# CALIBRATING AUTOMATIC EXPOSURE CONTROL FOR DIGITAL RADIOGRAPHY

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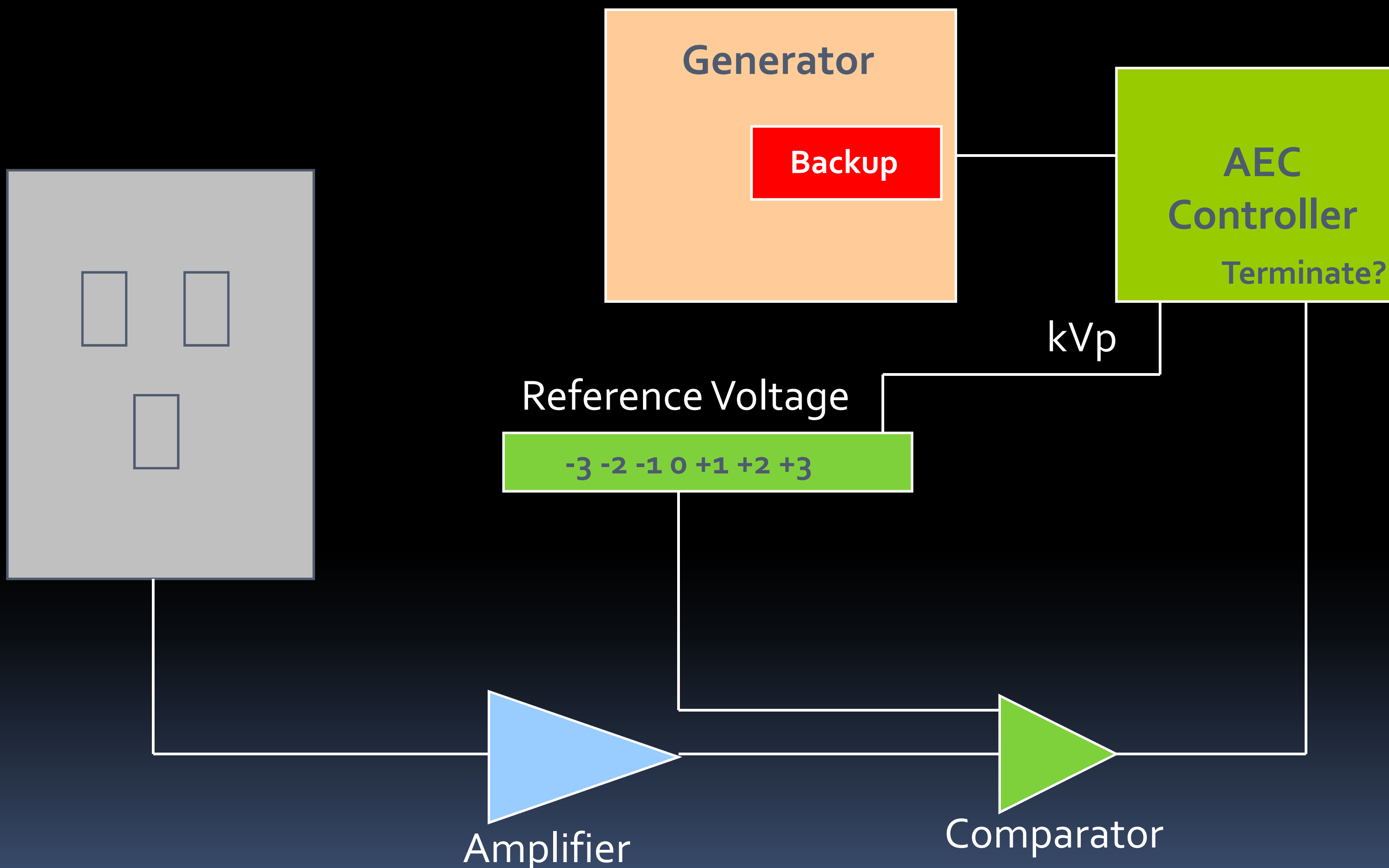
# Introduction

- AEC is an essential part of modern radiographic systems
  - Consistent, reproducible exposures
  - Compensation for a wide range of factors
    - Patient – size, anatomy imaged
    - Technical factors – kVp, time, desired receptor dose
- Calibrations may need to be adjusted for digital receptors
  - Energy response
- Film O.D. can no longer be used to verify calibration

# AEC System Diagram




Loosely based on Bushberg, Seibert, Leidholdt, and Boone, The Essential Physics of Medical Imaging.

# Fundamental AEC performance characteristics

- Initial acceptance testing
  - Sensor selector/location
  - Density correction
  - Screen sensitivity adjustment
  - Sensitivity vs. speed setting
  - Reproducibility
  - AEC balance/field sensitivity matching
  - AEC sensitivity
  - Patient thickness tracking
  - kVp tracking
    - Beam quality correction curve
  - Backup timer
  - Cell mapping
  - Minimum response time
- Ongoing QC testing
  - AEC sensitivity
  - Density correction
  - kVp tracking
  - Patient thickness tracking
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  - AEC balance
  - Backup timer
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AAPM 2008 – Extensive look at many fundamental performance characteristics

http://www.instablogsimages.com/images/2007/11/23/digital-flat-panel-x-ray-detector_28.jpg

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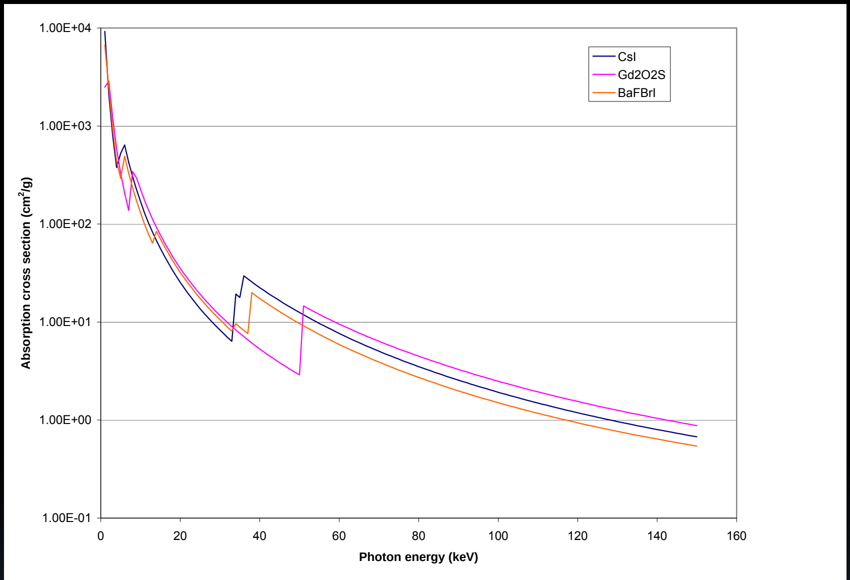
# kVp correction

- Many existing AEC systems were calibrated for use with screen-film systems
- The energy response of gadolinium oxysulfide ($Gd_2O_2S$) screens is substantially different from that of image receptors used in digital radiography
- Thus, to properly expose digital radiographs, we must recalculate the kVp correction curve for our AEC systems to respond correctly considering the image receptor characteristics



# kVp correction curves for DR

- Doyle and Martin have calculated theoretical kVp correction curves for both CR and iDR detectors
- Also note that the addition of small amounts of Cu filtration does not significantly affect the calibration

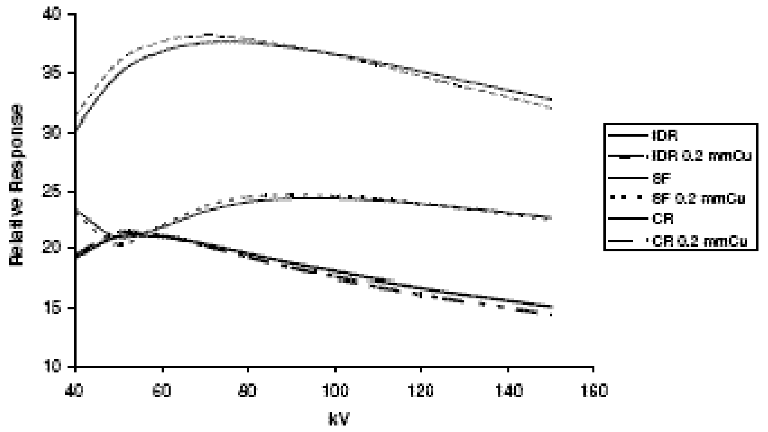



Figure 1. Variation of phosphor sensitivity with tube potential for a gadolinium oxysulphide ($Gd_2O_2S$) film-screen phosphor (0.20 mm thick), BaF(Br85%, I15%) CR phosphor (0.22 mm) and a CsI IDR phosphor (0.50 mm). Data are shown for x-ray beams filtered by 2.5 mm of aluminium, and by 2.5 mm of aluminium plus 0.2 mm of copper.

