Patient Dose and the Modern Angiographic System
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AAPM Annual Meeting
July 2010

Educational Objectives
- Review fluoroscopic dose quantities
- Understand the operation of kerma-area product meters
- Learn how to verify the accuracy of integrated dosimetry systems in fluoroscopy equipment
- Understand how to measure phantom entrance air kerma rates
- Review factors that affect fluoroscopy dose rates and image quality

Motivation
- Display and recording of patient dose for fluoroscopically-guided interventional (FGI) procedures allows for:
  - Avoidance of skin injury
  - Determination of whether skin injury may occur
  - Compliance with regulations in many states
- Measurement of dose to standardized phantoms allows for:
  - Determination of integrated dosimetry accuracy
  - Optimization of dose rate settings for clinical use

Initiative to Reduce Unnecessary Radiation Exposure from Medical Imaging
The Food and Drug Administration recently released an Initiative to Reduce Unnecessary Radiation Exposure from Medical Imaging. This new initiative is designed to reduce unnecessary radiation exposure from medical imaging procedures, which can save patients money, improve overall health care quality, and reduce the long-term risk of cancer. In support of this goal, FDA will work with the medical community and other stakeholders to ensure that patients receive the radiation dose that is appropriate for their needs. FDA will also work with medical imaging equipment manufacturers to improve the design and performance of imaging equipment.
Fluoroscopic Dose Quantities

- **Air Kerma**
  - Kerma accumulated in air at a specific point
  - $K_a,i$ – incident air kerma
  - Units: gray (Gy)
  - Without backscatter

- **Air Kerma**
  - $K_{a,r}$ – total air kerma at the reference point
  - Value is the total accumulated during a procedure
  - Reference point is approximate location of patient’s entrance surface
  - Defined relative to the fluoroscopy gantry by IEC (2000 and 2008) and FDA (2009)

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C-arm Reference Point Location

- 15 cm from isocenter toward x-ray tube
- Note that a manufacturer may specify a different reference point location

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Other System Reference Point Locations

- **Undertable x-ray tube:**
  - 1 cm above the tabletop
- **Overtable x-ray tube:**
  - 30 cm above tabletop
  - X-ray tube in lowest position possible
- **Lateral type:**
  - 15 cm from table centerline toward x-ray tube
  - X-ray tube in closest position

Air Kerma-Area Product

- $P_{KA}$ - Air kerma $\times$ x-ray beam area
  - Units: Gy-cm$^2$
  - Value is the total accumulated during a procedure
  - Without backscatter
  - Beam area is determined in a plane perpendicular to the central beam axis
  - Variations in air kerma over the beam area are averaged

Air Kerma-Area Product

- $P_{KA}$ is the same value at any distance from the x-ray source
  - $K_1/K_2 = (d_2/d_1)^2$
  - $A_1/A_2 = (d_2/d_1)^2$

Peak Skin Dose

- $D_{skin,max}$ - Dose to the most highly-irradiated local area of skin, includes backscatter
- Corrections needed to estimate $D_{skin,max}$ from $K_{x,y}$:
  - Backscatter
  - Actual source-skin entrance distance
  - Table and pad attenuation
  - Mass attenuation coefficient ratio air: tissue
  - Account for movement of the x-ray beam
  - Addl. discussion in Tues, Thurs R/F CE sessions

Regulations: FDA

- For fluoroscopes manufactured after June 2006:
  - Display of $K_{x,y}$ (mGy) and $K_{x,y}$ rate (mGy/min) at the operator’s working position
  - Note $P_{KA}$ is not required
Regulations: IEC

- Display of $K_{\alpha x}$ (mGy) and $K_{\alpha x}$ rate (mGy/min) at the operator's working position
- Display of $P_{WA}$
  - need not be at the operator's working position

Example Integrated Dosimetry Displays

Display of $K_{\alpha x}$ (mGy) and $K_{\alpha x}$ rate (mGy/min) at the operator's working position

