Exposure Indices and Target Values in Radiography: What Are They ~~and How Can You Use Them~~?

Definition and Validation of Exposure Indices

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OUTLINE

- Introduction
  - Dose trends in digital radiography: Motivation for EI Development
  - Dose limitation of screen-film radiography
- Nomenclature Zoo: The dark ages before EI
- EI definition
  - EI validation measurements
- Derived quantities:
  - Target EI, DI
- Sources of variability of EI
  - SID variability
  - X-ray spectrum
    - kVp dependence
    - Beam quality, anti-scatter grid
    - Beam hardening (patient thickness)
  - Positioning/collimation
  - Metal implants
- AEC and EI

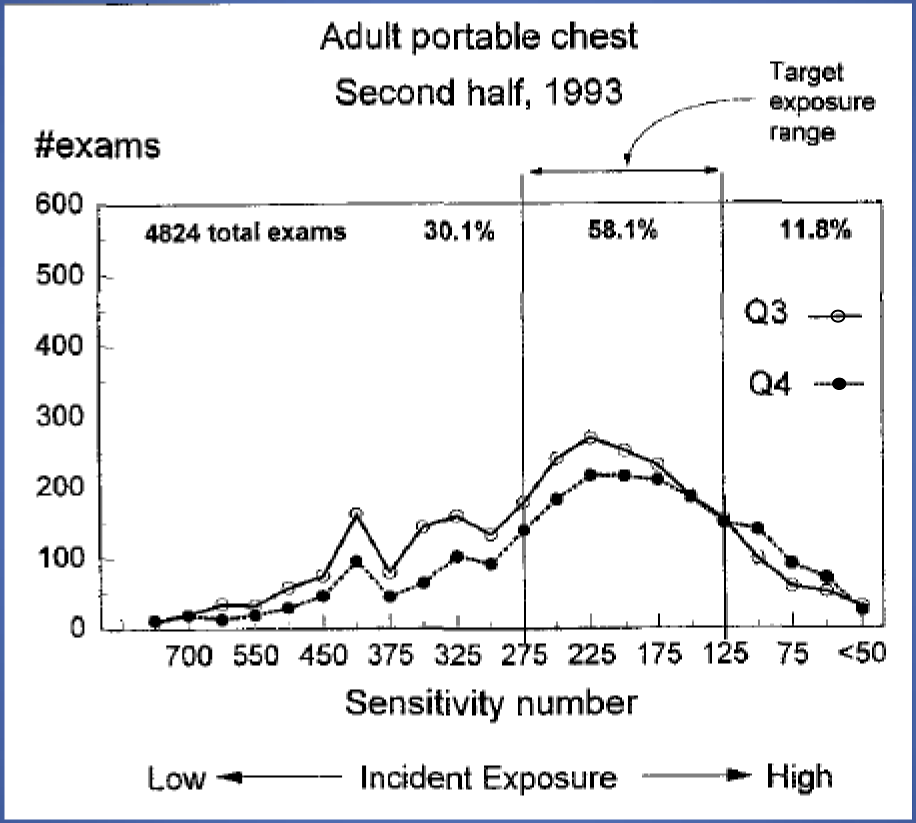
1993: Potential for excess patient exposure with CR is recognized

"It is possible to use storage phosphor radiography (SR) devices in a manner that results in excess exposure to the patient without the operators knowledge. "

- Automatic correction for the final optical density (OD) of the image prevents the technologist and radiologist from recognizing overexposure

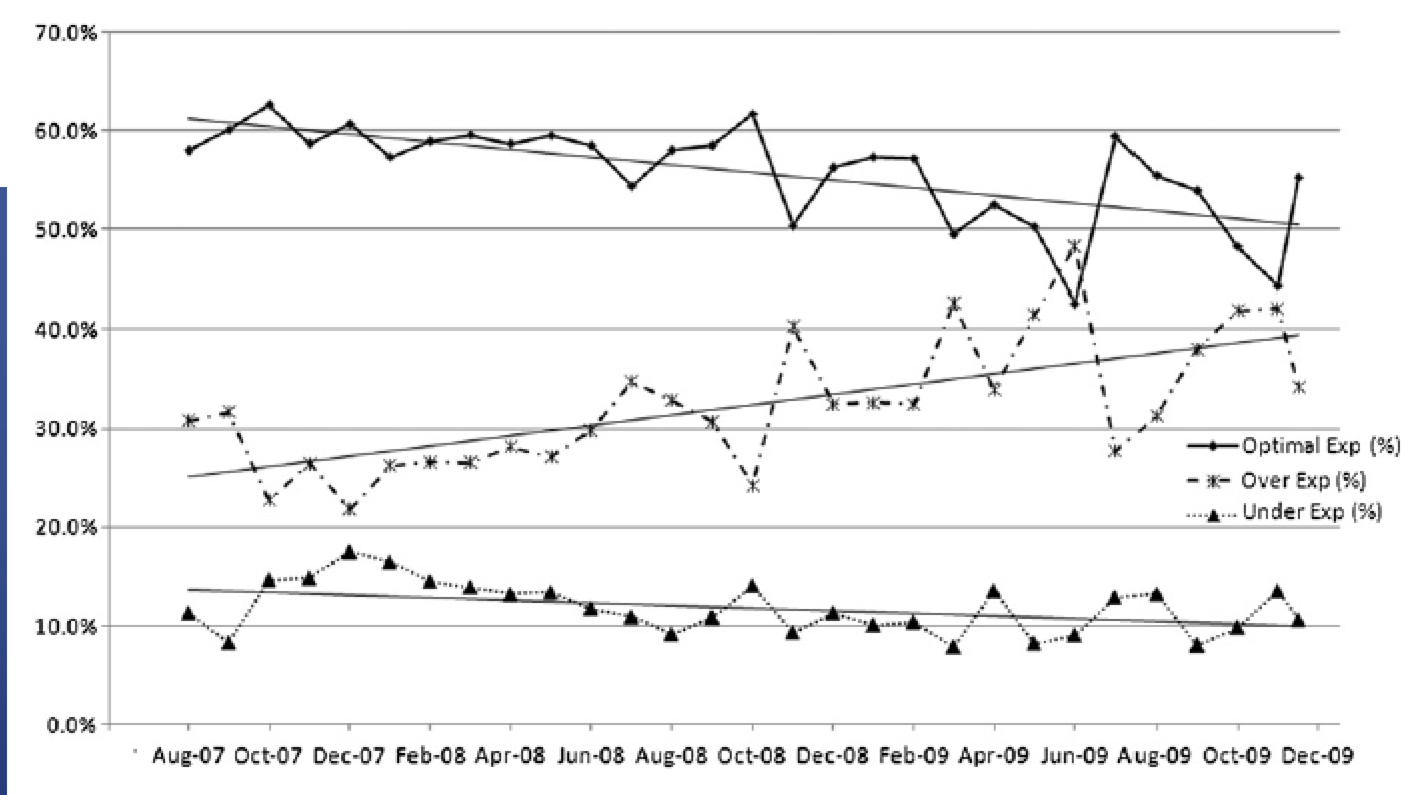
- High-exposure produces acceptable images:
  - Chest phantom at 32 x typical exposure (0.86 R).
  - Pelvis phantom at to the tube limit (4.8 R)

M. T. Freedman, E. V. Pe, S. K. Mun, S.-C. B. Lo, M. C. Nelson. "Potential for unnecessary patient exposure from the use of storage phosphor imaging systems", Proc. SPIE 1897(1993)



J. A. Seibert, D. K. Shelton, E. H. Moore. Computed radiography X-ray exposure trends. Academic Radiology, Vol. 3, Issue 4, p313–318 (1996)

Exposure Creep in Computed Radiography:



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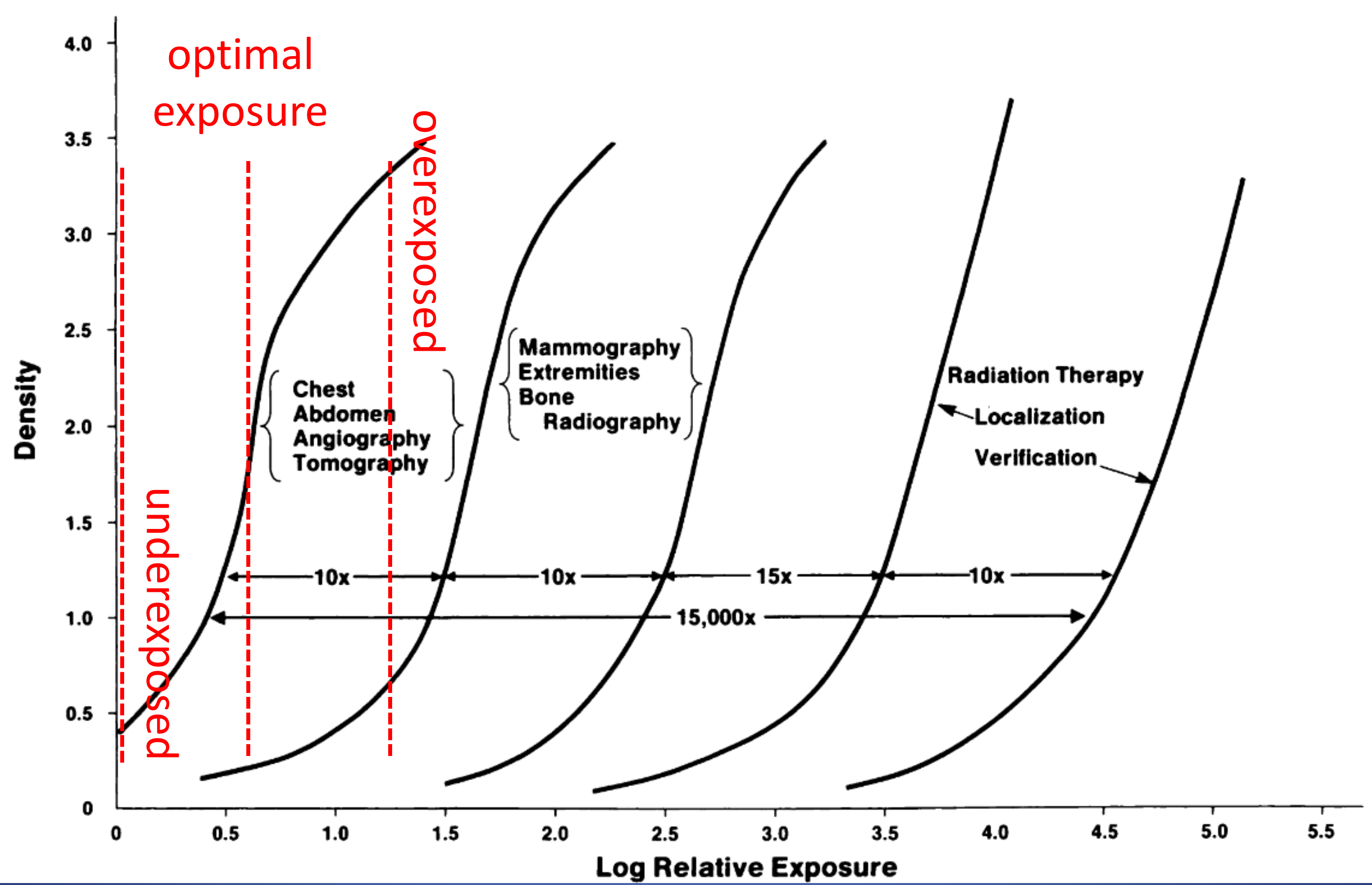
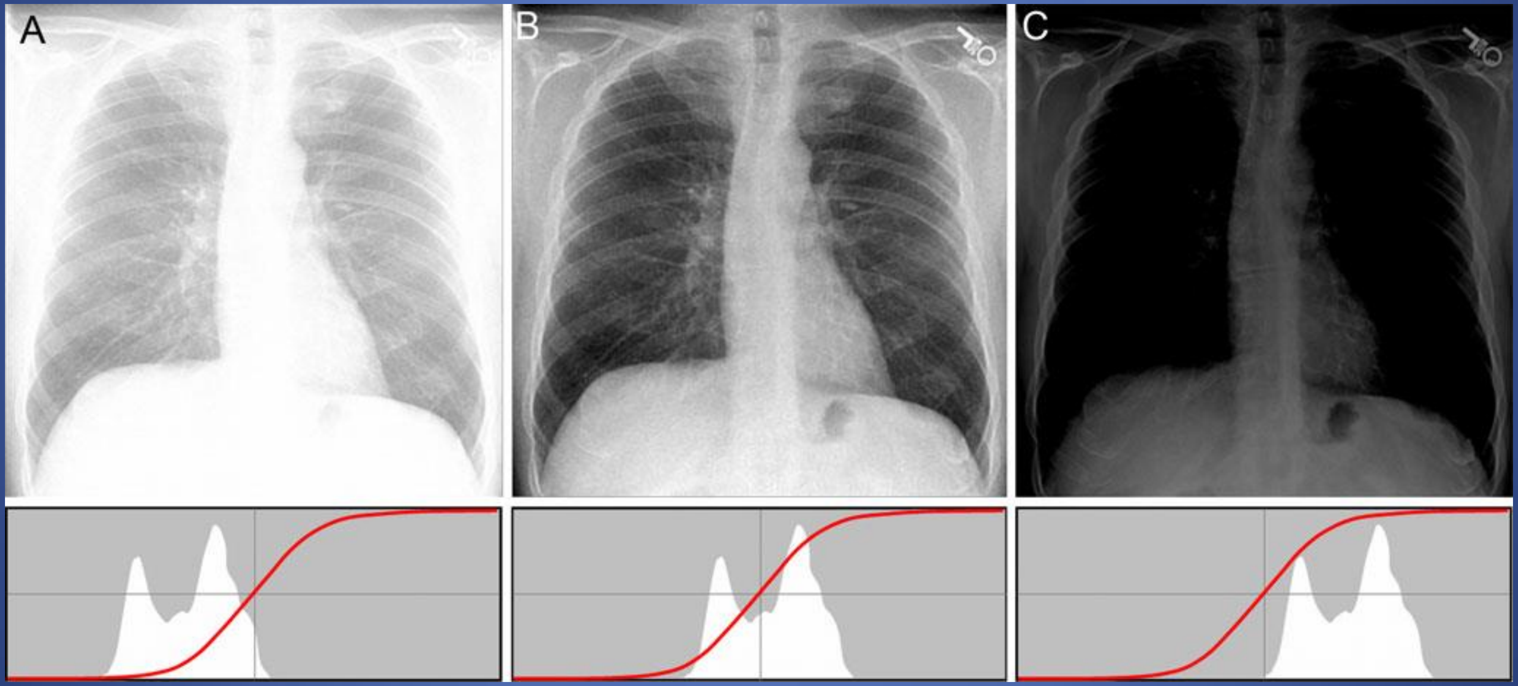
J Med Radiat Sci. 2014 Jun; 61(2): 112–118.

