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X-ray fluoroscopy imaging in the invasive cardiac laboratory:

Medical physics support of a contemporary practice

Kenneth A. Fetterly, Ph.D.

2013 AAPM Spring Clinical Meeting

Outline

1. Introduction to the cardiac invasive laboratory
2. Introduction to interventional x-ray systems
3. System performance testing
4. Strategies for patient dose reduction
5. Novel, new, and emerging technologies

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1. Introduction to the invasive cardiovascular laboratory

- Type of procedures
- Imaging equipment
- X-ray imaging tasks

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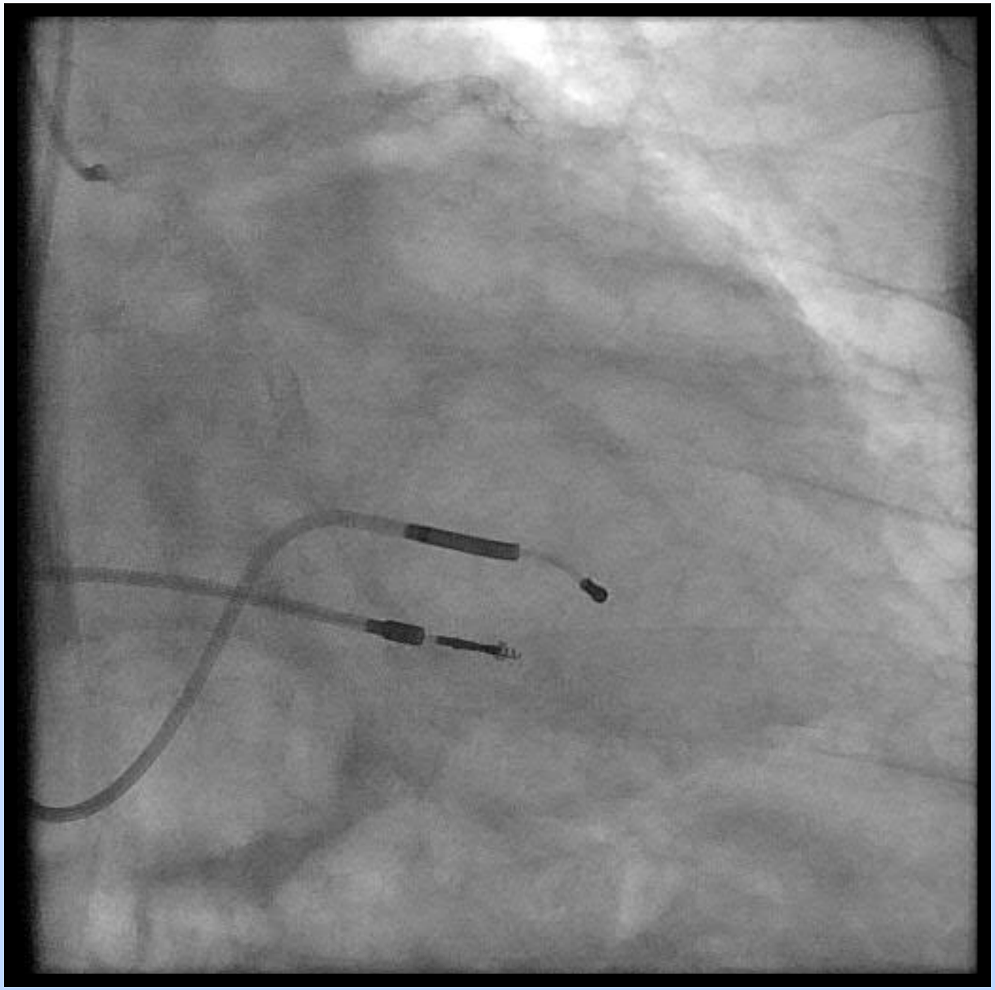
Coronary artery disease
Partially occluded circumflex artery



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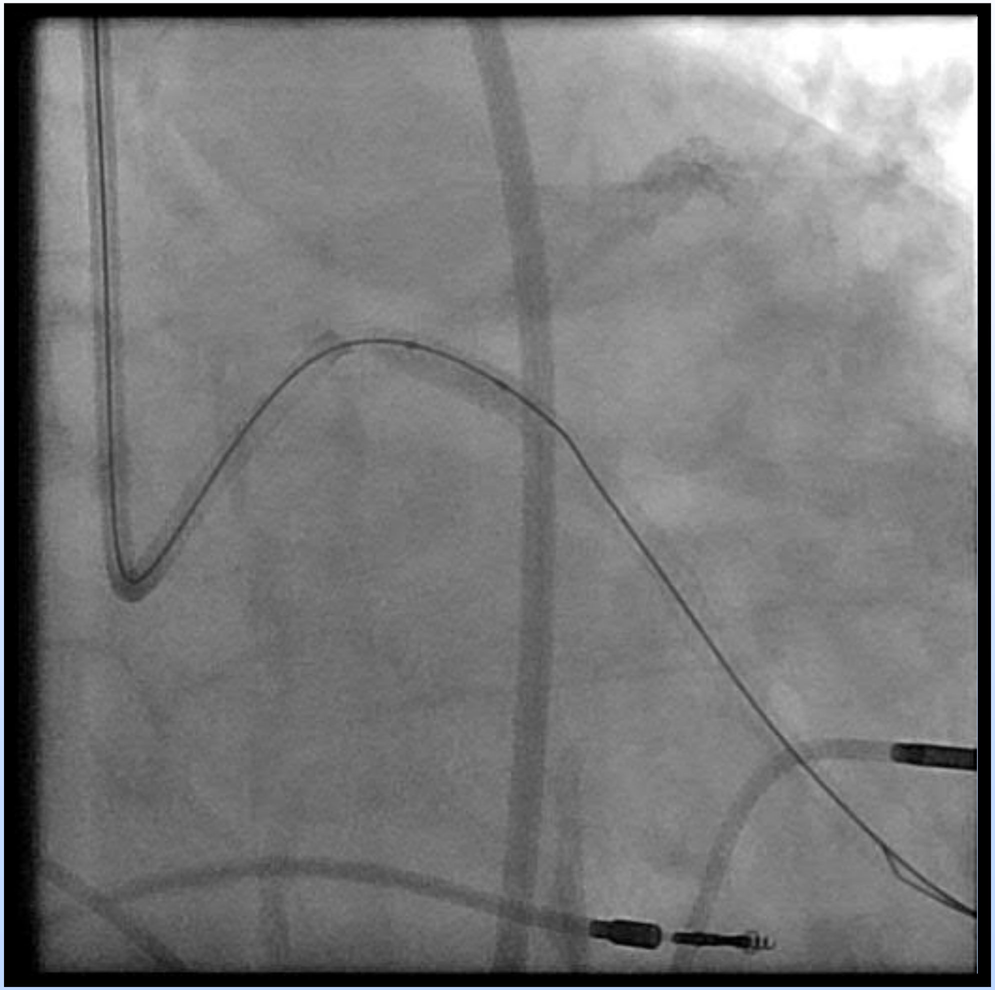
Coronary artery disease
Stent deployment by balloon inflation



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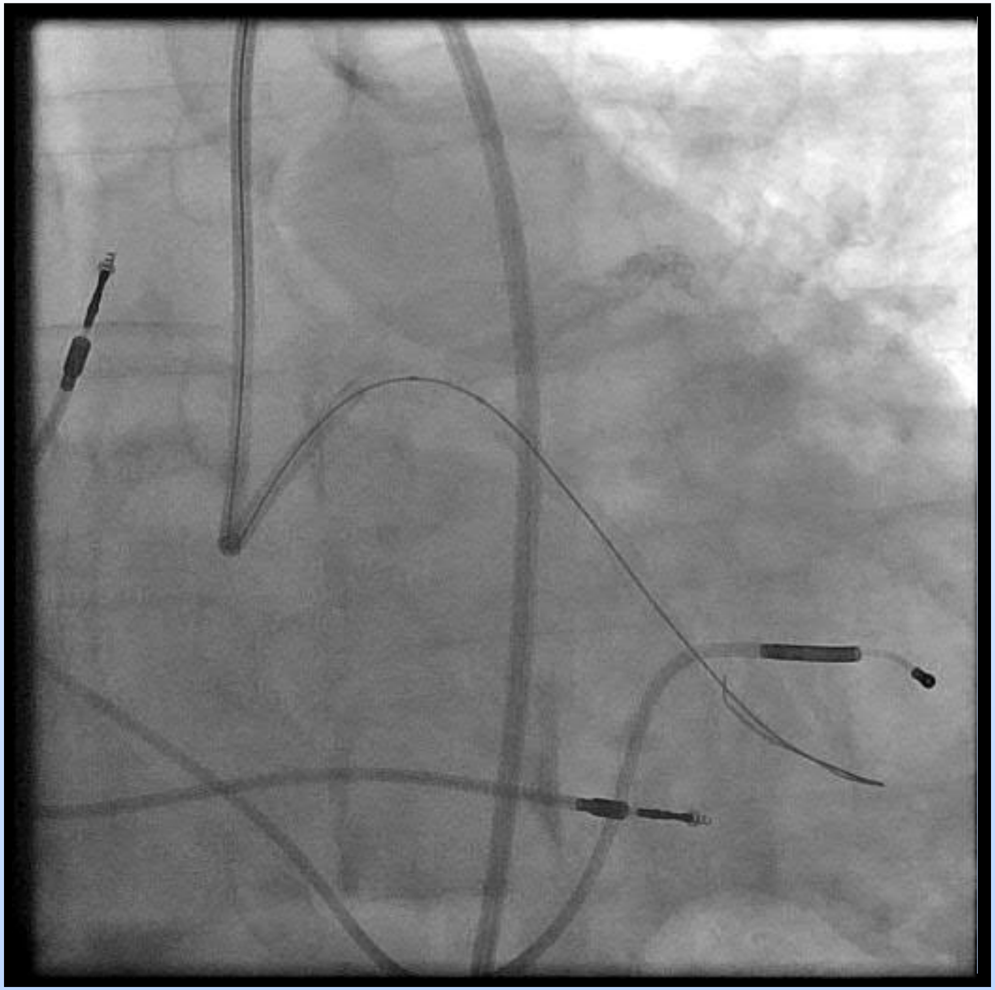
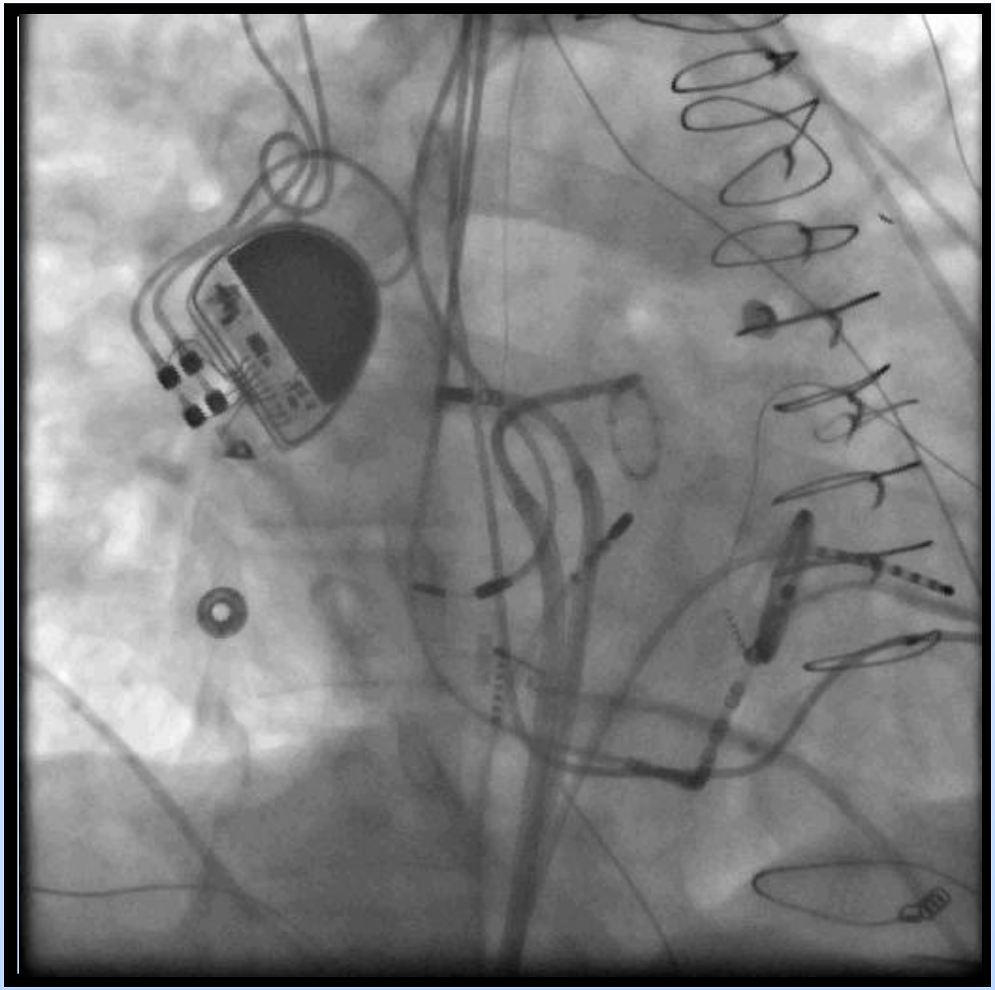
Coronary artery disease
Post-intervention patent artery



Ablation for atrial fibrillation



Transcatheter aortic valve replacement

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2. Interventional x-ray systems
Major components

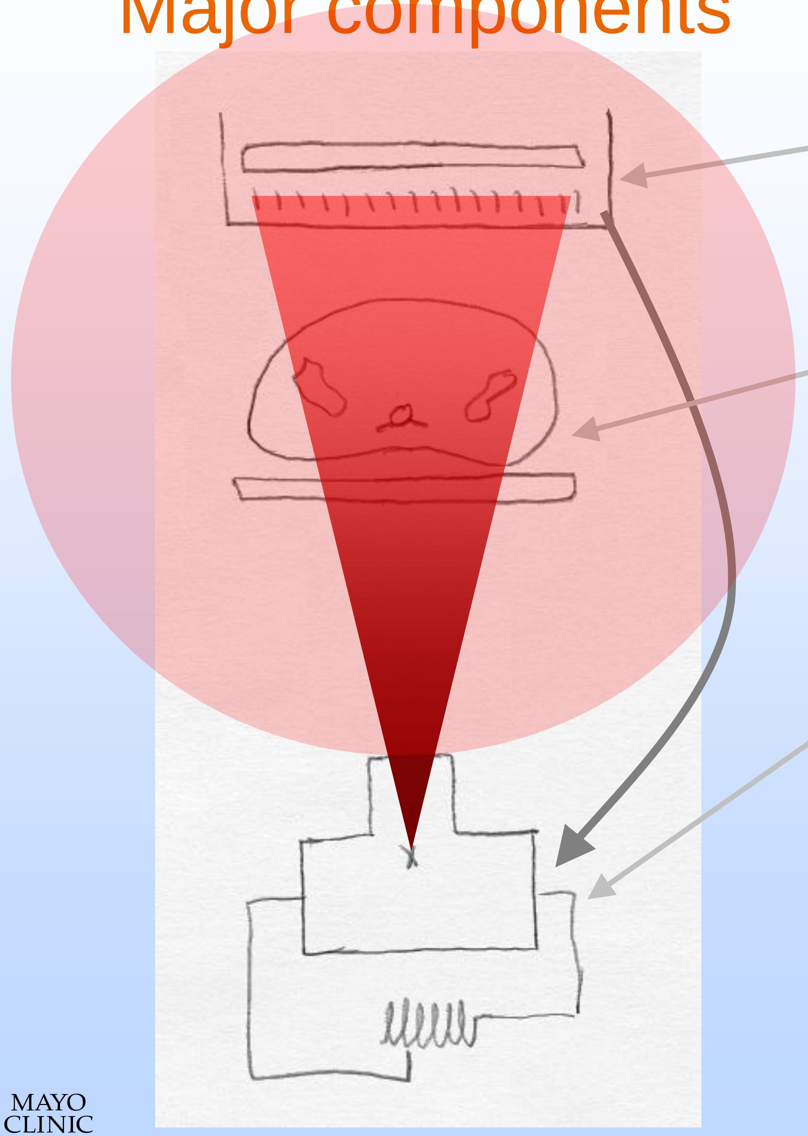

Image receptor

- Anti-scatter grid
- X-ray detector, fixed target dose

Patient

- X-ray attenuation
- X-ray scatter
- Radiosensitive

X-ray tube

- X-ray energy (kVp)
- Current (ma)
- Frame rate (s^{-1})
- Pulse duration (ms)
- Beam filtration (mm Cu)