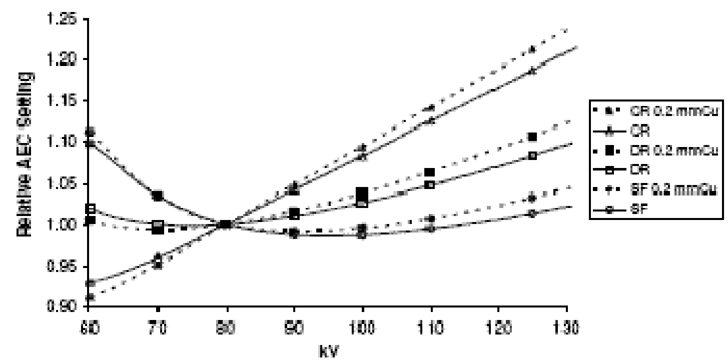
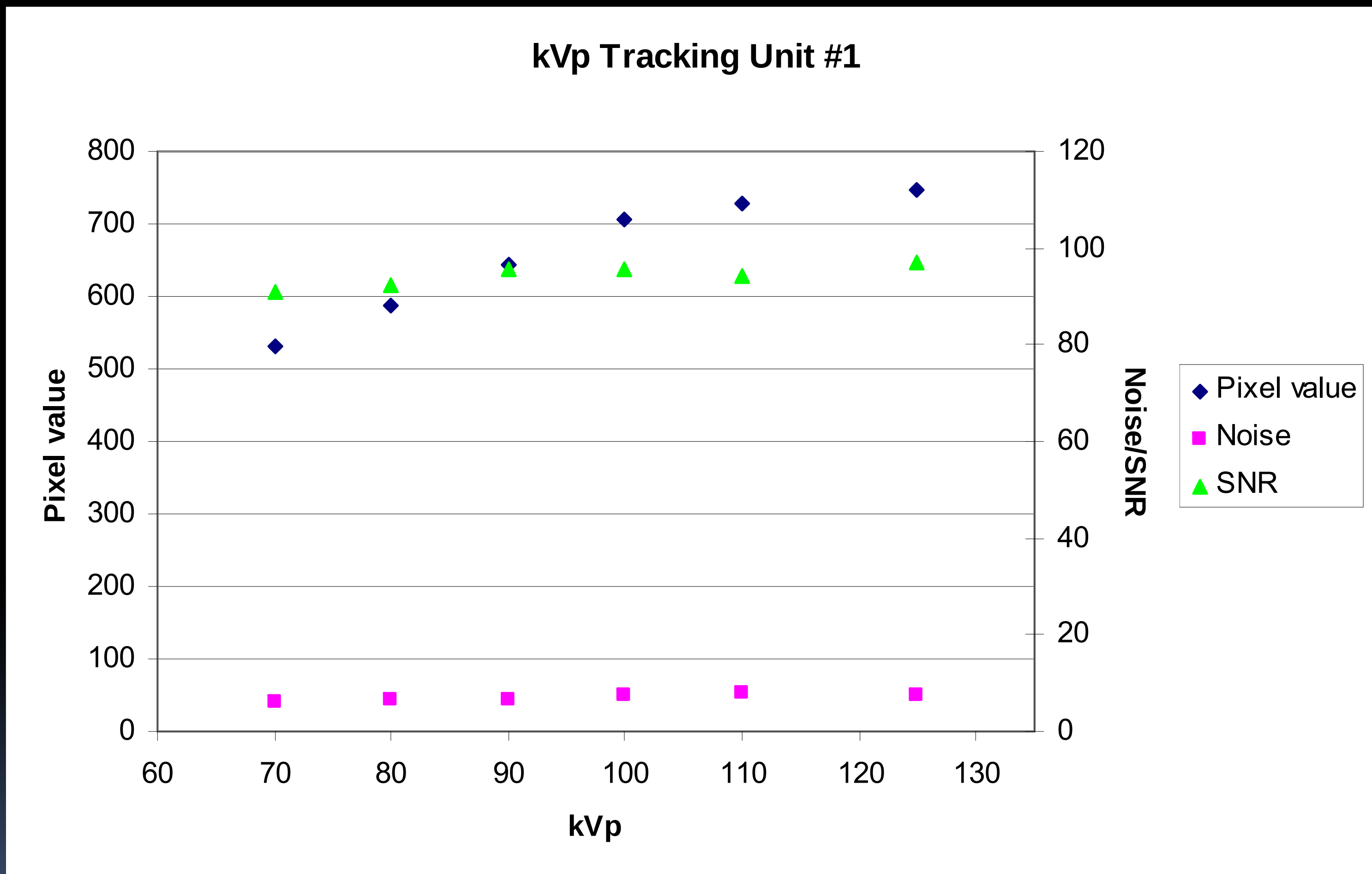
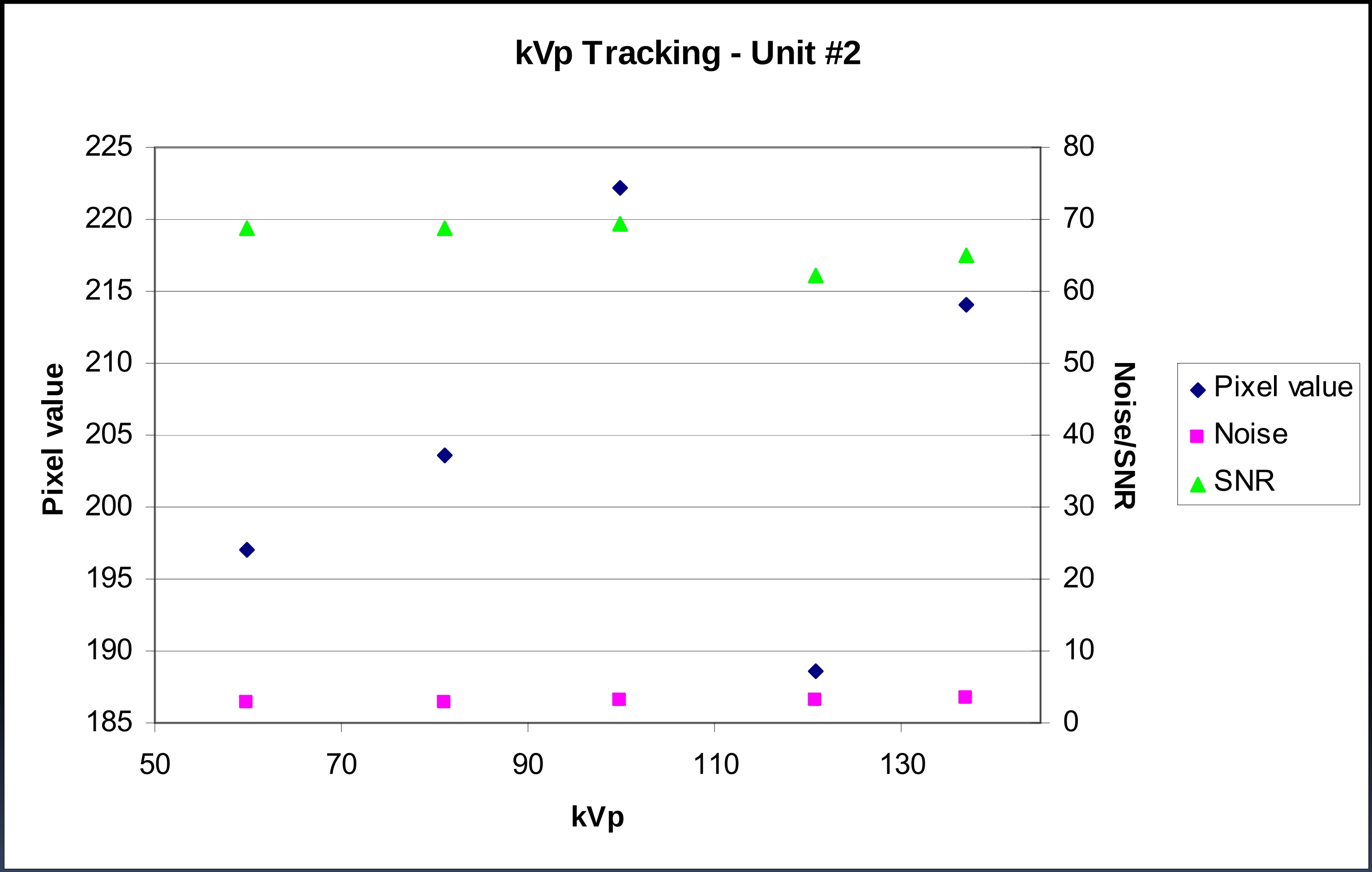



Figure 2. Theoretical evaluation of the variations in AEC setting for image receptor doses with a film-screen system, a CR system and an IDR system for x-ray beams with and without an additional 0.2 mm copper, normalized to the response at 80 kV.

Doyle, P and Martin, CJ, Calibrating automatic exposure control devices for digital radiography, Phys. Med. Biol. **51**:5475-5485, 2006.



kVp Tracking Unit #1
Pixel value
800
700
600
500
400
300
200
100
0
120
100
80
60
40
20
0
Noise/SNR
60
70
80
90
100
110
120
130
kVp
Pixel value
Noise
SNR


kVp Tracking - Unit #2
225
220
215
210
205
200
195
190
185
Pixel value
80
70
60
50
40
30
20
10
0
Noise/SNR
50
70
90
110
130
kVp
Pixel value
Noise
SNR

# AEC Balance

- Field sensitivity matching
- To achieve consistent exposures for all views, AEC cells should be balanced
- Manufacturers of x-ray systems use several different schemes for AEC balancing
- Thus, a one-size-fits-all test will not be valid if you work with a variety of systems

# AEC Balance

- Test AEC balance during acceptance testing to set a baseline standard for balance
- Ask your service engineer about the calibration/balancing procedure
  - Many manufacturers today use AEC systems that are not serviceable for balance – they can only be replaced
  - In this case you are stuck with manufacturer's balance scheme
  - Other manufacturers still have tunable AEC cells
    - Pots in generator
    - Software interface
    - Pots in detector housing
- Published guidelines/recommendations
  - ± 5% across all combinations (AAPM 14)*

# AEC Balance

- Cells must also be matched when used in combinations
- AEC systems may terminate the exposure when the most sensitive cell reaches the required current, or may average the signal between the cells being used
- Same criteria apply

| | C | L | R | L+R | L+C | R+C | All |
|---|---|---|---|---|---|---|---|
| **Unit 1** | 6.32 | 7.23 | 7.16 | 7.16 | 6.73 | 6.7 | 6.83 |
| **Unit 2** | 46.6 | 69.9 | 70.4 | 69.9 | 55.7 | 55.9 | 59.8 |
| **Unit 3** | 4.5 | 4.32 | 4.44 | 4.39 | 4.39 | 4.44 | 4.39 |

See also *'X-ray generator and automatic exposure control device acceptance testing'* by Raymond P. Rossi, M.S., in Specification, Acceptance Testing and Quality Control of Diagnostic X-ray Imaging Equipment, Proceedings of the 1991 AAPM Summer School

# AEC SENSITIVITY

# Methods for calibration

- Noise-based method
- $K_a$-based methods
  - Use a CR cassette with a cutout for a detector
  - Solid-state detector behind grid
  - Pre-detector $K_a$ and primary transmission through grid*
- Exposure indicator (EI) – based methods
  - EI
  - Pixel value
    - Characteristic function
  - SNR

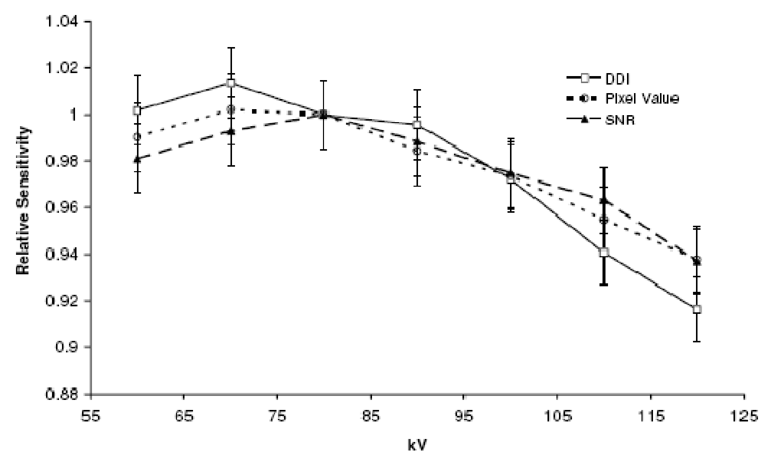


Figure 3. Comparison of the relative sensitivities of indicators that relate to image plate response for an Agfa CR system, normalized to the response at 80 kV. Error bars indicate an achievable tolerance of 3% in adjusting the AEC.

Doyle, P and Martin, CJ, Calibrating automatic exposure control devices for digital radiography, Phys. Med. Biol. **51**:5475-5485, 2006.

# Noise-based AEC calibration

- For each kVp, an S number can be associated with the standard deviation of pixel values that produce the desired noise characteristics
- Recommend use of an SNR-based threshold for choosing noise level
  - Example: $SNR_{threshold}$ of 5 → Signal difference of 50 can be seen with $\sigma = 10$
  - Still some determination to be done
- **Setting up AEC in *Semi-automatic* EDR mode yields clinically valid results in *Automatic* EDR mode**

**Christodoulou, EG, Goodsitt, MG, Chan, H, and Hepburn, T, Phototimer setup for CR imaging, Med. Phys. 27:2652-2658, 2000.**

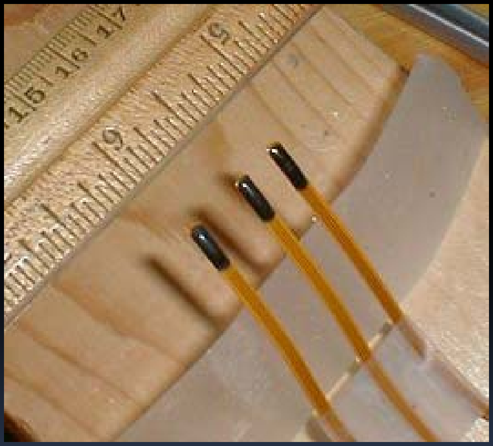
# $K_a$-based methods

- CR cassette with cutout*
- S ~ 200/E, E = exposure (mR) for Fuji CR
- Cutout machined into IP cassette to accept solid state dosimeter
  - Introduces realistic scatter* from cassette, overcomes cassette sensing

**Doyle P, Gentle D, Martin CJ, Optimising automatic exposure control in computed radiography and the impact on patient dose, Rad. Prot. Dosim. 114:236-39, 2005.**

