Radiation Exposure for CR/DR - What, Why, Where, How?

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CSRT Annual Conference

November 13, 2011

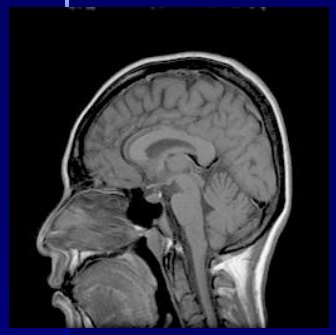
Cedars-Sinai Medical Center - Los Angeles

Learning Objectives

- Explain technology of available and future digital radiography technology
- Understand underlying system operation and characteristics
- Compare CR/DR image acquisition and display advantages / disadvantages
- Discuss Methods to monitor Patient Exposures

“Digital” Radiology

Digital Radiography

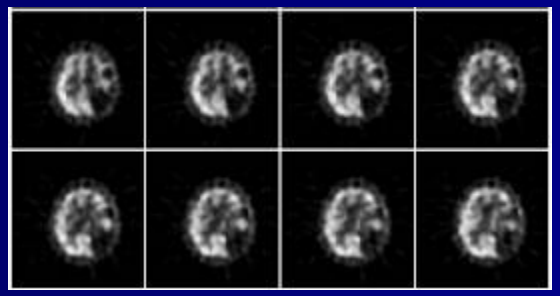


MRI

PACS

Interventional Angio

CT



Nuclear Medicine

Ultrasound

Fundamentals of Digital Radiography

- Screen-film radiography
- Analog versus digital
- Digital image acquisition and display
- Pre and post processing
- Radiation dose issues

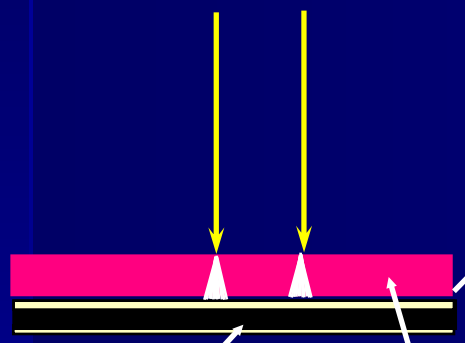
The new millennium

- 100 years of diagnostic radiography based upon screen-film detectors
- Electronic imaging and digital acquisition devices are now in the majority phase of implementation
- Paradigm shift from analog to digital imaging is changing the rules..... and education ..... and training

Digital X-ray Detector

1. Acquisition

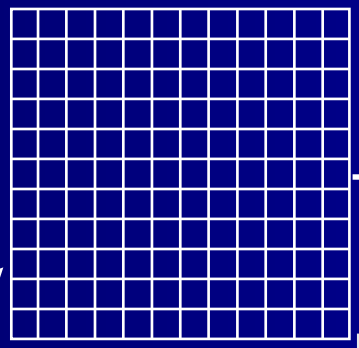
Transmitted x-rays through patient



Charge collection device

X-ray converter
x-rays → electrons

Digital Pixel Matrix

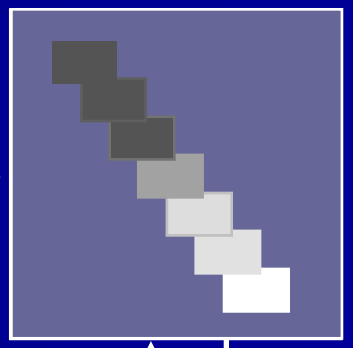


Analog to Digital Conversion

Digital processing

2. Display

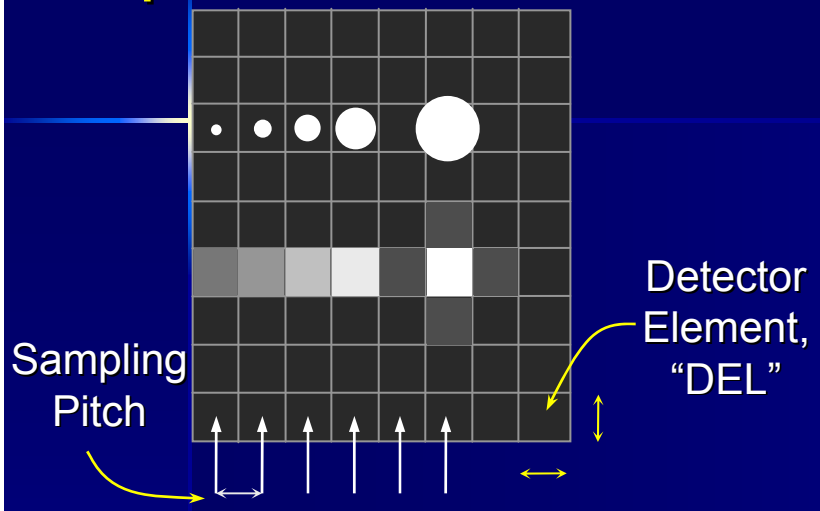
Digital to Analog Conversion

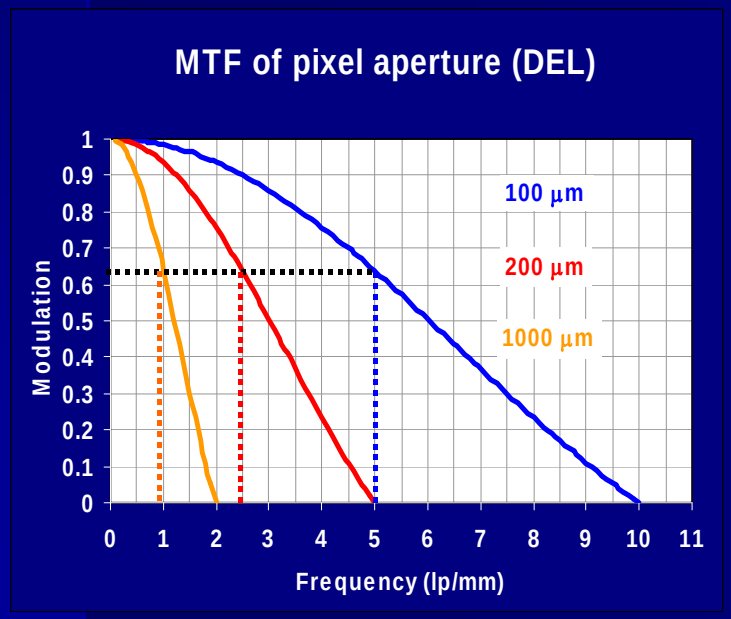


3. Archiving

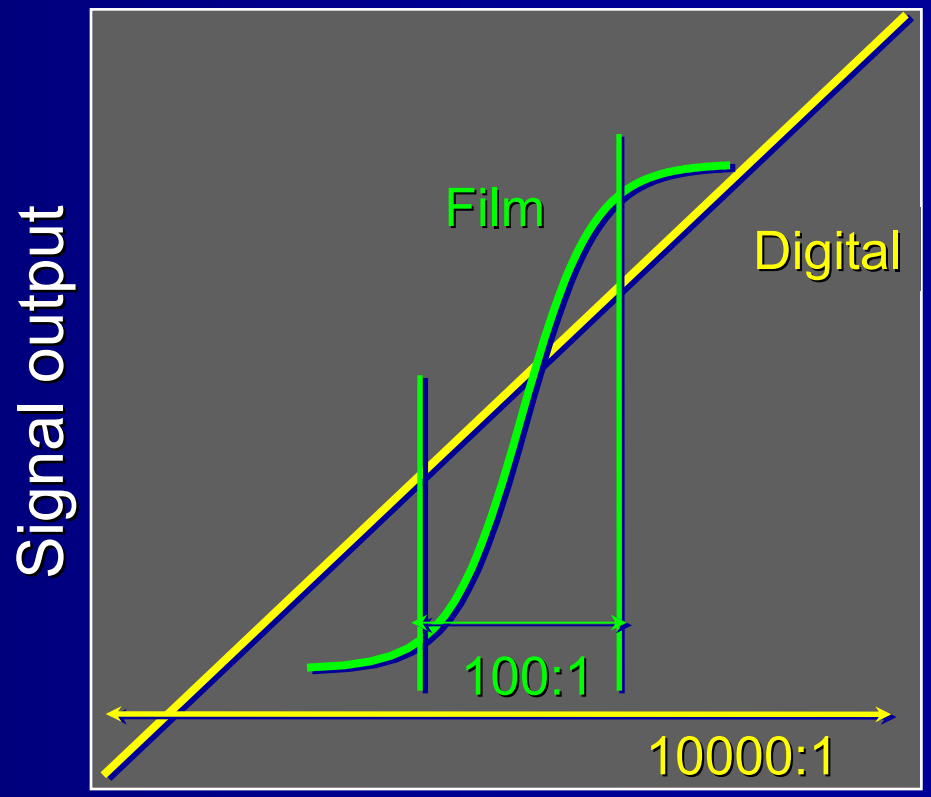
Analog versus Digital

Spatial Resolution





Exposure Latitude



Display adjustments

- LUT: Look up table
  - Dynamic conversion of digital data through a translation table
  - *Non-destructive* variation of image brightness and contrast
  - Reduced *display* dynamic range requires compression of image range data

Window Width / Window Level

SNR and CNR

- SNR: Average value / Std Dev of background
- CNR: Δ Attenuation / Std Dev of background
  - Contrast: tissue differences, tissue/bone differences
  - Dependent on subject contrast (x-ray energy), size of object, and digital image processing
- Perceptual vision studies: a minimum CNR of 3 to 5 is necessary to reliably detect a “medium size” object in a *uniform*, noisy background

Available digital radiography technology, 2010

- CR: Photostimulable Storage Phosphor (PSP)
  - Cassette-based detectors/readers
  - Flying spot mechanical changers
  - Line scan integrated detectors
- CCD: Charge-Coupled Device
  - 2-D lens coupled systems
  - 1-D slot-scan systems
- Thin-Film-Transistor (TFT) flat panel
  - Indirect detection (scintillator)
  - Direct detection (semi-conductor)

Future “in-progress” technologies

- Hybrid direct / indirect flat panel TFT with variable gain
- Direct semiconductor materials with HgI_2 , PbI_2
- X-ray photon counters based on gas detectors or silicon strip detectors
-)…
- Complementary Metal Oxide Semiconductor (CMOS)

Digital Detector Technologies

Cassette based

- Point-scan PSP
- TFT with Gd_2O_2S
- CMOS with CsI

Cassette-less based

- Line-scan PSP
- Optically coupled CCD
- Slot-scan CCD array
- TFT Indirect detection
- TFT Direct detection
- Photon counting detection

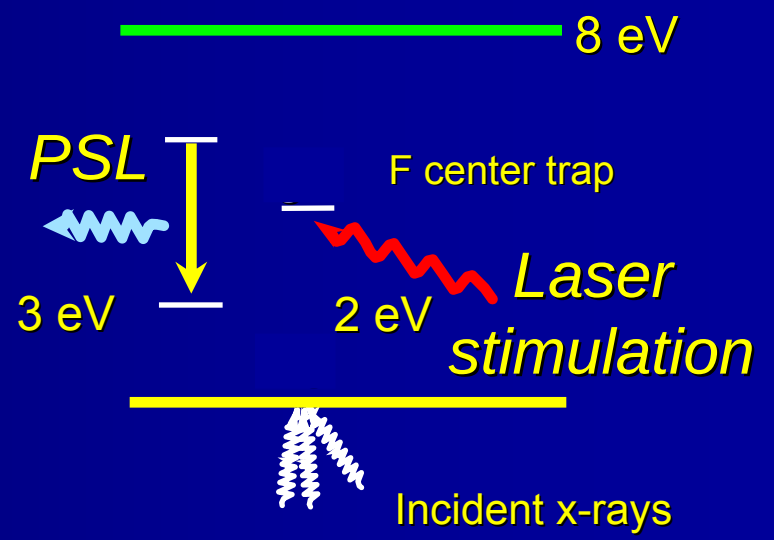
- Radiography
- Mammography
- Fluoroscopy

PSP Radiography (CR)

- Currently *the* major technology available for large field-of-view digital imaging
- Based upon the principles of photostimulated luminescence; 20+ years of experience
- Operation emulates the screen-film paradigm in use and handling.. (flexible but labor intensive)
- Manufacturing trends:
  - Smaller, faster, less expensive

