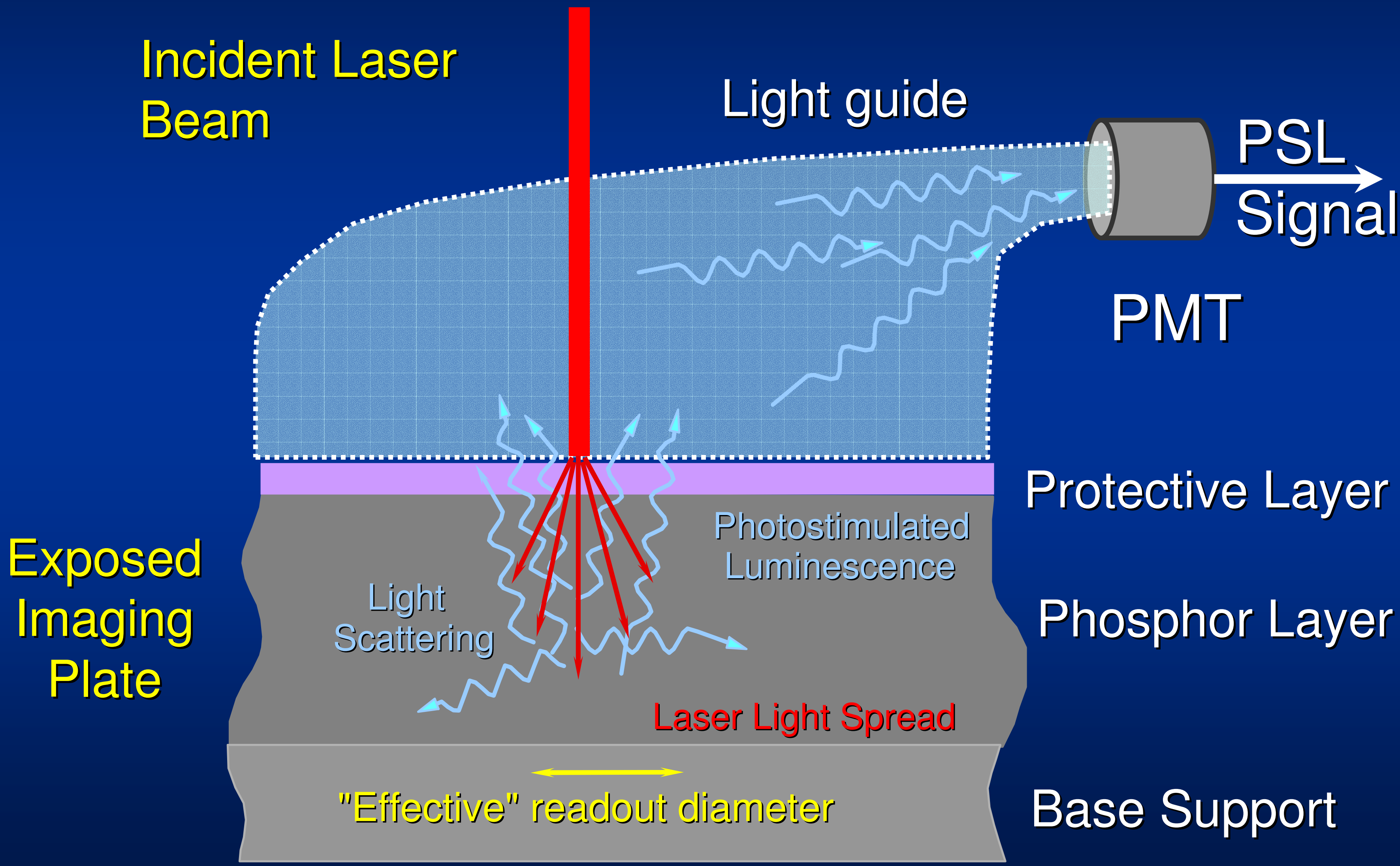


PSLC complexes (F centers) are created in numbers proportional to incident x-ray intensity

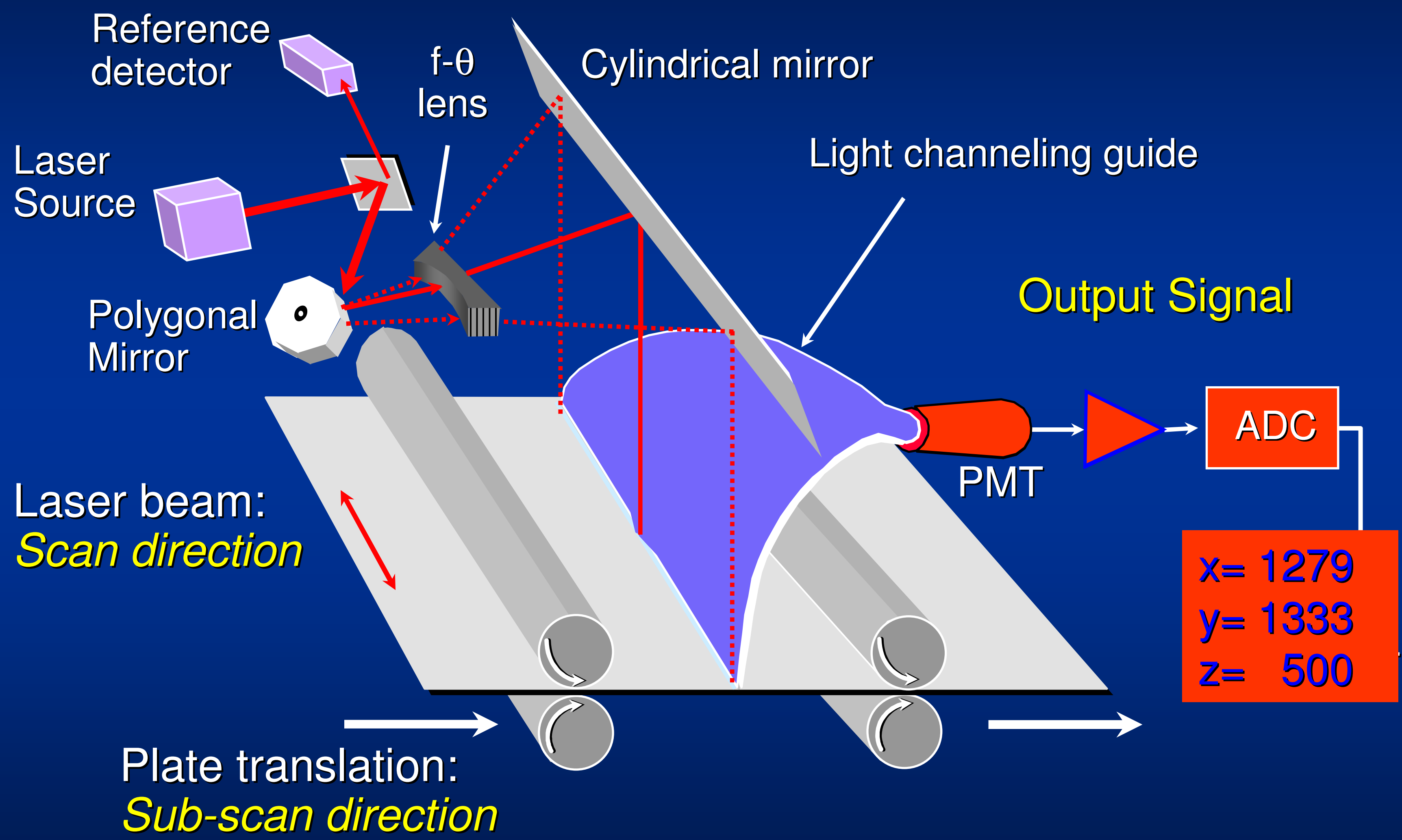
Stimulation and Emission Spectra

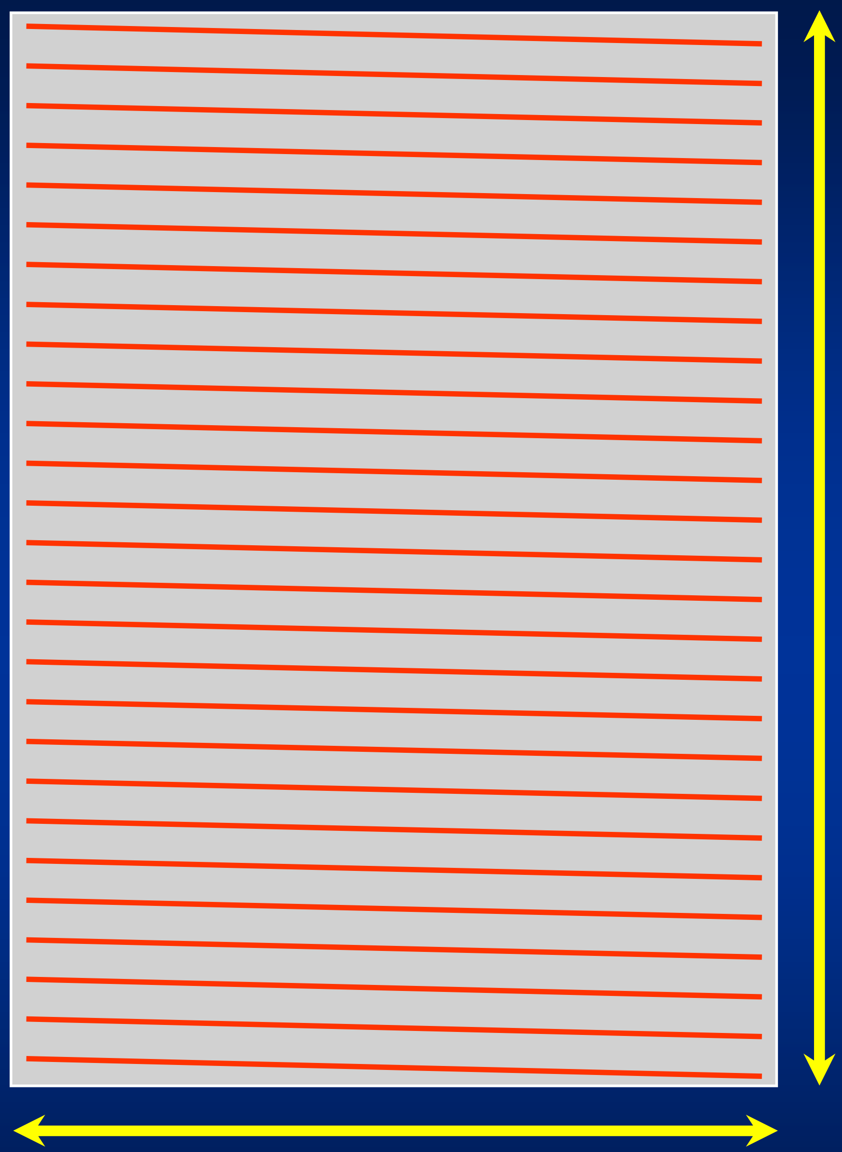


Photostimulated Luminescence



CR: Latent Image Readout





Mechanical / optical device

Sub-scan Direction

Plate translation

Typical CR resolution:

35 x 43 cm -- 2.5 lp/mm (200 µm)
24 x 30 cm -- 3.3 lp/mm (150 µm)
18 x 24 cm -- 5.0 lp/mm (100 µm)

Screen/film resolution:

7-10 lp/mm (80 µm - 25 µm)

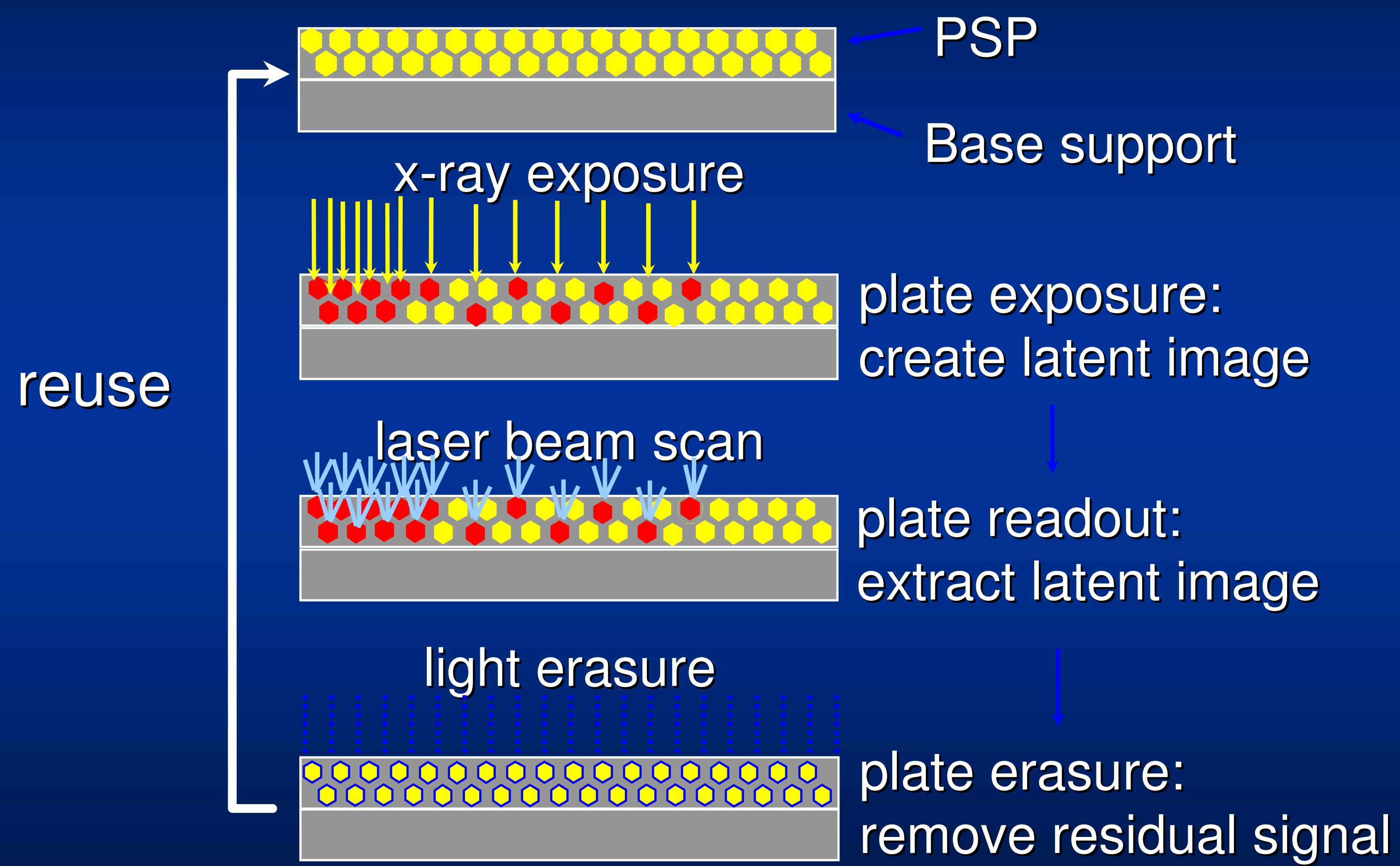
Scan Direction

Laser beam deflection

Mechanical – optical consequences

- Scan / sub-scan resolution differences
- Aspect ratio accuracy
- Distance measurement calibration