# $K_a$-based methods

- Solid-state dosimeter with lead backing can be used to reduce the effect of backscatter
- Not possible for all DR systems



http://www.rpi.edu/dept/radsafe/public_html/RADIATION%20DETECTORS_files/MOSFET.jpg

http://www.unfors.com/products.php?catid=168

**Doyle P, and Martin CJ, Calibrating automatic exopsure control devices for digital radiography, Phys. Med. Biol. 51:5475-85, 2006.**

# Pre-detector $K_a$

- Simple measurement to make
- Eliminates backscatter
- Necessitates measurement of $T_p$ or $B$ of anti-scatter grid
- Some inaccuracy introduced due to beam hardening by grid which is not considered in this measurement

# EI-based

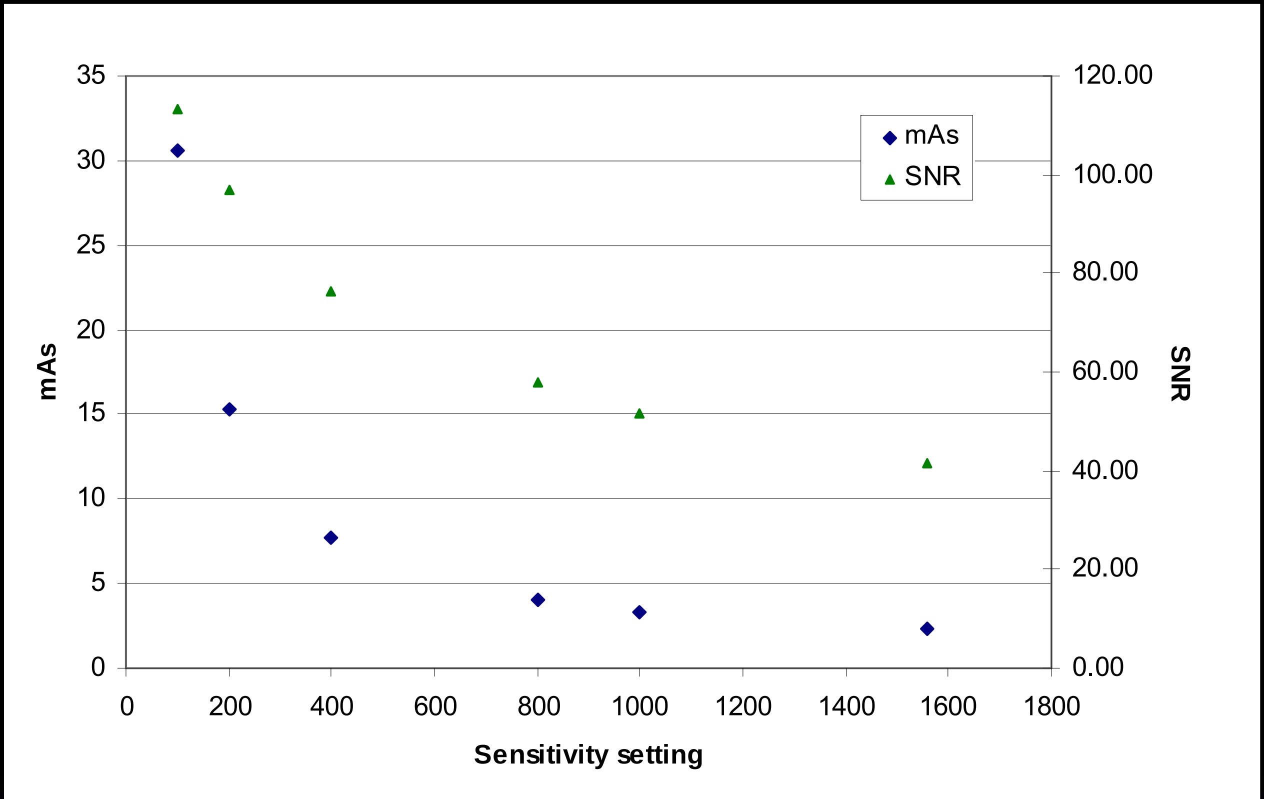
- Calibrate using the EI provided by the manufacturer
- Many caveats to consider
    - Calibration conditions
        - AEC
        - Detector
        - EI
    - Practicality
    - Usefulness of EI
- Basically the same as $K_a$-based methods
    - Dependence of EI on beam conditions, grid, etc.

# Three different methods…

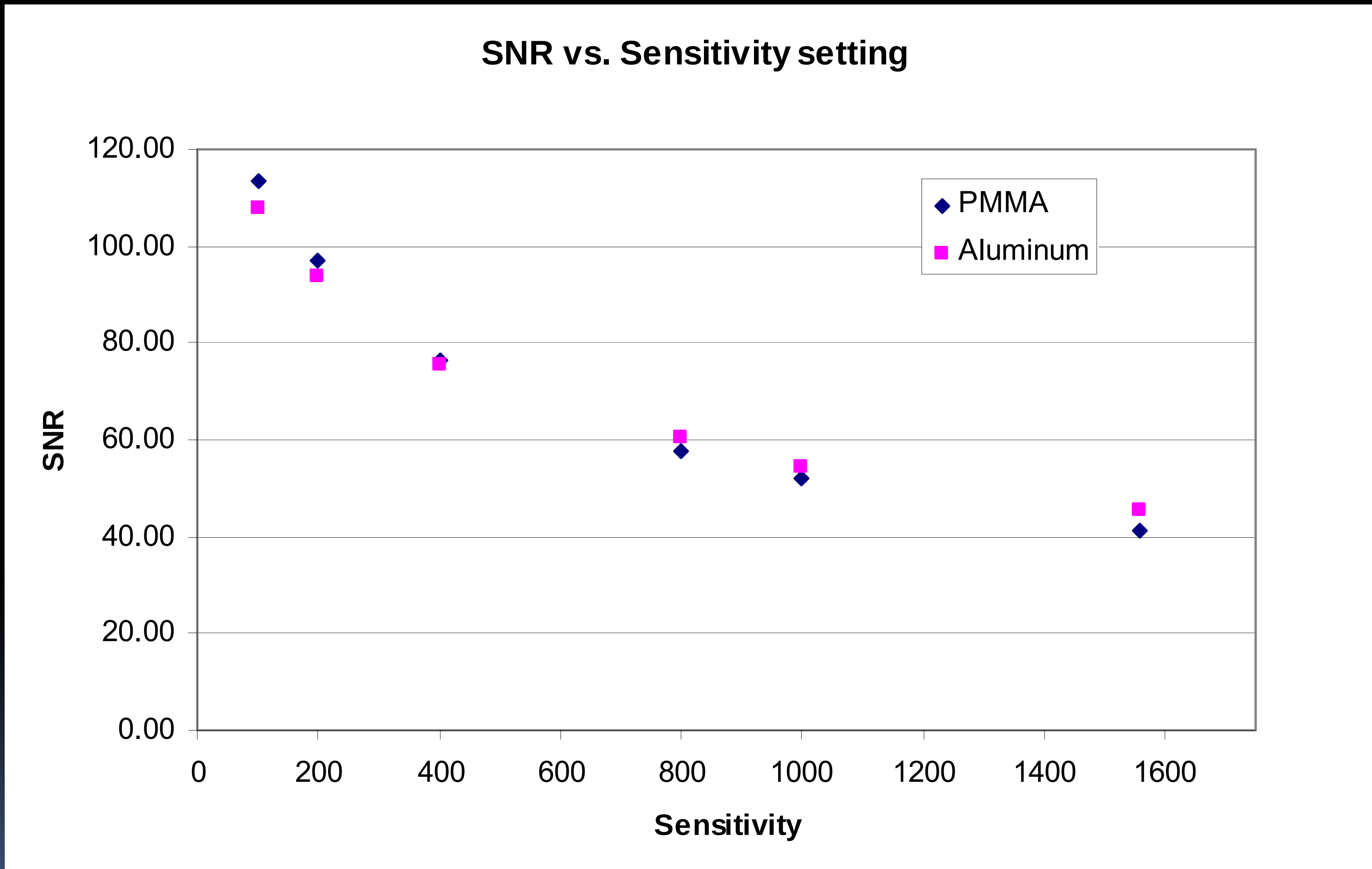
- GE
  - Variable PMMA thickness (vs kVp) to calibrate EI
  - 20 mm Al phantom to calibrate AEC and detector
  - 80 kVp
- Siemens
  - 0.6 mm Cu filter to calibrate AEC, EI, and detector
  - 70 kVp
- Fuji
  - 80 kVp bare beam to calibrate EI
  - We use 0.5 mm Cu + 1 mm Al
  - They don't calibrate the AEC for retrofitted systems

# To what value should I calibrate?

- CR – Calibrate AEC to deliver the desired $K_a$ at the image plane
  - Vary $K_a$ by body part and view using exposure indicator targets
    - E.g. S = 200 general, S = 100 extremity
- DR – Calibrate AEC to manufacturer's specifications
  - E.g. 2.5 µGy @ 400 sensitivity setting
  - Use sensitivity setting to vary $K_a$ by body part and view




$$\mathrm{mAs}_2 = \mathrm{mAs}_1 \times \frac{S_1}{S_2}$$


SNR vs. Sensitivity setting
120.00
100.00
80.00
60.00
40.00
20.00
0.00
SNR
0
200
400
600
800
1000
1200
1400
1600
Sensitivity
PMMA
Aluminum

# CR

- Test tool (e.g. Radchex)
- CR plate, Sensitivity (semi-EDR), calibrated reader (use EI)
- Measure X or $K_a$ at detector plane

Simplest

↓

Most Complex

# Test tools

- A common test tool is the CR Radchex meter
- Consists of a sensor that mimics the response of a CR screen
- Insert in Bucky, make exposure, get reading
- Tables provided to convert CRLU to EI or $K_a$