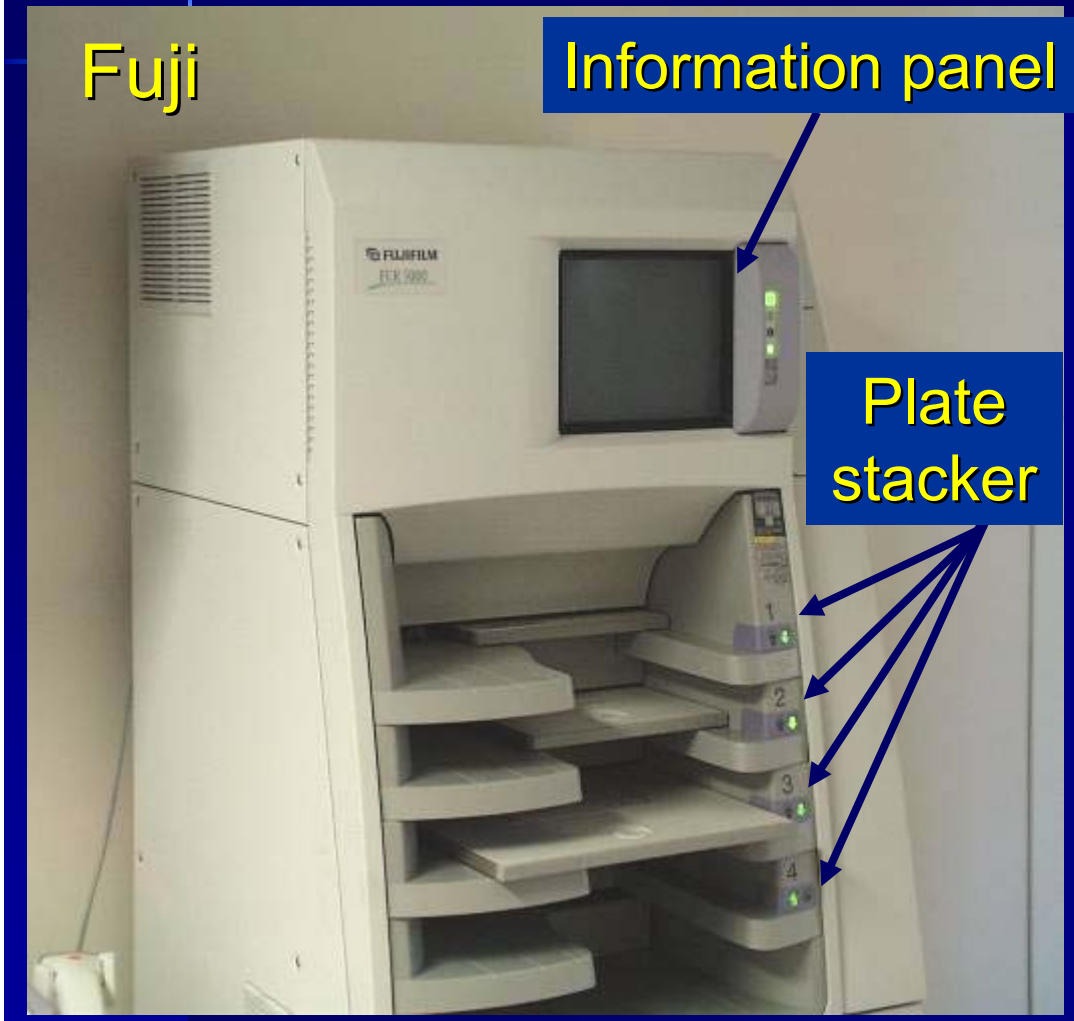
PSP Detector

- Photostimulable Storage Phosphor (PSP)

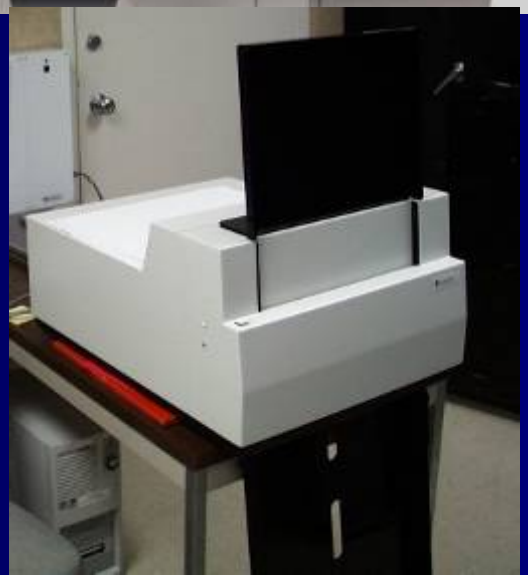


- Coating thickness:
  - Standard resolution: ~100 μm BaFBr
  - High resolution: ~50-70 μm BaFBr
- Dual-side read; structured phosphor – CsBr

Computed Radiography “reader”



Computed Radiography “reader”



CR "system": more than the IP's and the reader!!

Image Acquisition

CR Reader

CR QC Workstation

DICOM / PACS

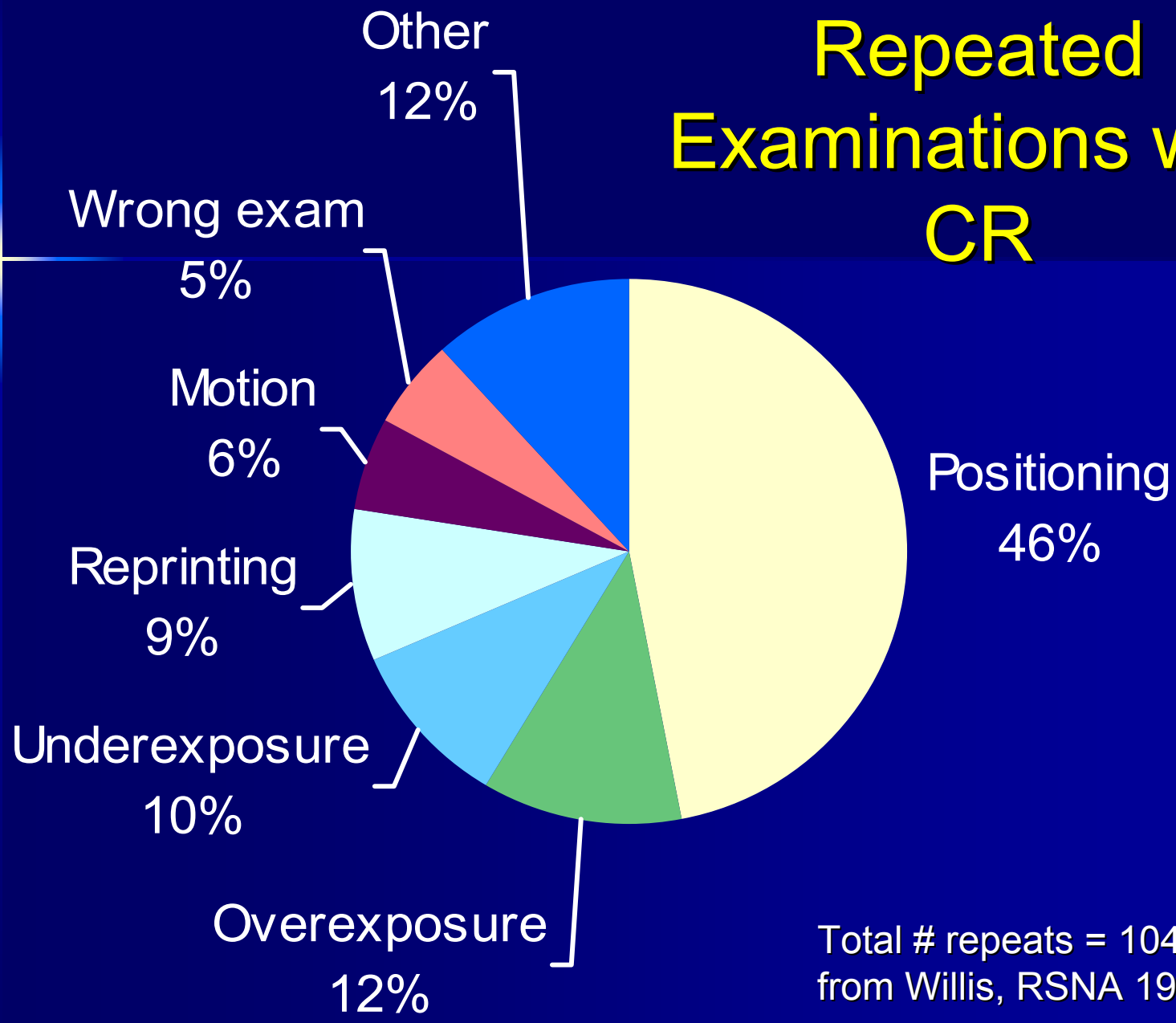
Laser film printer

Display / Archive

CR / DR: Radiation Exposure

- CR & DR systems exhibit wide dynamic range
- CR & DR provide ability to reduce retakes due to inappropriate radiographic techniques
- The *ability to lower radiation dose* depends on detector efficiency (DQE) and *required* SNR
- CR system ~200 speed for general applications DR system speed depends on DQE (efficiency)
- Exposure indices MUST be monitored

Repeated Examinations with CR

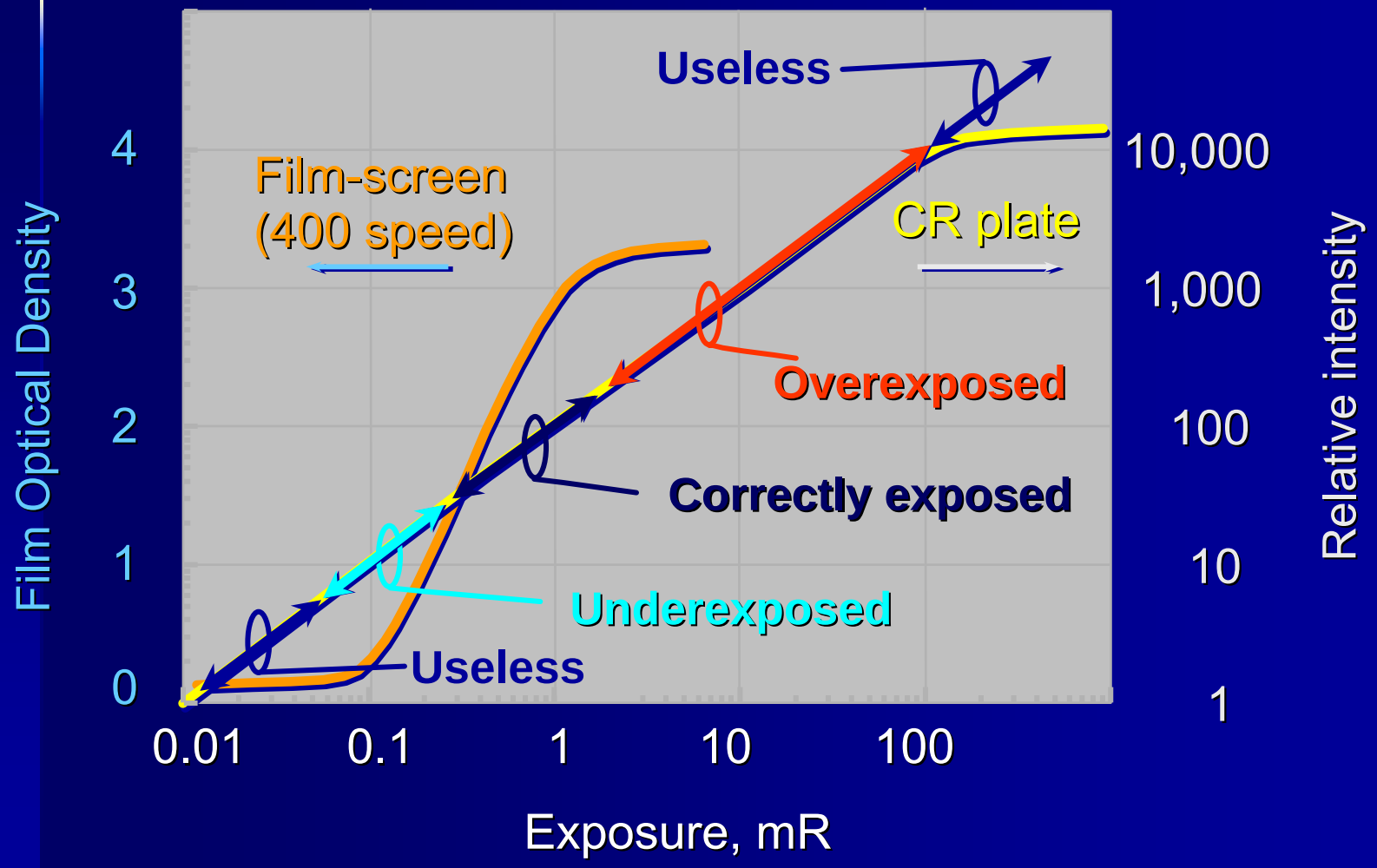


Total # repeats = 1043
from Willis, RSNA 1996

Why is incident detector exposure important?