Phosphor Plate Cycle



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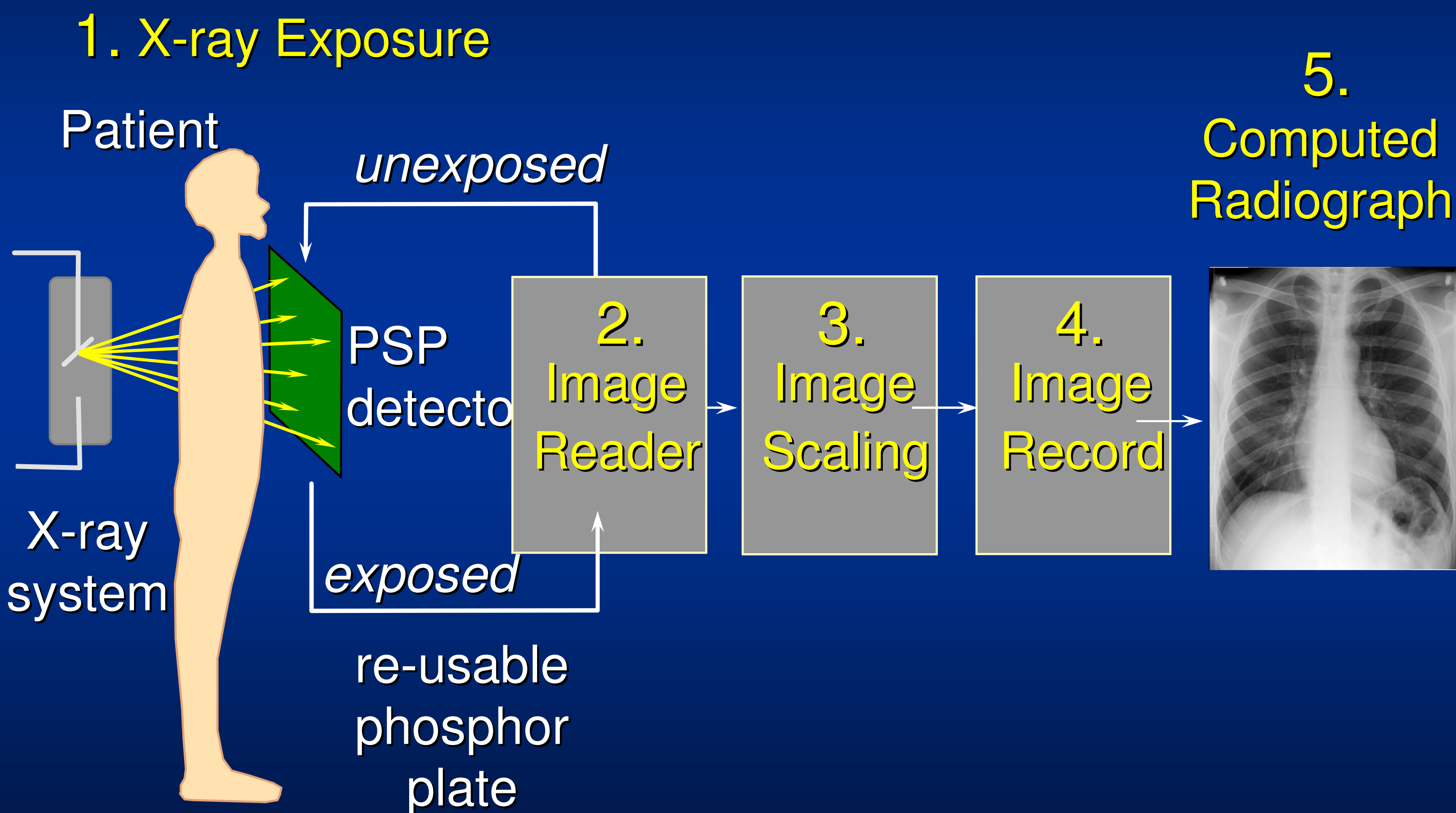
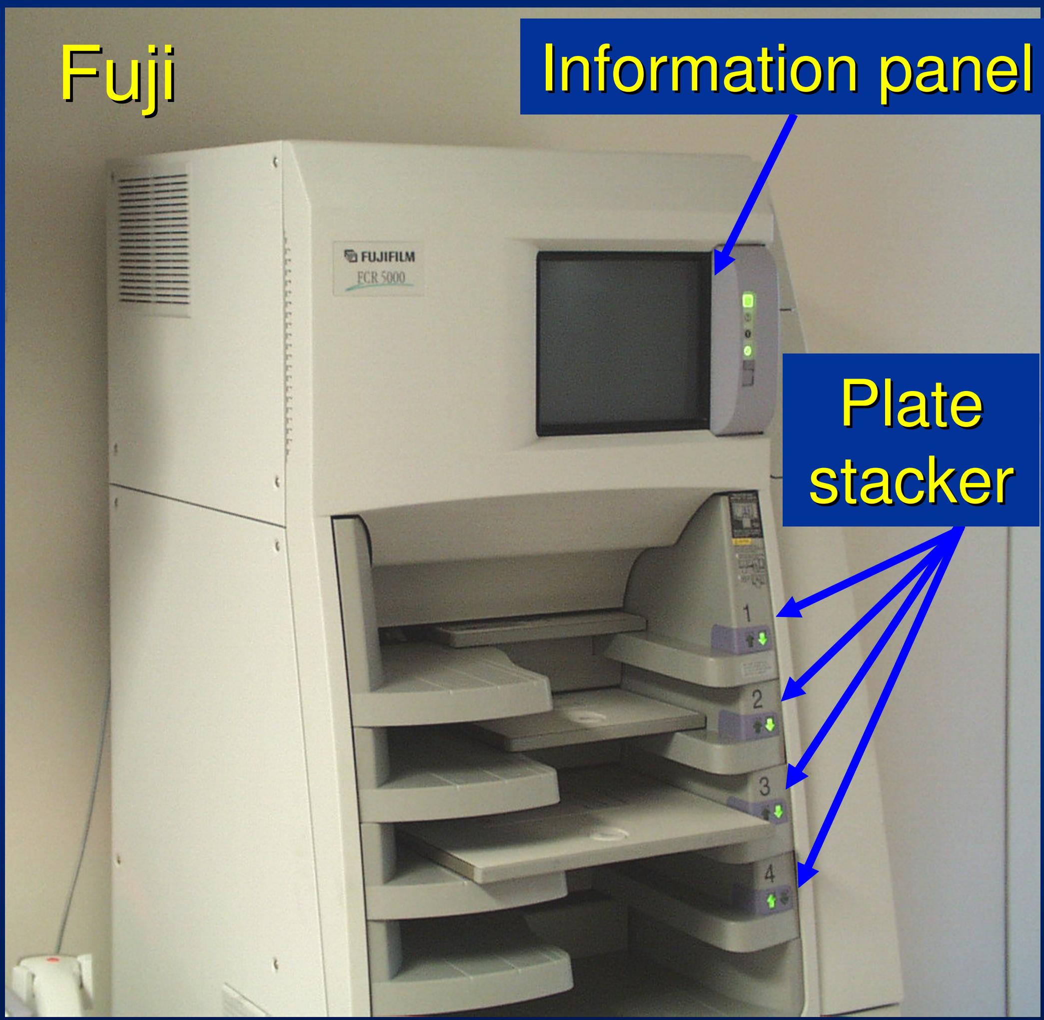
CR Image acquisition

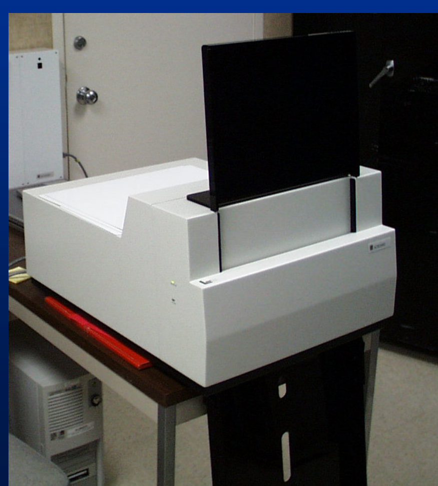


Computed Radiography "reader"



Computed Radiography “reader”

Lumisys



CR “system”: more than the IP’s and the reader!!

Image Acquisition

CR Reader

CR QC Workstation

DICOM / PACS

Laser film printer

Display / Archive

CR Networking

- Modality Worklist Input (from RIS via HL-7)
- Technologist QC Workstation
  - Image manipulation processing reconciliation
  - Reconciliation and image QA
- PACS and DICOM
  - Digital Imaging COmmunications in Medicine
  - Provides standard for modality interfaces, storage/retrieval, and print
- DICOM image output

CR Vendors

- Fuji
- Agfa
- Kodak/Lumisys
- Konica/Minolta
- Orex
- Others

CR Trends

- Lower system costs, smaller size
- Integrated QC workstations
- DICOM output; PACS interfaces
- Image processing improvements

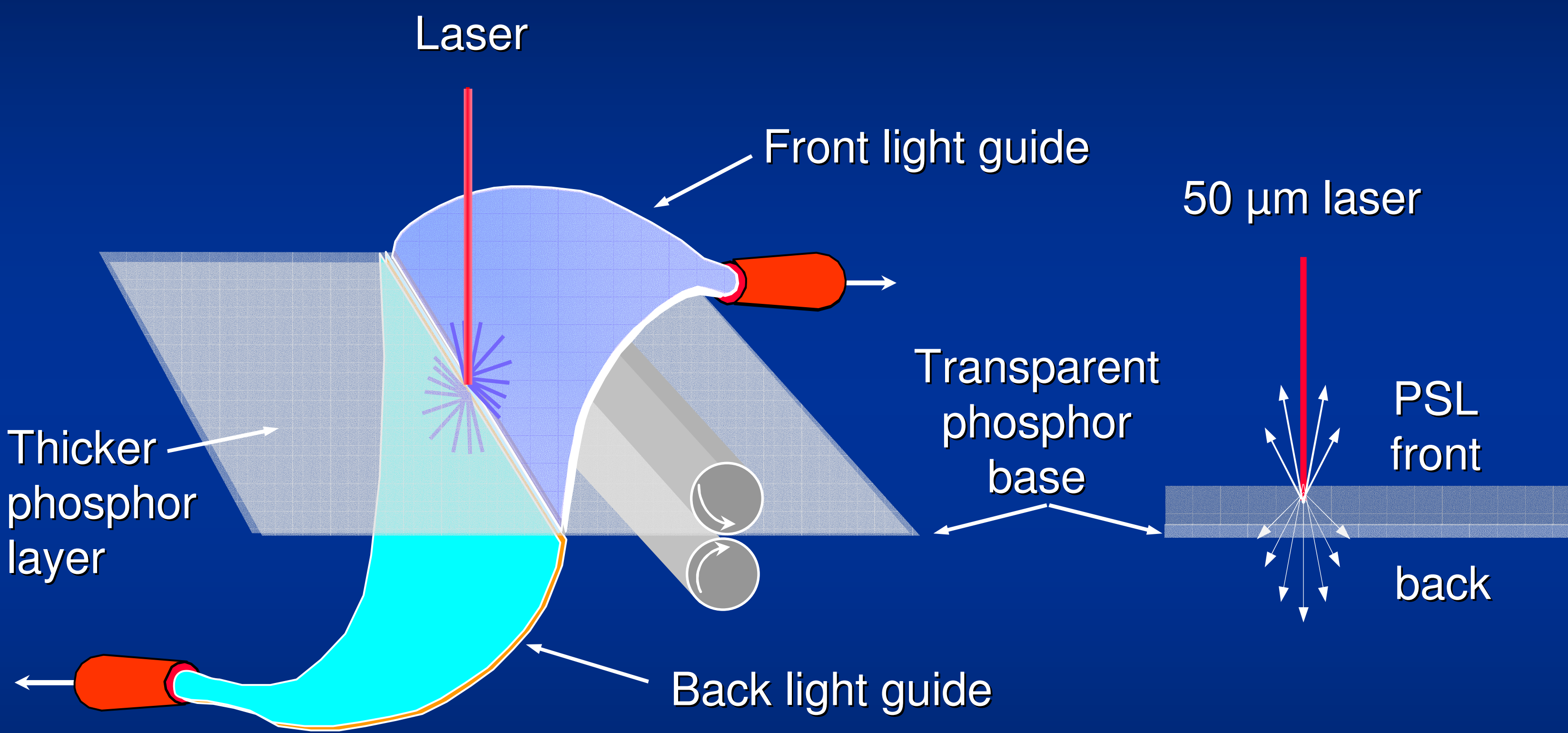
CR Innovations

- High-speed line scan systems (<10 sec)
- Dual side readout
- Structured PSP

} (increase DQE)

- Mammography applications
- Low cost table-top CR readers

Dual-side readout



CR Mammography

CR Reader
50 µm spot

Modality Worklist

CR QC Workstation

CR Cassettes

24 x 30 cm

18 x 24 cm

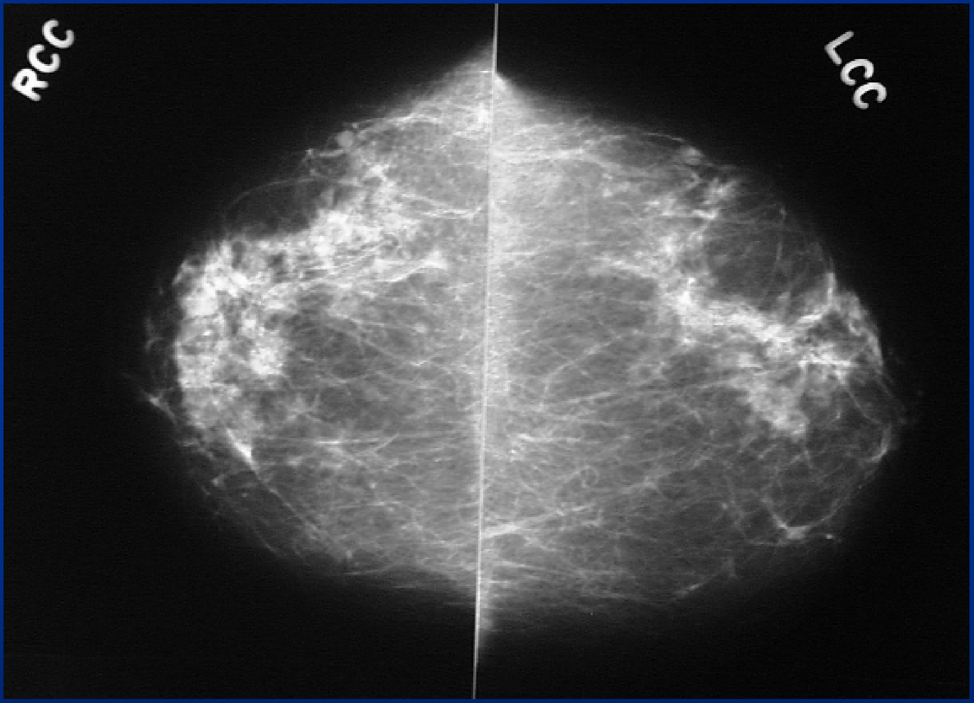
Image size:
36 MB (18x24)
50 MB (24x30)

