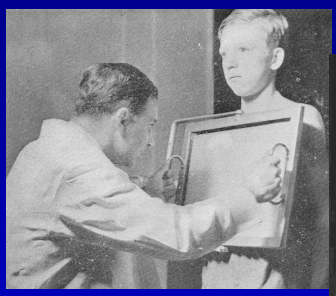
Fluoroscopic Imaging Equipment Considerations for Optimization of Performance and Dose



Phil Rauch
Henry Ford Health Systems
Detroit, MI

Fluoroscopic Technology (*Real-time* image production & display)

X-ray Intensity Distribution

↓

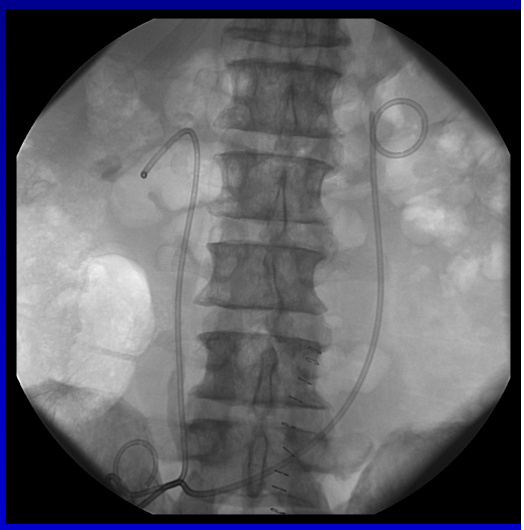
Radiation Capture (Detector)

↓

Output Light Intensity Distribution

↓

Visible Image (Film, Display Monitor)



Dose Reduction vs Image Quality

- **Dose reduction depends on….**

….technology

….proper equipment design

….proper set up of equipment parameters

….proper utilization of the equipment

….knowledge and skill of the radiologist

Dose Reduction vs Image Quality

- **Image quality depends on….**

….technology

….proper equipment design

….proper set up of equipment parameters

….proper utilization of the equipment

….knowledge and skill of the radiologist

but the pursuit of dose reduction and image quality is like……

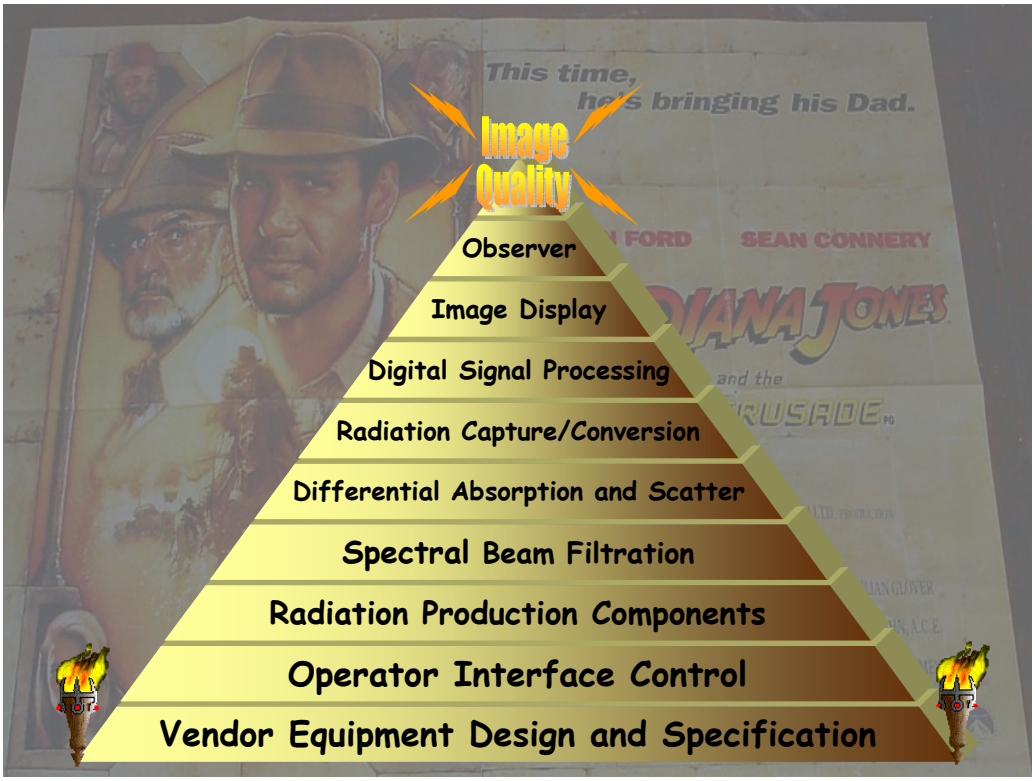
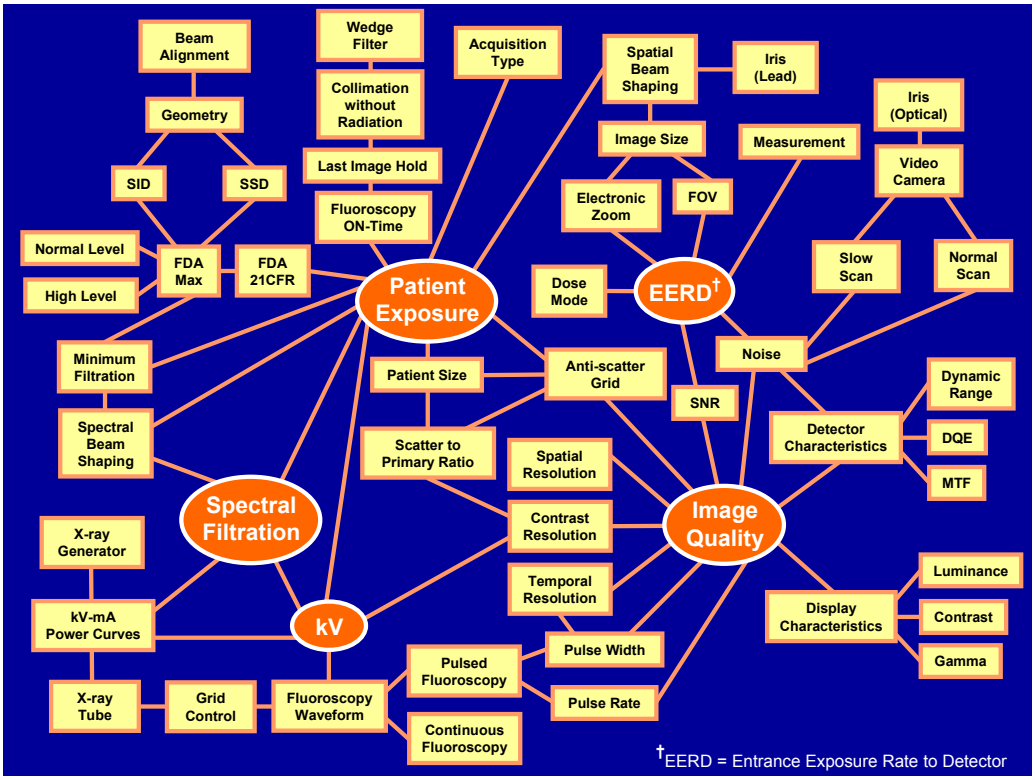
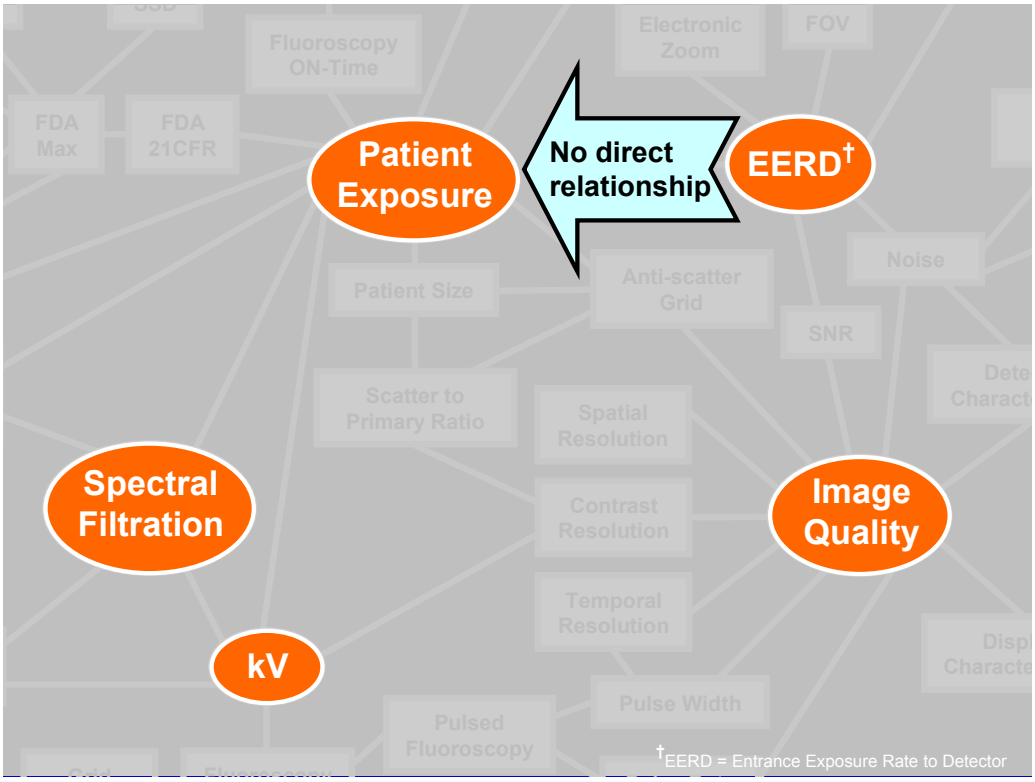
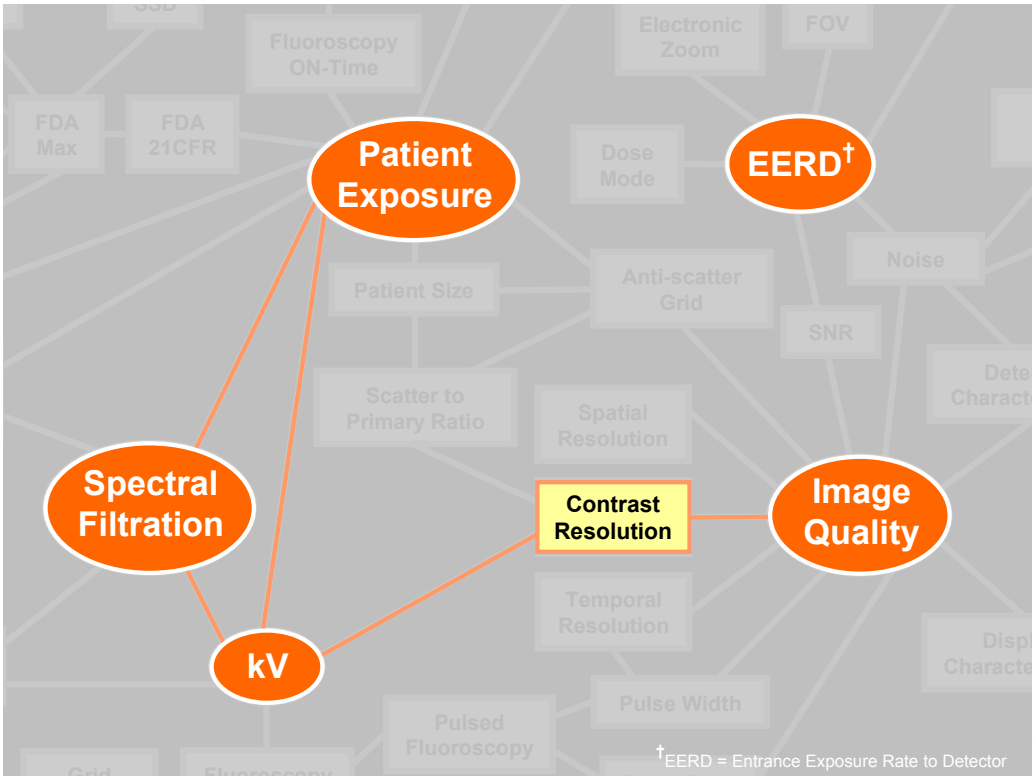


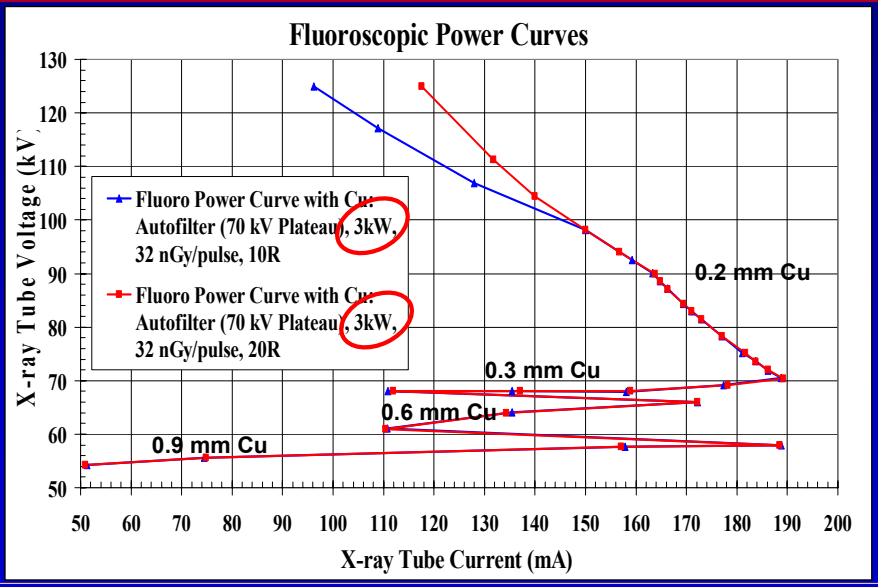
Image Quality
Observer
Image Display
Digital Signal Processing
Radiation Capture/Conversion
Differential Absorption and Scatter
Spectral Beam Filtration
Radiation Production Components
Operator Interface Control
Vendor Equipment Design and Specification


Beam Alignment
Wedge Filter
Acquisition Type
Spatial Beam Shaping
Iris (Lead)
Iris (Optical)
Geometry
Collimation without Radiation
Image Size
Measurement
Video Camera
SID
SSD
Last Image Hold
Electronic Zoom
FOV
Fluoroscopy ON-Time
Normal Level
High Level
FDA Max
FDA 21CFR
Patient Exposure
Dose Mode
EERD†
Slow Scan
Normal Scan
Minimum Filtration
Patient Size
Anti-scatter Grid
Noise
Dynamic Range
Spectral Beam Shaping
Scatter to Primary Ratio
SNR
Detector Characteristics
DQE
MTF
Spatial Resolution
Spectral Filtration
Contrast Resolution
Image Quality
X-ray Generator
Temporal Resolution
Luminance
kV-mA Power Curves
kV
Display Characteristics
Contrast
Pulse Width
Pulsed Fluoroscopy
Gamma
X-ray Tube
Grid Control
Fluoroscopy Waveform
Pulse Rate
Continuous Fluoroscopy
†EERD = Entrance Exposure Rate to Detector