- Is proportional to the image SNR (for given DQE)
- Signal to Noise Ratio → "image quality"
- Is indirectly related to patient exposure
- Image appearance and detector exposure are not linked as with screen-film receptors
- Exposure indicators can assist the technologist in identifying appropriate "equivalent speed"

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

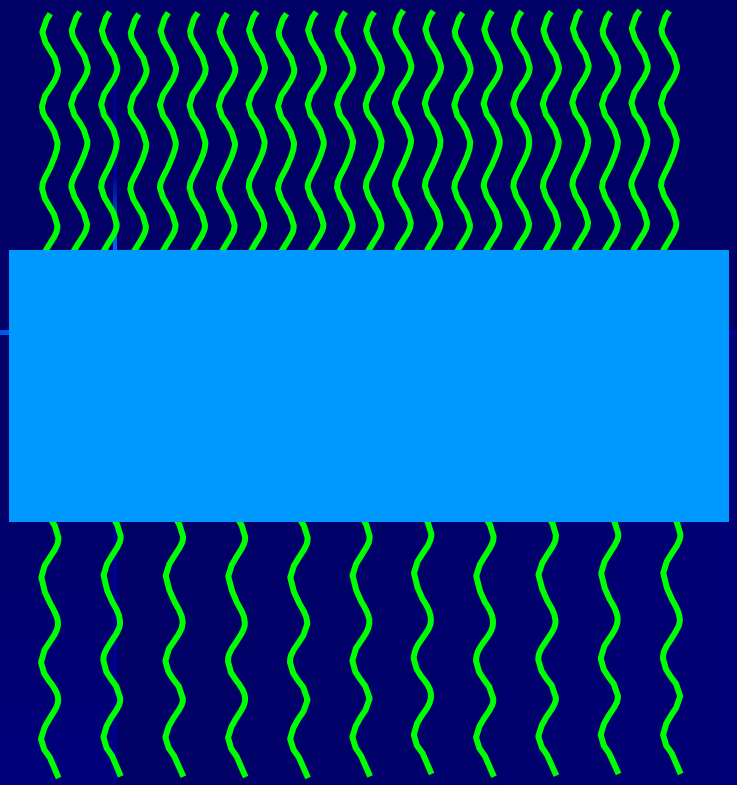


Observations on initial use of CR/DR

- **Problem**: cause and effect (exposure and OD) is disconnected with digital radiography
- **Outcome**: technologist frustration/confusion
- **Solution**: understand fundamentals of digital image acquisition and consequences of inappropriate settings / configurations; provide tangible *feedback*

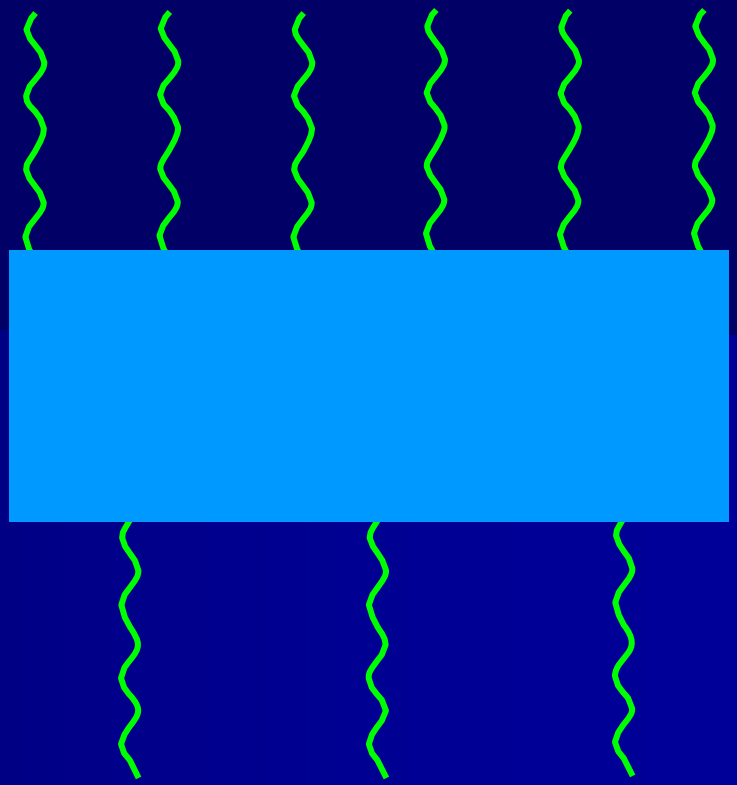
“Speed”

- “Speed” is inappropriate for digital systems
- A digital system can operate at a selected “speed”
- Is image ideal?
  - Low speed = low contrast, saturation
  - High speed = noisy
- “Speed class” is preferred term
- Operational receptor exposure.
  - 300 speed class ≅ 300 speed S/F
  - 100 speed class ≅ 100 speed S/F
  - 800 speed class ≅ 800 speed S/F



200 speed Class CR/DR

20 mAs – 75 kVp



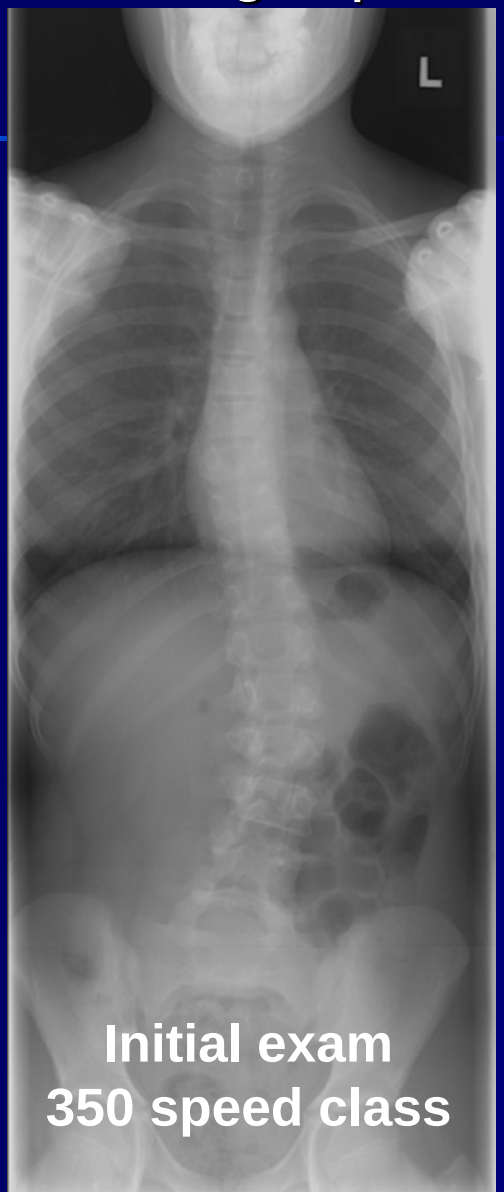
800 speed Class CR/DR

5 mAs – 75 kVp

With digital systems, technique used determines "speed class"

Use “pick a speed” to advantage

– Operate at high speed class when high noise is tolerable



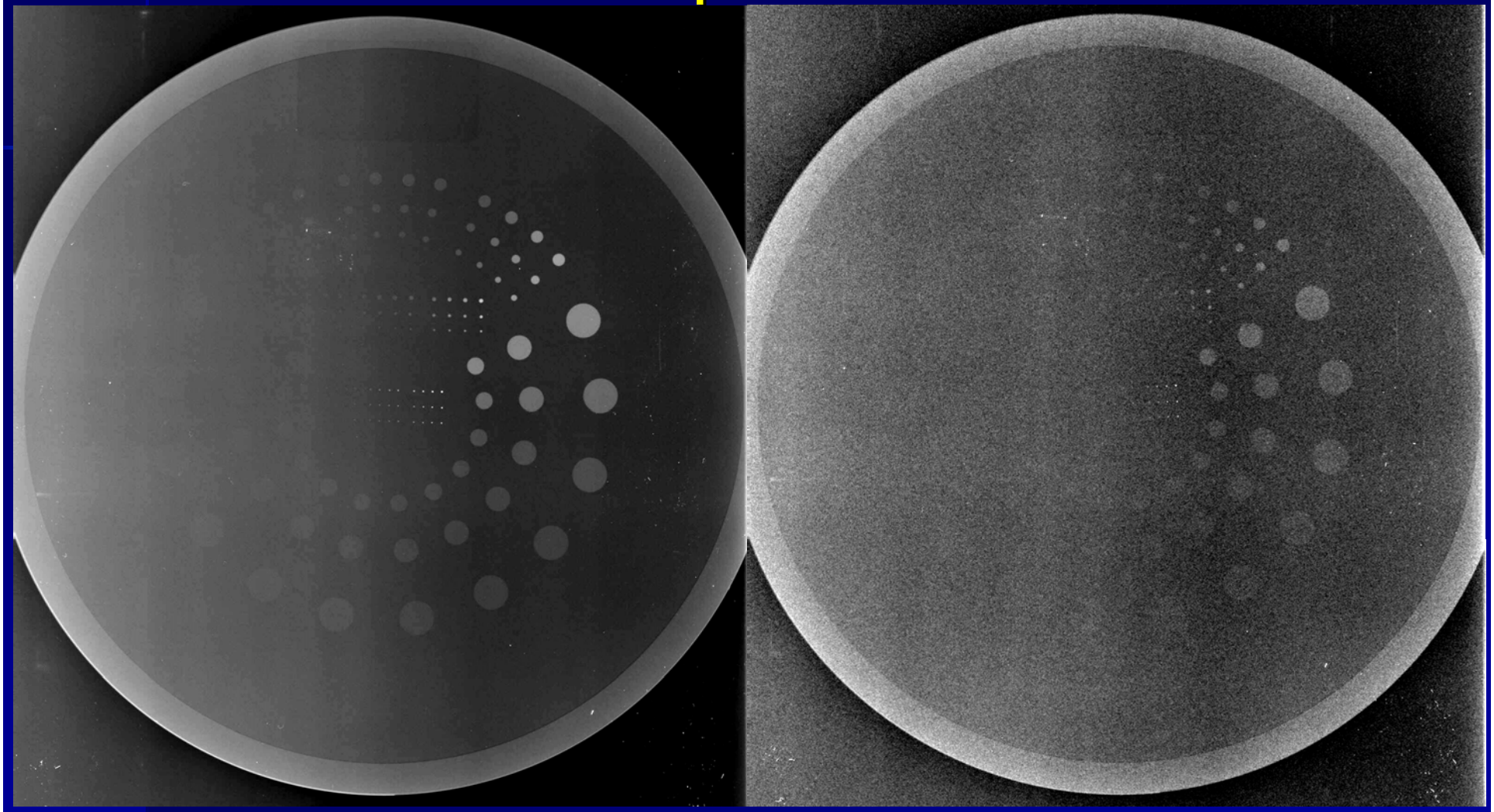
Longitudinal scoliosis study for pediatric patient.

Net effect: Lower total dose for patient.