CR: direct replacement for screen-film

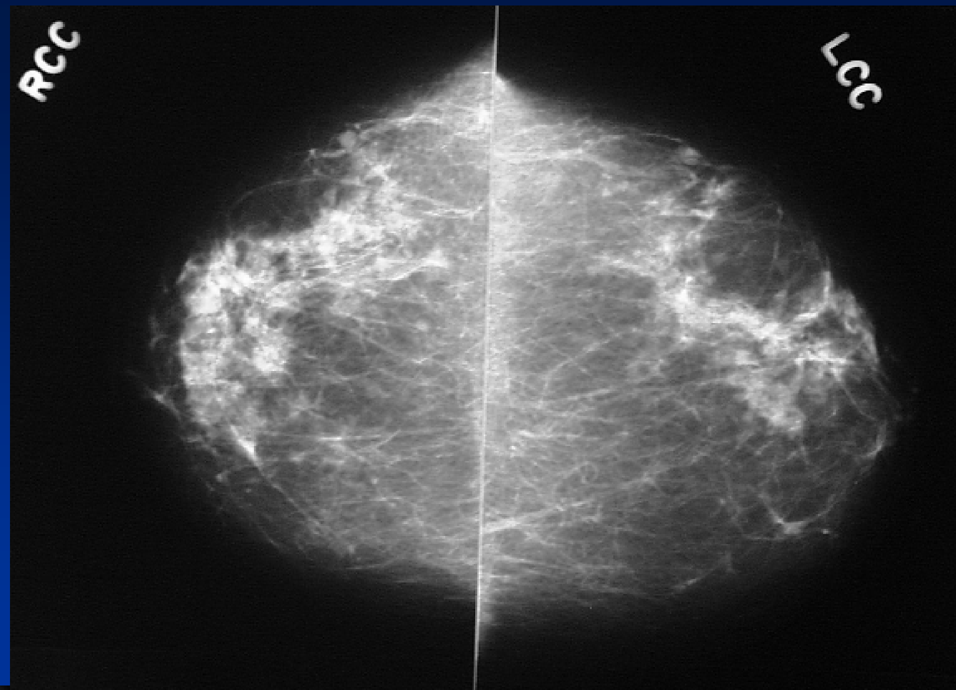
Conventional Screen-Film

Computed Radiography

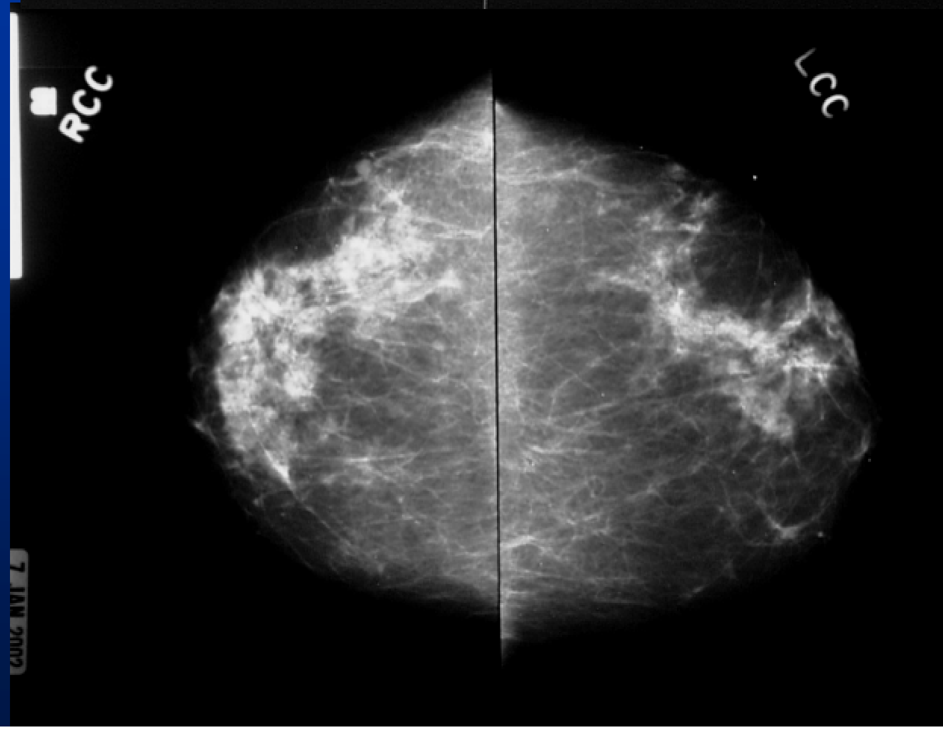
Dry Laser Printer



CR

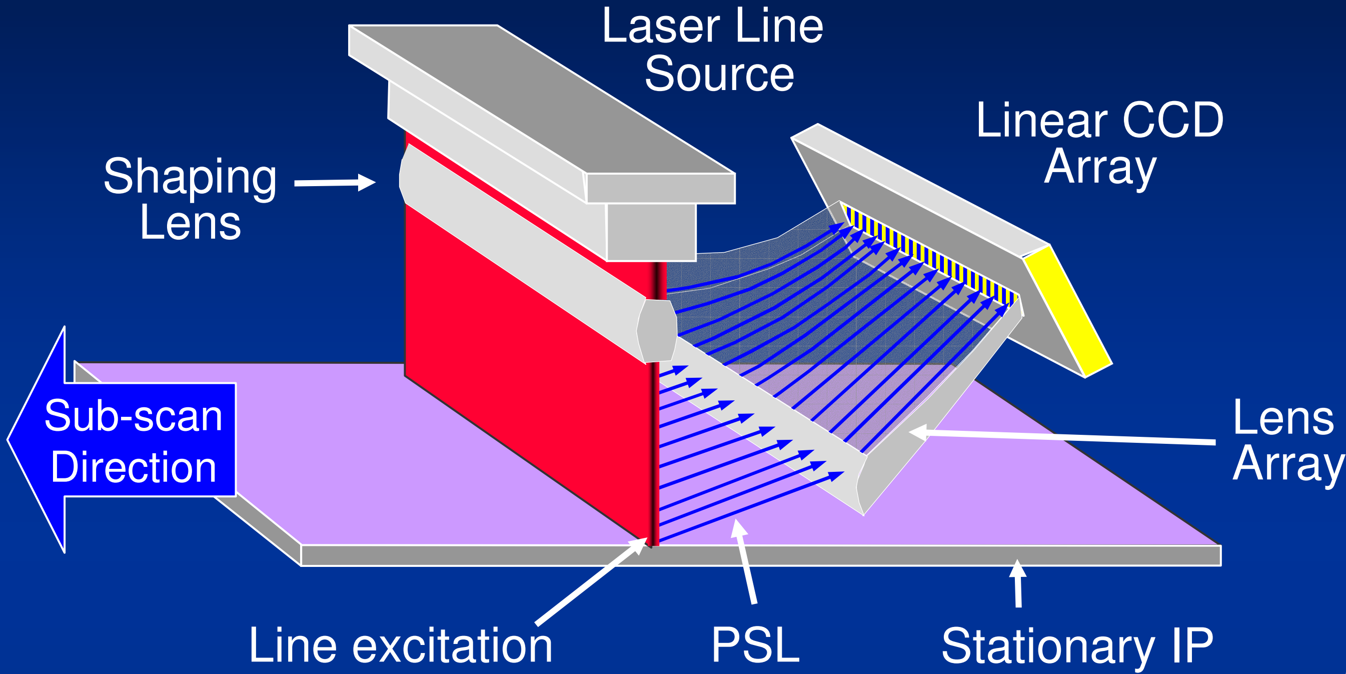


Screen-Film

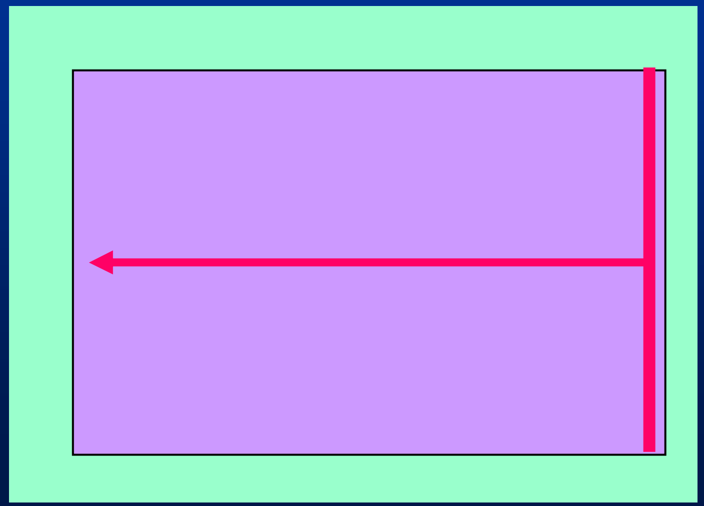


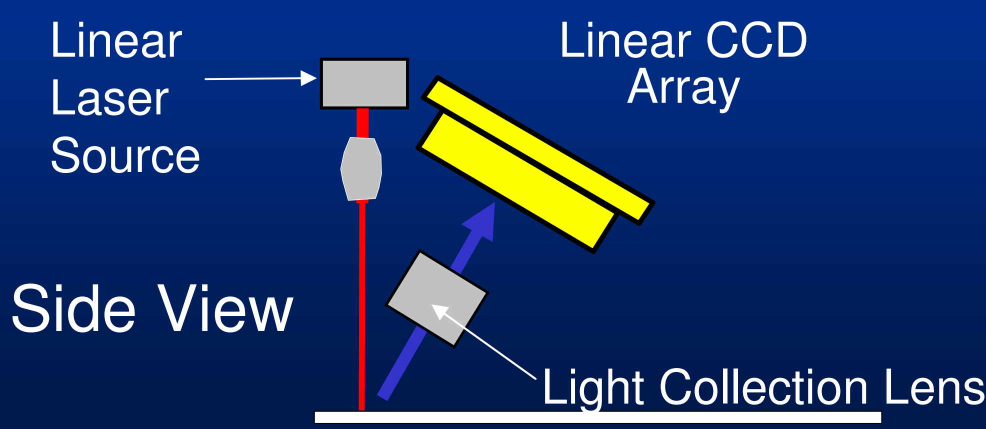
Exactly same position and compression

CR "line-scan"

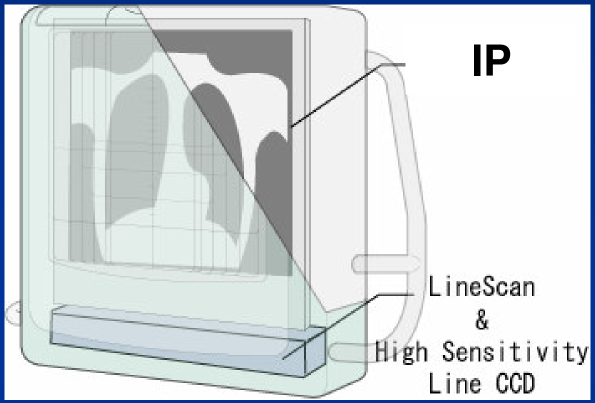


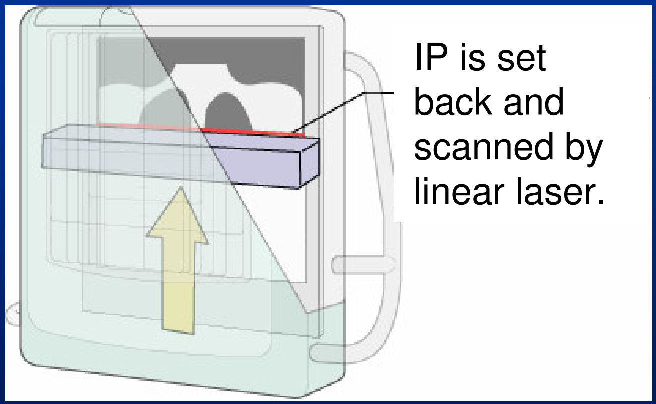
5 sec scan





Fuji "Velocity"; Agfa "Scan Head"





- Faster
  - 5-10 second scan
  - Turn around ~30 sec
- Compact
  - Simplified components
  - Les expensive
- Better?
  - Quantitative analysis still required

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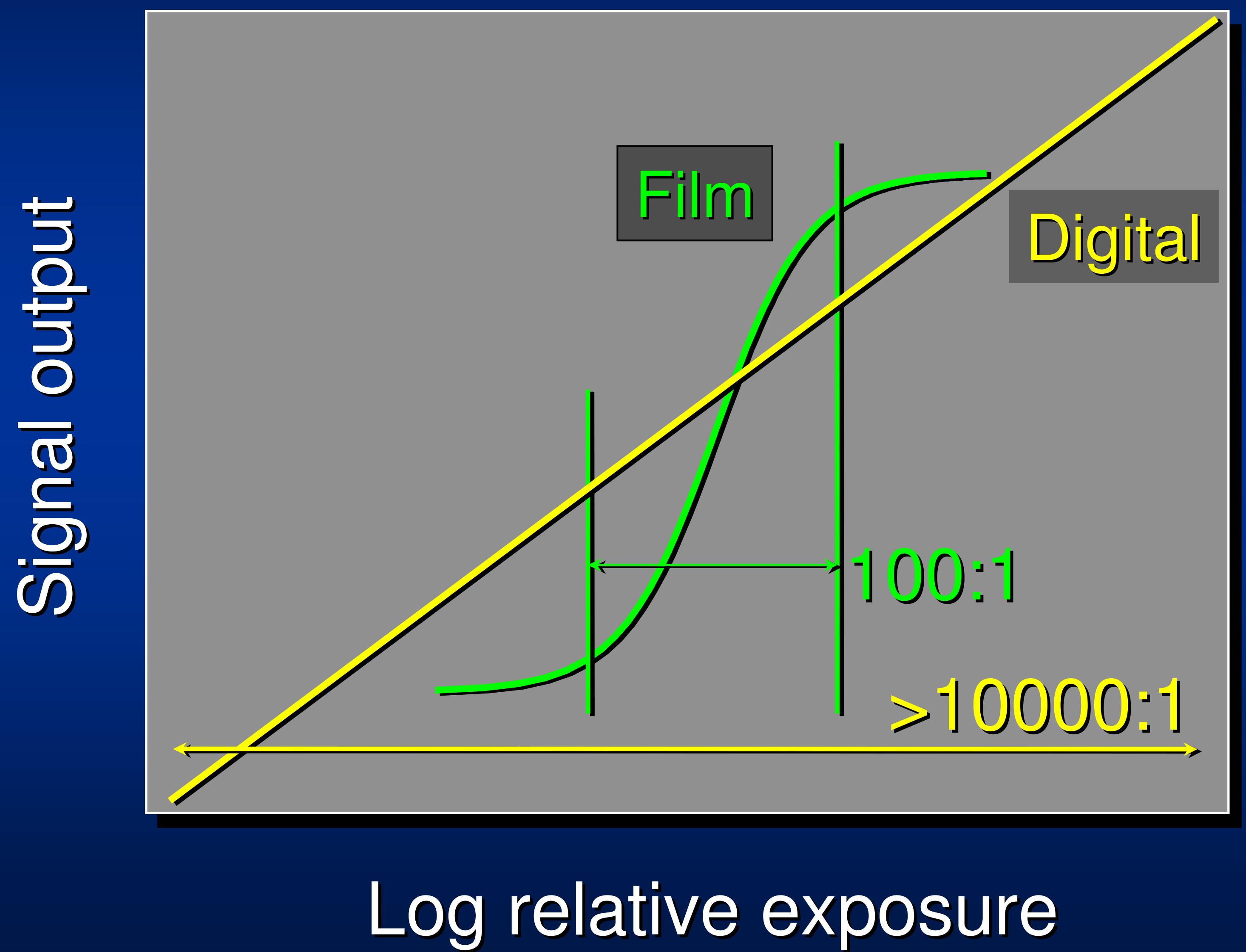
Signal to Noise Ratio (SNR)

- Determines detectability of an object
- The signal is derived from the x-ray quanta
- The noise is from a variety of sources:
  - X-ray quantum statistics
  - Electronic noise
  - Fixed pattern noise
  - Sampling noise (aliasing)
  - Anatomical noise
- Display of SNR must be matched to human visual system response

Exposure Latitude: Dynamic Range

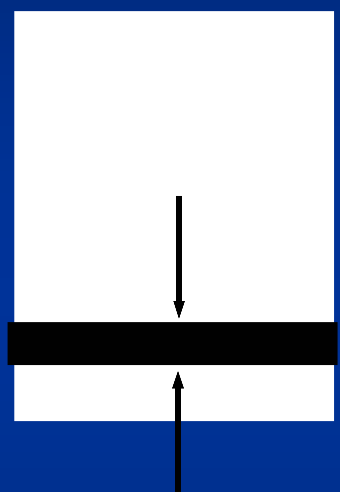


Pre-Processing

Two major steps correct and adjust for:

- Detector / x-ray system flaws
  - Pixel defects
  - Sensitivity variations (e.g., light guide in CR)
  - Offset gain variations
- Wide detector dynamic range
  - Identify image location
  - Scale image data
  - Optimize quantization levels for “post-processing”

Shading correction techniques for CR: correct light guide gain variations



n lines
fast-scan

Apply offset correction to uniform IP exposure, n averages:

$$I_O(x) = \langle I(x)_i - O(x)_i \rangle ; \quad i = 1, n$$

Create normalized shading correction array:

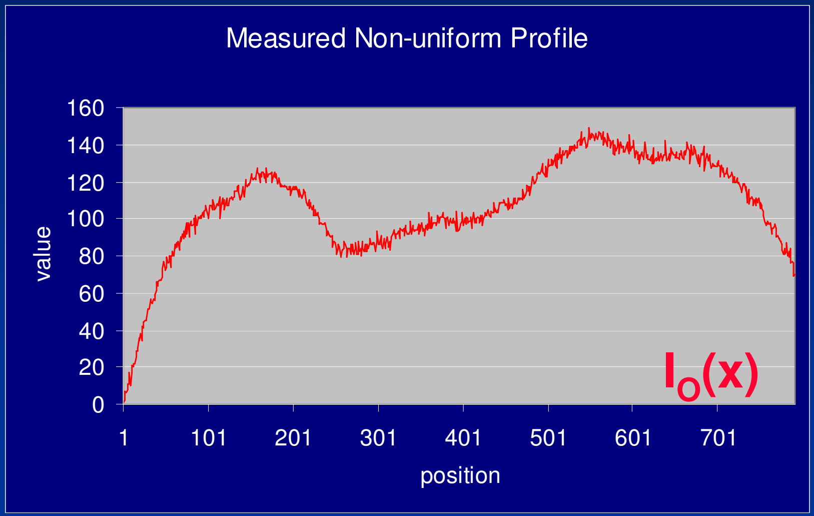
$$Sh(x) = \frac{\langle I_O \rangle_x}{I_O(x)}$$

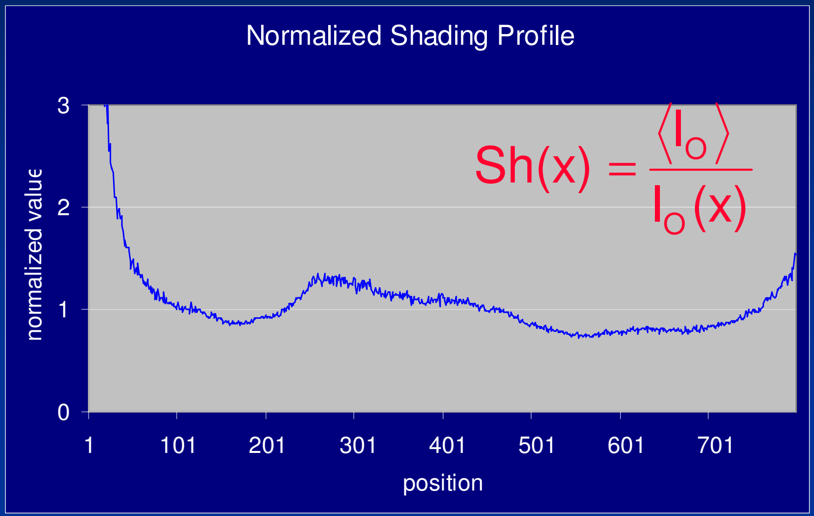
← mean value for all x

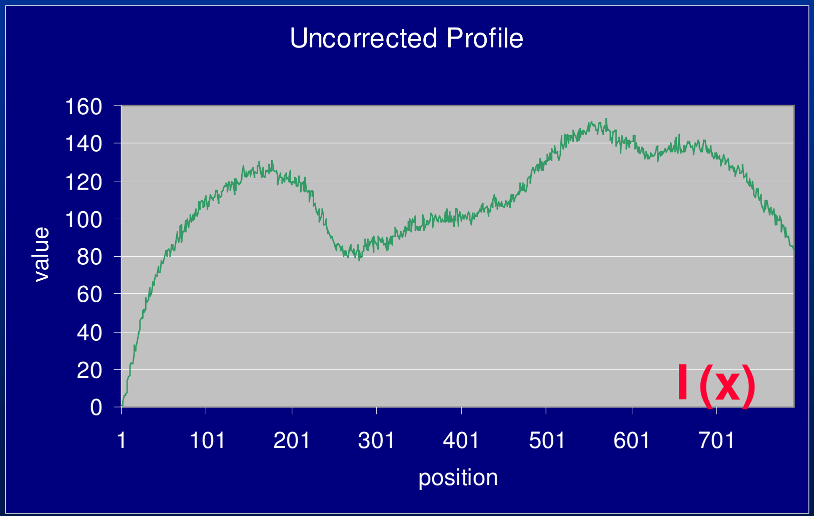
Implement shading correction (line by line):

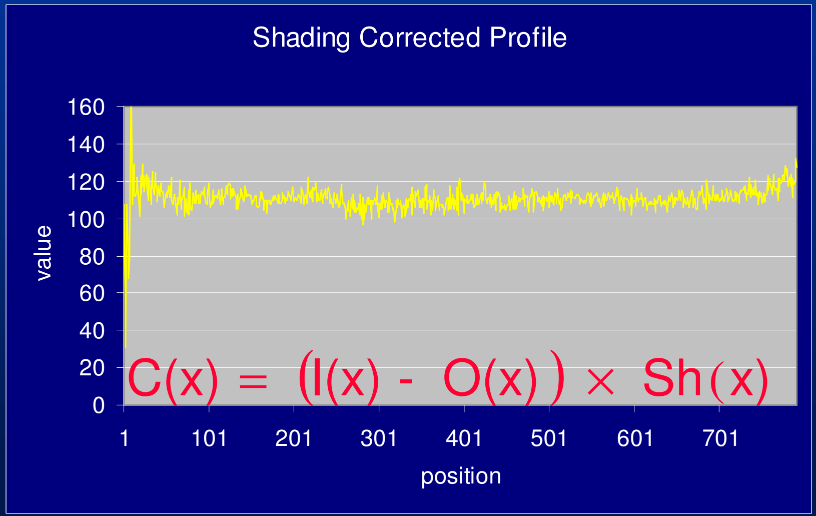
$$C(x) = \left(I(x) - O(x) \right) \times Sh(x)$$