Fluoroscopy ON-Time
Electronic Zoom
FOV
FDA Max
FDA 21CFR
Patient Exposure
No direct relationship
EERD†
Noise
Patient Size
Anti-scatter Grid
SNR
Scatter to Primary Ratio
Spatial Resolution
Spectral Filtration
Contrast Resolution
Image Quality
Temporal Resolution
kV
Pulse Width
Pulsed Fluoroscopy
†EERD = Entrance Exposure Rate to Detector

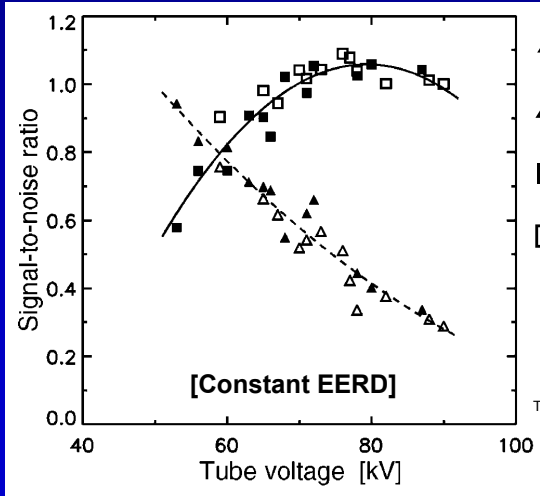

Fluoroscopy ON-Time
Electronic Zoom
FOV
FDA Max
FDA 21CFR
Patient Exposure
Dose Mode
EERD†
Noise
Patient Size
Anti-scatter Grid
SNR
Scatter to Primary Ratio
Spatial Resolution
Spectral Filtration
Contrast Resolution
Image Quality
Temporal Resolution
kV
Pulse Width
Pulsed Fluoroscopy
†EERD = Entrance Exposure Rate to Detector

Fluoroscopy (New Paradigm)



Fluoroscopy (New Paradigm)

- Contrast to Noise Ratio vs KVp



▲ Low attenuation region (high signal), 0.2 mm Cu
△ Low attenuation region (high signal), 0.4 mm Cu
■ High attenuation region (low signal), 0.2 mm Cu
□ High attenuation region (low signal), 0.4 mm Cu

The British Journal of Radiology, 77 (2004), 479–487

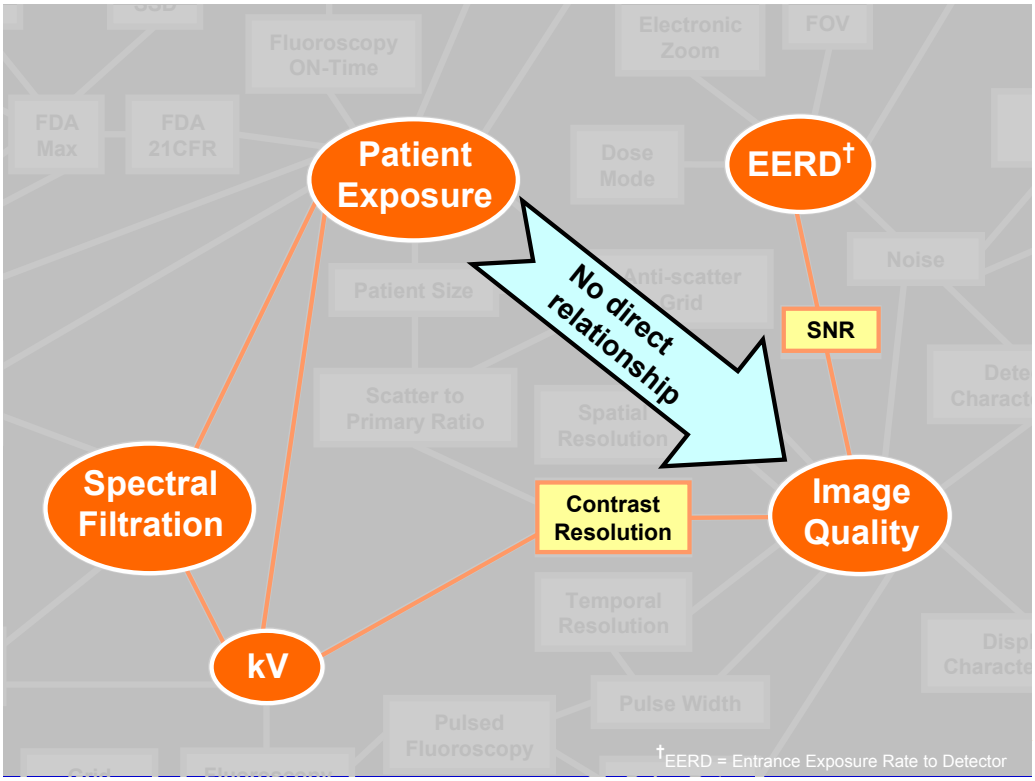


Image Quality: What is it?

- "Image quality depends only on intrinsic, objective physical characteristics of an imaging system, and can be measured independently of an observer"

Definitions courtesy Ralph Schaetzing, Agfa Corp.

Detector Input Dose Rates (FP)

Detector Metrics

Image Intensifier

Flat Panel

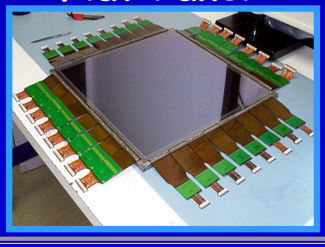
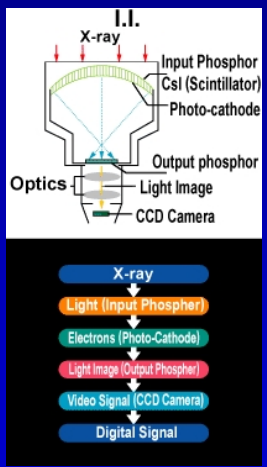
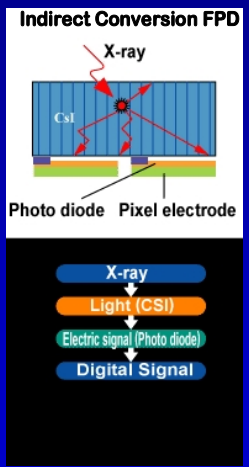
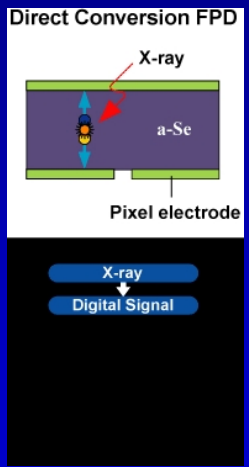


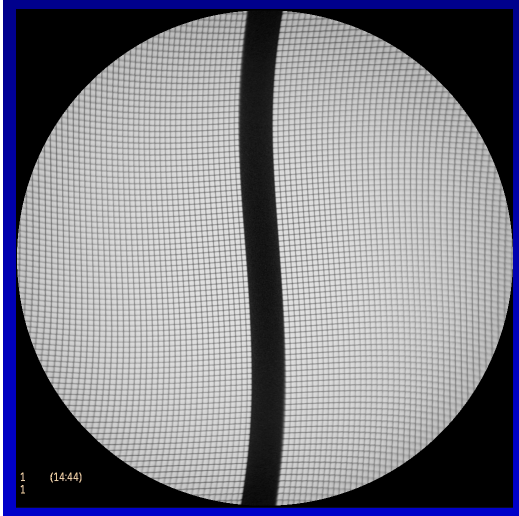
Image Detector

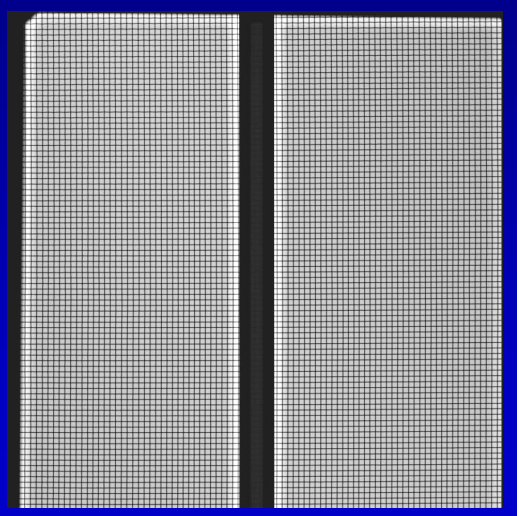






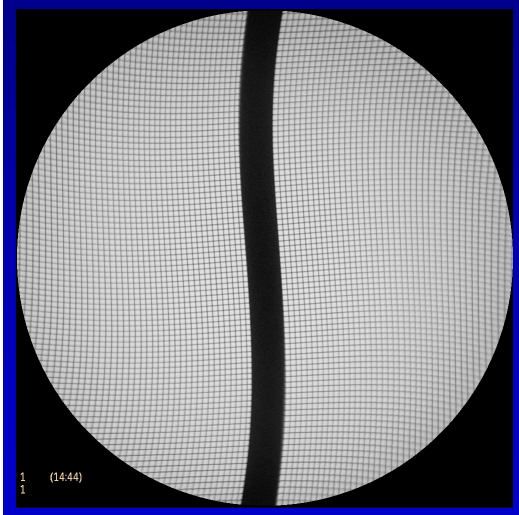
Distortion

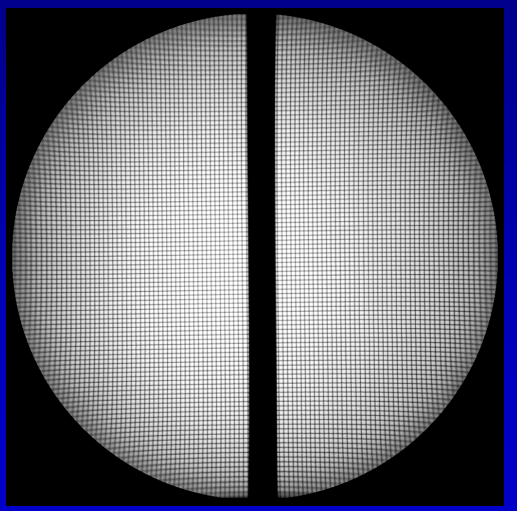




XRII | Flat Panel

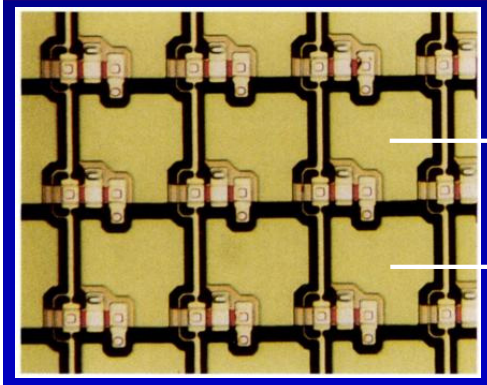
Distortion





XRII | XRII

Pixel Pitch – Estimated Resolution



Detector	Mfg.	Pixel Pitch	Nyquist (lp/mm)	Nyquist x 2^(.5) (lp/mm)	Mesh Lines per Inch at 45-degrees
Safire (a-Se, a-Si TFT)	Shimadzu	0.150	3.33	4.71	120
Philips, Siemens (CsI(Tl), a-Si TFT) - Angio	Trixell	0.154	3.25	4.59	117
Philips, Siemens (CsI(Tl), a-Si TFT) - Cardiac	Trixell	0.184	2.72	3.84	98
GE, Revolution (CsI(Tl), a-Si TFT)	GE	0.200	2.50	3.54	90

(I'm from the motor city – Detroit)

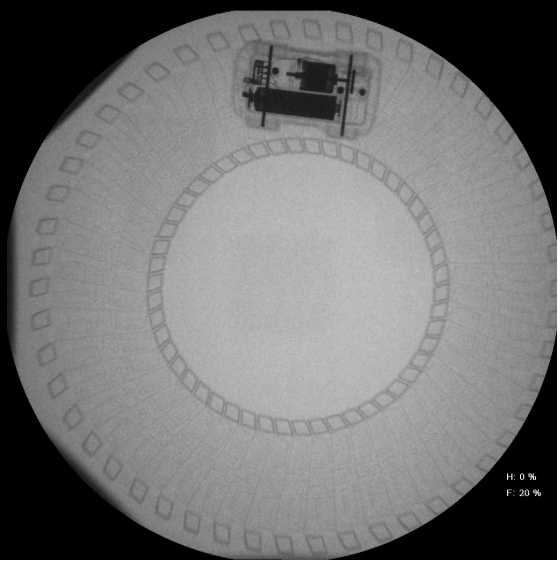


Image Detector (Fluoro LIH)

- Can you match the fluoroscopy LIH image to the detector?
  - A. Image Intensifier
  - B. Indirect Flat Panel
  - C. Direct Flat Panel

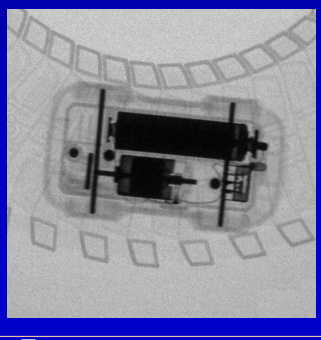
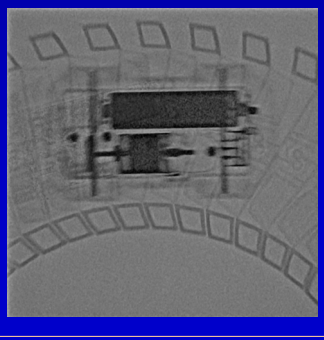
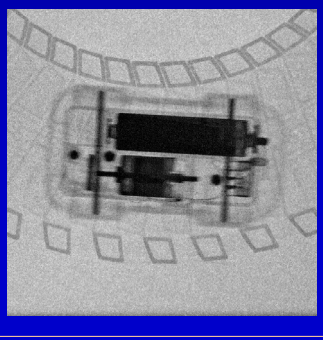
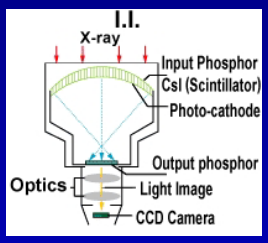
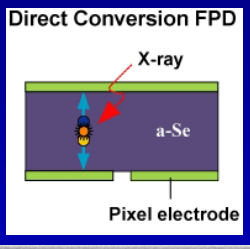
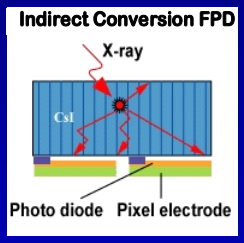




