

Radiation Safety in Fluoroscopy

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Disclosures

E. Leidholdt receives royalties from the sales of a textbook.

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Major Components of a Fluoroscope

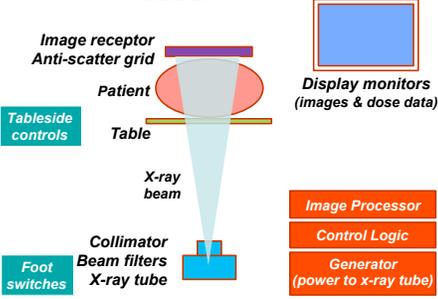


Image receptor
Anti-scatter grid
Patient
Table
X-ray beam
Collimator
Beam filters
X-ray tube
Tables side controls
Foot switches
Image Processor
Control Logic
Generator (power to x-ray tube)
Display monitors (images & dose data)

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Configurations of Fluoroscopes

GI & GU system with x-ray tube under the table.



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Configurations of Fluoroscopes

General purpose
C-arm system with
large diameter image
intensifier tube.



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Configurations of Fluoroscopes

General purpose
C-arm angiography
and interventional
system with a
flatpanel image
receptor.



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Configurations of Fluoroscopes

Biplane C-arm system with small area flatpanel image receptors for cardiology and neuroradiology



Biplane systems allow less contrast material to be used, because 2 projections can be imaged simultaneously.

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Configurations of Fluoroscopes

Mobile C-arm

Most mobile C-arms have a fixed 100 cm source to image receptor distance.

Note that the spacer device is not attached to the x-ray source.



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Configurations of Fluoroscopes



120 cm
90 cm

Source-to-image distance nominally 100 cm

X-ray tube (source)

On most non-mobile systems, the image receptor can be moved toward or away from the x-ray tube.

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Doses from Medical Exposures

Doses to Patients from Medical Exposures - left to the judgment of the physician.

The physician must balance the risk to the patient from the radiation exposure with the benefit from the contemplated procedure.

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Doses from X-Ray Imaging

In fluoroscopy, a wide range of exposures is possible. Increasing the exposure to the patient by increasing the mA (fluoroscopy) or mAs/image (fluorography) reduces image noise, thereby improving the conspicuity of low contrast and small structures.

The goal of x-ray imaging is to produce images adequate for the clinical task, not ideal images.

Not all tasks require equal image quality.

The radiation dose to the patient should be optimized. (The doses to the patient should be kept as low as reasonably achievable [ALARA].)

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Effective Doses from X-Ray Examinations

Typical Effective Dose
(mSv)

Chest radiographs, PA and lateral	0.1
Mammogram, screening, 2 view	0.4
KUB radiograph	0.7
Upper GI study (barium swallow)	6
Lower GI study (barium enema)	8
CT of the abdomen	8
PTCA (coronary angioplasty)	10
Radiofrequency cardiac catheter ablation	17

(Mettler et al., 2008)

The largest effective doses in medical x-ray imaging are from CT and some fluoroscopically-guided interventional procedures.

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Skin Reactions

- Time of expression can range from minutes to years.
- Severe early effects, occurring within weeks, are likely due at least in part to depletion of the germinal cell layer of the epidermis.
- Late effects, occurring in many months to years, are likely mostly due to injury to the vasculature.

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Skin Reactions

Factors other than radiation dose affecting reactions:

- The dose rate and fractionation. Delivering a dose at a low dose rate or in fractions separated by time reduces the effect.
- Some chemicals and drugs can increase or reduce the sensitivity. In particular, some drugs used for chemotherapy decrease the threshold doses for radiation injury.
- Some hereditary disorders of DNA repair, such as ataxia-telangiectasia.
- Previous large doses from fluoroscopy or radiation therapy.

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Skin Reactions

Skin injury – case study

A 40-year-old man underwent coronary angiography, coronary angioplasty, a second angiography procedure (due to complications), and placement of a coronary artery bypass graft, all on March 29, 1990.



Photograph of the patient's back 6-8 weeks after the procedures.

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Skin Reactions

Skin injury – case study

Patient's back, late summer 1990.
Skin has the appearance of a
healed burn, except for a small
ulcerated area near the center.



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Skin Reactions

Skin injury – case study

The injury approximately 18 to 21
months after the procedures,
showing necrosis of the skin.



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Skin Reactions

Skin injury – case study

The injury eventually received a
skin graft.

The skin dose is not known.
However, from the injury, it is likely
that the dose exceeded 20 Gy.

(Source: www.fda.gov/cdrh/rsnai)



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Skin Reactions

SKIN INJURIES FROM FLUOROSCOPY

Not thermal burns; the pathophysiology and time course differ.

In severe cases, tissues beneath the skin are also commonly affected.

Severe skin injuries from fluoroscopy are extremely painful.

Precautions should be taken to prevent biopsies of injured skin.

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Skin Reactions

Dose (gray)	Prompt (0-2 wks)	Early (2-8 wks)	Mid-term (6-52 wks)	Long-term (> 40 wks)
0-2	No observable effects	No observable effects	No observable effects	No observable effects
2-5	Transient erythema	Epilation	Recovery from epilation	No observable effects
5-10	Transient erythema	Erythema, epilation	Recovery; at higher doses, prolonged erythema, permanent partial epilation	Recovery; at higher doses, dermal atrophy or induration
10-15	Transient erythema	Erythema, epilation, possible dry or moist desquamation; recovery from desquamation	Prolonged erythema; permanent epilation	Telangiectasia; dermal atrophy or induration; skin likely to be weak
> 15	Transient erythema; after very high doses, edema and acute ulceration	Erythema, epilation; moist desquamation	Dermal atrophy; ulceration due to failure of moist desquamation to heal; at higher doses, dermal necrosis	Telangiectasia; dermal atrophy or induration; possible late skin breakdown; wound may persist and progress into a deeper lesion

(adapted from Balter et al., 2012)

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Interactions of X-Rays with Matter

Diagnostic imaging x-rays mostly interact with matter by:

Photoelectric Absorption

X-ray photon is absorbed by an atom, with the emission of an orbital electron.

Predominates at low x-ray energies and in high atomic number elements.

Compton Scattering

X-ray scatters from an orbital electron that is ejected from the atom.