1-D Shading Correction





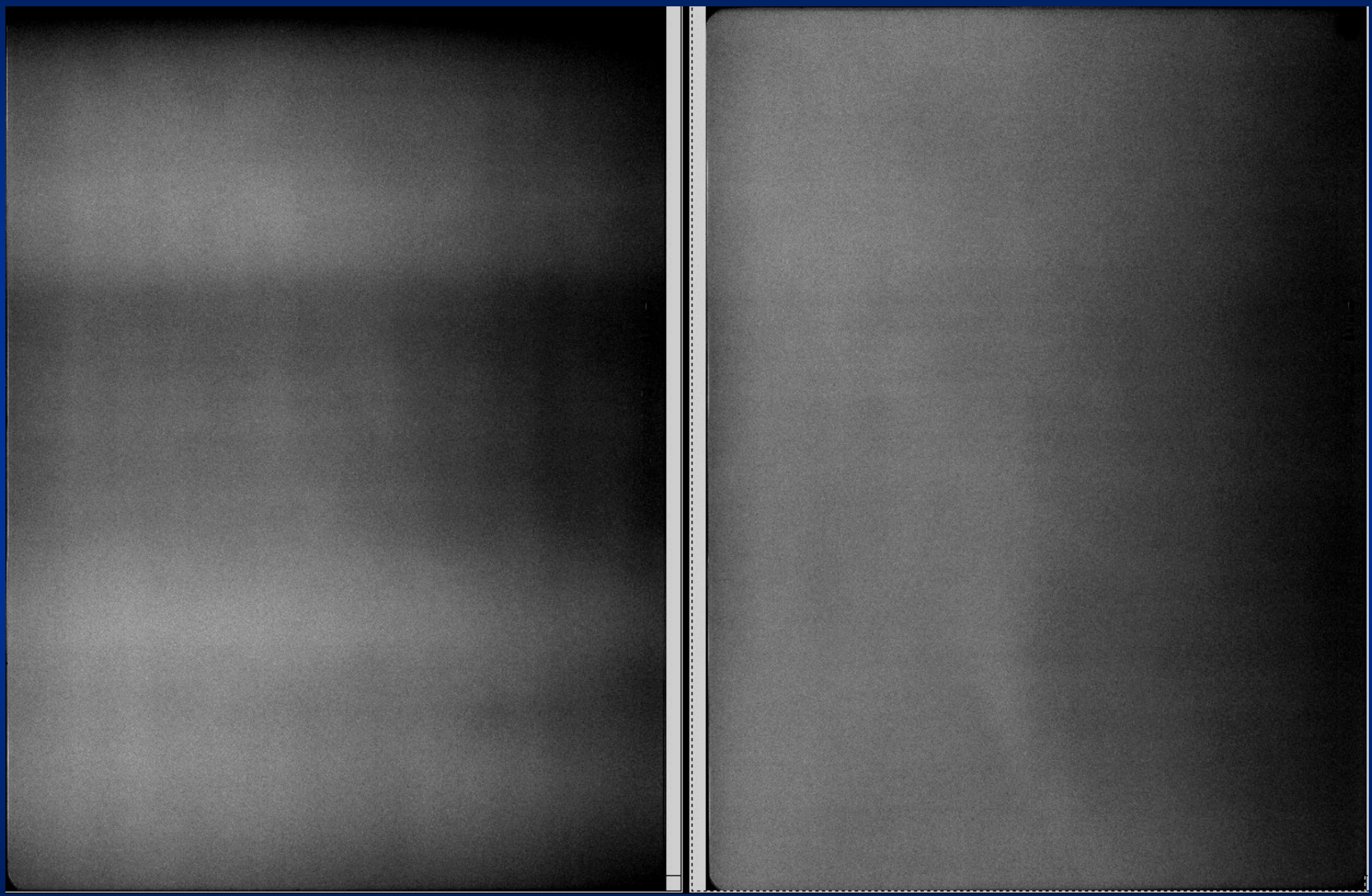




CR Shading Correction

- Uncorrected image
- Shading corrected

Scan direction →



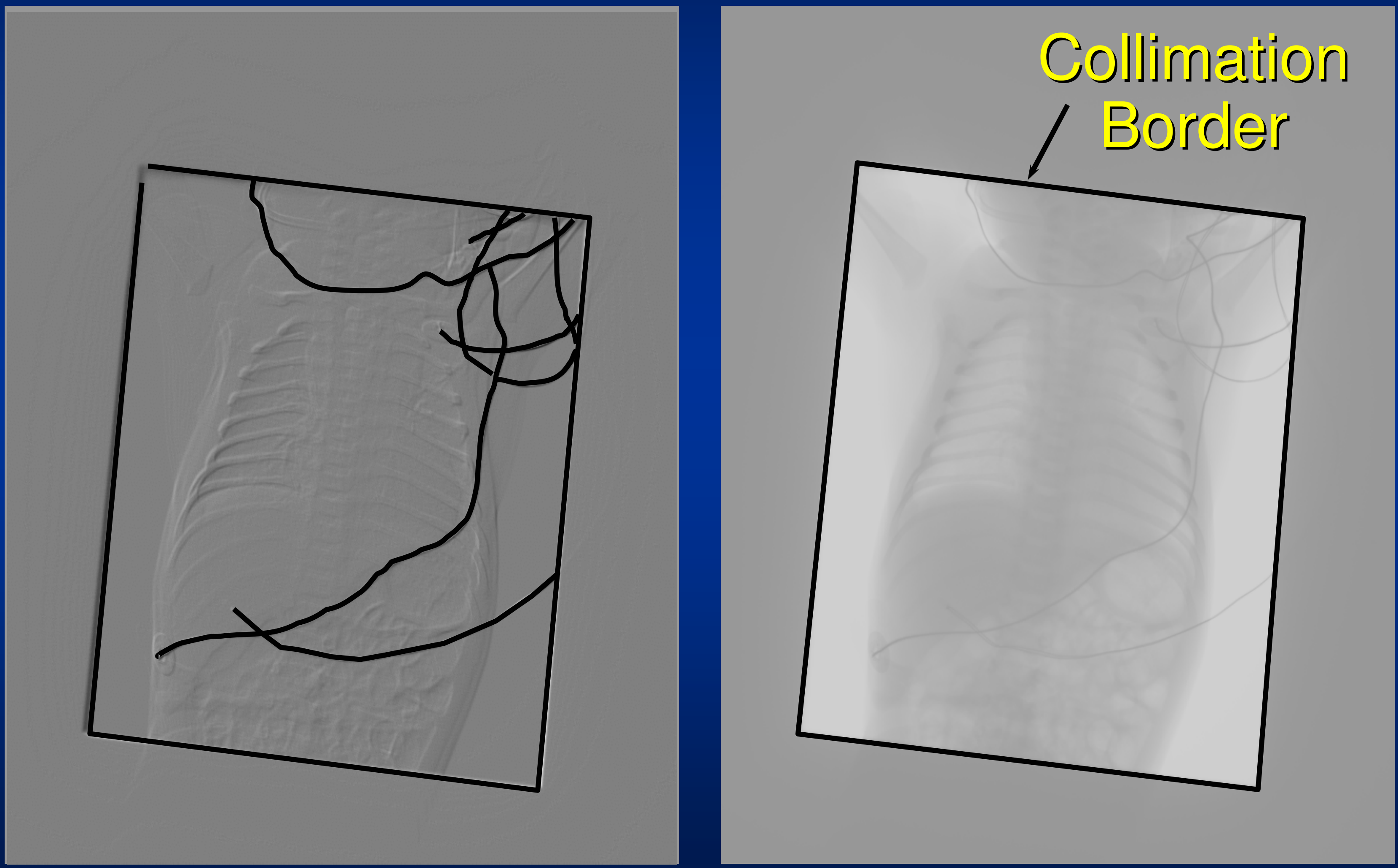
Cathode Anode Cathode "Heel" effect → Anode

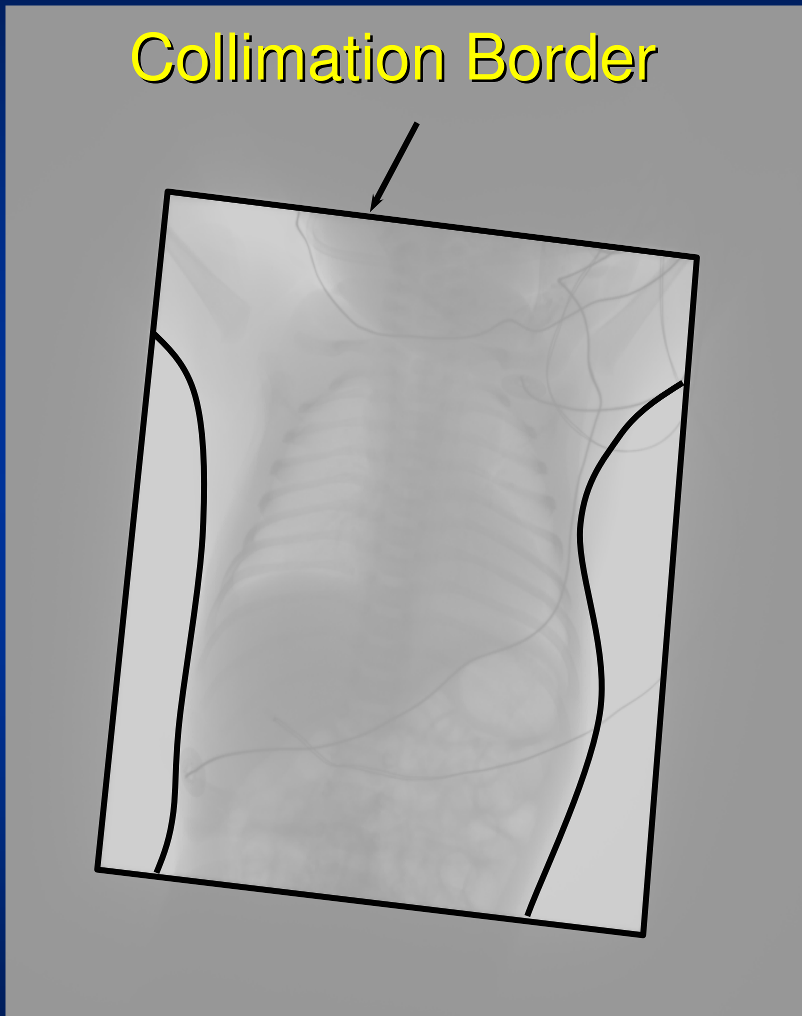
Note: Shading calibration recommended at least every 6 months

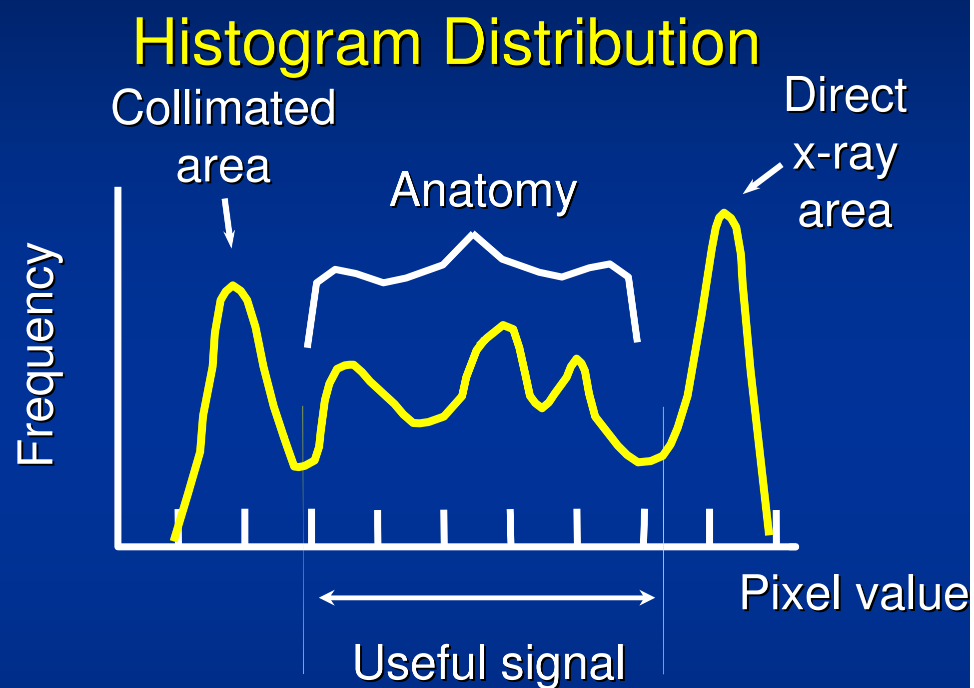
CR Image Manipulation

- Image pre-processing: segmentation
  - Find the pertinent image information
  - Scale the data via histogram analysis

Collimation area(s) determined



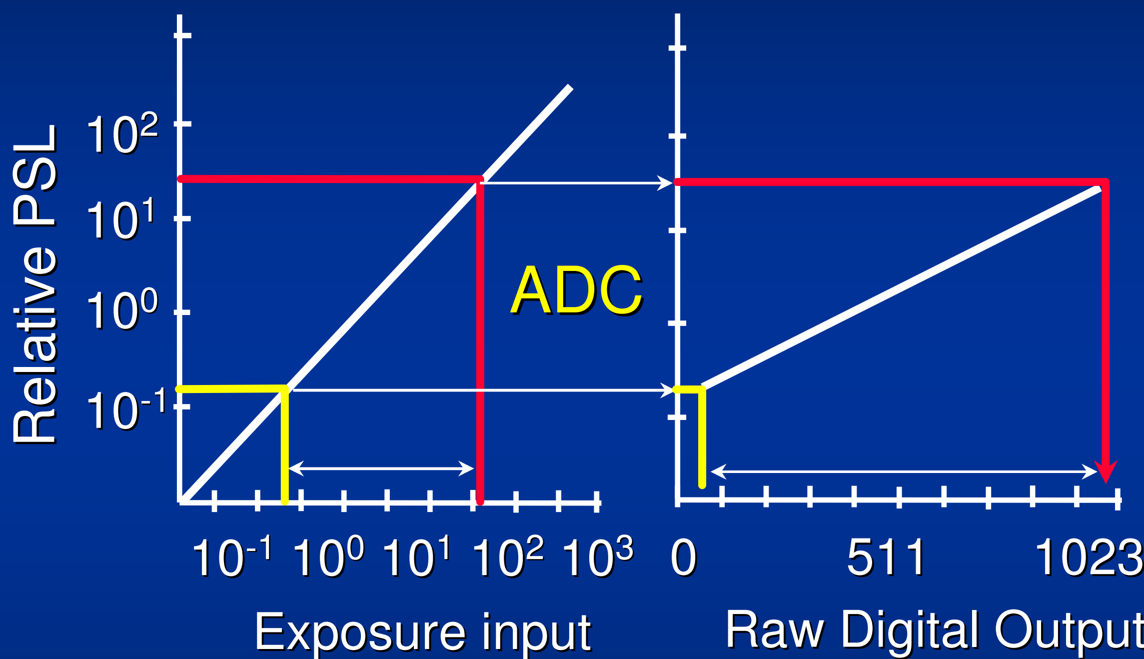




The shape is dependent on radiographic study, positioning and technique

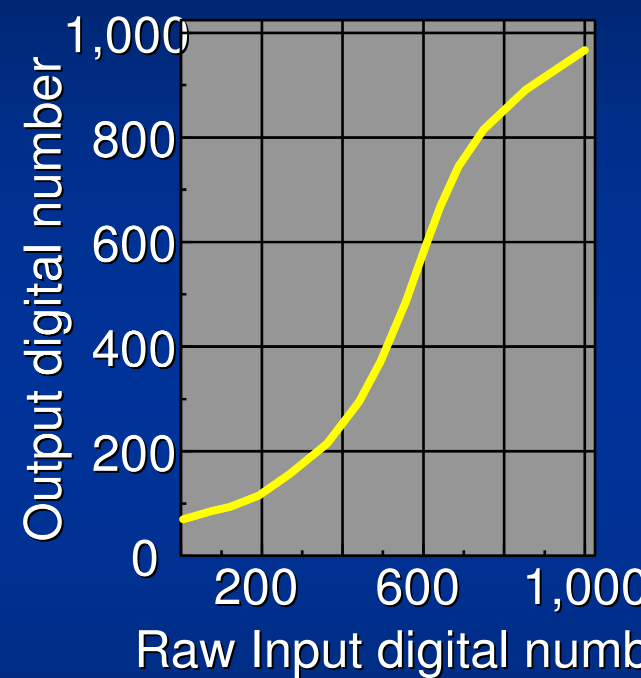
Data conversion

Exposure into digital number



Grayscale transformation

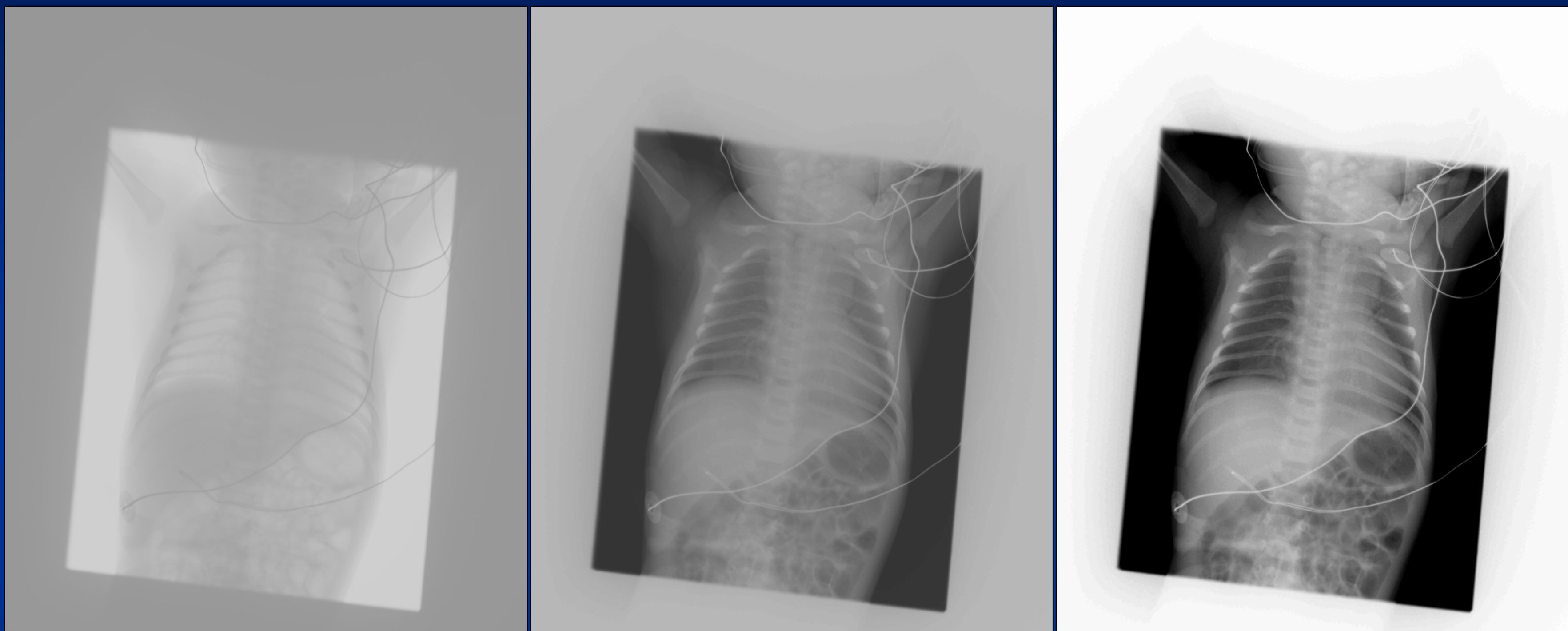
Input to output digital number



Histogram

1. Find the signal
2. Scale to range
3. Contrast enhancement

← Raw, raw (no pre-processing)