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System control
The basics

- Automatic exposure rate control (AERC)
  - Image detector has a program-specific target dose
  - Patient attenuates primary beam
  - X-ray tube output is adjusted to achieve detector target dose
  - For fluoro, maximum air kerma rate is regulated
- Output variables
  - Tube current
  - Peak tube potential
  - Pulse duration
  - Focal spot size
  - Filter composition and thickness (fixed or dynamic)

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System control
Experimental setup

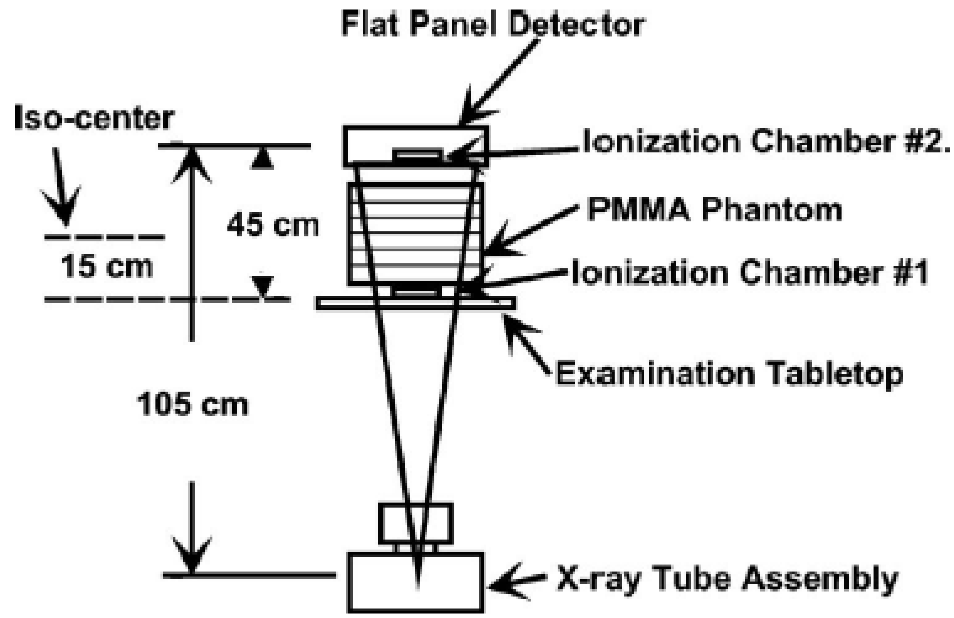

FIG. 1. Experimental/geometrical arrangement. Ionization chamber 1 is employed for monitoring patient air kerma rate (PAKR) while ionization chamber 2 is employed for recording the flat panel input air kerma rate (FPIAKR).

Lin, Med Phys, 2007(34)

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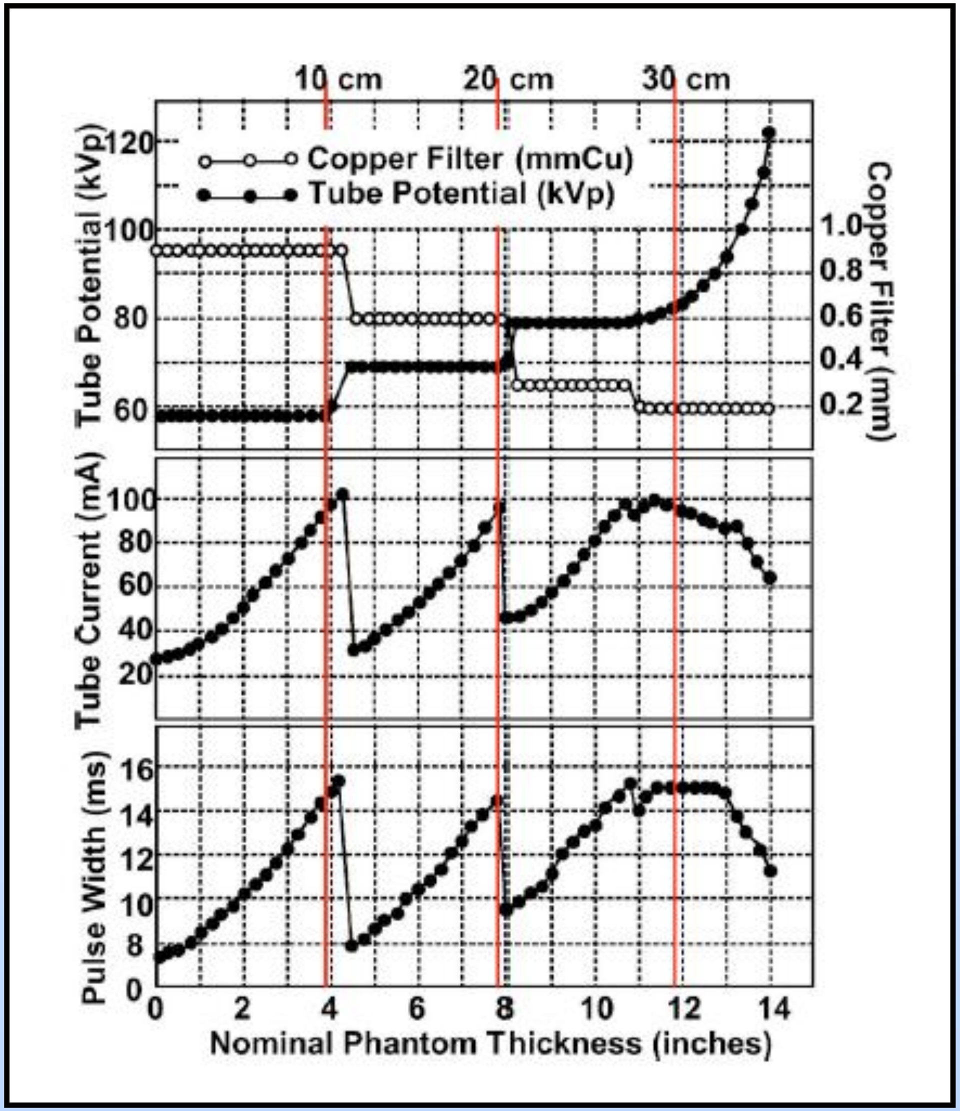
System control
A modern example



Lin, Med Phys, 2007(34)

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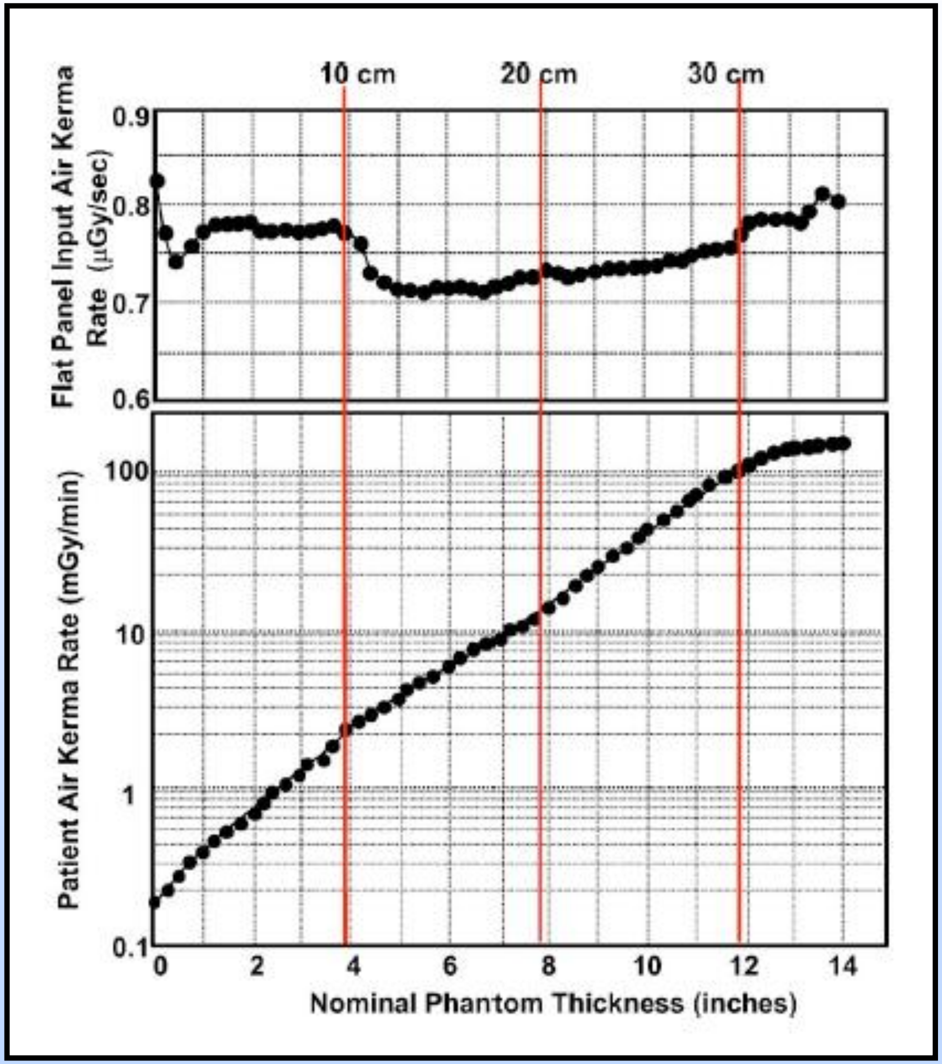
System control
A modern example



Lin, Med Phys, 2007(34)

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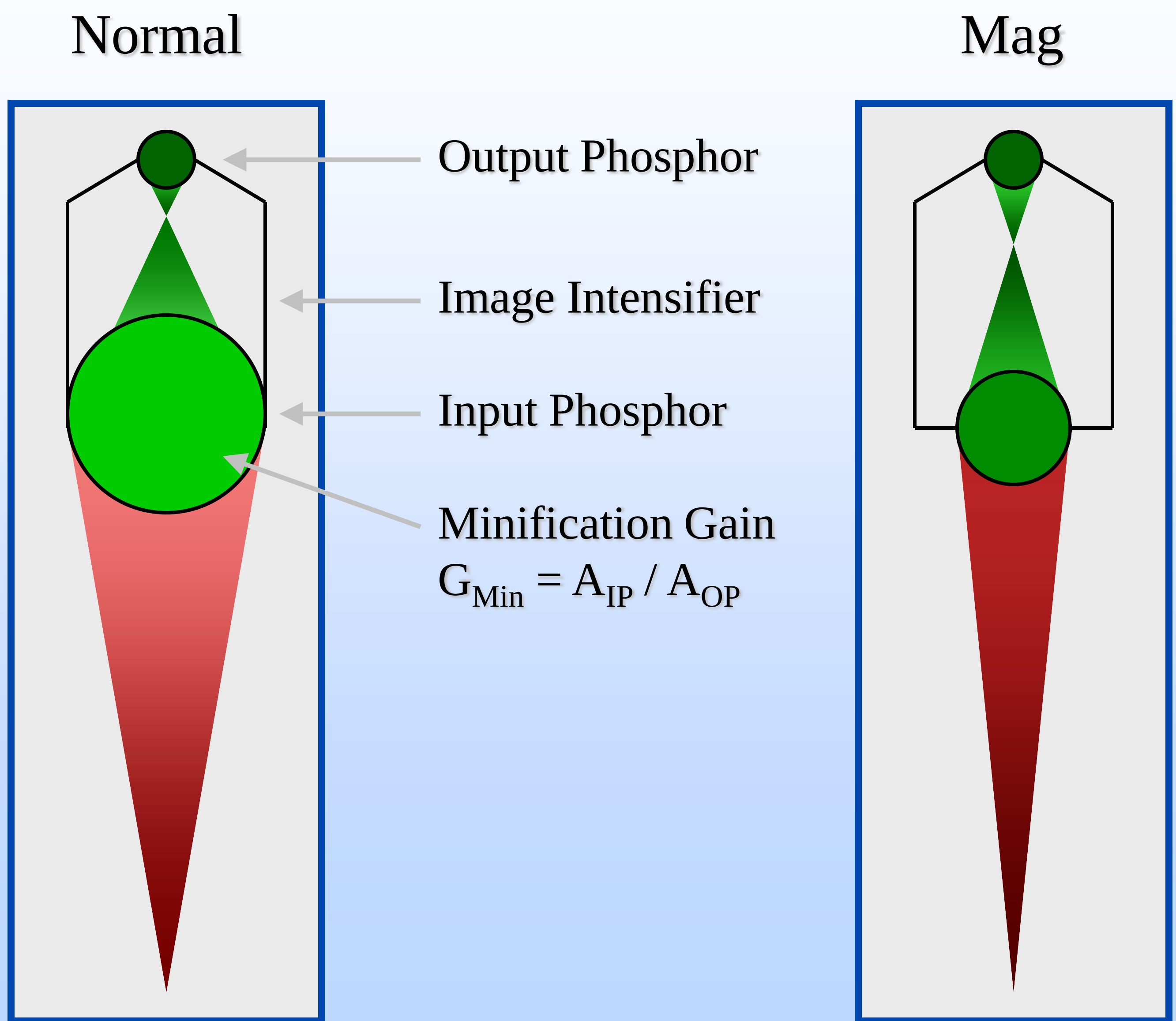
System control