http://disccorp.mb.ca/products/Wired_CRRadchex.html

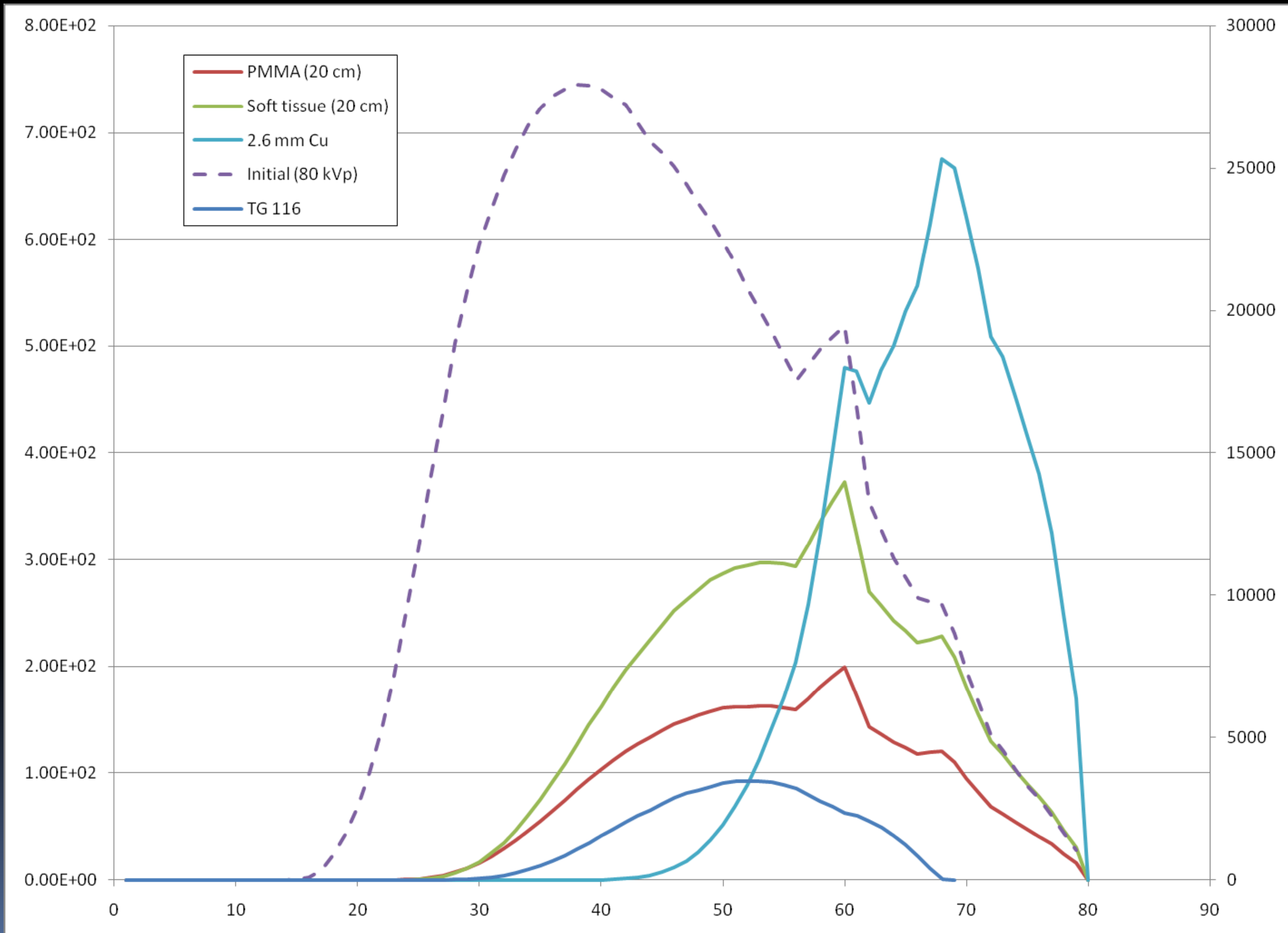
# Radchex meter

## Pros

- Fast
- Does not require plate or reader
- Easy
- Defeats cassette sensing

## Cons

- May not exactly simulate response of CR plate
- May not exactly simulate clinical situation
- Expensive
- Lack of patient-like attenuator
- Transmitted spectrum through 1.5 mm Cu – CRLU to EI conversion may not be correct

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TRIAD
SENSITIVE AREA

## X-Ray-Light Energy Conversion Efficiency Values for the CR Radchex for Various Beam Conditions

| Beam Condition | Conversion Efficiency (CRLU/mR) | Conversion Efficiency (CRLU/μGy) |
|---|---|---|
| Scatter-Free | 14.10 CRLU/mR | 1.61 CRLU/μGy |
| Low Scatter | 12.80 CRLU/mR | 1.46 CRLU/μGy |
| Medium Scatter (in bucky) | 12.05 CRLU/mR | 1.37 CRLU/μGy |
| High Scatter | 10.00 CRLU/mR | 1.14 CRLU/μGy |
| Air with 3mm total Al | 8.06 CRLU/mR | 0.92 CRLU/μGy |
| Air with 4mm total Al | 10.22 CRLU/mR | 1.17 CRLU/μGy |
| Air with 5mm total Al | 11.65 CRLU/mR | 1.33 CRLU/μGy |

## CR Manufacturer Plate Reader Values Corresponding to CR Radchex values

(Assuming that the reader is calibrated using the manufacturers specifications)

| CRLU | EI | IGm @ 200 Speed Class | S# | Disc Relative Imaging Speed(2000 / CRLU) |
|---|---|---|---|---|
| 5.00 | 1550 | 1.75 | 409 | 400 |
| 6.00 | 1629 | 1.83 | 341 | 333 |
| 7.00 | 1695 | 1.9 | 292 | 286 |
| 8.06 | 1757 | 1.96 | 253 | 248 |
| 10.00 | 1851 | 2.05 | 204 | 200 |
| 10.22 | 1860 | 2.06 | 200 | 196 |
| 11.65 | 1917 | 2.12 | 175 | 172 |
| 12.05 | 1932 | 2.13 | 170 | 166 |
| 12.80 | 1958 | 2.15 | 160 | 156 |
| 14.10 | 2000 | 2.2 | 145 | 142 |

# CR plate and reader

- Use a patient-equivalent attenuator and expose a CR plate in the Bucky
  - ‘Test’ plate confirmed to be uniform with clinical stock
  - Reader calibration must be verified
- Exposure indicator is the test quantity
  - ‘Test’ mode – e.g. Sensitivity, Semi-EDR


TRIAD 2

# CR plate and reader

## Pros

- Cheap
- Simple if reader calibration is known to be good
- Exactly simulates response of CR plate
- Simulates clinical situation
- Defeats cassette sensing

## Cons

- Reader must be calibrated
- Takes more time than Radchex meter
  - Multiplied with more exposures
  - Wait period


TIMEX
QUARTZ

# Measure $K_a$

- Use ionization chamber in Bucky to measure $K_a$
- Doyle et al. proposed that an old cassette be modified to hold a solid state device to more accurately simulate the clinical case
- A solid state dosimeter can also be used
  - Behind AEC chambers
  - Pb-backed, so less backscatter concern
    - Does not integrate scatter from 2π in front
  - Still helpful to “mount” to keep centered

Doyle P, Gentle D, Martin CJ, Optimising automatic exposure control in computed radiography and the impact on patient dose, Rad. Prot. Dosim. 114:236-39, 2005.

# Measure $K_a$

## Pros

- Cheap†
- Accurately simulates clinical situation
- Direct measurement of $K_a$
- Independent verification – does not rely on plates or reader

## Cons

- Does not simulate response of CR plate*
- Time consuming
  - Setup
- Requires additional equipment (modified cassette)

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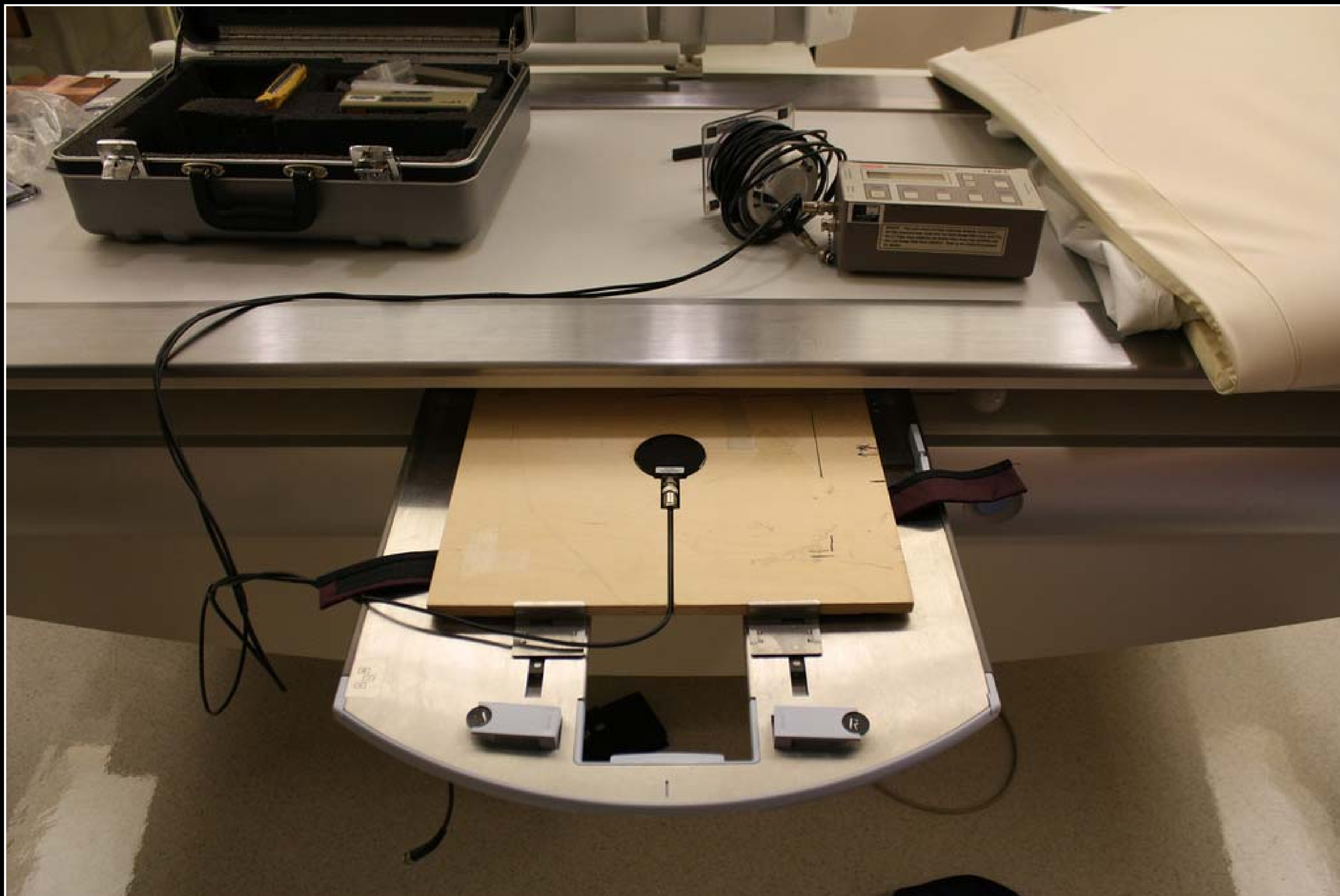


# Comparison of methods

| Scenario | mAs | S# | µGy | CRLU/Speed # |
|---|---|---|---|---|
| CR cassette w/screen | 72.5 | 196 | 8.53 | |
| CR cassette w/o screen | 86.1 | | | |
| 15 cc chamber in wood | 78.7 | | 11.39 | |
| 15 cc chamber in wood w/Pb | 73.4 | | 13.74 | |
| Nothing in Bucky | 87.7 | | | |
| Unfors Xi | 91.1 | | 9.95 | |
| Radchex w/PMMA* | 82.2 | | 11.5 | 15.7/127 |
| Radchex w/1.5 mm Cu* | 22.4 | | 11.6 | 18.6/107 |

Target $K_a$ in Bucky at detector plane = 8.76 µGy

8.76 µGy to plate under calibration conditions (0.5 Cu/1 Al) yielded S# of 191

# iDR and dDR

- Use exposure indicator to determine $K_a$
  - Must verify accuracy of indicator
    - TG 116
- Measure pre-detector $K_a$ and calculate $K_a$ at detector plane
  - Need to know $T_P$ of grid
  - Depends on calibration conditions
- Measure $K_a$ at detector plane
- Measure CF for clinical conditions and use it to calculate $K_a$