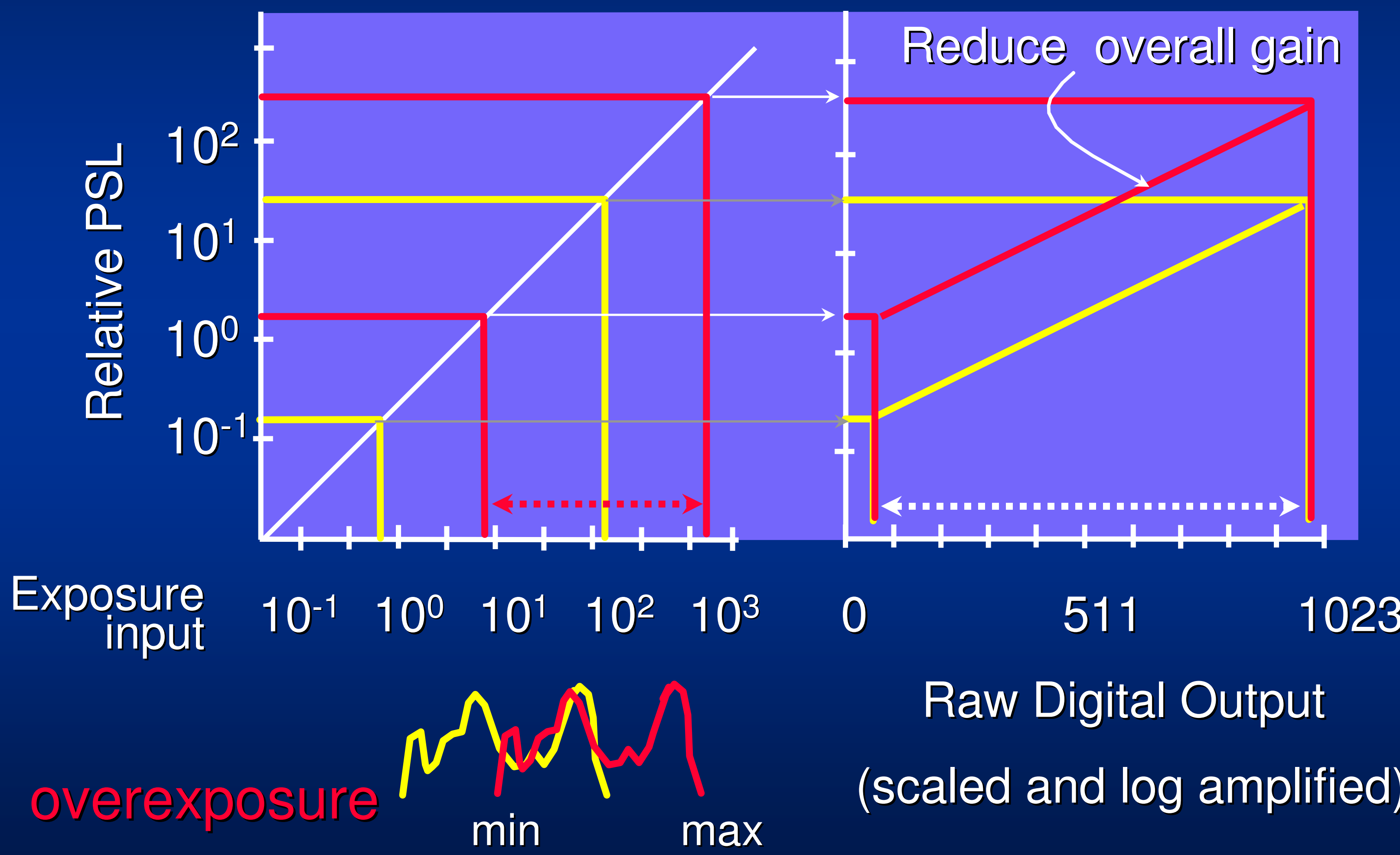


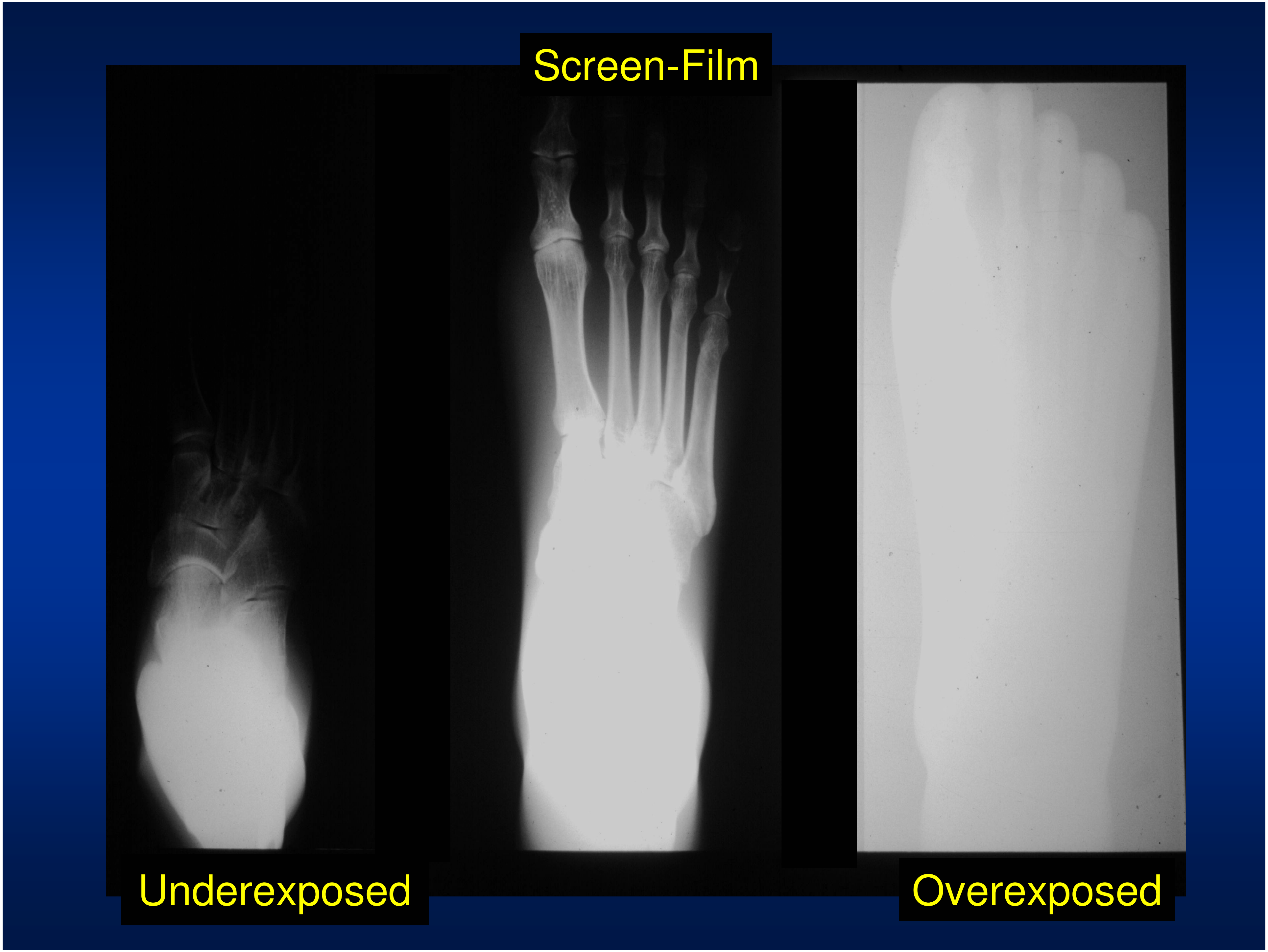
Raw (original) | Raw ranged | Processed

1. Find the signal
2. Scale to range
3. Contrast enhanced

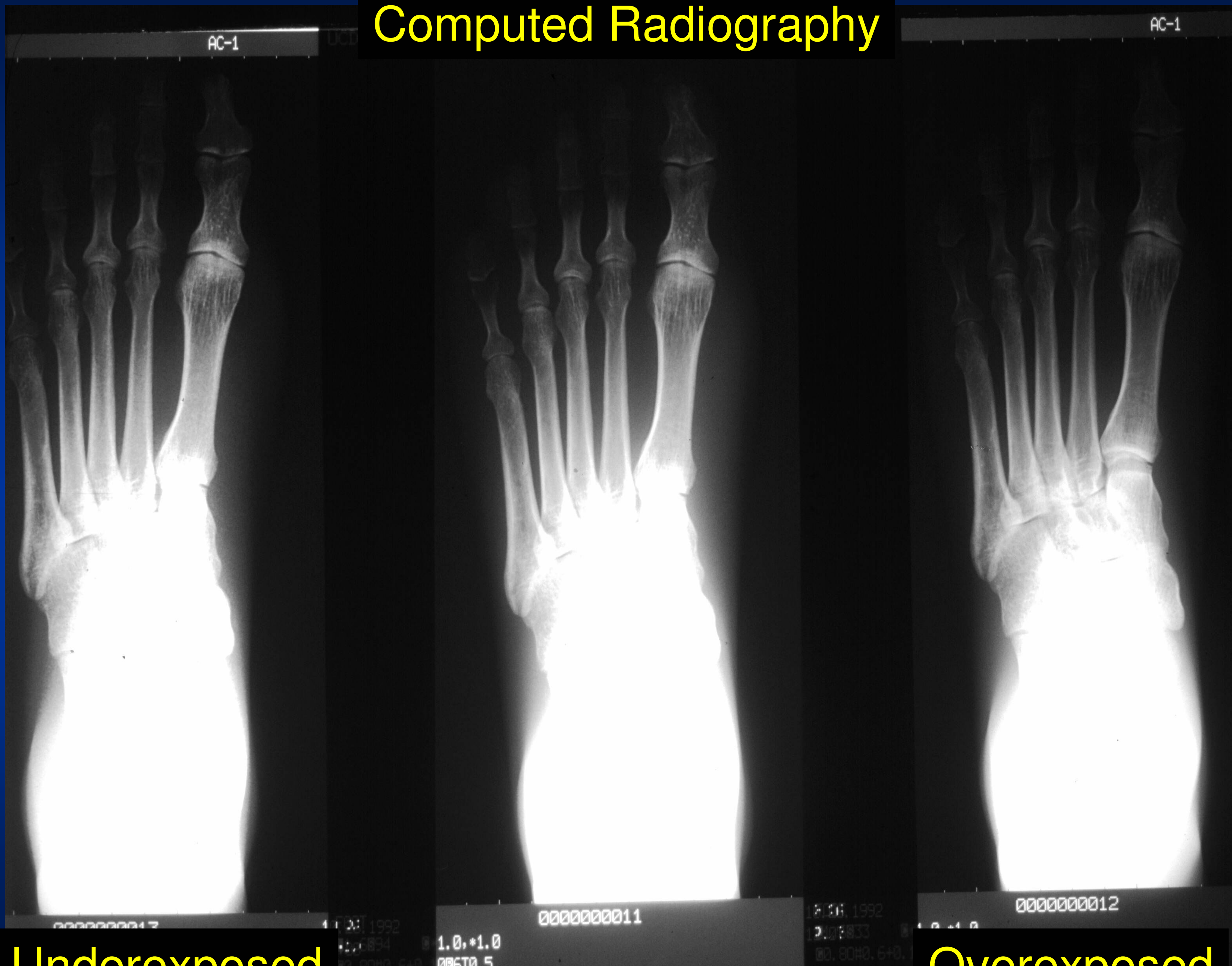
Data conversion for overexposure

Exposure into digital number




Screen-Film
Underexposed
Overexposed

Computed Radiography



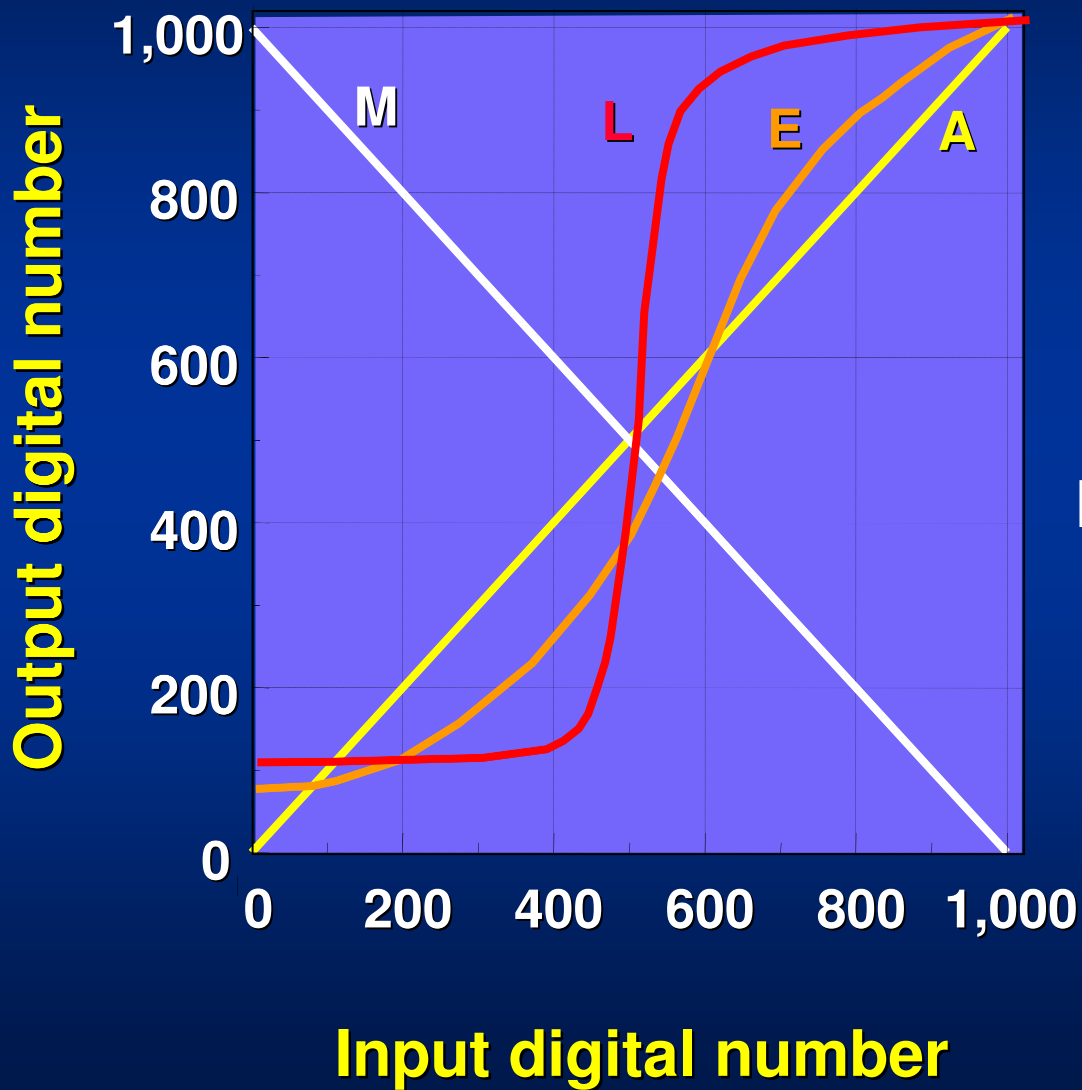
Underexposed

Overexposed

CR Image manipulation

- Image post-processing:
  - Contrast enhancement
  - Anatomy specific grayscale manipulation
  - Spatial frequency enhancement

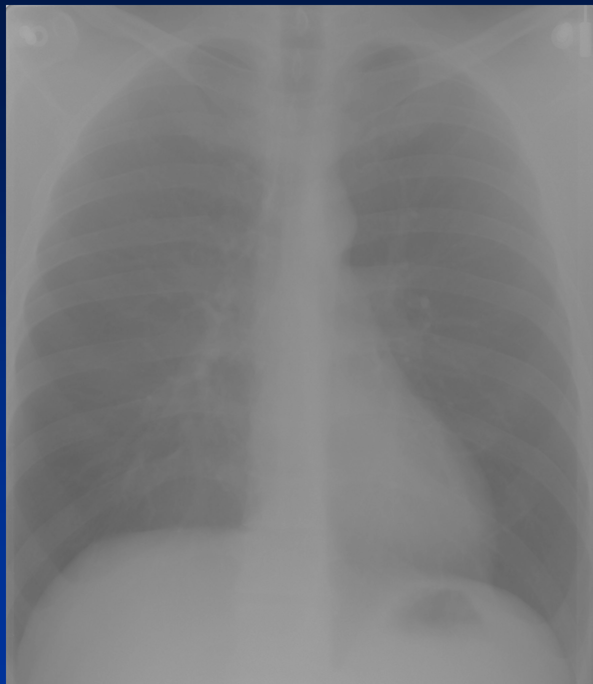
Look-up-table transformation



Fuji System
Example LUTs

Fuji CR Parameter Settings

Anatomy	LUT shape parameters				Frequency enhancement parameters		
Anatomical region	**GA**	**GT**	**GC**	**GS**	**RN**	**RT**	**RE**
General chest (LAT)	1.0	B	1.6	-0.2	4.0	R	0.2
General chest (PA)	0.6	D	1.6	-0.5	4.0	R	0.2
Port Chest GRID	0.8	F	1.8	-0.05	4.0	T	0.2
Port Chest NO GRID	1.0	D	1.6	-0.15	4.0	R	0.5
Peds chest NICU/PICU	1.1	D	1.6	-0.2	3.0	R	0.5
Finger	0.9	O	0.6	0.3	5.0	T	0.5
Wrist	0.8	O	0.6	0.2	5.0	T	0.5
Forearm	0.8	O	0.6	0.3	5.0	T	0.5
Plaster cast (arm)	0.8	O	0.6	0.4	5.0	T	0.5
Elbow*	0.8	O	0.6	0.4	7.0	T	1.0
Upper Ribs*	0.8	O	1.6	0.0	5.0	R	1.0
Pelvis*	0.9	O	0.6	0.2	6.0	T	1.0
Pelvis portable	0.9	O	0.6	0.2	4.0	T	0.5
Tib/Fib	0.9	N	0.6	0.25	5.0	F	0.5
Foot	0.8	O	0.6	0.3	5.0	T	0.5
Foot*	1.2	N	0.6	-0.05	7.0	T	0.5
Os Calcis	0.8	O	0.6	0.4	5.0	F	1.0
Foot cast	0.8	O	0.6	0.5	5.0	F	0.5
C-spine	1.1	F	0.6	0.5	5.0	P	0.5
T-spine	0.8	F	1.8	-0.05	4.0	T	0.2
Swimmers	1.2	J	0.9	0.3	5.0	T	0.5
Lumbar spine	1.0	N	0.9	0.4	5.0	T	1.0
Breast specimen	2.5	D	0.6	0.35	9.0	P	1.0