Effect of field size, traditional II



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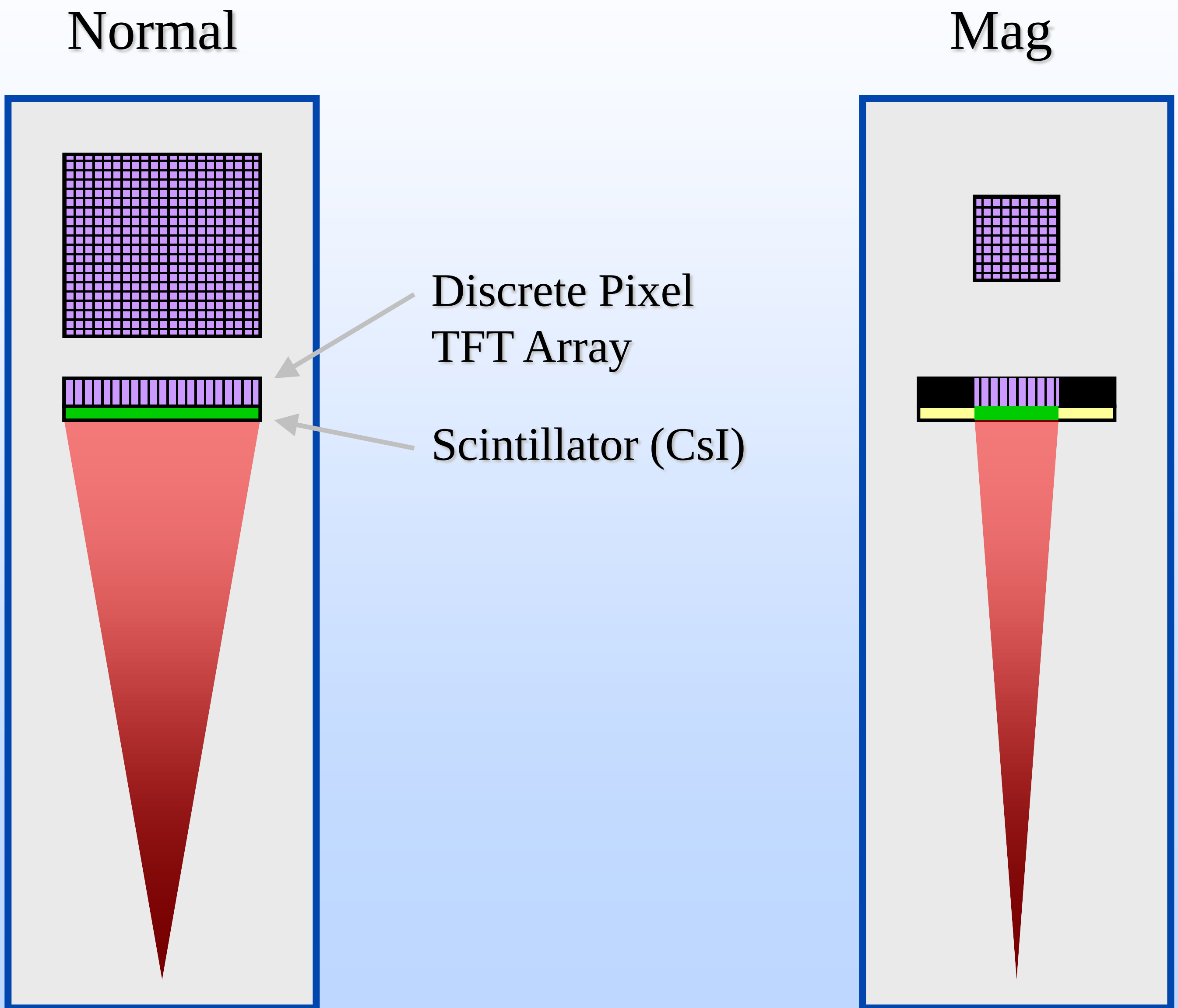
System control
Effect of field size, traditional II

- Traditional image intensifier (II) automatic brightness control (ABC) maintained image brightness
  - Constant light intensity from the output phosphor
  - X-ray tube output was then inversely proportional to input intensifier field area
  - Patient dose was inversely proportional to field area and increased with decreasing FOV (or increasing electronic magnification)

System control

Effect of field size, FP system



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System control
Effect of field size, FP system

- Flat panel (FP) image receptor systems control image brightness via image processing
  - There is not a technical need to change dose rate as a function of field size, or Mag mode
  - For new systems, detector target dose varies as a function of field size
  - Tube output vs FOV relationship is usually inversely proportional to FOV area or to linear FOV size.
  - As FOV decreases, displayed image Mag increases, the density of photons incident on the target anatomy increases, and the image looks better (and patient dose increases)

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3. System performance testing

- Resolution
- Beam quality
- Contrast to noise ratio
- Air kerma rate and patient entrance dose rate

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Resolution

- Influenced by
  - Detector resolution
  - Focal spot penumbral blur
  - Image matrix resize for display
  - Image processing (noise reduction and detail enhancement)

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Resolution

- Include object plane measurements
  - Use clinically relevant range of distances
- Test small (fluoro, acquisition) and large (acquisition) focal spots
- Test relevant FOVs
  - Watch for 2x2 pixel binning for large FOVs

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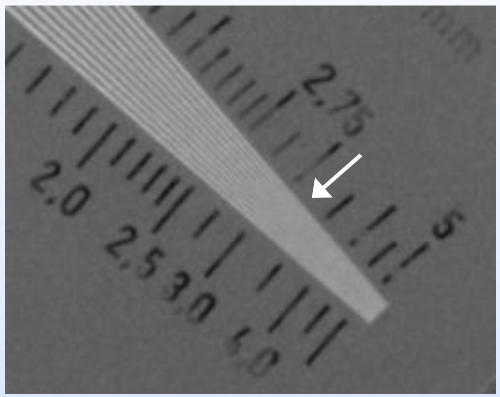
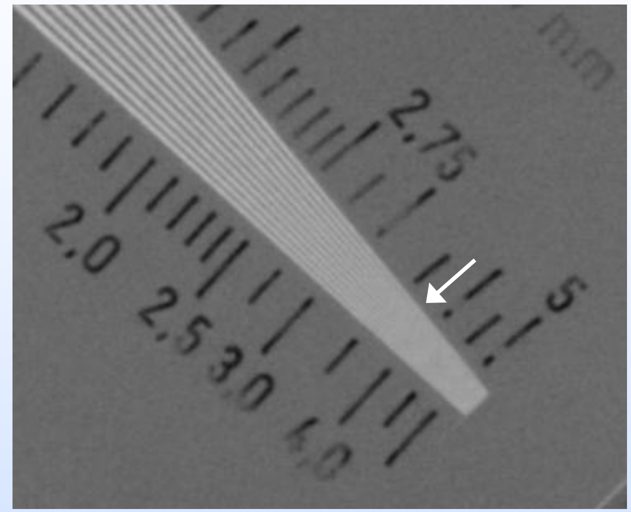
Resolution
Geometric magnification and penumbral blur

Mag = 1

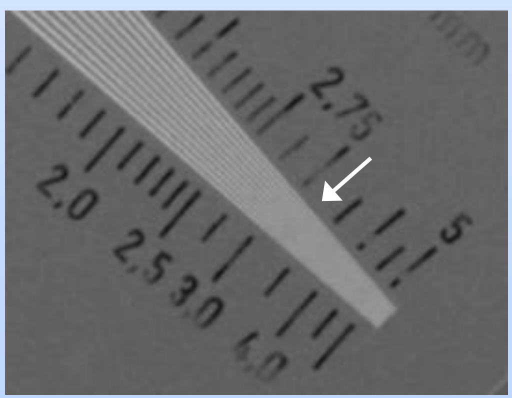
Mag = 1.5

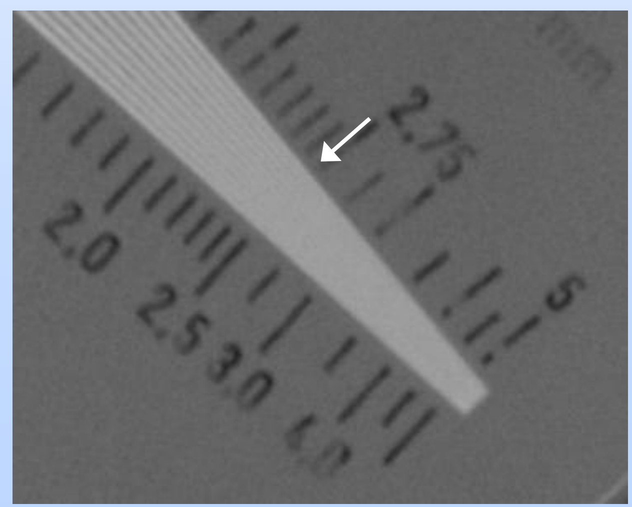
Small focal spot





Large focal spot





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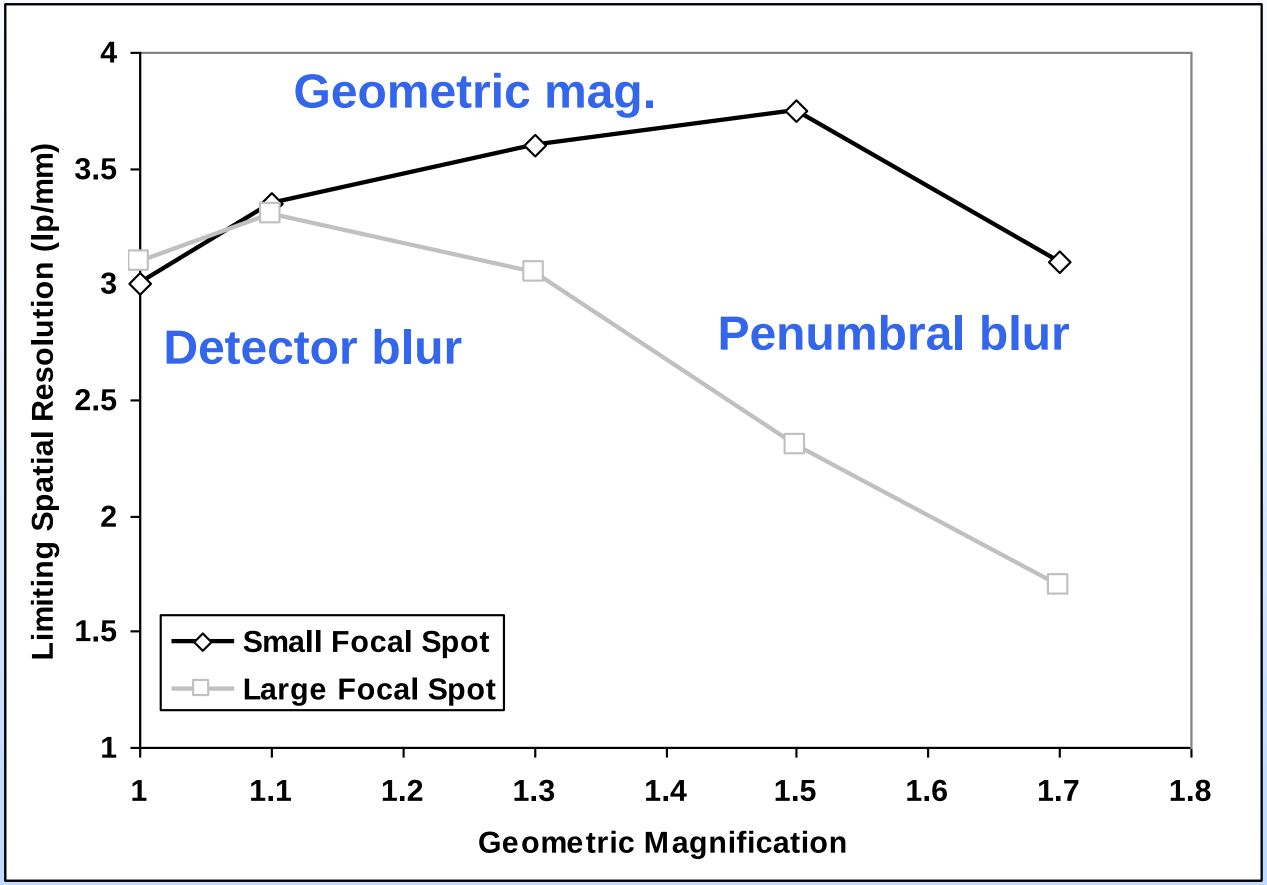
Resolution
Influence of focal spot, geometric magnification, and focal spot penumbral blur



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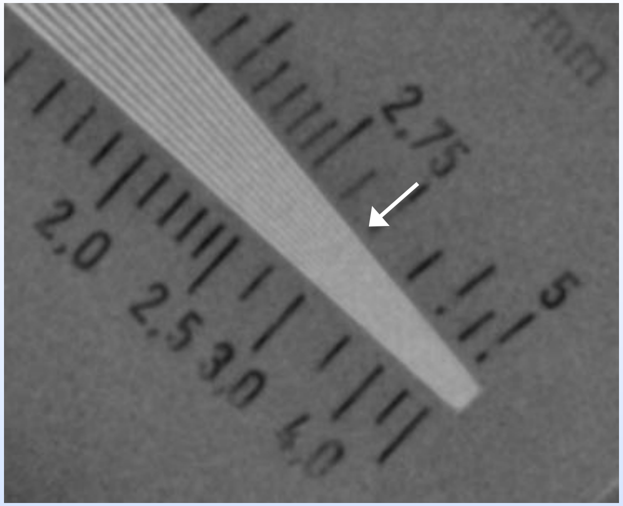
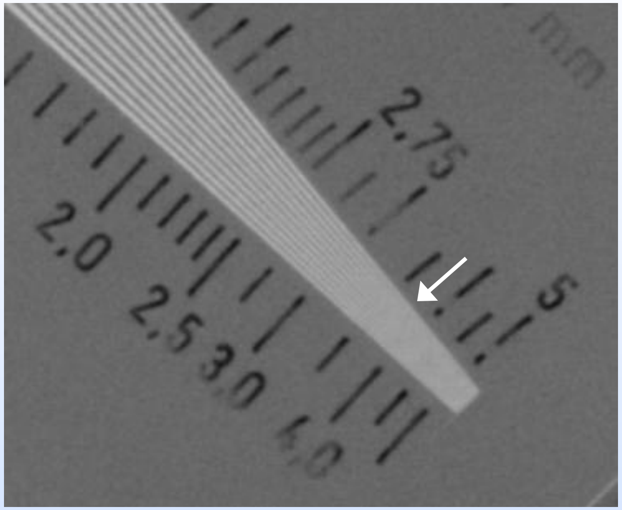
Resolution
Effect of image processing, Mag = 1.5