Screen-film systems: Inherent dose limitation



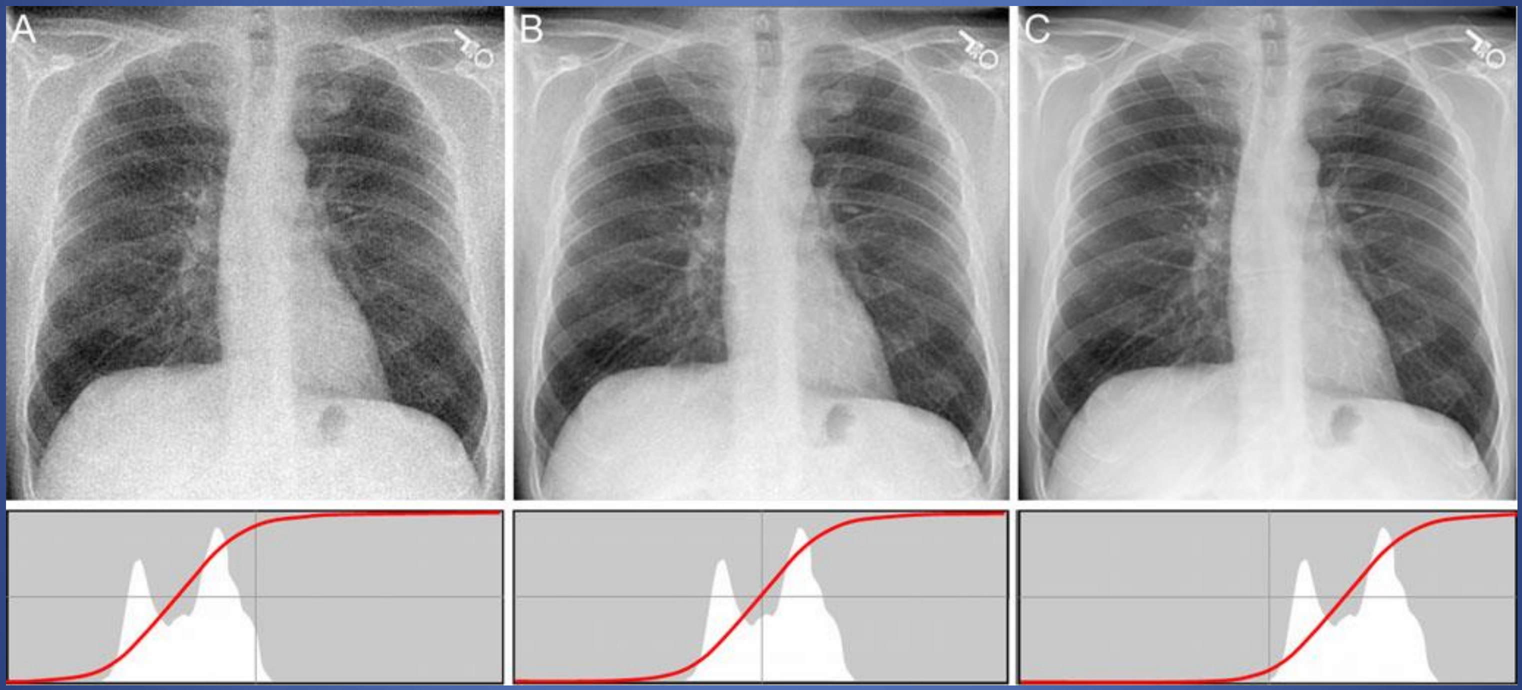
Haus, A. G., & Cullinan, J. E. (1989). Screen film processing systems for medical radiography: a historical review. Radiographics, 9(6), 1203–1224.

Screen-film detector



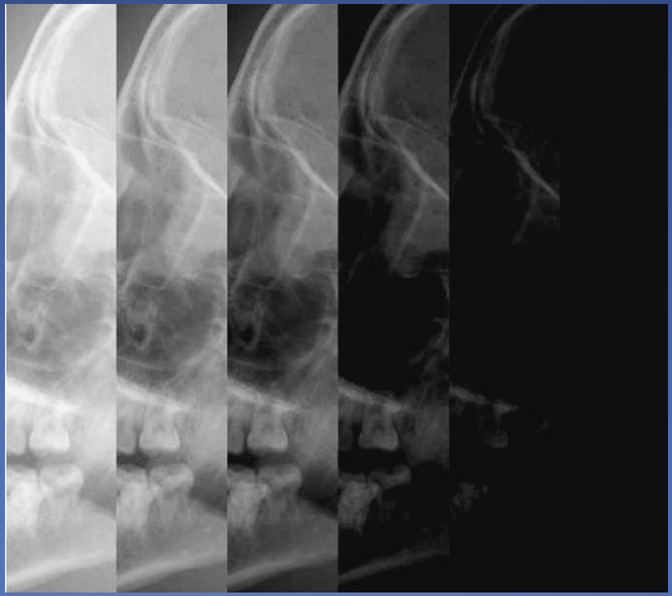
J. A. Seibert, R. L. Morin. The standardized exposure index for digital radiography: an opportunity for optimization of radiation dose to the pediatric population. Pediatric Radiology, 41(5) (2005)

Digital detector

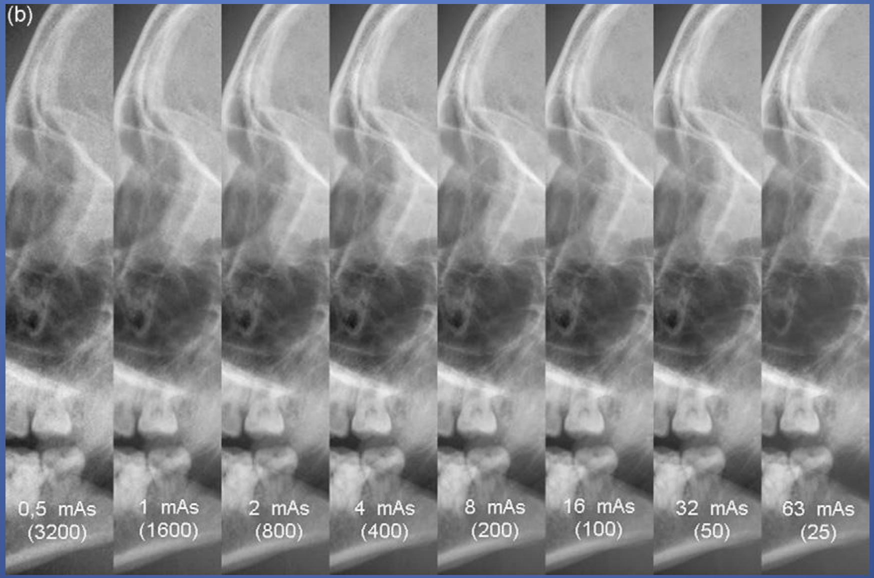


J. A. Seibert, R. L. Morin. The standardized exposure index for digital radiography: an opportunity for optimization of radiation dose to the pediatric population. Pediatric Radiology, 41(5) (2005)

Screen-film system



Flat-panel detector



0.5mAs

63mAs

M. Uffmann, C. Schaefer-Prokop / European Journal of Radiology 72 (2009) 202–208

Combatting dose creep: Exposure Indices

Nomenclature Zoo: The dark ages preceding the IEC standard

Manufacturer	Form	Units	Value at 1 mR to detector
Fuji	$200/S \propto X$	Unitless	$S = 200$
Kodak	$EI + 300 = 2X$	mbels	$EI = 2000$
Agfa	$lgM + 0.3 = 2X$	bels	$lgM = 2.2$
Canon	$REX \propto X$	Unitless	f(brightness, contrast)
DAP	DAP/field size $\propto X$	dGy-cm^2	f(field size, grid, patient)
GE/entrance dose	Entrance dose $\propto X$	mGy, SDD-25cm	f(field size, grid, patient)

Willis, C.E. (2004). "Strategies for dose reduction in ordinary radiographic examinations using CR and DR." *Pediatr Radiol* 34(Suppl 3):S196–S200.

Nomenclature Zoo: The dark ages preceding the IEC standard

Manufacturer	Symbol	5 μGy	10 μGy	20 μGy
Canon (brightness = 16, contrast = 10)	REX	50	100	200
IDC (ST=200)	F#	−1	0	1
Philips	EI	200	100	50
Fuji, Konica	S	400	200	100
Carestream (CR, STD)	EI	1,700	2,000	2,300
Siemens	EI	500	1,000	2,000

J. A. Seibert, R. L. Morin. The standardized exposure index for digital radiography: an opportunity for optimization of radiation dose to the pediatric population. Pediatric Radiology, 41(5) (2005)

Nomenclature Zoo: The dark ages preceding the IEC standard

Table 1 Manufacturer and exposure index parameters used for digital radiography systems

Manufacturer	Exposure indicator name	Symbol	Units	Exposure dependence, X	Detector calibration conditions
Fujifilm	S value	S	Unitless	$200/S \propto X$ (mR)	80 kVp, 3 mm Al "total filtration" *S*=200 @ 1 mR
Carestream	Exposure index	EI	Mbels	EI+300=2X	80 kVp, 1.0 mm Al+0.5 mm Cu; EI=2000 @ 1 mR
Agfa	Log of median of histogram	lgM	Bels	lgM+0.3=2X	400 speed class, 75 kVp+1.5 mm Cu; lgM=1.96 @ 2.5 μGy
Konica	Sensitivity number	S	Unitless	For QR=k, $200/S \propto X$(mR)	QR=200, 80 kVp, S=200 @ 1 mR
Canon	Reached exposure value	REX	Unitless	Brightness=c_1, Contrast=c_2, REX $\propto$ X[1]	Brightness=16 Contrast=10 REX≈106 @ 1 mR[1]
Canon	EXP	EXP	Unitless	EXP $\propto$ X	80 kVp, 26 mm Al, HVL=8.2 mm Al, DFEI=1.5 EXP=2000 @ 1 mR
GE	Uncompensated detector exposure	UDExp	μGy air kerma	UDExp $\propto$ X (μGy)	80 kVp, standard filtration, no grid
GE	Compensated detector exposure	CDExp	μGy air kerma	CDExp $\propto$ X (μGy)	Not available
GE	Detector exposure index	DEI	Unitless	DEI ≈ratio of actual exposure to expected exposure scaled by technique and system parameters. Expected exposure values can be edited by user as preferences.	Not available
Swissray	Dose indicator	DI	Unitless	Not available	Not available