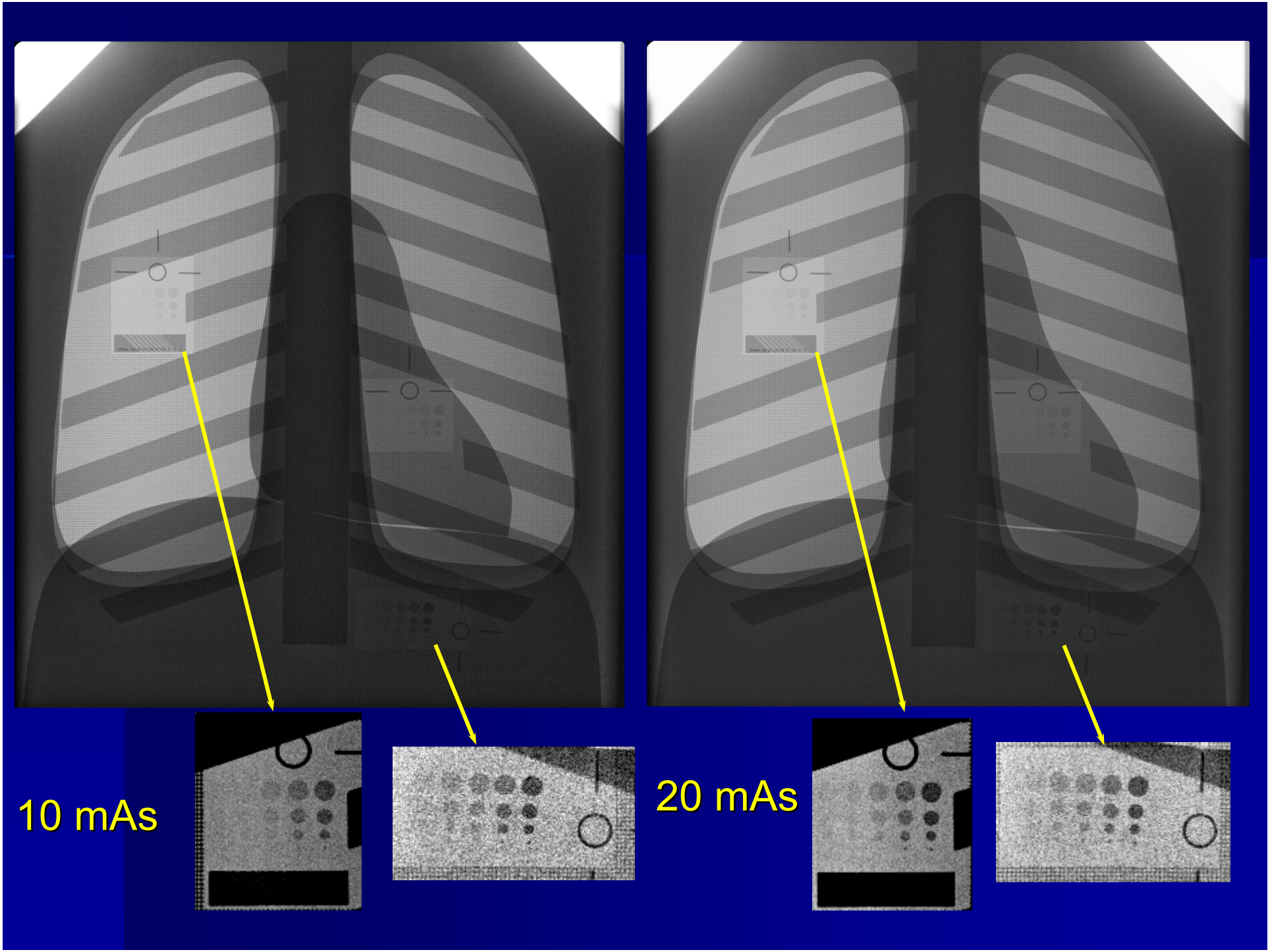
How low can you go?

- Dependent on the needed image fidelity
- Determined by the detector efficiency
- Detailed by the system exposure index

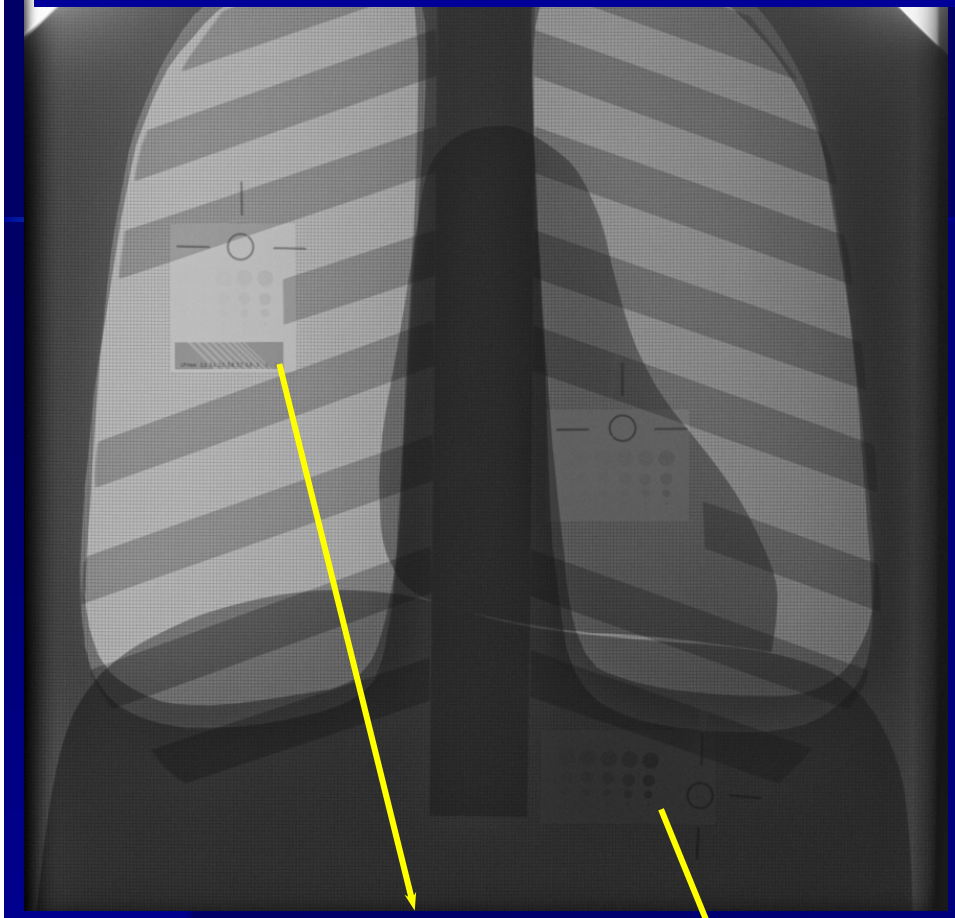
Low Contrast Response: Leeds TO-16

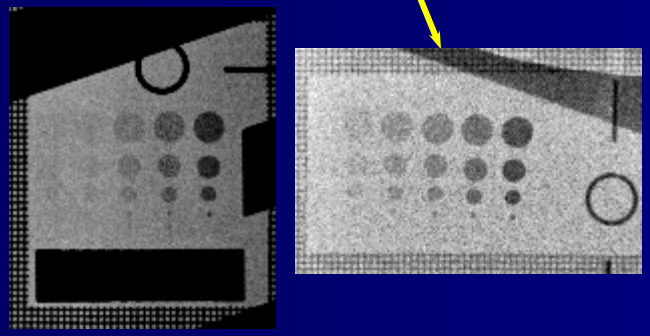


3.5 mR 70 kVp 0.5 mR

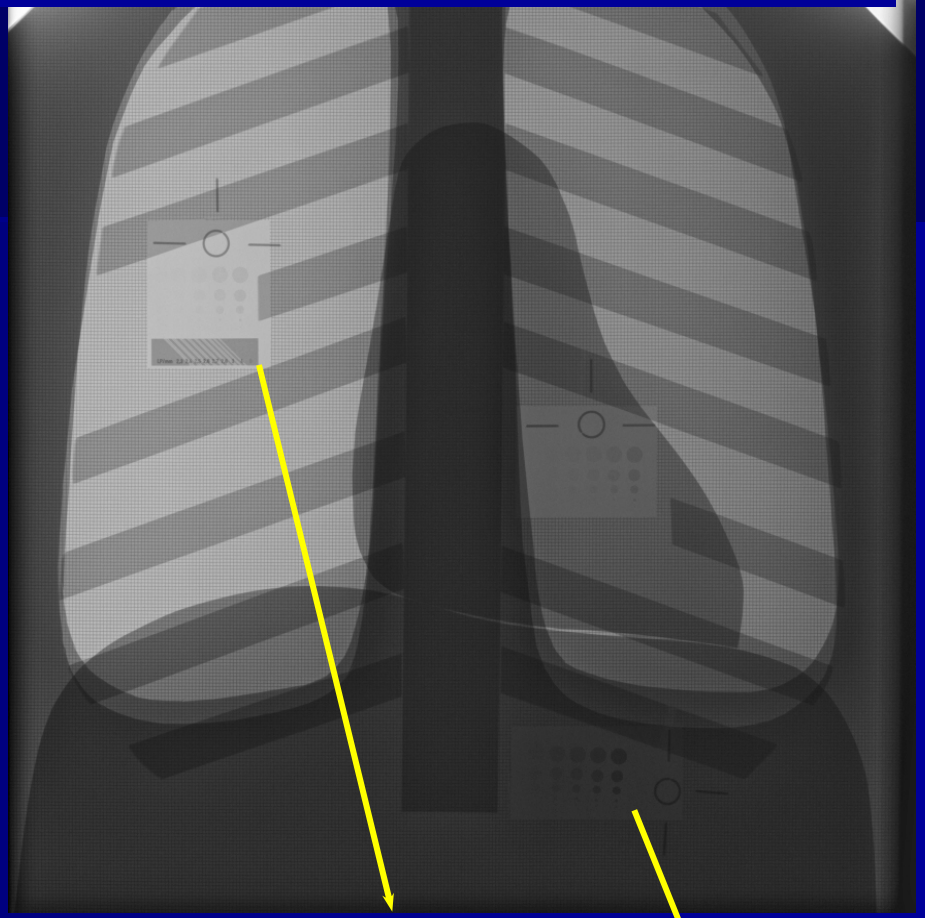

10 mAs
20 mAs

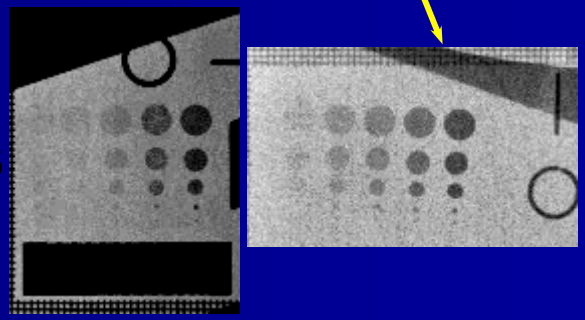
Exposure too high becomes counterproductive!!





50 mAs





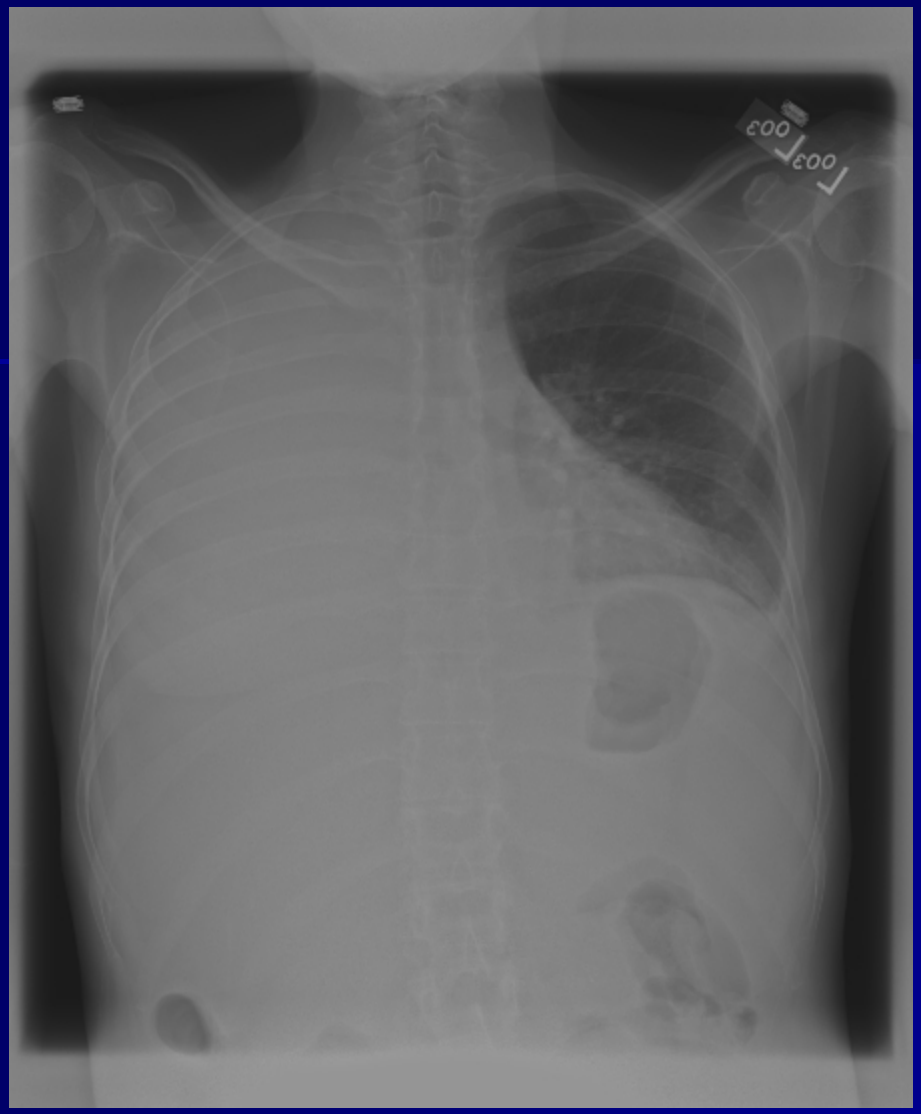
100 mAs

How do manufacturers indicate estimated exposure index?