Image Detector (Fluoro LIH)







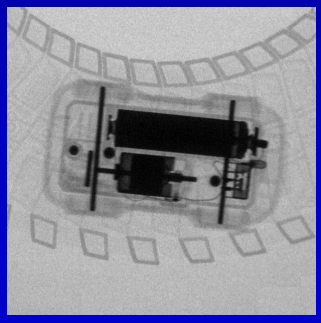
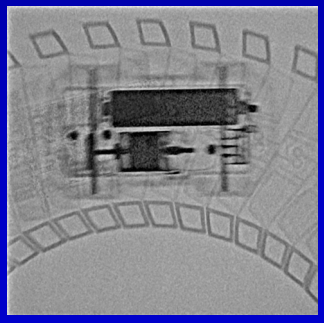
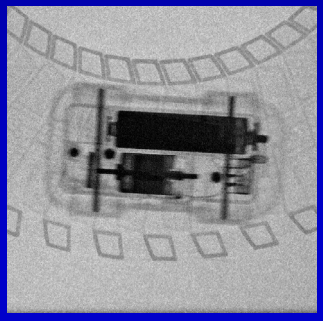
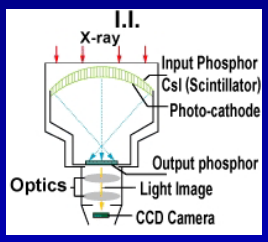
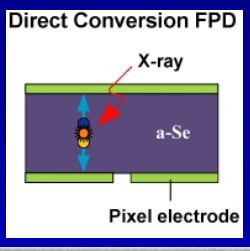
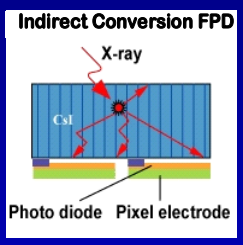
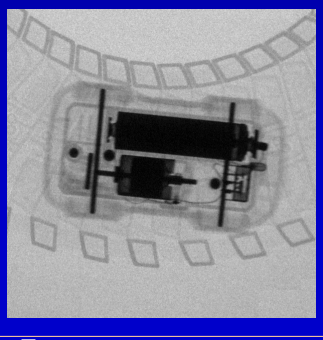




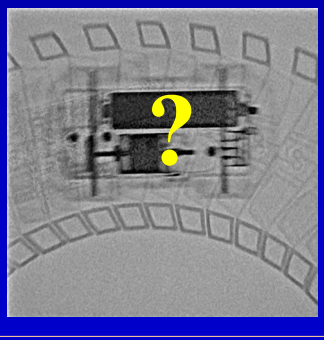
Image Detector (Fluoro LIH)

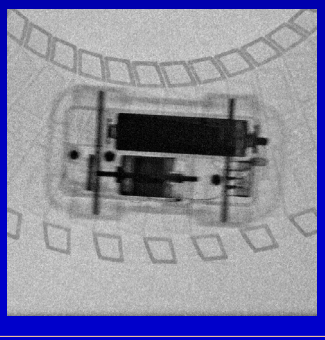




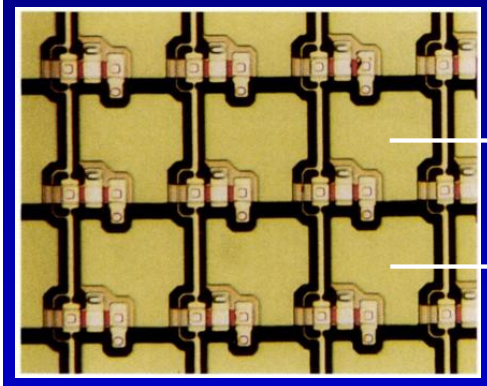






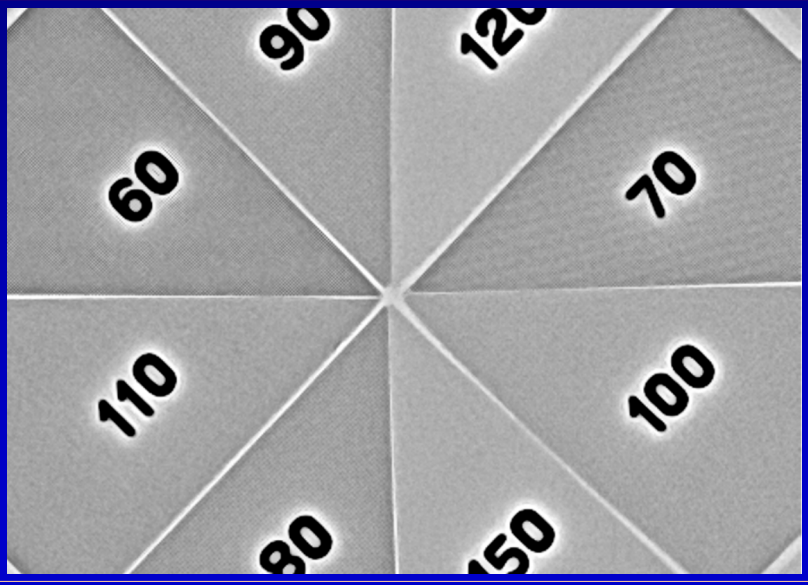


Pixel Pitch – Direct Capture

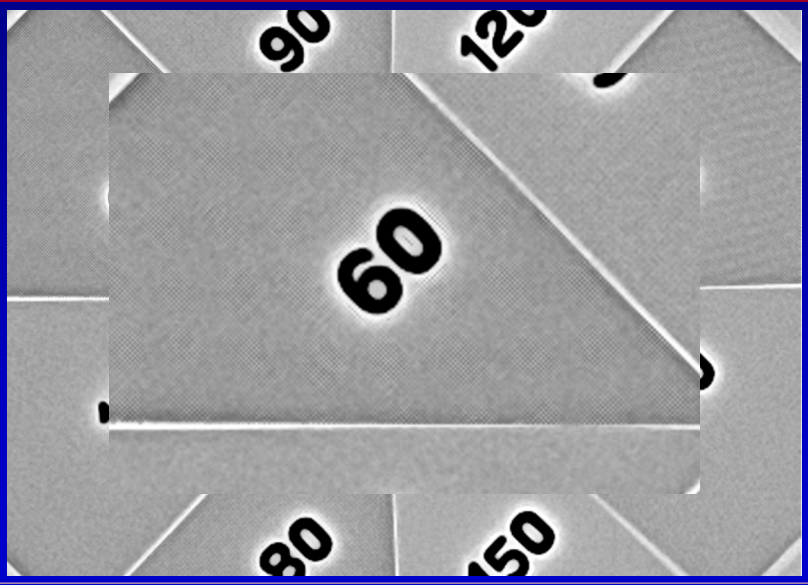


Detector	Mfg.	Pixel Pitch	Nyquist (lp/mm)	Nyquist x 2^(.5) (lp/mm)	Mesh Lines per Inch at 45-degrees
Safire (a-Se, a-Si TFT)	Shimadzu	0.150	3.33	4.71	120

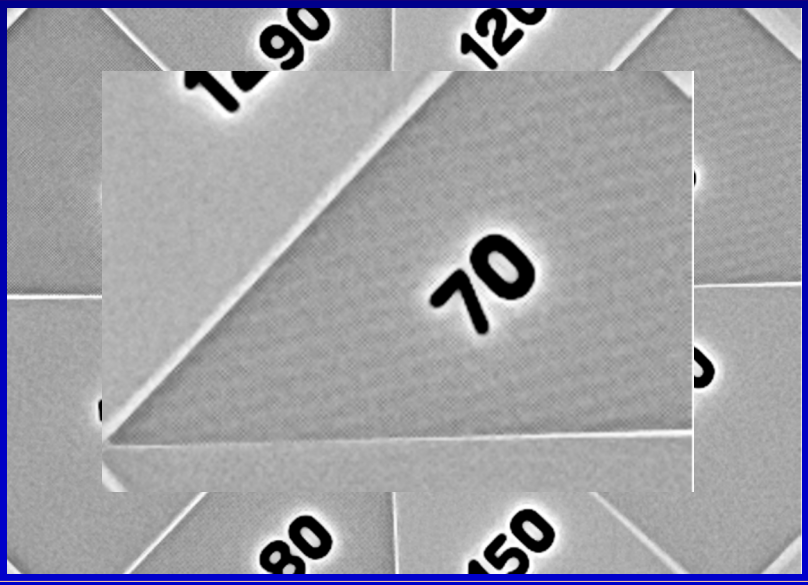
a-Se Detector, Pixel Pitch 0.15 mm



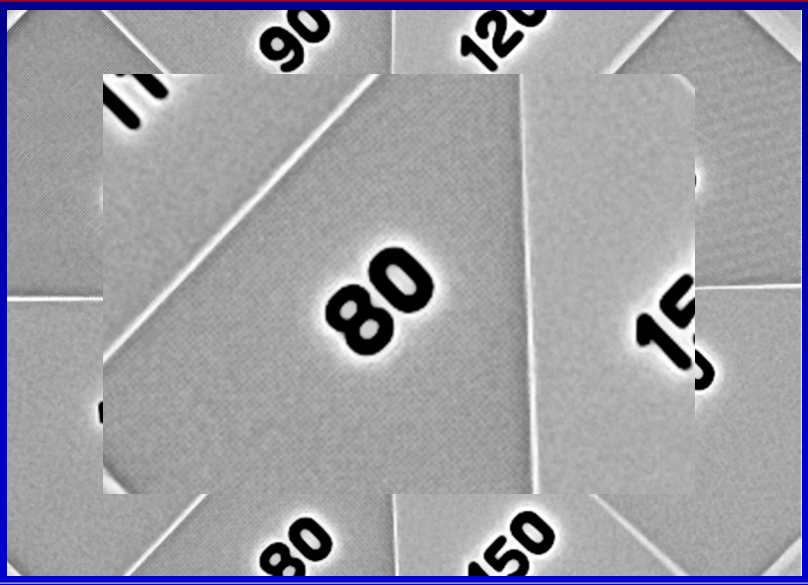
a-Se Detector, Pixel Pitch 0.15 mm



a-Se Detector, Pixel Pitch 0.15 mm



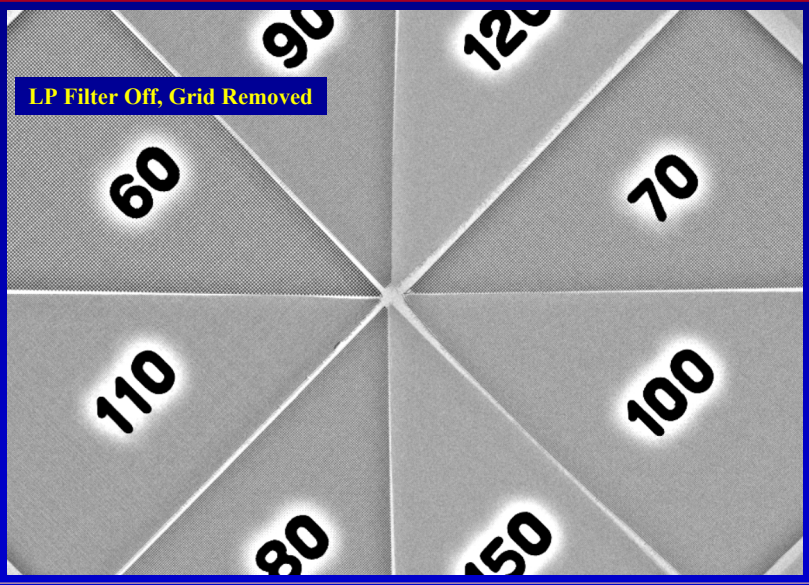
a-Se Detector, Pixel Pitch 0.15 mm



a-Se Detector, Pixel Pitch 0.15 mm

- Stationary anti-scatter grid (44 l/cm)
- Low pass filter was utilized to remove grid lines from the image
- This severely compromised the potential high spatial resolution of this detector
- Verification by temporarily turning off the lp filter and removing the grid

a-Se Detector, Pixel Pitch 0.15 mm



a-Se Detector, Pixel Pitch 0.15 mm

a-Se Detector, Pixel Pitch 0.15 mm

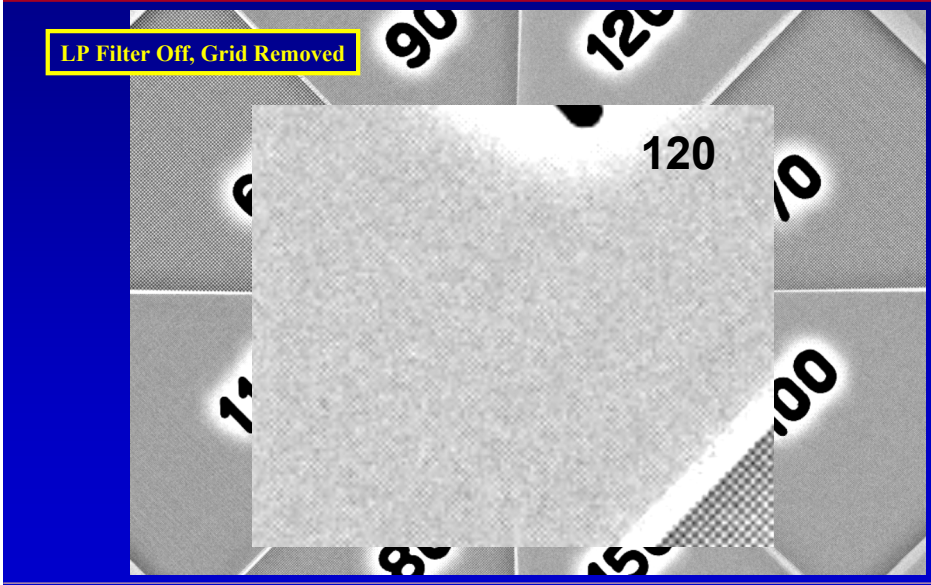
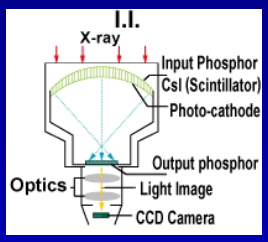
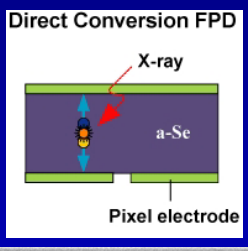
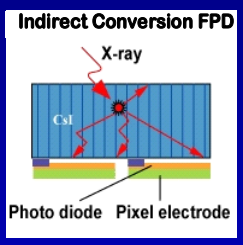
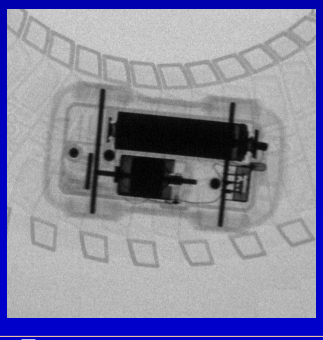