J. A. S … for
optim…

IEC 62494-1: Medical Electrical Equipment – Exposure Index of Digital X-ray Imaging Systems (2008)

- Purpose: Establish an easily recognizable measure of adequate of detector exposure
  - prevent overexposure
  - underexposure -> unacceptable image noise, in principle recognizable in the image

IEC 62494-1: Medical Electrical Equipment – Exposure Index of Digital X-ray Imaging Systems (2008)

- Applies to
  - Computed radiography systems based on stimulable phosphors
  - Flat-panel detector based systems
  - Charge-coupled device based systems
- Single-exposure events only

IEC 62494-1: Medical Electrical Equipment – Exposure Index of Digital X-ray Imaging Systems (2008)

- Excluded:
  - Image Intensifier-based systems
  - Mammographic/Dental systems
  - Multi-exposure systems
    - Tomosynthesis
    - Dual energy
    - Multiple views on single receptor

IEC 62494-1: Medical Electrical Equipment – Exposure Index of Digital X-ray Imaging Systems

DEFINITIONS

- Exposure index EI:
  - Measure of the detector response in relevant image region
- Relevant image region:
  - examination-specific sub-area(s) of image containing the diagnostically relevant information
- Value of interest:
  - central tendency of the original data in the relevant region

IEC 62494-1: Medical Electrical Equipment – Exposure Index of Digital X-ray Imaging Systems

$$EI = c_0 \cdot g(V)$$

- EI: Exposure index
- g(V): inverse calibration function
- V: value of interest of relevant region
- $c_0 = 100\mu Gy^{-1}$

IEC 62494-1: Medical Electrical Equipment – Exposure Index of Digital X-ray Imaging Systems

- Target exposure index EI_T:
  - expected value of the EI when exposing the image receptor properly
  - may depend on type of detector, type of examination, diagnostic question and other parameters

IEC 62494-1: Medical Electrical Equipment – Exposure Index of Digital X-ray Imaging Systems

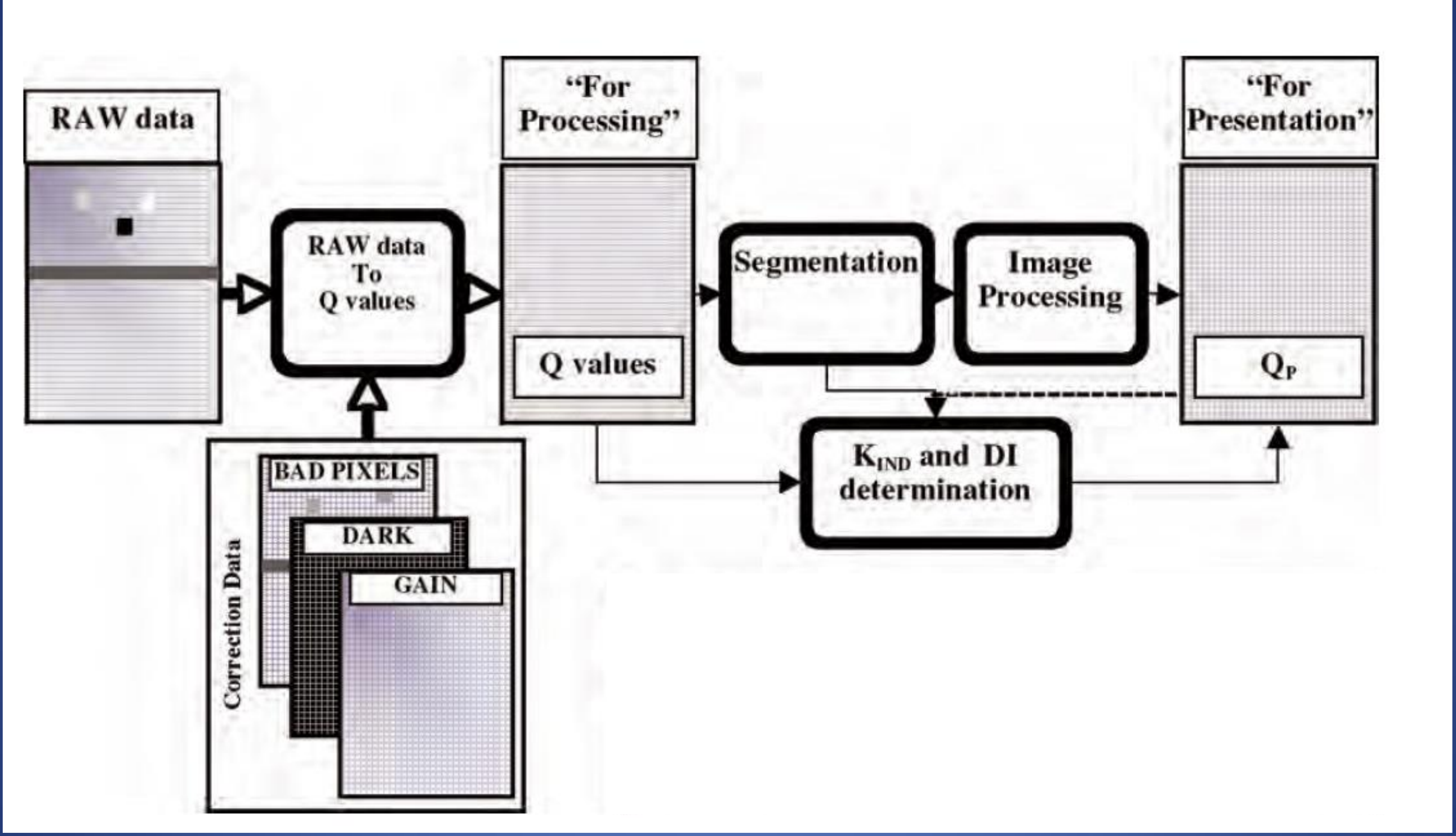
- Calibration condition:
  - Set of conditions under which EI calibration is done
- Calibration function:
  - Expresses the value of interest as function of the image receptor air KERMA; valid under calibration conditions

IEC 62494-1: Medical Electrical Equipment – Exposure Index of Digital X-ray Imaging Systems

- Image receptor air KERMA:
  - AIR KERMA at the position of the detector surface, free-in-air (excluding backscatter)
- Detector surface:
  - Accessible area closest to image receptor plane
- Image data: Original data
  - corrections allowed have been applied, may include logarithmic or square-root characteristic

IEC 62494-1 Original data

- Allowed corrections:
  - bad or defective pixel correction
  - flat-field correction consisting of any or all of:
    - radiation-field non-uniformity correction
    - pixel offset correction
    - pixel gain correction
    - scan velocity variation correction
  - geometrical distortion correction
- Corrections shall be made as in normal clinical use



AAPM REPORT NO. 116

IEC 62494-1 Original data

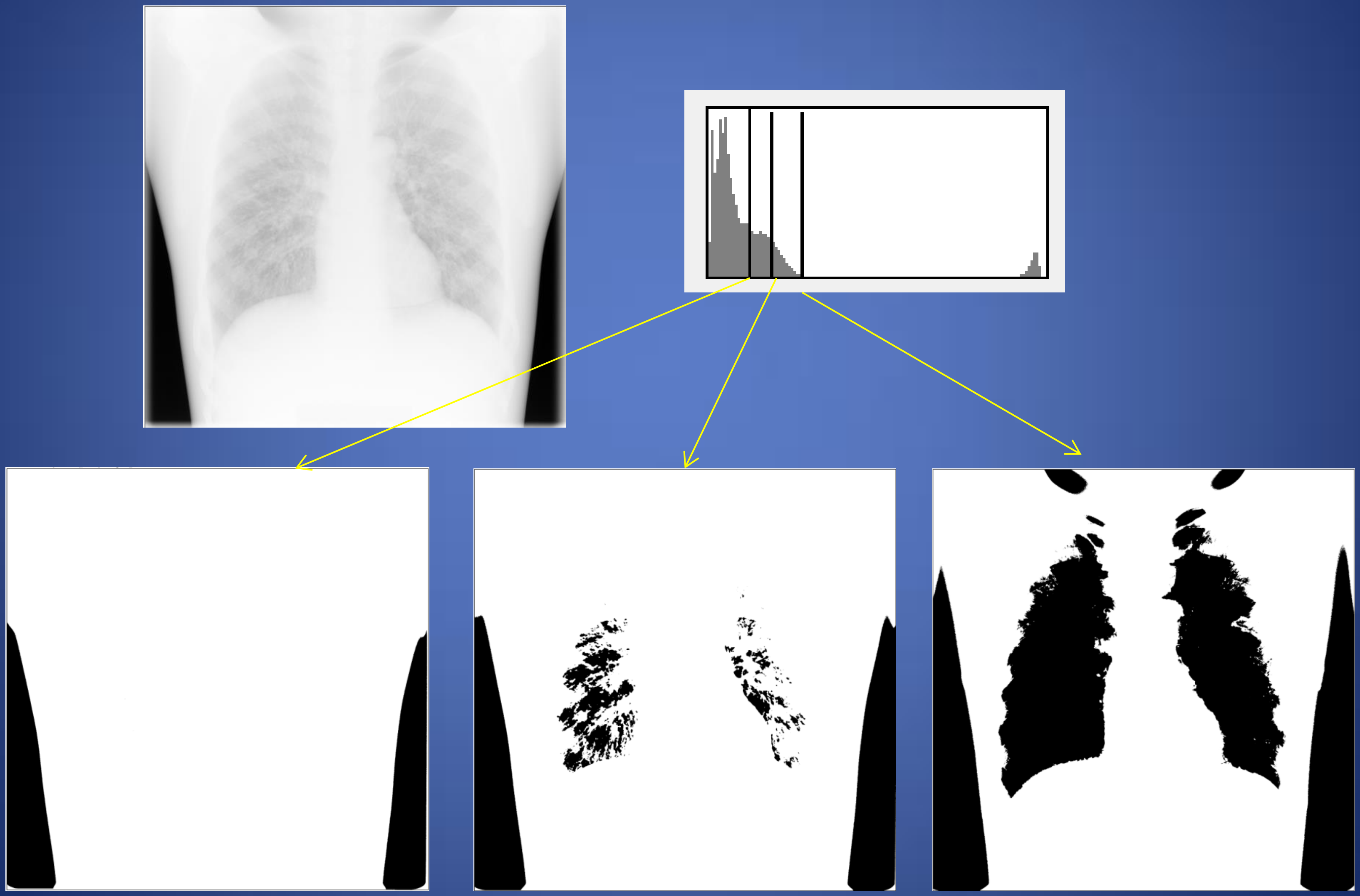
- For-presentation enhancements are NOT allowed
  - edge enhancement
  - noise smoothing
  - histogram equalization
  - …
- Linear processing <u>for enhancement</u> is NOT allowed, even if image independent
  - only if linear image processing is part of physical concept, and processing is independent of image content

Relevant image region

Relevant image region: Attenuated region relevant to diagnostic purpose

- Identification by means of
  - image segmentation
  - histogram based
  - other methods
- METHOD SHALL BE DOCUMENTED
  - Single method is preferable and may be part of future definition of EI

Identifying the relevant region



Value of Interest

Value of Interest: Central tendency of original data in the relevant image region

- Calculated by use of any recognized statistical method
  - mean
  - median
  - mode
  - …
- METHOD SHALL BE DOCUMENTED

The Calibration Function f

$$V_{CAL} = f(K_{CAL})$$

- V_{CAL}: Value of interest under calibration conditions
- (Interpolate to obtain continuous function)

Calibration conditions

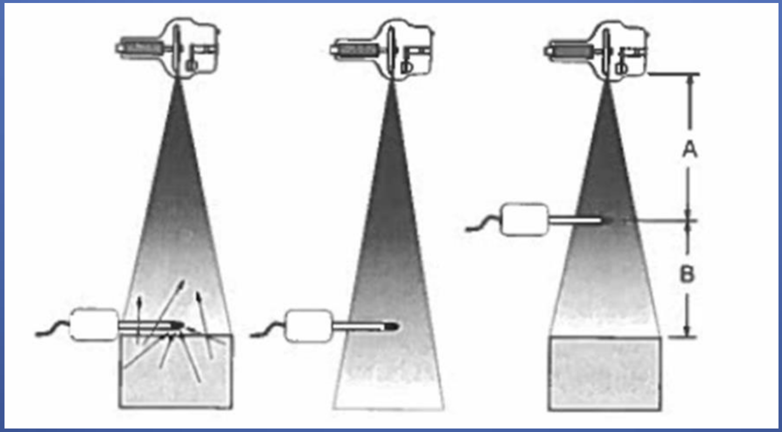
- Homogeneous irradiation of image receptor
- Value of interested computed from the central 10% of the image receptor area
- K_{CAL} within operating range of detector
- K_{CAL} measured without backscatter
- Single fixed radiation beam quality
  - For other beam qualities, relation between EI and K_{CAL} will deviate due to energy response of detector, scattered radiation and other effects

Radiation Quality for Calibration (IEC)

- HVL of 6.8±0.3 mm Al
- Added filtration of EITHER
  - 21mm Al
  - Or, 0.5mm Cu and 2mm Al
- X-ray tube voltage 66kV-74kV
- Adjust tube voltage to achieve the target HVL
- Added filtration and tube voltage shall be documented.