The scattered x-ray photon has less energy than the initial photon.

The probability of scatter is proportional to the number of electrons per volume.

Each produces an energetic electron, capable of breaking chemical bonds, that deposits its energy within mm of the interaction.

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Dose Rates in Fluoroscopy

TYPICAL EXPOSURE RATES FOR A NON-OBESE PATIENT

The radiation dose in the patient is greatest at the skin where the x-ray beam enters the patient. The dose falls-off greatly with depth in the patient, typically being just a few percent of the entrance dose-rate where the beam exits the patient.

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Production of X-Rays and Formation of the Image

COMPONENTS OF A FLUOROSCOPE

- X-Ray Tube
- Generator - provides high voltage to x-ray tube
- X-Ray Beam Filters
- Collimator
- Grid for Scatter Reduction
- Image Receptor
 - Image Intensifier Tube and Video Camera
 - Solid-State ("Flat Panel") Receptor
- Image Display System
- Automatic Exposure Rate Control System ("Automatic Brightness Control")

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Production of X-Rays and Formation of the Image

X-RAY TUBE

- Glass envelope
- Cathode with tungsten filaments (electron source)
- Tungsten anode (electron target and x-ray source)

X-ray tube with rotating tungsten anode. The filaments for the large and small focal spots are inside indentations in the cathode and are not visible in this view. The bronze color inside the glass is evaporated tungsten that condensed on the interior surface of the glass during use.

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Production of X-Rays and Formation of the Image

X-RAY TUBE

Cathode – electron source



A helical tungsten filament is heated by a large current at a low voltage, causing the emission of electrons.

Most x-ray tubes have at least two filaments to provide focal spots of different sizes.

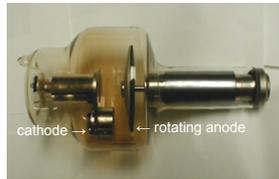
The smaller filament provides better spatial resolution, but less power.

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Production of X-Rays and Formation of the Image

X-RAY TUBE

Anode – electron target and x-ray source



On high output fluoroscopes, the anode is a rotating disk of tungsten alloy with a beveled edge.

A large voltage (typically 60 to 115 kV) between the anode and cathode accelerates the electrons to high kinetic energies and directs them onto a tiny area on the anode called the *focal spot*.

The electrons striking the focal spot produce x-rays.

Most of the electron beam's energy is deposited as heat; only about a percent of the energy is emitted as x-rays.

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Production of X-Rays and Formation of the Image

X-RAY TUBE

Focal Spots

A smaller focal spot provides better spatial resolution.

A smaller focal spot provides less maximal x-ray beam intensity.

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Production of X-Rays and Formation of the Image

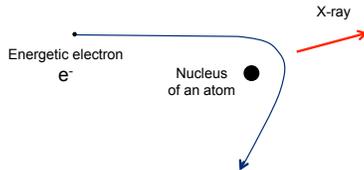
X-Ray Tube Voltage (kV)
 Voltage applied between the cathode and anode.
 Increasing the kV increases the amount and energy (penetrability) of x-rays.
 Major user-selectable factor determining image contrast
 Higher kV reduces image contrast.
 Higher kV (with appropriate mA reduction) reduces entrance skin dose.

X-Ray Tube Current (mA)
 Electrical current between the cathode and anode.
 Amount of x-radiation is proportional to the tube current.

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Production of X-Rays

X-rays are produced when electrons with large kinetic energies are decelerated.

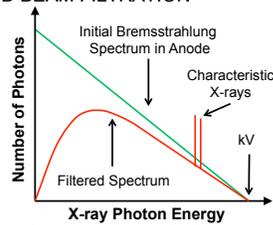


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Production of X-Rays and Formation of the Image

X-RAY SPECTRUM AND BEAM FILTRATION

The x-rays emitted from the anode form a continuous spectrum.



Low energy x-rays have too little energy to penetrate the patient and would contribute unnecessary dose, mostly to the skin and other superficial tissues.

X-ray machines used for medical imaging have thin sheets of Al, Cu, or another material in the beam port to preferentially attenuate these low energy x-rays.

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Production of X-Rays and Formation of the Image

COLLIMATOR

Adjustable lead shutters at the beam port that are used to limit the primary x-ray beam to the portion of the patient to be imaged.

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Production of X-Rays and Formation of the Image

COLLIMATOR

Collimation does not significantly reduce skin dose and may slightly increase it.

Good Collimation:

- Reduces the volume of the patient that is in the primary beam, thereby reducing the effective dose to the patient.
- Reduces the size of a skin injury, if an injury occurs.
- Reduces the overlapping of radiation fields on the skin. Skin injuries may occur when two radiation fields overlap.
- Improves image contrast & reduces random noise by reducing scatter.
- Reduces dose to staff.

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Production of X-Rays and Formation of the Image

COLLIMATION EXAMPLE

X-ray field reduced by 1/8 on each side by collimation.



Collimator Fully Open



Field Collimated

X-ray field area on skin, energy imparted to patient, and dose to staff are all reduced by a factor of almost 2.

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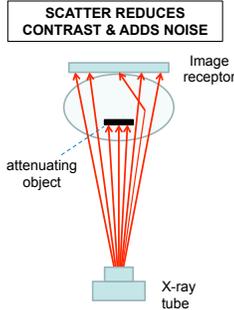
Production of X-Rays and Formation of the Image

SCATTER AND IMAGE QUALITY

When imaging thick body parts, a large fraction of the x-ray photons reaching the image receptor are scattered photons.

Scatter that reaches the image receptor degrades image contrast and adds random noise.

The scatter fraction increases with x-ray field size and patient thickness.



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Production of X-Rays and Formation of the Image

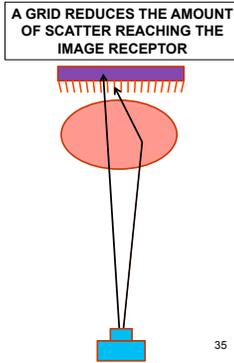
SCATTER REDUCING GRIDS

A grid is a plate with many tiny lead strips, separated by a material of low attenuation, just before the image receptor.

The grid greatly reduces the scatter fraction reaching the image receptor, thereby improving image contrast.