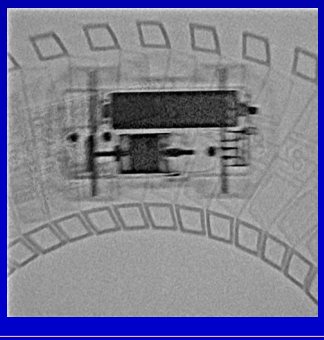
Image Detector (Fluoro LIH)

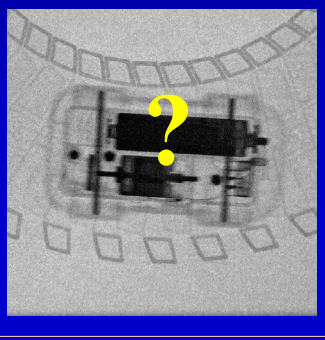












Indirect conversion

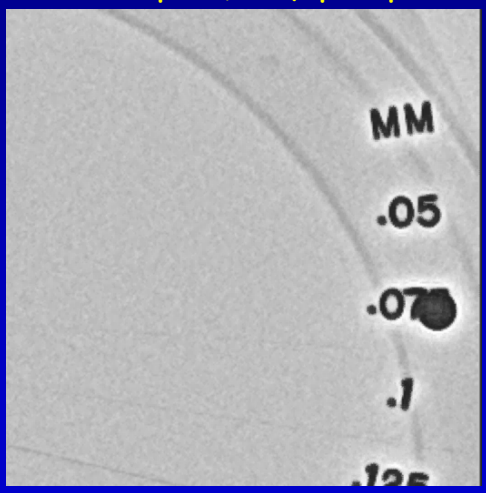
- Pixel binning was used for the chosen field of view resulting in a reduction in detail resolution
- Recursive filtering was utilized, and this resulted in edge blurring (more on this later)

Resolution

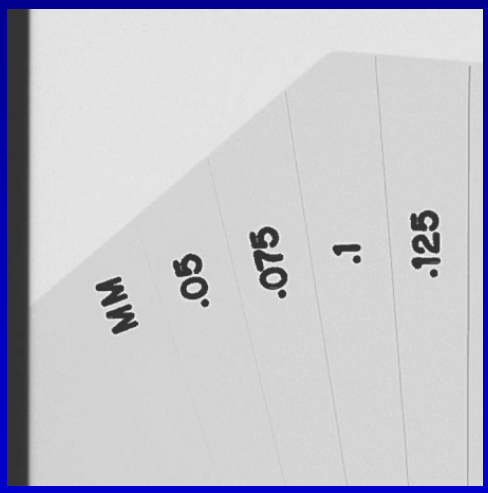
Can you see a 50μ wire using a flat panel detector with a pixel pitch of 150μ? With a pixel pitch of 200μ?

Resolution

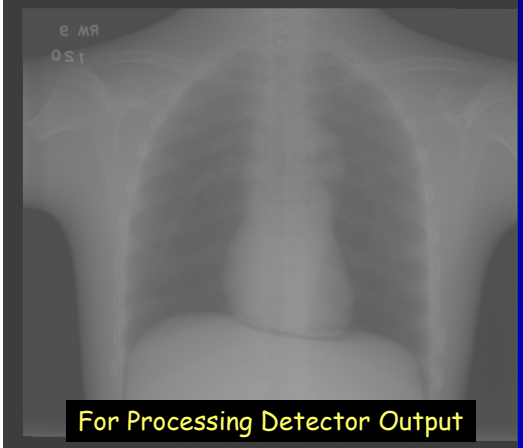
Direct Capture, 150μ pixel pitch



Indirect Capture, 200μ pixel pitch



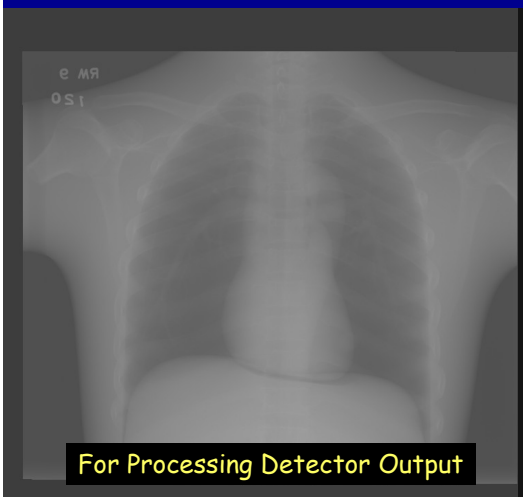
Radiation Capture/Conversion



Digital Signal Processing

- Exposure scaling
- Segmentation
- Histogram analysis
- Multi-scale frequency enhance
- Noise reduction
- Edge restoration
- Dynamic range rendering
- Grayscale presentation

Radiation Capture/Conversion



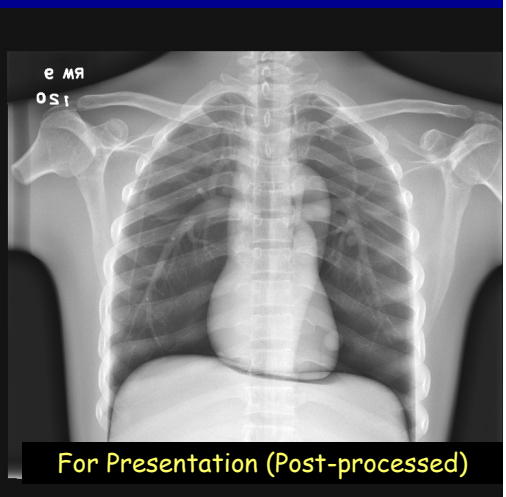
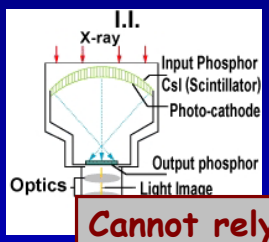
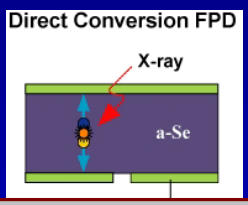
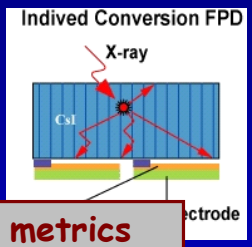


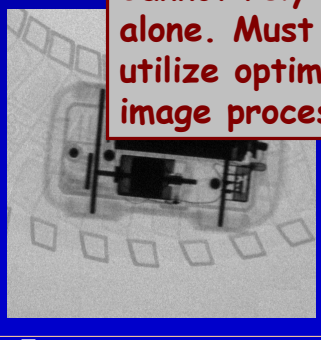
Image Detector (Fluoro LIH)

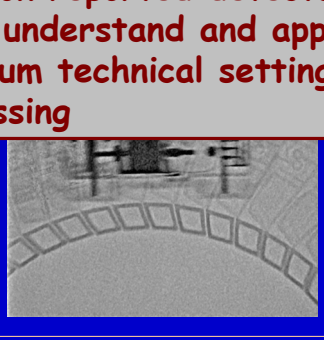






Cannot rely on reported detector metrics alone. Must understand and appropriately utilize optimum technical settings and image processing

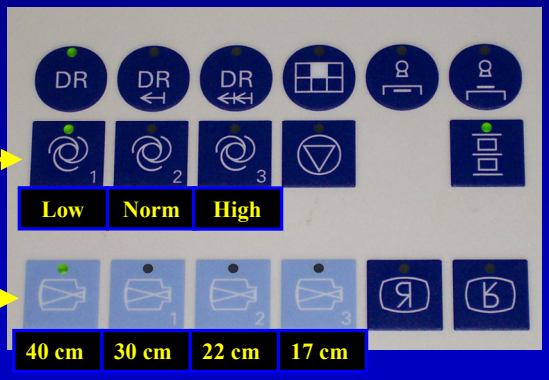




Detector Input Dose Rates (XRII)

Dose Rate Selection →

Field of View Selection →



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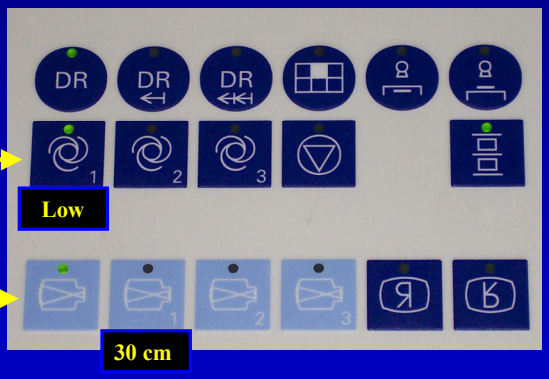
Dose Rate Selection →

Field of View Selection →



Continuous Fluoroscopy: Input dose per frame of fluoroscopy?

Detector Input Dose Rates (XRII)

- Low Dose Mode
- Cont. Fluoroscopy
- 30 cm FOV

Detector Input Dose/Fr?

A. 0.37 μR (3.2 nGy)
B. 0.75 μR (6.6 nGy)
C. 1.5 μR (13.1 nGy)
D. 3.0 μR (26.3 nGy)
E. 6.0 μR (52.6 nGy)
F. No Clue

……values assume FDA minimum beam filtration

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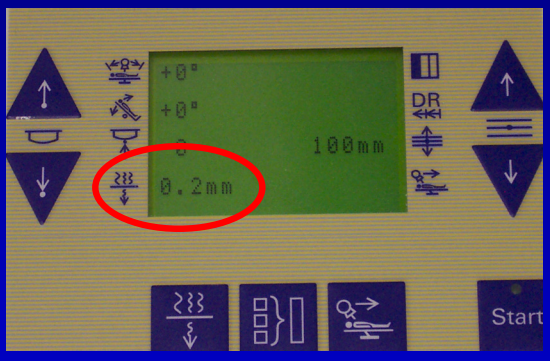


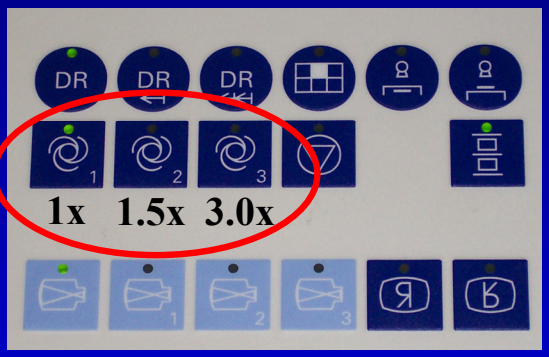
……values assume FDA minimum beam filtration

……can use 2x these values if minimum 0.2 mm Cu beam filtration is utilized

Detector Input Dose Rates (XRII)

- Low Dose Mode
- Cont. Fluoroscopy
- 30 cm FOV

Detector Input Dose/Fr?



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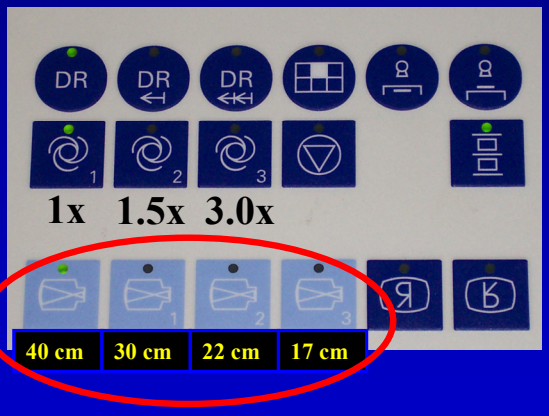
- Low Dose Mode
- Cont. Fluoroscopy
- 30 cm FOV

Detector Input Dose/Fr?



Detector dose scales inversely as either the ratio of the FOV, or as the ratio squared

Video Frame Rate

What is the video frame rate in the U.S.A.?

Ans: 30 video frames per second

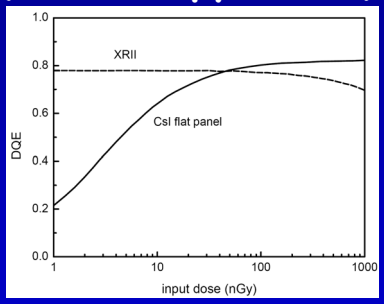
Detector Input Dose Rates (XRII)

- Rauch's 30-30-30 Rule:
  - For a nominal 30 cm image intensifier field of view (FOV),
    Pulse rate of 30 pps,
    Set the EERD to 30 μR/sec
  - For other FOV's, scale by either the ratio of the FOV (auto optical lens aperture) or the square of the ratio
  - Double the values if spectral beam filtration (e.g. minimum 0.2 mm Cu) is utilized

For flat panel, special consideration is required!!

Detector Input Dose Rates (FP)

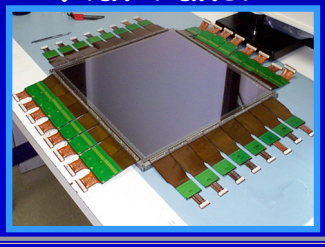
Detector Metrics (Fluoroscopy Doses)



Adapted from Koch, A., Macherel, J.M., Wirth, T., de Groot, P., Ducourant, T., Couder, D., Moy, J.P., & Calais, E. (2001). Detective quantum efficiency of an X-ray image intensifier chain as a benchmark for amorphous silicon flat panel detectors, Proc. SPIE, 4320, 115-20

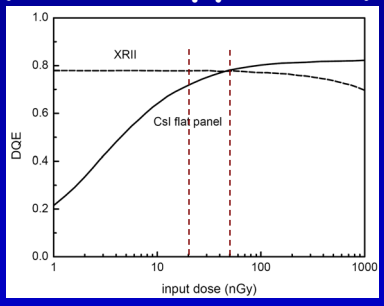
Image Intensifier

Flat Panel



Detector Input Dose Rates (FP)

Detector Metrics (Fluoroscopy Doses)

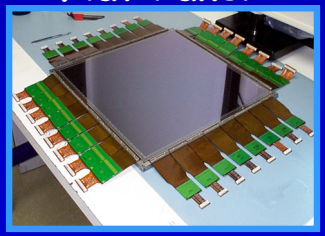


"The minimum operating dose level is defined by the magnitude of the noise arising in the AM array and readout electronics. This typically sets the lower operating limit for detector dose at 20-50 nGy."