DICOM Dose Structured Report

- Includes fields for dosimetry system information

Kerma-Area Product Units

- Be aware that the units for $P_{WA}$ from integrated dosimetry systems vary with manufacturer and software revision:
  - mGy-cm²
  - $\mu$Gy-cm²
  - cGy-cm²
  - dGy-cm²
  - Gy-cm²
  - mGy-m²

- IEC 60601-2-43 2nd edition specifies Gy-cm²
Integrated Dosimetry Methods

Various methods for determining $K_{a,i}$ and $P_{\text{KA}}$ are in use:

1. $P_{\text{KA}}$ meter with calculation of $K_{a,i}$ from area determined by known collimator positions
2. $P_{\text{KA}}$-$K_{a,i}$ dual chamber meter
3. Calculation of $K_{a,i}$ from kVp, mA(s) and pre-determined air kerma output values, with calculation of $P_{\text{KA}}$ from known collimator positions

$P_{\text{KA}}$ Meter

- Transmission, parallel plate ionization chamber
- Not visible in the image
- Transparent to allow for light field use

$P_{\text{KA}}$-$K_{a,i}$ Dual Chamber Meter

- $P_{\text{KA}}$ meter with a small air kerma measurement area in center
- Mounted in the same manner
- Air kerma value at the reference point is determined by inverse square distance correction
- Tracking of collimator positions not needed
- Measures $K_{a,i}$ at the center of the beam
- Instead of beam average when exposure is not uniform
Use of Wedge Filters

- Wedge filters (equalization filters) are located in front of the $P_{kA}$ meter.
- Locations are typically not tracked like the collimator locations used to define the irradiated field size.
- For integrated dosimetry using a $P_{kA}$ meter, when wedge filters are used:
  - $P_{kA}$ value is averaged over beam area.
  - $K_{air}$ will be underestimated.

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Integrated Dosimetry System Validation

- Laboratory conditions used to calibrate $P_{kA}$ meters will vary from clinical conditions.
  - Value is affected by scattered and extra-focal radiation, which vary with x-ray tube, $P_{kA}$ meter position and x-ray energy.
  - Accuracy of integrated dosimetry systems should be verified under clinical conditions.
- Initially and after service affecting dose monitoring (e.g., $P_{kA}$ meter or x-ray tube replacement).
Integrated Dosimetry System Validation

- Method described here was adopted from the RAD-IR Study *
- RAD-IR study
  - Patient dose data was recorded for over 2,000 interventional radiology procedures over 3 years at 7 facilities with 16 imaging planes
  - Protocol developed to validate consistency and accuracy of $P_{eq}$ and $K_{eq}$ readout

* Balter et al, JVIR 2004; 15:909

Materials

- PMMA attenuator blocks
  - At least 25 x 25 cm to fully cover the beam field of view at the image receptor
  - Sheets to make up 10, 20 and 30 cm thicknesses
- Field size measuring plate
- Ionization chamber dosimeter and holder
- Tape measure

Dosimeter Selection

- Ionization chamber is recommended
  - Provides a flat energy response over a wide x-ray energy range
  - For solid state detectors with energy compensation, there are no NIST specified calibration beams that match the typical Cu-filtered interventional fluoroscopy beam

Methods

- Determine the source-to-isocenter distance for the C-arm to be tested
  - From manufacturer’s specifications or:
  - Manually by positioning an object so that it is centered in both vertical and horizontal projections of the C-arm
- Note that isocenter locations vary, e.g.
  - Siemens Artis and Philips Allura : 75 cm
  - Multistar: 80 cm, Siemens Artis Zee: 78.5 cm
Methods

- Determine the location of the reference point for the C-arm to be tested
  - From the manufacturer’s specifications or
  - Assume the FDA/IEC definition of 15 cm from isocenter toward the x-ray source

Methods

- Position the C-arm horizontally
  - Use maximum SID
  - 30 cm PMMA next to image receptor on the tabletop
  - Position the field size measuring plate
    - Perpendicular to and centered on the central beam axis and
    - At the reference point

Methods

- Select the medium FOV mode and collimate to an approximately 10 x 10 cm field
- Record the actual field dimensions to determine irradiated area
Methods