The grid also absorbs a large fraction of the unscattered photons, requiring a larger mA and increasing patient dose.

In low scatter situations (e.g., small body parts and small children), removing the grid can greatly reduce patient dose.



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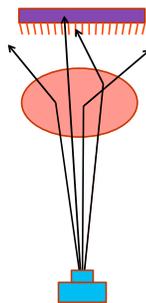
Production of X-Rays and Formation of the Image

GRIDS and GAPS

It is usually preferable to keep the image receptor close to the patient.

In cases in which the image receptor must be kept a significant distance from the patient, the gap causes much of the scatter to miss the image receptor.

In this case, removal of the grid can reduce patient dose.



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Production of X-Rays and Formation of the Image

Geometric Image Magnification

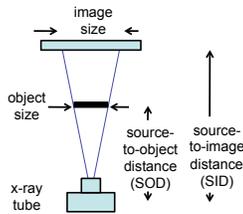
Placing an object at a distance from the image receptor causes geometric magnification of the image.

By similar triangles:

$$\frac{\text{image size}}{SID} = \frac{\text{object size}}{SOD}$$

$$\text{image size} = \frac{SID}{SOD} \cdot \text{object size}$$

However, this also increases dose to the object due to the inverse square law.



Production of X-Rays and Formation of the Image

IMAGING CHAIN

The intensity pattern in the x-ray beam that exits the patient contains information.

The imaging chain is a series of components that capture much of the information in this beam and produces images that can be viewed.

These components are:

Scatter-reducing grid, if used

Image receptor

Image intensifier tube optically coupled to a video camera

Flatpanel solid state image receptor

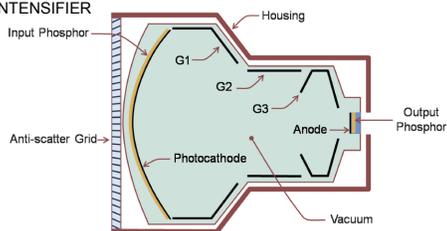
Analog-to-digital converter

Digital image processor

Display monitor - Cathode ray tube or LCD flatpanel display

Production of X-Rays and Formation of the Image

IMAGE INTENSIFIER TUBE



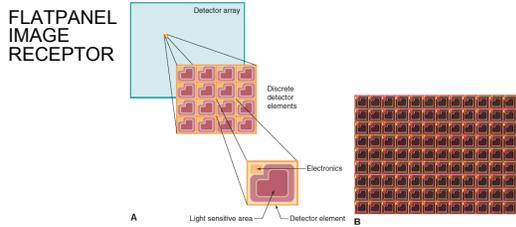
X-ray photons striking the input phosphor create light photons.

Many of these strike the photocathode, releasing electrons.

The electrons are accelerated to the anode by a very large voltage and create light when they strike the output phosphor.

A video camera is optically coupled to the output window.

Production of X-Rays and Formation of the Image

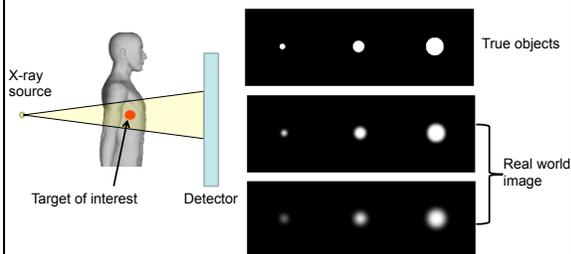


A phosphor layer optically coupled to a silicon TFT array. X-ray photons striking the phosphor layer create light. Each detector element contains a photodiode and a capacitor to store the electrical charge. The detector elements are read, a row at a time.

Image Quality

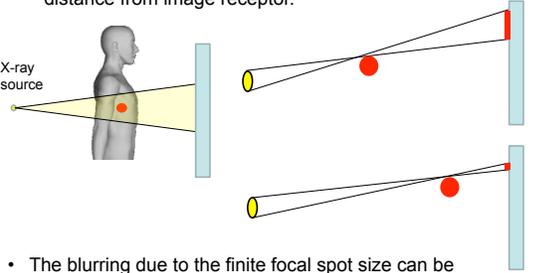
- Spatial Resolution
Ability to resolve small objects in close proximity
- Image Contrast
Brightness differences in the image
- Image Noise
"Graininess" of the image

Spatial Resolution



Factors that affect Spatial Resolution

- X-ray tube focal spot size, in conjunction with distance from image receptor.

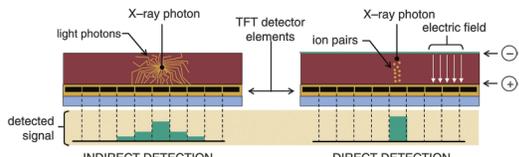


- The blurring due to the finite focal spot size can be minimized by reducing the Patient-to-Imager distance.

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Factors that affect Spatial Resolution

- The finite size of detector pixel and the interaction process between x-rays and detectors
- The x-ray signal detection technique affects spatial resolution
 - Direct detection method has better spatial resolution than Indirect detection method.



Ref.: The Essential Physics of Medical Imaging (3rd)

Factors that affect Spatial Resolution

- Number of pixels in digital image (512 x 512 or 1024 x 1024)
- Post processing software
- Display monitors (e.g., number of pixels in display)

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Image Contrast

Brightness differences in the image

- Subject Contrast
- Detector Contrast
- Display Contrast

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Image Contrast

- Subject Contrast
 - The fundamental contrast from the object itself
 - Lung nodule vs. Liver lesion

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Image Contrast

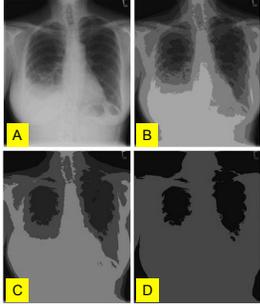
- Detector Contrast
 - Detector's response to signal
 - Screen film vs. Digital radiography

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Image Contrast

- Displayed Contrast
 - Bit depth of images
 - Display setting

A: 8 bits
B: 3 bits
C: 2 bits
D: 1 bit



Ref.: The Essential Physics of Medical Imaging (3rd)

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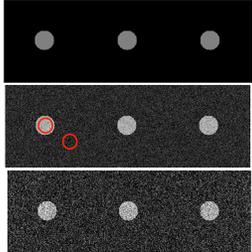
Factors that affect Contrast

- Scattering of x-rays in the patient reduces contrast
- Scatter increases with thickness of patient and x-ray field size
- Increasing kV reduces contrast
- Ambient room lighting (reflection of ambient light from faces of display monitors reduces apparent contrast)

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Image Noise

- The emission of x-ray photons, their interactions as they pass through the patient, and their interactions with the image receptor are random processes.
- This causes random variations in the amount of energy deposited on specific areas of the image receptor.