Radiation Measurements for Calibration (IEC)

- Measurement shall be done free-in-air, without backscatter
  - If image receptor cannot be removed, measurement should be performed half-way between x-ray tube and image receptor, at maximum SID



SPIE Handbook of Medical Imaging, Vol. I, Chapt. 1. SPIE press, 2000

The Inverse Calibration Function g

$$K_{CAL} = g(V_{CAL}) = f^{-1}(V_{CAL})$$

- The inverse calibration function $g(V)$ is used to compute EI for all radiographic techniques
- The manufacturer shall specify $g(V)$ and provide its valid range
- The inverse calibration function shall have an uncertainty of less than 20%.

Under calibration conditions:

$$EI = c_0 \cdot K_{CAL}$$

- K_{CAL}: Image receptor Air Kerma in micro-Gray
- c_0 = 100 micro-Gy^{-1}

Making it useful: The Deviation Index

$$DI = 10\ log_{10}\left(\frac{EI}{EI_{target}}\right)$$

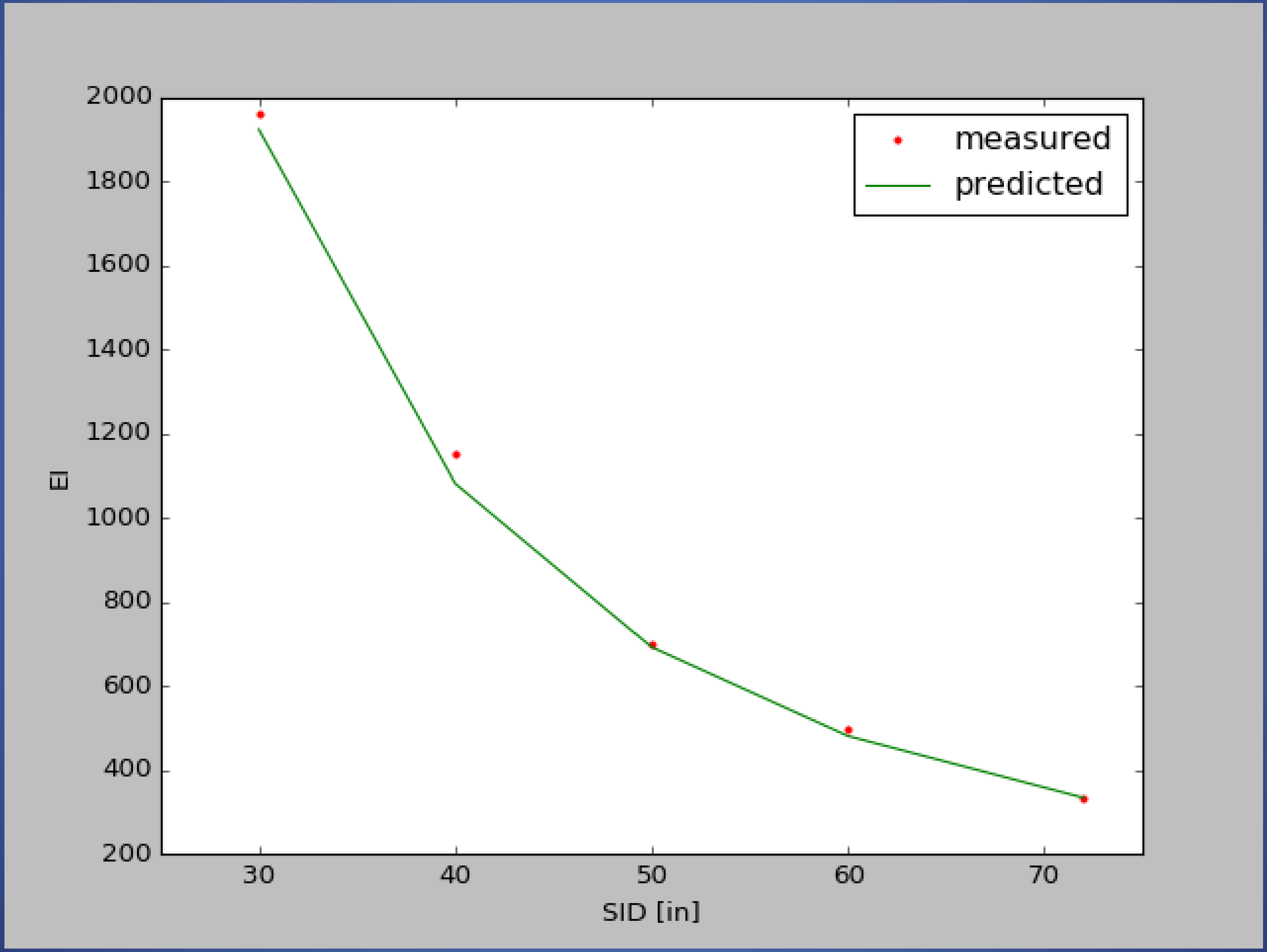
- DI: Deviation index
- DI measures the difference between image EI and the target value, EI_{target}
  - DI = 0: EI equals EI_{target}
  - DI = 3: EI is twice EI_{target}
  - DI = -3: EI is half EI_{target}

Why is this useful?

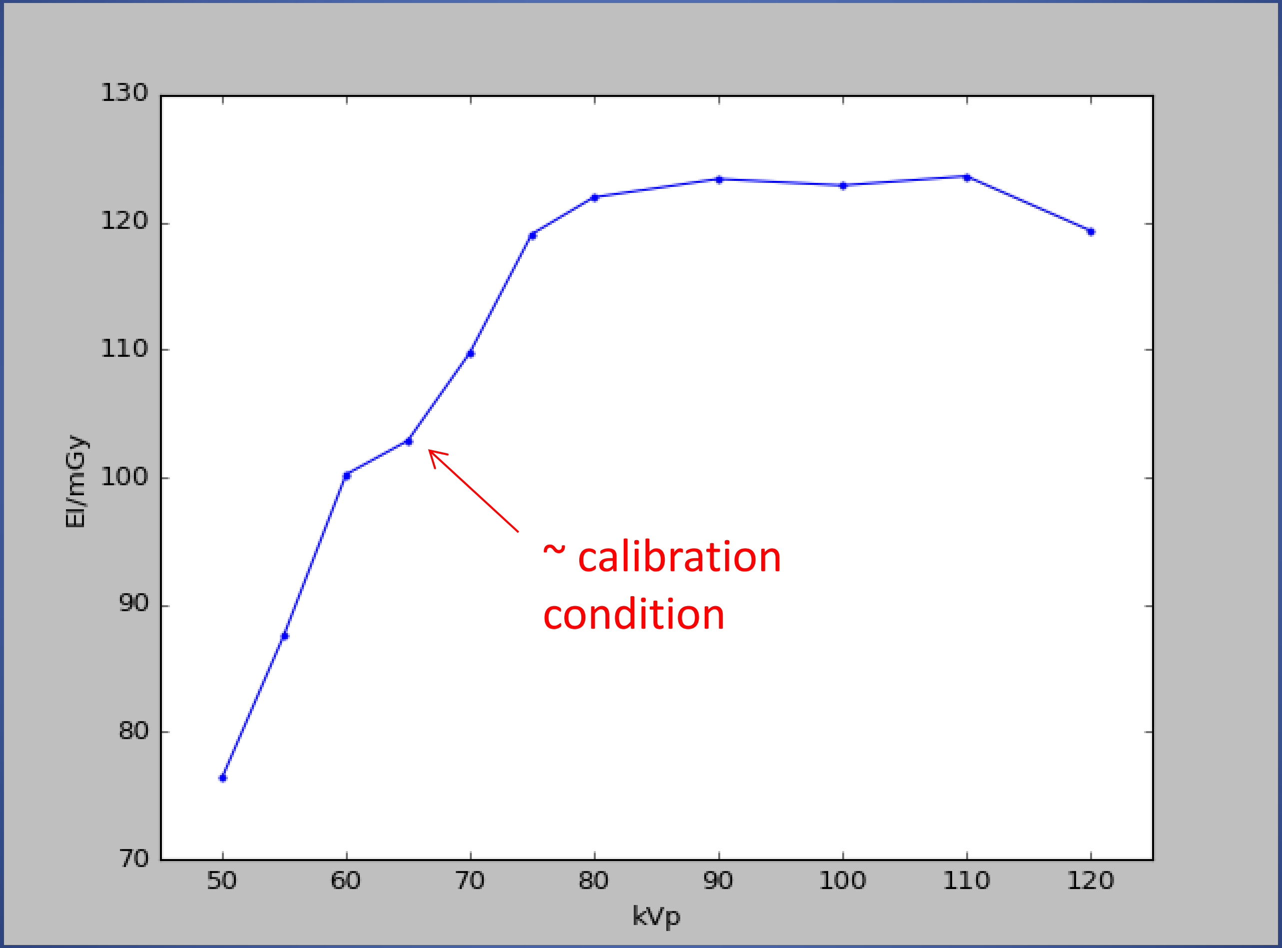
- In general, EI_{target} values are set for each protocol
- Technologist does not need to remember EI_{target}
- DI can be used to alert technologist/radiologist whether over/underexposure has occurred
- EI_{target} can compensate for deviations from calibration conditions (kVp, grid, AEC speed)

Sources of EI Variability

Sources of EI variability: SID



Sources of EI variability: kVp



20 mm Al phantom

Data courtesy of A. Sanchez, PhD

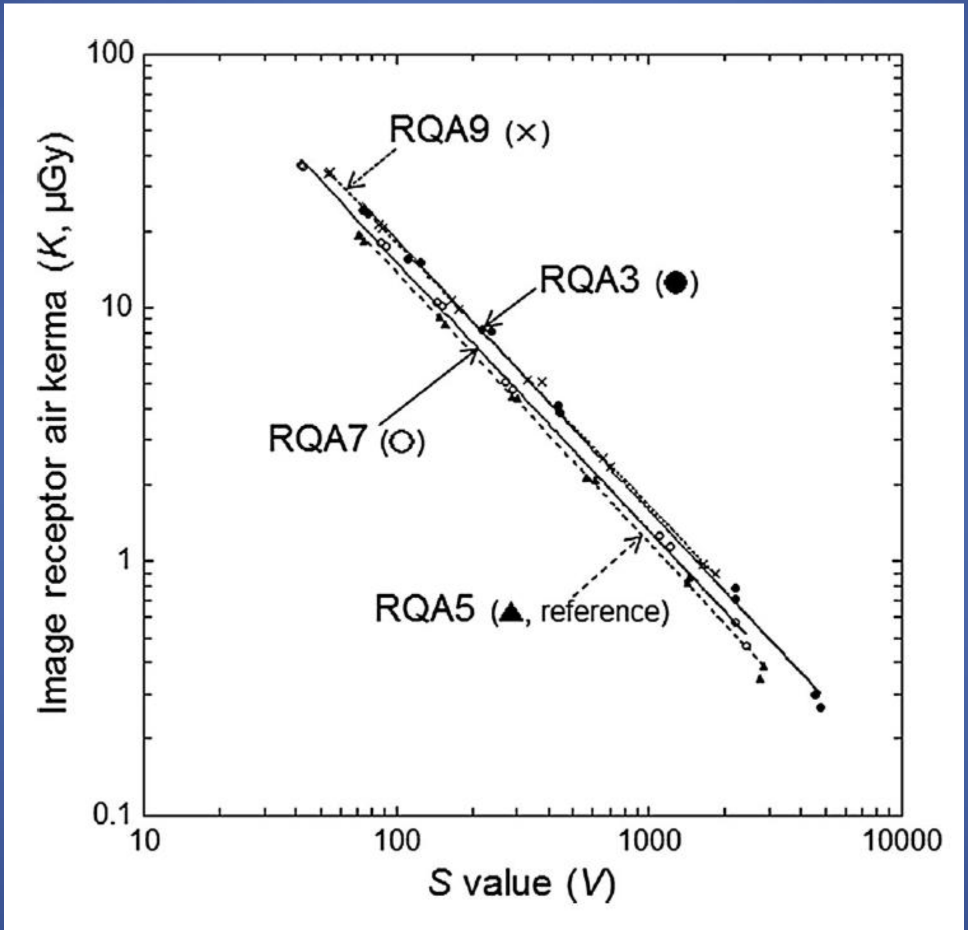
Sources of variability of EI: X-ray beam quality