Simplest

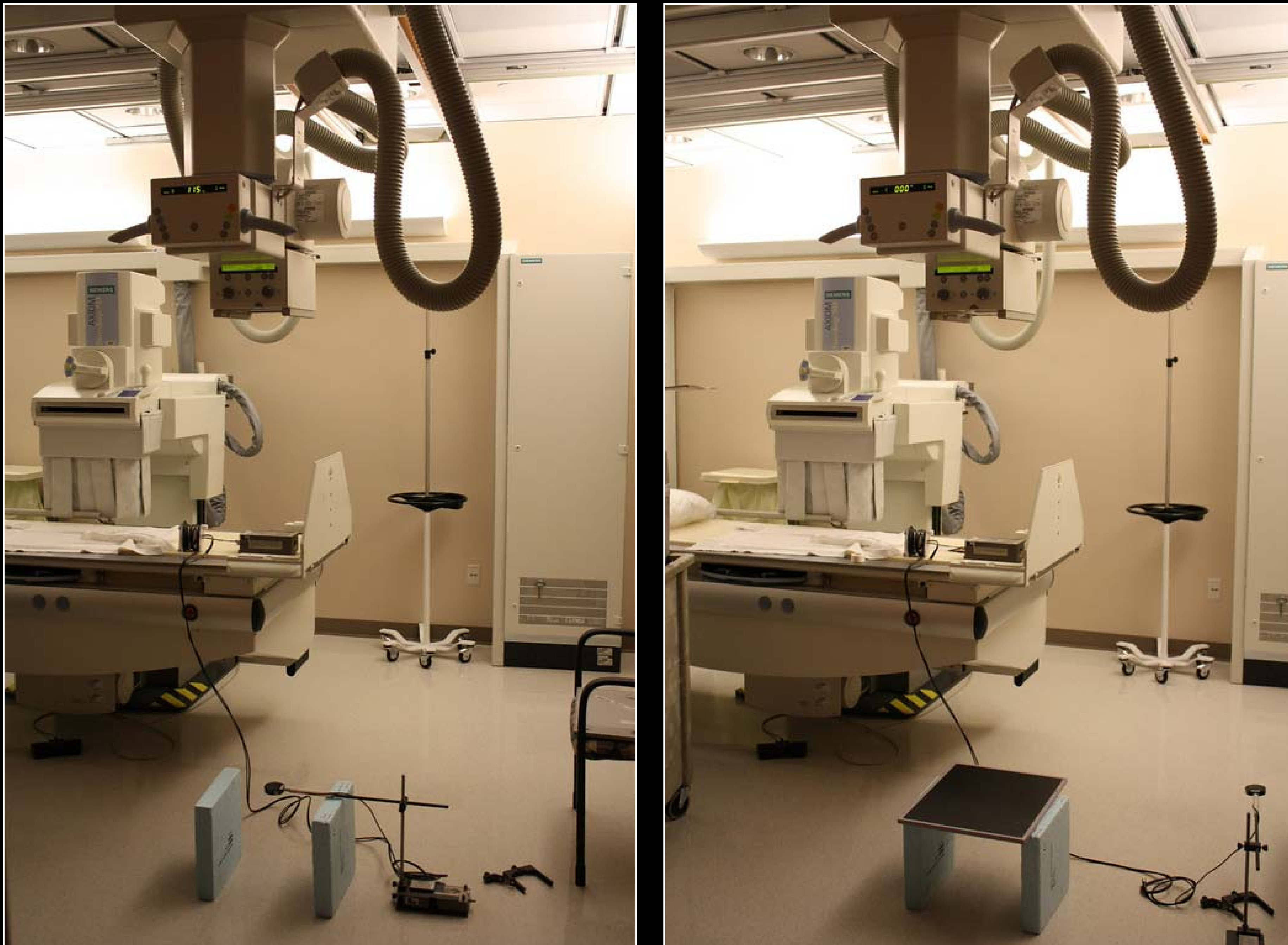
↓

Most Complex

# Ideally

- Verify EI at calibration conditions and use the EI to calibrate the AEC
- Manufacturer methods
  - GE: 2.5 µGy to detector @ 400 sensitivity, measured, factors applied for distance and table/cover
    - Without grid if removable
    - "Grid factor" used for dedicated chest systems
    - 20 mm Al phantom, 80 kVp
      - Unfortunately, EI conditions are different
  - Siemens: Detector dose = 1000/Sensitivity
    - 2.5 µGy @ 400 sensitivity, no grid, 70 kVp
    - EI conditions are the same

# VERIFYING THE EI



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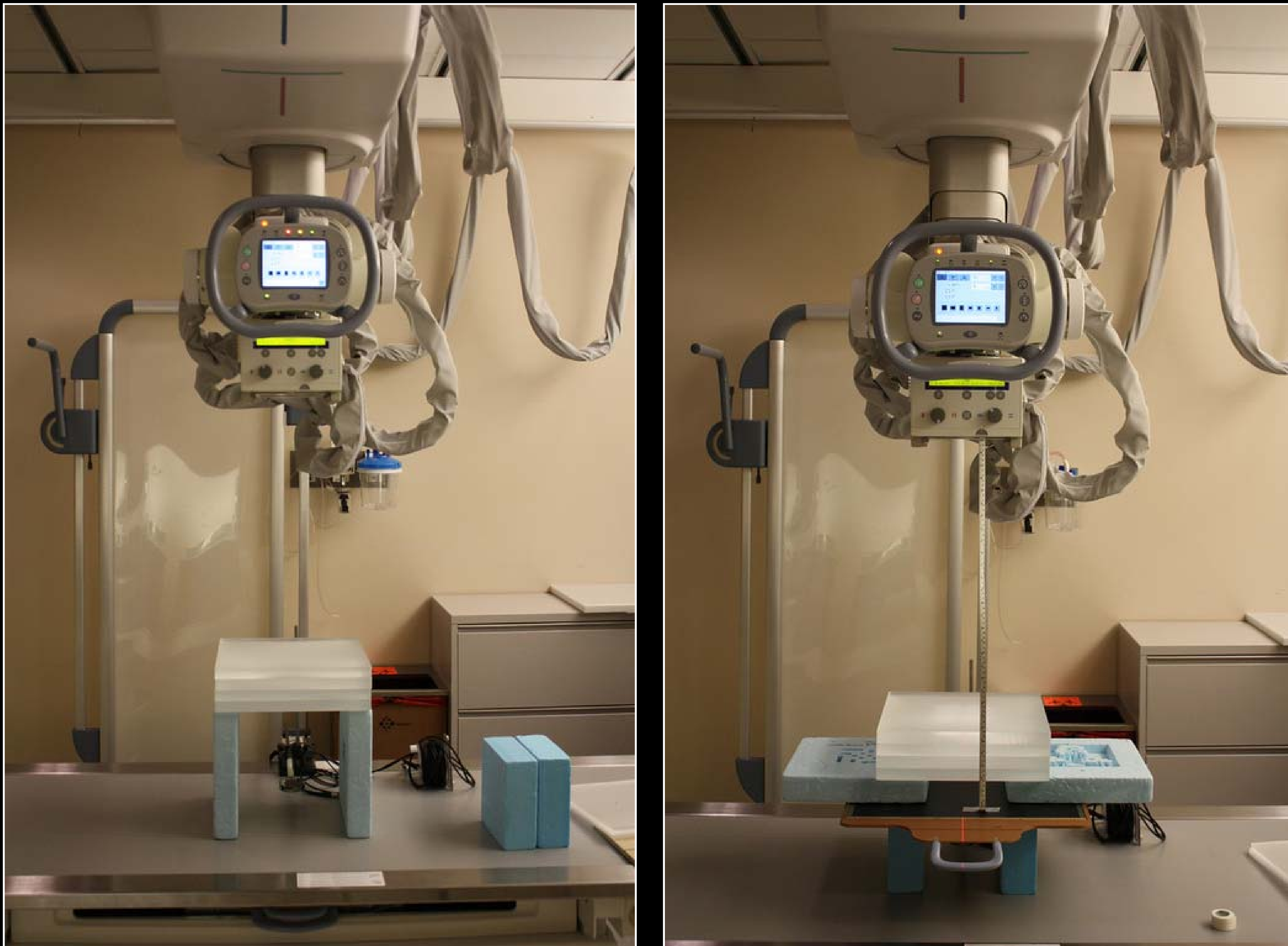

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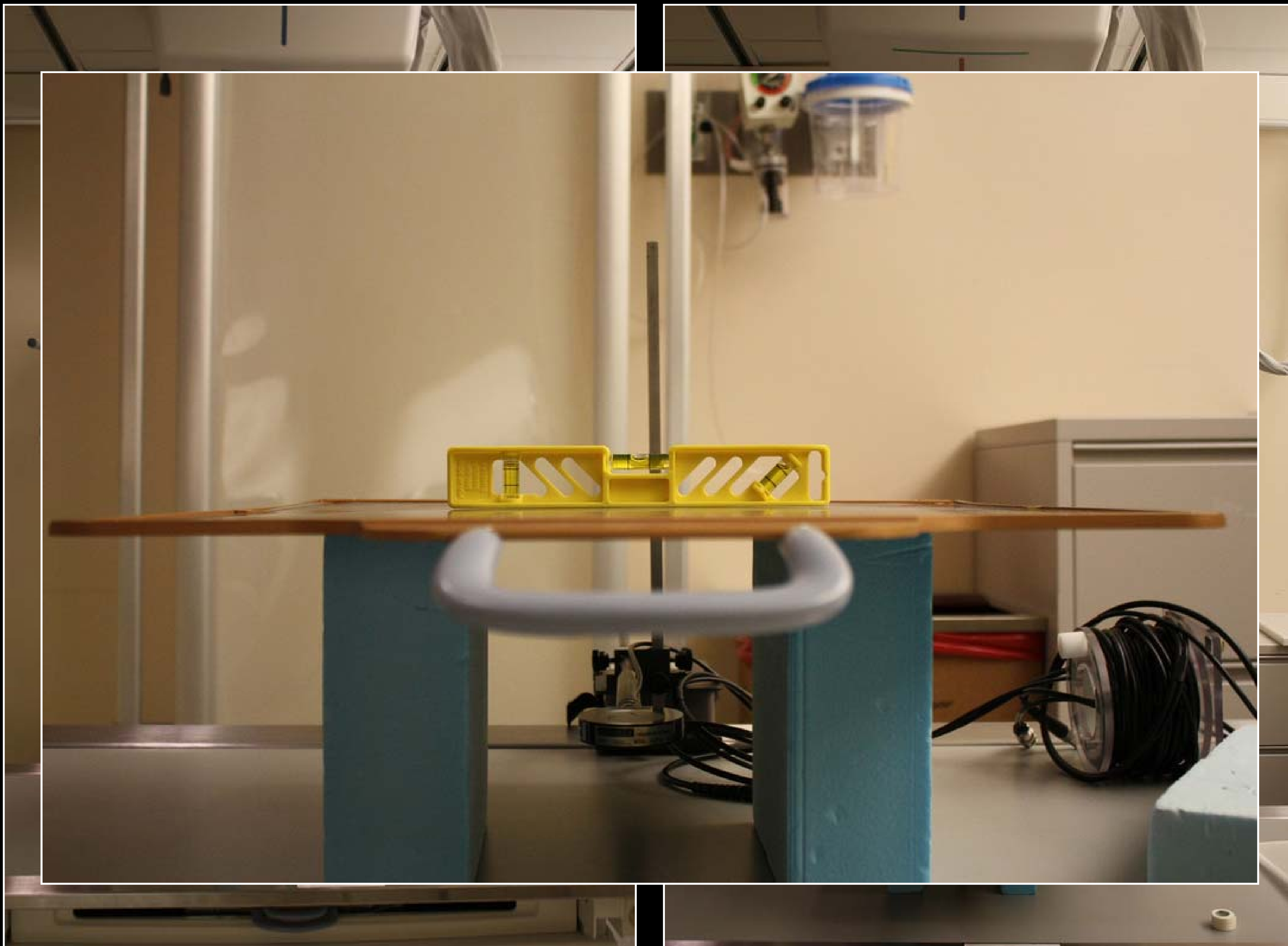