- Remove the field size measuring plate and place the dosimeter probe at the reference point location
- Record initial $R_{Ka}$ and $K_{Ka}$ readings
- Fluoro using dose accumulate mode on dosimeter until accumulated air kerma is at least 100 mGy
- Record final $R_{Ka}$ and $K_{Ka}$ readings and calculate difference
- Multiply probe air kerma by irradiated area to determine probe air kerma-area product
- Compare probe readings with integrated dosimetry values for $R_{Ka}$ and $K_{Ka}$

Repeat air kerma measurement for cine or digital acquisition mode
- Remove 10 cm PMMA without moving the dosimeter probe
- Repeat fluoro and acquisition dose measurements with 20 cm PMMA
- Remove 10 cm more PMMA and repeat

Control Limits

- FDA(2009)
  - $K_{Ka}$ shall not deviate > ± 35% for > 100 mGy
- IEC(2000)
  - $K_{Ka}$ shall not deviate > ± 50% for > 100 mGy
  - $R_{Ka}$ shall not deviate > ± 50% for > 2.5 Gy-cm²
- IEC(2010)
  - $K_{Ka}$ shall not deviate > ± 35% for > 100 mGy
  - $R_{Ka}$ shall not deviate > ± 35% for > 2.5 Gy-cm²
Measurement Accuracy

- Uncertainty in external dose measurements
  - Uncertainty in probe readout (±5%)
  - Error in probe position (±2 mm or 3%)
  - Error in irradiated area (±2 mm per side or 3%)
- Total uncertainty for $K_{a,r}: ±6$
- Total uncertainty for $P_{k_A}: ±7$

Integrated Dosimetry System Validation

- Alternative method using an external $P_{k_A}$ meter:
  - Place at least 20 cm from collimator to avoid scatter
  - Select x-ray beam size to be completely within the external ionization chamber
  - Use a $P_{k_A}-K_{a,r}$ dual chamber meter to simultaneously measure $K_{a,r}$ values

Field Adjustment of $P_{k_A}$ and $K_{a,r}$

- Some manufacturers provide a method of adjusting $P_{k_A}$ and $K_{a,r}$ values on individual imaging systems in the field
- Manual adjustment (older models only)
- Software calibration
- If no field adjustment is possible, a correction factor for $P_{k_A}$ and $K_{a,r}$ values can be calculated as the integrated dosimetry system readout to probe ratio

Clinical implementation

- Validation procedure has been used at our facility to test 11 C-arm imaging planes annually for the past 7 years
- Includes 2 fluoroscopy system manufacturers and 5 equipment models
Integrated Dosimetry System Validation

- Results
  - System dose readout error found to be quite high (-20% to +34%)
  - Dose readout is relatively consistent over 7 year period

Table and Pad Attenuation

- Note that some manufacturers include table attenuation in $P_{\text{B}}$ and $K_{a,r}$ readout values
- One manufacturer applies a correction factor weighted for x-ray tube under-table and over-table/lateral angulation:
  - Table attenuation 0.86, 50%/50% under/over-table use assumed
  - Therefore, probe:system ratio expected is 0.93 using protocol described above
Table and Pad Attenuation

To perform skin dose estimates from $K_a$ values, a correction for table and pad attenuation should be included.

Alternatively, the integrated dosimetry system readout can be calibrated to include table and pad attenuation if the x-ray tube is generally under the table clinically.

Typical table and standard pad attenuation factor is 0.7 - 0.8. Heavily attenuating pads (gel pads) can be as high as 0.5 *.

* Geiser, Huda and Gkanatsios, Medical Physics 1997

Integrated Dosimetry Systems

Additional information and guidance is coming.