- Fuji: "S" – sensitivity number
  - $S \cong 200$ / Exposure (mR)
- Kodak: "Exposure Index" – *EI*
  - $EI \cong 1000 \times \log(\text{Exposure [mR]}) + 2000$
- Agfa: "lg M" – relative exposure database
- Konica: REX – Relative EXposure (similar to S#)
- IDC: "*f*-number": $\pm 1\ f = \pm 2^f$ change in exposure
- DR: most systems currently ***do not*** have a feedback signal... but use phototiming (AEC) technique

Exposure Indicator Uses

- Monitor detector exposure index distributions
- Determine technical change for optimal receptor exposure
  - "S" value linear, inverse
    - S = 600, but want 300 → double receptor exposure
  - EI and LgM logarithmic, direct
    - EI =1500, but want 1800 → double receptor exposure
    - LgM =1.8 but want 2.1 → double receptor exposure



EI = 2400

- Over exposed 4X
  - Want EI = 1800 - 1900
  - Repeat using ¼ mAs & collimate.

Barry Burns, UNC

Barry Burns, UNC

Initial evaluation on QC monitor

– Image appearance – OK, but S = 360 (low for extremities)

Barry Burns, UNC

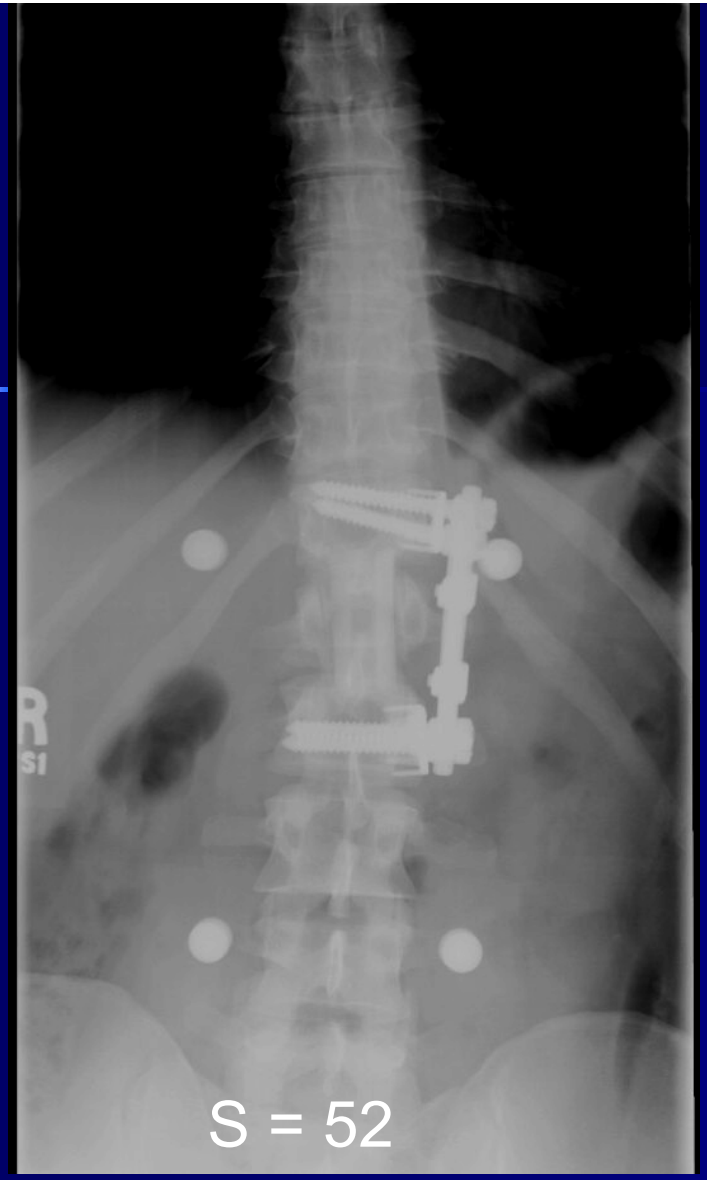
Underexposure

Zoom image

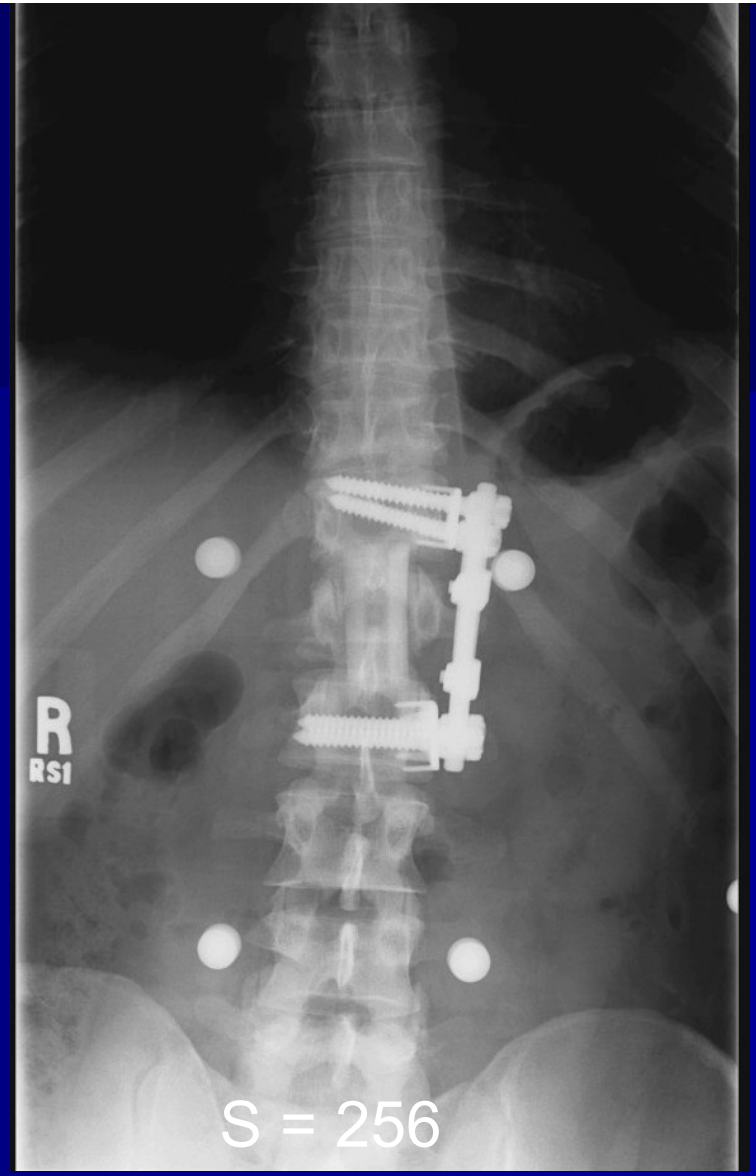
- Substantial mottle
- Loss of trabecular details.

Overexposures

- Reduced contrast
- Loss of structural information
- Detector saturation

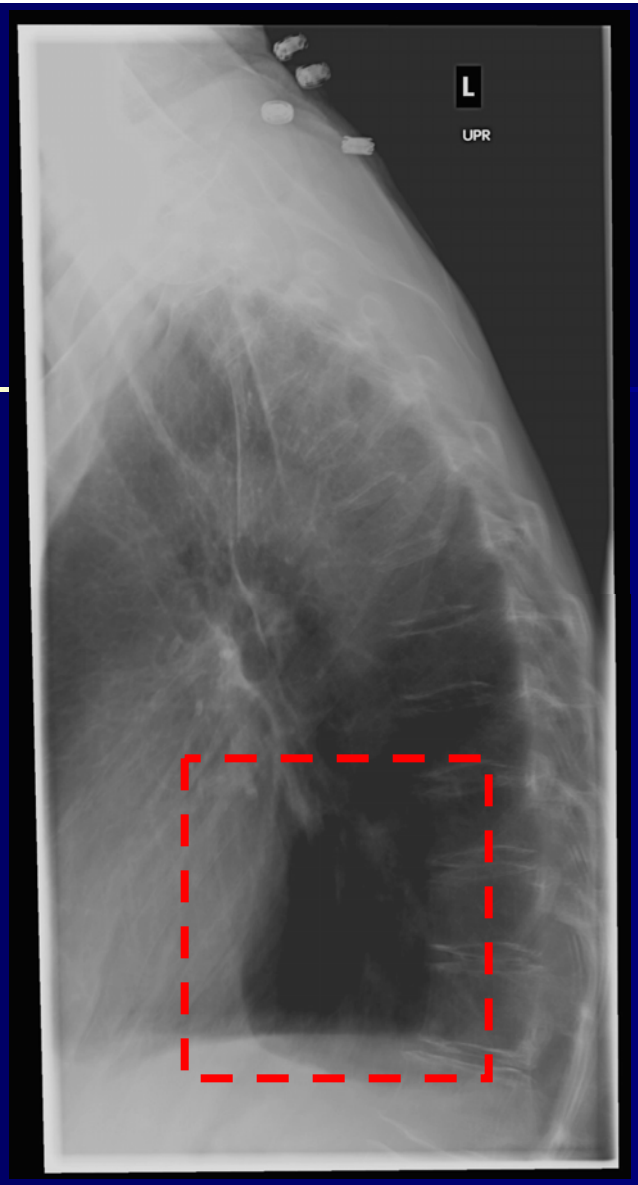


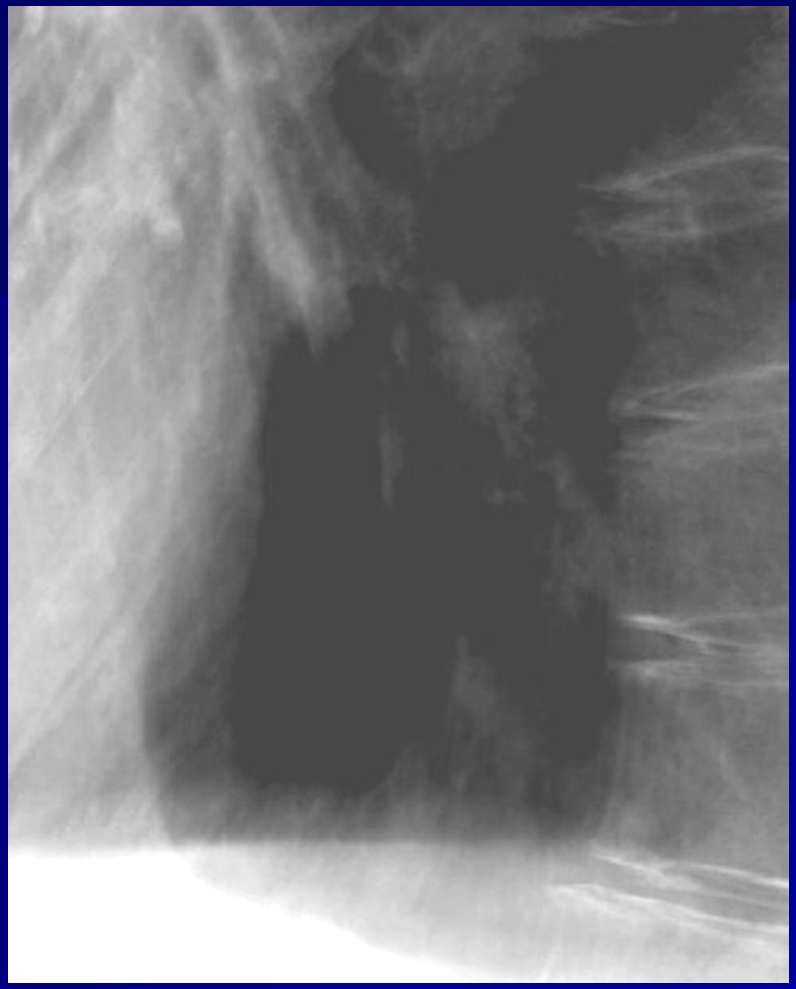
320 mAs – 88 kVp
Overexposed 5X
Want S ~ 250