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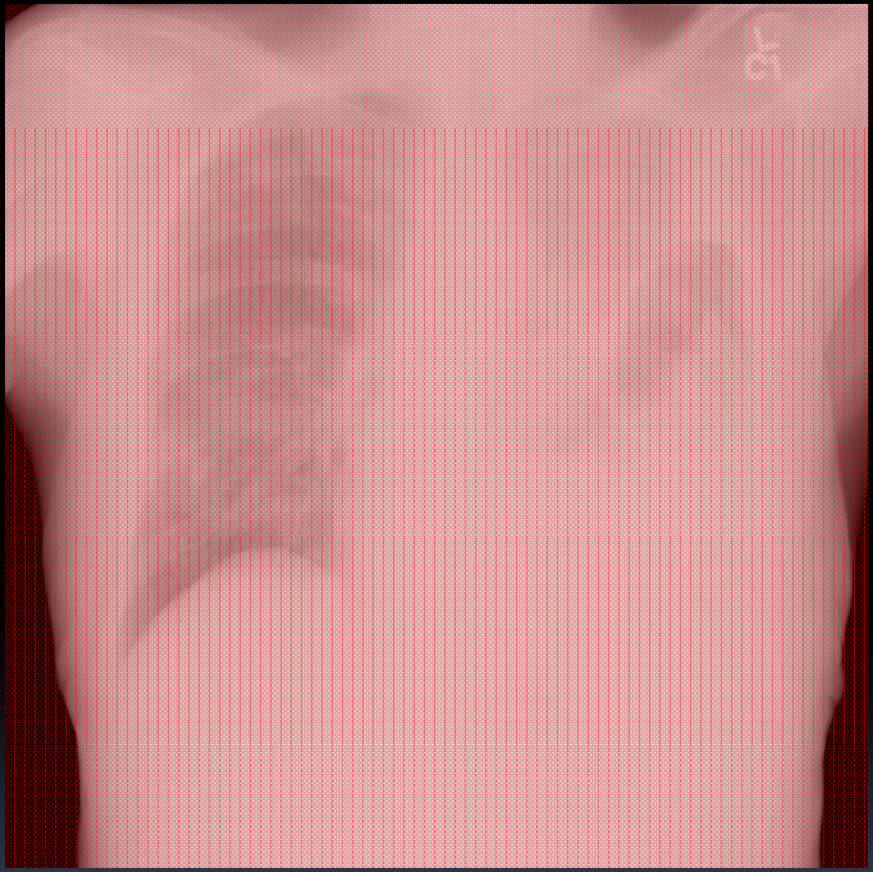
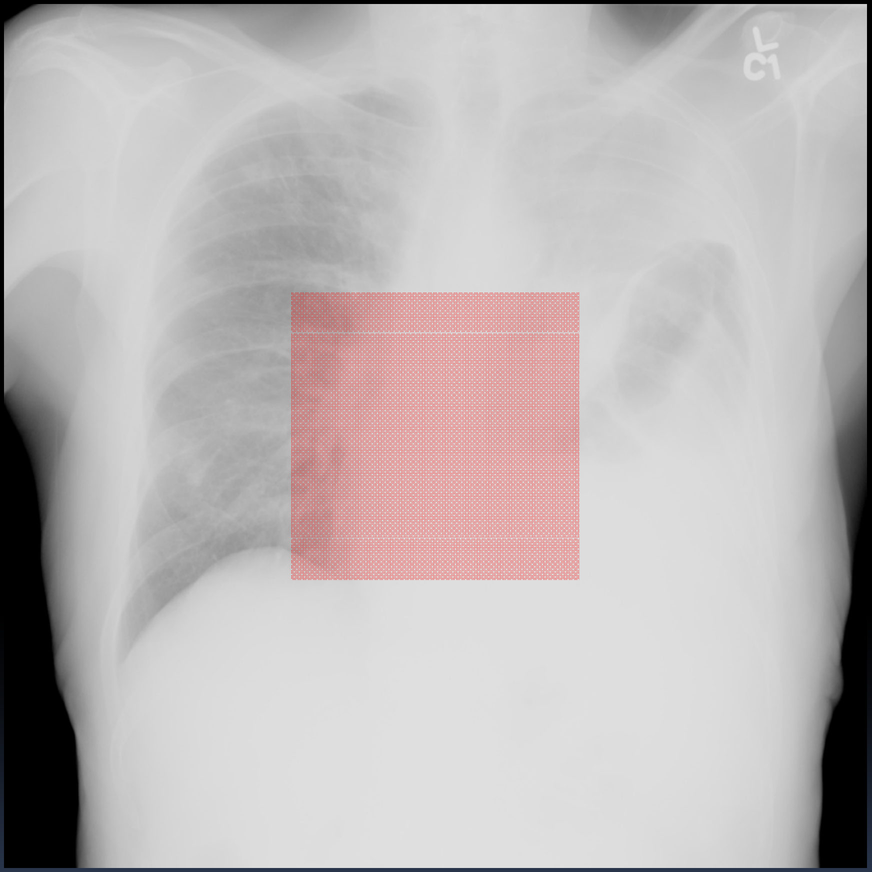
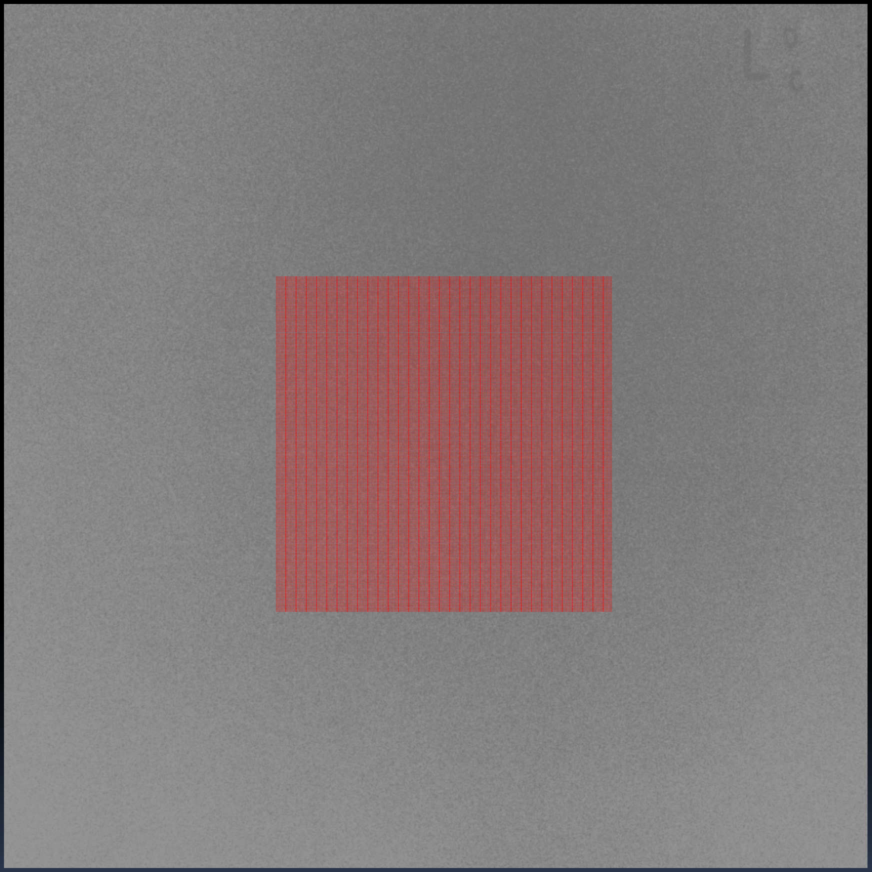


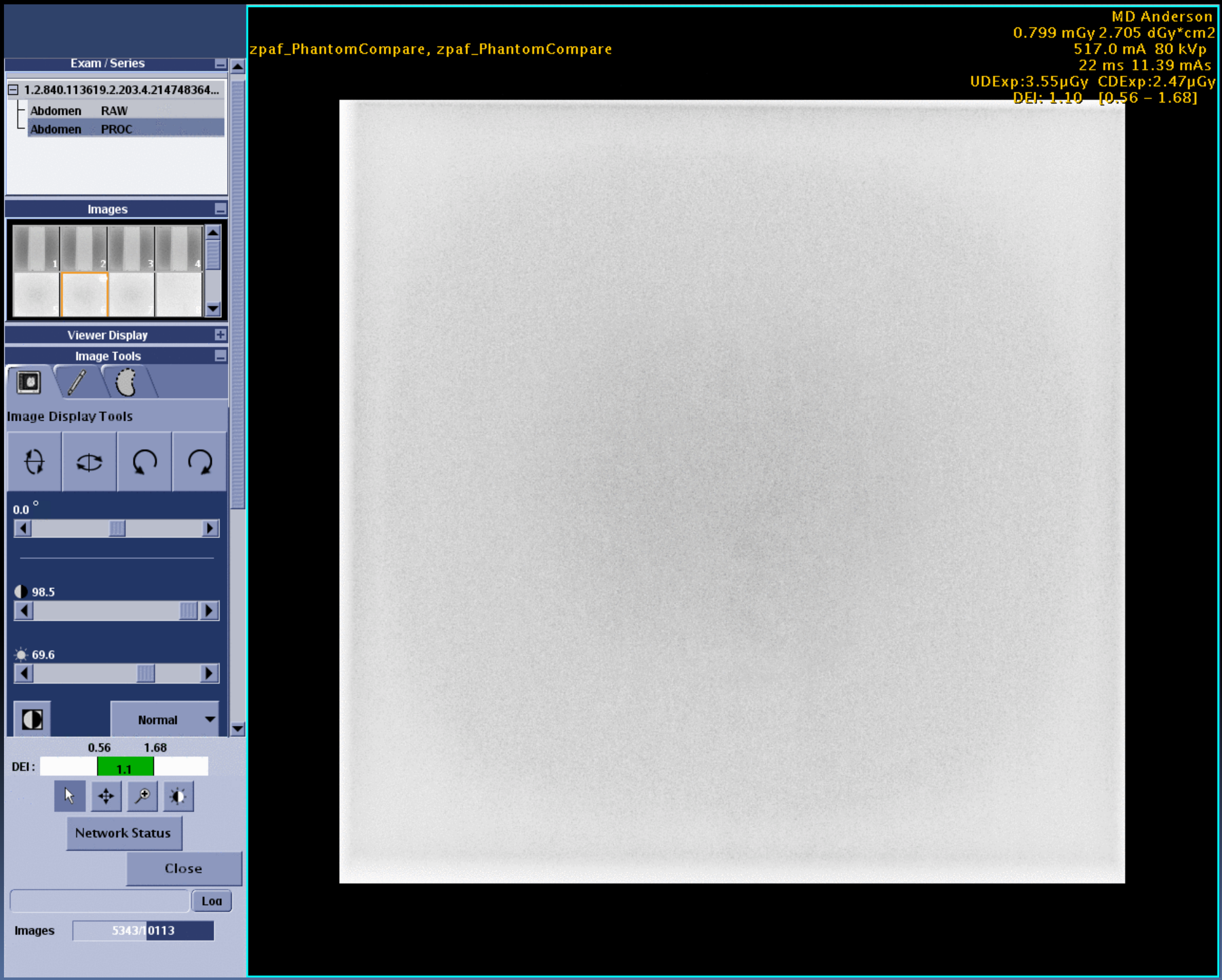

GE




Siemens

# Technical mode



MD Anderson
0.799 mGy 2.705 dGy*cm2
517.0 mA 80 kVp
22 ms 11.39 mAs
UDExp:3.55µGy CDExp:2.47µGy
DEI: 1.10 [0.56 – 1.68]
zpaf_PhantomCompare, zpaf_PhantomCompare
Exam / Series
1.2.840.113619.2.203.4.214748364...
Abdomen RAW
Abdomen PROC
Images
Viewer Display
Image Tools
Image Display Tools
0.0 °
98.5
69.6
Normal
0.56
1.68
DEI :
1.1
Network Status
Close
Log
Images
5343/10113

# GE EI verification

| Scenario | UDExp (μGy) | CDExp (μGy) | DEI | Measured pre-grid (μGy) | Post-grid ($T_p$) (μGy) | Post-grid (B) (μGy) |
|---|---|---|---|---|---|---|
| 70 kVp no grid | 4.95 | 5.59 | 1.32 | 5.53 | 5.53 | |
| 80 kVp no grid | 5.84 | 5.84 | 1.46 | 5.48 | 5.48 | |
| 90 kVp no grid | 5.07 | 4.74 | 1.21 | 4.46 | 4.46 | |
| 70 kVp grid | 4.28 | 3.41 | 1.45 | 8.86 | 4.34 | |
| 80 kVp grid | 3.21 | 2.23 | 1.00 | 5.48 | 2.74 | 1.69 |
| 90 kVp grid | 2.82 | 1.91 | 0.82 | 4.46 | 2.19 | |