- CR system
- RQA 3,5,7,9 beams
- Value of interest: S-value
  - Semi-auto mode (fixed latitude L=1)
- Receptor dose range: 0.25-37 micro-Gy

X-ray beam quality	Half-value layer (mm Al)	Added filtration (mm Al)	Tube voltage (kV)
RQA3	5.0	10	51
RQA5	7.1	21	71
RQA7	9.1	30	89
RQA9	11.5	40	118

S. Yasumatsu, T. Nobukazu, K. Iwase, Y. Shimizu, J. Morishita. Effect of X-ray beam quality on determination of exposure index. Radiol Phys Technol (2016) 9:109–115

Sources of variability of EI: X-ray beam quality



S. Yasumatsu, T. Nobukazu, K. Iwase, Y. Shimizu, J. Morishita. Effect of X-ray beam quality on determination of exposure index. Radiol Phys Technol (2016) 9:109–115

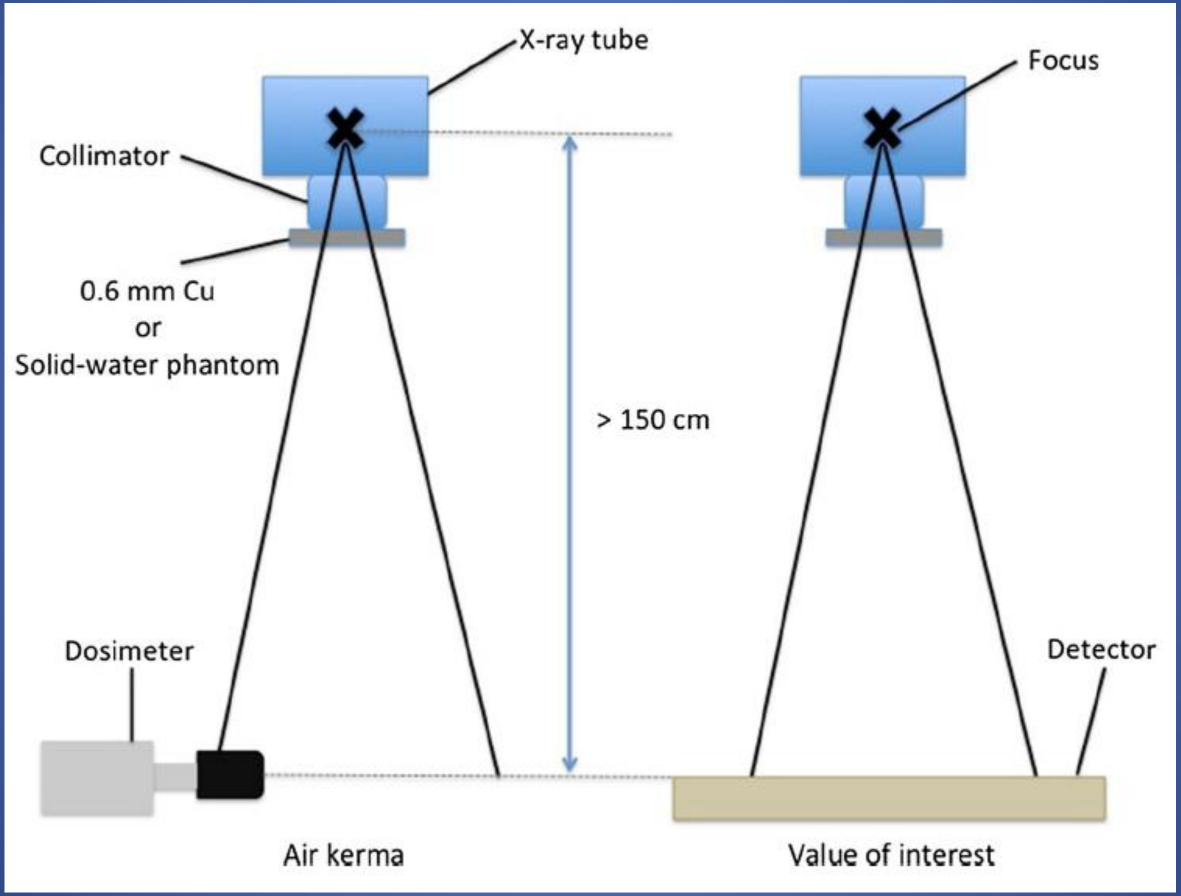
Sources of EI variability: Anti-scatter grid

	EI value and PD_{EI} (%)			
S value	EI_5 in RQA5	EI_3 in RQA3	EI_7 in RQA7	EI_9 in RQA9
600	204	276 (35.3 %)	228 (11.8 %)	283 (38.7 %)
400	315	425 (34.9 %)	351 (11.4 %)	431 (36.8 %)
200	661	890 (34.6 %)	732 (10.7 %)	884 (33.7 %)
100	1388	1864 (34.3 %)	1527 (10.0 %)	1814 (30.7 %)

		HVL (mm Al)		
Basis	Grid ratio	First	Second	Average
RQA5	None	6.86	6.84	6.85
	6:1	6.96	6.92	6.94
	8:1	7.01	6.99	7.00
	10:1	7.14	7.25	7.20
	12:1	7.29	7.28	7.29

S. Yasumatsu, T. Nobukazu, K. Iwase, Y. Shimizu, J. Morishita. Effect of X-ray beam quality on determination of exposure index. Radiol Phys Technol (2016) 9:109–115

Sources of EI variability: Patient thickness

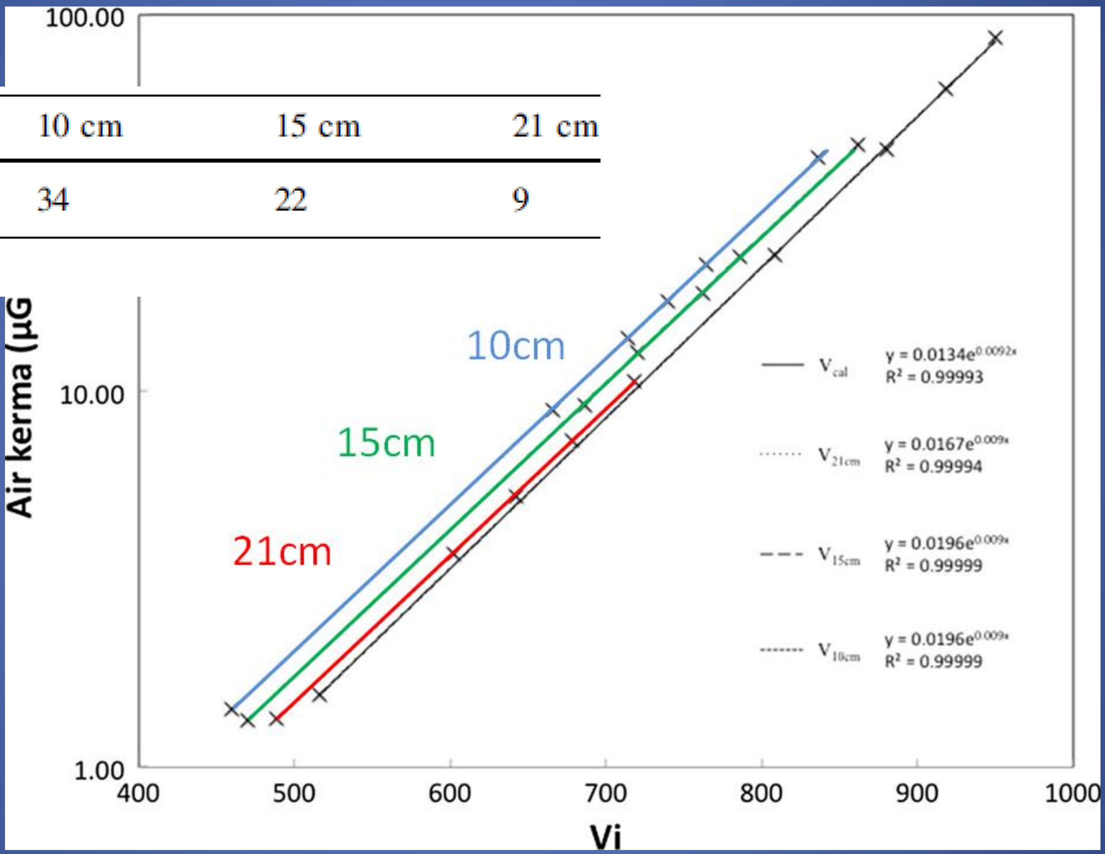


S. Yasumatsu, T. Nobukazu, K. Iwase, Y. Shimizu, J. Morishita. Effect of X-ray beam quality on determination of exposure index. Radiol Phys Technol (2016) 9:109–115

Sources of EI variability: Patient thickness

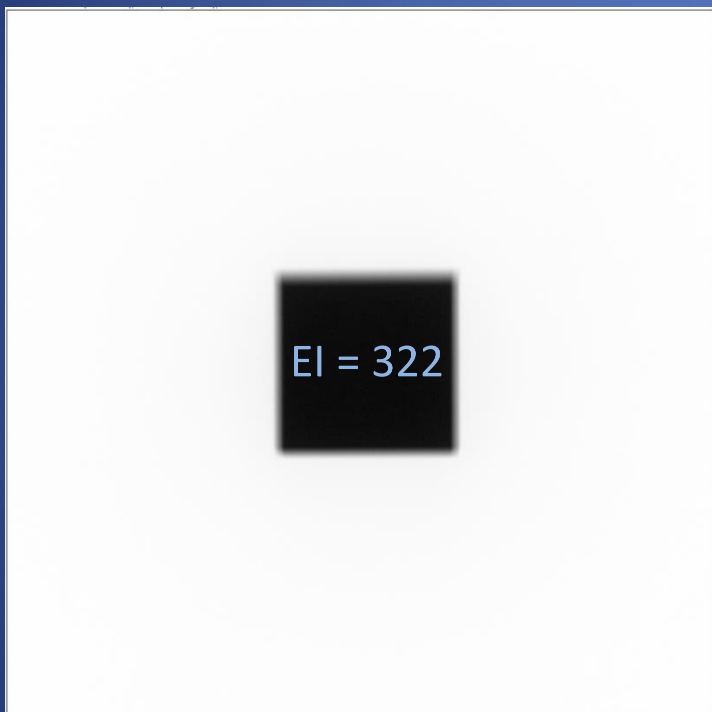
Subject thickness	10 cm	15 cm	21 cm
Error	34	22	9