Cowen AR et al., Solid-state, flat-panel, digital radiography detectors and their physical imaging characteristics, Clin Radiol (2008)

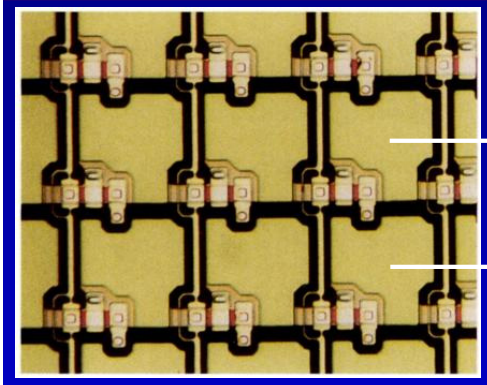
Image Intensifier

Flat Panel



2008 AAPM – Phil Rauch, Henry Ford Health Systems

Pixel Pitch – Air Kerma per Pixel



Detector	Mfg.	Pixel Pitch
Safire (a-Se, a-Si TFT)	Shimadzu	0.150
Philips, Siemens (CsI(Tl), a-Si TFT) - Angio	Trixell	0.154
Philips, Siemens (CsI(Tl), a-Si TFT) - Cardiac	Trixell	0.184
GE, Revolution (CsI(Tl), a-Si TFT)	GE	0.200

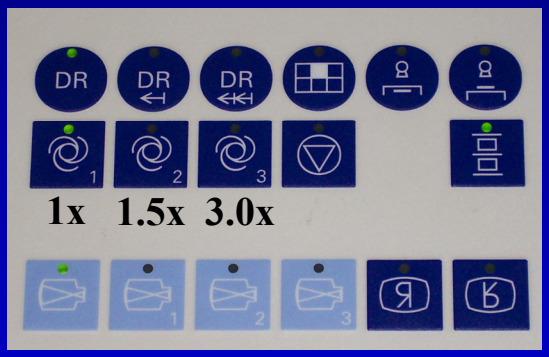
For the transition from XRII to Flat Panel, the required EERD can be estimated by determining the air kerma required for the XRII when it is operating at the same pixel pitch at that for the flat panel.

Pixel Pitch vs Input Dose

Pixel Pitch (mm)	Equivalent XRII Diam (cm) for 1024 Pixels	Diam^2	Ratio wrt 30 cm FOV	EERD (µR)	EERD (nGy)
XRII					
0.293	30.00	900.00	1.00	1.00*	8.76
Flat Panel					
0.150	15.36	235.93	3.81	3.81	33.42
0.154	15.77	248.68	3.62	3.62	31.70
0.184	18.84	355.01	2.54	2.54	22.21
0.200	20.48	419.43	2.15	2.15	18.80

**Per Rauch's 30-30-30 rule*

Detector Input Dose Rates



What about *pulsed* fluoroscopy?

Dose Per Pulse (<30 pps)

- For pulse rates lower than 30 pps, use Aufrichtig* perceptual pulsed fluoroscopy scale factor to adjust dose per frame for different frame rates

$$(\text{Dose/Pulse})_2 = (\text{Dose/Pulse})_1 * \text{SQRT}[(\text{Pulse Rate})_1/(\text{Pulse Rate})_2]$$

Example: Change from 30pps to 7.5 pps

$$(\text{Dose/Pulse})_2 = (\text{Dose/Pulse})_1 * \text{SQRT}[30/7.5]$$

$$= (\text{Dose/Pulse})_1 * 2$$

*Perceptual comparison of pulsed and continuous fluoroscopy, Richard Aufrichtig, Med. Phys. 21 (2), February 1994

Fluoroscopic Image Quality

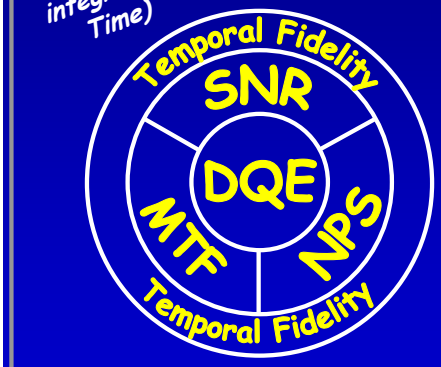
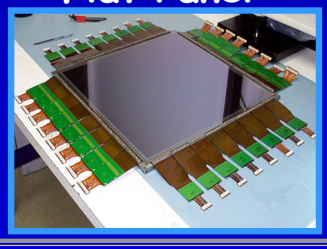
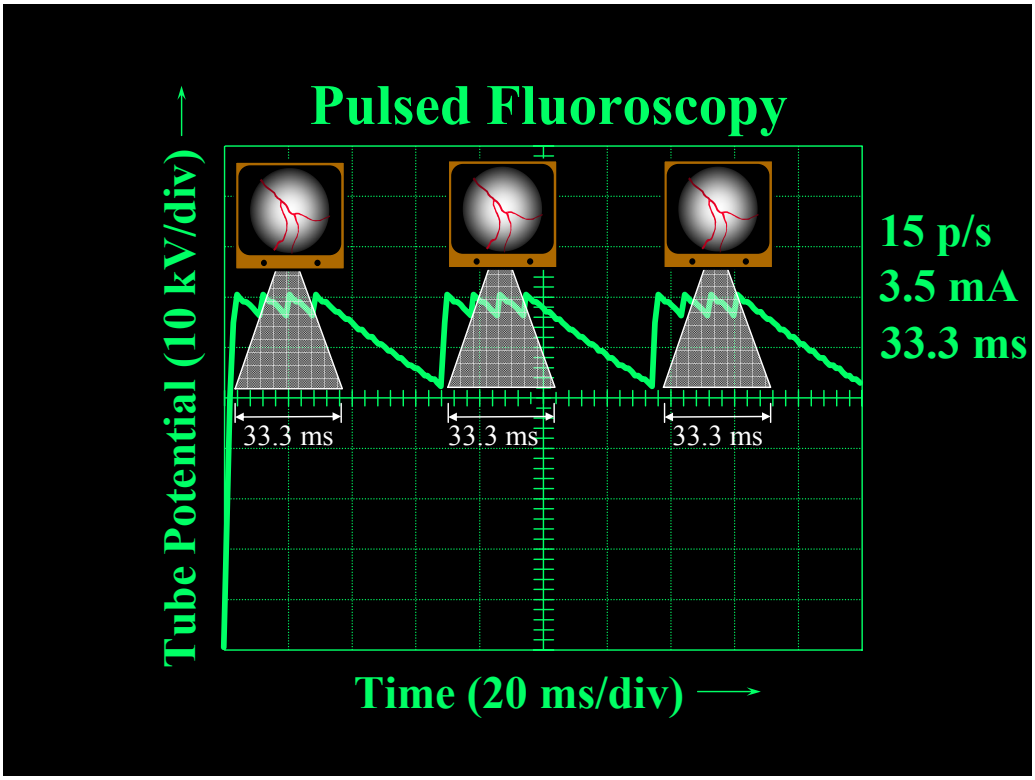
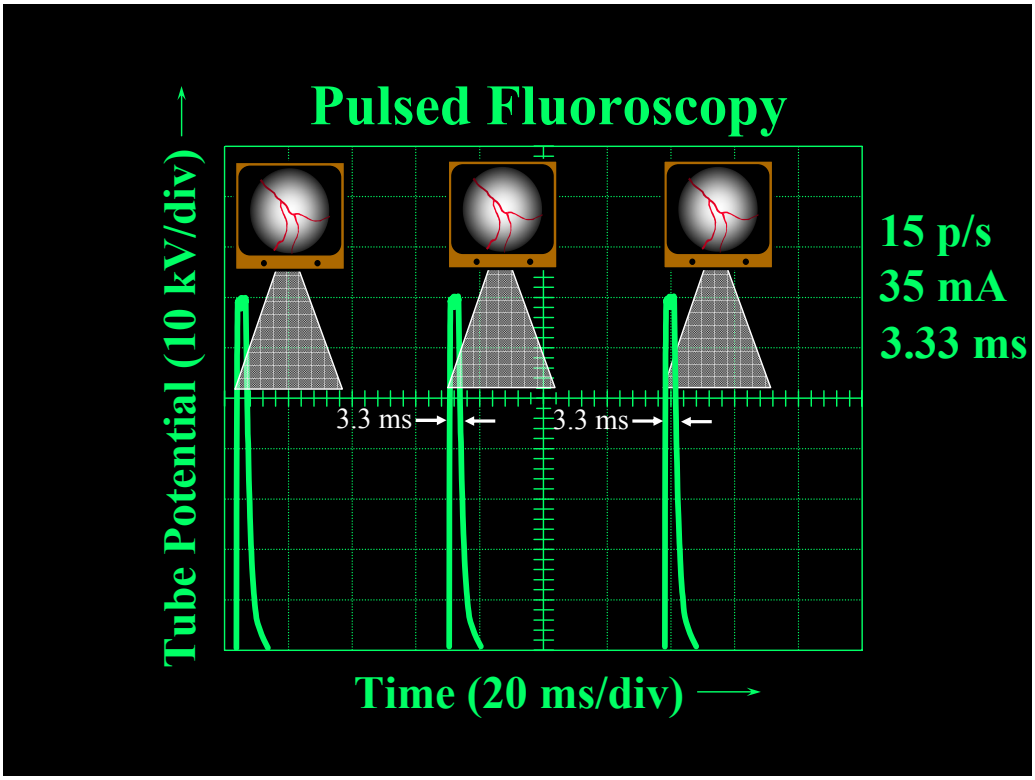


Image Intensifier

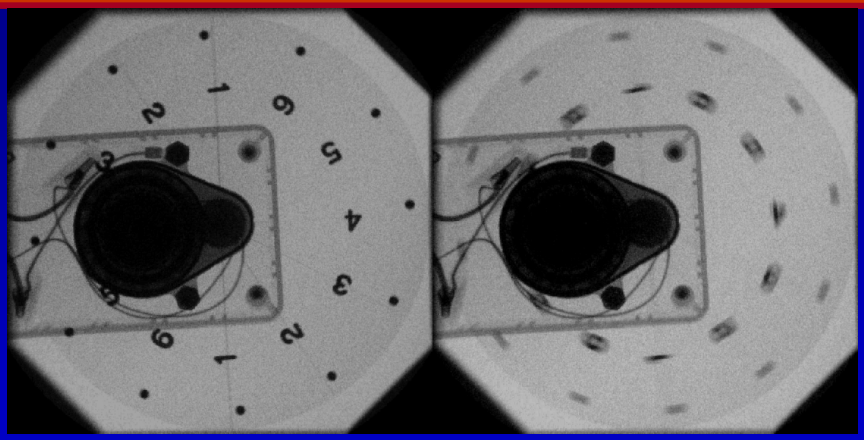
Flat Panel







Exposure ON-time – Pulsed vs Cont



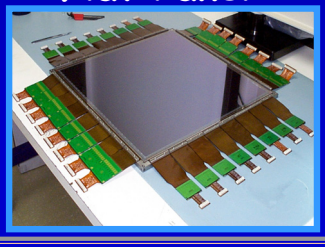
Pulsed Fluoro*
(30 pulses per sec)
*Displayed at 7.5 fps

Continuous Fluoro*
(30 video frames per sec)
*Displayed at 7.5 fps

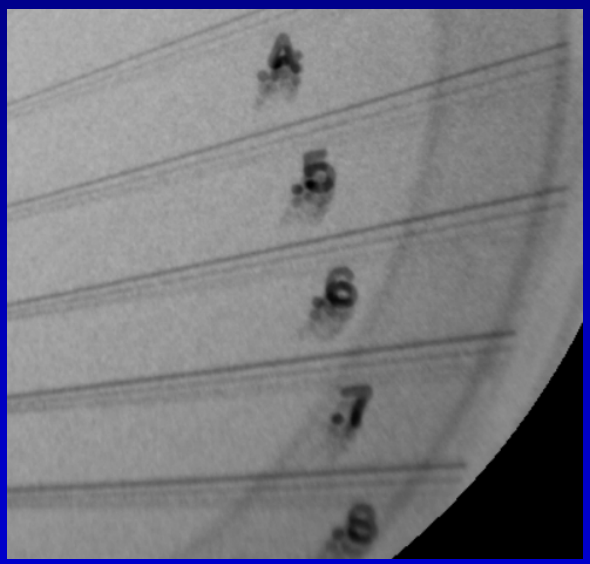
Fluoroscopic Image Quality

Image Intensifier

Flat Panel



Lag (Signal Retention)

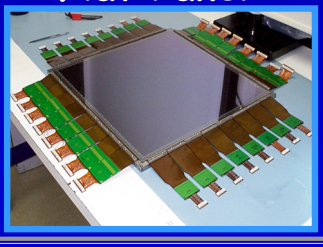


Measured by the signal retained in the third video field following removal of the image source

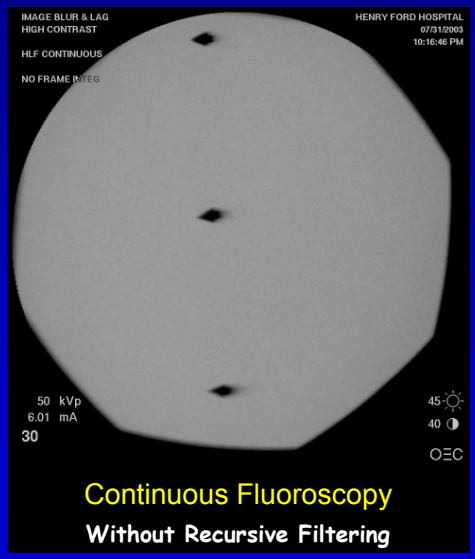
Fluoroscopic Image Quality

Image Intensifier

Flat Panel

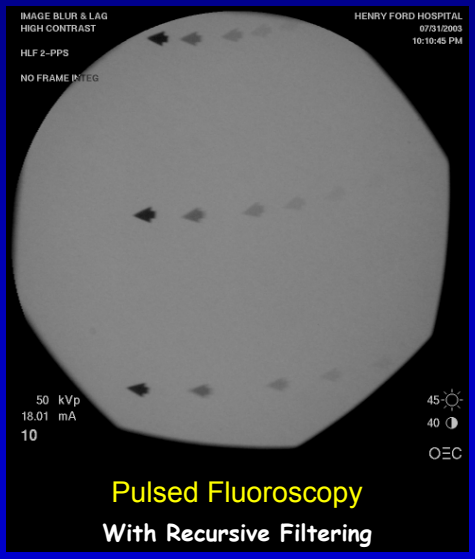


Blur versus Recursive Filtering



Continuous Fluoroscopy

Without Recursive Filtering



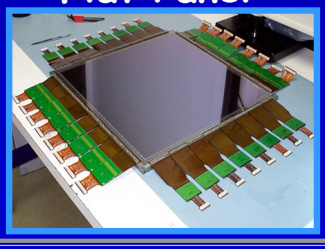
Pulsed Fluoroscopy

With Recursive Filtering

Fluoroscopic Image Quality

Image Intensifier

Flat Panel



Perceptual Integration

Where are the 3's

895842541283564210265017265127065759242965765150159901765129156017650176576031416768737976671516161449120241717245670124550145657659824421054232067512768869625289809491988948384826614525629495668924560

30 Frames/sec

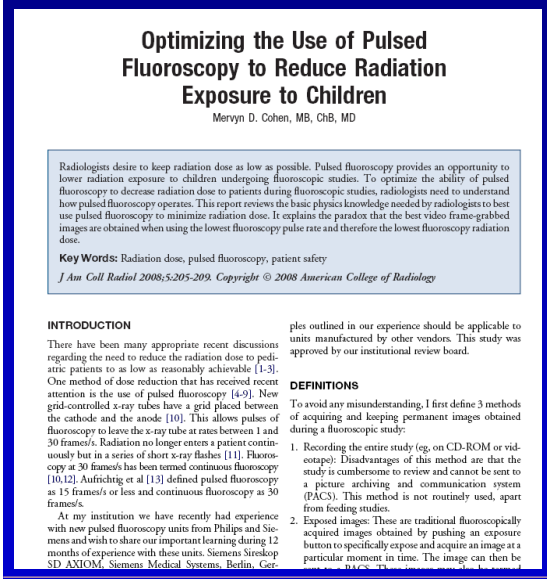
Perceptual Integration

Where are the 3's

8958425412835642102650172651270657592429
6576515015990176512915601765017657603141
6768737976671516161449120241717245670124
5501456576598244210542320675127688696252
8980949198894838482661452562949566892456

8 Frames/sec

Pulsed Fluoroscopy



Optimizing the Use of Pulsed Fluoroscopy to Reduce Radiation Exposure to Children

Mervyn D. Cohen, MB, ChB, MD

Radiologists desire to keep radiation dose as low as possible. Pulsed fluoroscopy provides an opportunity to lower radiation exposure to children undergoing fluoroscopic studies. To optimize the ability of pulsed fluoroscopy to decrease radiation dose to patients during fluoroscopic studies, radiologists need to understand how pulsed fluoroscopy operates. This report reviews the basic physics knowledge needed by radiologists to best use pulsed fluoroscopy to minimize radiation dose. It explains the paradox that the best video frame-grabbed images are obtained when using the lowest fluoroscopy pulse rate and therefore the lowest fluoroscopy radiation dose.