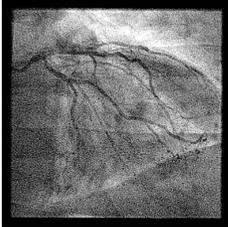
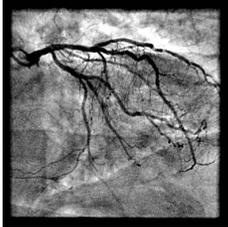


Contrast-to-Noise Ratio = $(\text{Mean}_{\text{object}} - \text{Mean}_{\text{bg}}) / \text{Noise}_{\text{bg}}$

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Image Quality

STATISTICAL (RANDOM) NOISE (Quantum Mottle)

Low Dose (fluoro LIH)

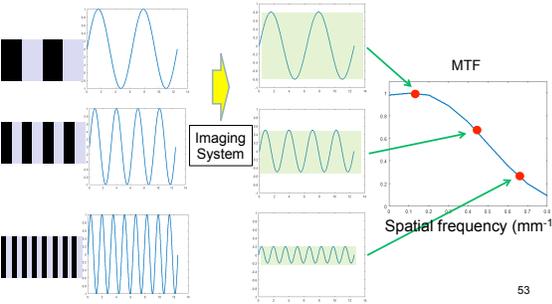
High Dose (cine frame)

Images courtesy S. Balter, Ph.D., Columbia University

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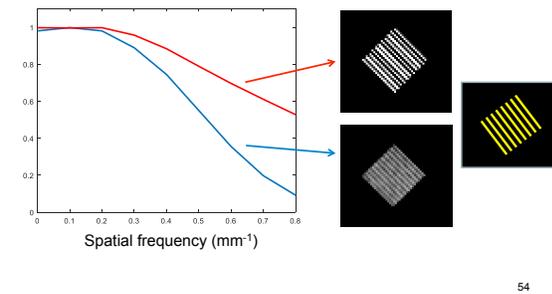
Quantitative Description of Image Quality Metrics

- Spatial Resolution – Modulation Transfer Function (MTF)



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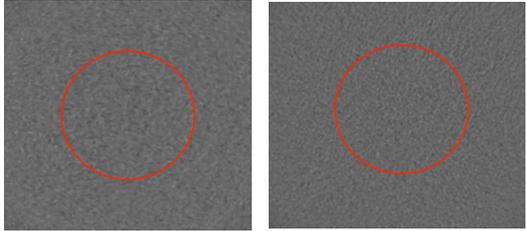
Modulation Transfer Function (MTF)



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Image Noise

- It is not just about Standard Deviation measurement !

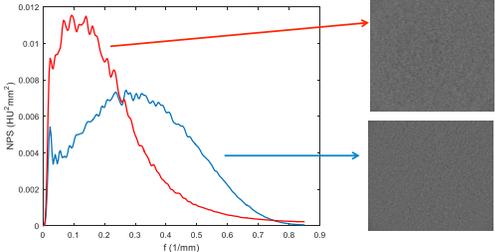


Standard Deviation = 10 HU Standard Deviation = 10 HU

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Mathematical Description of Image Quality Metrics

- Noise Power Spectrum (NPS)
 - Describes the distribution of noise of different frequency
 - The area under the curve is the standard deviation of ROI.



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Spatial Resolution, Contrast, Noise

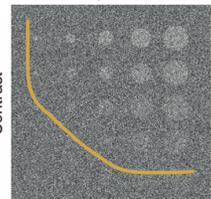
Detection task is the final result that depends on the overall effect of Spatial Resolution, Contrast, and Noise.

Low noise



Detail

High noise



Detail

Ref.: The Essential Physics of Medical Imaging (3rd)

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Modes of Operation

- Automatic Exposure Rate Control ("Automatic Brightness Control")
- High Dose Rate Mode (not all fluoroscopes have it)
- Electronic Magnification Modes
- Pulsed versus Continuous Fluoroscopy
- Image Recording (Fluorography)

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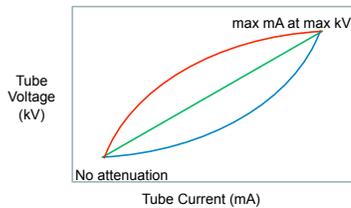
Modes of Operation

- Manual Mode
 - Operator selects kV and mA
 - Seldom used.
- Automatic Exposure Rate Control
 - Measures amount of signal at the image receptor.
 - Adjusts kV and mA (or pulse duration) to maintain constant signal to the image receptor.

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Modes of Operation

Automatic Exposure Rate Control
May have settings which provide different compromises between kV and mA, which produce more contrast with more dose to the patient or less contrast with less dose.



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Modes of Operation

High Dose Rate ("Boost") Mode (optional)

Fluoro machines with AERC cannot exceed 88 mGy/min (10 R/min) at a specified point except during recording of images (e.g., cinefluorography) or unless an optional high-level control is activated.

Use of the high dose rate mode reduces quantum mottle in the image, but greatly increases the dose-rate to the patient.

The FDA and states set a dose-rate limit of 176 mGy/min (20 R/min) when the high level control is activated.

Activation of the high-level mode requires the operator to continuously activate a control.

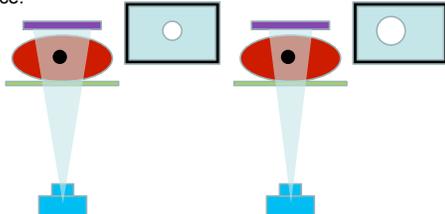
A continuous audible signal is provided to indicate that the high level control is activated.

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Modes of Operation

Electronic Magnification Modes

In magnification modes, the image from only part of the image receptor is displayed using the entire display device.