60 mAs – 88 kVp

Barry Burns, UNC

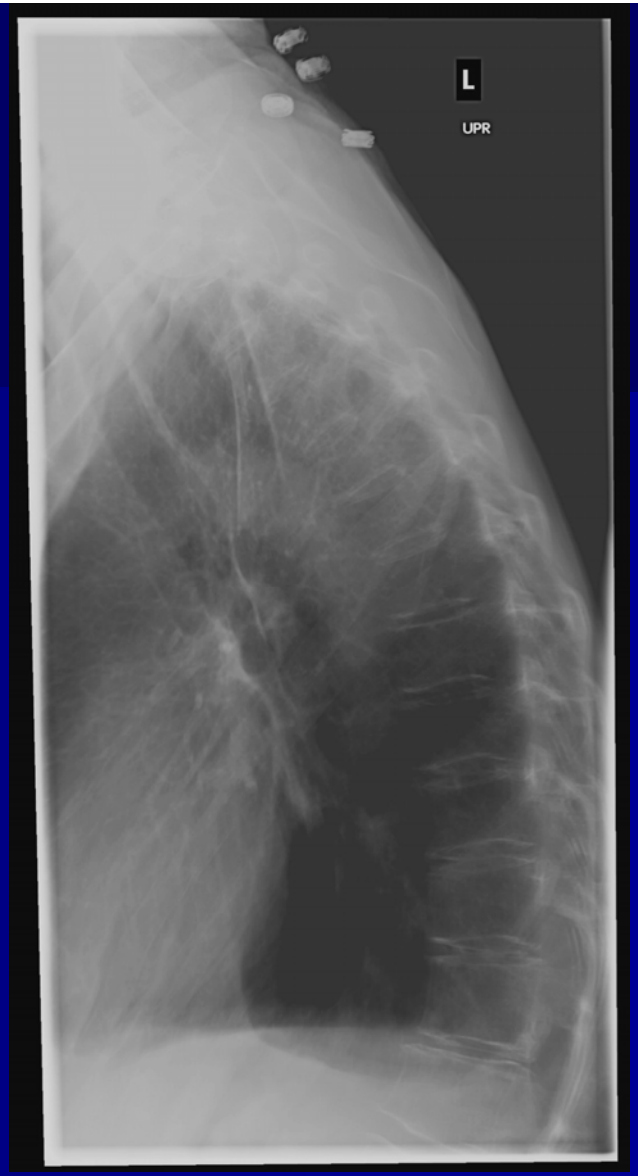




S = 40
Over Exposed 7X
Plate Saturation

Barry Burns, UNC

S = 150
Over Exposed ~2X



S = 40
Over Exposed 7X
Plate Saturation

Barry Burns, UNC

Exposure with CR/DR

- Incident exposure can be “hidden”
- Low exposures have excessive image noise
- High exposures are difficult to discern and can lead to saturation / loss of signal (over the top)
- Compensation can lead to technique complacency: “just enough” is desired
- Feedback is necessary but indices are confusing and very different, depending on manufacturer!

Sensitivity number, S (Fuji CR)

- Estimate of the incident exposure on the IP
- Comparable to screen-film “speed”
- Based on amplification required to map median histogram value to 511 (0 to 1023)
- Dependent on histogram shape, segmentation, *and* examination selected

Fuji Example

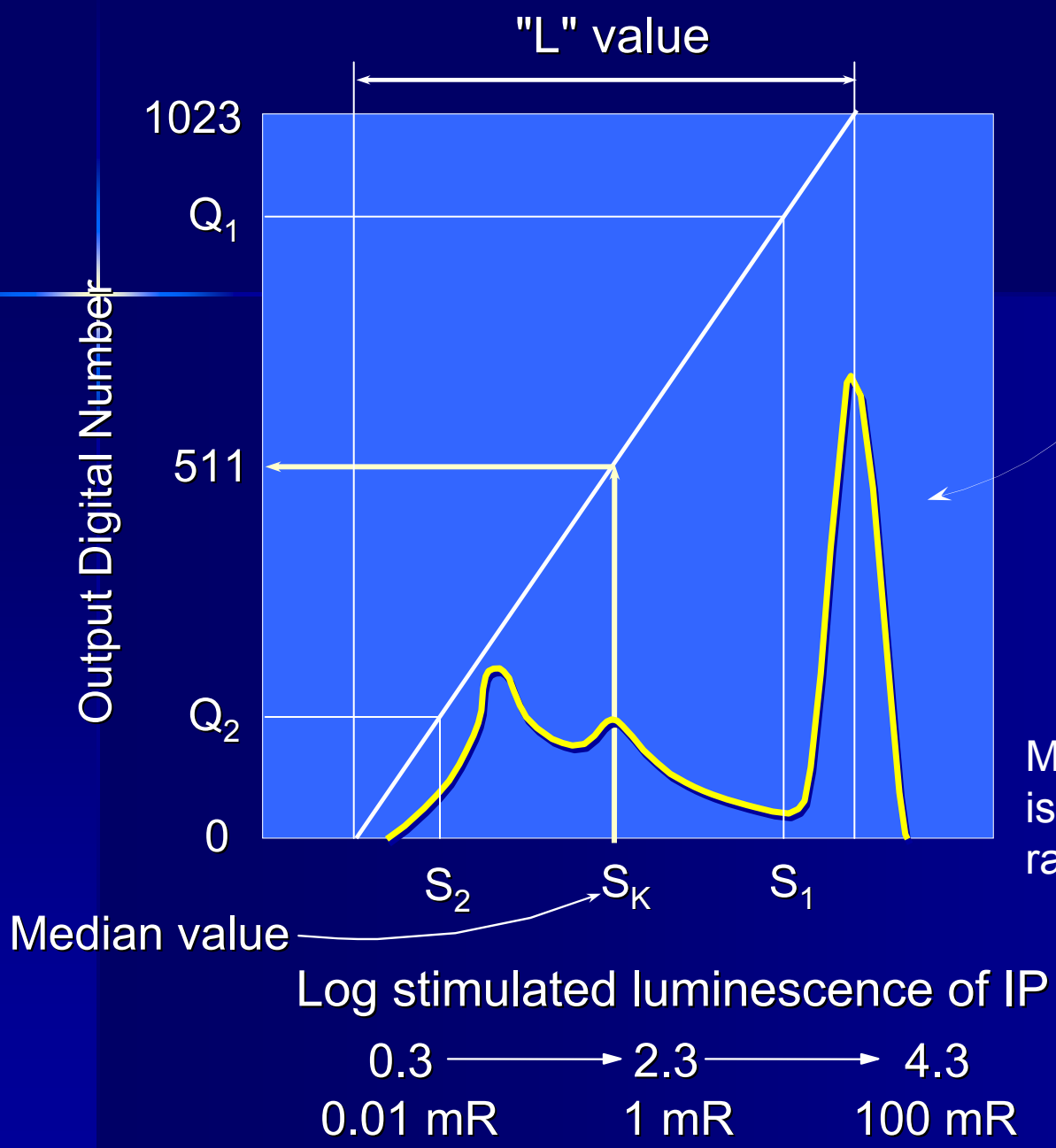


Image Histogram

$$S \cong \frac{200}{\text{exposure (mR)}}$$

Median value of "useful range" is mapped to middle of output range (511) via +/- applied gain

Exposure Index variability

- X-ray beam spectrum (kV and filtration)
  - "EI" number varies with beam hardness (calibration required)
- Collimation (beware of "electronic" collimation)
- Delay time from exposure to readout
  - Causes *significant* variation in EI number due to spontaneous fluorescence
  - Effect is greatest within first 5 minutes

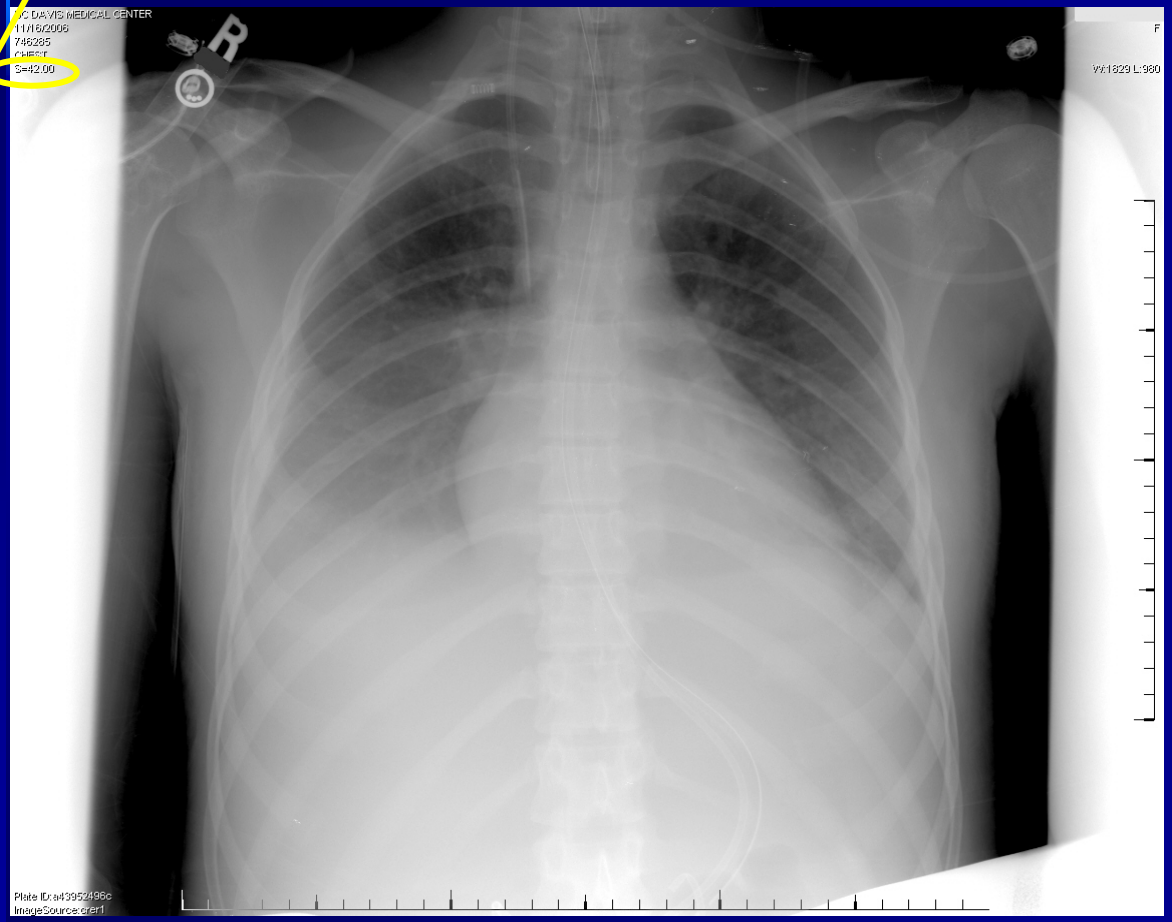
Exposure Index variability

- Image processing algorithms
  - Histogram shape specific
    ..... a wrist histogram a lot different than a chest!!
  - Segmentation can fail due to inappropriate algorithm

  - Ability to change index number interactively?!
  - Defeats purpose of Exposure Index
  - Changing value can compromise image quality
  - Most low S numbers (overexposure) are shifted higher, which saturates signals in output image

Why not change "S" number?

S=42



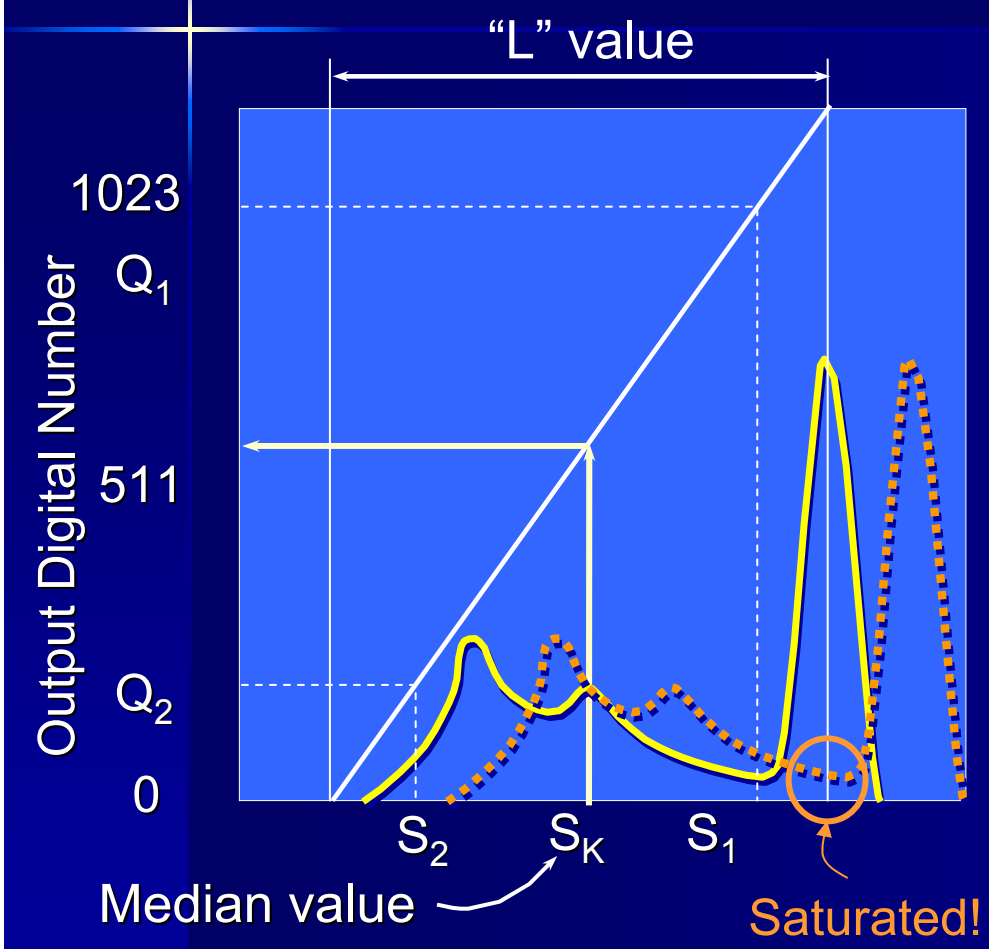
5x over-exposure!