Contrast Enhancement →

Edge Enhancement →

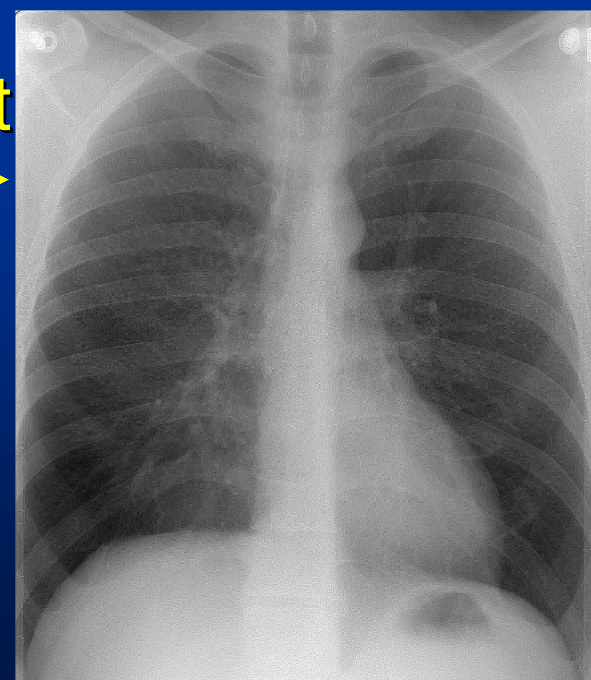


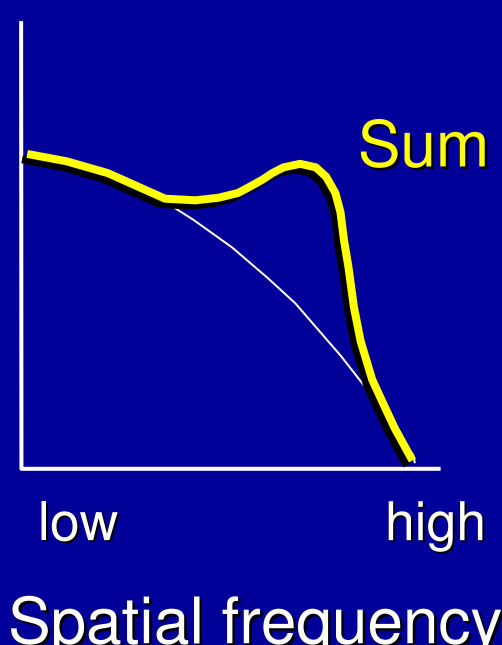
Image Inversion ←

Spatial Frequency Processing

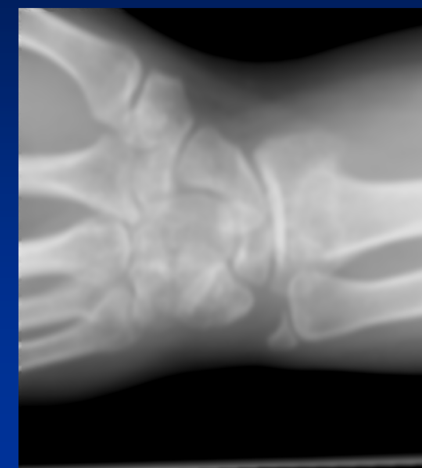
"Edge Enhancement"

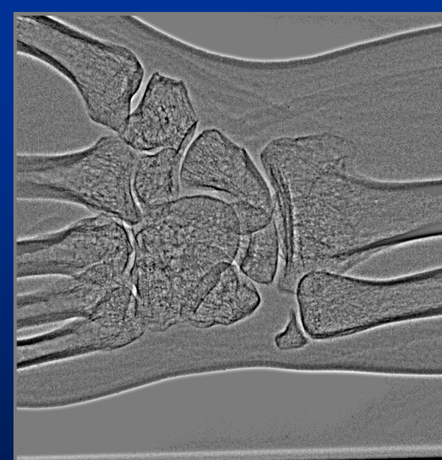
Edge Enhanced:

Difference + Original




Original


Blurred

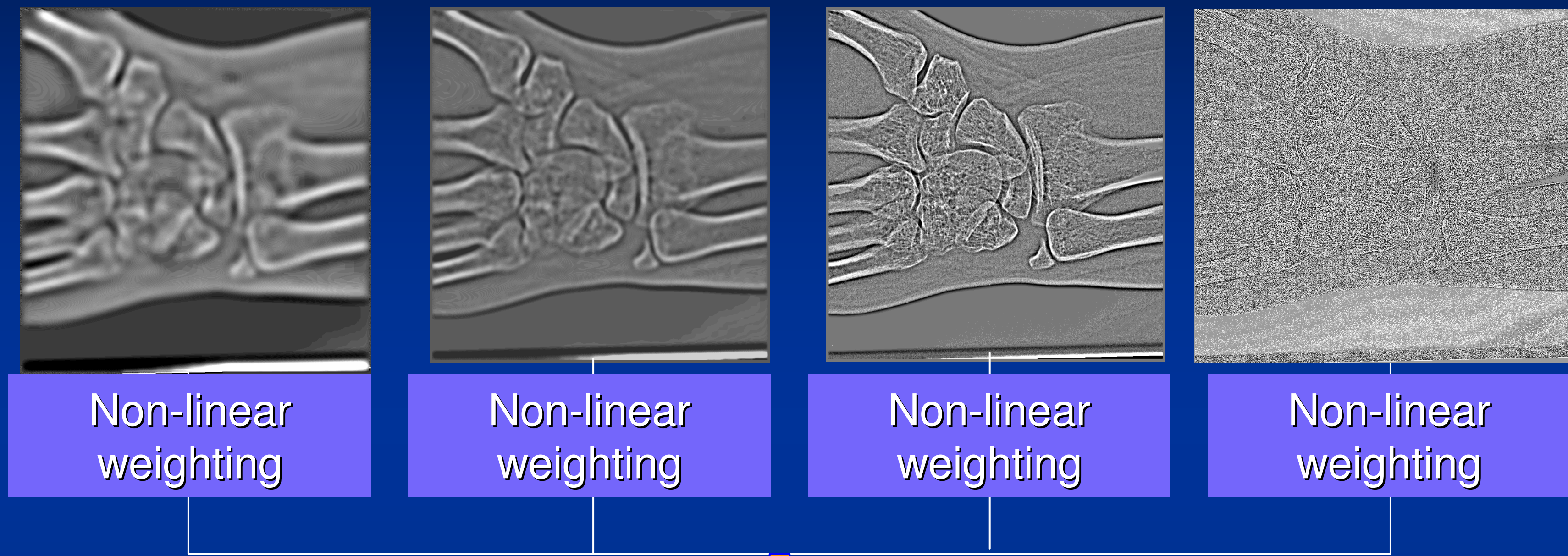

Difference


Edge enhanced

Multiscale enhancement of images

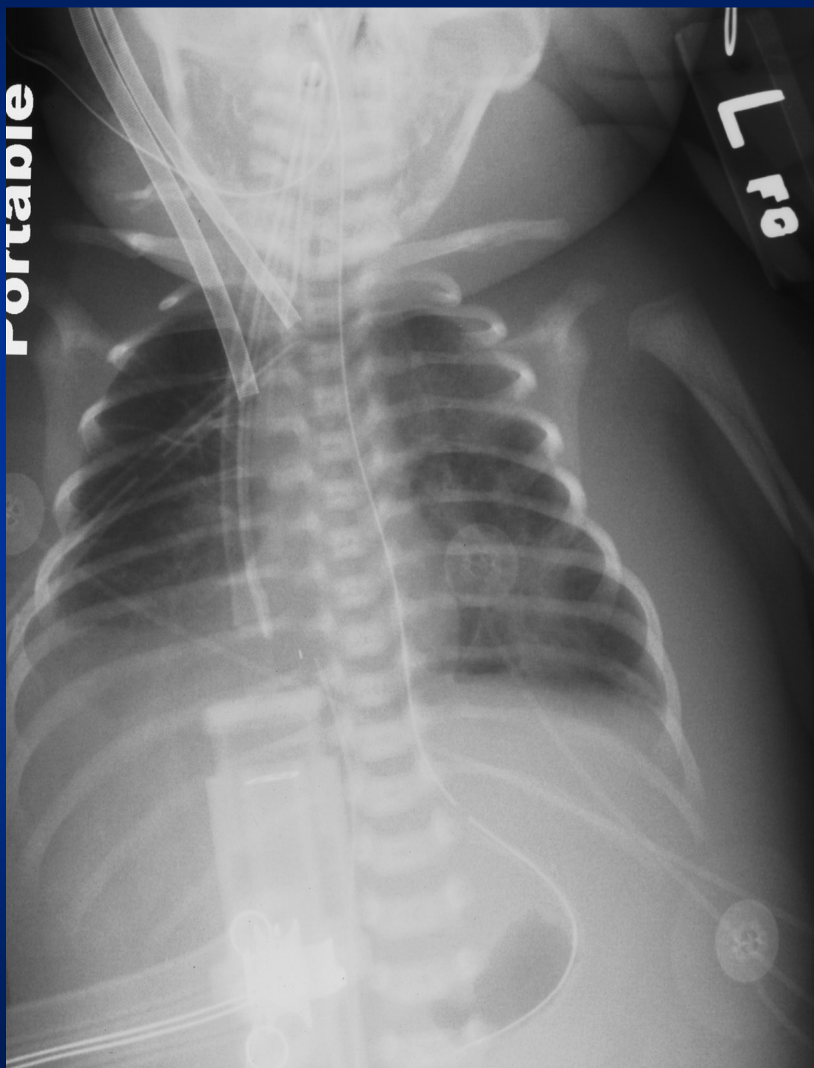
- Algorithm:
  - Decompose the image into several frequency channels (pyramidal decomposition)
  - Process each frequency scale (sub-band) non-linearly to equalize detail amplitude (structure boost)
  - Recombine each “scale” to form final output
  - Protect image from unacceptable noise