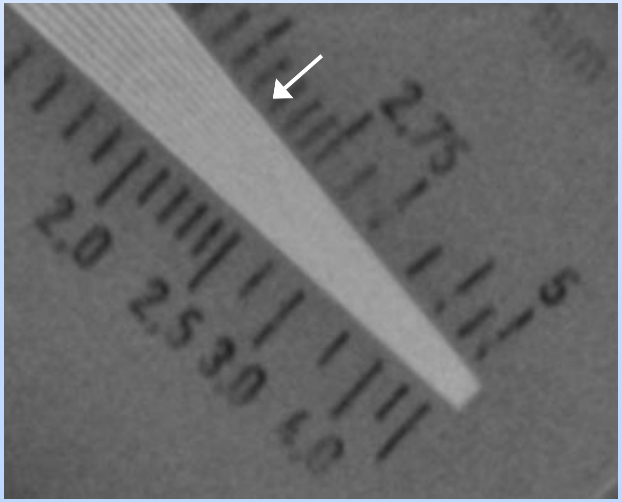
Processed | Unprocessed

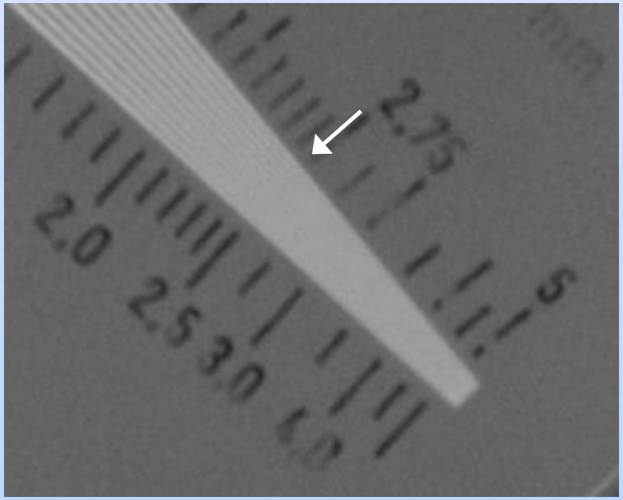
Small focal spot





Large focal spot





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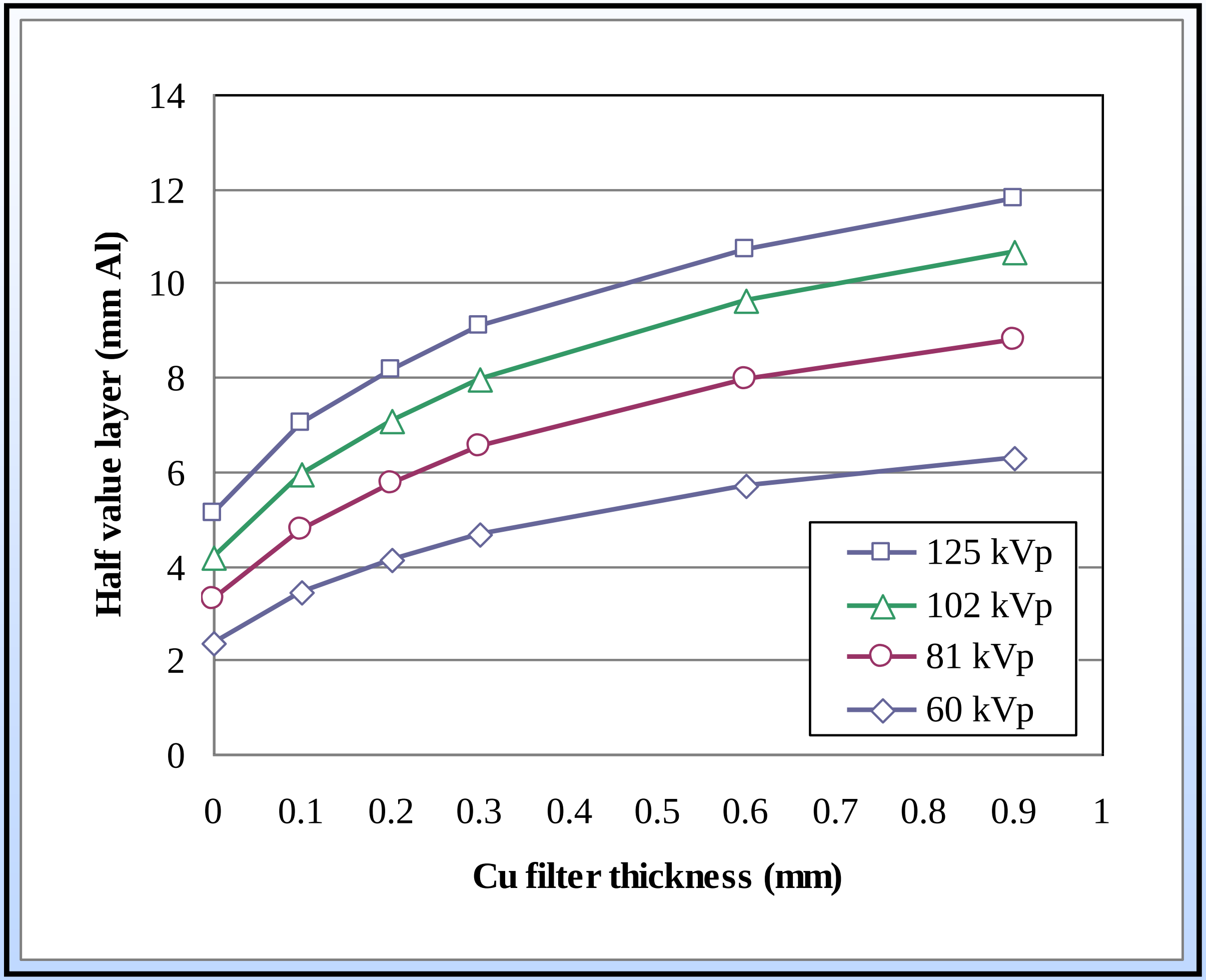
Beam quality

- Combination of kVp and HVL
- Legal minimum HVL values are too low to optimize image quality vs. patient dose
- Cu filters are used to remove low energy photons from the beam
  - Routinely used for fluoroscopy
  - Should also be standard for all acquisition imaging
  - 0.1 mm Cu reduces K by 40% and CNR by 10%

HVL with Cu filtration

0.1 mm Cu increases HVL by 35% to 45%



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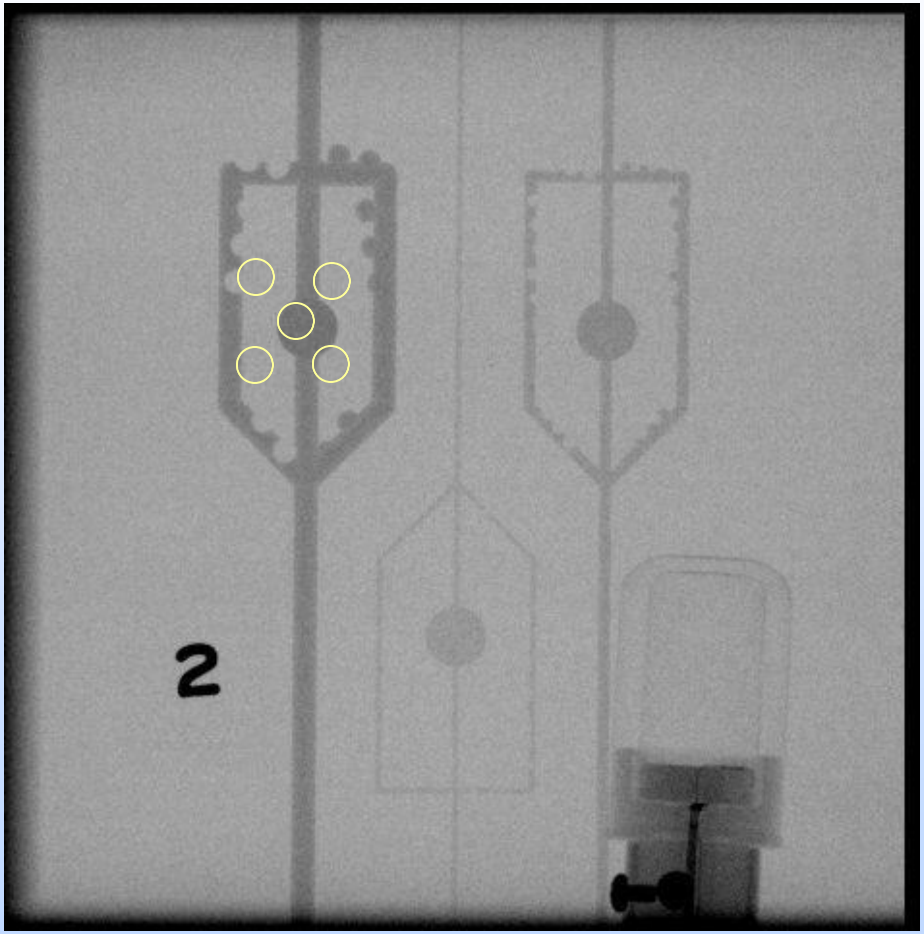
Contrast to noise ratio

- Human observer contrast and CNR phantom assessment is imprecise
- CNR measurements are straightforward
  - Use unprocessed image data
- CNR measurements provide insight into relationship between image quality and patient entrance air kerma rate
  - As a function of patient size
  - For various imaging modes

Contrast to noise ratio
DSA artery phantom, 150 mgI/ml



10 cm phantom
- **62 kVp**
- **0.9 mm Cu**
- **800 ma**
- **6.8 ms**
- **7.3 mGy/min**

CNR = 4.3

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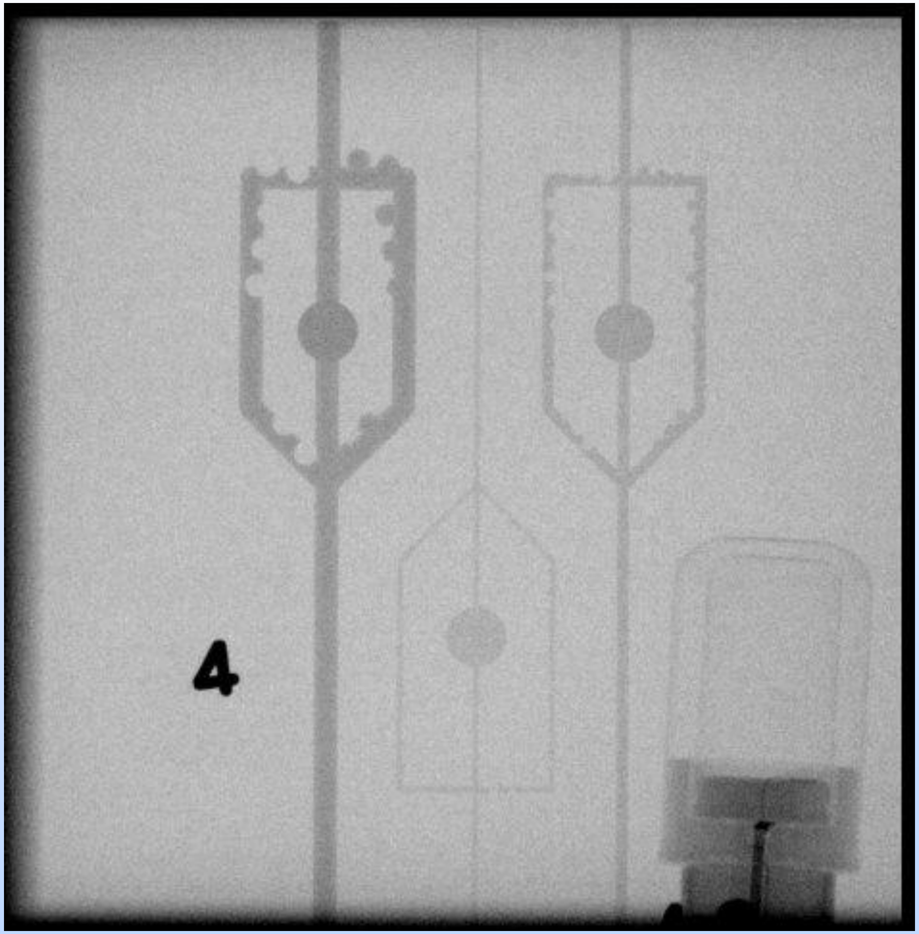
Contrast to noise ratio
DSA artery phantom, 150 mgI/ml



20 cm phantom
- **68 kVp**
- **0.2 mm Cu**
- **800 ma**
- **6.8 ms**
- **112 mGy/min**

CNR = 3.9

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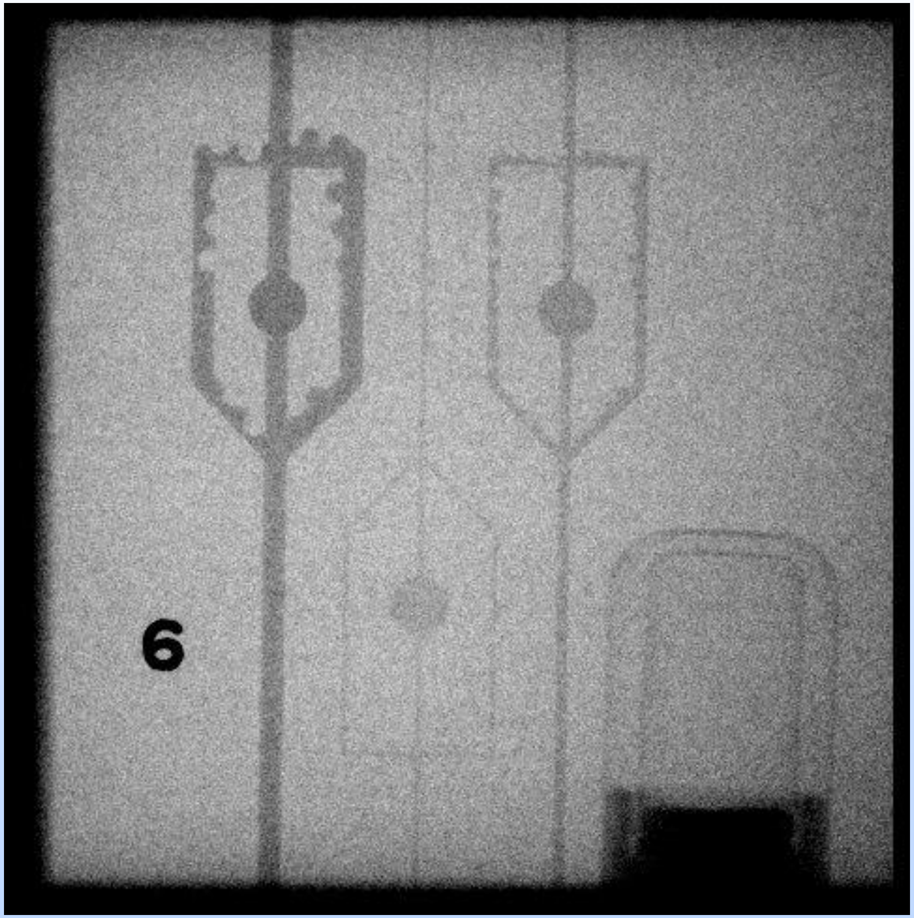
Contrast to noise ratio
DSA artery phantom, 150 mgI/ml



30 cm phantom
- **95 kVp**
- **0.1 mm Cu**
- **800 ma**
- **7.0 ms**
- **570 mGy/min**