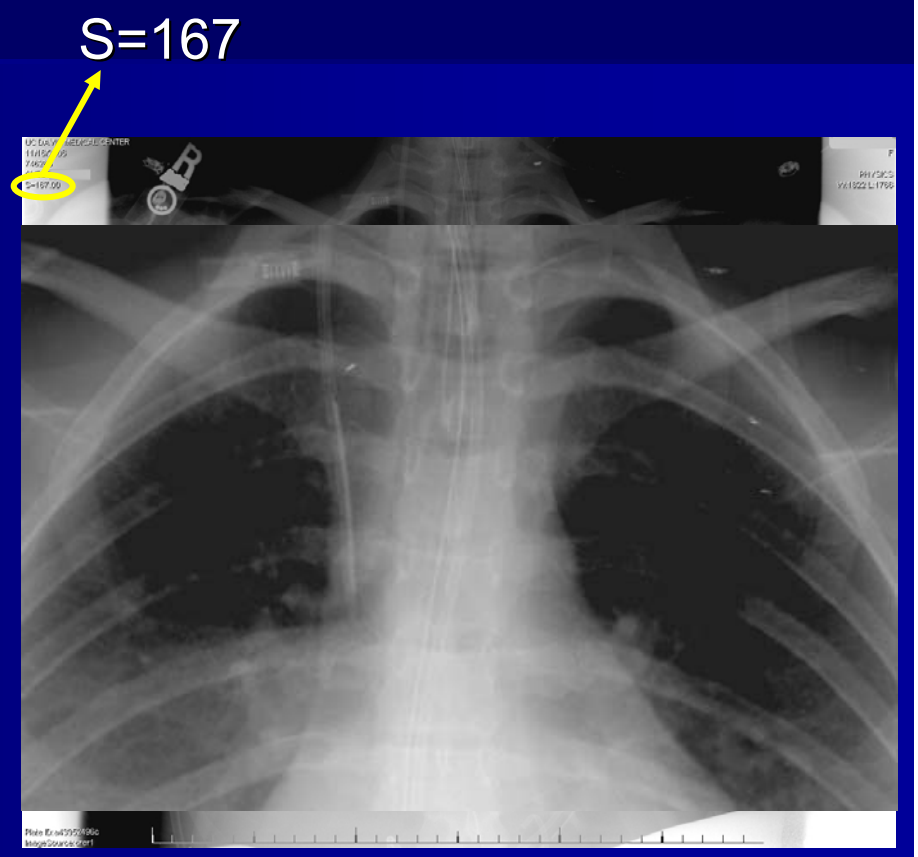
But image appears OK!

and is OK…

But…..

Changing index shifts histogram!





Exposure OK?..... NO!!
Database is "OK"

What S value is appropriate?

(or any exposure index value…..)

- Examination specific — 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

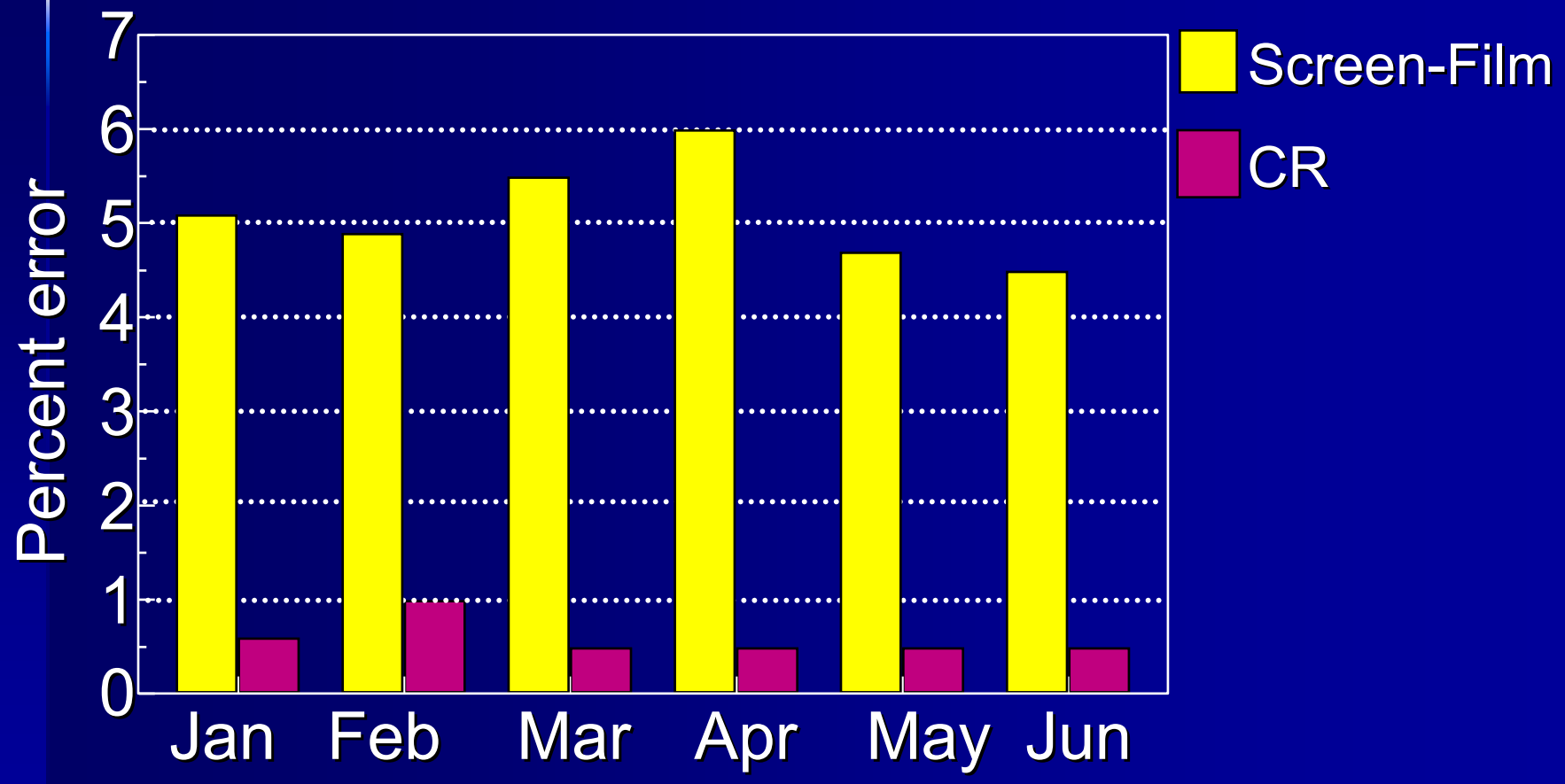
	E	F	G	H	I	K	N	O	P
1	PatientName	Birth Date	Sex	Study Date	Study Time	Body Part Examined	S-Value	L-Value	IP Number
2			M	20040210	155430	LOW_EXM	200	40	a08405654c
3			M	20040210	155430	LOW_EXM	100	17	a20053338c
4			M	20040225	135515	HEAD	167	16	a07777523c
5			M	20040225	135515	HEAD	159	17	a07778322c
6			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

What can you do with the data?

- Illustrate usage and exposure trends
- Determine detector speed class values
- Generate data for technologist feedback
- Document CQI process for digital radiography
- Use as a tool for education and training