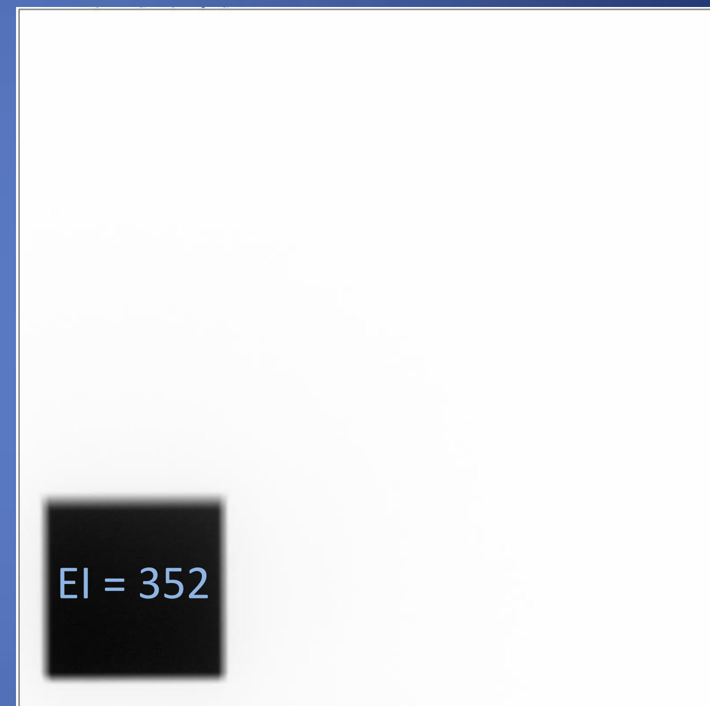
Unit: %



S. Yasumatsu, T. Nobukazu, K. Iwase, Y. Shimizu, J. Morishita. Effect of X-ray beam quality on determination of exposure index. Radiol Phys Technol (2016) 9:109–115