Key Words: Radiation dose, pulsed fluoroscopy, patient safety

J Am Coll Radiol 2008;5:205-209. Copyright © 2008 American College of Radiology

INTRODUCTION

There have been many appropriate recent discussions regarding the need to reduce the radiation dose to pediatric patients to as low as reasonably achievable [1-3]. One method of dose reduction that has received recent attention is the use of pulsed fluoroscopy [4-9]. New grid-controlled x-ray tubes have a grid placed between the cathode and the anode [10]. This allows pulses of fluoroscopy to leave the x-ray tube at rates between 1 and 30 frames/s. Radiation no longer enters a patient continuously but in a series of short x-ray flashes [11]. Fluoroscopy at 30 frames/s has been termed continuous fluoroscopy [10,12]. Aufrichtig et al [13] defined pulsed fluoroscopy as 15 frames/s or less and continuous fluoroscopy as 30 frames/s.

At my institution we have recently had experience with new pulsed fluoroscopy units from Philips and Siemens and wish to share our important learning during 12 months of experience with these units. Siemens Sireskop SD AXIOM, Siemens Medical Systems, Berlin, Ger-

ples outlined in our experience should be applicable to units manufactured by other vendors. This study was approved by our institutional review board.

DEFINITIONS

To avoid any misunderstanding, I first define 3 methods of acquiring and keeping permanent images obtained during a fluoroscopic study:

1. Recording the entire study (eg, on CD-ROM or videotape): Disadvantages of this method are that the study is cumbersome to review and cannot be sent to a picture archiving and communication system (PACS). This method is not routinely used, apart from feeding studies.
2. Exposed images: These are traditional fluoroscopically acquired images obtained by pushing an exposure button to specifically expose and acquire an image at a particular moment in time. The image can then be

Must increase the dose per pulse as the fluoroscopic pulse rate is decreased

Counters the increased perception of noise as pulse rate is reduced

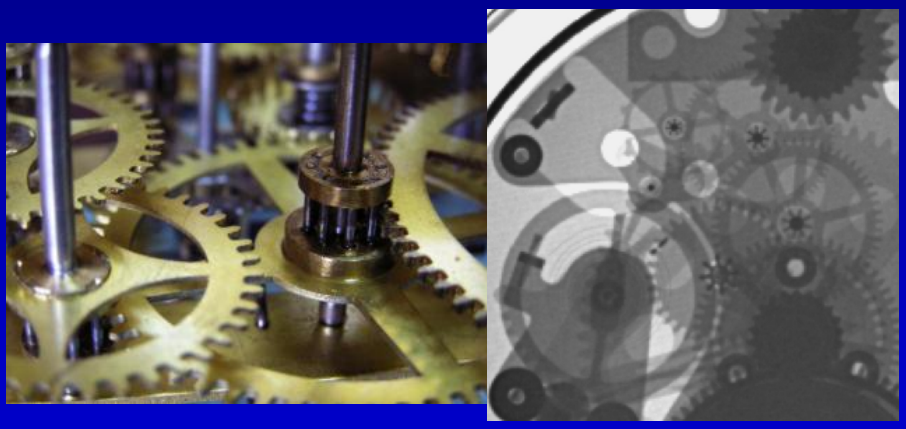
Greatly improves the quality of the LIH image, often obviating the need to create a radiographic spot image

The short exposure time per frame greatly improves motion blurring

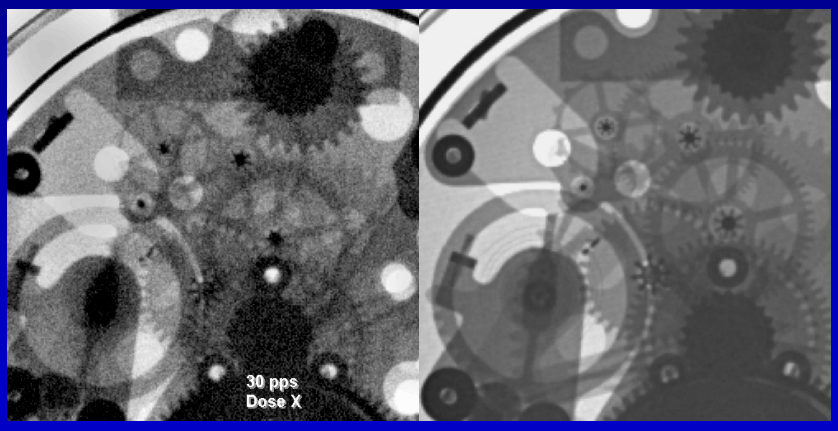
Real reduction in patient dose with improvement in image quality

More likely to use the lower frame rates due to lower perceived noise

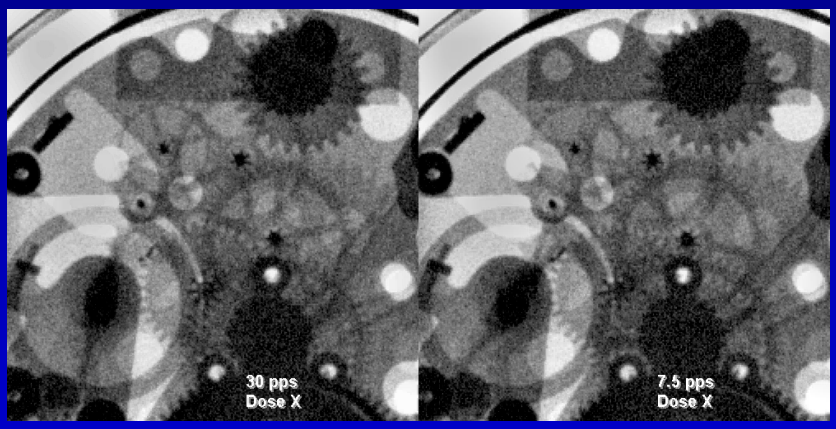
Dose Per Pulse



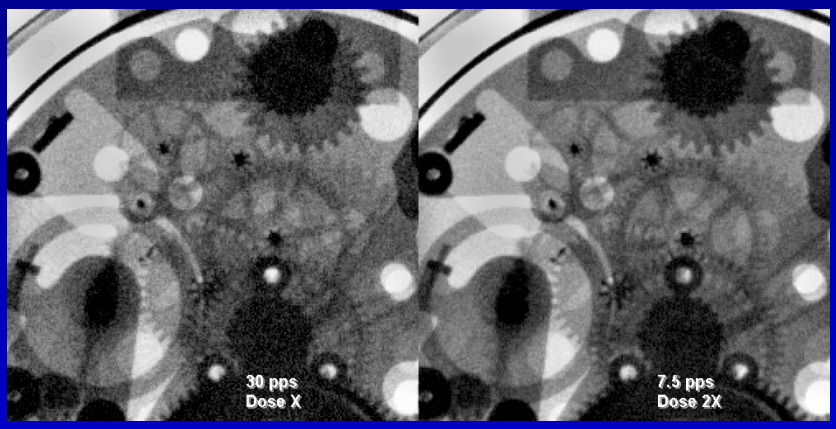
Dose Per Pulse



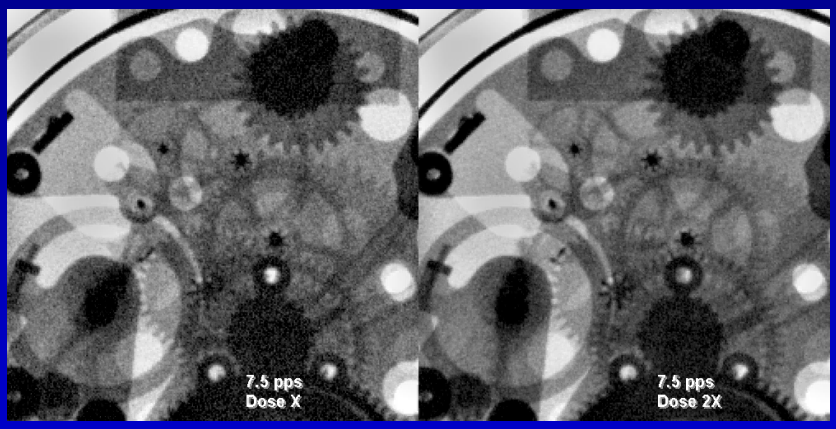
Dose Per Pulse



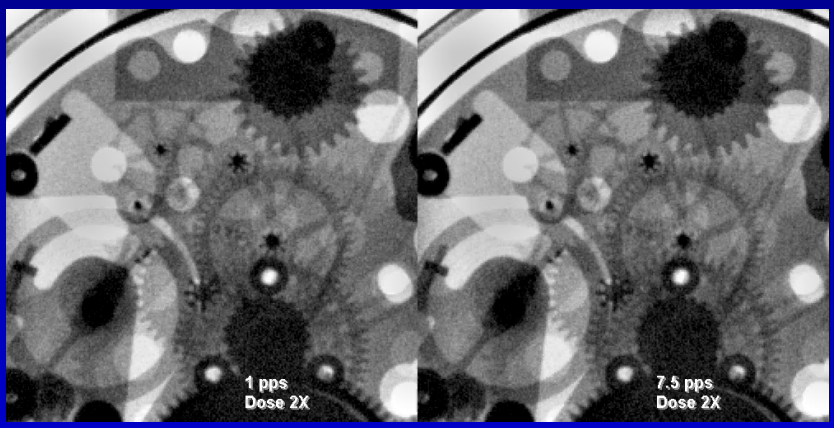
Dose Per Pulse



Dose Per Pulse



Dose Per Pulse



Subtle sources of increased dose (Re: Image Gently)

- Poor geometry
  - Short source to skin distance
  - Large gap between patient and image receptor

Imager Geometry

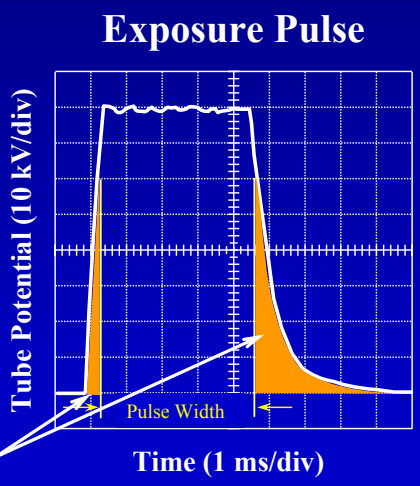
Imager Geometry

Subtle sources of increased dose (Re: Image Gently)

- Poor geometry
  - Short source to skin distance
  - Large gap between patient and image receptor
- **Capacitive discharge from high tension cables during pulsed fluoroscopy**

Exposure ON-time

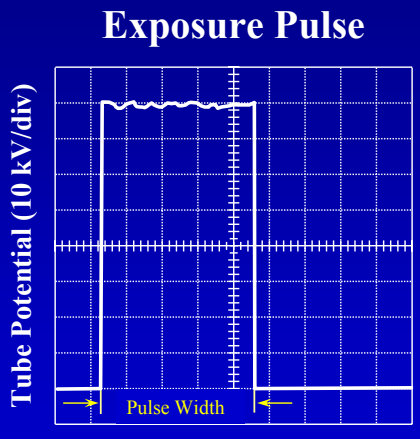
X-ray ON-pulse



Regions of non-useful radiation production. Potential for higher skin dose

Exposure ON-time

X-ray ON-pulse



Grid-controlled **pulse leads to greater control and reduced skin dose**

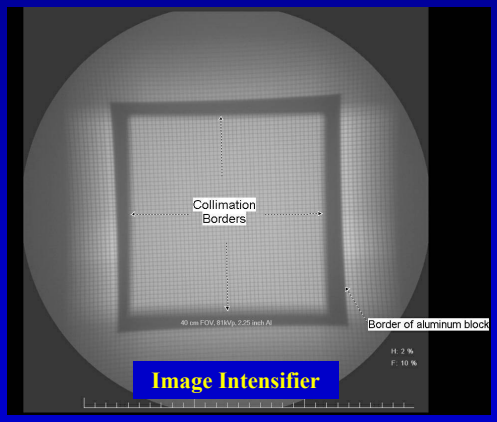
Subtle sources of increased dose (Re: Image Gently)

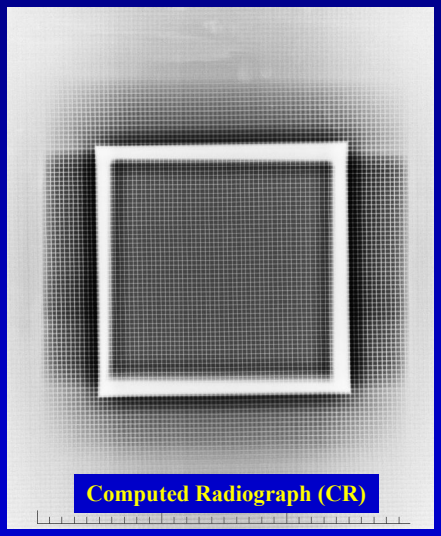
- Poor geometry
  - Short source to skin distance
  - Large gap between patient and image receptor
- Capacitive discharge from high tension cables during pulsed fluoroscopy
- **Collimator leakage**