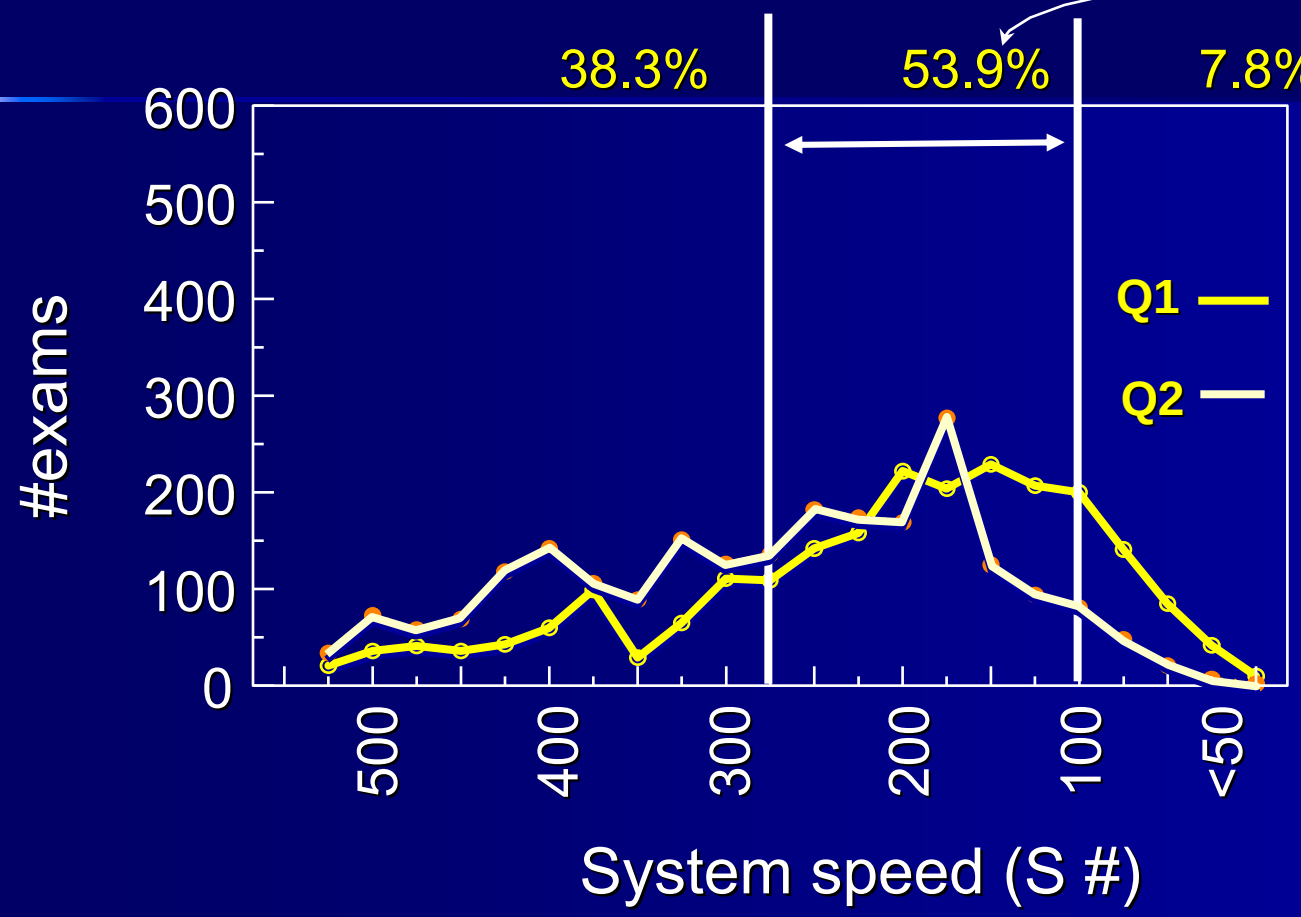
Image retake rates

Retake rate evaluation -- 1st half, Initial Year of Use



Adult portable chest calculated plate exposures

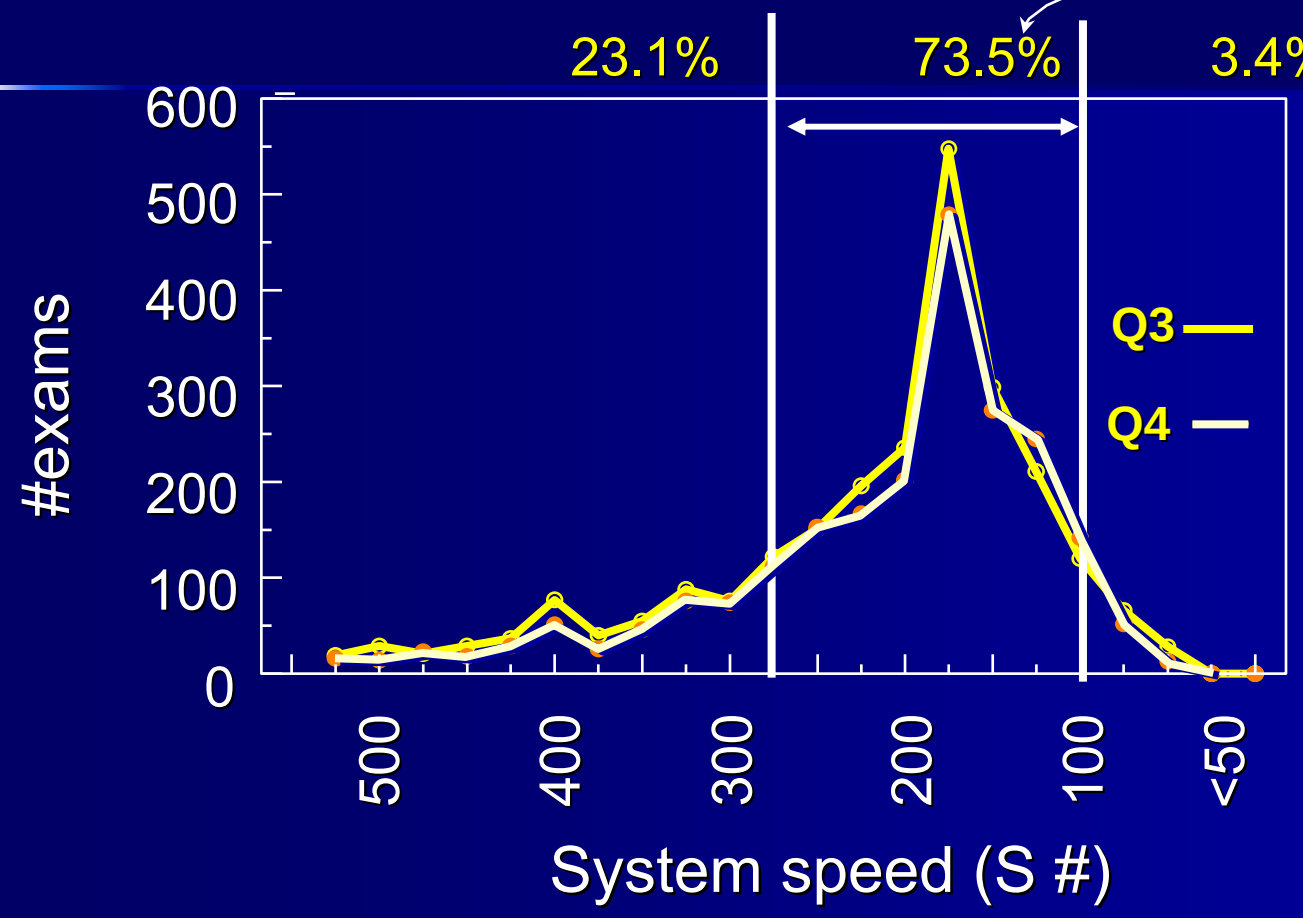
First half of Year 1 Use: 4000 exams



Low ← Incident Exposure → High

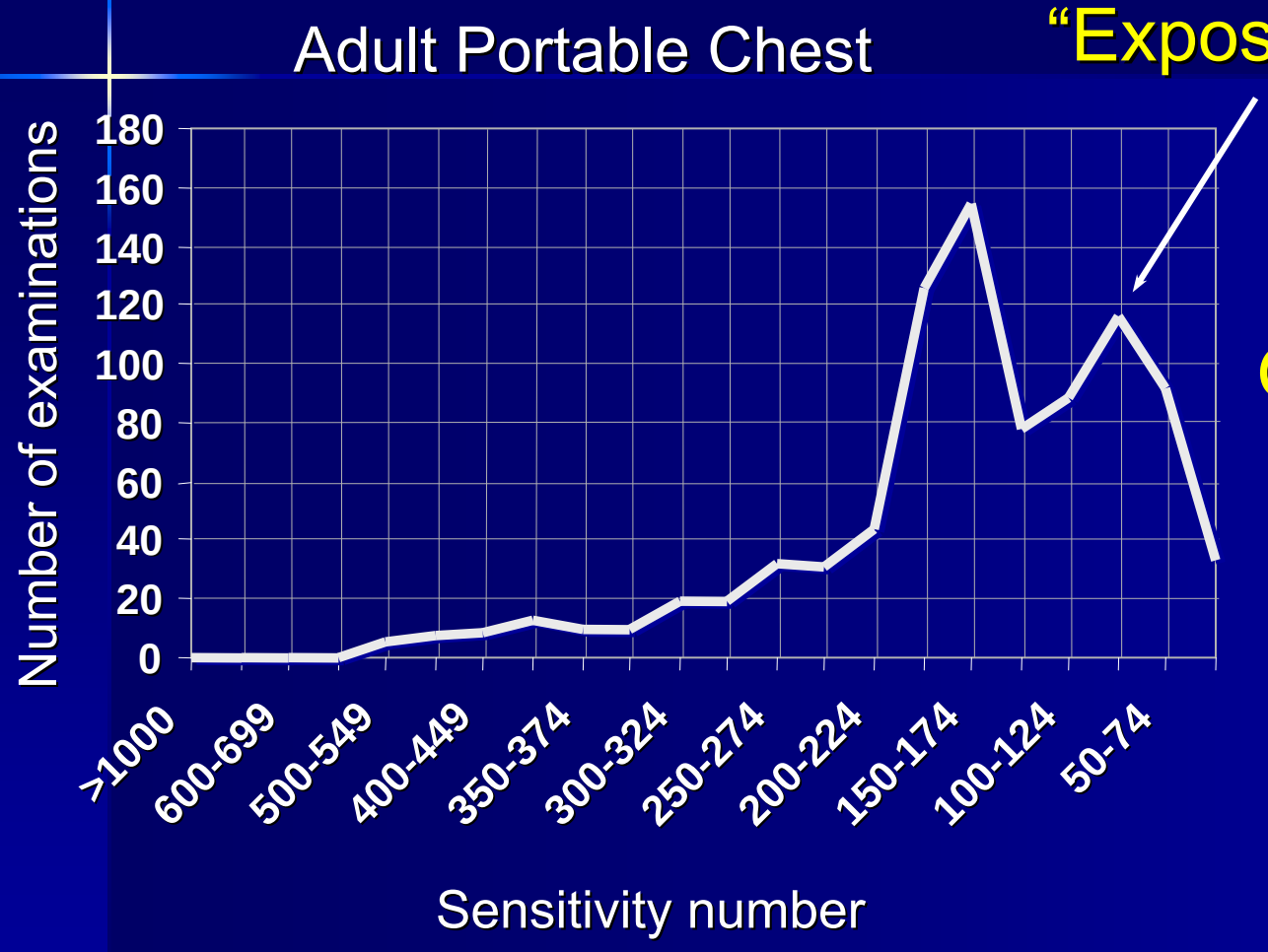
Adult portable chest calculated plate exposures

Second half,Year One of Use, 4000 exams



Low ← Incident Exposure → High

One Month - 2 years Later



"Exposure Creep"

Grid technique without a grid

Guidelines for QC based on Exposure (typical adult exam)

System "speed"	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

What the exposure index doesn't directly tell you……

- Patient dose
  - Dose is dependent on patient size, attenuation properties, technique & setup
- Image quality
  - Quality is mainly based upon SNR and patient positioning; a target exposure index value **does not guarantee IQ**

Detector exposure index: Do's and Don'ts

- Do a periodic review of exposure logs
- Do look for outliers and repeat offenders
- Do use as a feedback tool
- Do ensure proper detector/reader calibration
- Do NOT place too much importance on value
- Do NOT allow arbitrary value adjustment

Standardization Effort in progress

- American Association of Physicists in Medicine Task Group 116
- Collaborative effort
  - Manufacturers
  - Vendors
  - Physicists
  - IEC (international standards organization)
- Develop common “Exposure Indices” across detectors and manufacturers
- Provide means for placing in DICOM header

What should the manufacturers provide?

- Standardized method to report incident exposure
- A method to *visibly display* the exposure estimate
- Audible alert when an “out of range” situation occurs
- Implement an exposure “target”, specific to each exam
- Interface to x-ray systems to get kVp, mA, time data for determination of entrance exposure (usually standard for DR and automatic CR)... & adopt DICOM DX object

CR/DR implementation

- Standardized Radiographic Technique Charts
  - Age/Size Based
  - Programmable
    - AEC
    - Manual
  - *Should* be Used

Keith Strauss, Boston Childrens

Automatic Exposure Control

- AEC calibration goal: achieve desired SNR
- Manual calibration: achieve known exposure index value for known exposure
- Automatic calibration: use detector system response
- More difficult and time consuming for cassette and reader – based CR detectors

Automatic Exposure Control

- AEC's built into most flat panel TFT's
- AEC & CR
  - Both are alignment sensitive
  - AEC must be calibrated for CR
    - Battle with service engineer, depending on CR training
  - With AEC calibrated for CR, mAs adjustments for kVp variation should be properly determined
  - Should be under anatomy of interest; alter location and active cells based on anatomy or pathology

Patient Exposure Reduction

- Employ lowest exposure for diagnostic images
  - Highest “speed class” practical
  - Accurate technique charts and calibrated AEC
- Limit volume irradiated
  - Collimation – Effective dose
- Use appropriate techniques
  - Higher kVp, additional filtration, grid optimization
- Set up longer distance (within grid focal range)
  - 44” – 48” SID
- Employ patient lead shielding when practical
  - Potential histogram analysis error

Increase kVp within reasonable limits

Technical Factors vs. ESE

AP knee - 8:1 / 103 Al interspace grid

mAs / kVp	ESE	% Change
15 / 75	72	-
9 / 80	61	- 15 %
7 / 85	50	- 30 %

ESE – Entrance Skin Exposure in mR

Added Filtration with ESE Reduction

	0.10 mm Cu	- 25%
	0.30 mm Cu	- 35%
Sandwich	0.050 mm Mo 0.030 mm Cu 1.0 mm Al	- 35%

Note:
Increased tube loading, and mAs / kV settings “appear” high

Tradeoffs of Image Quality and Dose

- Subject Contrast
  - Low kVp.... ↑ dose
  - High SNR .. ↑ dose
  - Use Grid.... ↑ dose
- Spatial Resolution
  - Small pixel ... ↑ dose
  - Low fill-factor.. ↑ dose
- Technique
  - ↑ Tube filtration.. ↓ dose
  - ↑ kVp .... ↓ dose
  - ↓ FOV ... ↓ dose
  - ↑ High DQE .... ↓ dose
- Patient motion
  - High kVp → Low mAs
  - Positioning aids, beam attn.
- Detector
  - High DQE → CsI phosphor
  - Flat-field → Calibration?
  - Cost (CR-$; DR-$$)
  - Patient Positioning
- Processing
  - Optimization for exam
  - Contrast enhancement
  - Frequency enhancement

Radiation Dose for CR

- Variable Speed Detector (~200 - 300 equiv speed)
- Optimal dose *for typical adult chest image is 1.5 - 2X higher* than 400 speed screen/film...why?
  - Lower absorption efficiency
  - Quantum and electronic noise
  - Readout inefficiencies of latent image
- Anti-scatter grids necessary for most procedures

Radiation Dose for DR

- Dependent on signal and noise characteristics
- Structured noise (dead pixels, etc) lowers DQE
- Higher DQE: lower dose with same image SNR

Conclusions: CR/DR and Exposure

- Flexibility is a double-edged sword with CR/DR
  - reduced retakes
  - variable speed (tailor exposure to exam).... but
  - more difficult to *correctly* use
- *All* digital systems should log and monitor detector exposure indices as part of the QC program
- Good image quality and *appropriate SNR* are more important than low radiation dose
- Continuous *retraining and feedback* are necessary!

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