Sources of EI variability: Positioning





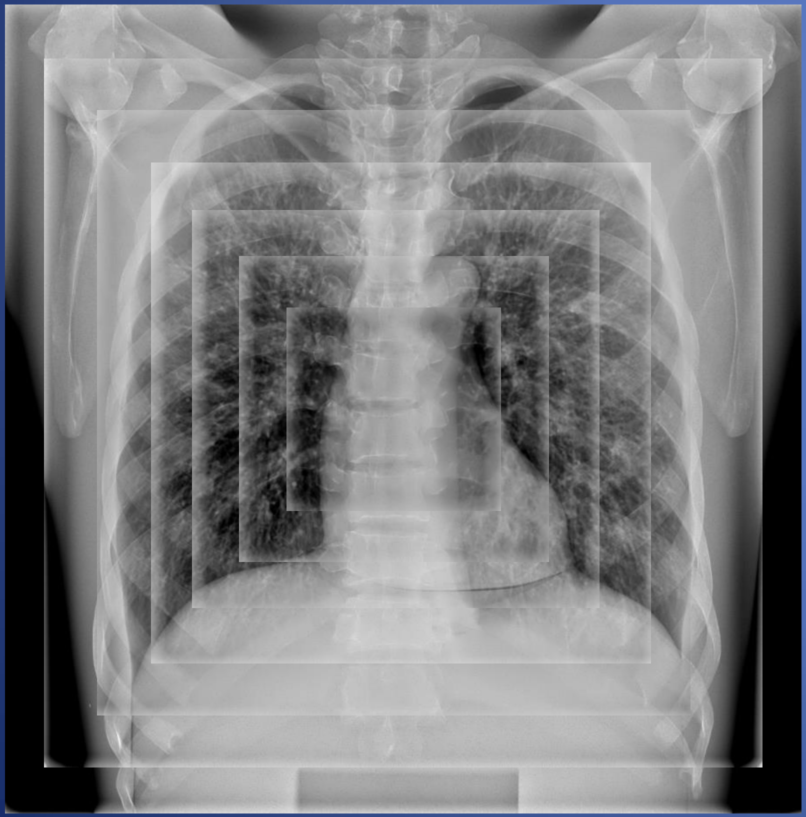
for-processing images

Sources of EI variability: Positioning

EI = 218

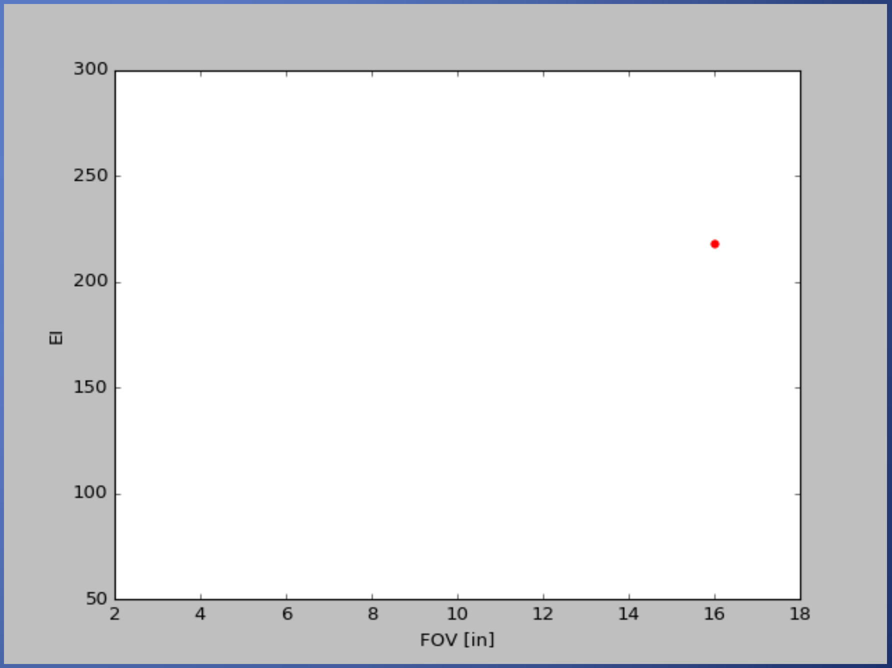
EI = 249

Effect of collimation



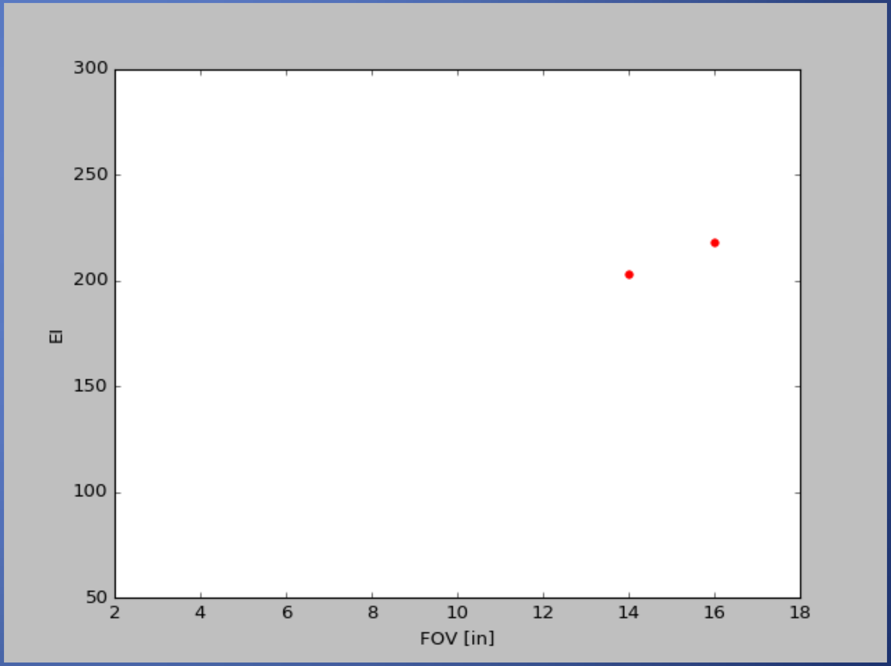
Effect of collimation

EI = 218



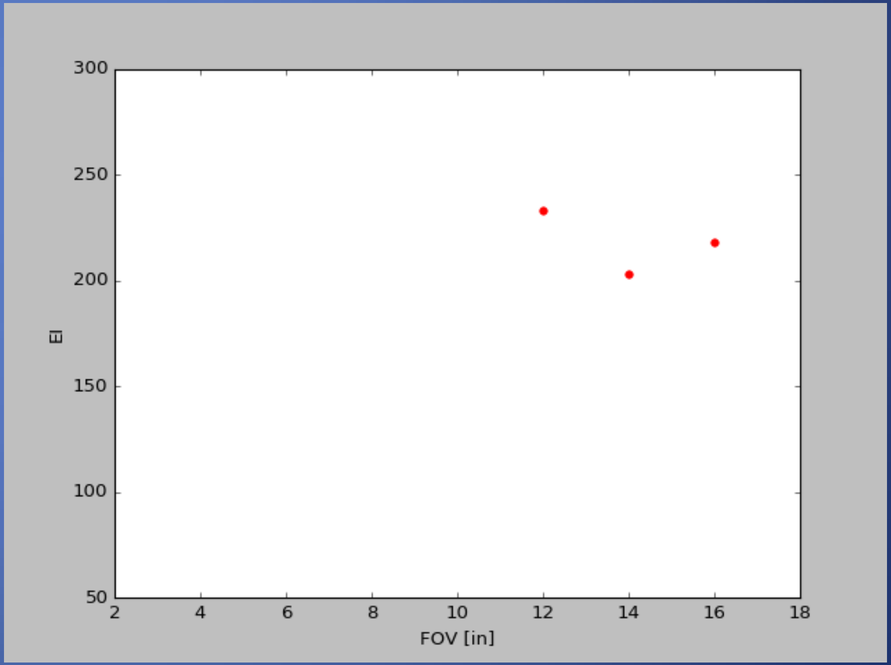
Effect of collimation

EI = 203



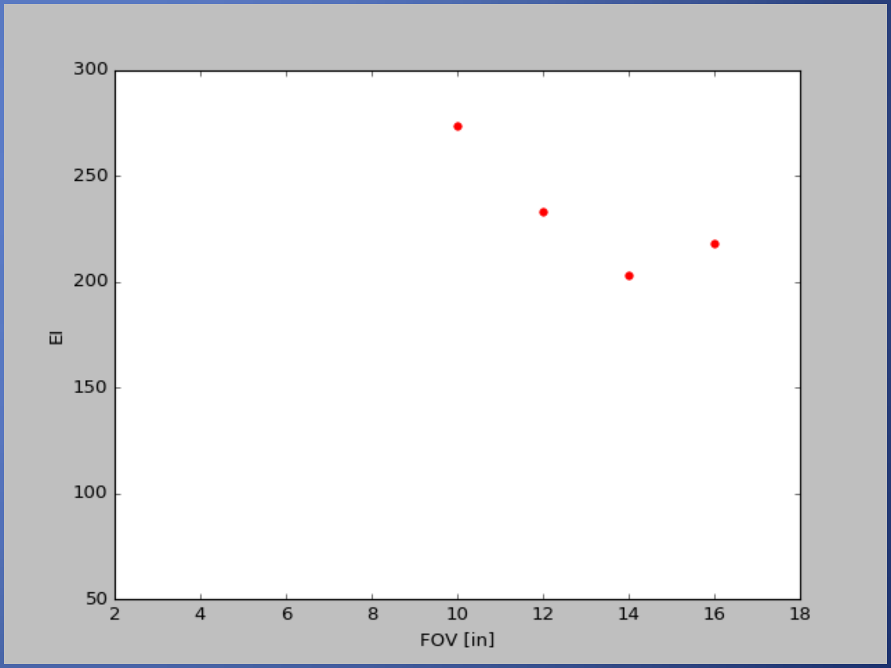
Effect of collimation

EI = 233



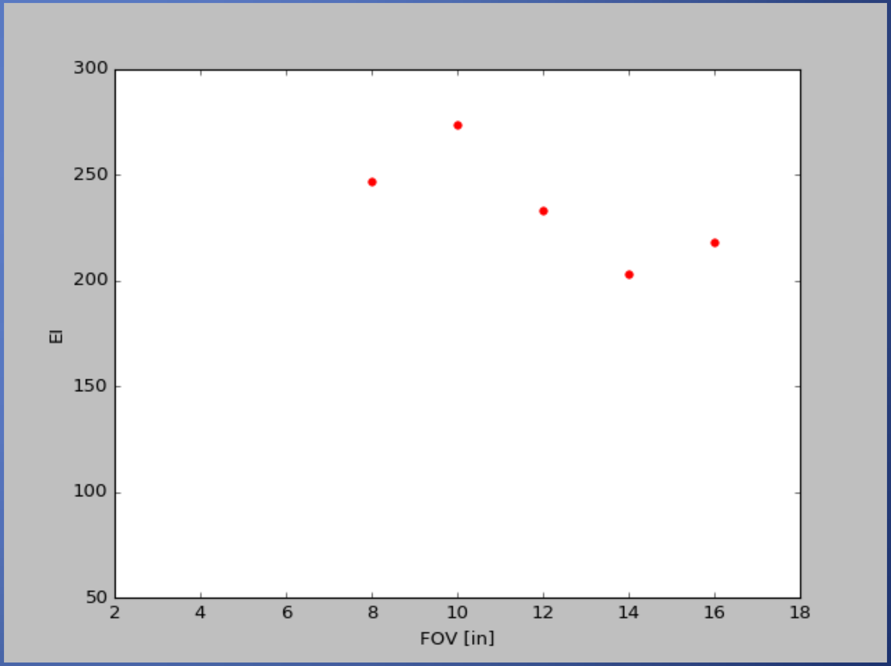
Effect of collimation

EI = 274



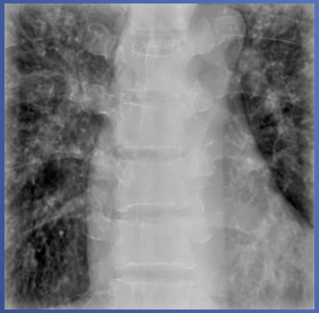
Effect of collimation

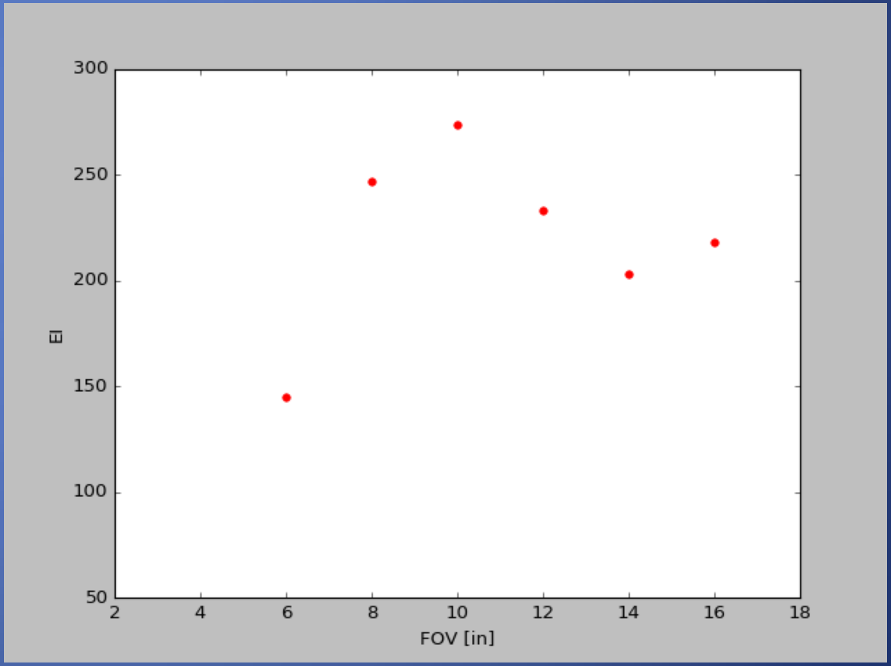
EI = 247



Effect of collimation

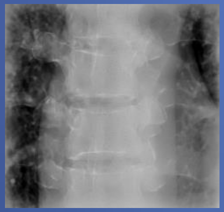
EI = 145

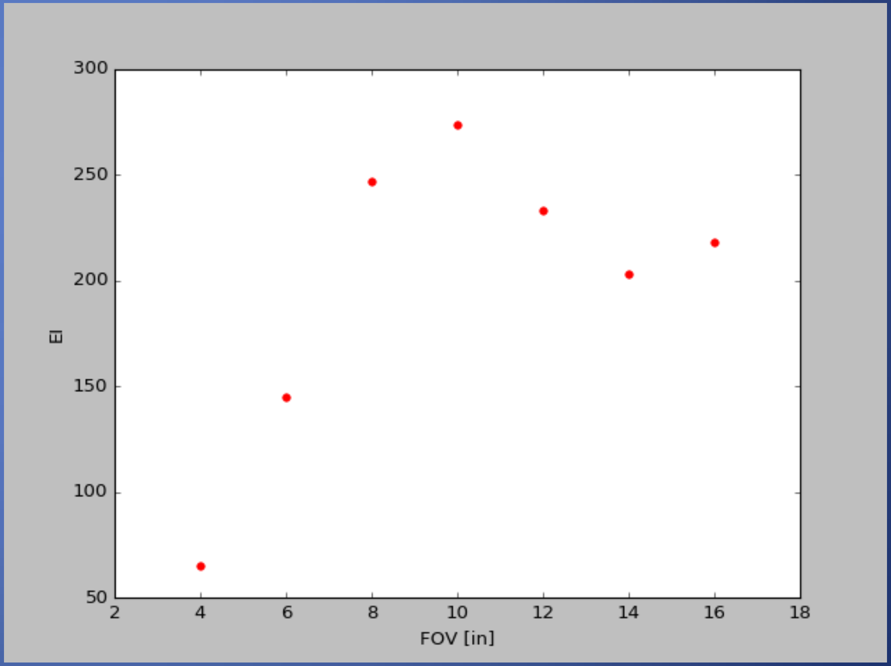




Effect of collimation

EI = 65



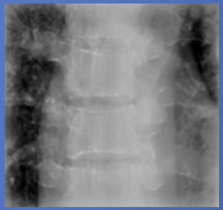


Anatomical Image Content Matters

EI = 274

large portion of lung in image (low attenuation)

EI = 65



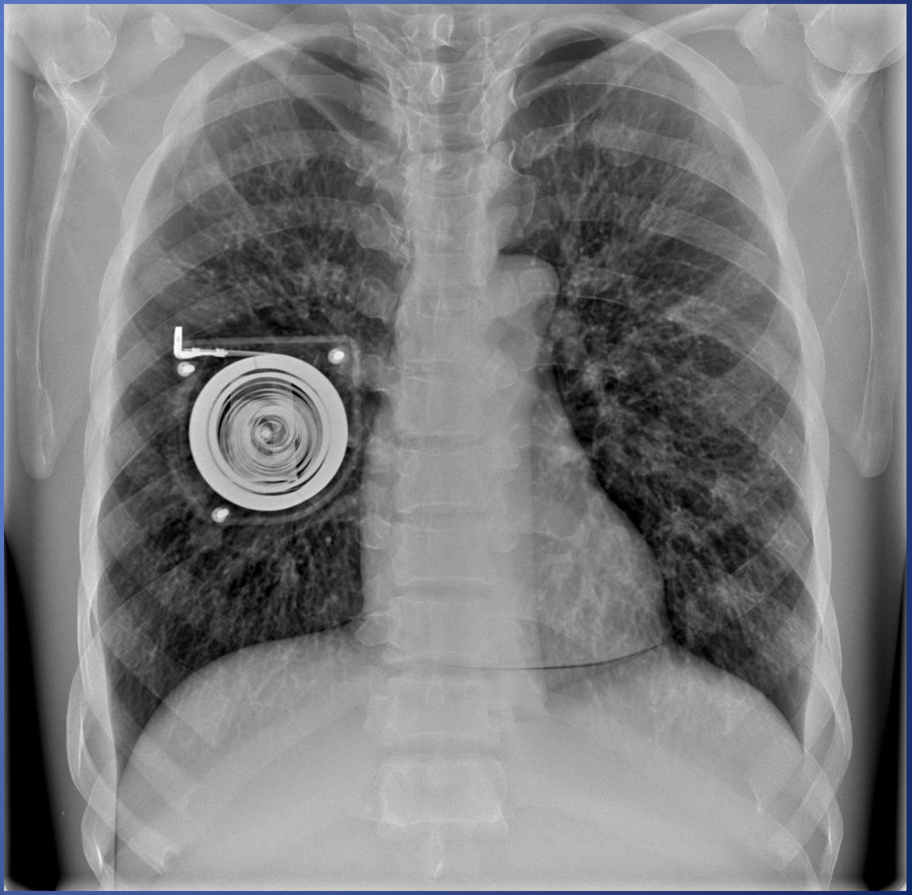
mostly highly attenuating structures in image

Collimation changes the anatomical content of the image

Sources of EI variability: Metal Implants

EI = 203

EI = 189



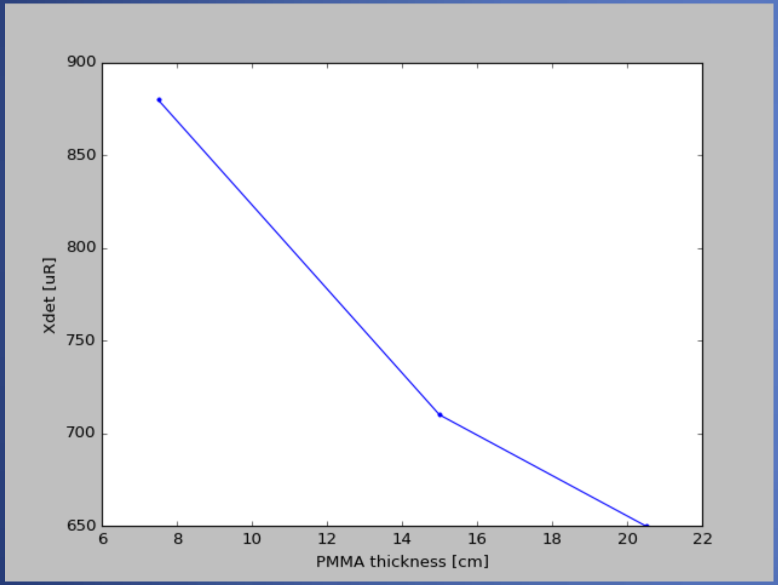
AEC and EI

AEC and EI

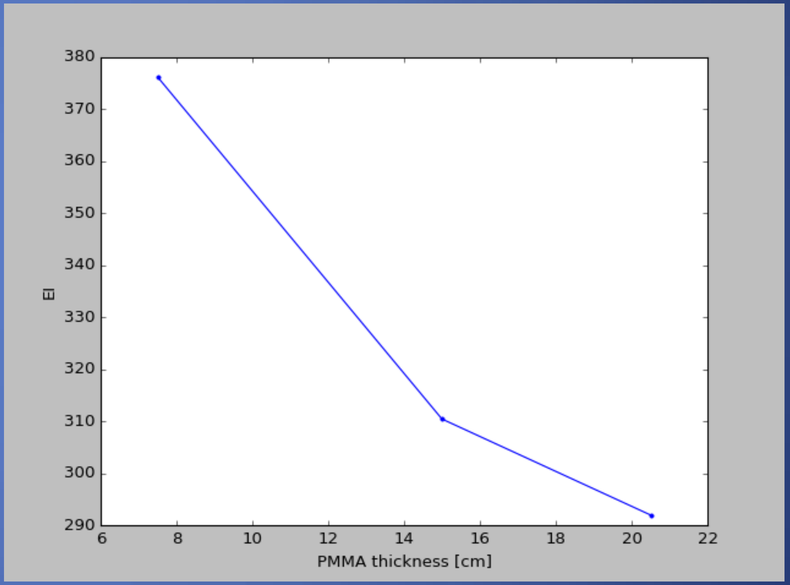
- The purpose of Automated Exposure Control (AEC) is to achieve a constant exposure to the detector, regardless of patient size
- AEC is based on ion chamber cells that are located in the x-ray beam path just in front of the detector