The collimator reduces the x-ray field size to match the area of the image receptor that is used.

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Modes of Operation

Electronic Magnification Modes

Magnify the image.

Slightly improve the spatial resolution.

Because random image noise becomes more apparent, the fluoroscope automatically increases the x-ray beam intensity.

Doubling the magnification (e.g., 9-inch mode → 4.5 inch mode) typically produces a two (newer systems) to four-fold increase in the dose-rate.

Because the volume of the patient in the x-ray beam is reduced, the integral dose (dose × volume) does not greatly change.

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Modes of Operation

Pulsed versus Continuous Fluoroscopy

In pulsed fluoroscopy, the x-ray tube produces short pulses of x-rays several times a second.

Between pulses, the last image is stored in memory and displayed on the display monitor.

The number of frames per second can be selected by the operator. 30, 15, 7.5, and 3.75 pulses per second are common.

Pulsed fluoroscopy at reduced frame rates can greatly reduce patient dose. Typical values:

- 30 f/s dose rate similar to continuous fluoro
- 15 f/s dose rate is half
- 7.5 f/s dose rate is one-fourth

At low pulse rates, motion appears jerky.

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Modes of Operation

Image Recording (Fluorography)

Spot image – single image is recorded

Cinefluorography (“cine imaging”) – a series of images is recorded to depict a dynamic phenomenon, such as the passage of a bolus of contrast material through a coronary artery or the movement of a catheter.

Digital subtraction angiography (DSA) – a mask image, acquired before the injection of contrast material, is subtracted from one or more images acquired when contrast material is in the vasculature.

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Modes of Operation

Image Recording (Fluorography)

In fluoroscopy, the human visual system effectively averages several frames, reducing the perception of random noise.

In fluorography, the dose per frame is typically greatly increased over that of fluoroscopy to limit random noise.

The dose per frame is particularly high for DSA.

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Modes of Operation

Image Recording (Fluorography)

Cinefluorography is the acquisition of many images a second for cine display.

The dose to the patient is:
(dose per image) x (frame rate) x (duration of imaging)

Although cine can be done at up to 60 frames/second, adult cardiac angiographic imaging is commonly conducted at 15 frames/second.

The average dose rate during cinefluorography is **about 15 times higher** than that of fluoroscopy at the same rate.

When greater random noise can be tolerated in recorded images, fluoro store ("fluoro grab"), which stores low-dose fluoroscopy frames, can be used.

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Other Features

Last Image Hold

Last image is stored and displayed after production of x-rays ceases.

Last-image-hold reduces patient exposure, especially the operator is not highly experienced and in teaching situations.

Fluoro Store

Last several seconds of fluoro images are stored and can be displayed.

Timer and Audible Signal

An audible signal sounds after every five minutes of fluoroscopy.

Virtual Collimation

Permits adjustment of the collimator without producing x-rays.

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Controls and Displays



The dose optimizing features, controls, labels on controls, and displays vary greatly among models.

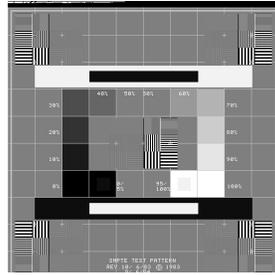
Equipment manuals may not adequately describe them and the manufacturer's applications specialists may not fully understand them.

The physician operator and imaging technologists must become familiar with them.

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Controls and Displays

SMPTE Test Pattern is useful for testing display monitors and adjusting room lighting.



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Factors Determining Patient Doses

- X-Ray Energy Spectrum (kV and beam filtration)
- Collimation of X-ray Beam
- Grid for Scatter Reduction
- Efficiency of the Image Receptor
- Desired Signal-to-Noise Ratio
- Source-to-skin distance and distance from patient to image receptor
- Thickness of the patient along the beam path (patient body habitus and angulation of the beam)
- Skill of the clinician.

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Fluoroscopic Dose Rates

Fluoroscopy is usually performed using automatic exposure rate control, which adjusts the kV and mA to maintain a constant dose rate at the image receptor.

Patient entrance exposure rate depends upon the thickness of the patient and beam angulation and mode of operation (e.g., electronic magnification). Typical entrance air kerma rates are 20-50 mGy/min for a patient of average thickness in non-magnification mode.

The air kerma rate (AKR) may not exceed 88 mGy/min (exposure rate of 10 R/min), except when recording images or when an optional high-level control is actuated.

The AKR may not exceed 176 mGy/min (exposure rate of 20 R/min) when the high-level control is actuated.

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Fluoroscopic Doses

Other factors determining dose

- Magnification modes – significantly increase dose, but reduce the volume in the primary beam.
- Use of pulsed fluoro at low pulse rates instead of continuous fluoro can significantly reduce dose.
- Last image hold feature can significantly reduce dose, particularly for teaching situations and less experienced users.
- Images recorded.

73

Metrics of Patient Dose

Dose metrics displayed by fluoroscopes:

- Reference point air kerma
- Air kerma area product
- Total fluoro time



Tilt	0
SID	120
FD	13.0
X-ray disabled	
Exp	30
Fluo	Normal
Time	19:29
AK	1484.90
DAP	184522
58:00	

74

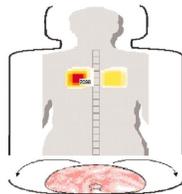
Patient Dose Metrics

Metrics we want, but usually don't have:

- Peak skin dose
- Skin dose maps

One manufacturer offered an option that created maps of the dose distribution on a patient's skin (CareGraph, Siemens Medical Solutions). This system is no longer sold.

Such information is available on some new systems.



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Patient Dose Metrics

Fluoro Time

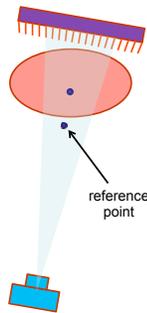
- May be the only dose metric displayed by fluoroscopes manufactured before June 10, 2006.
- Doesn't account for dose from image recording.
- Doesn't account for factors such as thickness of patient and distance from the x-ray source.
- Doesn't account for settings on fluoroscope (e.g., pulse rate, mag mode).
- **Correlates poorly with peak skin dose.** Should be used as the primary dose metric only when cumulative air kerma and KAP are not available.