Collimator Leakage

All collimators leak radiation

FDA allows leakage rate to be 100 mR/Hr at 1 meter (Max kV and max continuous rate)





Collimator Leakage

- *Not* Due to Scatter

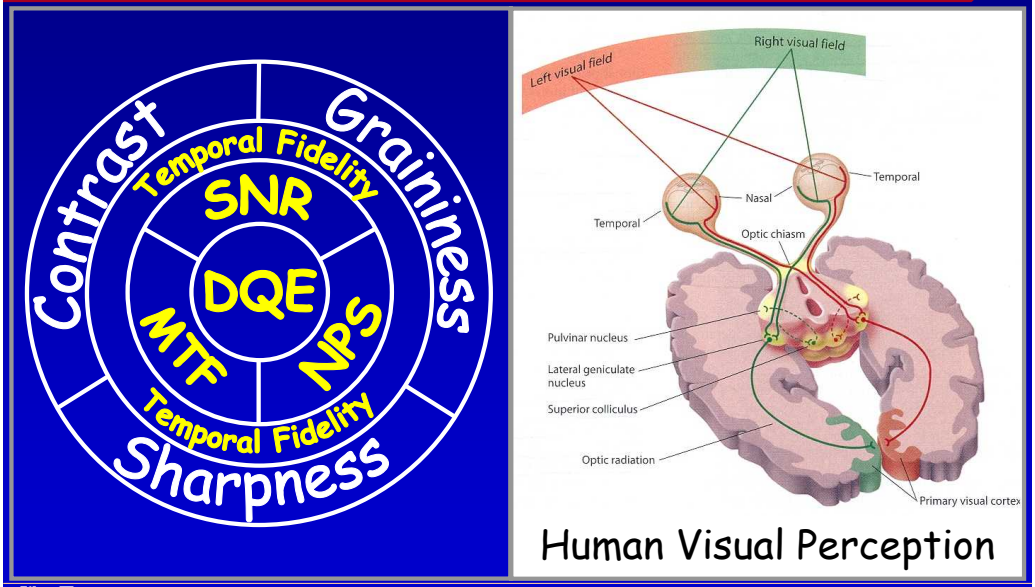
Wire screen was setting above the aluminum blocks

Image Quality: What is it?

- "Image quality depends only on intrinsic, objective physical characteristics of an imaging system, and can be measured independently of an observer"
- "Image quality is whatever the observer says it is (i.e., it is a subjective perception of the image, 'in the eye of the beholder')"

Definitions courtesy Ralph Schaetzing, Agfa Corp.

Fluoroscopic Image Quality

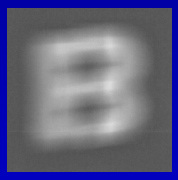


Human Visual Perception

- Can result in different interpretations of the same image
- Can make up for deficits in image quality

Sharpness and HVP

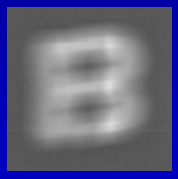
- What is this?



Sharpness and HVP

- What is this?

  Although this image is quite unsharp, that is not the underlying reason that the image is difficult to interpret....

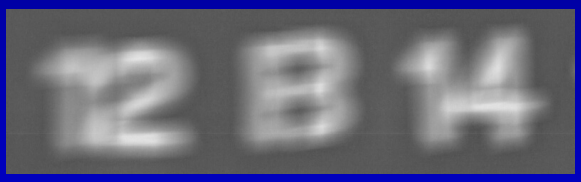


....this task is difficult because the image is presented out of context

Sharpness and HVP

- What is this?

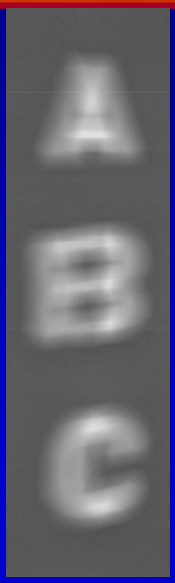
  Image presented in context



Sharpness and HVP

- What is this?

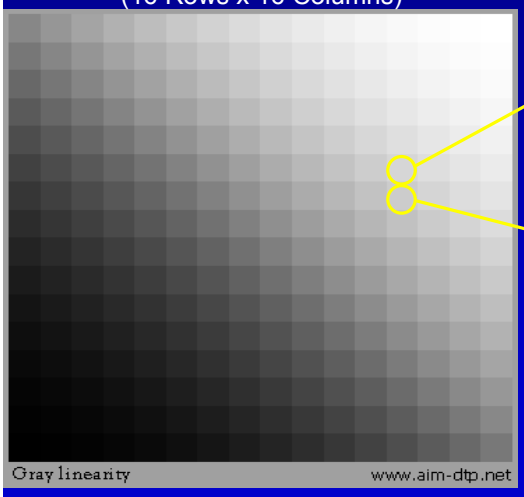
  Same image, different context



Medical imaging must always be conducted within a specified context

Contrast and HVP

256 Gray Levels
(16 Rows x 16 Columns)



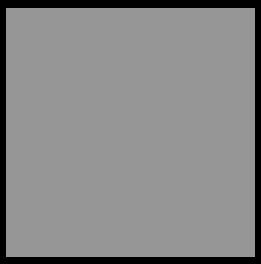
I_1

I_2

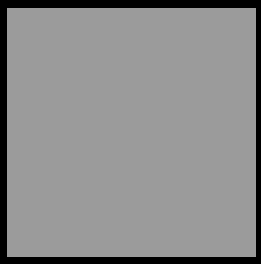
Contrast, $(I_2-I_1) / (I_2+I_1)$

Contrast and HVP

Although these squares have measurably different gray levels, there is no perceptible contrast difference



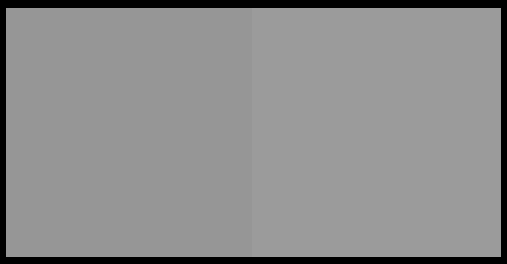
Grey Level 150



Grey Level 155

Contrast and HVP

- Mach Bands



Grey Level 150 Grey Level 155

Contrast and HVP

The letters of the word black are perceived to be of a darker shade of gray than the letters of the word white

Alan Gilchrist, "Seeing in Black & White", Scientific American Mind (2008)

Contrast and HVP

The letter H appears to have changed its shade of gray

Contrast and HVP

B's are all gray level 150

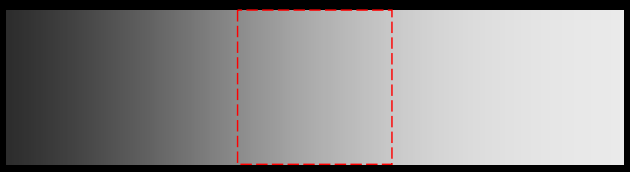
H's are all gray level 119

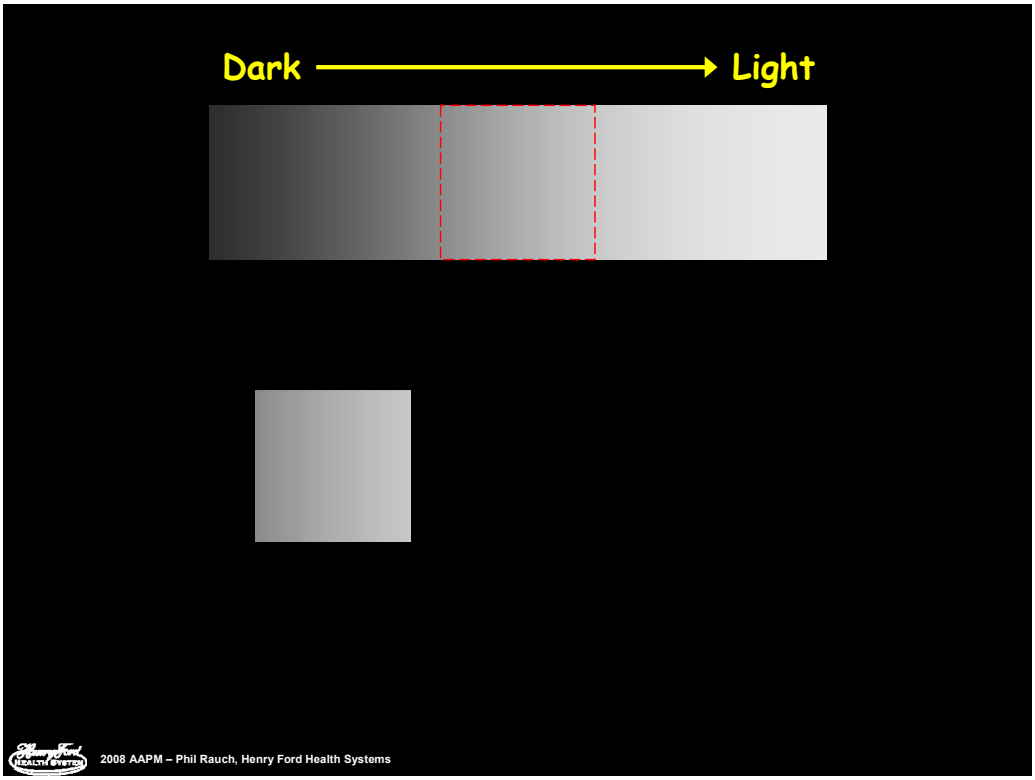
In reality all of the H's are of the same shade of gray and are darker than the B's

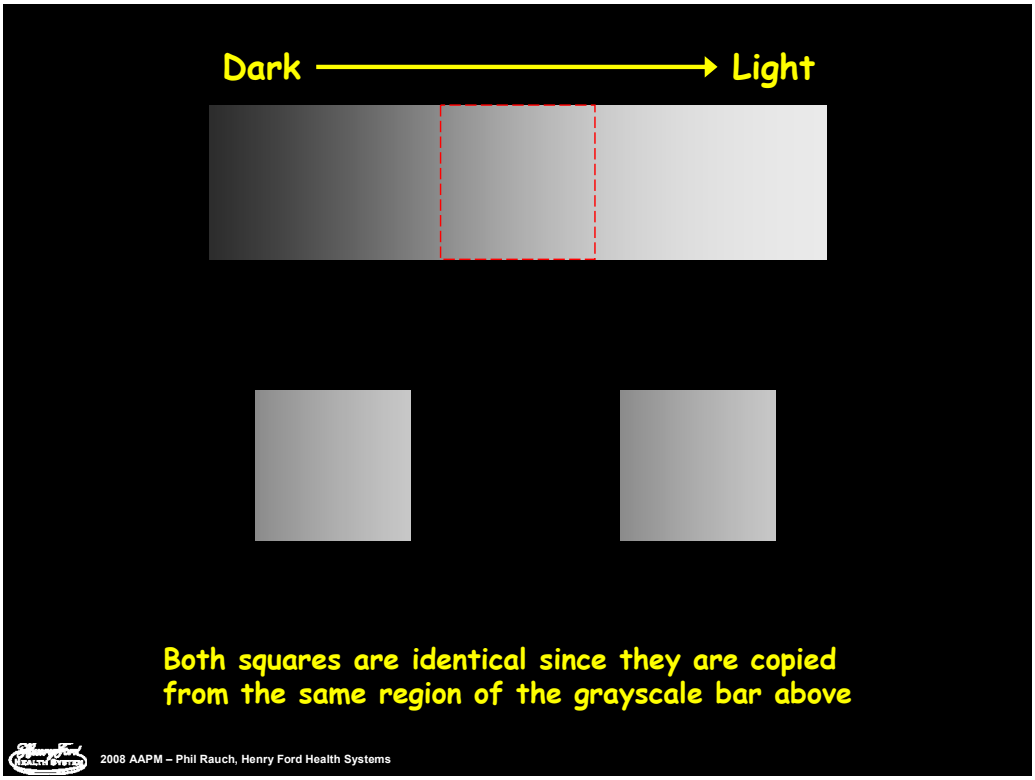
Dark ⟶ Light

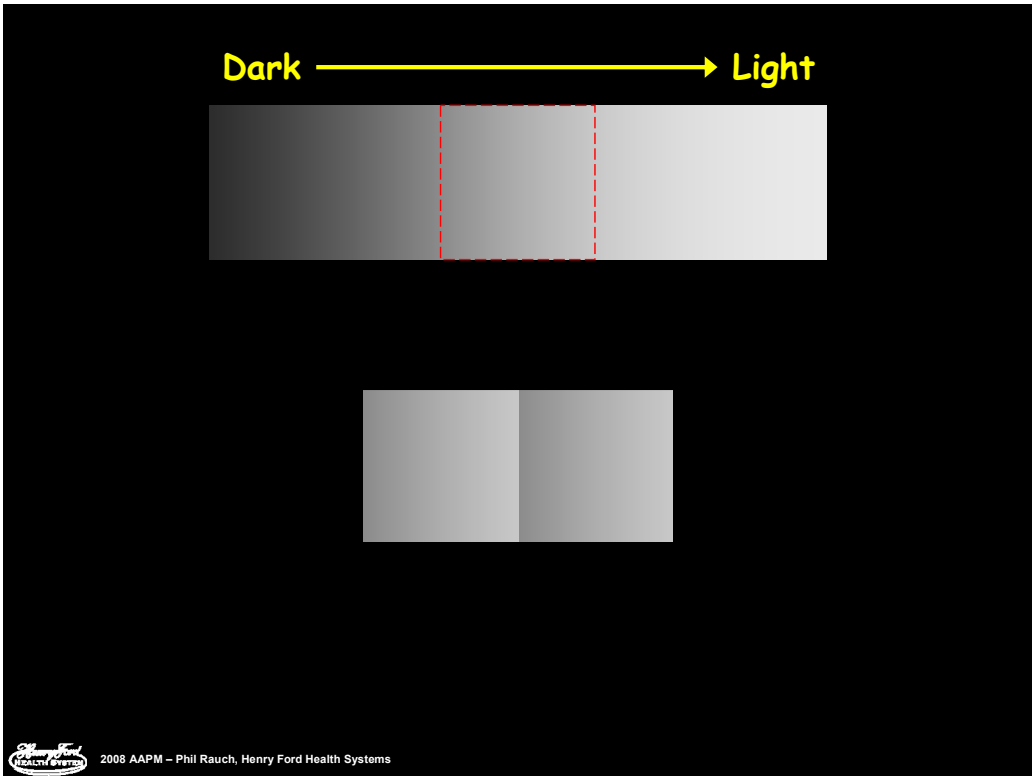
Human visual perception can result in two identical objects being perceived as having different gray levels