CNR = 2

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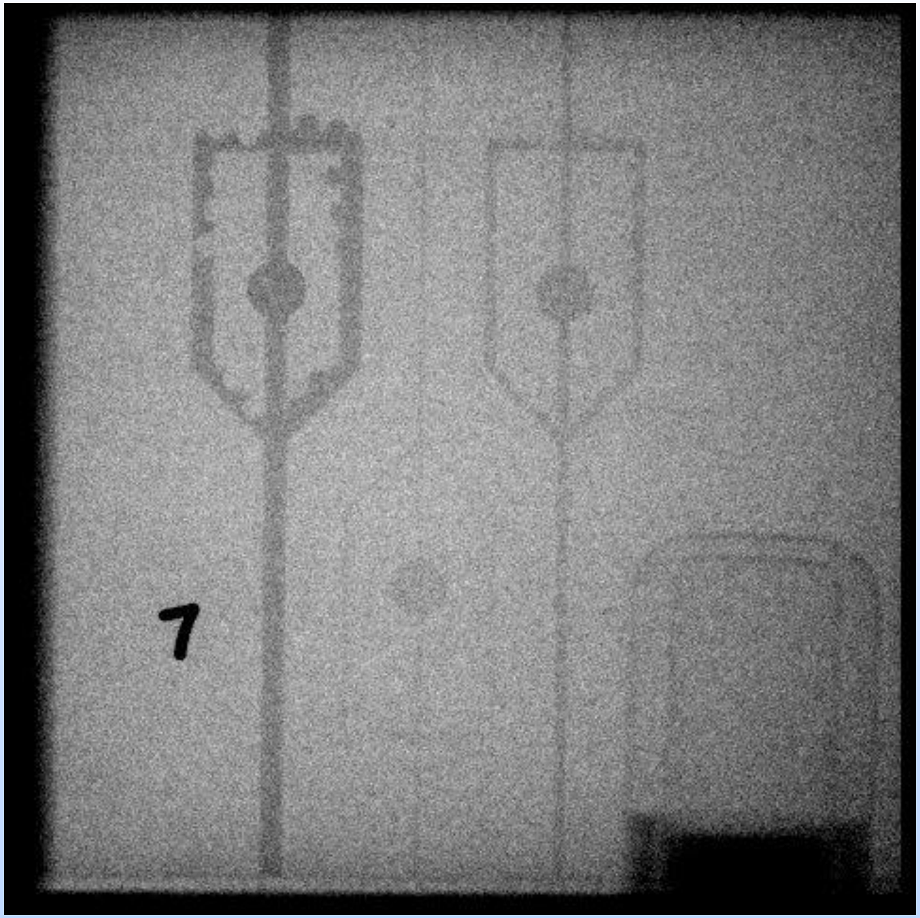
Contrast to noise ratio
DSA artery phantom, 150 mgI/ml



35 cm phantom
- **105 kVp**
- **0.1 mm Cu**
- **700 ma**
- **10.1 ms**
- **1,060 mGy/min**

CNR = 1.5

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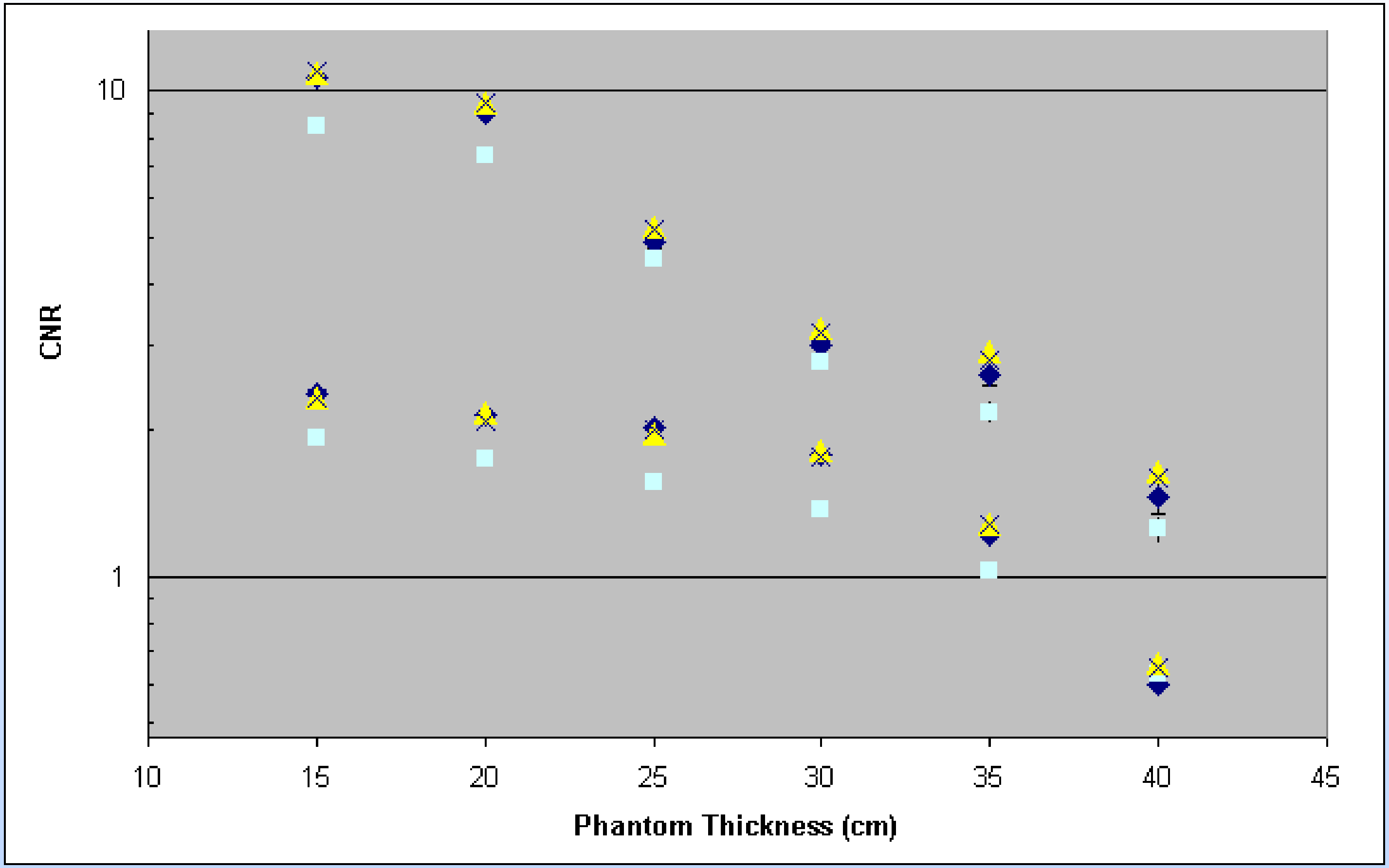
Contrast to noise ratio
Acquisition and fluoroscopy for 4 systems



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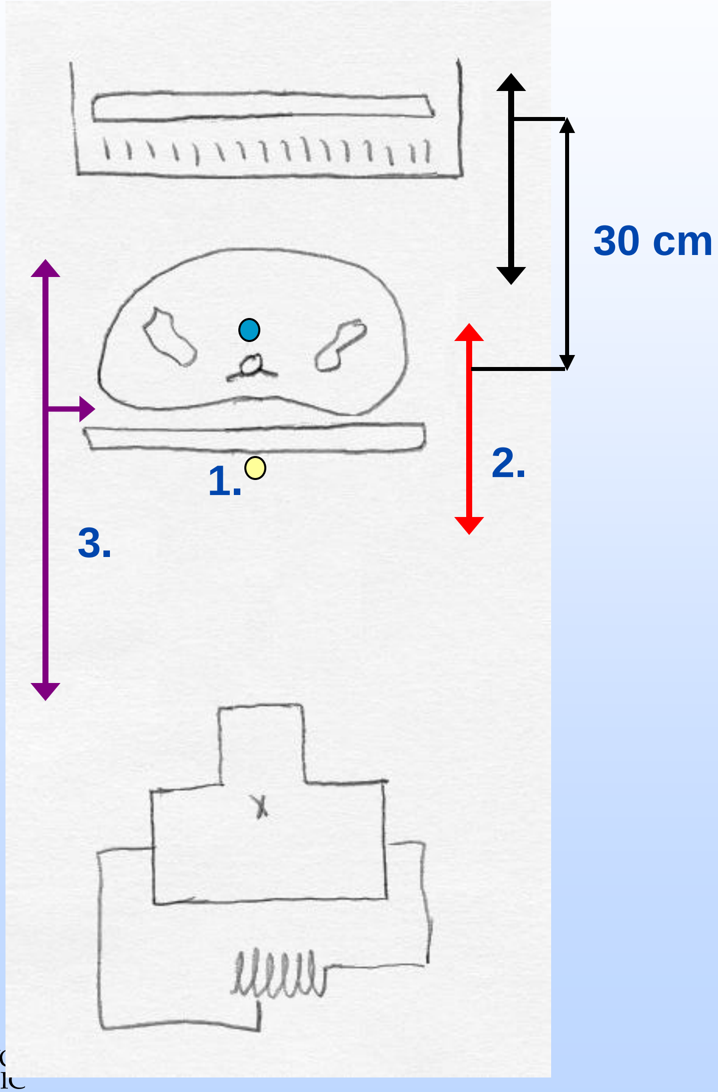
Air kerma monitoring
Important points in space



1. Air kerma reference point
   - fixed point in space at which patient air kerma ($K_{a,r}$) is reported
   - from isocenter, 15 cm toward the x-ray tube
2. FDA air kerma rate limit (range)
   - variable location to compare air kerma rate to the FDA limit
   - from detector, 30 cm toward x-ray tube
3. Patient skin (range)
   - variable location of patient skin surface
   - minimum possible distance determined by the x-ray tube cone

NCRP 2010

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FDA regulation
fluoroscopy air kerma limit

- Legal maximum air kerma rate (K_{FDA}) is 10 R/min (88 mGy/min) for normal fluoroscopy
  - At a distance of 30 cm on the x-ray tube side of the image receptor (↕)

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Patient dose monitoring

- On-board air kerma-area product (P_{KA}) meter (or calibrated algorithm) measures x-ray tube output
- Air kerma at the reference point ($K_{a,r}$) calculated from P_{KA}, x-ray beam size, and distances
  - Reference point defined as 15 cm on the x-ray tube side of the *system isocenter* (○)
  - ± 35% tolerance is allowed
  - ± 35% tolerance allows for reported $K_{a,r}$ and P_{KA} values that differ by 2x for the same tube output
  - Recommendation – use ± 20% tolerance

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Real-world skin dose rate

- Given geometry of clinical procedures, instantaneous $K_{a,r}$ rate as reported by system can exceed K_{FDA}
  - by more than 2x!
- Dependent on patient position within the beam, patient entrance K rate can be even higher!
- Finally, multiply for back-scatter factor 1.4, and then…
- Instantaneous patient skin dose rate can be as high as 280 mGy/min
  - Skin dose of 2 Gy in 7.1 minutes!

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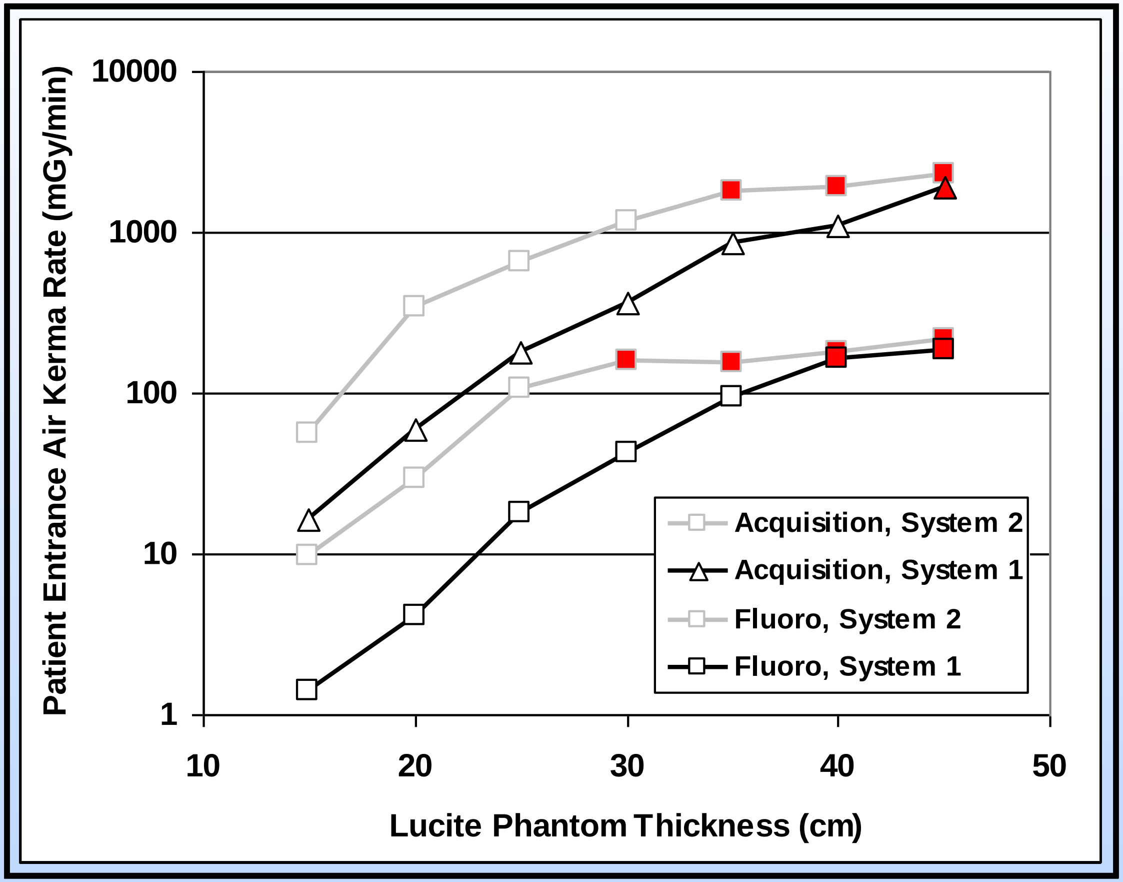
Real-world patient entrance air kerma rate



System 1 managed for low dose rate

System 2 managed for high image quality

Red for maximum air kerma rate

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Air kerma rate

- Should be measured for a clinically relevant range of patient sizes and imaging modes
  - Not just to satisfy the 88 mGy/min legal limit!
- Know how air kerma rate responds to patient size for fluoroscopy
  - Test low, normal, and high rate modes
  - Nominal 2x change between modes should be expected for average-sized patients
  - 44 mGy/min max air kerma rate modes are of limited utility for adult patients

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Air kerma rate

- Understand how air kerma rate responds to patient size for acquisition imaging modes (cine, DSA)
  - There is not a legal maximum acquisition mode air kerma rate
  - Actual maximum acquisition air kerma rate often exceeds 2,000 mGy min^{-1}.
  - Given geometry and BSF, instantaneous skin dose rate can exceed 3,000 mGy min^{-1}.
    - 2 Gy in 40 seconds.