# Siemens EI verification

| Scenario | EXI | Calculated from EXI (μGy) | Measured pre-grid (μGy) | Post-grid ($T_p$) (μGy) |
|---|---|---|---|---|
| 60 kVp no grid | 354 | | 2.24 | 2.24 |
| 70 kVp no grid | 401 | 2.65 | 2.20 | 2.20 |
| 81 kVp no grid | 496 | | 2.27 | 2.27 |
| 60 kVp grid | 358 | | 4.28 | 2.77 |
| 70 kVp grid | 389 | 2.57 | 4.18 | 2.74 |
| 81 kVp grid | 439 | | 4.52 | 3.00 |

# Effect of table or cover

- Attenuation by the table may be significant
  - Manufacturer 1: 0.80 to 0.82 from 60 – 81 kVp
  - Manufacturer 2: 0.91 at 80 kVp
- Detector covers had very little influence

# Other considerations

- Measuring $K_a$ at detector plane may not be possible
- Removal of the anti-scatter grid may alter AEC response
- Exposure indicator is usually provided
- Would like to verify it's performance under calibration conditions (hopefully the same as AEC conditions) and with presence of grid
  - kVp correction – if EI is correct under calibration conditions for AEC, rely on kVp correction/SNR tracking instead of worrying about EI and kVp dependence

# Clinical simulation

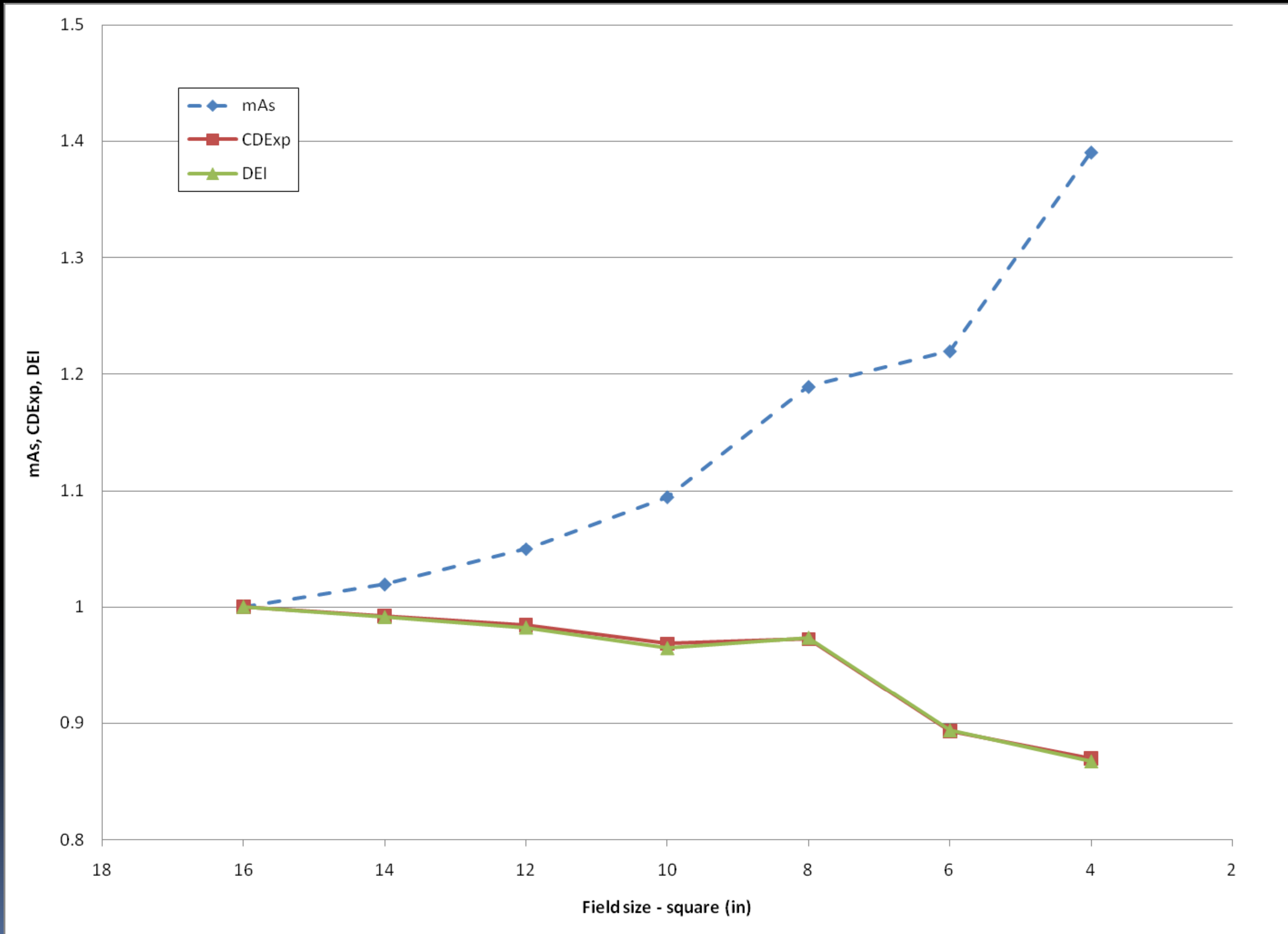
- 8" PMMA phantom
- 10 x 10 in field size at tabletop
- AEC, center cell
- GE: 80 kVp
- Siemens : 70 kVp

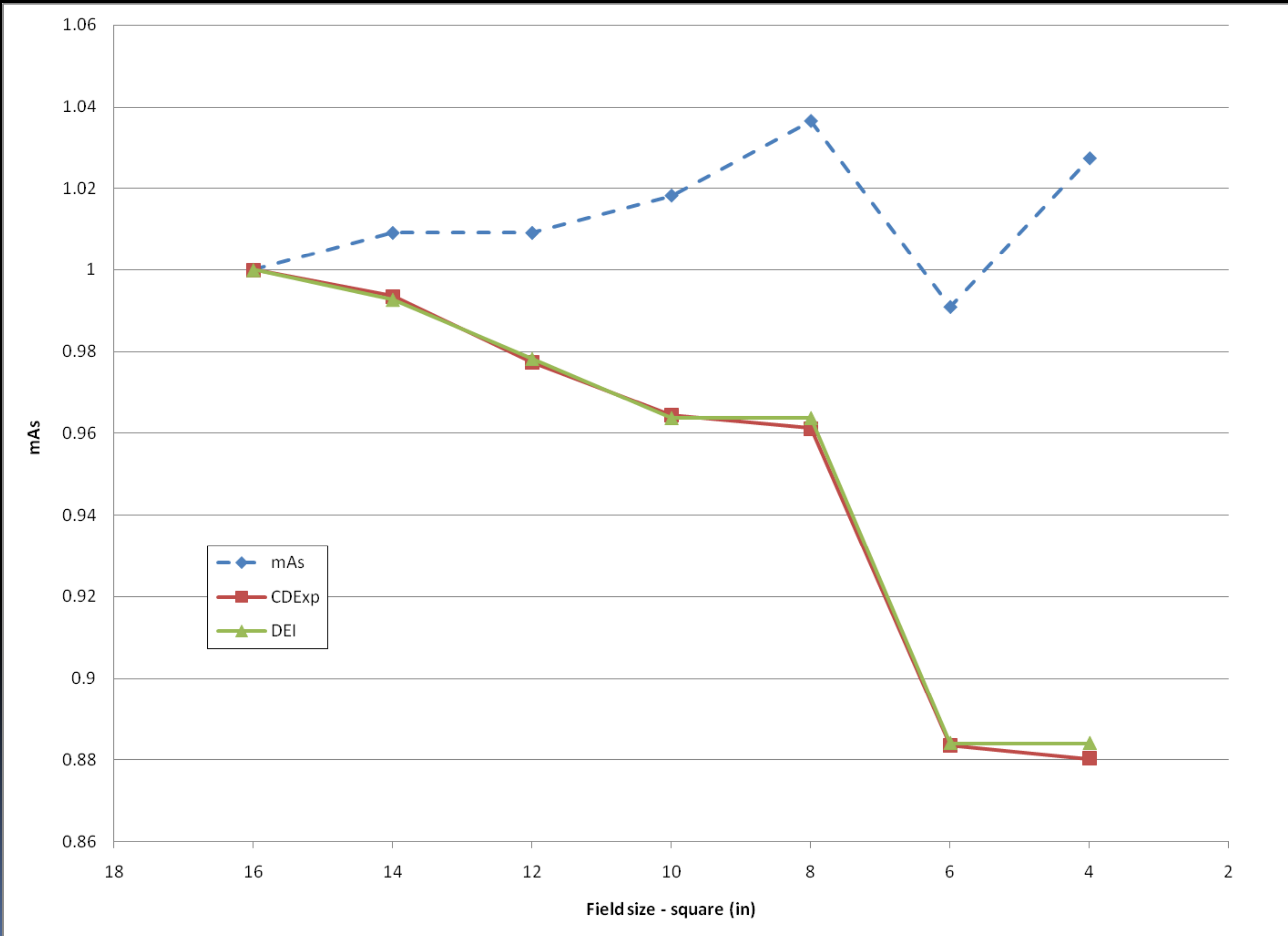
| mAs | UDExp (µGy) | CDExp (µGy) | DEI |
|---|---|---|---|
| 11.29 | 3.53 | 2.45 | 1.1 |

| mAs | EXI | Calculated (µGy) |
|---|---|---|
| 27.76 | 284 | 1.88 |

# Other questions

- Dependence of AEC calibration on field size
- Batch-to-batch PMMA variation


mAs
CDExp
DEI
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
mAs, CDExp, DEI
18
16
14
12
10
8
6
4
2
Field size - square (in)


1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
0.88
0.86
mAs
mAs
CDExp
DEI
18
16
14
12
10
8
6
4
2
Field size - square (in)

# Batch-to-batch PMMA

- I tested two different batches of PMMA, and found:
  - 3% variation in mAs
  - 1% variation in EI
- n=1, variation in batches/sources of PMMA was not a concern

# One


http://www.toolandtechnology.com/images/vernier%20calipers.jpg

# Huge

learnwithmst.wordpress.com

# Problem

http://www.ricardodiaz.com/wp-content/uploads/2009/01/axe.jpg

# Image receptor dose

- Relatively simple task with screen/film imaging – achieve O.D. in linear portion of H+D curve
- Digital imaging is not contrast-limited, but noise limited
- How can you set up your AEC system to deliver the desired amount of ***noise*** in an image?
- AEC system must be calibrated to deliver the desired $K_a$ to the image receptor
- Fundamental difference from S/F: Wide range of $K_a$ will yield usable images, must decide on acceptable noise level in images

Rong XJ, Shaw CC, Liu X, Lemacks MR, Thompson SK, *Comparison of an amorphous silicon/cesium iodide flat-panel digital chest radiography system with screen/film and computed radiography systems — A contrast-detail phantom study*, Med. Phys. **28**(11):2328-35, 2001.

**Use of scored images of contrast-detail phantom (CDRAD) under clinical image processing conditions to attempt to determine detector exposure required to achieve similar detectability for small low-contrast targets**

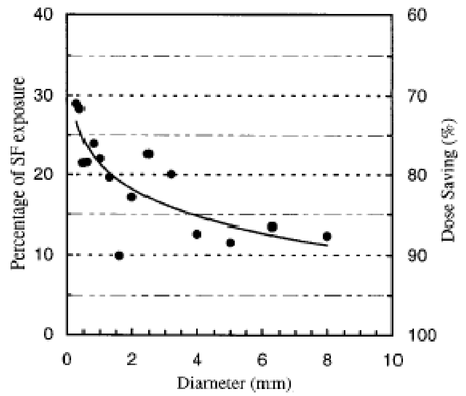



FIG. 9. Dose savings by using the flat-panel system to achieve the same performance as the screen/film system.