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Patient Dose Metrics

Reference Point Air Kerma ($K_{a,r}$)

- Air kerma at a defined point in the center of the x-ray beam
- Units: mGy
- Displayed by all fluoroscopes made on or after June 10, 2006.
- For a C-arm fluoroscope, it is specified at a reference point 15 cm from the isocenter toward the x-ray source.



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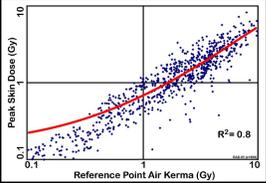
Patient Dose Metrics

Reference point air kerma is not the peak skin dose:

- It is measured at the reference point. The skin may be closer to or farther away from the x-ray source.
- It does not account for the use of multiple non-overlapping x-ray fields.
- It does not include scatter from the patient. Scatter from the patient causes the skin dose to exceed the air kerma by a factor of about 1.2 to 1.4.
- It does not account for attenuation by the table.

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Patient Dose Metrics



Reference point air kerma usually exceeds peak skin dose, but not always.

709 cases from RAD-IR Study.
Graph courtesy Stephen Balter, Ph.D.
Columbia University.

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Patient Dose Metrics

Reference Point Air Kerma

- For many procedures, it overestimates the peak skin dose, by a factor up to about 2.
- There are other procedures (e.g., TIPS) for which it reasonably estimates the skin dose.
- Can underestimate the skin dose if a single field is mostly used and the skin is much closer to the x-ray tube than the reference point.
- It is currently the best dose metric displayed by most fluoro machines for monitoring, during a procedure, the risk of skin injury and, afterwards, stratifying patients into those needing and not needing follow-up.

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Patient Dose Metrics

Air Kerma Area Product (KAP, P_{KA} , sometimes DAP)

- Air kerma at a distance from the source multiplied by the cross-sectional x-ray beam area.
 - The air kerma in the beam decreases as square of the distance from the x-ray tube focal spot and the beam cross-sectional area increases as the square of the distance. Thus, the KAP is constant with distance.
- Units displayed vary with manufacturer:
mGy·cm², μGy·m², cGy·m²

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Patient Dose Metrics

Air Kerma Area Product (KAP, P_{KA} , sometimes DAP)

- Indicates the total amount of x-ray energy imparted to the patient.
- As a QA metric:
 - Assesses the use of beam collimation.
 - Does not provide any information on source-to-skin distance.
 - May be best QA metric for procedures that do not pose a risk of skin injury.

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Patient Dose Metrics

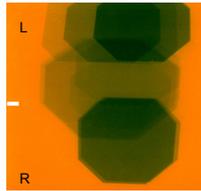
Dosimeters or film can be placed on the patient's skin to measure skin dose



Landauer
MicroStar System



Unfors Patient Skin Dosimeter
• Audible and visual warnings
• Small silicon sensors



GAFCHROMIC
Dosimetry Film

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Patient Dose Metrics

Dosimeters or film placed on the patient's skin to measure skin dose

- For dosimeters, may miss location of peak skin dose unless many dosimeters are used.
- Most facilities do not use dosimeters or film to monitor skin dose.

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Patient Dose Metrics

New Dose Displays

- As of 2016, most major manufacturers of fluoroscopes are offering innovations in monitoring of patient doses.
- At least one manufacturer is providing skin dose maps and peak skin dose.
- Another is displaying estimated skin dose by body zone.
- These are not standardized.

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Patient Dose Metrics

Uses of the dose metrics:

- During the procedure, provide information to the physician about the amount of radiation delivered.
- After the procedure:
 - Stratify patients into those needing and those not needing follow-up for possible skin injury.
 - Documenting in the patients' medical records the dose delivered to inform clinicians planning future procedures.
- Quality assurance regarding radiation management.

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Potentially-High Radiation Dose Procedures

- An FGI procedure should be classified as a *potentially-high radiation dose procedure* if more than 5 % of cases of that procedure result in $K_{a,r}$ exceeding 3 Gy or P_{KA} exceeding 300 Gy·cm² (NCRP Report No. 168).
- These are procedures in which there is a possibility of a clinically-significant tissue injury from the radiation.
- These can include:
 - Diagnostic and interventional coronary artery procedures
 - Cardiac radiofrequency catheter ablation
 - Endovascular repairs and embolizations, including EVARs
 - TIPS

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Protection of the Patient

- The physician supervising the operation of the equipment and any staff operating the equipment must understand the various modes of operation of the particular machine and the controls and dose implications of each.

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Protection of the Patient

Actions:

- Before the procedure
- During the procedure
- After the procedure

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Protection of the Patient

BEFORE THE PROCEDURE

- Screen female patients of reproductive age for pregnancy.
- Consider factors that may increase a patient's risk of skin injury (e.g., some drugs, DNA repair disorders, some diseases, and previous irradiation).
- Before potentially-high dose procedures, examine the patient's skin for evidence of injury from previous fluoroscopic or radiation oncology procedures.
- Be aware that larger and obese patients receive much higher doses.
- Obtain consent.
- Select appropriate settings on the fluoroscopy.

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Protection of the Patient

Body Habitus of the Patient

Image receptor
Patient
Table
X-ray source

Larger and more obese patients receive larger doses.

91

Protection of the Patient

- Keep the source-to-skin distance (SSD) as large as possible.
 - (Keep the patient's skin as far from the x-ray tube as possible.)
 - When the x-ray tube is below the patient, keep the patient table as high as feasible (but not so high as to hinder the procedure).
 - Operators of small stature may need to stand on a platform during some procedures.
- Keep the image receptor close to the patient.

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Protection of the Patient

Distance of the Patient from the X-ray Source

Image receptor
Patient
Table
X-ray source

Increasing the distance between the patient and the x-ray source reduces the skin dose.

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Protection of the Patient

Distance of the Image Receptor from the Patient

For fluoroscopes that allow the image receptor to be moved toward the x-ray source, reducing the patient-to-image receptor distance reduces the dose to the patient. ⁹⁴

Protection of the Patient

- Non-mobile fluoroscopes must not allow the x-ray source to be closer than 38 cm to the skin (FDA regulations).
- C-arm fluoroscopes may have a cone or other spacer device on the x-ray tube.
- The cone may be removable.
- Leaving it off increases the risk of patient injury.