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Patient radiation air kerma rate

- Even with properly functioning interventional fluoroscopy systems, patient radiation air kerma rates can be very high
- High air kerma is associated with
  - Detector target dose
  - Frame rate
  - Lack of beam filtration
  - Large patients
  - Steep projection angles
  - Long x-ray tube to detector distance
  - Short x-ray tube to patient skin distance

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4. Strategies for patient dose reduction

- Patient air kerma monitoring
- Spectral filtration
- Detector target air kerma
- Frame rate
- Low, normal, and high air kerma rate fluoroscopy
- Patient size and projection angle
- Custom settings for pediatric patients

Patient air kerma monitoring

- Record procedure cumulative air kerma ($K_{a,r}$) for each patient procedure
- Review $K_{a,r}$ monthly
    - Look for temporal trends
    - Investigate outliers, especially high
    - Differences in procedure room, physician, etc.
    - Quantify effect of changes
- There are many opportunities for quality improvement related to patient dose

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Spectral filtration

- Quite possibly the simplest way to reduce patient skin dose
- 0.1 mm Cu
  - reduces patient dose by 40%
  - decreases CNR by 10%
  - Use Cu for all imaging modes, not just fluoro

Detector target air kerma

- Patient K rate ~ target K
- By default, systems are configured to provide excellent image quality
- Reduce target K to reduce patient dose
- Reduce in 10% - 20% increments to minimize immediate clinical impact
- Set default fluoro to very low level
- Provide a fall-back plan to the physicians to return to the ‘old’ settings during the procedure

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Frame rate

- 30 fps
  - High patient K and/or low K per frame
  - Not necessary and should be avoided entirely for adult patients
  - Useful for small pediatric patients with very rapid heart motion
- 15 fps
  - Current standard for adult cath acquisition imaging
  - Standard for fluoroscopy at most sites

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Frame rate

- 7.5 fps
  - Adequate for most adult fluoroscopy
  - Expect nominal ½ dose reduction compared to 15 fps
  - For large patients, allows higher K per frame within max K rate range
  - Watch for systems for which K rate is not proportional to frame rate!

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Low, normal, and high dose rate fluoroscopy

- Low fluoro
  - Set lowest clinically useful fluoro dose rate as the system default
  - Frame rate 7.5 fps
  - Detector target dose as low as possible
  - Strive for low dose with adequate image quality rather than excellent image quality with high dose rate
  - Set maximum rate to 88 mGy/min to maintain utility for large patients
    - Maximum rate 44 mGy/min is of limited utility because IQ is inadequate for large patients

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Low, normal, and high dose rate fluoroscopy

- Normal fluoro
  - 7.5 fps to 15 fps and/or detector increased K
  - Should have improved image quality compared to low fluoro
  - Set maximum rate to 88 mGy/min to maintain utility for large patients
  - Use when low fluoro does not provide adequate image quality
  - Never use 30 fps fluoroscopy for adult cath procedures

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Low, normal, and high dose rate fluoroscopy

- High fluoro
  - 7.5 fps to 15 fps and/or increased detector K
  - Never use 30 fps
  - Should have improved image quality compared to normal fluoro
  - Set maximum rate to 174 mGy/min to provide maximum fluoro image quality (audible alert required)
  - Use very sparingly and only when excellent fluoro image quality is necessary
  - Manage systems to avoid using acquisition imaging to overcome lack of fluoro image quality

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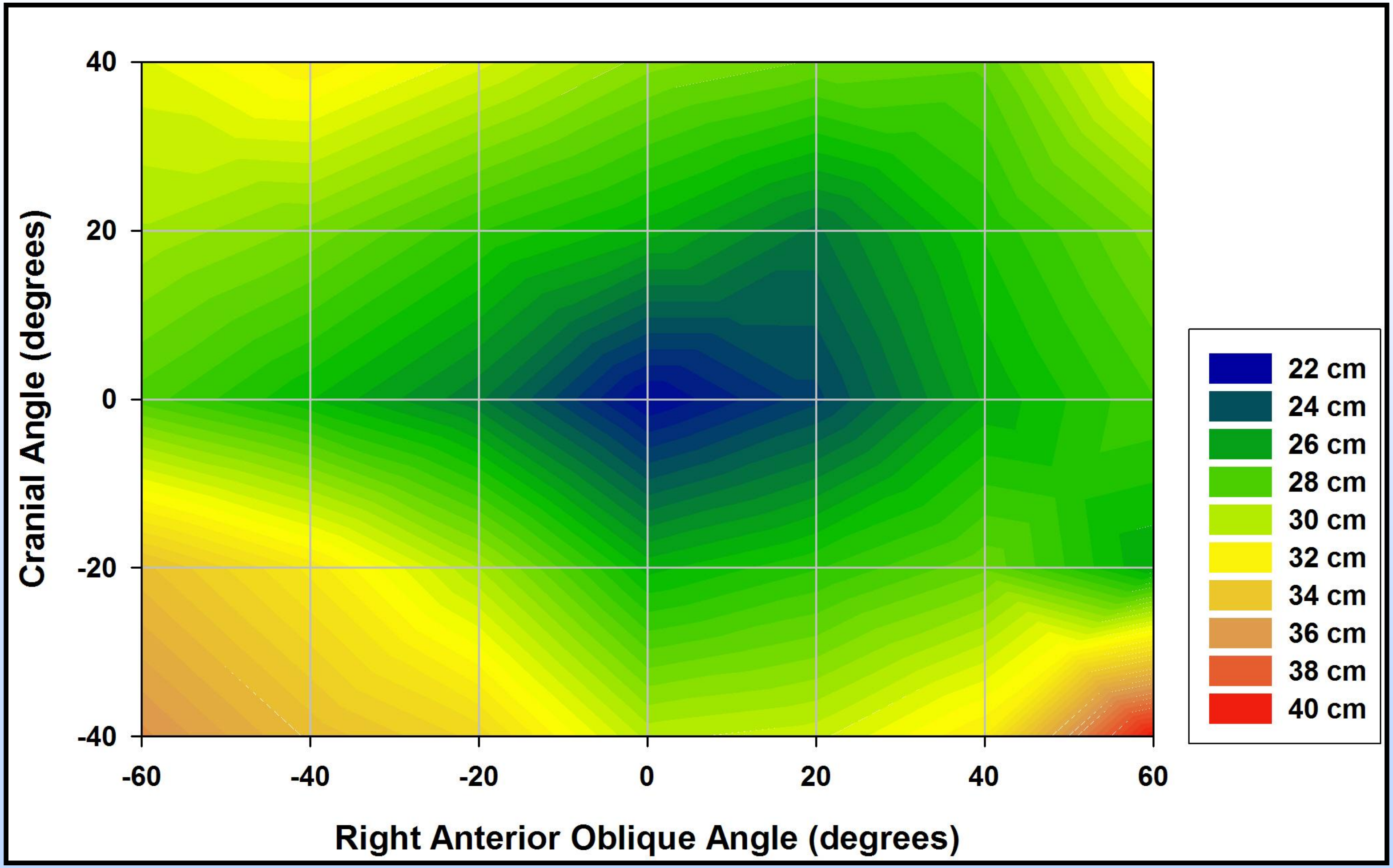
Patient thickness and projection angle
Cardiac cath lab patients



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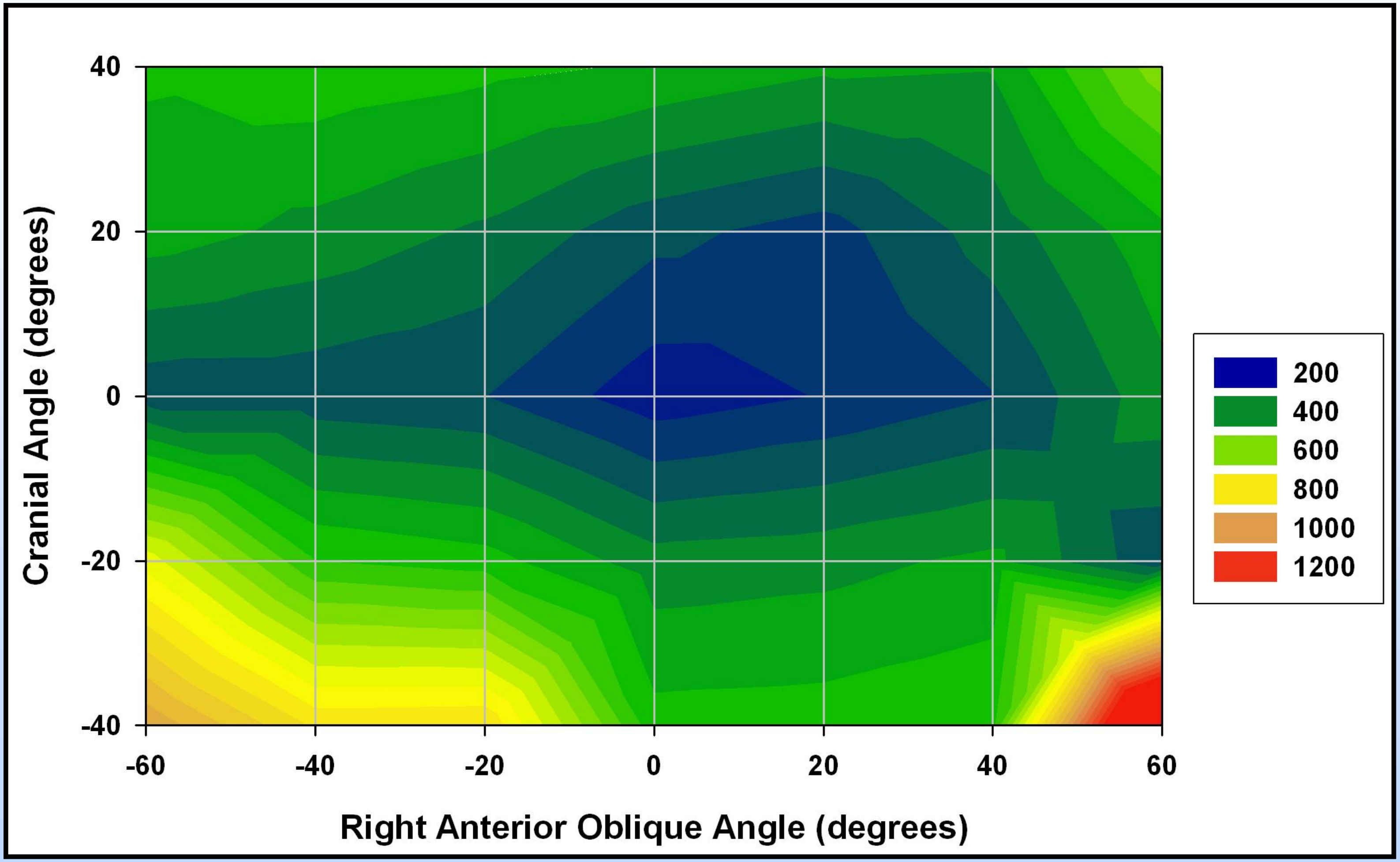
Skin air kerma rate and projection angle
Patient average (mGy/min)



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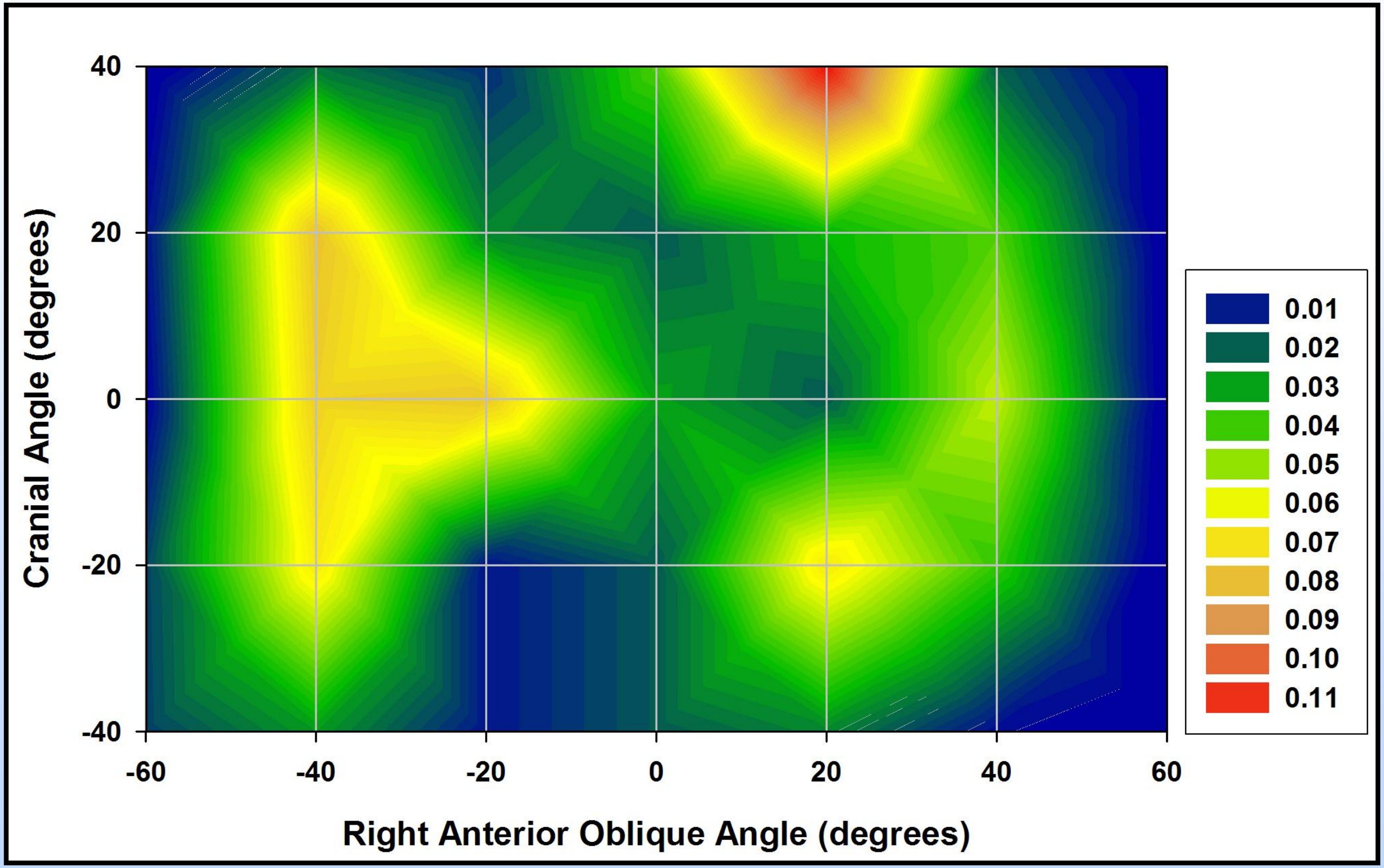
Relative frequency of projection angles
Coronary artery procedures



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Custom settings for pediatric patients

- Children are more radiosensitive than adults
- Primarily structural heart disease
- Rapid heart rate and high velocity motion
- Lower scatter to primary ratio
- Cannot simply use adult programs and expect that AERC will provide optimum results
- Custom pediatric programs are required

Gislason et. al, Med. Phys. 37(10) 2010

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Children 20 kg to 60 kg

- Detector target dose 20% lower than adult
- 7.5 fps low dose rate fluoro
  - Option for higher frame rate
- 15 fps acquisition
- Grid use optional
  - Removing the grid will reduce dose rate by ~35%
  - Reduction in image quality likely noticeable

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Children <20 kg

- Detector target dose at least 20% lower than 20 kg to 60 kg
- 7.5 fps low dose rate fluoro
  - Option for higher frame rate
- 30 fps acquisition
  - To capture very fast motion
- Grid removal required
  - Removing the grid will reduce dose rate by ~35%
  - Image quality reduction is negligible