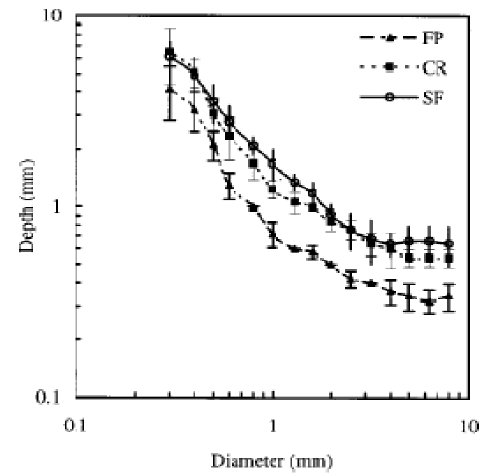



FIG. 4. Contrast-detail curves of the screen/film, flat-panel, and computed radiography systems evaluated. Images acquired using the flat-panel and computed radiography systems were primed with clinical default protocols.

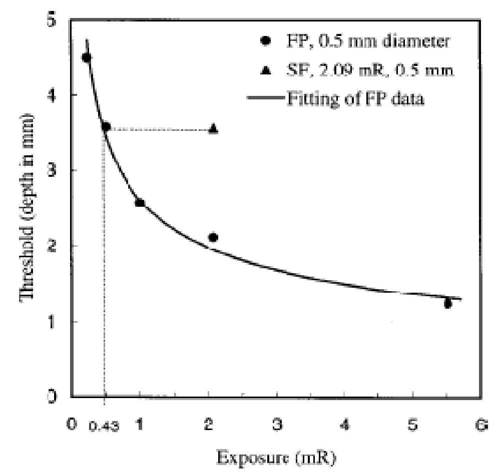
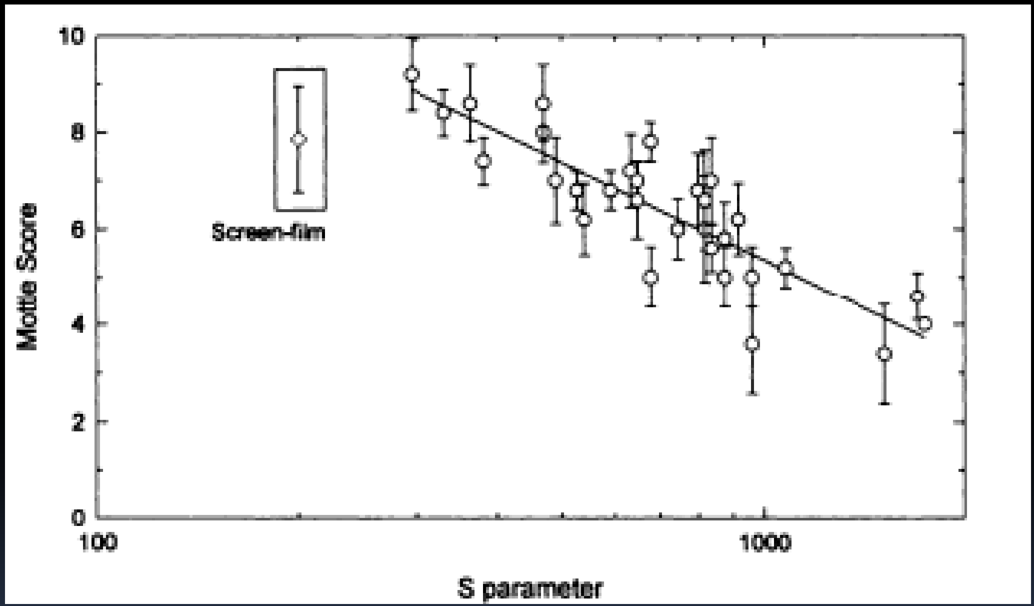



FIG. 10. The determination of exposure (0.43 mR) required for the flat-panel image so that it corresponds to the threshold contrast value of the screen/film image (2.09 mR) for 0.5 mm diam objects. Exposures required for objects of 0.3 mm–8.0 mm were also obtained and shown in Fig. 9. For 0.5 mm diam objects, the exposure for the FP image is about 21% of that used for the SF image corresponding to the same threshold value. Hence, the dose saving is about 79% for objects of 0.5 mm diam.

**Conclusion: 0.43 mR required to achieve similar LCD for 0.5 mm object compared to 2.09 mR for the same screen-film image (21%)**

Huda W, Slone RM, Belden CJ, Williams JL, Cumming WA, Palmer CK, *Mottle on computed radiographs of the chest in pediatric patients*, Med. Phys. **199**:242-252, 1996.

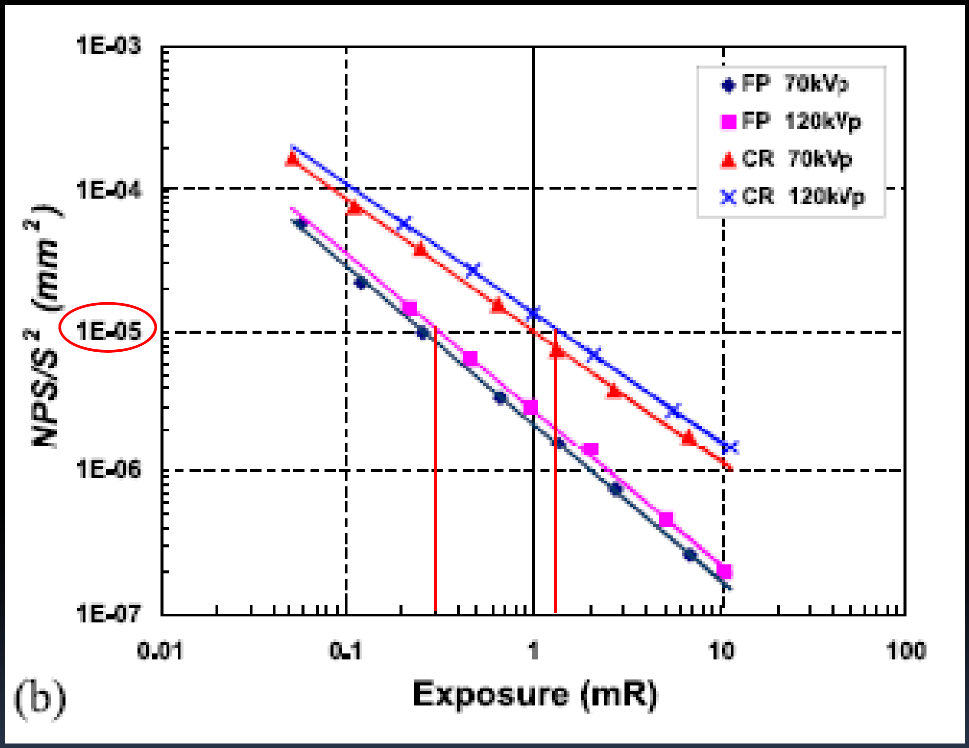
**Use of a rating system based on degrees of mottle to determine what sensitivity number of a Fuji AC series would be needed to match the mottle in a 600-speed s/f system, then use the actual sensitivity numbers measured to compare CR to s/f.**




**Conclusion: To achieve comparable mottle to 600-speed s/f system a two-fold increase in exposure is needed as compared to mean sensitivity number. An exposure consistent with a 200-speed s/f system would be needed to achieve negligible mottle.**

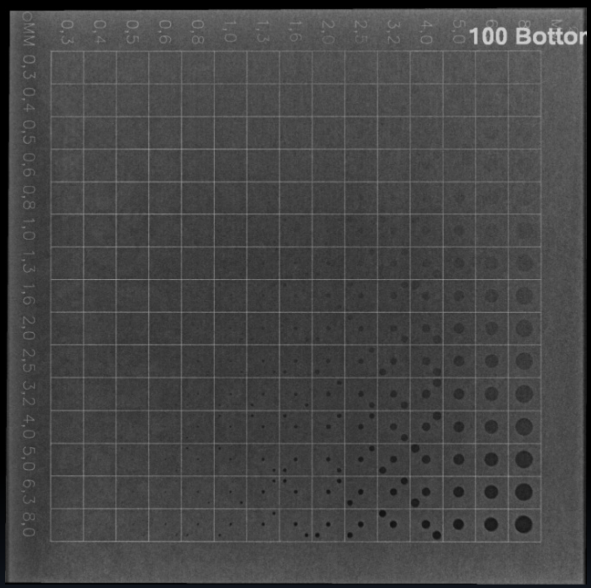
Liu X and Shaw, CC, *a-Si:H/CsI(Tl) flat-panel versus computed radiography for chest imaging applications: image quality metrics measurement,* Med. Phys. 31(1):98-110, 2004.

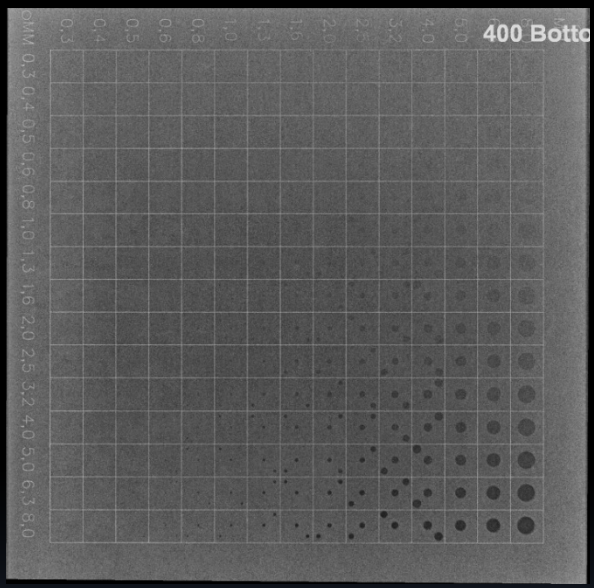
**Compare indirect digital radiography and cassette-based digital radiography systems in terms of fundamental image quality metrics.**

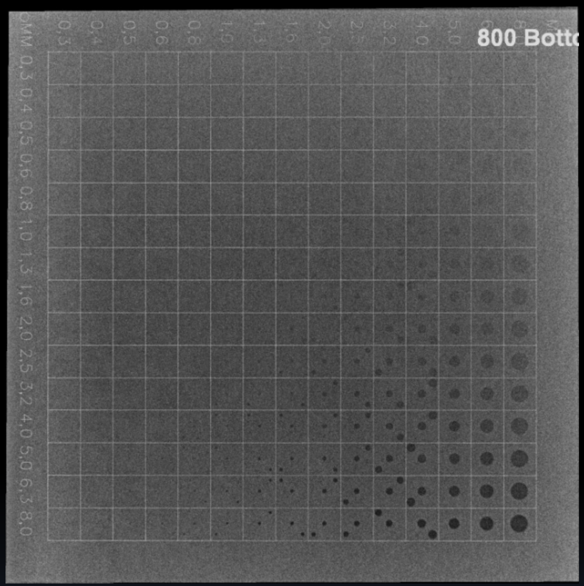



**Conclusion: Indirect digital radiography detector has significantly higher DQE and lower NPS than cassette-based digital radiography (CR) detector. The magnitude of the differences is illustrated in the graphs from the manuscript.**

**Give radiologists a visual idea of what the impact of dose to the image receptor is on image quality – CDRAD phantom exposed under PMMA**




**Can also be done with other phantoms – ACR R/F phantom, anthropomorphic phantom, or even add noise to a patient image for comparison**

# Caveats

- Image processing has a large impact on noise (low-contrast detectability) and high-contrast resolution, and thus AEC sensitivity should be configured with this in mind.
- Also, pixel size has an impact on noise in images – this is especially important for digital receptors where pixel size is variable, such as PSP systems

# Conclusions or

- Several methods can be used for AEC sensitivity calibration
- Other AEC performance characteristics should be monitored and evaluated
- Exposure conditions have a tremendous impact on AEC sensitivity calibration
- Clinical exposures are made using clinical exposure conditions
  - Grid
  - Scatter
  - Field size

# Questions left unanswered

- How does one decide what dose to the receptor is needed?
- How does one evaluate the impact of increased or reduced detector dose?
  - Dose – fairly easy
  - Image quality – hard
    - Clinical images – anatomical noise
    - Image processing
    - Not round objects and nice orderly line pairs
    - This is a really hard question