⁹⁵

Protection of the Patient

- Select pulsed fluoro mode and select the lowest pulse rate that is clinically acceptable during each part of the procedure.
- Minimize fluoro time.
 - Fluoro only to observe motion or to select a view for image recording.
 - If you are not looking at the monitor, your foot should be off the pedal. Use the last-image-hold feature to study the image.
- Use the least acceptable image magnification.
- Limit the use of high-level (boost) mode.
- Use aggressive beam collimation. Collimation reduces effective dose of the patient and staff and improves image contrast.

⁹⁶

Protection of the Patient

Angulation of X-ray Beam

Image receptor
Patient
Table
X-ray source

Increasing the angle of the x-ray beam from P-A or A-P increases dose to the patient. This also occurs with CC tilt.

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Protection of the Patient

Dose Spreading

"Dose spreading" is the use of multiple x-ray fields on the skin to reduce the maximal dose to the skin.

Dose spreading can work well in cardiac fluoroscopy, which is performed with narrow x-ray beams and where widely varying beam angles are used to view the anatomy.

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Protection of the Patient

Dose Spreading

Attempts at dose spreading can increase the peak skin dose significantly if the beams overlap on the skin (Pasciak and Jones, 2011). (Overlap is more likely with wide beams.)

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Protection of the Patient

- Be aware of particularly sensitive tissues such as the breast in girls and younger women, eyes, and thyroid.
- Use gonadal shielding when the patient's gonads are in the primary beam and shielding them will not obscure anatomy that must be viewed.
- If scatter is small (small children), removal of the grid can greatly reduce dose.
- Ensure that the patient's arms are out of the beam in oblique and lateral views.

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Protection of the Patient

Case in which a patient's arm was accidentally positioned in the x-ray beam during an ablation for supraventricular arrhythmias.

The patient's arms may be hidden by drapes.



(Wong L., Rehm J. Radiation Injury from a Fluoroscopic Procedure, N Engl J Med, June 17, 2004 Vol. 350 No. 25, e23).

101

Protection of the Patient

- Minimize image recording.
- Use the lowest acceptable cine frame rate (typically 15 frames/s for adults in cardiac angiography).
- Use lower dose fluoro store instead of higher dose imaging recording when the higher image noise can be tolerated.

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Protection of the Patient

Several of the operator-selectable factors that affect dose rate have a multiplicative effect:

Example:

- Continuous mode instead of pulsed fluoro at 7.5 f/s: 2.6 x
- Source-to-skin distance 60 cm vs. 70 cm: 1.3 x
- Magnification mode 20 cm vs. 28 cm: 1.5 x
- Gap between patient and image receptor of 15 cm: 1.3 x
- Total increase in dose rate: $2.6 \times 1.3 \times 1.5 \times 1.3 = 6.6$

Example from Wagner, Archer, Cohen, 2000.

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Protection of the Patient

Notifications to the Operator

The Society of Interventional Radiology and National Council on Radiation Protection and Measurements recommend that a technologist, nurse, or another person be assigned to notify the operator when the following dose metrics are reached:

Parameter	First Notification	Subsequent Notifications
Peak skin dose	2000 mGy	500 mGy
Reference point air kerma	3000 mGy	1000 mGy
Kerma area product*	300 Gy·cm ²	100 Gy·cm ²
Fluoro time	30 min	15 min

* Assuming a 100-cm² field at the patient's skin. The value should be adjusted to the actual procedural field size.

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Protection of the Patient

AFTER THE PROCEDURE

- Document the skin doses (if available), reference point air kerma, kerma-area-product, fluoroscopic beam-on time and number of images recorded for each patient procedure as clinical QA metrics.
- For procedures exceeding a threshold (e.g., air kerma exceeding 3 Gy):
 - Record the estimated skin doses and locations of irradiated skin in the patient's medical record.
 - Counsel the patient on possible effects and to contact you if effects occur.
 - Arrange for follow-up of the patient.

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Protection of the Patient

PATIENT FOLLOW-UP WHEN THE SKIN DOSE IS OF CONCERN

- Unless skin dosimeters or radiation dose monitoring film is used, it is currently difficult to accurately estimate skin doses.
- For procedures for which the reference point air kerma exceeds a threshold (perhaps 3 Gy), inform the patient of possible effects, instruct the patient on examination of the skin, and arrange for follow-up.
- Arrange for such a patient to be examined at about two to three weeks after the procedure to see if main erythema occurs. If main erythema does not occur by 30 days, the peak skin dose was likely less than 6 gray and further follow-up is likely unnecessary.
- If main erythema occurs, notify the patient and arrange for further follow-up.

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Protection of the Patient

PATIENT FOLLOW-UP WHEN THE SKIN DOSE IS OF CONCERN

- Prevent dermatologists from performing biopsies.
- Serious injuries, as defined in 21 CFR 803, must be reported to the device manufacturer.
- The Joint Commission defines a skin dose exceeding 15 gray as a sentinel event. TJC guidance suggests that this should include all procedures within a period of six months or a year.
 - Note: This definition of a sentinel event is very awkward. Peak skin dose is seldom known. Estimations of peak skin dose have large uncertainties.

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Protection of Staff

Basic Principles of Radiation Protection

- Time
- Distance
- Shielding

Most actions that reduce dose to the patient also reduce doses to staff.

Good communication is important. Announce when you are about to activate fluoroscopy and image recording so staff can step back or go behind shielding.

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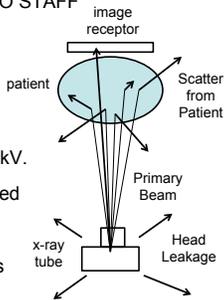
Exposure Rates in Fluoroscopy

SOURCES OF EXPOSURE TO STAFF

The major source of exposure to staff is scatter from where the x-ray beam enters the patient.

Tube head leakage is not significant except at very high kV.

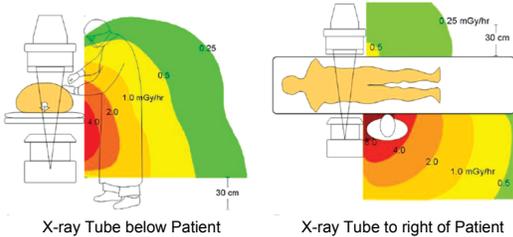
When the x-ray beam is oriented at an oblique angle or laterally, the dose to the operator is highest when he or she is on the same side of the patient as the x-ray tube.