Sub-bands of the image are independently optimized

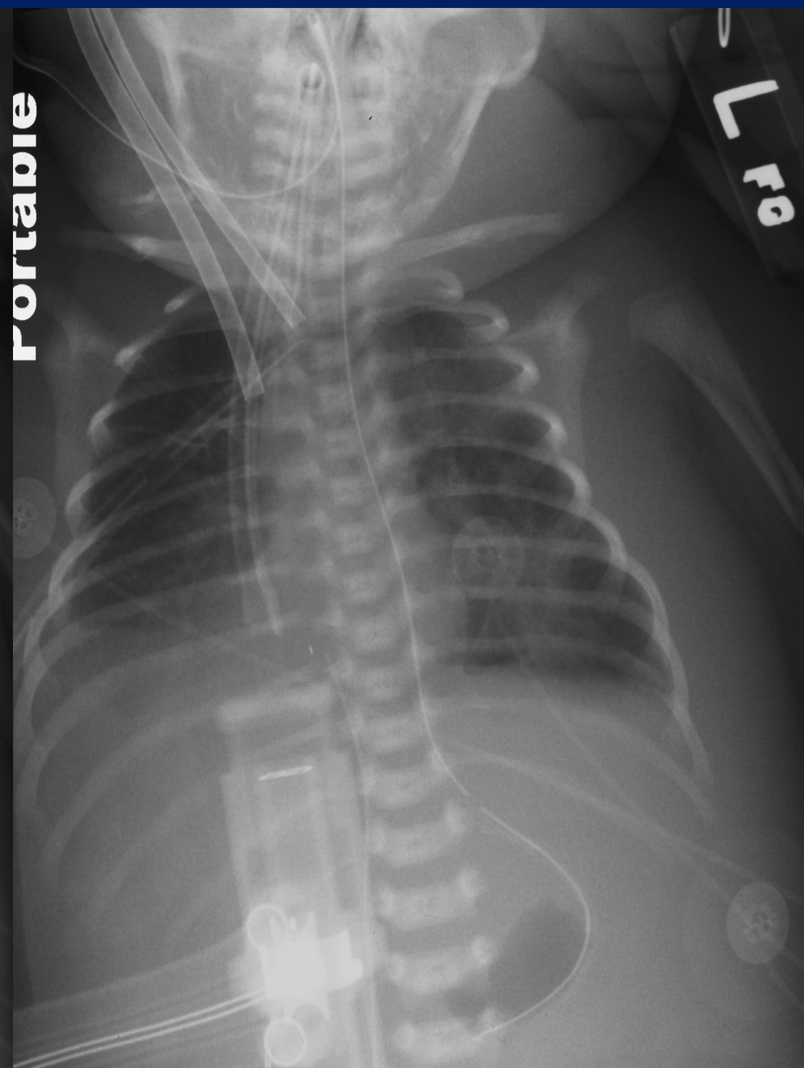


"Multi frequency" enhanced image

Standard Processing

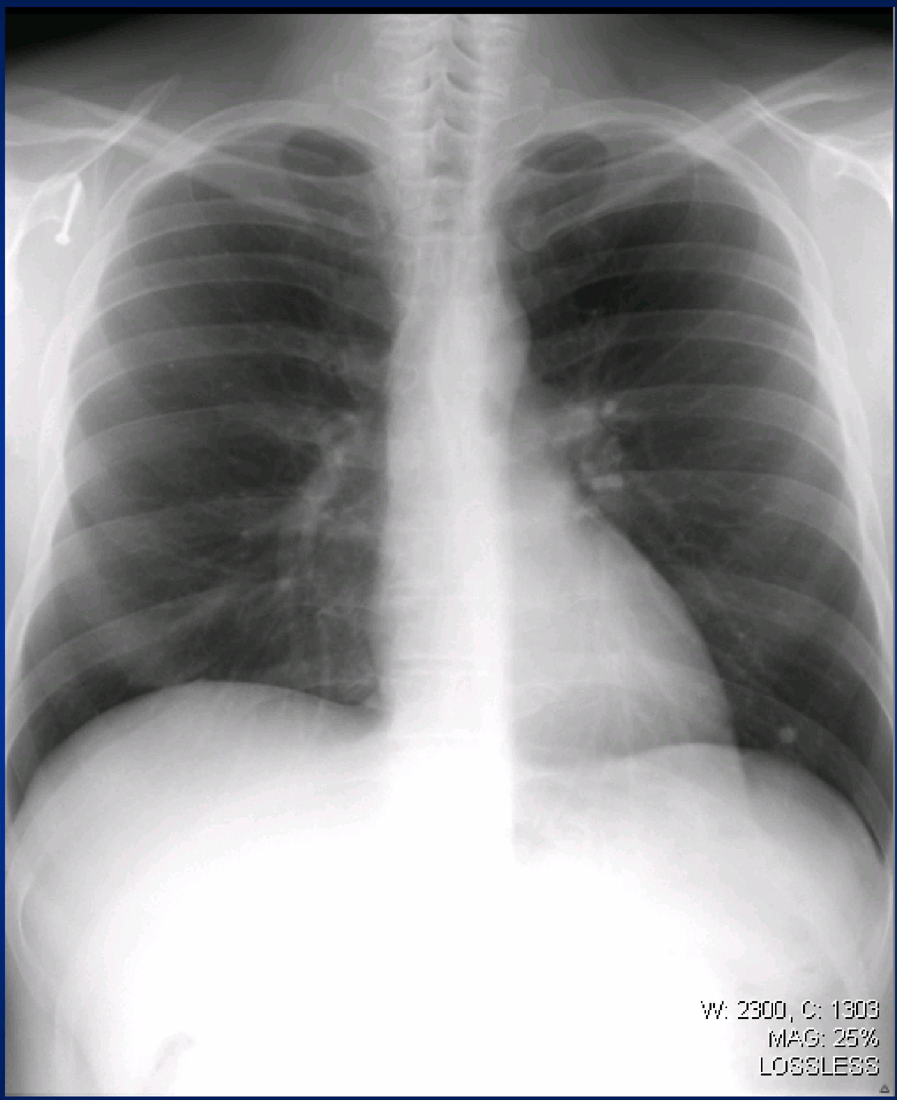


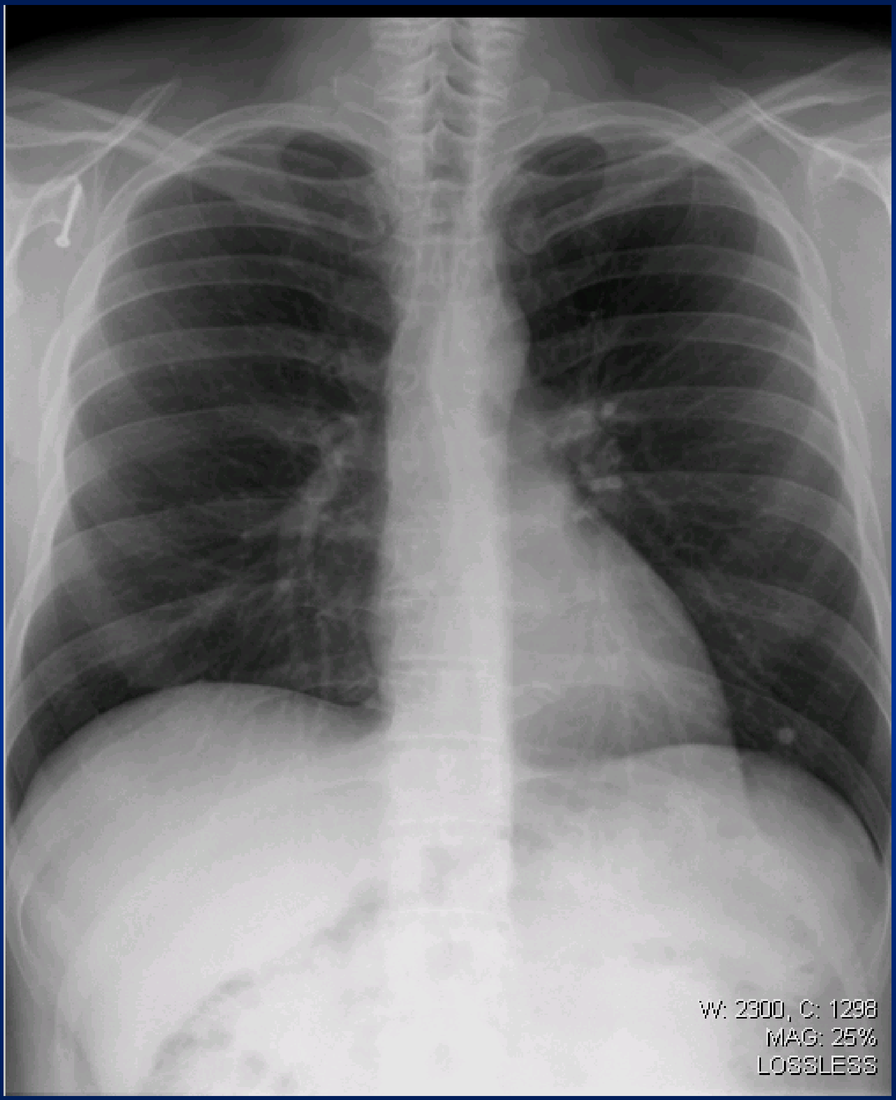
Multi-frequency Processing



Courtesy of Keith Strauss

Example Images





Standard Processing

MUSICA® Processing

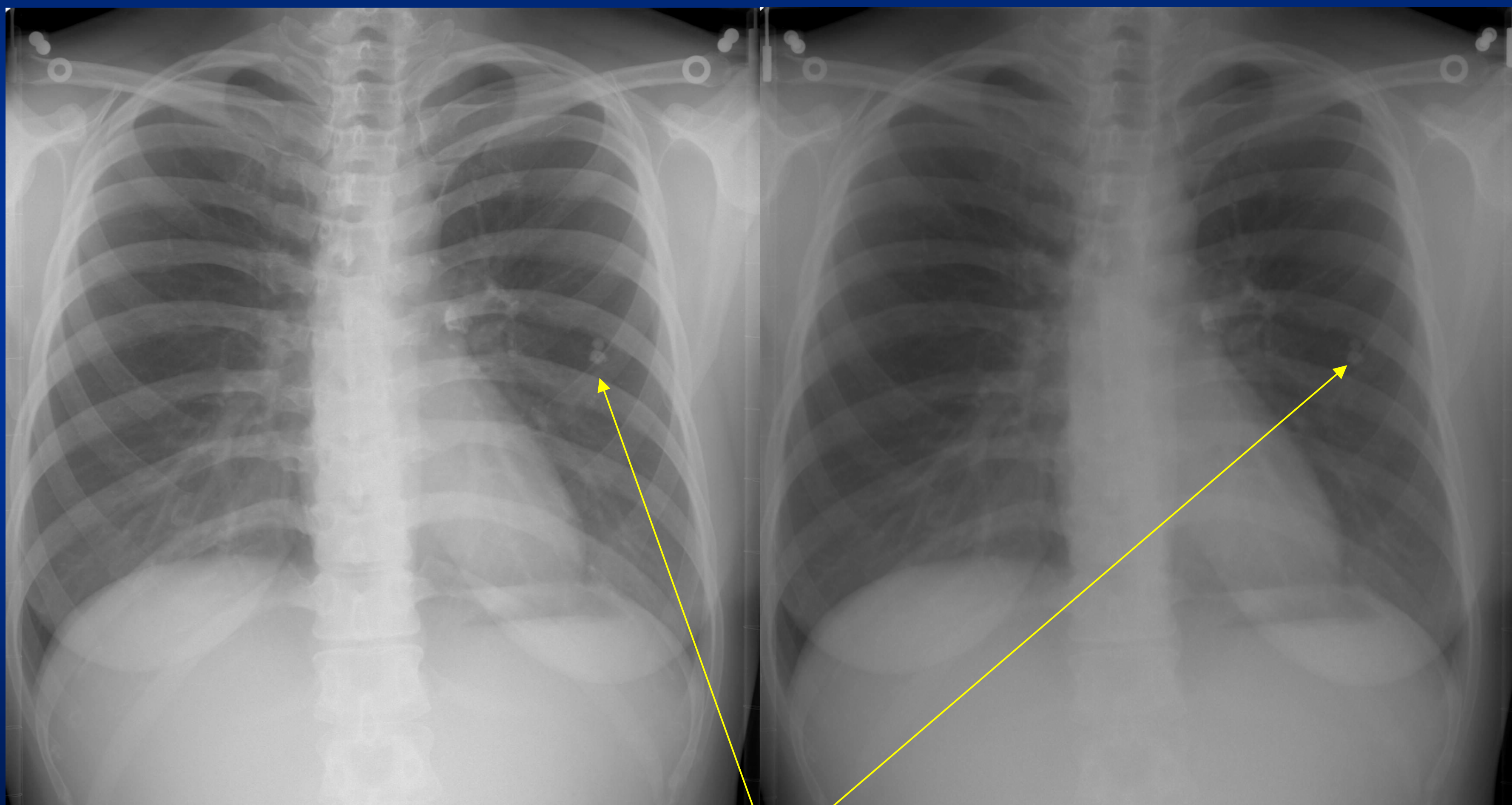
Courtesy of Chuck Willis

Enhanced Visualization Processing

- Patented algorithms for superior image processing
- Split image into low & high frequency components
  - Reduce contrast of low frequency image
  - Preserve high frequency image
- Recombine images

EVP Example

Dual Energy Imaging with CR



Tissue-selective Images

Soft – tissue Only

Bone Only

Nodule *not* in soft tissue image → Nodule calcified

Image processing

- Contrast and spatial frequency enhancements are crucial for image optimization and efficient information delivery to the diagnostician
- Pre-processing (shading) correction must be verified
- Disease and anatomy-specific processing and Computer Aided Diagnosis are new issues

Outline

- Digital radiography system overview
- CR system function
- Image data acquisition
- Image pre- and post-processing
- Physicist role with CR implementation
- Exposure indicators
- CR Image quality: resolution, SNR, DQE

Physicist responsibilities

- Technical expert and liaison
  - Radiologists, technologists
  - Administrators, IT staff, clinical engineering
- Knowledge of CR system characteristics
- Establish / assist CR image quality program
- Verify proper exposure/technique usage
- Assist in specification (RFP), analysis, purchase

Clinical considerations

- CR reader throughput needs
- Number of IP’s, cassettes, grids
- Identification terminals, interfaces to RIS / HIS / PACS
- Image processing functionality
- Quality control phantom and software
- Service, warranty contracts, siting reqts

CR Specifications

- Image Quality
  - Comparable image quality for all vendors
  - Structured phosphor, dual side readout……
  - Use in radiation therapy?   (IMRT)
- System throughput
  - "Large" systems: ~ 120 – 140 plates/hr
  - "Small" systems: ~40 – 60 plates/hr
- RIS / PACS interfaces; hardcopy?
  - Modality worklist and DICOM conformance
- Quality Control phantoms and software program
- Vendor service

CR in a PACS environment

- "Unprocessed" versus "Processed" images
  - 3 levels: "raw-raw", "original", "contrast/spatial enhanced"
  - Unprocessed images require *Vendor-specific* algorithms on PACS
  - Processed images require DICOM or image specific LUTs
- Unprocessed images more flexibility to manipulate image
- Processed images do not require proprietary software
- Configuration management is crucial for success

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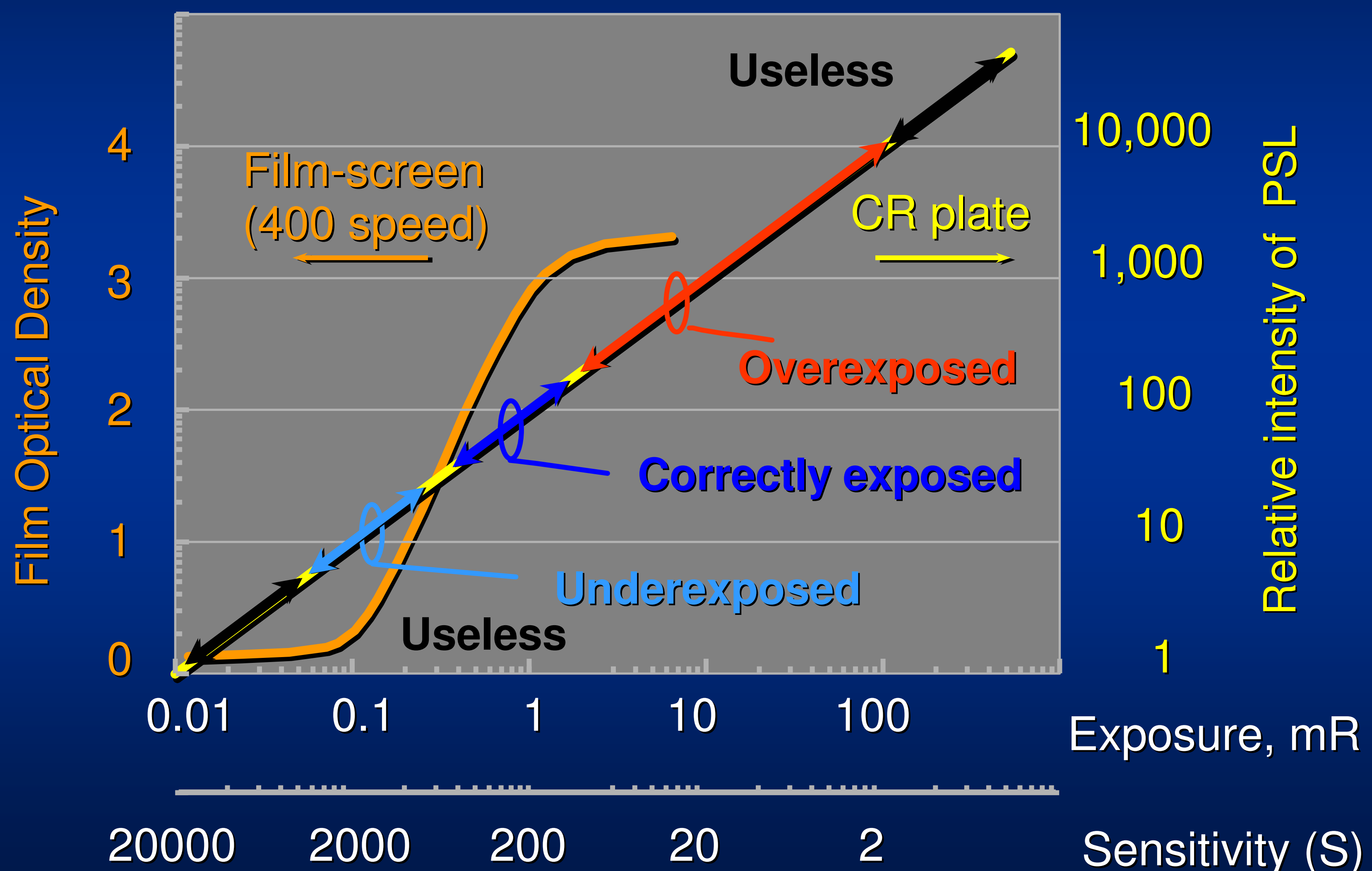
Why is incident detector exposure important?

- Determines the image SNR (for given DQE)
- Disconnect between image appearance and exposure
- Indirectly determines exposure to patient
- Indicators can assist the technologist in achieving correct "equivalent speed"

Characteristic Curve:
response of screen/film and CR / DR



How do manufacturers indicate incident exposure?

- Fuji: "S" – sensitivity number
  - $S \cong 200$ / Exposure (mR); 1 mR @ 80 kVp ~ 200
- Kodak: "Exposure Index" – EI
  - $EI \cong 1000 \times \log$ (Exposure [mR]) + 2000;
    1 mR @ 80 kVp + 0.5 mm Cu + 1 mm Al
    +300 EI = 2X exposure; -300 EI = ½ exposure
- Agfa: "lg M" – log of the median of the histogram
  - lgM=2.56 for 20 μGy @ 75 kVp + 1.5 mm Cu
    +0.3 lgM = 2X exposure; -0.3 lgM = ½ exposure
- Values are based upon the signal amplification required to properly scale PSL, which is dependent on incident exposure

What S value is appropriate?

- Examination specific

	UCDMC targets
– Adult exams (CXR, abdomen, etc)	150 – 300
– Extremities (ST plates)	75 – 150
– Pediatrics	300 – 600

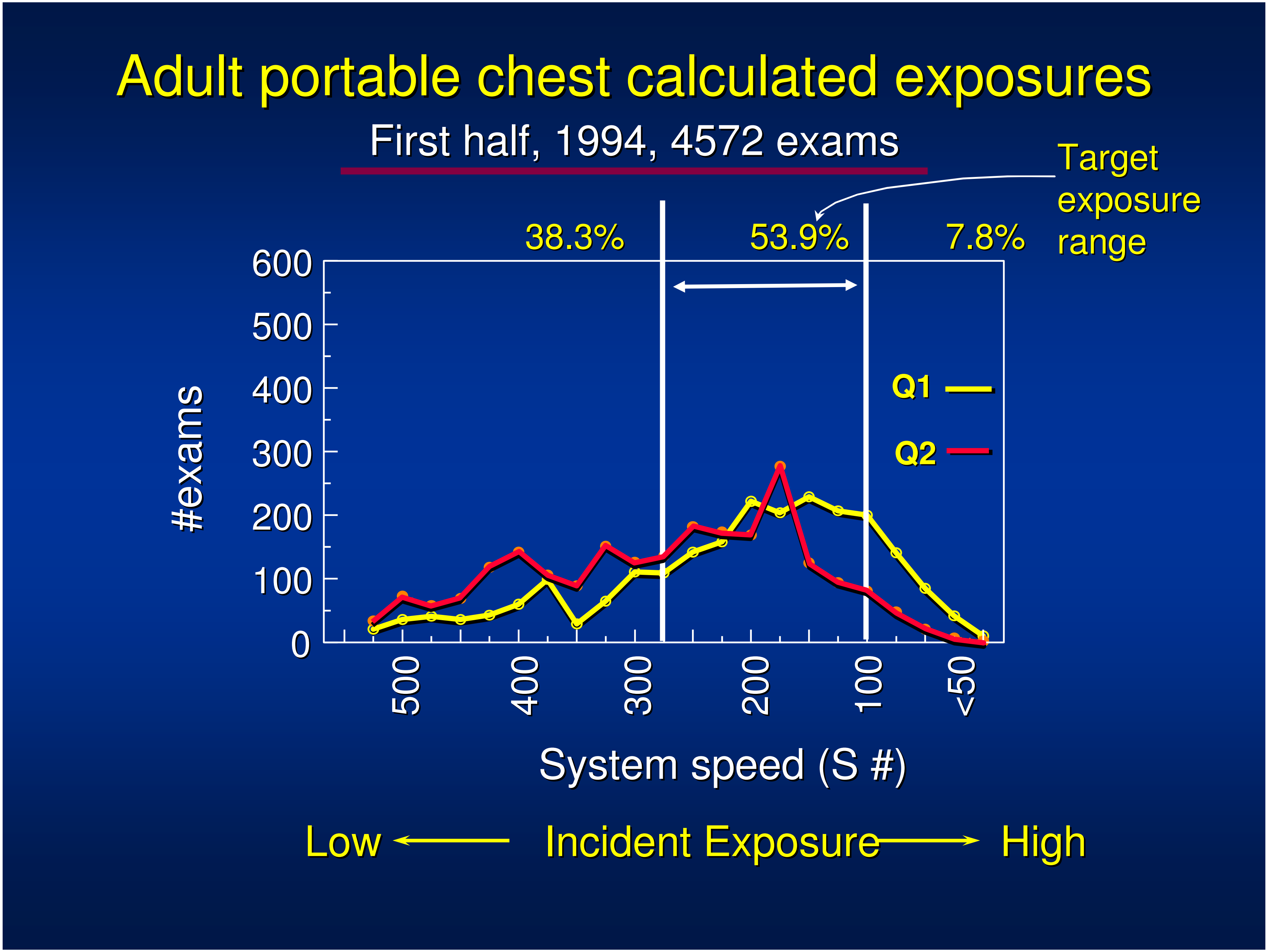
- Variable speed should be used to advantage
- Anatomical information can be lost with too high or too low exposure

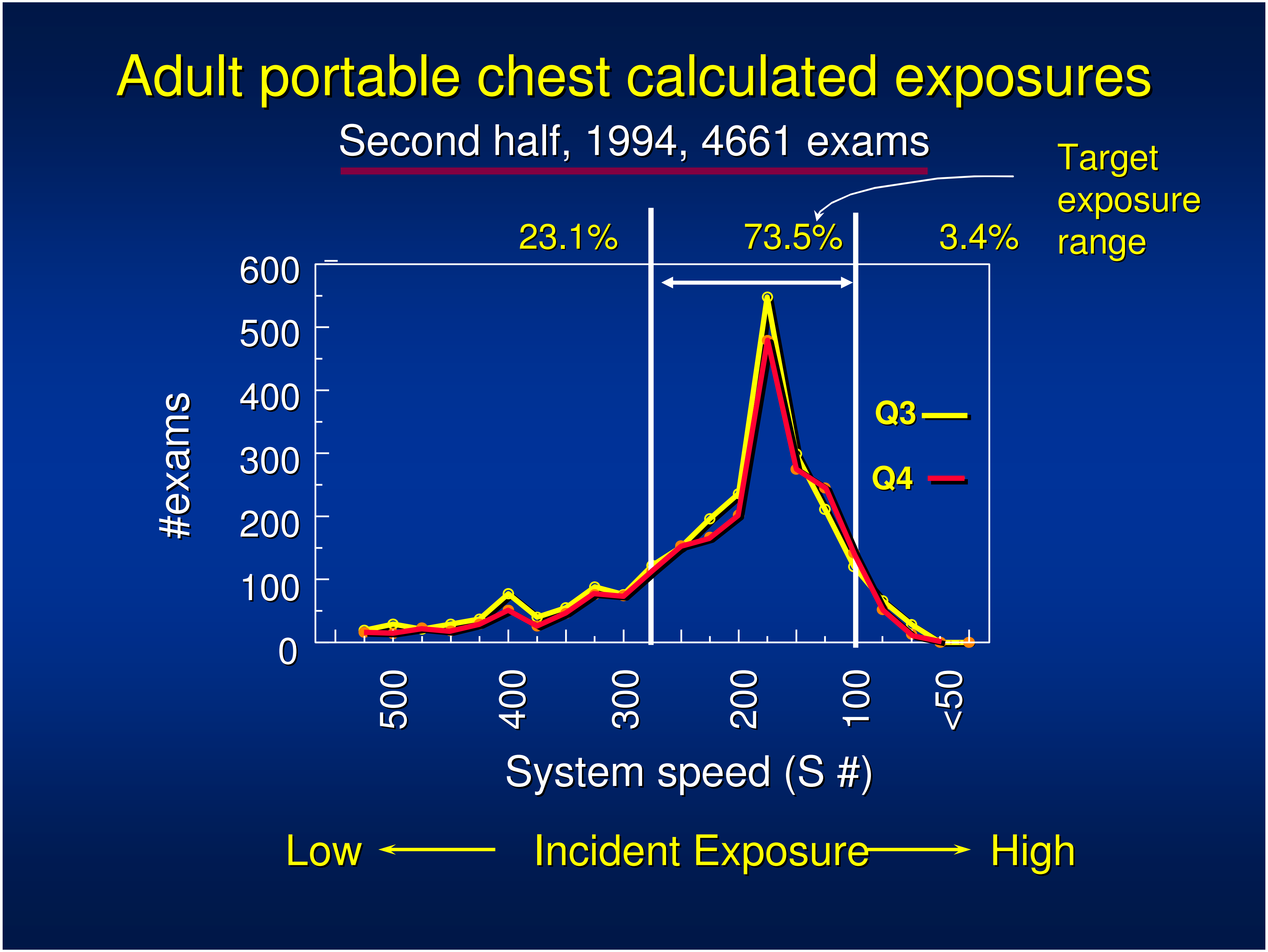
How do you get the data?