AEC and EI

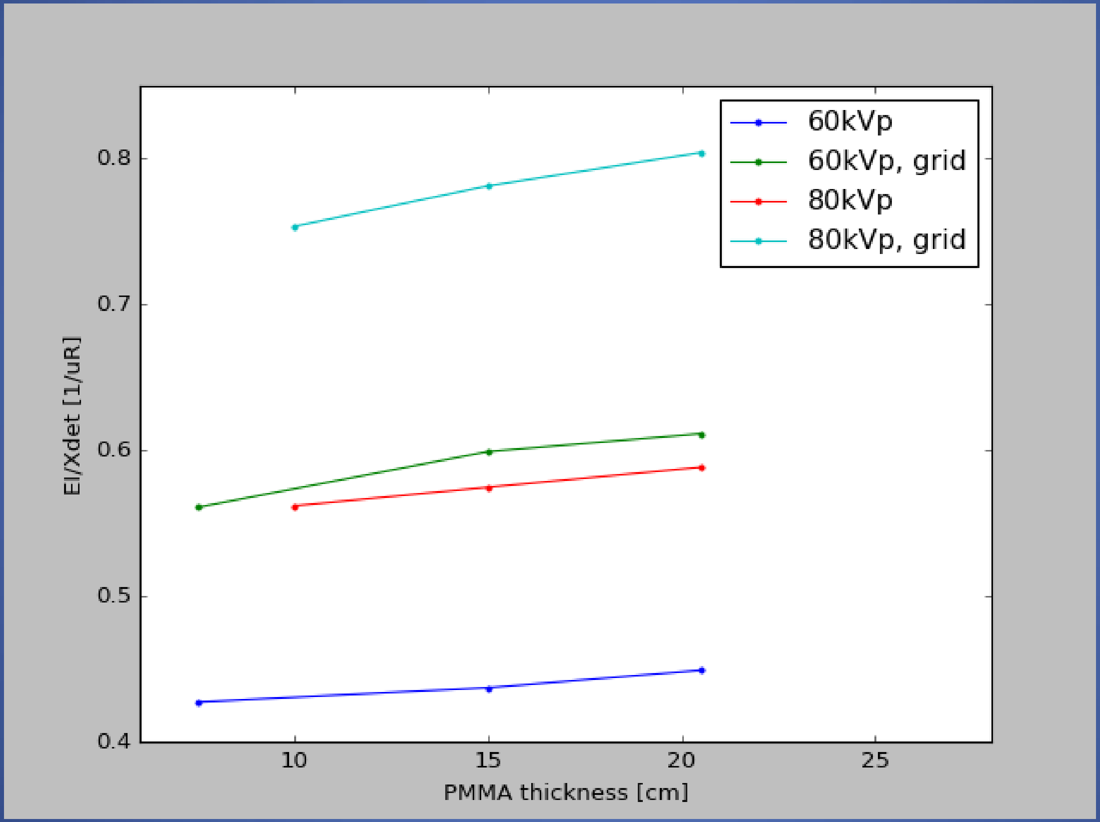
Detector entrance exposure (uR)



EI



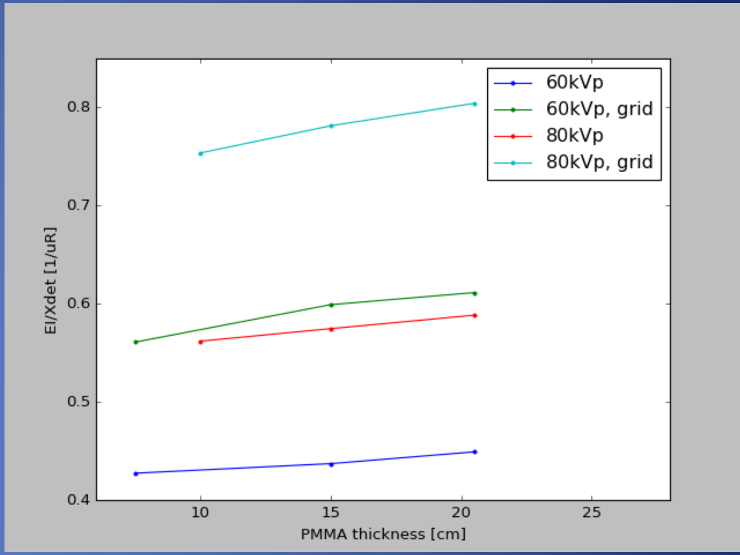
AEC and EI



60kVp
60kVp, grid
80kVp
80kVp, grid
EI/Xdet [1/uR]
0.4
0.5
0.6
0.7
0.8
10
15
20
25
PMMA thickness [cm]

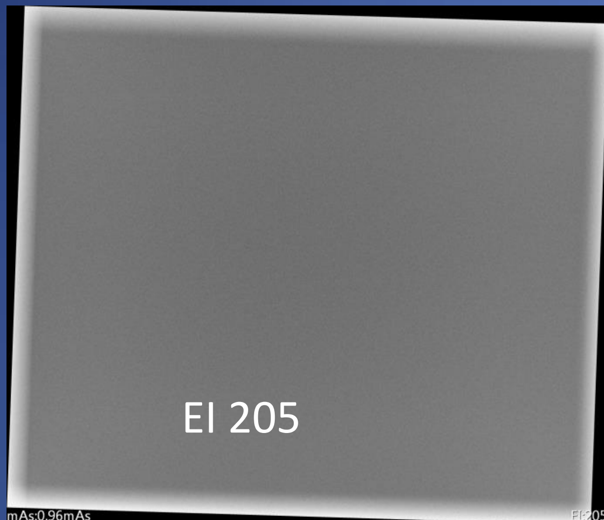
AEC and EI

- EI/X_{det} remains ~flat as patient thickness varies
- However, the resulting EI/X_{det} varies strongly with exposure condition (kVp, grid)
- In an ideal world, this would be compensated for by modifying the target EI.



Examples

Example: Intermittent problems

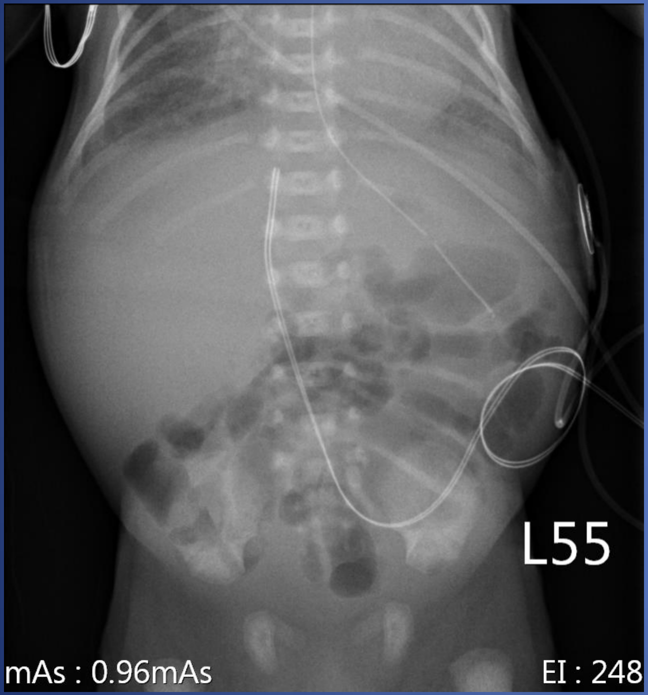


Battery replacement resolved the issue

Case courtesy of Z. F. Lu, PhD

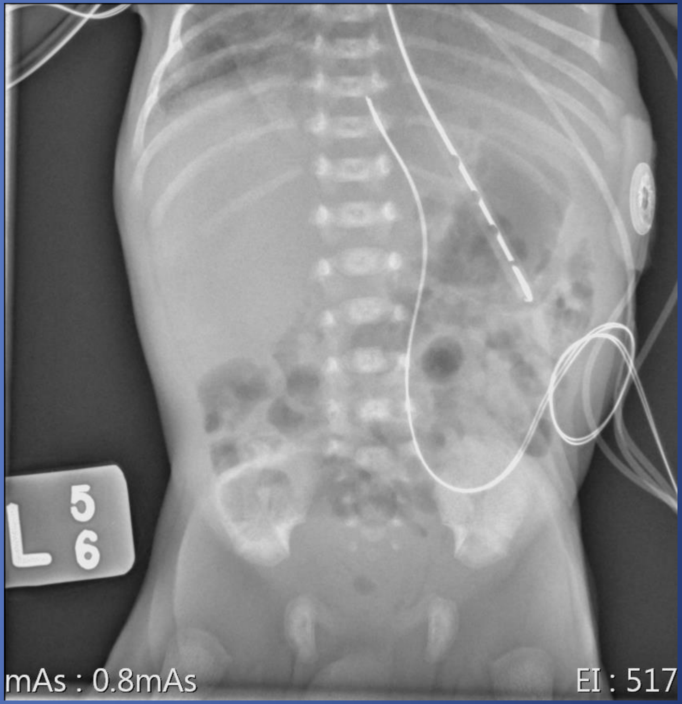
Example: EI can be an unreliable metric in isolated cases

Today



52kVp
SID = 28in
ESE = 4.3mR

Yesterday



58kVp
SID = 36in
ESE = 2.6mR

Case courtesy of A. Sanchez, PhD

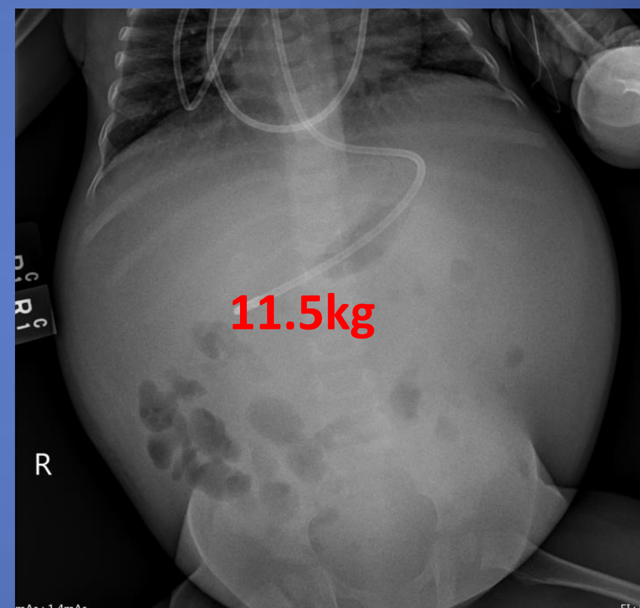
How is the EI on day 6 lower yet higher technique? Same thickness?

Day 1

1mAs
60kVp
EI: 191

SID: 30"
thickness: 12cm
Incident beam: 4.4mR

Day 6

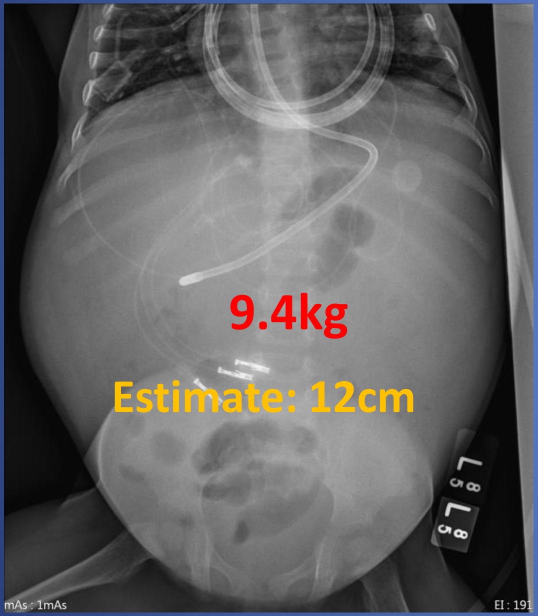


1.4mAs
62kVp
EI: 91

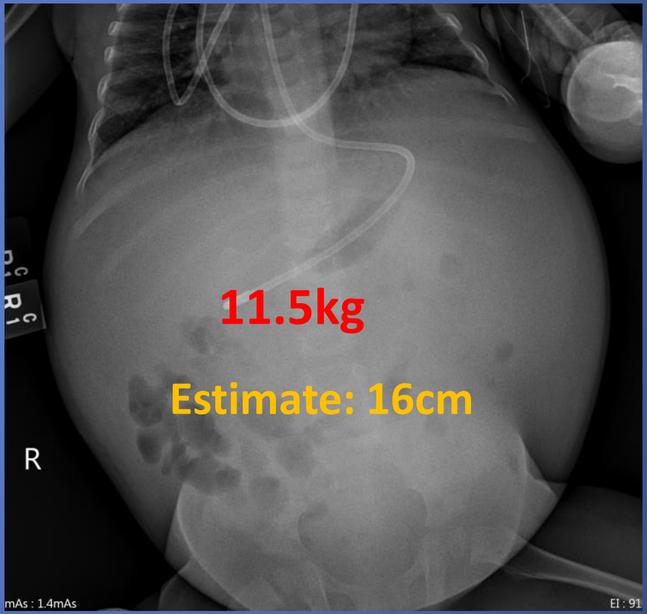
SID: 30"
thickness: 12.5cm
Incident beam: 6.6mR

EI and incident exposure can be used to estimate patient thickness

Day 1



Day 6



G. Andria, *et al*. Dose Optimization in Chest Radiography: System and Model Characterization via Experimental Investigation. IEEE TRANS. INSTR. MEAS. 63(5) 1163, 2014.

Summary

- The exposure index quantifies detector entrance air kerma
  - Strongly dependent on technique selection
  - Many sources of variability
- Useful concept if used carefully

The End