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Exposure Rates in Fluoroscopy

EXPOSURE TO STAFF



(Diagrams from Schueler, BA, *Operator Shielding: How and Why*. Tech Vasc Interv Radiol. 2010 Sep;13(3):167-71)

110

Protection of Staff

SHIELDING OF STAFF

Wearable

Protective aprons

Thyroid shields

Shielded glasses, goggles, or face shields

Lead gloves - must be at least 0.5 mm lead equivalent

Rolling freestanding lead shields

Transparent ceiling-suspended shields

Lead curtain below patient table

Lead in walls of room and control booth window

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Protection of Staff

Protective Aprons

- Lead Thickness - typically 0.25, 0.375, and 0.5 mm lead equivalent
- Skirt-vest combinations and other designs - place much of the weight on the hips.
- Non-lead aprons can produce equivalent attenuation at slightly less weight than conventional lead aprons.
- Ancillary personnel should wear wrap-around aprons.
- Should be handled gently and stored on hangers to avoid formation of cracks.



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Protection of Staff

SHIELDING OF STAFF

- Shielded glasses - should have side-shields because the operator faces the display monitor during x-ray production.
- Thyroid shield



113

Protection of Staff

SHIELDING OF STAFF

Rolling freestanding shields



114

Protection of Staff

SHIELDING OF STAFF

Transparent ceiling-suspended shield

Should be positioned so the operator can see the beam entrance site on the patient through the shield.



Lead curtain below patient table

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Protection of Staff

SHIELDING OF STAFF

Transparent ceiling-suspended shield

Should be close to patient and toward the operator



Lead shield beside and lead curtain below the patient table

(Photo from NCRP Report No. 168. Reprinted with permission of the National Council on Radiation Protection and Measurements, <http://NCRPonline.org>).

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Protection of Staff

HANDS IN THE X-RAY BEAM

- Avoid whenever possible.
- If unavoidable, ensure your hands are on the side of the patient opposite the x-ray tube.
- Particularly avoid cases in which your hands are in x-ray beam not attenuated by the patient.
- Leaded gloves in the beam may cause the fluoroscope to increase output.
- A finger dosimeter can monitor dose to the hand.



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Protection of Staff

- Wear protective clothing
- Use shielding
- Maintain distance from the where the beam intercepts the patient
- During oblique and lateral projections, it is preferable for the operator to be on the same side as the image receptor
- The operator should warn staff before starting fluoro and particularly before cine and DSA runs



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Measuring Exposures of Medical Staff

PERSONAL DOSIMETERS

Body dosimeter



Finger dosimeter



The dosimeters above are typically worn for a month and returned to the vendor. The vendor reads them and sends a dose report.

Self-reading dosimeter



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Measuring Exposures of Medical Staff

PERSONAL DOSIMETERS

Two options for wearing dosimeters with a lead apron:

- Single dosimeter outside the apron at the collar, or
- A dosimeter outside the apron at the collar and another dosimeter on the chest or abdomen under the apron.

Finger dosimeter when the hands may receive a much larger dose than the body.



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Measuring Exposures of Medical Staff

PERSONAL DOSIMETERS

Do not share dosimeters with other people.
Store in a low background area.

COMMON PROBLEMS WITH DOSIMETERS

Lost
Not worn
Washed in laundry
Left in x-ray room (often on a lead apron)
Left in hot car in the sun

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Fluoroscopy Policy

Each facility should have a fluoroscopy policy:

- Training and credentialing of fluoroscopy operators and supervisors
- Training of assisting staff
- Screening of patients for risk factors before procedures
- Best practices for minimizing patient dose
- Best practices for minimizing doses to staff
- Recording indices of patient dose
- Follow-up of patients whose dose indices exceed a threshold
- Monitoring dose indices in a QA program
- Oversight by Radiation Safety Committee and RSO

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Regulatory Environment

- US Food and Drug Administration (FDA)
 - regulates the manufacture of x-ray machines
 - requires reports of serious injuries and deaths from medical devices (21 CFR Part 803)
- State Governments - Most states regulate the medical use of x-ray machines at non-federal facilities

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State Regulations

Annual Dose Limits for Staff:

- 50 mSv (5 rem) effective dose equivalent
- 500 mSv (50 rem) to the skin of the extremities
- 150 mSv (15 rem) to the lenses of the eyes

Occupational doses must be kept as low as reasonably achievable (ALARA).

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State Regulations

PREGNANT STAFF

- Pregnant staff have two options:
 - Do not declare pregnancy – no fetal dose limit; subject to same dose limits as other staff
 - Voluntarily declare pregnancy – fetal dose limit
- Additional dosimeter is issued to wear on the abdomen under protective apparel.
- Fetal dose limit is 5 mSv (0.5 rem) for duration of the pregnancy.
 - Efforts must be made to avoid substantial variation above a uniform monthly rate.
- Under-apron dosimeter is highly unlikely to show a dose approaching this limit.

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Summary – Protection of the Patient

- Screen for risk factors. Be aware obesity increases dose
- Maximize the distance of the patient from the x-ray source.
- Minimize the image-receptor-to-patient distance.
- Select lower dose modes and lower fluoro pulse rates.
- Select the lowest acceptable magnification.
- Remove the grid for small patients, small body parts, and when the image receptor is far from the patient.
- Aggressively collimate the x-ray beam.
 - Use "virtual collimation" to adjust the shutters.
- Minimize beam on-time. Fluoro only to see motion. Use tap fluoro. Use last image hold to study the image.
- Minimize image recording. Use fluoro-store as a low dose alternative when you can tolerate the increased noise.
- Be aware steep beam angles increase dose.
- Ensure, in steep oblique and lateral projections, that the patient's arm is not in the beam.

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Acknowledgments

Several slides are adapted from another presentation prepared in collaboration with Cynthia Wilson, RN, Cardiac Cath Lab Manager, VA Palo Alto Health Care System.

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Several photographs are courtesy of Stephen Balter, Ph.D., FACR, FAAPM, FSIR, Columbia University. This presentation is heavily influenced by his work.

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Questions or Comments?

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