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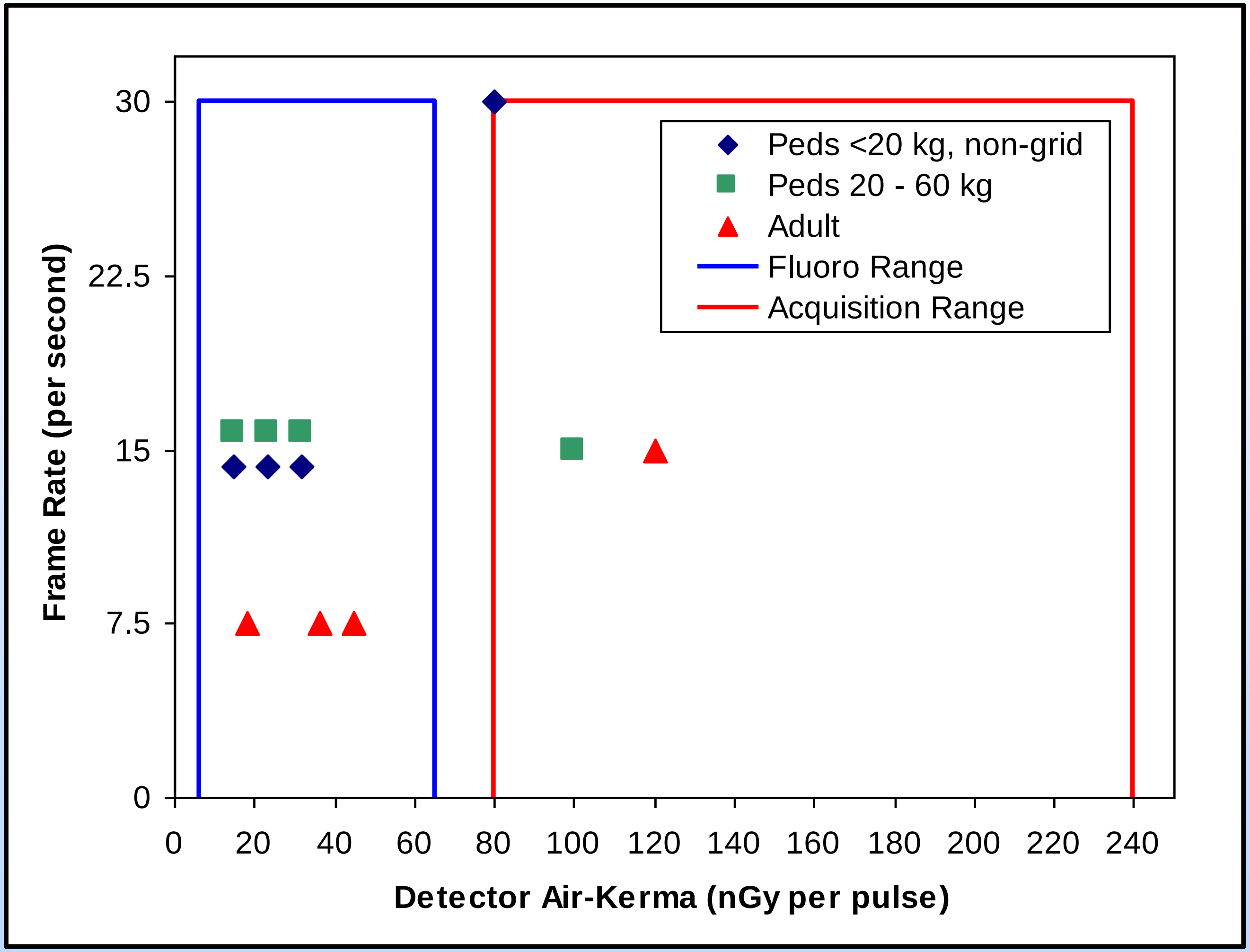
Detector target air kerma and frame rate



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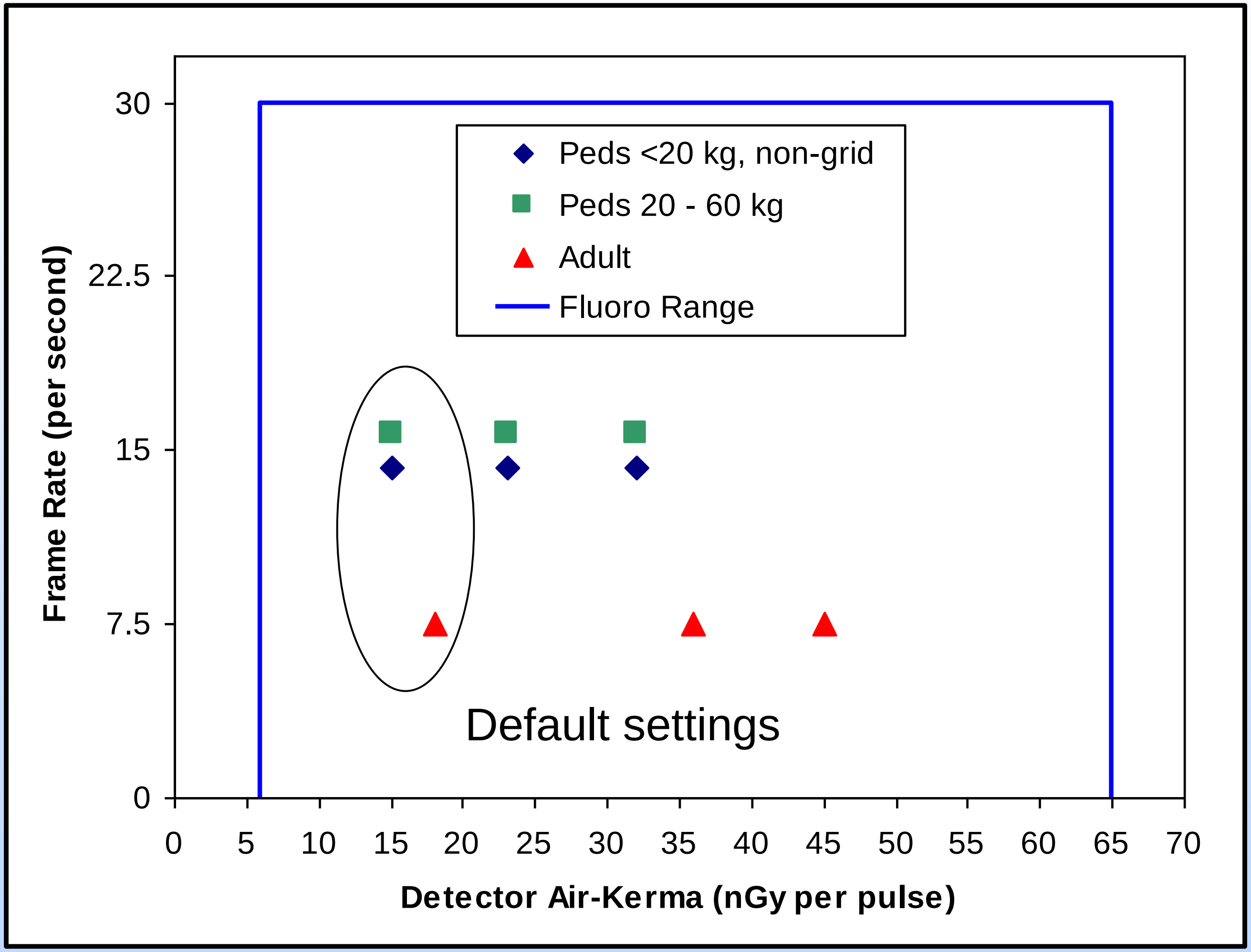
Detector target air kerma and frame rate



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Patient population dose reduction

- There is opportunity for radiation dose reduction in all invasive cardiac labs
- Getting started
  - Requires active participation from physicians, technologists, vendor representatives, RSO, and medical physicist
  - Learn, teach, and implement best practices
  - Review patient dose metrics ($K_{a,r}$, P_{KA}) monthly
  - Measure air kerma rate vs patient thickness
  - Make incremental changes over time

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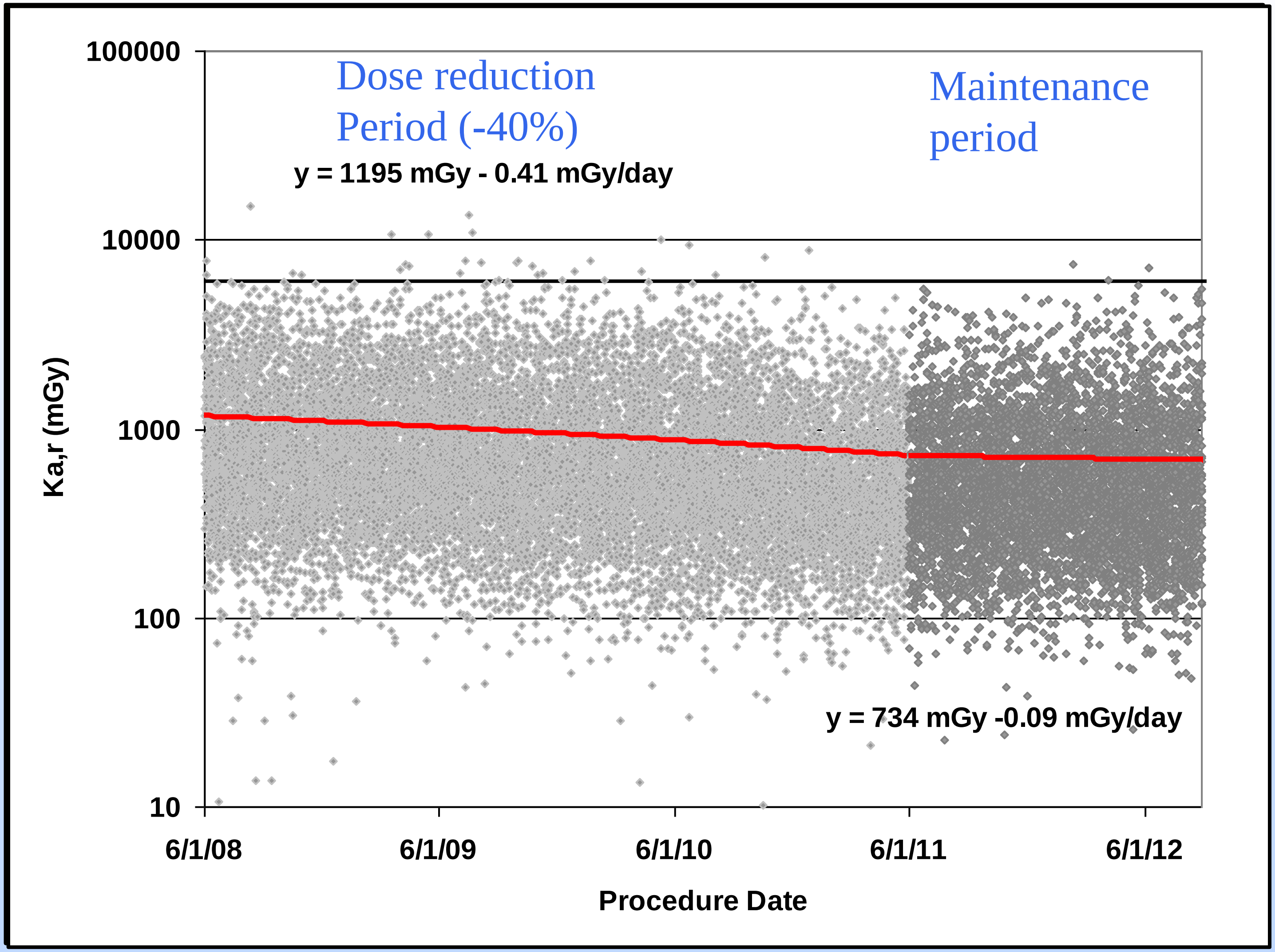
Adult cardiac cath patient dose reduction

Change in $K_{a,r}$ over time



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Patient population dose reduction

- Distribution of P_{KA} and $K_{a,r}$ is nearly Log-normal
  - Use Log(P_{KA}, $K_{a,r}$) for statistical analysis
- Variability of $K_{a,r}$ is huge
  - 95th percentile is 15x greater than 5th percentile
  - Two-tailed t-test requires 2,200 observations per group required to detect a 10% change ($p<0.05$, power 80%)
  - Data stratification by procedure type or patient size may help to isolate high-radiation procedures
  - Longitudinal analysis is necessary
- Fluoro time is a poor surrogate for P_{KA} or $K_{a,r}$

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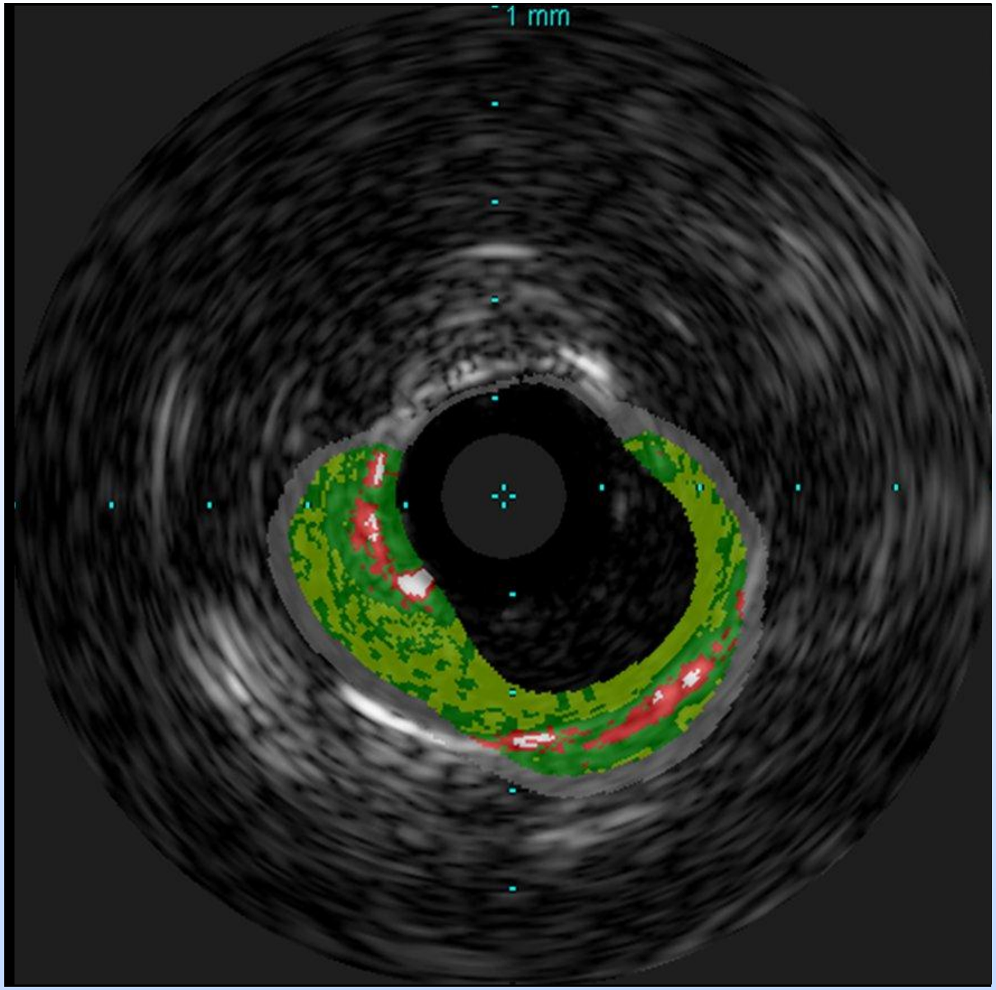
5. New and emerging technologies