AAPM Task Group 190: Accuracy and Calibration of DAP meters in Diagnostic Radiology

Chair: Pei-Jan P. Lin
Charge:
- Develop integrated dosimetry evaluation protocol
- Survey clinical fluoroscopic equipment: accuracy and calibration methods

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Phantom Air Kerma Rate

- Why measure phantom fluoroscopy entrance-surface air kerma rate (EAKR)?
- Verify appropriate dose rates are available when acceptance testing new equipment
- Compare to other equipment
- Compare to benchmark values
- Quality control monitoring of equipment performance

EAKR Measurement

- Use clinical exposure conditions
  - Patient-equivalent attenuator (produces an exit beam with adequate scatter)
  - Range of phantom thicknesses
  - Clinical source-to-image receptor distance

Materials

- PMMA attenuator blocks
  - At least 25 x 25 cm to fully cover the beam field of view at the image receptor
  - Sheets to make up 10, 20 and 30 cm thicknesses
- Ionization chamber dosimeter
- Tape measure

Methods

- Use 10 cm air gap between phantom and image receptor, adjust SID for each thickness
- Measure EAKR for all magnification modes and all clinically-used dose modes
Benchmark EAKR Values

- From survey of 41 fluoroscopy systems, mean (quartiles) EAKR for 15-18 cm FOV *:
  - 20 cm thickness – 26 (14-38) mGy/min
  - 30 cm thickness – 110 (67-150) mGy/min
- Additional benchmark data is needed
- CRCPD NEXT Cardiac Catheterization results will be available soon

* Laskey, Wondrow, Holmes, Variability in fluoroscopic x-ray exposure in contemporary cardiac cath lab, JACC 2006

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Fluoroscopy Mode Options

- Modern fluoroscopy units include multiple optional modes
- Parameter selection can significantly affect dose rates and image quality
- Adjustments in parameter selection may be needed when measured dose rates are above 75th percentile benchmark values

Fluoroscopy Mode Options

- Several different dose modes should be available for selection by the operator
  - Low: for positioning fluoro, high contrast object placement and sensitive patients
  - Medium: for routine work
  - High: for selective use in difficult imaging conditions
Fluoroscopy Mode Options

- Variable rate pulsed fluoroscopy
- Spectral beam filtration
- kVp selection
- Automatic dose rate control algorithms
- Image processing

Spectral Beam Filtration

- Extra filtration added to reduce low energy x-rays absorbed in patient tissue
- Copper (Cu) is most common
- Tantalum (Ta) is also used
- Reduces patient entrance air kerma rate
- Minimal effect on image quality

Spectral Beam Filtration

- Chart showing the number of x-rays (X10^6) at different x-ray energies (keV) with different copper thicknesses (0 mm Cu, 0.3 mm Cu, 0.6 mm Cu, 0.9 mm Cu).

Spectral Beam Filtration

- Chart showing the entrance air kerma rate (EAKR, mGy/min) at different beam filtrations (mm Cu).
Spectral Beam Filtration
- Optimum filtration thickness depends on patient attenuation
- More filtration for smaller patients and body parts
- Less filtration for thicker patients to avoid tube overheating
- Requires use of higher mA for adequate penetration

kVp Selection
- Increase from 70 to 80 kVp decreases entrance-surface air kerma rate by 33%
- Disadvantage: Contrast decreases also

Automatic Dose Rate Control
- Automatic variation in kVp, mA, pulsewidth and filtration thickness
- Different algorithms are available to optimize fluoroscopic image quality for different procedure types, body parts, pediatrics

Reference: Lin, Medical Physics 2007
Image Processing

- Allows partial retrieval of image quality loss from use of dose reduction options
- Includes:
  - Video frame averaging
  - Edge enhancement
  - Contrast enhancement

Conclusions

- Validation of the accuracy of air kerma-area product and reference point air kerma display values is recommended
- Measurement of fluoroscopy phantom entrance-surface air kerma rate is a valuable way to optimize and benchmark performance

References (1)


References (2)

- Laskey WK, M Wondrow, DR Holmes, Variability in fluoroscopic x-ray exposure in contemporary cardiac catheterization laboratories, JACC 2006; 48:1361.
- Lin PP, The operation logic of automatic dose control of fluoroscopy system in conjunction with spectral shaping filters, Medical Physics 2007; 34:3169.