Dark ⟶ Light




Dark
Light
2008 AAPM – Phil Rauch, Henry Ford Health Systems


Dark
Light
Both squares are identical since they are copied from the same region of the grayscale bar above
2008 AAPM – Phil Rauch, Henry Ford Health Systems



Contrast and HVP

Dynamic Range Rendering

I.I. – 66 dB → 48 dB
CR – 80 dB → 48 dB

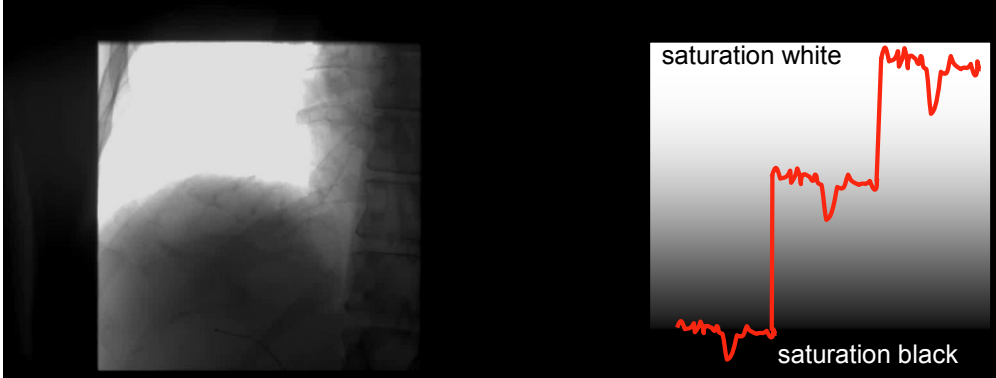


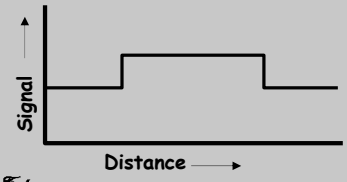
Image Characteristics

Dynamic Range Rendering

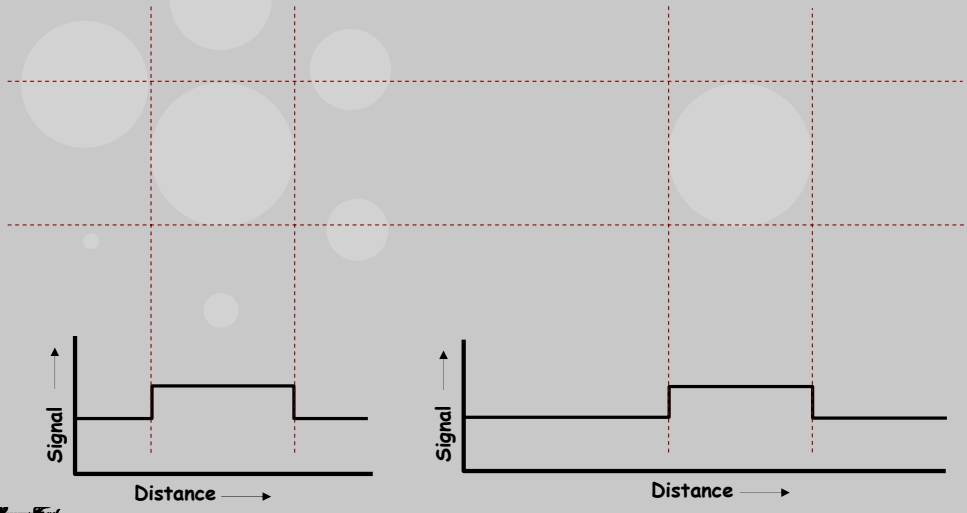
Image Characteristics

Dynamic Range Rendering

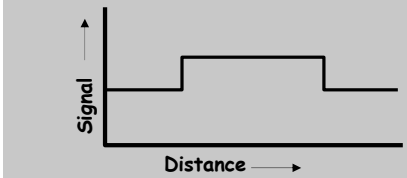
HVS – Contrast Blindness

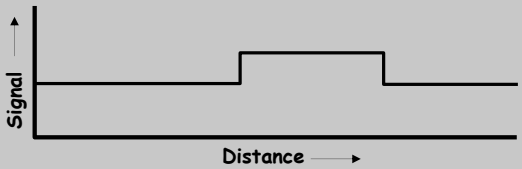


HVS – Contrast Blindness

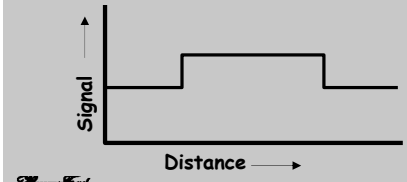


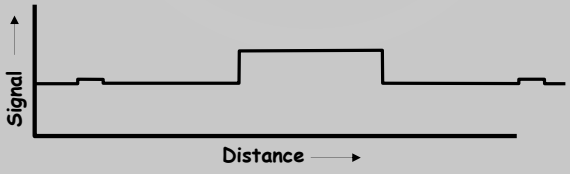
HVS – Contrast Blindness



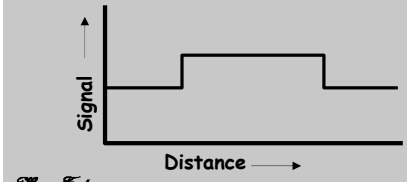


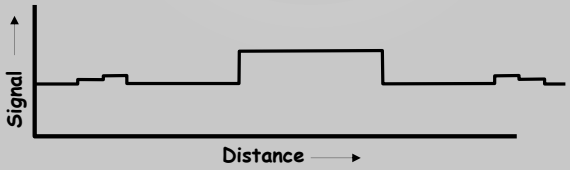
HVS – Contrast Blindness



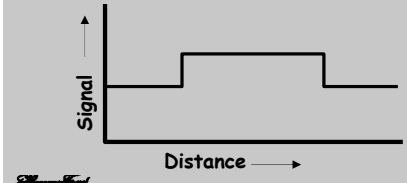


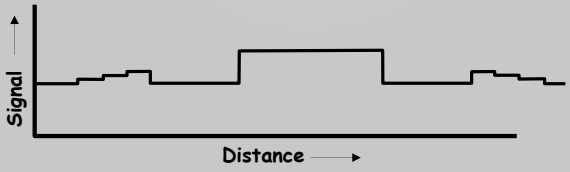
HVS – Contrast Blindness



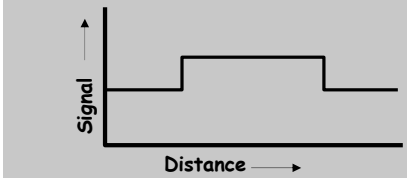


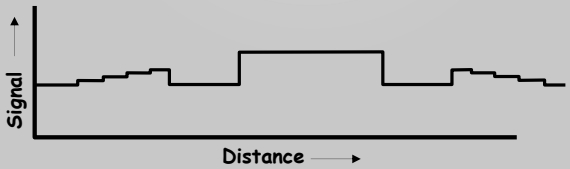
HVS – Contrast Blindness



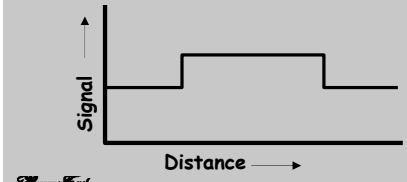


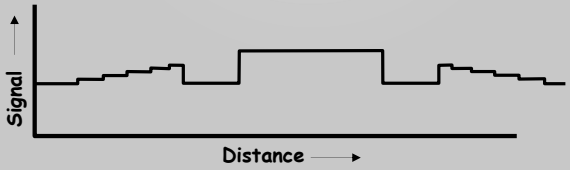
HVS – Contrast Blindness





HVS – Contrast Blindness





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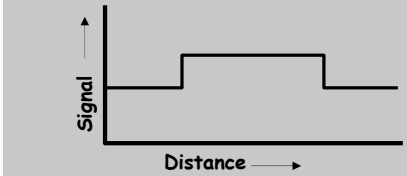
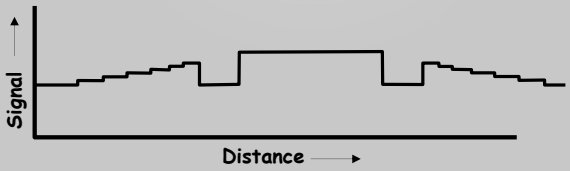
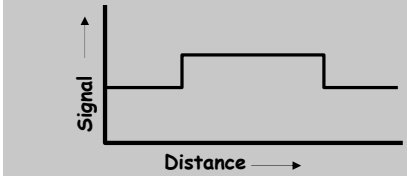
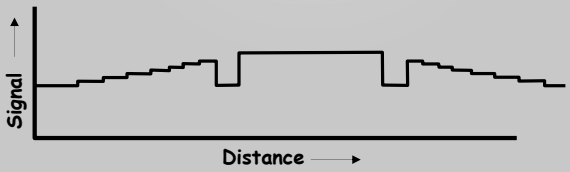
HVS – Contrast Blindness





HVS – Contrast Blindness





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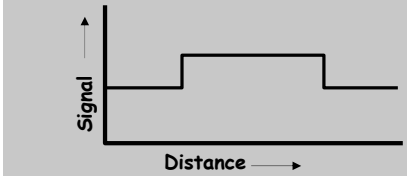
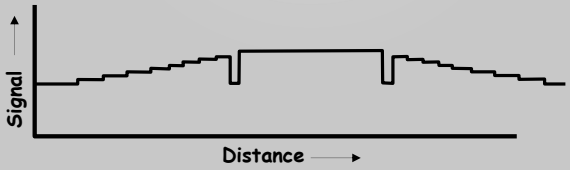
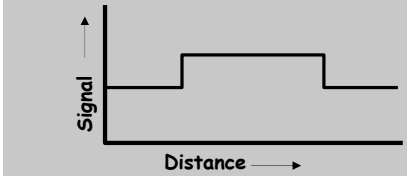
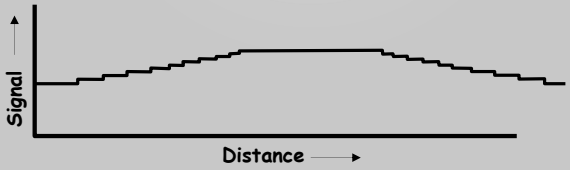
HVS – Contrast Blindness



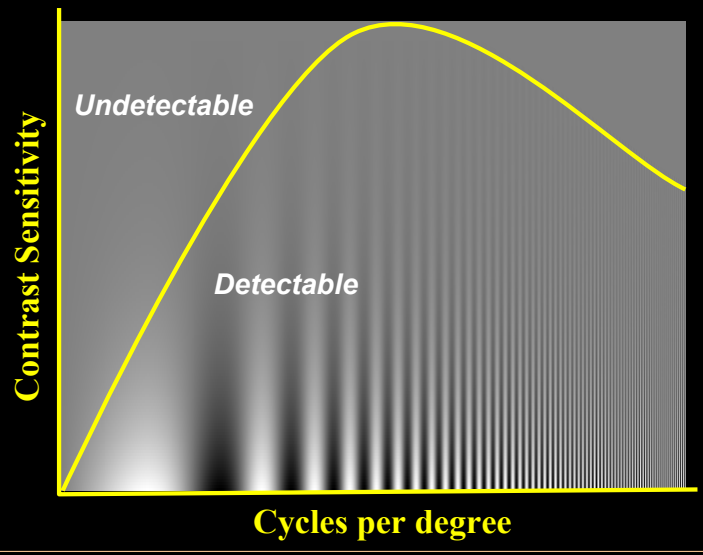


HVS – Contrast Blindness





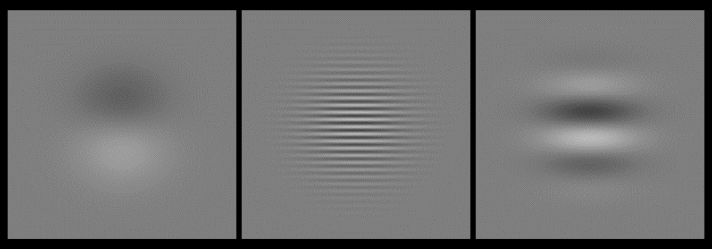
Human Visual System



HVS – Contrast Perception

GABORI ATTACK

Gabori, like the ones shown below,
can sneak up slowly from anywhere.



Squash them quickly before they get you! But only click where you know you see a Gabori sneaking up through the fog. Tripple click when you've had enough.

Quit

The Contrast Sensitivity Function (Peter Wenderoth)

http://neurovision.berkeley.edu/Demonstrations/VSOC/vsoc_main.html

Image Quality: What is it?

- "Image quality depends only on intrinsic, objective physical characteristics of an imaging system, and can be measured independently of an observer"
- "Image quality is whatever the observer says it is (i.e., it is a subjective perception of the image, 'in the eye of the beholder')"
- "Image quality is defined by an observer's ability to achieve an acceptable level of performance for a specified task"

Definitions courtesy Ralph Schaetzing, Agfa Corp.

Image Interpretation

Successful interpretation depends on…

- Image Attributes
- Human Observer (education, experience)
- Human Visual Perception
- Pattern Recognition
- Clarity of the imaging task
- Minimal external distractions
- Level of confidence

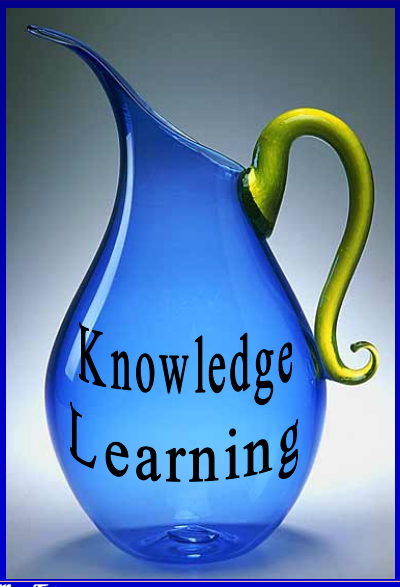
Conclusions

- Image quality is not just detector metrics
- Image quality is not just a subjective impression
- Image quality is a moving target
- Patient dose need not be linked to detector dose or kVp
- Demand and use aggressive spectral filtration

Conclusions

- Be willing to break the *commandment* "High kV, Low mA", but only if aggressive spectral filtration is present
- Use pulsed fluoroscopy and the Aufrichtig scale to produce better images, not solely to reduce dose
- Remember that visual perception can sometimes mask the true nature of image attributes

My wish for you…



…a thirst for knowledge and learning that will last a lifetime

Imaging Task

Find the human face……

The Contrast Sensitivity Function (Peter Wenderoth)
http://neurovision.berkeley.edu/Demonstrations/VSOC/vsoc/vsoc_main.html

Thank you

Phil Rauch

philr@rad.hfh.edu