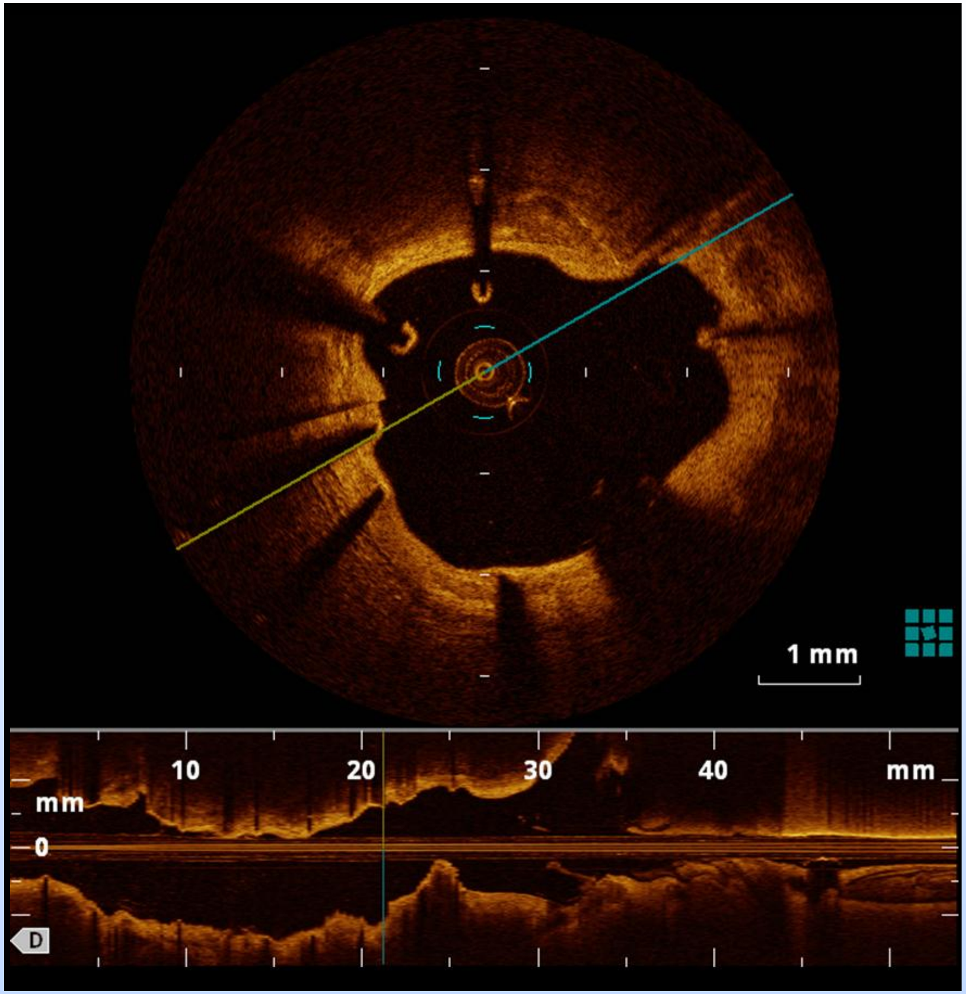
- Intra-vascular ultrasound (IVUS)
- Optical coherence tomography (OCT)
- Cone-beam CT
- 3D Ultrasound
  - Trans-esophageal echocardiography, intra-cardiac ultrasound
- RF mapping and navigation

Intra-vascular ultrasound



With virtual pathology

Optical coherence tomography



Very high resolution, very low tissue penetration

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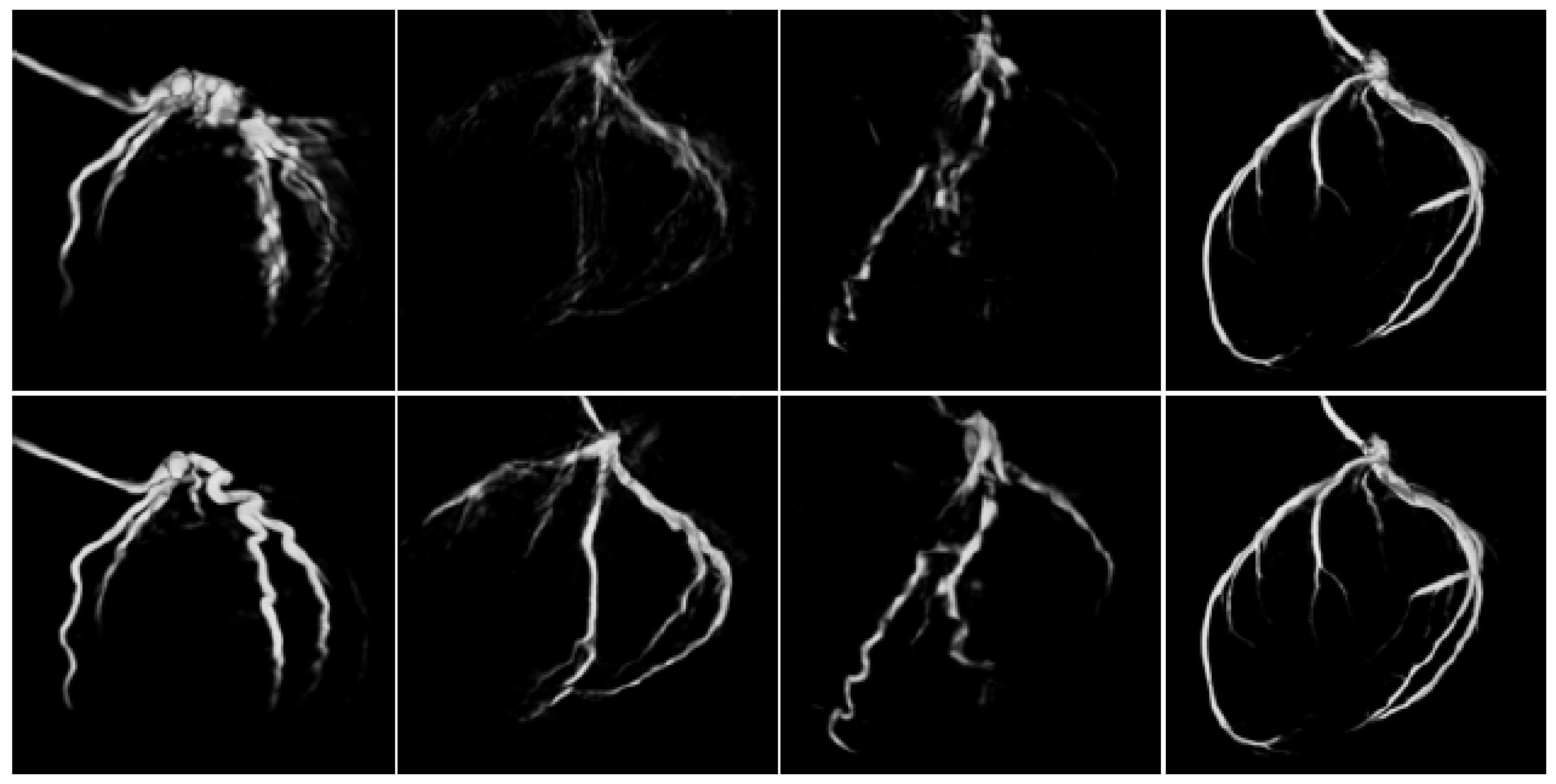
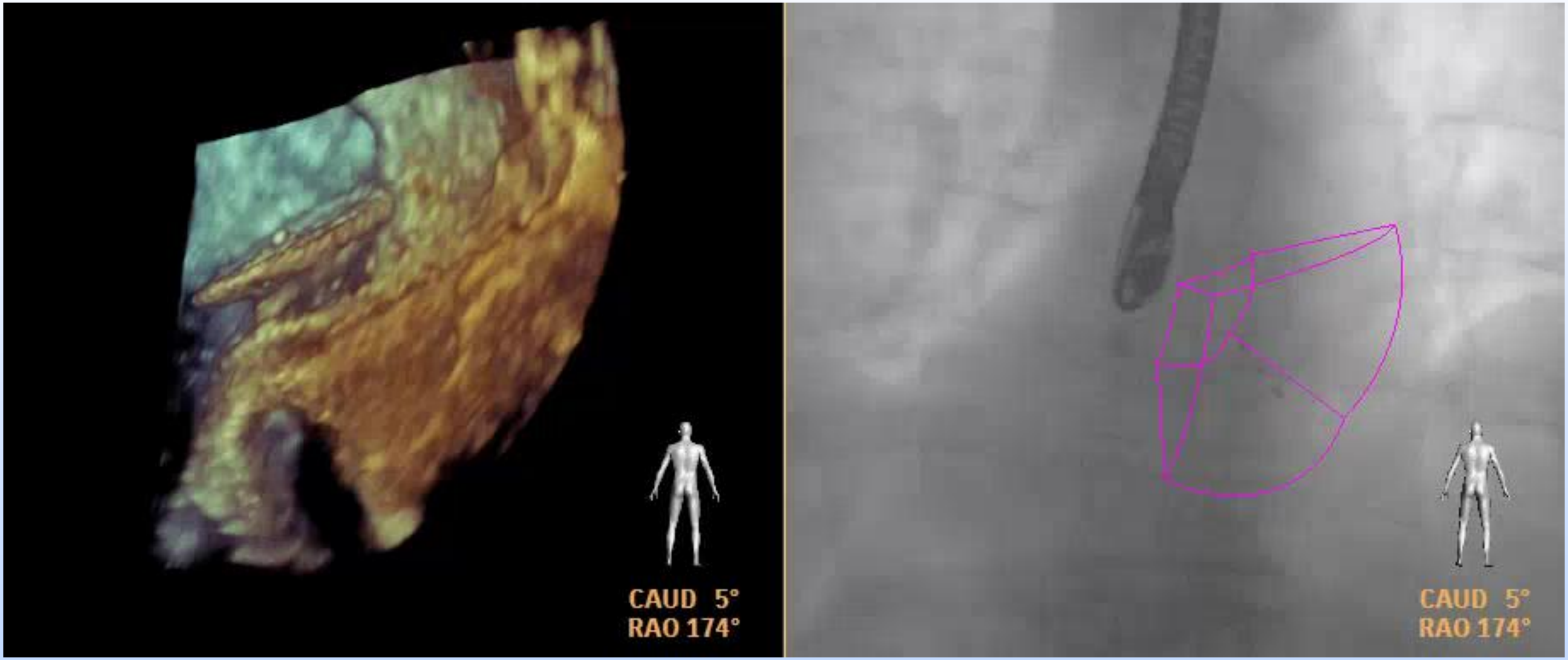
Cone-beam CT



On-going advances in motion compensation for cone-beam CT

Rohkohl 2010

4D ultrasound



For treating valve and structural heart disease

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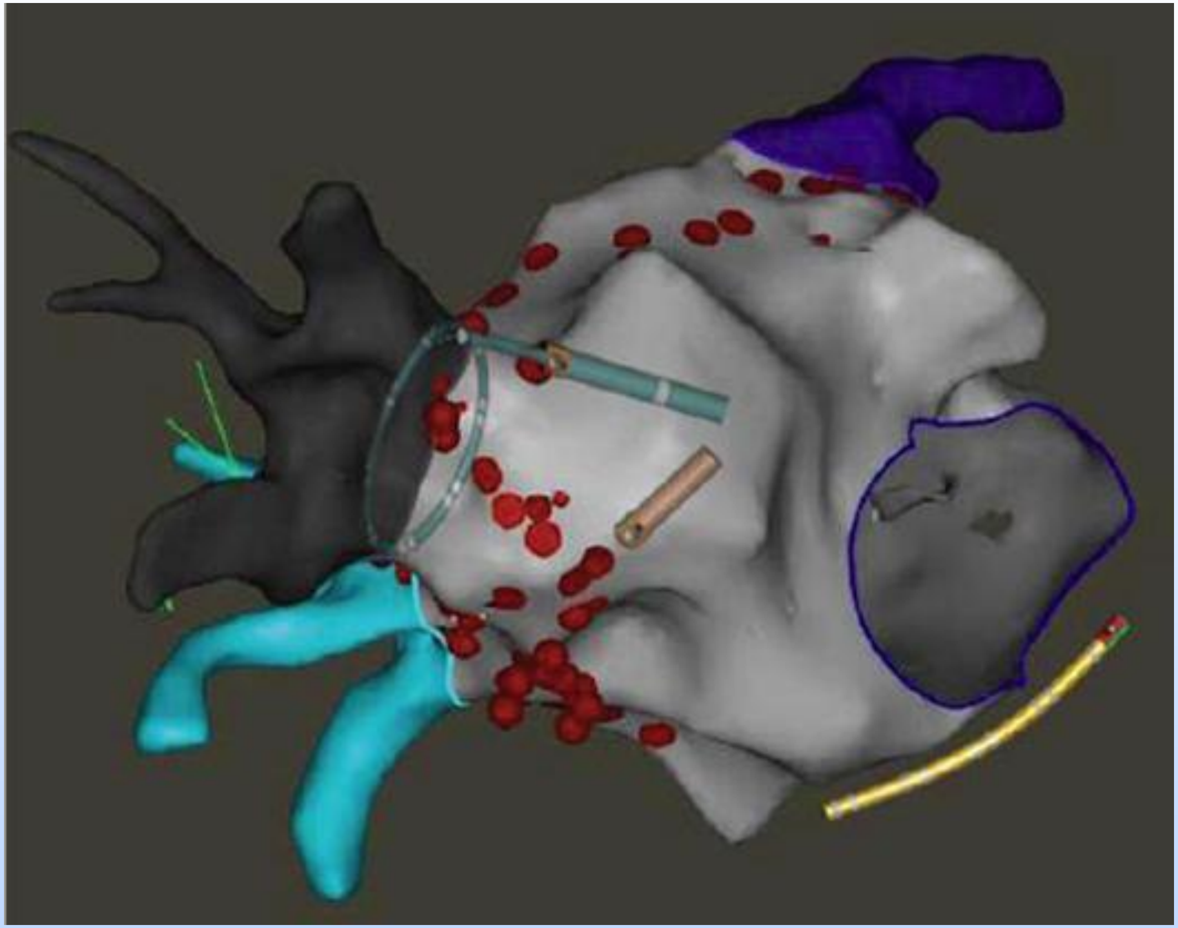
RF mapping and navigation



For treatment planning and recording during EP ablation procedures

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NCRP 168 Acronyms and Symbols

- $K_{a,e}$ – entrance surface air kerma
- $K_{a,i}$ – incident air kerma
- $K_{a,r}$ – air kerma at the reference point
- K_{FDA} – U.S. FDA compliance air kerma rate limit
- P_{KA} – air kerma-area product
- SID – x-ray source-to-image-receptor distance
- SSD – x-ray source-to-skin distance
- RDSR – DICOM Radiation Dose Structure Report

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