- System dependent
- In some cases offered by vendor with optional QC package
- Can export data into excel spreadsheet

sampleIIPoutput.xls

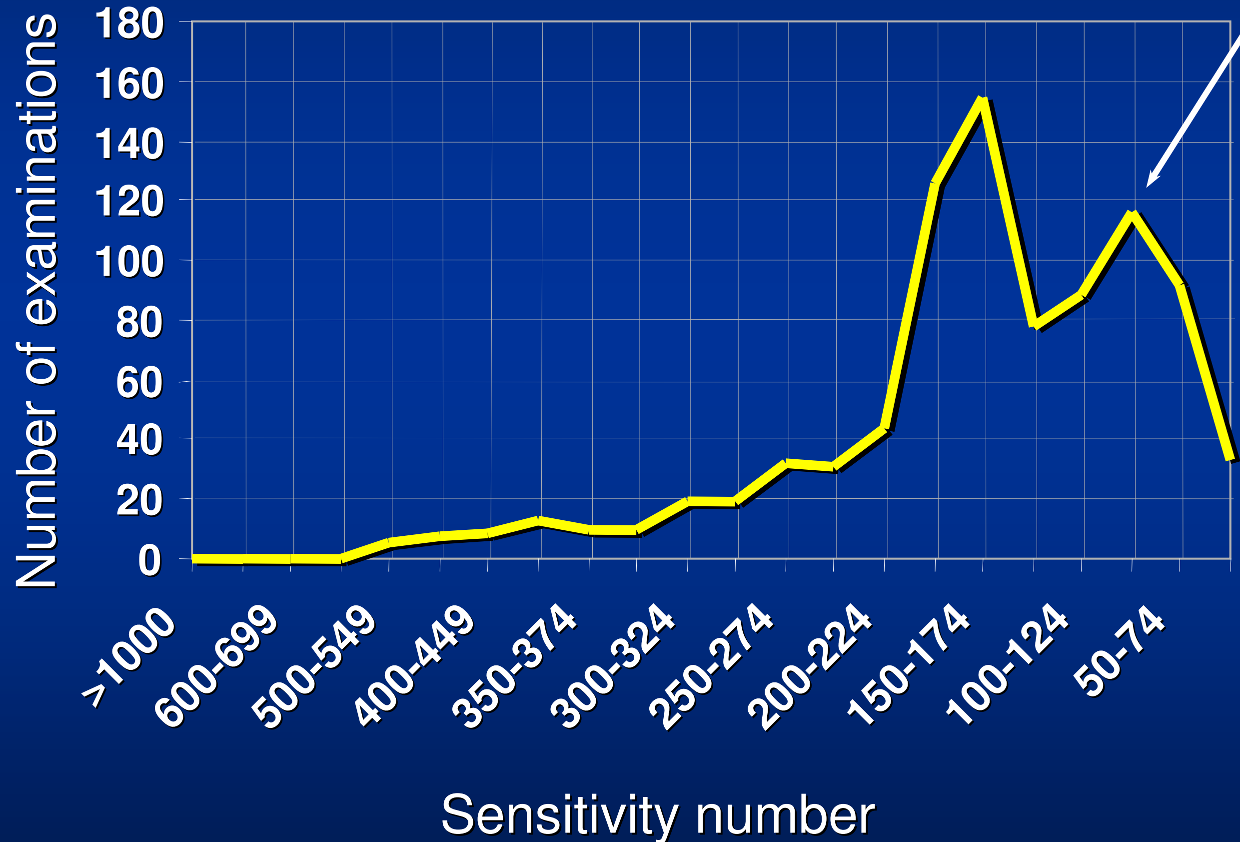
	PatientName	Birth Date	Sex	Study Date	Study Time	Body Part Examined	S-Value	L-Value	IP Number
2			M	20040210	155430	LOW_EXM	200	40	a08405654c
3			M	20040210	155430	LOW_EXM	100	17	a20053338c
4			M	20040225	135515	HEAD	167	16	a07777523c
5			M	20040225	135515	HEAD	159	17	a07778322c
6			M	20040225	135515	HEAD	159	22	a07911149c
7			M	20040225	135515	HEAD	124	22	a07778322c
8			M	20040225	135515	HEAD	159	18	a07778049c
9			M	20040301	101028	CHEST	382	23	a08089458c
10			F	20040302	115810	ABDOMEN	110	20	a09875296c
11			F	20040302	115810	ABDOMEN	118	26	a41507681c
12			F	20040302	115810	ABDOMEN	142	17	a09875296c
13			F	20040302	115810	ABDOMEN	139	20	a08807915c
14			F	20040302	115810	ABDOMEN	142	20	a41507681c
15			F	20040302	115810	ABDOMEN	318	16	a08089847c
16			F	20040302	115810	ABDOMEN	129	19	a41507681c
17			F	20040302	115810	ABDOMEN	126	18	a08807915c


Adult portable chest calculated exposures
First half, 1994, 4572 exams
Target exposure range
38.3%
53.9%
7.8%
600
500
400
300
200
100
0
#exams
Q1
Q2
500
400
300
200
100
<50
System speed (S #)
Low
Incident Exposure
High



Adult portable chest calculated exposures
Second half, 1994, 4661 exams
Target exposure range
23.1%
73.5%
3.4%
600
500
400
300
200
100
0
#exams
Q3
Q4
500
400
300
200
100
<50
System speed (S #)
Low
Incident Exposure
High

April 1 - 17, 1996
Adult Portable Chest



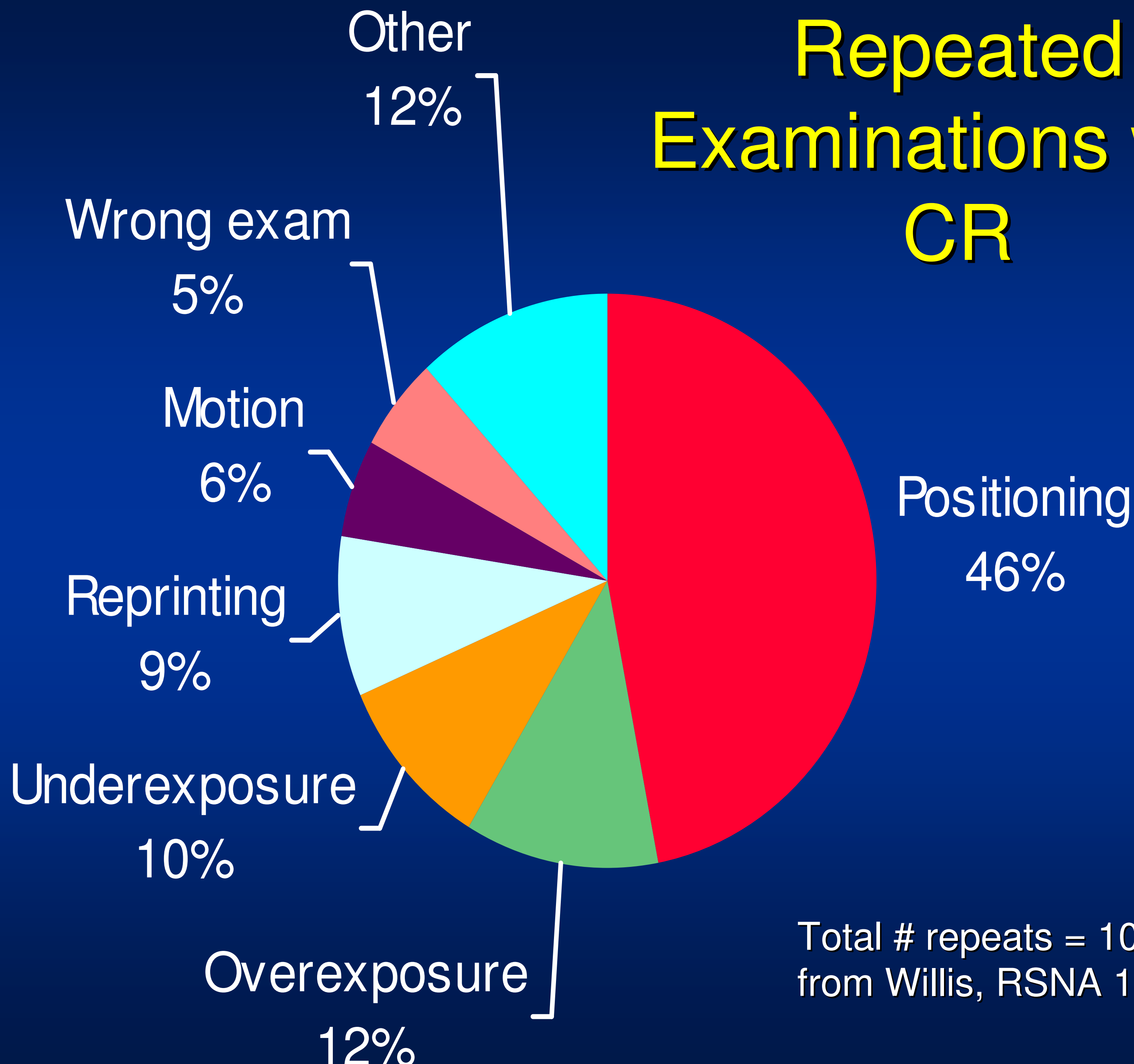
"Exposure Creep"

Grid technique without a grid

Guidelines for QC based on Exposure

S number	Inc.Exposure	Indication
>1000	<0.2 mR	Underexposed: **repeat**
600 – 1000	0.3-0.2 mR	Underexposed: QC exception
300 - 600	1.0-0.3 mR	Underexposed: QC review
150 - 300	1.3-1.0 mR	Acceptable range
75 -150	1.3-2.7 mR	Overexposed: QC review
50 - 74	4.0-2.7 mR	Overexposed: QC exception
<50	>4.0 mR	Overexposed: **repeat**

Repeated Examinations with CR



Total # repeats = 1043
from Willis, RSNA 1996

What should the manufacturers provide?

- A method to *visibly display* the exposure estimate on the image intuitively….. S number, Exposure Index, lgM
- Alert the technologist in some fashion (e.g., audibly) when an out of range situation occurs
- Implement an exposure database, specific to a given examination
- Interface to x-ray systems to get kVp, mA, time data for determination of entrance exposure

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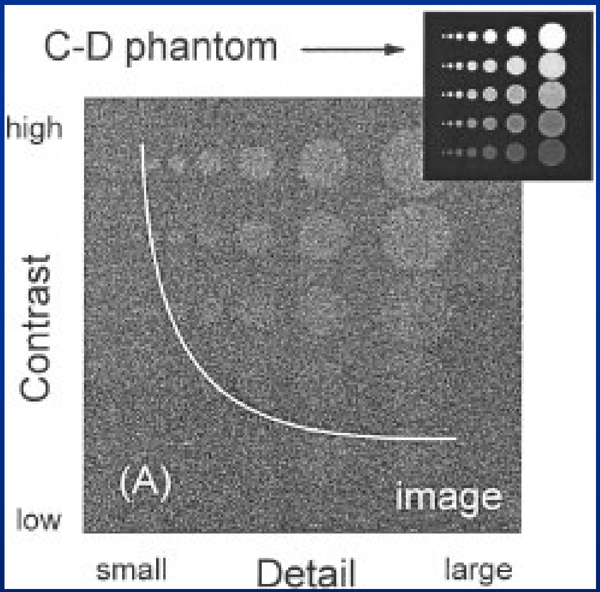
Visual Detection of Object

- SNR (CNR) is x-ray quanta dependent
- Detection is determined by CNR and object size



$$\text{Signal} \propto N_0 \eta g$$

$$\text{Variance, } \sigma_q^2 \propto N_0 \eta g (g^2 + \sigma_g^2)$$

$$\text{SNR}^2 = N_0 \eta \frac{1}{1 + \sigma_g^2 / g^2}$$

k is threshold detection CNR = 3 to 5

$$k = \text{SNR} \times d \times C$$

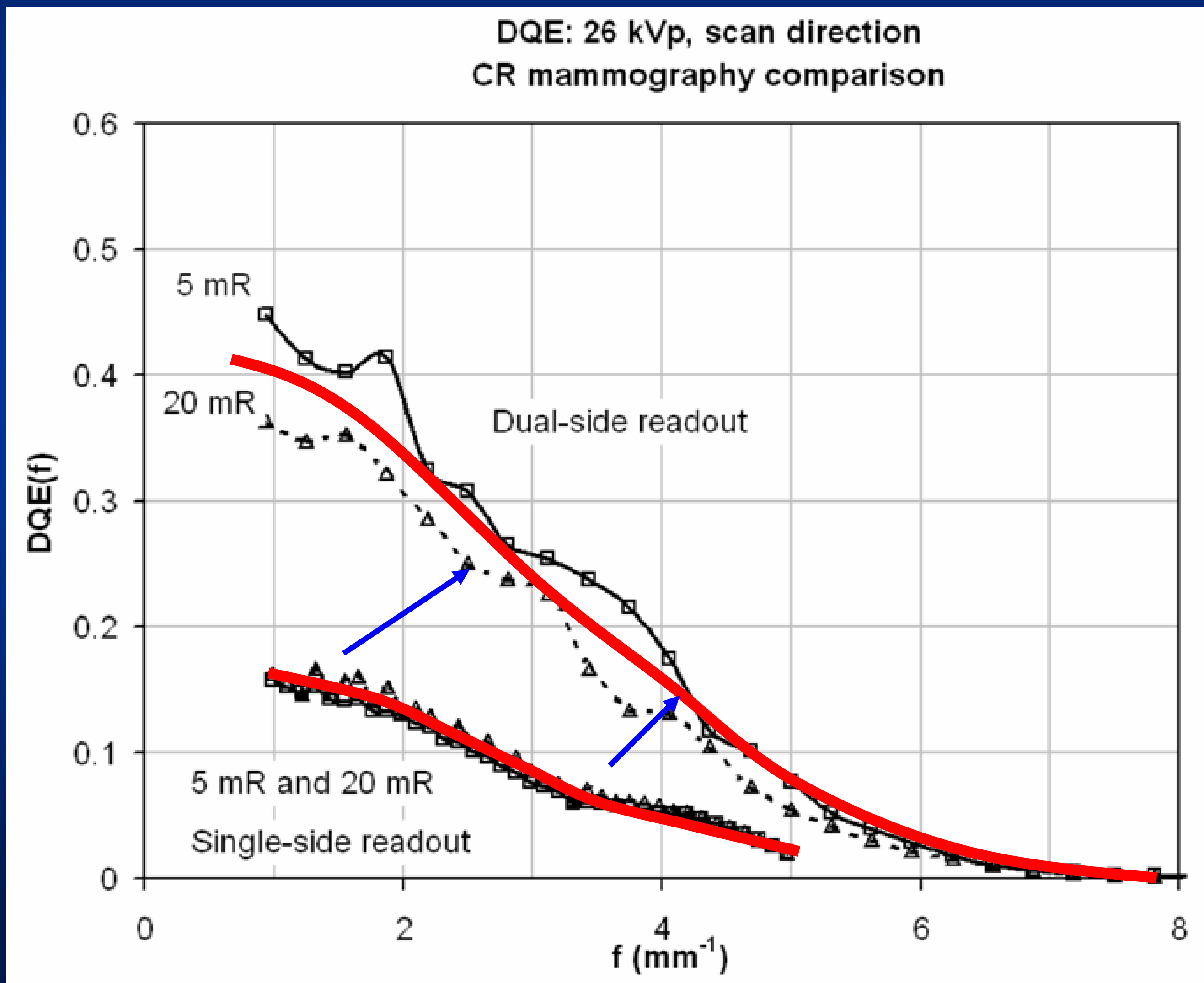
(circular object of diameter d and contrast C)

Detective Quantum Efficiency (DQE)

$$\mathrm{DQE}(f) = \frac{\mathrm{SNR}_{\mathrm{out}}^2}{\mathrm{SNR}_{\mathrm{in}}^2} = \frac{\mathrm{MTF}(f)^2}{\mathrm{NPS}_{\mathrm{N}}(f) \times q}$$

- A measure of the *information transfer efficiency* of a detector system
- Dependent on:
  - Absorption efficiency
  - Conversion efficiency
  - Spatial resolution (MTF)
  - Conversion noise
  - Electronic noise
  - Detector non-uniformities / pattern noise

CR: DQE improvements will lead to lower dose systems



Summary

- CR and DR are quickly replacing S/F
- CR must be considered as a “system”
- Knowledge of system operation is crucial
- Technological advances will continue
- CR and DR are complementary
  - CR is flexible, cost effective
  - DR is dose efficient, has high throughput